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ABSTRACTS

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Plenary Lectures

Unraveling the Impact of Greenhouse Gases and Aerosols on Changes in Extreme Rainfall

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Model projections of the future climate revealed that climate change is expected to alter the large-scale pattern in mean precipitation, the seasonal rainfall characteristics, the frequency and intensity of extreme weather events, the risks of water scarcity and flood, as well as the amount of water discharge in many rivers of the world.

Based on previous formal detection and attribution analysis, we found that the slowly evolving increase in greenhouse gas emissions and the inhomogeneous spatial repartition of anthropogenic aerosols emissions have already influenced the observed changes in precipitation and aridity through two emerging mechanisms: a global warming-driven land aridification and intensification of the wet-dry rainfall patterns, and an aerosol-driven inter-hemispheric temperature contrast governing the position of the tropical rain belt position.

In this work, we explored the other end of the hydrological spectrum and investigated the underlying causes of the recent observed changes in extreme rainfall events. We focused on the changes in extremes derived from daily rainfall data, with an emphasis on 1) the role of anthropogenic aerosols; 2) the role of climate sensitivity, and 3) the role of horizontal resolution, along with an analysis evaluating the sensitivity of results to the choice of precipitation extreme indices and observational datasets. Finally, we compared our results with those obtained with traditional and machine-learning methods.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Improved Homogenisation of Observations Shows Steadier and Faster Historical Global Warming

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Instrumental climate records are foundational for understanding Earth's climatic history, not only for quantifying historical climate changes but also for benchmarking climate models and refining the accuracy of climate predictions. Despite their crucial role, the task of estimating Earth's surface temperatures since 1850 —through data gathered from an extensive network of terrestrial weather stations and oceanic voyages -— presents substantial challenges. Specifically, early temperature measurements are fraught with biases and errors from diverse sources, complicating efforts to achieve a consistent and homogeneous dataset.

In this talk, I will review the history and recent advances in statistical methods for homogenising ocean and land temperature records, as well as the inter-calibration across these two data archives. These include a physics-informed group-wise inter-comparison method for homogenising sea-surface temperatures, an improved pair-wise homogenisation algorithm for land station temperatures, and a coupled model of air-sea heat exchange for inter-calibrating ocean and air temperatures along coasts. Compared with existing approaches, these methodological advancements improve the accuracy of detecting, estimating, and adjusting data biases. Multiple lines of evidence including metadata, physical knowledge, paleo proxies, and historical documents are used to check the results of these statistical analyses.

Applying these methodological advancements, we first homogenise ocean and land temperature archives individually and then across the two archives to obtain a consistent estimate of global temperature records, which we call the Dynamically Consistent ENsemble of Temperature (DCENT). DCENT is a global, gridded data set that features 200 members that comprehensively represent uncertainty.

DCENT shows a steadier and 10% larger increase in global mean surface temperatures since 1850. The steadier warming in DCENT better aligns with the expected temperature responses to external radiative forcing, implying a reduced role for internal variability in historical warming patterns. The greater warming points to an earlier surpassing of the 1.5°C target set forth in the Paris Agreement, with five-year-average temperatures expected to exceed this threshold by 2029.

Despite these advancements, opportunities exist to further improve the accuracy and completeness of historical climate records. Future efforts could involve the continued rescue of data and metadata, improving regional reconstructions, and better integrating instrumental records and paleo proxies. Equally important, extending homogenisation to encompass multiple types of climate records, for example, temperature and sea-level pressure, promises to yield a more coherent understanding of historical climate variations. Together, these avenues of research hold the potential to further refine our understanding of Earth's historical climate and better inform climate projections.

Multi-century disaster gaps followed by strong clusters of extreme precipitation – understanding the irregular occurrence of local heavy rainfall

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Historical archives and climate model simulations show that there can be multi-century periods with no local extreme precipitation, referred to as disaster gaps, followed by temporal clusters of extreme precipitation within few decades. The irregular occurrence of extreme precipitation represents a major challenge for detection and attribution of climate signals, adaptation planning, and for insurance pricing. Here, we use the first large ensemble of a convection-permitting model (including twelve 100-year simulations) and multi-century GCM simulations to study the irregular occurrence of local precipitation extremes.

We show that local extreme precipitation events occur highly irregularly, with potential clustering (11% probability of five or more 100-year events in 250 years) or long disaster gaps with no events (8% probability for no 100-year events in 250 years). Even for decadal precipitation records, there is almost a 50% chance of a complete absence of any tail events in a 70-year period, the typical length of observational or reanalysis data. This generally causes return levels – a key metric for infrastructure codes or insurance pricing – to be underestimated.

We then explore whether the occurrence of extreme precipitation events is purely random ("white noise") or induced by low-frequency modes of internal variability, such as the multi-decadal variability in the North Atlantic. Surprisingly, we find based on millennial climate simulations and large initial condition ensembles that long-term variability in extreme precipitation is largely random, with no clear indication of low-frequency decadal to multidecadal variability.

The irregular occurrence of events and particularly the long disaster gaps make it challenging to estimate return periods for planning and for extreme event attribution. If a standard GEV model is fit to data lacking tail events, the resulting return levels are biased low, and consequently, the return period of extreme events is substantially overestimated. We evaluate the potential of employing information across neighboring locations, which substantially improves the estimation of return levels by increasing the robustness against potential adverse effects of long-term internal variability.

Deep Learning for Statistical Downscaling: Recent Advances and Perspectives

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Recent advances in artificial intelligence in the field of deep learning are producing major breakthroughs in several areas of meteorology and climate. In particular, these techniques have been recently introduced for statistical downscaling of climate change projections under the perfect prognosis approach [1,2], allowing continental-wide applications in the framework of the CORDEX initiative [3]. One of the reasons why deep learning models are gaining prominence is their ability to achieve downscaled projections with a relatively low computational cost, in contrast to regional climate models, which demand specialized infrastructures and a significant amount of time. Although these results have sparked the interest of researchers and stakeholders in this field, several important aspects remain unexplored.

One of the main concerns in the climate community arises from the inherent difficulty in interpreting and understanding deep learning models, an aspect generally referred to as the black-box nature of deep learning models. This raises concerns regarding the ability of these models to adhere to physical constraints and accurately learn patterns grounded in physics, an aspect that is crucial for instilling confidence in the extrapolation process. Recently, eXplainable Artificial Intelligence (XAI) techniques have been applied to this problem [4-6], revealing key information regarding the inner functioning of these models and helping to identify model pitfalls (e.g. when extrapolating to future scenarios [7]). Some recent experiences have also shown that it is possible to impose certain physical constraints on these models in a straightforward way [8,9], helping to make them more robust and credible.

Besides this challenge, there are other issues that require attention from the downscaling community, such as the spatial and multivariate consistency of the resulting projections or the need for uncertainty quantification, especially under climate change conditions. Generative models seem promising for these problems but applications are still limited.

In this talk we revise the recent work done in this field, focusing on the different deep models introduced in the downscaling literature, discussing their advantages and limitations, and providing some perspectives for future development.

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[2] Baño-Medina, J., Manzanas, R., & Gutiérrez, J. M. (2021). On the suitability of deep convolutional neural networks for continental-wide downscaling of climate change projections. Climate Dynamics, 57, 2941-2951.

[3] Baño-Medina, J., Manzanas, R., Cimadevilla, E., Fernández, J., González-Abad, J., Cofiño, A. S., & Gutiérrez, J. M. (2022). Downscaling multi-model climate projection ensembles with deep learning (DeepESD): contribution to CORDEX EUR-44. Geoscientific Model Development, 15(17), 6747-6758.

[4] Baño-Medina, J. (2020, September). Understanding deep learning decisions in statistical downscaling models. In Proceedings of the 10th International Conference on Climate Informatics (pp. 79-85).

[5] Rampal, N., Gibson, P. B., Sood, A., Stuart, S., Fauchereau, N. C., Brandolino, C., ... & Meyers, T. (2022). High-resolution downscaling with interpretable deep learning: Rainfall extremes over New Zealand. Weather and Climate Extremes, 38, 100525.

[6] Balmaceda-Huarte, R., Baño-Medina, J., Olmo, M. E., & Bettolli, M. L. (2024). On the use of convolutional neural networks for downscaling daily temperatures over southern South America in a climate change scenario. Climate Dynamics, 62(1), 383-397.

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[9] Harder, P., Hernandez-Garcia, A., Ramesh, V., Yang, Q., Sattegeri, P., Szwarcman, D., ... & Rolnick, D. (2023). Hard-Constrained Deep Learning for Climate Downscaling. Journal of Machine Learning Research, 24(365), 1-40.

Can past analogue events inform on climate risk

Gabriele HEGERL

University of Edinburgh, United Kingdom

This presentation discusses examples of how climate risk can be informed using observed events, and considering how such events may change in the future. I will introduce the topic using examples, such as historic heat waves in the UK. Analogue methods can be used to push past events into the future, and attribution results to evaluate changes in frequency with evolving greenhouse gas forcing. However, some risks don't change linearly, and consequences of extreme events may change under further warming. While historical events can inform on the chain of impacts in a specific case, they can only provide a range of possibilities, and may miss feedbacks that are more likely to occur in a warmer climate, such as soil moisture drought or fire. This talk links to the World Climate Research Programme lighthouse activity on safe landing climates

Modeling of spatial extremes in environmental data science: Time to move away from max-stable processes

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Environmental data science for spatial extremes has traditionally relied heavily on max-stable processes. Even though the popularity of these models has perhaps peaked with statisticians, they are still perceived and considered as the "state-of-the-art" in many applied fields. However, while the asymptotic theory supporting the use of max-stable processes is mathematically rigorous and comprehensive, we think that it has also been overused, if not misused, in environmental applications, to the detriment of more purposeful and meticulously validated models. In this talk, I will first review the main limitations of max-stable process models, and strongly argue against their systematic use in environmental studies. I will then discuss alternative modeling solutions based on more flexible frameworks using the exceedances of variables above appropriately chosen high thresholds, as well as modern fast and efficient deep-learning-based statistical inference methods, and illustrate their practical use in applications. In particular, I will describe examples where flexible spatial extremes models are used to understand the joint behavior of surface temperature extremes in the Red Sea, as well as high air pollution levels over the entirety of Saudi Arabia. I will end the talk with an outlook on future research, highlighting seven recommendations moving forward and the opportunities offered by hybridizing machine learning with extreme-value statistics.

Bayesian nonparametric emulation and calibration of climate models

Matthias Katzfuss

University of Wisconsin–Madison, United States of America

A climate model (CM) is a set of differential equations representing the behavior of the Earth system. For a given input-parameter value, the CM encodes a distribution that is analytically intractable but samples of which can be produced at high computational cost by running the CM with slightly perturbed initial conditions. The goal is to calibrate the CM by finding the parameter value that most closely matches the CM to the true climate distribution. We propose CM calibration via Bayesian optimization using a flexible probabilistic surrogate consisting of autoregressive Gaussian processes whose inputs include the CM input parameters. Our framework is scalable and hence it can be applied to large spatial climate fields. We demonstrate the performance of the approach on numerical examples.

Changepoint Estimation in Climatology

Rebecca Killick[1], Michael Holloway[2], Mengyi Gong[1]

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In contrast with other fields, it is well accepted in Climatology that climate time series contain changes over time; whether as part of station moves, and/or evolving climate dynamics. There are many different (statistical) ways to model these changes over time. This talk introduces the field of changepoint detection as the simplest departure from the assumption of constant (statistical) properties over time. Following an introduction to the benefits and limitations of changepoint models we will touch on two recent developments in changepoints for climatological data; detecting changepoints in spatio-temporal data motivated by air quality, and how changepoints can be used to model soil moisture drydown dynamics.

Air quality is an important measure for both ongoing public health and as part of climate modelling. Changes in the spatio-temporal distribution of air quality are important in the short term, e.g. for managing biohazards, and in the longer term for informing climate scenarios or predicting response to climate forcings. We present a spatio-temporal changepoint method that utilises a generalised additive model (GAM) dependent on the 2D spatial location and the observation time to account for the underlying spatio-temporal process.

Improvements in real-time soil sensing opens up new opportunities for gaining a deeper understanding of the dynamics of soil properties. It also calls for the development of efficient data analysis methods that can extract physically interpretable information about soil processes from real-time data. We describe an automated, changepoint-based method that can be used to define a ``soil signature'' - where physically interpretable quantitative metrics characterising soil properties and processes are extracted from continuous data. These features can then be associated to the soil texture of the field sites and climate regimes, as well as consideration of degradation and restoration of these soil properties over time.

Using spatial extreme-value theory with machine learning to model and understand spatially compounding extremes

Jonathan KOH

University of Bern, Switzerland

When extreme weather events affect large areas, their regional to sub-continental spatial scale is important for their impacts. We propose a novel methodology that combines spatial extreme-value theory with a machine learning (ML) algorithm to model weather extremes and quantify probabilities associated with the occurrence, intensity and spatial extent of these events. The model is here applied to Western European summertime heat extremes. Using new loss functions adapted to extreme values, we fit a theoretically-motivated spatial model to extreme positive temperature anomaly fields from 1959--2022, using the daily 500-hpa geopotential height fields across the Euro-Atlantic region and the local soil moisture as predictors. Our generative model reveals the importance of individual circulation features in determining different facets of heat extremes, thereby enriching our process understanding of them from a data-driven perspective. The occurrence, intensity, and spatial extent of heat extremes are sensitive to the relative position of individual ridges and troughs that are part of a large-scale wave pattern. Heat extremes in Europe are thus the result of a complex interplay between local and remote physical processes. Our approach is able to extrapolate beyond the range of the data to make risk-related probabilistic statements, and applies more generally to other weather extremes. It also offers an attractive alternative to physical model-based techniques, or to ML approaches that optimise scores focusing on predicting well the bulk instead of the tail of the data distribution.

Predicting the counterfactual: challenges and opportunities of forecast-based attribution

Nicholas James LEACH[1,2], Shirin Ermis[1], Olivia Vashti Ayim[1], Sarah Sparrow[3], Fraser Lott[4], Linjing Zhou[5], Pandora Hope[5], Dann Mitchell[6], Antje Weisheimer[7,8], Myles Allen[1,9]

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Interest in the question of how anthropogenic climate change is affecting extreme weather has grown considerably over the past few years - and 2023 was no exception. This increase in interest has brought a need for robust approaches that are able to quantitatively answer this question rapidly after an event occurs. However, conventional attribution frameworks using statistical or dynamical climate models have been challenged by several recent events that lay well beyond the historical record.

While such events have proven difficult to attribute using conventional methodologies, many were surprisingly well forecast by high-resolution numerical weather prediction systems. These systems generally lie at the state-of-the-art in the spectrum of earth system modelling, and their deficiencies are well documented and understood. We suggest that they therefore represent an opportunity for answering attribution — and other weather and climate risk-related — questions, based on models that are demonstrably able to simulate the often non-linear physics of the extremes that we are most interested in. This can increase the confidence in any attributable changes assessed since such changes can be explained in terms of the underlying physical processes. Further, as attribution science extends beyond purely physical assessments and into socioeconomic impacts, this opportunity will grow: weather models are already widely used by risk and emergency management professionals as inputs to hazard models. A final advantage of basing attribution statements on weather forecast models is that it is not only apparent when a forecast model can be used — but also when the model has a crucial deficiency as indicated by a forecast bust. In this case it would be clear that making a quantitative attribution statement would not be appropriate.

In this talk, we will introduce the work we have done in leveraging weather forecasts to carry out event attribution analyses. We will discuss challenges over current experiment design and ideas about how best to move forward, and potential opportunities for identical experiment designs outside of event attribution. As part of this discussion, we will present a new set of perturbed forecasts for attribution, initialised twice per week during the 2022-23 (NH) winter season in both pre-industrial and future climates. This season of forecasts represents the milestone of moving from experiments targeting isolated events and towards a real-time operational system.

Strong El Niño events lead to robust multi-year ENSO predictability

Nathan Lenssen[1,2,3], Pedro DiNezio[2], Lisa Goddard[3,8], Clara Deser[4], Yochanan Kushnir[5], Simon Mason[3], Matt Newman[6], Yuko Okumura[7]

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The El Niño - Southern Oscillation (ENSO) phenomenon -- the dominant source of climate variability on seasonal to multi-year timescales -- is predictable a few seasons in advance. Forecast skill at longer multi-year timescales has been found in a few models and forecast systems, but the robustness of this predictability across models has not been firmly established owing to the cost of running dynamical model predictions at longer lead times. In this study, we use a massive collection of multi-model hindcasts performed using model analogs to show that multi-year ENSO predictability is robust across models and arises predominantly due to skillful prediction of multi-year La Nina events following strong El Niño events.

Paper: N. Lenssen, P. DiNezio, L. Goddard, C. Deser, Y. Kushnir, S. Mason, M. Newman, Y. Okumura (under review), "Strong El Nino Events Lead to Robust Multi-Year ENSO Predictability" Geophys. Res. Lett. Preprint: 10.22541/essoar.169867644.44652031

Interpretable stochastic weather generator, application to a crop model, and climate change analysis

David METIVIER

INRAE, France

The challenges of climate change force industrials to carefully analyze the resilience of their assets to anticipate future weather conditions. In particular, the estimation of future extreme hydrometeorological events, like the frequency of long-lasting dry spells, is critical for hydropower/nuclear generation or agriculture. Stochastic Weather Generators (SWG) are essential tools to determine these future risks, as they can quickly sample climate statistics from models. In this work, the SWG described and validated with French historical data is based on a spatial Hidden Markov Model (HMM). It generates (correlated) multisite precipitation, with a special focus on the correct reproduction of the distribution of dry and wet spells. The hidden states are viewed as global weather regimes, e.g., dry all over France, rainy in the north, etc. The resulting model is fully interpretable; it can even approximately recover large-scale structures such as North Atlantic Oscillations. The model achieves very good performances, specifically in terms of extremes, e.g., drought statistics. Its architecture allows easy integration of multiple weather variables. We show an application where it is used to generate realistic precipitation, temperature, solar radiation and evapotranspiration time series as inputs to a crop model. We'll also show how the model parameters evolve when trained on RCP climate scenarios and the impact of these changes on extreme climatic events.

Thirty years of optimal fingerprinting : What has it achieved?

Peter Alister STOTT

Met Office, United Kingdom

I will review the history of optimal fingerprinting over the last thirty years and its contribution to understanding the causes of climate change. In the context of the hugely important necessity to curb global greenhouse gas emissions, what has optimal fingerprinting achieved historically and what is its role today?

Developments and challenges in attributing climate change impacts

Sabine Undorf[1], Asya Dimitrova[1,2], Luke Harringon[3], Gabi Hegerl[4], Aglaé Jézéquel[5,6], Joyce Kimutai[7], Eunice Lo[8], Matthias Mengel[1], Sarah Perkins-Kirkpatrick[9], Rosa Pietroiusti[10], Izidine Pinto[11], Andrew Schurer[4], Paolo Scussolini[12], Sebastian Sippel[13], Dáithí Stone[14], Rupert Stuart-Smith[15], Wim Thiery[10], Bridging Climate and Impact Attribution Workshop[16]

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Identifying and quantifying the impacts of climate change already being observed is of interest to society and science alike. Attribution studies to that effect are multiplying, increasingly engaging expertise from relevant scientific disciplines as diverse as ecosystem science and economics while still leaving gaps. These studies rely on a variety of different data and methods and differ widely in research scope and focus; even the terminology is debated. As a result, it becomes increasingly difficult to see which questions are (not) addressed by different attribution studies, and, inversely, what data and methods should best be used in new studies on underattributed regions/hazards/impacts. This lack of clarity hinders progress in climate impact attribution.

Here, we offer a collective contribution from many climate (impact) attribution experts to help overcome these obstacles. In particular, we will aim to shed light on the contemporary state of attribution science by mapping existing studies to the causal chain, or spectrum, spanning all the way from anthropogenic emissions, ensuing changes in atmospheric composition, changes in climate and weather, in the physical world, and in the biosphere and industry, to society. We will note that the literature has drawn different lines within this spectrum, for example, between studies that link observed changes/events in a ‘climate-related system’ to anthropogenic climate forcing, and those that link from the observed changes in climate to ‘changes in natural, human or managed systems’ (IPCC, 2022). We will suggest that this split is increasingly artificial and that the methodological differences resulting in attribution to anthropogenic or observed climate change are one approximation among many others, such as attribution to greenhouse gas forcing or combined anthropogenic forcing, the appropriateness of which depends on the specific research aims.

We will then highlight three main components of attribution studies, including the breadth of types of observations and models and their respective peculiarities for the different parts of the climate/impact spectrum, and how to generate counterfactual data, and climate counterfactuals in particular. We will then discuss key choices made in attribution studies, such as the choice of analytical framework, of counterfactual generation, of how many, and which, links within the causal spectrum are covered, and we will mention factors influencing this choice and their implications for uncertainty propagation. We will then look at the various possible societal uses of attribution studies and how they map onto these methodological choices, namely awareness raising to motivate action; risk management and adaptation; Loss and Damage; and climate litigation, and present characteristics of attribution studies facilitating these uses as well as potential risks.

Finally, we will clarify in which respects the existing practices in their variety constitute obstacles or enablers of scientific progress and of societal use of the results in ways that do not miss- or overinterpret the scientific results. We will conclude by identifying practical obstacles for extended and improved climate impact attribution science, and suggest steps to overcome them, especially considering the heterogeneity and interdisciplinarity of all the causal links involved in such analyses.

Session 01: Climate Records (oral presentations)

Climate records: dataset creation, homogenization, gridding and uncertainty quantification, including observationally constrained analyzed and reanalysed products

Propagation of uncertainties from space geodetic measurements to the global ocean heat content and the earth energy imbalance

Michaël ABLAIN[1], Benoit MEYSSIGNAC[2], Robin FRAUDEAU[1], Florence MARTI[1], Victor ROUSSEAU[1], Pierre PRANDI[3]
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Altimetry missions now provide nearly 30 years of precise, accurate, and continuous, near-global sea-level measurements, thanks to the TOPEX/Poseidon, Jasons (1,2,3) and more recently Sentinel-6 Michael Freilich reference missions. These measurements are used to construct the global mean sea level record, enabling us to estimate its evolution (+3.3 mm/year) and acceleration (+0.12 mm/year²) with great accuracy (respectively 0.3 mm/year and 0.07 mm/year² within a 90% confidence interval). By combining these altimetry measurements with space gravimetry (GRACE and GRACE-FO missions) measurements of the ocean mass variations (or barystatic sea level variations), the ocean heat content change and the Earth's energy imbalance (+0.8 W.m-2) can be deduced with high accuracy (+0.16 W.m-2 within a 90% confidence interval, (Marti et al., 2023)) over 2002-2022.

This study aims at presenting how the uncertainties are propagated from space geodetic measurements to the global ocean heat content (GOHC) change and the Earth energy imbalance (EEI). We compute the error covariance matrices of the total sea level and barystatic sea level observations, using two different approaches: an uncertainty budget approach (Guérou et al., 2022) and an ensemble approach (Blazquez et al., 2018). The resulting error covariance matrices are then propagated to account for the entire processing chain of the GOHC and EEI climate indicators. Once the GOHC and EEI error covariance matrices are known, the statistical parameters (e.g. trend, acceleration) can be estimated at any time-spans from the mathematical formalism defined in (Ablain et al., 2019) consisting of fitting a trend or an acceleration from a linear regression model.

This work was performed based on global mean time-series, and investigations are ongoing to characterise the uncertainties at regional scales both for altimetry (Prandi et al., 2021) and gravimetry inputs.

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Assessing Seasonal Rainfall Trend in Federal Capital Territory (FCT) Abuja Nigeria

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Abstract.

Increased loss of lives and damage to properties caused by flash floods prompted the evaluation of the seasonal rainfall trend in the Federal Capital Territory (FCT) Abuja; this study used daily Reanalysis data obtained from the National Oceanic and Atmospheric Administration (NOAA), National Centres for Environmental Prediction (NCEP), Climate Prediction Centre (CPC), and Famine Early Warning System (FEWS) combined archive. The data has been transformed into three sets of periods: three months, yearly, and five-year cumulative of 1991-2019. Linear regression analysis was employed to establish a trend in seasonal rainfall, and a test of the significance of the trend was done using Pearson's Chi-square. A graphical distribution was used to show how seasonal rainfall is distributed within the FCT. Descriptive statistics examined the relationship between ENSO phases and rainfall. The result showed that Bwari recorded the highest average seasonal rainfall, with the Abaji record as the least. It implies that the highest seasonal rainfall amount was recorded over the northern part of the (FCT). The general ENSO analysis indicated that 13.3% showed no agreement, while about 86.7% agreed that the ENSO phases drive rainfall patterns. The neutral phase had agreed by 50%, followed by El Nino, with 13.3%. This finding has given insight into the rainfall pattern, which will, in turn, give an understanding of the possible cause of the increase in flash floods and form a basis for scientific advisory. These results will contribute immensely to climate change adaptation in the FCT of Nigeria.

Keywords: Climate change, Seasonal Rainfall, Flash Flood, ENSO Phase

Intercomparison of climatologies and trends in ocean precipitation across multiple datasets

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For this study we compared climatologies and trends of ocean precipitation from a variety of satellite-based datasets and reanalyses from the Frequent Rainfall on Grids (FROGs) database over the 2001-2020 period. Using a set of indices to look at frequency and intensity aspects of mean and extreme precipitation, we found that satellite and reanalyses climatologies were similar when considering total wet-day precipitation although reanalyses tended to be slightly wetter in the tropics. When looking at wet-day precipitation intensity, however, satellites produce more intense values particularly in convergence zones but reanalyses tend to rain more frequently. When assessing the climatology of the wettest day of the year we find that satellites produce more intense precipitation in cyclogenesis regions and there is larger spread amongst products. The spread is largest in the tropics for intensity-based measures.

For trends, there is a lot of uncertainty across all aspects of precipitation we assessed. This is likely due to different issues in the reanalyses and satellite products. When there are large significant trends in a given product there is generally little agreement with the sign of these trends amongst other products at least for precipitation total, intensity and frequency. In fact in many cases, particularly for the satellite products there are opposite signs of significant trends. For wet-day precipitation totals, the satellite products tend towards increasing trends while the reanalyses tend towards decreasing trends. For intensity-based measures there is some coherence in the reanalyses in the extratropics and in the tropics for wettest day trends. Some products exhibit virtually no trend across all latitudes e.g. CMORPH for satellite-based products and to a lesser extent JRA-55 for the reanalyses. IMERG exhibits unusual behaviour between the tropics and extratropics and due to large interdependencies between products, a similar pattern is imprinted to some extent on GPCP. There are few spatially coherent significant trends in any product except IMERG where there are obvious regions in the tropics with decreasing trends and in the extratropics with increasing trends.

One interesting conclusion from this study is the physically unexpected negative trends in satellite data between 2001-2020 in the tropics despite the warming trend in SST over this period. Reanalyses on the other hand meet physical expectations in response to anthropogenic forcing with an increased wettest day trend in the tropics.

Has there been a recent acceleration in global warming?

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The global mean surface temperature is a widely used metric for monitoring the evolution of climate change. There is currently a debate in the climate literature as to whether there has been a significant surge or acceleration in the rate of climate change during the last three decades. Here we address this question from a statistical perspective and assess whether an increase in the rate of global warming is detectable. We use changepoint models, specifically designed to objectively identify the time of change in the parameters of a statistical model, to analyze four records of global mean surface temperature over 1850-2023. Our results show limited evidence for a warming surge– in most datasets there is no change detectable in the rate of warming beyond the 1970s. Furthermore, we estimate the minimum magnitude required for a surge to be detectable.

A non-stationary geostatistical model for the stochastic interpolation of daily rain gauge observations in mountain areas

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In mountains, topography-atmosphere interactions generate orographic effects which shape the spatial patterns of rainfall. The transitions between wet and dry areas can occur within few kilometers, creating strong horizontal gradients of rainfall statistics. The spatial variability of rainfall statistics breaks the hypothesis of stationarity on which rely most geostatistical models that are used for the spatial analysis of rainfall data, and in particular for gridding spatially sparse rain gauge observations. Using stationary models to process non-stationary data can lead to a degraded performance in spatial prediction, and to an unrealistic assessment of associated uncertainties.

To overcome these limitations, we present in this work a fully non-stationary trans-Gaussian geostatistical model dedicated to the stochastic interpolation of daily rain gauge observations over complex topography. This model allows not only for a non-stationary marginal distribution of daily rainfall accounting for rainfall intermittency and non-Gaussian intensity, but also for a non-stationary covariance structure of Matérn type that models the spatial dependencies.

The model is tested for the Island of Hawaiʻi (State of Hawaii, USA) where rainfall gradients are amongst the strongest on Earth and can reach 1000 mm.year-1/km. The model is tested for the stochastic interpolation of daily rainfall observations carried out by a network of 79 rain gauges covering the whole island. To make our model operable in practice, we designed a procedure to infer model parameters from rain gauge observations that are freely available in near-real-time on the Hawaiʻi Climate Data Portal. We also provide an efficient algorithm for stochastic interpolation on large grids, paving the way to applications on larger areas such as entire mountain ridges. Model assessment demonstrates good skills at interpolating sparse rain gauge observations in a strongly non-stationary context, and a proper assessment of interpolation uncertainties.

Reassessing the highest temperature recorded in Ireland at Kilkenny Castle on 26 June 1887

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1887 was an exceptional year in Ireland, the drought from early spring to autumn was the worst in 250 years and June 1887 was remarkably warm with twelve stations across Ireland recording highest daily maximum air temperatures of greater than 28 degrees Celsius, and seven stations recording values of 30 degrees Celsius or more. Indeed, the maximum daytime air temperature recorded at Kilkenny Castle on 26th June 1887 of 33.3 degrees Celsius still holds the record as the highest maximum temperature recorded in any month in Ireland. However, in the past few years there has been some debate about the veracity of the Kilkenny Castle record. Maximum air temperature records of most European countries were set in the 21st Century, in line with trends of a warming climate. Whilst Ireland recorded its second-highest temperature and warmest year in the 21st Century, it is the only European country to have a maximum air temperature record in the 19th Century. Met Éireann have recently completed a re-evaluation of the Kilkenny Castle record in 1887.

A number of the stations, including Kilkenny Castle were not available in digital format so prior to re-evaluating the record, data rescue was performed on all available paper records. Reassessment of the Kilkenny Castle record included analyses of the synoptic situations during June 1887, a literature review of journal, newspapers and other articles available for the time period in question, assessment of station metadata such as station inspection reports, comparison of Kilkenny maximum and minimum temperature series from 1885 to 1933 with other available stations in Ireland and extreme value analysis.

This presentation will discuss the steps undertaken to reassess the highest ever recorded air temperature for Ireland and the results and conclusion of the study.

Sector specific extension to an extremes indices dataset and comparisons to reanalyses

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For over two decades, indices have been used to effectively characterise changes in climate extremes, as demonstrated by several iterations of the Intergovernmental Panel on Climate Change assessment reports. The use of standardised climate extremes indices allows derived products to be widely and easily shared, and standardised software running alongside (training) workshops enables the widest set of contributors to the resulting data products. The most recent in situ observational product, HadEX3, is being extended to include indices which have been recommended by the WMO as being more relevant to specific sectors, such as health, agriculture and water resources. We outline the features of this extension (named HadEX3-ETSCI) which are intended to assist decision makers with accurate information on how these sector relevant measures have changed over time.

Despite the use of standardised indices and software alongside workshops, spatial and temporal gaps remain in the data products constructed from in situ observations. Thus, we also present a detailed comparison of the extended HadEX3 with indices calculated from a number of reanalyses. Temporal agreement between HadEX3 and the reanalyses is high for the temperature indices, especially those indices derived from exceedances of percentile thresholds. However, large differences can occur between all products for indices based on absolute values, especially for precipitation. Spatially, agreement is lower in regions where data are sparser, areas at high elevation or where the in situ observations have been interpolated into different climatic zones.

Satellite derived trends and variability of CO2 concentrations in the Middle East during 2014–2023

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The Middle East has major sources of anthropogenic carbon dioxide (CO2) emissions, but a dearth of ground-based measurements precludes an investigation of its regional and temporal variability. This is achieved in this work with satellite-derived estimates from the Orbiting Carbon Observatory-2 (OCO-2) and OCO-3 missions from September 2014 to February 2023.

The annual maximum and minimum column (XCO2) concentrations are generally reached in spring and autumn, respectively, with a typical seasonal cycle amplitude of 3–8 ± 0.5 ppmv in the Arabian Peninsula increasing to 8–10 ± 1 ppmv in the mid-latitudes. A comparison of the seasonal-mean XCO2 values with the CO2 emissions estimated using the divergence method stresses the role played by the sources and transport of CO2 in the spatial distribution of XCO2, with anthropogenic emissions prevailing in arid and semi-arid regions that lack persistent vegetation.

In the 8-year period 2015–2022, the XCO2 concentration in the United Arab Emirates (UAE) increased at a rate of about 2.50 ± 0.04 ppmv/year, with the trend empirical orthogonal function technique (TEOF) revealing a hotspot over northeastern UAE and southern Iran in the summer where anthropogenic emissions peak and accumulate aided by low-level wind convergence.

A comparison of the satellite-derived CO2 concentration with that used to drive climate change models for different emission scenarios in the 8-year period revealed that the concentrations used in the latter are overestimated, with maximum differences exceeding 10 ppmv by 2022. This excess in the amount of CO2 can lead to an over-prediction of the projected increase in temperature in the region, an aspect that needs to be investigated further.

This work stresses the need for a ground-based observational network of greenhouse gas concentrations in the Middle East to better understand its spatial and temporal variability and for the evaluation of remote sensing observations as well as climate models.

On the automatic application of a standard and enhanced quality control process for daily precipitation since 1960s in South America

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Long-term weather observations are essential to understanding past climate and extreme weather events. However, in many regions of the world, observational records are affected by many systematic quality data issues. Previous research has evidenced that these affect large fractions of observational datasets and remain largely undetected with standard data quality control procedures, particularly in areas with sparse coverage, topographic complexity, and low financial resources. One of the most effective ways to reduce these quality issues is by applying enhanced processes through data visualization techniques that let users manually correct errors or remove specific periods of the dataset. Nevertheless, by increasing the number of weather stations and the size of the study area, the data visualization approach is impractical and inefficient. In this regard, the proposed research aims to create a quality-controlled dataset of a raw daily precipitation database (> 14 000 time series) for the whole of South America by employing fully automatic standards and enhanced quality control procedures. To achieve this purpose, we first applied the standard quality control procedure, which consists of well-known tests from preceding research. In a second step, we developed and applied the enhanced quality control procedure that inspects often overlooked issues such as asymmetric rounding patterns, measurement precision inconsistencies, truncations, small gaps, and weekly cycles. Considering that South America presents a diversity of climates (tropical to sub-polar climates), enhanced quality control was applied following a climate-based classification using the percentage of wet days (dry to humid). Preliminary results indicated that the most important issues in the raw daily precipitation time series in South America were related to small gaps and asymmetric rounding patterns that can be traced back to measurement errors by the observers. Further, it was found that some specific regions suffer from measurement precision with no decimal values, such as Colombia, Uruguay, and northern Argentina. In addition, as the design of the enhanced quality control was empirically formulated, we also tested using high-quality and raw datasets from Switzerland (68 time series) and Spain (Aragon, 2317 time series), respectively. Similarly, for the South America database, we detected in Spain time series issues that come from small gaps, but for the Switzerland dataset, only one single station was flagged. This initial analysis evidenced many common data quality issues in South America that are usually not identified and attributed. Although the enhanced quality approach could identify very high-quality time series, it is still possible that some issues are not yet detected, and a trade-off between the number of removed time series and the reduction of the spatial coverage should also be considered to retain enough observed information in South America. Finally, the subsequent dataset will be used to create a gridded dataset of daily precipitation for the study area using weather reconstruction approaches since 1960s.

Locally Stationary Mapping and Uncertainty Quantification of Ocean Heat Content Based on Argo Profiles During 2004-2022

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Argo floats provide us with a unique opportunity to measure the global and regional Ocean Heat Content (OHC) and improve our understanding of Earth Energy Imbalance (EEI). Yet, producing Argo-based OHC estimates with reliable uncertainties is statistically challenging due to the complex structure and large size of the Argo dataset. Here we present the latest version of our mapping and uncertainty quantification framework for Argo-based OHC estimation based on state-of-the-art methods from spatio-temporal statistics. The framework is based on modeling vertically integrated Argo temperature profiles as a locally stationary Gaussian process defined over space and time. This enables us to produce computationally tractable OHC anomaly maps based on data-driven decorrelation scales estimated from the Argo observations. Our modeling choices for the mean field and the covariance function are validated using statistical cross-validation. We quantify the uncertainty of these maps using locally stationary conditional simulation ensembles, a novel approach that leads to principled uncertainty quantification that accounts for the spatio-temporal correlations in the OHC anomalies. The mapping framework is implemented in an open-source codebase that is designed to be modular, reproducible and extensible. We present a new Argo OHC data product with uncertainties for 2004-2022 based on this framework and report on various climatological estimates and their uncertainty obtained using this product.

Climatic warming in Shanghai over the recent 150 years based on homogenised temperature records

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Xujiahui (XJH) station in downtown Shanghai holds the longest continuous daily temperature series in China, which is unique for assessing modern climate change and impacts but must be homogenised. Due to non-natural factors such as changes in the observation system, the daily temperature series needs to be homogenized to accurately reflect the long-term climate change. Previous studies have established a normalized daily temperature sequence in Shanghai from 1873 to 1997 (Yan et al., 2001) and a monthly sequence up to recent years (Cao et al., 2013; 2017; Li et al., 2018), but both are multi-station concatenated series. The present work established a set of homogenised monthly and daily surface air temperature (SAT) series during 1873–2019 at XJH. Two major inhomogeneous break points (around 1954 and 1993) were identified in the original SAT series, which had been overlooked in previous works. The inhomogeneous biases were adjusted via the inter-station deviation analysis. The adjusted SAT series shows a warming trend of 1.9℃ per century compared with 1.7℃ per 100 years in the original series. The multi-decadal variations of quasi-32-year and quasi-64-year periods are weaker in the adjusted series than in the original series, suggesting overestimated multi-decadal variability in the original data due to inhomogeneous biases. Relative to the early period 1873–1900, the recent decade (the 2010s) is warmer by 2.2℃. Urbanisation has been responsible for approximately 19.3% of the rapid warming since the 1980s, which is smaller than the result calculated using the original sequence. The high and low SAT extremes exhibit significant warming, especially after the 1970s. The trend in the low SAT extremes in the adjusted series

is substantially larger than in the original series, implying that previous studies might underestimate the warming in cold extremes. The homogenised daily temperature series in XJH more accurately reflects the climate change in modern Shanghai urban areas, which may provide a new data basis for more related research.

A new statistical method for the homogenization of GNSS Integrated Water Vapour time series

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Water vapor plays a key role in the Earth's climate as a dominant greenhouse gas. It is also the most efficient actor of heat transfer from the surface to the atmosphere and from low to high latitudes which shapes the global circulation and weather systems. Monitoring and understanding the spatial and temporal variability and changes of water vapor are thus of crucial importance.

This work aims at constructing a global Integrated Water Vapour (IWV) climate data record from ground-based GNSS data. Although, GNSS observations are available with high accuracy in all weather conditions, abrupt shifts in the IWV time series have been reported. Such shifts are due to changes in instrumentation, in station location and environment, and in processing methods. Homogenization is a crucial step to detect and correct such non-climatic signals.

We have developped a differential homogenization method which involves three steps.

1) First, change-points are detected from the difference series (GNSS – reference) with the help of the GNSSseg segmentation package (Quarello et al., 2022). The method uses a difference series in order to cancel out the common climatic variations. It also accounts for changes in the variance on fixed intervals (monthly) and a periodic bias (annual) due to representativeness differences between GNSS and the reference (in our case the ERA5 reanalysis). Because the change-points detected in the difference series could be either due to GNSS or to the reference (ERA5), the next step is the attribution.

2) Second, the detected change points are attributed to either GNSS or to the reference (ERA5) using a statistical test based on linear regression and a predictive rule based on the Random Forest learning algorithm (Nguyen et al., 2023). This step requires additional neighbors stations (at least one).

3) The last step is the correction. Here the raw GNSS series are corrected for the shifts which are attributed to the GNSS.

We will present details of the method and results of an application to a global network of GNSS stations. We will also analyze the impact of homogenization on linear trend estimates for stations with up to 30 years of observations.

Quarello et al., 2022, https://doi.org/10.3390/rs14143379

Nguyen et al., 2023, https://hal-obspm.ccsd.cnrs.fr/IGN-ENSG/hal-04014145v1

Uncertainty characterization of Mean Sea Level measurements from satellite radar altimetry

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Satellite radar altimetry provides accurate measurements of ocean surface topography over 30 years, from TOPEX/Poseidon to Sentinel-6A. These measurements are used to estimate regional and global sea level long term variability with great accuracy. An error budget approach allows to estimate reliable uncertainties on sea level trends (+/- 0.3 mm/yr, 90%CI) and accelerations (+/-0.07 mm/yr/yr, 90%CI) coming from uncertainties in the observing system. This approach is used both at global and regional scales in order to provide a thorough description of uncertainties to downstream users.

In this talk, we aim to present how the uncertainty budget is constructed as well as the framework used to propagate these uncertainties to sea level trends and accelerations. Several limitations of our current uncertainty budget are also discussed, along with current investigations to overcome some of these limitations. Foreseen improvements of the mathematical framework currently in use are also presented.

Advancements in Changepoint Analysis and Its Impact on Climate Time Series

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Changepoint methods are indispensable in the analysis of climate time series. This presentation delves into the latest research findings regarding both single and multiple changepoint methods, shedding light on the current advancements in changepoint analysis within the statistical community. Additionally, it presents two compelling applications of changepoint analysis in climate data: climate time series homogenization and the identification of global warming surges.

An apparent multi-decadal global ocean cold anomaly in the early twentieth century temperature record

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The observed temperature record, combining sea surface temperatures (SST) with near-surface air temperatures over land (LSAT), is crucial for understanding climate variability and change. However, early records of global mean surface temperature (GMST) estimates are uncertain due to changes in measurement technology and practice, alongside incomplete spatial coverage.

Here, using regularized linear regression models, we independently reconstruct GMST from SST and LSAT data for the time period from January 1850 to December 2020. We demonstrate that the land- and ocean based GMST estimates show very similar variability and long-term changes, both in the early (1850-1900) as well as in the late record (post-1950). For example, GMST of the past decade (2011-2020) increased by 1.06°C (LSAT-based) and 1.10°C (SST-based) relative to an early reference period (1850-1900), which is both well within IPCC AR6 estimates.

However, the GMST estimates show pronounced disagreement in the early 20th century (1900 up to around 1930), when the SST-based GMST estimates are on average around 0.3°C colder than the LSAT-based estimates. The multi-decadal ocean cold anomaly cannot be explained by a forced response in an attribution setting, but internal variability in climate models cannot explain the observed land-ocean discrepancy either. We show here that several lines of evidence based on attribution, statistical time scale analysis, comparison of coastal grid cells and paleoclimate data support the argument that the observed global SST record may be implausibly cold in the early twentieth century.

A correction of the ocean cold anomaly would result in a more modest early twentieth century warming trend, a lower estimate of decadal-scale variability inferred from the instrumental record, and better agreement between simulated and observed warming than existing datasets suggest.

A noisy-input generalised additive model for relative sea-level change along the Atlantic coast of North America

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The 2021 Intergovernmental Panel on Climate Change report highlighted how rates of sea level rise are the fastest in at least the last 3000 years. As a result, it is important to understand historical sea level trends at a global and local level in order to comprehend the drivers of sea level change and the potential impacts. The influence of different sea level drivers, for example thermal expansion, ocean dynamics and glacial – isostatic adjustment (GIA), has changed throughout time and space. Therefore, a useful statistical model requires both flexibility in time and space and have the capability to examine these separate drivers, whilst taking account of uncertainty.

The aim of our research is to develop statistical models to examine historic sea level changes for North America's and Ireland's Atlantic Coast. For our models, we utilise proxy data from salt marsh cores and tidal gauge data which provide relative sea level estimates. The statistical approach employed is that of extensions of Generalised Additive Models (GAMs), which allow separate components of sea level to be modelled individually and for smooth rates of change and accelerations to be calculated.

The model is built in a Bayesian framework which allows for external prior information to constrain the evolution of sea level change over space and time. The proxy data is collected from salt-marsh sediment cores and dated using biological and geochemical sea level indicators. Additional tide gauge data is taken from the Permanent Service for Mean Sea Level online. Uncertainty in dating is extremely important when using proxy records and is accounted for using the Noisy Input uncertainty method (McHutchon and Rasmussen 2011).

By combining statistical models, proxy and tidal gauge data, our results have shown that current sea level along North America's east coast is the highest it has been in at least the last 15 centuries. The GAMs have the capability of examining the different drivers of relative sea level change such as GIA, local factors and eustatic influences. Our models have demonstrated that GIA was the main driver of relative sea level change along North America's Atlantic coast, until the 20th century when a sharp rise in rates of sea level change can be seen.

Monthly Mean Surface Wind Speed Data Homogenization and Trend Characterization

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Using hourly surface wind speed data from 155 stations in Canada, this study developed a homogenized monthly mean wind speed dataset for the period 1953-2023 and used the dataset to characterize observed changes in surface wind speed in Canada. The hourly data were first quality controlled and adjusted for non-standard anemometer heights before being used to calculate monthly mean series. To identify artificial discontinuities, the monthly series were subject to a semi-automated comprehensive data homogenization procedure, which uses a combination of station metadata and multiple statistical tests with and without using reference series, with the automated results being reviewed manually using metadata and visual inspection of the multiphase regression fits with expert judgement. As a result, all the 155 data series were identified to have one or more artificial discontinuities, which were diminished by quantile matching adjustments. Anemometer height change, station joining, relocation, instrument changes/problems were found to be the main causes of data inhomogeneities. The homogenized dataset for 1953-2023 shows wind stilling in region from northern British Columbia (BC) to southern Yukon-Northwest Territories and from southern Prairies to Quebec-Labrador, which was matched with wind strengthening in most of the other regions, particularly in the region from southern-central BC to the Rocky Mountains, the Maritimes, and the high Arctic.

Sensitivity of Percentile-Based Extreme Temperature Indices: Implications for Climate Change Monitoring in an Era of Accelerated Warming

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The current study explores the significant implications of selecting different base periods for climate change monitoring in the era of accelerated warming. Specifically, it compares a relatively colder reference span (1961-1990) to a warmer one (1988-2017) concerning the trend measurements of widely used percentile-based extreme temperature indices. These indices are part of the 27 core metrics recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI), essential for climate change monitoring and covering indicators such as warm/cold spells and warm/cold days and nights. Although designed to facilitate cross-regional comparability under similar analyses, the examination of climate change with differing base periods and periods of interest undermines this comparability.

In contrast to 'day-count' indices with fixed thresholds, where different base periods affect the intercept but not the slope, our analysis reveals that percentile-based temperature indices (e.g., days below the 10th or above the 90th percentiles), exhibit high sensitivity to the choice of base periods. Consequently, the interpretation of trends in percentile-based indices may distort researchers' conclusions.

Our results indicate a substantial amplification in the trend magnitude of cold percentile-based indices e.g., frequency of cold days/nights and cold spells and a significant reduction in the trend magnitude of warm indices e.g., frequency of warm days/nights and warm spells, when percentiles are derived from a base period including records from the last two decades (e.g., 1981-2010, 1988-2017). These effects are even more pronounced in studies covering only the last 30-40 years.

Session 01: Climate Records (poster presentations)

Climate records: dataset creation, homogenization, gridding and uncertainty quantification, including observationally constrained analyzed and reanalysed products

Comparison of changepoint methods for homogenization of precipitation

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Homogenization of climate data requires different tools from different areas of statistics to be brought together and tailored for a specific purpose. Several homogenization techniques have been proposed over the years and an EU COST action from 2007-2011 invited the community to submit their approaches to be part of a wide comparison of techniques for homogenization of precipitation data. Once part of the homogenization pipeline is the detection of abrupt shifts or changepoints. Since 2010 changepoint detection has seen a resurgence with many novel techniques proposed and the field has advanced significantly.

This study compares the modern statistical changepoint methods with the currently widely used homogenization pipelines for monthly precipitation data. We use simulations based on modifying real-world data with different types of change, some which haven't been considered within the literature but are predicted by the climate models.

Calculation of Irelands LTA grids 1961-2020

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Long term average (LTA) grids for Ireland have recently been calculated as part of the generation of 1991-2020 climate normals. Using a dataset of monthly rainfall and air temperature station data across the period 1961 to 2020 allow the recent normals period to be compared with a separate 30-year span from 1961 to 1990. An increase in mean air temperature of 0.7oC and annual rainfall of 7% was found for Ireland when the two LTA were compared.

This presentation will focus on the methodology used to create the data series, from quality control of the daily station data, homogenisation, infilling of missing data and the gridding of the station rainfall and temperature parameters. A total of approximately 1,000 rainfall and 210 air temperature station datasets were collated.

Homogenisation was performed using MASH for both the rainfall and temperature datasets. The infilling methodology combines a gridding, spatial ratio and spatial regression technique to optimally predict missing station monthly data, thus boosting the number of rainfall stations available from an average of approximately 600 observing over the period to the 1,000 stations used for the calculation of the grids.

A regression-kirging methodology was applied to the gridding of the rainfall data and regression-IDW for air temperature. Accuracy of the gridding algorithm was determined through an adjusted R-squared analysis of the regression and a LOOCV RMSE analysis of the full gridding algorithm. The quality of the grids were also assessed with the annual rainfall having a RMSE of 3.7% and the mean air temperature grids having a RMSE of 0.14oC.

A key aspect of the methodology is that a series of monthly grids from 1961 to 2020 are generated and any combination of grids can be aggregated and compared with smooth anomaly plots being created.

Spatial interpolation of seasonal precipitations in a complex topographical region - comparing several statistical models

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Knowledge of seasonal precipitation is essential for many societal sectors, such as agriculture, energy production, industrial production, and tourism. In specific hydro-meteorology applications, grid maps of seasonal precipitation are often needed. Going from rain gauge measurements to a grid map requires interpolation and is inherently uncertain. In this study, we intend to assess the interpolation and extrapolation performances of various statistical models, including Ordinary Kriging (OK), Kriging with External Drift (KED), Geographically Weighted Regression (GWR), and Random Forest (RF). 3,189 rain gauges and simulations from the Convection-Permitting Regional Climate Model (CP-RCM) AROME are available in France over the 1982—2018 period.

Using AROME as an explanatory variable improves both interpolation and extrapolation performances. KED and RF have the best cross-validation scores in a high rain gauge density network but struggle to extrapolate. GWR is more robust for both interpolation and extrapolation. RF extrapolation issue is overcome by interpolating the ratios between observed and AROME precipitation. With this approach, RF has the best cross-validation scores for both low and high rain gauge density while being able to extrapolate. The obtained precipitation maps show high spatial and seasonal variability. This study emphasizes the interest of interpolating the ratio error of CP-RCM simulations in a complex topography region.

Development of Climatological Normal 1991-2020 for the Indonesia Region

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BMKG, Indonesia

Climate normals are basically the average climatic conditions of a particular location over a defined period of time. The climatological normal has two main purposes, as a benchmark or reference against which conditions (especially current or recent conditions) can be assessed, and as an indicator of the conditions likely to occur at a particular location. According to the WMO, the climatological standard normal is an average of climatological data calculated for consecutive 30-year periods, e.g. 1 January 1981 to 31 December 2010, and the last climatological standard normal period was 1 January 1991 to 31 December 2020. The 1991-2020 standard climatology is used to update the standard climatology for the previous period (1981-2010). WMO, as a global institution, collected climatological normals from 141 countries and territories in the six WMO regions, including Indonesia. Based on the mandate from WMO, Indonesia submitted climatological normal stations from 29 provinces containing 108 parameters from 14 variables using the R package (Climatol and Clino tools) developed by WMO.

This paper aims to provide a general overview of the calculating climate normal in Indonesia using ground-based weather station data from 1991-2020. It evaluates climatology normal results in different procedures, with Climatol and without Climatol. Climatol has three functions; those are for quality control, homogenization, and filling of missing data of a set of climate series. Climatol uses regression methods to fill in blank data by spatial interpolation from neighboring stations within an area and SNHT (Standard Normal Homogeneity Test) method for homogenization.

CLINO are tools used to calculate statistical measures to summarize the data that provides a comprehensive picture of typical climate conditions and their variability. This technique outperforms all alternative datasets because it uses the highest percentage of original data with the smallest RMSE value. The results show that climatology normal of maximum temperatures generated using climatol is lower than the maximum temperatures generated without climatol. The homogenization process minimizes variation in heterogeneous datasets. It also minimizes the difference between two means in a dataset with a breakpoint (on a heterogeneous dataset). General evaluation shows that climatological normal in Indonesia in every single station has large variations from other stations. Hopefully, the results of this climate normal calculation can be used as a normal reference for at least the next 10 years and will be applicable in various related fields, particularly for the Indonesian region.

A NASA GISTEMPv4 Observational Uncertainty Ensemble

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The historical global temperature record is an essential data product for quantifying the variability and change of the Earth system. In recent years, better characterization of observational uncertainty in global and hemispheric trends has become available, but the methodologies are not necessarily applicable to analyses at smaller regional areas, or monthly or seasonal means, where station sparsity and other systematic issues contribute to greater uncertainty. This study presents a gridded uncertainty ensemble of historical surface temperature anomalies from the Goddard Institute for Space Studies (GISS) Surface Temperature (GISTEMP) product. This ensemble characterizes the complex spatial and temporal correlation structure of uncertainty, enabling better uncertainty propagation for climate and applied science in applications of historical temperature products at spatial scales from global to regional and temporal scales from centennial to monthly. This work details the methodology for generating the uncertainty ensemble, presents key statistics of the uncertainty evolution over space and time, and provides best practices for using the uncertainty ensemble in future studies. Summary statistics from the uncertainty ensemble agree well with the previous GISTEMP global uncertainty assessment, providing confidence in both.

MapEval4OceanHeat (ME4OH): an objective assessment of mapping methods used to estimate ocean heat content change

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Knowledge of the spatiotemporal evolution of ocean heat content (OHC) is essential to our understanding of both past and future climate change. At global scales, ocean heat uptake is a key element of the global energy and sea level budgets and provides a powerful constraint on climate sensitivity and past climate forcings. At regional scales, OHC changes are important to our understanding of climate variability and for the development, initialization, and evaluation of seasonal-to-decadal prediction systems. However, international intercomparison efforts have repeatedly shown large spread in both global OHC change and the spatial patterns of change over the past decades estimated by various research groups. Even for the relatively well-observed 0-700 m ocean, the uncertainty introduced by the choice of mapping method remains large.

MapEval4OceanHeat (ME4OH) initiative is an international collaborative project working on the objective assessment of a wide range of mapping methods based on "synthetic" ocean observations from high-resolution climate and ocean modeling systems. In the ME4OH framework, the model is sub-sampled according to the spatiotemporal distribution of in situ ocean temperature observations in the EN4 dataset. These synthetic observations are then used as the input to the same mapping methods routinely deployed to map observed changes in ocean temperature and heat content. This presentation will outline the experimental design of ME4OH and present preliminary results from comparing the model "truth" (based on a 1/10th degree ocean model simulation) with the output from spatial mapping methods used by the different international research teams. This approach allows us to evaluate the strengths and limitations of contemporary mapping approaches and assess our ability to constrain observed OHC change at global and regional scales. While our focus is on ocean temperature and heat content change, a similar approach could be applied to other variables.

A detailed stationarity analysis and trend modelling of French daily precipitations

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An extensive dataset of French daily precipitations is built with the records from Météo-France and EDF networks, with about 900 time series, mostly complete from 1950 to 2022. This dataset is screened and homogenised in order to remove erroneous values and temporary biases induced by changes in the location, the close environment or the rain gauge itself. A global temperature proxy accounting for the synoptic zone of influence for France is computed based on the GISTEMP reanalysis, averaging the SST (sea surface temperature) on near Atlantic Ocean and west Mediterranean Sea.

Various precipitation statistics are computed on this dataset with four seasons considered: mean annual (or seasonal) precipitation, dry day frequency, average of wet days precipitation, daily annual (and seasonal) maximum, etc. These variables (and the SST proxy) are averaged on sliding windows (25 to 35 years) to provide a climatological perspective. They are completed by GEV regional fits computed both on the global period and on the sliding windows. The stationary hypothesis has been tested both on annual, and climatological (i.e. time-window averaged) values of the studied variables. Where the stationary hypothesis is rejected, trends models (climatological variables against SST proxy) are established.

Global statistics and maps of tests and trends are presented. For some of the variables, they show clear seasonal and spatial patterns: for example, the mean annual precipitation is clearly decreasing in the south half of France, while lightly increasing in the northern half. This pattern is accentuated in winter, but different in fall, when, apart for the South-West of France, all the mean seasonal precipitations show an increasing trend. This is different for daily maxima: for annual (and fall seasonal) maxima, a clear increasing trend is shown around the Mediterranean coast and along the Rhone valley, whereas in winter the trend pattern is close to the one of seasonal mean precipitation. On average on this dataset, for climatological windows of 35 years, the mean annual precipitation trend is +4%/°K, and the mean of annual maxima is around +9%/°K, both with significant seasonal variations.

This work provides a robust and extensive dataset for the stationarity/trend analysis of the French daily precipitation. The impact of the data screening and homogenisation is evaluated, underlining the importance of this task in the study of climatological trends. The analysis shows contrasted regional and seasonal patterns for the different variables. The SST proxy is an efficient first-order explanatory covariable of these trends, but fails to capture some variability, in particular for the first decades of the records. Other large-scale driver of the French climate should be introduced aside the SST proxy for a better modelling of the trends, and a future use in the climatic projections of French precipitations.

Atmospheric Features via Topological Data Analysis

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We use the Morse filtration from topological data analysis to develop the seahorse and horseZ plots for investigating waves in the atmosphere, as defined by geopotential heights. The seahorse gives a summary of the wave features over a set of fixed latitudes, while the horseZ assesses the waves and their heights against a historical record. We present some case studies focused on extreme heat events to show how this tool might be used.

Extending the Observational Record of Compound Drought and Heatwave Events for Future Risk Management

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Compound drought and heatwaves (CDHWs) generate significant socioeconomic losses as demonstrated by large-scale events such as the European 2003 heatwave. Such events are anticipated to increase in their magnitude and frequency with further climate warming, however the limited sample of CDHWs captured during the instrumental period limits our understanding of their drivers and potential impacts. This research will identify CDHWs within the instrumental record and assess how they are expressed in tree-ring chronologies via PDSI measurements. Based upon this, extreme hot and dry events will be identified in tree-ring data over the last millennia enabling analysis of the characteristics of CDHWs over longer timescales through the application of proxy system modelling. Initial results suggest the Northern Hemisphere midlatitudes as a hotspot for CDHWs, this area is well covered by tree-ring records supporting the proposed methodology.

Session 03: Space-time statistical methods (oral presentations)

Space-time statistical methods for modelling and analyzing climate variability

Empirical Orthogonal Functions and their latest developments

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Empirical Orthogonal Functions (EOFs) is the keystone method for dimension reduction of spatio-temporal data. It was first formalised in 1957 and it basically consists in realising a Principal Component Analysis on spatio-temporal data. After 1957, a flourishing literature focused on EOFs and derived methods. The applications were mainly restricted to meteorology and climate applications. However, they have been extended recently to several fields of applications in environmental science (e.g. ecology, geology) leading to new methodological developments related to EOF.

The last review paper of EOF dates back to 2008 and does not consider the most recent developments and extensions of these methods. In this presentation, we summarise the main developments that have occurred in the last years. These are mainly related to two types of issue: (1) conducting EOFs on multivariate sparse and heterogeneous data and (2) setting spatial orthogonality constraints on EOFs.

The first issue typically raises the question of extracting the main patterns from several variables that have sparse data coverage. For instance, one would like to map multivariate data from climate stations (e.g. humidity, temperature, pressure) to extract their common patterns. A hierarchical statistical approach allows to handle variables that are observed following different probability distributions while extracting the main modes of variations through a probabilistic formulation of EOFs.

The second issue deals with the constraints that are set between the EOFs plans. Typically, standard EOFs do not provide spatially orthogonal patterns i.e. cross-covariograms of the different EOFs maps do not show spatial independence. Methods have been developed to provide spatially de-correlated plans such as Empirical Orthogonal Maps (EOM) or Independent Component Kriging (ICK). These typically allow to create spatially orthogonal plans by realising a second rotation after the first EOF. For EOM, the second rotation consists in conducting an additional EOF for some spatial increment. For ICK, this consists in finding rotations that provide independent components while EOF only provides de-correlated plans.

We present each method based on a climate dataset from the South Eastern Pacific. Finally, we point out the limits of these methods and highlight future research avenues for this type of statistical approach.

Exploring Climate Extremes: Mode-Based Pattern Recognition with Koopman Operator Theory

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Extreme climate events have become more frequent and their impacts are intensifying in many regions of the world, which becomes even more severe under projections of further global warming. In this respect, we aim to develop a pattern recognition framework of extreme events. The overall goal is to improve the accuracy of forecasting for extreme events.

In the spirit of equation-free modelling, we apply the Koopman operator theory to describe the behaviour of a climate variable, i.e. dynamical quantity $u(x,t)$, that evolves through space x and time t. To approximate the Koopman operator, which generates dynamics of the variable, we apply the variant of the dynamical mode decomposition (DMD) method. This method is designed for extracting coherent spatiotemporal structures, which in superposition approximate the original complex system. However, the challenge is to find the best mode for a system, with respect to the extremes. Some variants of the DMD, like sparsity-promoting DMD (spDMD) have already been developed, but so far the focus has not been on the system's extreme behaviour.

This method aims to identify the most relevant spatiotemporal patterns of climate extremes and to explain their evolution, which is expected to be nonlinear. Although the method itself is primarily designed for diagnostics, it can also be used to predict future states of the system.

Modeling CO2 concentration in the atmosphere using spatio-temporal random fields on meshed surfaces defined from advection-diffusion SPDEs

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The aim of this work (Pereira et al., 2023) is to propose a statistical model for spatio-temporal data on meshed surfaces based on the SPDE modeling approach (Lindgren et al., 2011). To do so, we consider a class of advection-diffusion SPDEs (Clarotto et al., 2022) defined on smooth compact orientable closed Riemannian manifolds of dimension 2, and their discretization using a Galerkin approach (Pereira et al., 2022). We show how this approach allows to easily propose scalable algorithms for the simulation, inference and prediction of Gaussian random fields that are solutions to the discretized SPDE. We apply the method to a simulated spatio-temporal dataset with advective and diffusive behavior on the sphere and to a real case study about the concentration of CO2 in the atmosphere on the surface of the globe. In this setting, the proposed approach is able to mimic the process and to make sound short-term predictions of its evolution.

Spatio-temporal weather generator for the temperature over France

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Weather generators are simulators useful to reproduce climate variability and generate a great number of situations for meteorological variables according to a statistical model fitted on observations. Most weather generators provide simulations for one or several meteorological variables site by site. We aim in this work to design a spatial weather generator for one meteorological variable. We focus on temperature.

The mean and variance are each modeled as a trend and a seasonality function. Trends are non-parametric functions while seasonality parts are written as trigonometric polynomials. They are fitted separately on each site iteratively: first, a non-parametric regression is applied to extract the trend in the mean. Then, a linear regression on trigonometric coefficients allows to extract the seasonality of the mean. The same procedure is repeated to determine both the trend and seasonality in standard deviation. The results of these single-site decompositions are then extended to the whole domain by kriging for the seasonality coefficients and by inverse distance weighting for the trends. The stochastic part is modeled as a Gaussian field with a non-separable spatio-temporal correlation function. When combined with the interpolated deterministic components, this model becomes able to generate simulations on a grid for any desired time period.

The validation of the model is conducted by computing several statistics related to the expected properties of the generator. The main idea is to generate many simulations, obtain an empirical distribution of these indicators, and compare them to the observed values. The model is adequate if the observed values are in the range of the simulations. We choose indicators related to the spatio-temporal structure. The empirical pairwise correlations between points in space gives an approximate view to the spatial dependence. The pairwise conditional threshold exceedance, defined as the probability of exceeding a threshold at one point given another point does, gives insight into the extremal dependence. The auto-correlation function and heat wave length distribution at one point describe the temporal properties of the model.

Daily temperature data at 41 French stations are used to fit the model generator. For validation purposes, we conduct 100 simulations using identical spatial and temporal coordinates. The simulations of the Gaussian field are generated using 3 methods: first, using the full multivariate covariance matrix for every half-year. This is not possible in practice with more refined space grids, raising the need for the second simulation method: using the Gaussian properties to simulate iteratively at all points in space conditionally to the 10 previous days. The third method consists of using a full multivariate covariance matrix corresponding to a purely temporal model, to evaluate the gain of the spatial part.

It is found that the generator provides adequate simulations and allows the generation of spatially coherent temperature series. As Gaussian processes are known to perform poorly in extremal dependence, the conditional threshold exceedances for very large or very small thresholds are a bit inaccurate but still a great improvement from not using a spatial model.

The model is then used to generate series on a grid. They will be compared to an interpolated dataset obtained from the same station data we used. We will also investigate other simulation methods for Gaussian processes in order to be able to handle large datasets and several meteorological variables.

Evaluation of global teleconnections in CMIP6 climate projections using complex networks

Clementine DALELANE, Kristina WINDERLICH, Andreas WALTER

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We present an application of the graph-theoretical analysis tool delta-MAPS, which constructs complex networks on the basis of spatio-temporal gridded data sets, here sea surface temperature and geopotential height at 500 hPa. Complex networks complement more traditional methods in the analysis of climate variability, like the classification of circulation regimes or empirical orthogonal functions, assuming a new non-linear perspective. A number of technical tools and metrics (trend empirical orthogonal functions, distance correlation and distance multicorrelation, and the structural similarity index), borrowed from different fields of data science, are implemented in order to overcome specific challenges posed by our target problem.

After detrending with trend-EOFs, delta-MAPS assembles grid cells with highly coherent temporal evolution into so-called domains. The teleconnections between the domains are inferred by means of the non-linear distance correlation. We construct 2 unipartite (SST, Z500) and 1 bipartite (SST-Z500) networks for 22 historical CMIP6 climate projections and 2 century-long coupled reanalyses (CERA-20C and 20CRv3). Potential nonstationarity is taken into account by the use of moving time windows. The networks derived from projection data are compared to those from reanalyses by means of the stuctural similariry index.

Pacific climate variability and its regional impacts in warmer, stabilised climates

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The El Niño Southern Oscillation (ENSO) in the tropical Pacific is the main mode of inter-annual climate variability and a key driver of regional climate across much of the globe. Future changes in its behaviour are highly policy-relevant as they would have large impacts across many regions and significantly affect ecosystems and livelihoods. In this presentation, we explore how ENSO variability evolves in multi-century experiments under fixed atmospheric concentrations of greenhouse gases, where global mean surface temperatures are slowly stabilising.

We show how ENSO variability and its teleconnections change across a range of climate models and experimental designs, from the well-known, transient future projections based on scenarios used in CMIP6, to idealised projections where global temperatures are stabilising over multi-centennial timescales. Among others, we analyse experiments with the UK Earth System Model 1 where atmospheric concentrations of greenhouse gases are held constant at various levels, therefore spanning a broad range of global warming levels. We also analyse closely related experimental designs, such as emission-driven stabilisation experiments with ACCESS-ESM-1.5, and abrupt forcing experiments with the Community Earth System Model 1. To investigate the sensitivity of ENSO characteristics to forcing, rate of warming and response timescales, we contrast changes in ENSO characteristics across all available models and experimental designs, including initial-condition ensembles of short (<100 years) projections and multi-century long simulations. Preliminary results suggest that changes in future ENSO variability are highly model dependent but generally consistent across experimental designs within a single model framework.

Such differences are important to understand in the context of ambitious mitigation scenarios that aim to stabilise global temperatures at, or below, the Paris Agreement temperature targets.

Statistical dependency among persistent events: Jet stream configurations and their impact on the formation of mid-latitude heatwaves

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During the last years, the study of compound extremes has made vast progress in terms of the underlying statistical methodology as well as the variety of successful applications. However, tranditional approaches based on extreme value theory may not be well suited for statistical analysis in situations where (i) the events of interest cannot be associated with extremes of a specific (meteorological) quantity and/or (ii) persist over a considerable period of time, such that they do not represent point-like phenomena in time.

Regarding challenge (i), statistical association measures for point processes may provide a reasonable approach to establish linkages between irregularly recurring events of different types. Considering only the timing of those events and neglecting their possible amplitude (in case it can be defined), event coincidence analysis (ECA) provides a neat tool for determining the strength of corresponding statistical associations and testing for their significance. To also address challenge (ii), a new methodological variant of ECA is presented, which is referred to as interval coverage analysis (InCA), that allows quantifying the empirical frequency of co-occurrences between persistent events of different types. In the limit of vanishing event durations, the new interval coverage rates of InCA are identical to the event coincidence rates provided by ECA. By allowing for mutual time shifts between the different types of events under study as well as a temporal tolerance regarding their respective timing, fixed and even distributed time lags between the supposed causes and effects can be taken into consideration.

As an illustrative example, InCA is used for studying the spatial patterns of dependency between the timing of heatwaves in the Northern hemisphere mid-latitudes and a specific configuration of the atmospheric jet stream with two centers at different latitudes. The corresponding analysis reveals specific regions with elevated likelihood of heatwaves in the presence of a split (double-banded) jet stream, while the emergence of heatwaves is suppressed at the same time in other regions. The obtained results may thus guide further targeted research regarding the specific mechanisms leading to this regional differentiation in heatwave frequency.

A Bayesian spatio-temporal regression model to derive gridded monthly SPI-1 and SPI-3 maps

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The Standardized Precipitation Index is a key and valuable tool for characterising drought conditions. In drought monitoring, different sources of data (e.g. in-situ observations, reanalysis, satellites' products) are usually not analysed conjunctively. For instance, the Copernicus European Drought Observatory (EDO) continuously produces gridded SPI maps based on the ECMWF ERA5 reanalysis for calculating its flagship agricultural drought indicator Combined Drought Indicator (CDI), while SPI series based on in-situ observations are also provided to end users. To address this gap and improve the robustness of the drought information, this study introduces a Bayesian spatio-temporal regression model based on the Integrated Nested Laplace Approximation (INLA) and the Stochastic Partial Differential Equation (SPDE) to combine ERA5 and in-situ SPI data.

Here, we employ the INLA-SPDE approach to derive gridded monthly SPI-1 and SPI-3 maps for the period 1981-2022, within a study domain covering a portion of Europe and including France, Germany, Switzerland, and Italy.

To achieve a higher degree of physical coherence and to increase robustness, our regression model includes a spatio-temporal predictor, i.e., the 500hPa geopotential gradient to catch the pressure driving forcing of weather systems. A common Matern field is thus used to capture the spatio-temporal correlation of the ERA5 and in-situ SPI data. Due to the large space-time domain of our study, the regression analysis is run separately for each month (January-December) and for each variable (SPI-1/SPI-3). This approach provides a flexible model to produce accurate continuous gridded surfaces equipped with model-based uncertainties. Through simulation, we generate a distribution of plausible gridded SPI surfaces, which we summarize through measures of central tendency (posterior mean) and variability.

Characterization of hot-dry spatially compound events using probabilistic networks

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In the context of climate science, probabilistic network models (PNMs) have been used as machine learning techniques that allow for efficiently extracting the underlying spatial dependency structure in a graph and a consistent probabilistic model that is learnt from data (e.g. gridded reanalysis or climate model outputs). The graph and probabilistic model together constitute a truly probabilistic backbone of the climate system underlying the data. The complex dependency structure between the variables in the dataset is encoded using both pairwise and conditional dependencies and can be explored and characterized using network and probabilistic metrics. PNMs have been demonstrated to faithfully uncover the various long-range teleconnections relevant in temperature datasets, in particular those emerging in El Niño periods (Graafland, 2020).

The combination of multiple climate drivers and/or hazards that contribute to societal or environmental risk are the so-called compound weather and climate events. These compound events can be the result of a combination of factors over different dimensions: temporal, spatial, multi-variable, etc. (Zscheischler et al. 2020). In particular, spatially compound events take place when hazards in multiple connected locations cause an aggregated impact. In this work we apply PNMs to characterize the temporal and spatial dependencies of compound events resulting from concurrent temperature and precipitation hazards, which can potentially affect many sectors. Furthermore, PNMs are used to propagate evidence of different climate drivers to study the variability of this type of compound events.

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Classifications of atmospheric circulation patterns: a tool for explaining asymmetry in day-to-day temperature differences

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Substantial progress has been made in analyses of temperature means and extremes, while much less has been done in understanding short-term (intraseasonal and synoptic-scale) variability of temperature. One particular aspect of short-term temperature variability is day-to-day temperature difference (DTD). Large DTDs negatively affect human health and impact also animals and plants, hence posing one of the many weather-related risks to society.

Distribution of DTD in central Europe is asymmetrical. Skewness of DTD is negative over most of Europe in summer, while in winter, there is a tendency for positive skewness of DTD to occur in the north and for negative skewness to occur in the south and over the British Isles. However, mechanisms causing the asymmetry of DTD have only been hypothesized but not investigated yet in sufficient detail on spatial scales larger than local.

This contribution introduces classifications of atmospheric circulation patterns as a tool for explanation of the DTD asymmetry. The circulation conditions are described by spatially sliding classifications, i.e., separately performed classifications for individual gridpoints. The objectivized classification after Jenkinson-Collison and Grosswettertypen after Beck are used for this purpose. Both classifications are selected because of their easy implementation and intuitive interpretation. Anticyclonic types, types with a weak flow, and types with warm advection from south to southwest directions contribute to the DTD asymmetry in summer, while anticyclonic types and types with cold northerly to northeasterly advection contribute to the DTD asymmetry in winter.

The analysis if performed for ERA5 reanalysis. Daily minimum temperature is analyzed in winter and daily maximum temperature is analyzed in summer.

VARIATION OF DRY SPELL OVER MAKURDI, BENUE STATE, NIGERIA

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In the tropics, of all the climatic elements, rainfall is probably the most important as far as crop production is concerned, and the availability of water is one of the major climatic factors that affect plant growth, development, and yield (Yahaya, 2011). Precipitation does not usually occur daily during the rainy season. Subsequently, there are breaks in between rain spells and when these breaks become prolonged, plants may wilt or die. Assessing the vulnerabilities of different livelihoods to changes in dry spells is important for community resilience in Makurdi Benue State, Nigeria. Secondary data was used for this project. Daily rainfall data was obtained from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) (1991 to 2022). Examination of rainfall trend/variability and analysis of the historical pattern of dry spells in Makurdi, Benue State for the study period were carried out using Jeffreys's Amazing Statistics Program (JASP), a free and user-friendly statistical software. The dry spell variation for onset and cessation of rainfall over Makurdi was investigated using INSTAT+, software developed by the Statistical Services Centre, University of Reading, UK. The mean consecutive dry days during the Onset of rainfall was 6 days and 15 days for cessation respectively. Summarily, the results obtained revealed a slightly increasing trend for maximum dry spell length during the onset of rains, meaning its recurrence is increasing slowly in Makurdi while the trend for maximum dry spell length at the end of the season appears to be increasing significantly which indicates that dry spells towards the end of the season are more severe than dry spells at the beginning of the season and this harms agriculture and water resources management.

Surface time series models for large spatio-temporal datasets

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Due to the rapid development of complex, performant technologies, spatio-temporal data can now be collected on a large scale. However, the statistical modeling of large sets of spatio-temporal data involves several challenging problems. For example, it is computationally challenging to deal with large datasets and spatio-temporal nonstationarity. Therefore, the development of novel statistical models is necessary. Here, I will present a new methodology to model complex and large spatio-temporal datasets. In our approach, we estimate a continuous surface at each time point, and this captures the spatial dependence, possibly nonstationary. In this way, the spatio-temporal data result in a sequence of surfaces. Then, we model this sequence of surfaces using functional time series techniques. The functional time series approach allows us to obtain a computationally feasible methodology, and also provides extensive flexibility in terms of time-forecasting. We illustrate these advantages using a high-resolution wind speed simulated dataset of over 4 million values. Overall, the method uses a new paradigm of data analysis in which the random fields are considered as a single entity, a very valuable approach in the context of big data.

On the archetypal `flavours' and indices of ENSO

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El Nino-Southern Oscillation global (ENSO) imprint on sea surface temperature comes in many flavours or guises. In order to identify its tropical fingerprints and impacts on the rest of the climate system, we propose an approach based on archetypal analysis, an unsupervised pattern recognition method based on the identification of extreme configurations in the dataset under investigation. Relying on detrended sea surface temperature monthly anomalies over the 1982 to 2022 period, the technique recovers central and eastern Pacific ENSO phases identified by more traditional methods, and allows one to hierarchically add extra flavours and nuances to these. Archetypal patterns found compare favorably to categorical phase identification from K-means, fuzzy C-means and recently published network-based machine-learning algorithms. The archetypal analysis implementation can be straightforwardly modified for the on-line identification of ENSO phases in sub-seasonal-to-seasonal prediction systems and could complement current alert systems in characterising the diversity of ENSO and its teleconnections. Tropical and extra-tropical teleconnection composite patterns from various oceanic and atmospheric fields derived from the analysis are shown to be robust and physically relevant. Extending the archetypal analysis to sub-surface ocean fields improves the discrimination between phases when the characterisation of ENSO based on sea surface temperature is uncertain. We show that archetypal analysis on detrended sea-level monthly anomalies provides a clearer expression of ENSO types. When archetypal analysis is applied as a dimension reduction artifice, the resulting ENSO indices and corresponding patterns could be used as input to statistical prediction models, a strategy easily transferable to other weather and climate modes of variability.

Wet season onset and termination in south-western Cape, South Africa

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Understanding the seasonal characteristics of rainfall is important in determining any changes that may occur in the climate. Several studies have explored various ways of defining the wet season depending on the climate, location, and the purpose of the study. In this study a rain-based definition of the wet season onset and termination is presented. The wet season is defined using 5-day running sums and means. This method of defining the wet season was applied to rainfall data taken from the South African Astronomical Observatory (SAAO) that spans over 170 years since the early 1840s. The SAAO is located in Cape town, South Africa where the wet season occurs during the winter months. An analysis of onset and termination of the seasons indicated that recent decades, starting from 1958, were found to have a shorter mean season length than previous decades in the record. This decline was attributed to an increased incidence of late onsets and early terminations of the wet season, or a combination of both, particularly since the year 2000. An extension of the definition of the wet season is also discussed, that is meant to accommodate bimodal rainfall regimes where there are two temporally separated rainfall seasons, such as those that occur in parts of East and West Africa.

Multivariate spatio-temporal stochastic weather generator

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Stochastic weather generators are probabilistic tools used to simulate synthetic weather time series whose statistics resemble those observed. However, these tools face difficulties when it comes to accurately simulating multiple meteorological variables in space and time, because such cases necessitate a model that can capture the complex inter-variable and space-time dependencies.

In this study, we leverage the recent development of multivariate space-time covariance functions to model and simulate various weather variables, including temperature, precipitation, wind speed, humidity, and solar radiation, across different space-time locations. Specifically, we employ an approach that involves a non-linear and non-stationary marginal transformation of a multivariate Gaussian random field, characterized by a stationary and non-separable spatio-temporal multivariate cross-covariance function. To address the time-varying nature of the weather variables, we split the time domain into states called weather types.

The method is assessed on the Provence-Alpes-Côte-d’Azur region in France, which is characterized by heterogeneous topography and climate conditions. Evaluation results demonstrate the effectiveness of this new stochastic weather generator in reproducing a wide range of weather statistics, and its ability to simulate weather events that have not been previously observed. In the end, the proposed framework offers valuable insights for risk assessment.

Comparison of Spatial Models for Wind Resource in Ireland

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Our proposed research is focused on spatial models for building higher resolution (both spatially and temporally) wind maps for wind resource estimation. Our models also focuses on a framework to allow for estimation for a real time wind map to aid grid management.

For resource estimation current past data for wind speeds is usually either at synoptic weather stations or through Reanalysis data. Synoptic weather stations can be at a high temporal resolution but are typically spatially sparse. Higher resolution includes reanalysis data, including ERA5 and MERRA5. Some limitations of these include the temporal resolution (usually at 1 hour) and a spatial resolution that can be in the order of 20-30km+. Attempts to build higher resolution include the European Wind Atlas, however this involves a large amount of computational power and has only run until 2018.

Our research looks at a variety of spatial models to build high resolution wind maps. These use either met observations or reanalysis data points and interpolate to a high resolution grid. The series of models we've looked into include:

1) Ordinary Kriging, a relatively simple interpolation technique that interpolates values based on a weighted average. In this model correlation is assumed to be based only on distance (which is to say its stationary and isotropic).

2) Universal Kriging, interpolation that includes information on covariates. For this we use distance from the sea (from NASA), terrain roughness index and Corine land map.

3) Kriging with Geometric anisotropic modelling, there the correlation varies based on direction, and we apply a transform of coordinates to a coordinate space where the data is stationary.

4) Using the Stochastic Partial Differential approach to modelling spatial fields (as introduced by Lindgren, F., H. Rue, and J. Lindström. 2011. "An Explicit Link Between Gaussian Fields and Gaussian Markov Random Fields: The Stochastic Partial Differential Equation Approach (with Discussion).") This allows models where the covariance depends on covariates. For example the terrain or topography can influence the strength of correlation between two location, which the SPDE model can capture.

We will also look at a variety of approaches to transform the data and compare accuracies.

1) Use the original magnitude of wind speeds

2) Break the wind speed into the U and V components and fit two separate models and then combine at predicted locations.

3) Most of the described models rely on the underlying assumption that wind speeds are gaussian, whereas in practice they tend to follow a skewed distributed that is often modelled by a Weibull distribution. a transform of the data could make it approximately gaussian.

We will apply these techniques to a number of data sets. For example it can be first applied to ERA5 to build a spatial map at a sub kilometer resolution. The parameters fitted to this model can be then used as informative priors to build a spatial model using the sparses met station data. These can generate temporally high resolution data as met stations in Ireland have minute by minute observations. It also could lead to a creating real time wind maps where we have a live feed of wind speeds from met stations.

Another spatial aspect is studying the vertical wind profile spatially. As met stations are usually at 10m, but wind turbines are upwards of 100m, we need to look how to extrapolate values to turbine height. I'm currently using reanalysis data at various heights to build models. I'm currently acquiring measurements from wind turbines to substantiate the models, while also can be incorporated into the modelling. Therefore having a network of observations at various heights could provide a more complete estimation of resources available, and potentially lead to improved real time forecasting models.

On the statistical distribution of temperature and the classification of extreme events considering season and climate change – an application in Switzerland

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In recent years, the frequency of hot spells has increased, leading to a growing interest in quantifying the recurrence of extreme temperature events. However, extreme temperature anomalies occur not only as summer heat waves, but throughout the year. For example, cold spells in spring can have devastating effects on developing crops, while anomalously warm temperatures in early summer can have a greater impact on human well-being than hot spells in midsummer. In addition, warm temperature extremes in winter affect snow cover, which has a major impact on tourism, and water availability in spring and summer. A reliable classification of anomalous temperatures with respect to their season is therefore of great importance. In this study, we present a new approach to classify daily air temperature that takes into account both its seasonal cycle and climate change. Our methodology involves modeling the distribution of daily air temperature measurements from Switzerland using the skewed generalized error distribution with four time-varying parameters. This approach accounts for the non-Gaussian nature of daily air temperature. The climate trend is modeled linearly using the smoothed Northern Hemisphere temperature as an explanatory variable. Based on this statistical modeling, the daily observations are transformed into a standard normal distribution. The resulting standardized temperature anomalies allow meaningful comparisons of temperature anomalies within a year and between different years, and form the basis for a quantile-based empirical classification to determine return periods of temperature anomalies. The approach is well suited for classifying historical and current extreme temperatures, taking into account the expected temperature range at the time of the event. This is illustrated using the example of the 7-day heat wave in late June 2019, which is considered less likely than a similarly intense heat wave in mid-July of the same year. We also show the impact of climate change, which is evident in the increased likelihood of hot events and decreased likelihood of cold events in recent years compared to 50 years ago.

Regional and seasonal diversity of ENSO-precipitation teleconnections and their asymmetry in CMIP6 models

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El Niño Southern Oscillation (ENSO) is a prominent climate phenomenon affecting the variability of global and regional precipitation. The precipitation responses, during El Niño and La Niña phases, compared to neutral phase, are not mirror images of one another. In Australia, for instance, it is much wetter on average during La Niña (compared to the neutral phase) than it is drier during El Niño. This asymmetry plays an important role in explaining both multi-year droughts and drought-breaking rainfall. In this study, we assess 50 CMIP6 models against 20CR reanalysis and GPCC precipitation, in simulating the seasonal differences in asymmetric response of precipitation to ENSO across 46 IPCC AR6 Land regions. The asymmetry is computed using a precipitation composite technique and a model/regional outlook approach is utilized for model evaluation. Model performance in simulating teleconnections is found to be higher than the performance in simulating the associated asymmetry across all seasons. Model performance in capturing the regional diversity of asymmetry is found to be highest in austral spring. The model biases in asymmetry are related to the inability of the models to accurately simulate the skewness of the heavy tailed precipitation distributions and Niño3.4 SST distributions. In regions outside the Pacific and Indian Ocean basins, model bias in the skewness of local precipitation variability plays a bigger role in model asymmetry bias. This analysis contributes to better understanding the fidelity of CMIP6 models in capturing the asymmetric nature of teleconnections across different seasons and regions for better projections and planning of extremes such as floods and droughts in a warmer climate.

Bridging the divide between physical and statistical reasoning in climate variability and change

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There is a remarkable divide between the quality of statistical practice employed by climate scientists with a solid statistical training, and those with a more physics-based training who are generally using quite primitive, and in most cases unprincipled, methods. The latter appear to represent the majority. Examples include interpreting the outcomes of NHST's dichotomously, inverting the conditional, treating epistemic uncertainties as sampling uncertainties, and attempting to evidence a physical mechanism through a correlation between two variables without any attempt to control for confounding influences (as in, e.g., claims to find "emergent constraints" on climate model projections). Is it possible to find some middle ground, where the complementary strengths of the two groups of climate scientists can be somehow combined, and the results made intelligible to non-specialists? This requires bringing physical knowledge directly into the statistical analysis. It also requires using methods that are neither no more nor no less complicated than is needed for the question being asked, yet which are still principled in the sense of being anchored in the fundamental axioms of probability theory (i.e. logic). I will argue that fairly simple, physically motivated causal effect networks can offer such a meeting ground, with the further benefit that they can be readily re-used and re-purposed by others. I will present some recent examples in this respect, on detecting non-stationarity in the occurrence rates of atmospheric circulation regimes, and on quantifying the pathways and strengths of multiple interacting sources of predictability on S2S timescales.

Anomalías de temperaturas a través de la plataforma Giovanni de la NASA y su comparación con las temperaturas registradas en las principales estaciones meteorológicas de Nicaragua, período 2016-2020.

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This study includes the calculation and analysis of temperature anoma-lies, their trends and variations of daily and monthly data, obtained from the records of the main meteorological stations that the Nicaraguan Ins-titute of Territorial Studies (INETER) has in Nicaragua. In addition, ano-maly maps were obtained through NASA's Giovanni platform. For this, the average and maximum temperature records of the main meteorologi-cal stations in Nicaragua were collected and analyzed during the period from 2016 to 2020. The average temperature of each main annual station was first determined from these records, and it was obtained with this the total representative average for the Nicaraguan territory and in or-der to obtain the monthly and annual temperature anomaly, to compare the temperature anomalies through NASA's Giovanni platform with the average and maximum temperature anomalies, during that same period. The results show that warm (cold) events are related to dry and rainy seasons. These relationships can be useful in climate prediction, and particularly the event associated with ENSO that precedes precipitation or temperature.

Toward improved ocean heat content mapping and uncertainty quantification by modeling vertical spatio-temporal dependence

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Estimating ocean heat content (OHC) with reliable uncertainties is critical for understanding the evolution of Earth's climate, as the ocean has stored most of the energy accumulated in the climate system due to Earth Energy Imbalance. We use Argo profile data from 2004-2022 to map OHC. As fewer Argo observations are available deeper in the water column, previous studies have partitioned the ocean into at least two vertical sections and mapped each separately, which complicates the estimation of uncertainties when the maps are summed to get the total OHC. In this work, we consider the case of two vertical sections and

propose an improved mapping and uncertainty quantification method using bivariate locally stationary Gaussian processes and conditional simulations to map the two sections jointly while accounting for the correlation between them. We find that modeling this correlation results in improved OHC anomaly mapping and up to a 15% reduction of global OHC anomaly uncertainties in comparison to mapping the two layers separately without accounting for their dependence. These estimated uncertainties are essential to analyze the statistical significance of OHC anomalies both on a regional and global scale.

HWGEN: An Hourly Wind stochastic GENerator

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Wind is a key climate element in quantitative calculations and evaluations of many earth surface processes, such as evapotranspiration, wind power, wind erosion, wild fire and so on. At the same time, wind is a highly variable climate element in space and time, making the wind observations being often unable to meet the application requirements in terms of temporal resolution, spatial coverage and series length. In this study, we proposed a single-site stochastic wind generation model, named as HWGEN (Hourly Wind stochastic GENerator), for daily and hourly wind simulation, focusing on the improvement of the extreme wind. HWGEN includes two versions for single sites, HWGEN_D simulating wind direction and wind speed together and HWGEN_ND simulating wind speed without considering wind direction. HWGEN was calibrated and validated based on hourly wind observations from 388 meteorological stations with at least five effective years during 2000 to 2020 over northwest China, main area of wind resource and wind erosion over China. HWGEN was also compared with WINDGEN (WIND GENerator), an hourly generator in the process-based wind erosion prediction system (WEPS). Optimal distribution from two-parameter Weibull and Gumbel were determined for each wind direction and each station for 12 months to simulate daily average wind. A lognormal distribution was used to stochastically generate Uratio, which is defined as the ratio of daily maximum hourly wind to daily average wind, together with simulated daily average wind to generate hourly wind speed by a cosine function. In contrast to this, WINDGEN uses a constant monthly Uratio. Following conclusions can be drawn: (1) HWGEN_D decreases the MAPEs (Mean Absolute Percentage Errors) for simulating the frequencies of hourly wind speed ≥ 5m s-1 from 71.4 % to 25.7 %. (2) HWGEN_D decreases the MAPEs for AWPD (average wind power density) and Wf (average wind erosion force) from 71.6% to 26.5% and from 81.7% to 36.5%, respectively. (3) HWGEN_ND simulated the AWPD and Wf with the MAPEs of 32.2% and 53.5%, respectively, which is slightly worse than HWGEN_D, however, with one-tenth of parameters required by HWGEN_D. HWGEN has the potential to be used in the risk assessment of wind-related earth surfaces by simulating hourly wind speed of any length for the sites with observations and without observations by firstly interpolating HWGEN parameters and then simulating based on HWGEN from interpolated parameters.

Session 03: Space-time statistical methods (poster presentations)

Space-time statistical methods for modelling and analyzing climate variability

Down-scaling of open-boundary vector fields using Gaussian Markov random fields

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We present a procedure for reconstructing and down-scaling vector fields from sparse, noisy observations. This procedure is based on the stochastic PDE formulation for Gaussian Markov Random Fields. By applying the Helmholtz-Hodge decomposition for open-boundary flows to a vector field, we can construct a covariance kernel that models the physical properties of fluid flows. Our work also incorporates a procedure for inference of the harmonic vector field. We work towards incorporating anisotropy and non-stationarity into our procedure and show results on synthetic vector fields and real-world wind flow data.

Trends in surface air temperature and its short-term variability: How are they related? An analysis based on PCA

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The majority of climate detection studies focus on mean values and extremes; much less work has been done on detection of trends in variability. Short-term (intraseasonal) temperature variability can be quantified by several measures. In this contribution, we apply principal component analysis (PCA) in an attempt to find relations among trends in measures of temperature variability and between trends in mean temperature and in its variability.

We use several datasets, including station data (ECA&D), gridded data (E-OBS), and reanalyses (NCEP/NCAR, ERA5, 20CR), covering European landmass. Intraseasonal temperature variability is quantified four measures: seasonal standard deviation, difference between the 90th and 10th percentile, lag-1 day autocorrelation, and mean absolute day-to-day difference. Trends in these variability measures and in seasonal mean temperature are calculated for all seasons.

The trend values enter PCA. The input matrix is formed by values at individual sites (stations or gridpoints) in rows and temperature mean and variability measures in columns. This setting of the input matrix corresponds to PCA in an R-mode. We employ PCA in various settings (particularly data standardization, choice of similarity matrix, and rotation) to see which of them provides best interpretable outputs. We demonstrate that R-mode PCA is able to uncover mutual dependencies of the input variables and their regional variations. In the same vein, common behaviour and differences between datasets can be uncovered when R-mode PCA is applied to a set of datasets in columns instead of a set of variability measures.

Quantifying ENSO teleconnections in a variable climate

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The El Niño-Southern Oscillation (ENSO) is the leading mode of climate variability on interannual timescales. ENSO has far-reaching effects with strong relationships to temperature and precipitation variability for many regions around the world. Thus, there is a great deal of interest in quantifying ENSO relationships to regional climates and understanding their changes in a warming world, especially given implications for possible changes in flood and drought occurrence. However, ENSO teleconnections are inherently variable, so sample size and effects of decadal variability can influence the strength of ENSO teleconnections and the effect on climate model evaluation. In this study, we examine how variable ENSO-rainfall teleconnections are for regions across the world and the effect of sample size on establishing teleconnection strength. We also investigate effects on model evaluation of using different observational samples. We discuss implications for ENSO teleconnection analyses more broadly and considerations for model-based studies.

Low-frequency climatic variability and trends in Central Argentina

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The central region of Argentina has undergone significant changes in precipitation and temperature over the past decades, in both mean and variability values. The climate in this area exhibits an annual cycle, with the driest and coldest months occurring in winter (JJA) and the wettest and warmest months in summer (DJF). Influenced by the presence of the Andes acting as a barrier to moist westward flow from the Pacific Ocean, the region experiences particularly dry conditions with moisture flow entering from the north along the Andes eastern slopes. Additionally, the western branch of the South Atlantic Anticyclone contributes to the low-level north/northeastern flow, transporting warm and moist air to the subtropical region of South America, promoting environmental instability.

Better understanding of the regional climate change combined with natural variability across different time scales, is crucial to address the adverse impacts on various socio-economic activities in the region. Large-scale agricultural-livestock production and multiple hydroelectric power plants, dependent on river flow, are prominent in the area. However, despite the importance of the region, few studies have delved into a detailed description and understanding of its climate features. Hence, the objective of this work is to deepen the characterization and understanding of low-frequency variability and change of the climate in Central Argentina (region roughly limited by 66°W-61°W and 35°S-26°S) from 1959 to 2020.

To characterize average climate, its variability and changes, data on minimum temperature, maximum temperature, and precipitation were utilized from the National Meteorological Service, the Climatic Research Unit (CRU) database based on surface observations, and global data from the ERA5 reanalysis by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period 1959-2020.

Long-term trends were assessed using the Theil-Sen linear trend estimator for each variable in every season. This estimator, chosen for its non-parametric nature and insensitivity to outliers, offers a robust analysis. To capture interannual variability, Singular Spectrum Analysis (SSA) was applied for each variable to a representative time series of the region. The statistical significance of each component was determined through a Monte Carlo test, and significant components were correlated with large-scale circulation patterns using multiple linear regression, incorporating ERA5 sea-level pressure, geopotential, and wind data.

The linear trends from 1959 to 2020 indicate a notable rise in minimum temperature during spring and summer across the region (seasons considered in this study correspond to those of the Southern Hemisphere). Maximum temperature shows positive trends in spring across the region, and in summer the trends are positive towards the northwest and negative towards the southeast of the study region. Precipitation exhibits a slight negative trend in winter, indicating an intensification of the dry season, while no widespread changes were observed in autumn, spring, and summer.

The SSA analysis for minimum temperature shows a non-linear positive trend and an oscillation signal with a periodicity close to 3 years, that is strongly influenced by the El Niño-Southern Oscillation (ENSO) through a Rossby wave train identified in the circulation anomalies. The latter enhances the flow coming from the north, leading to higher temperatures during autumn, winter, and spring. Maximum temperature and precipitation display irregular leading SSA components with opposing signs in their interannual behaviors, suggesting that precipitation variability modulates that of maximum temperature. No significant circulation patterns are detected at the regional or global scale for this oscillation signal. An oscillation signal with a periodicity close to 3 years was also found for maximum temperature, but that is not distinctly associated with ENSO. In autumn and spring, positive maximum temperature anomalies described by this oscillation are associated with an anticyclonic circulation anomaly over Central Argentina. Lastly, precipitation exhibits an oscillation signal with a periodicity near 7 years. Positive regional precipitation anomalies described by this signal in winter are linked to an anticyclonic circulation anomaly over the South Pacific, that enhances the influx of humid air into Central Argentina.

This study provides valuable local climate insights, contributing to impact and risk assessment studies, and enhancing projections for future changes.

Analyzing Climate Trends in Southern Africa: A Comparative Study of Observed and Modeled Data on Regional Warming

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Temperature trends are an important parameter to measure the state of the climate, given they represent a direct response to anthropogenic radiative forcing. The year 2023 has been the warmest on record so far with many regions experiencing record heat events. Here, we assess changes in temperature over Southern Africa from five gridded datasets and the abilities of regional and global climate models' experiments in reproducing these. We found that the trends in the gridded dataset used in this study are not different from each other, and that temperature is increasing at a rate of 0.17°C per decade. Across the region, the warming rate varies spatially, with the north-western parts of the region experiencing 1.2 to 2 times faster warming than the global annual average. The results of our study clearly demonstrate that mean temperatures have emerged from natural climate variability. The earliest time of emergence occurs in Angola as early as the 1980s, while for other areas this emergence over natural variability is found post- 2010. This clearly suggests that many people in the region are already living with climate change. Our findings show there is a strong agreement among regional and global climate models in replicating these historical upward trends and agree on the direction underscoring their reliability in capturing the direction of climate change over southern Africa.

Basis for Change: Approximate Stationary Models for Large Spatial Data

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Climate processes in the Earth system are often characterized by large and heterogeneous fields collected over space. Traditionally, spatial models have relied on the Gaussian Process (GP) to fit stationary covariances to such data. As the size of climate data sets continues to increase, this approach has proven to be computationally infeasible, necessitating the use of approximate methods. A prominent category of such methods is "Fixed Rank Kriging" (FRK), where the GP is approximated as a sum of basis functions with random coefficients. Although this offers computational efficiency, it does not inherently guarantee a stationary covariance. To mitigate this issue, the basis functions can be "normalized" to maintain a constant marginal variance, avoiding unwanted artifacts and edge effects. This allows for the fitting of nearly stationary models to large, potentially non-stationary datasets, providing a rigorous base to extend to more complex problems. Unfortunately, the process of normalizing these basis functions is computationally demanding. To address this, we introduce two fast and accurate algorithms for the normalization step, allowing for efficient prediction on very fine grids. The practical value of these algorithms is showcased on observed climate data, where significant computational speedups are achieved. While implementation and testing are done specifically within the LatticeKrig framework, these algorithms can be easily adapted to any FRK method with basis functions distributed along a regular grid.

Unveiling seasonal synoptic-scale links: A global evaluation of atmospheric circulation and climate connections

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Our presentation focuses on the strength of the links between atmospheric circulation and leading surface climate elements, including temperature, precipitation and wind. In the past, these links were closely monitored over Europe and utilized in weather prediction. Now, they help us understand climate variability as well as ongoing climate trends and describe the role the ever changing atmospheric circulation plays in them. With new global-scale data sets available, which describe both historical and computer-simulated atmospheres, the focus of studies has been shifting onto other continents.

Our study aims to apply the traditional methodology of classifications of atmospheric circulation, utilizing an algorithm of k-means cluster analysis, in the global scale, hereby providing an overview of the strength of the links between atmospheric circulation and leading variables describing day-to-day changes in weather. We identify particularly strong links for some variables and seasons that lie outside of the traditional regions of study, including central and eastern Asia, central and western North Africa and subtropical South America and southern Africa. Physical interpretation of these strong links will be provided in the presentation, as well as an in-depth study of the role of methodological choices on our results.

Session 04: Weather/climate forecasting (oral presentations)

Weather/climate forecasting, predictability and forecast evaluation

Constraining near to mid-term climate projections by combining observations with decadal predictions

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The implementation of adaptation policies requires seamless and relevant information on the evolution of the climate over the next decades. Decadal climate predictions are subject to drift because of intrinsic model errors and their skill may be limited after a few years or even months depending on the region. Non-initialized ensembles of climate projections have large uncertainties over the next decades, encompassing the full range of uncertainty attributed to internal climate variability. Providing the best climate information over the next decades is therefore challenging. Recent studies have started to address this challenge by constraining uninitialized projections of sea surface temperature using decadal predictions or using a storyline approach to constrain uninitialized projections of the Atlantic Meridional Overturning Circulation using observations. Here, using a hierarchical clustering method, we select a sub-ensemble of non-initialized climate simulations based on their similarity to observations. Then, we try to further refine this sub-ensemble of trajectories by selecting a subset based on its consistency with decadal predictions. This study presents a comparison of these different methods for constraining surface temperatures in the North-Atlantic / Europe region over the next decades, focusing on CMIP6 non-initialized simulations.

Seasonal Forecasts of Winter Temperature Improved by Higher-Order Modes of Mean Sea Level Pressure Variability in the North Atlantic Sector

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The variability of the sea level pressure in the North Atlantic sector is the most important driver of weather and climate in Europe. The seasonal prediction system of Deutscher Wetterdienst includes an ensemble subsampling procedure that accounts for autumn/winter NAO and further circulation indices, which leads to an improved prediction skill of autumn/wintertime mean sea level pressure and near-surface temperature in Germany and across Europe.

At the heart of the procedure is the statistical prediction of the seasonal anomalies of the four leading Eigen-vectors of the SLP field over the Euro-Atlantic sector from global predictor fields (SST, snowdepth, sea ice concentration, temperature at 100hPa) at one to four months leadtime. We show the results of an application of a modern high-order tensor-variate regression model along with its induced increase in subsampling prediction skill compared to less structured regression models.

Forecast quality assessment of multi-annual predictions of mean and extreme temperature and precipitation: multi-model evaluation and impact of model initialisation

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Both natural variability and external forcings modulate variations in climate variables such as temperature and precipitation, as well as in the intensity and frequency of extreme climate events. Climate information years in advance may support the implementation of adaptation policies to limit risks and losses associated with climate variability and change. Decadal climate predictions are a source of climate information at annual to decadal time scales. The Decadal Climate Prediction Project (DCPP) of the Coupled Model Intercom-parison Project Phase 6 (CMIP6) provides a comprehensive set of decadal predictions from multiple forecast systems. However, before using the predictions, the forecast quality assessment is a crucial step to estimate their accuracy and find windows of opportunity (e.g. variables, regions and forecast periods) to provide climate services based on trustworthy information.

We evaluate the quality of the predictions produced with all the available forecast systems within CMIP6-DCPP and the multi-model ensemble. Several skill metrics are used to estimate different aspects of the quality of both deterministic and probabilistic predictions. Specifically, we evaluate predictions for the forecast years 1-5 of the mean and extreme indicators of both temperature and precipitation, as well as of the Atlantic Multi-decadal Variability (AMV) index and global surface air temperature (GSAT) anomalies. In addition, the CMIP6 historical forcing simulations produced with the same forecast systems have been included in the analysis to estimate the impact of the model initialisation. The prediction skill of the decadal multi-model ensemble is compared with different reference forecasts: the climatological forecast to estimate the added value with respect to a naïve forecast, the individual forecast systems to assess the benefits and drawbacks of using a multi-model ensemble, the uninitialised historical simulations to estimate the impact of the model initialisation, and a smaller multi-model ensemble built with the subset of systems that provide near-real-time predictions to assess how much skill is lost due to the limited number of operational forecast systems.

The multi-annual predictions show high skill in predicting mean temperature over most of the globe, the AMV index and the GSAT anomalies. The indices that measure temperature extremes are also skillfully predicted by the multi-model, although with lower skill than the mean temperature. On the other hand, the forecast quality for mean and extreme precipitation is generally low, and significant skill is found only over some limited regions. The comparison between the multi-model ensemble and individual forecast systems indicates that the best system usually provides the highest skill for a specific variable, region and forecast period. However, the multi-model ensemble outperforms at least 50% of the forecast systems, which makes it a reasonable choice for not having to select the best individual system for each specific case (for instance, when systematically providing forecasts of several variables, regions and forecast periods). The comparison of the decadal predictions and historical simulations suggests an added value from model initialisation for predictions of temperature over several ocean and land regions (which is higher for mean quantities than for the extreme indices), and for the AMV index and GSAT anomalies. The added value of the initialisation is smaller for predictions of mean and extreme precipitation. Finally, comparing the complete multi-model ensemble against the sub-ensemble providing near-real-time predictions, shows the benefit of using a large ensemble over several regions, particularly for temperature predictions.

This systematic evaluation of decadal prediction systems is essential when providing a climate service based on decadal predictions so that the user is informed about the trustworthiness of the forecasts for each specific region and extreme event. Also, comparing decadal hindcasts and historical simulations helps climate services providers select the highest-quality source from the different data sources currently available.

Verification of full distributions on decadal timescales

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Predictions focus regularly on the predictability of single values, like means or extremes. While these information offer important insights into the quality of a prediction system, some stakeholders might be interested in the predictability of the full underlying distribution. These allow beside evaluating the amplitude of an extreme also to estimate their frequency. Especially on decadal time scales, where we verify multiple lead years at a time, the prediction quality of full distributions may offer in some applications important additional value.

We will present the evaluation of full distributions by the application of the integrated quadratic distance (IQD). For this we analyse decadal predictions of the seasonal daily 2m-temperature within the MPI-ESM decadal prediction system. It demonstrates that an initialised prediction system has advantages in particular in the North Atlantic region compared to uninitialised historical simulations and a climatology, but depends on the season. Discussions will focus on strategies, opportunities and pitfalls of these evaluations and explicitly address topics around bias correction and significance calculation.

Improving MOS Random Forests for Post-processing Extreme Wind Gust Forecasts

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Extreme events, such as wind gusts or extreme precipitation, can generate huge impacts on our society. Accurate predictions of such events are thus vital for taking preventive measures. In spite of continued scientific progress in weather forecasting, ensemble forecasts exhibit biases and under-dispersion and have to be calibrated using observations before being used, e.g., in hydrological or renewable energy applications. Several post-processing techniques have therefore been developed and applied over the last decades in order to improve forecast quality. Many existing post-processing methods are parametric, i.e. they assume that the predictive distribution belongs to a class of known probability distributions. Parameters of the assumed distribution are then modeled as functions of predictors obtained from numerical weather prediction models, for example using nonhomogeneous regression or more advanced tree-based methods. One of the main limitations of such methods is that they often post-process intermediate or extreme events similarly, for example by considering a single family of probability distributions to describe the target variable or by using the same set of predictors in nonhomogeneous regressions, which could lead to suboptimal results for extremes. We propose to adapt a recently developed distributional tree-based technique (MOS Random Forests) used for ensemble post-processing to overcome this limitation by allowing the method to choose different statistical distributions and predictors to model intermediate and extreme values. The proposed method is applied to forecasts of 6-hourly maximum wind gusts from 2018 to 2022 over the Netherlands using the ECMWF-IFS ensemble data. Results are compared against several state-of-the-art parametric and non-parametric post-processing methods. In comparison with these alternatives, the proposed algorithm reasonably corrects intermediate values and shows skill improvements for wind gust extremes depending on lead times, stations and thresholds. However, it remains difficult to beat the raw forecasts of extremes. Therefore, it encourages further research on adding more flexibility to parametric methods for the post-processing of extreme weather forecasts.

Spatial Trends of Convective Available Potential Energy (CAPE) over Bangladesh and its eight regions for 40 years (1982- 2021)

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CAPE is the amount of energy an air parcel which is an indicator of atmospheric instability as it is required to predict the initiation of severe weather. CAPE can directly influence the circumstances of atmospheric convection phenomena. A long-term study on this thermodynamic factor needs to be carried out for the excellent prediction of convective activities. Developing climatology can bring out the proper distribution of CAPE in analyzing the thunderstorm phenomena in Bangladesh, which is the primary concern of the current research. The objective of this study has been followed through the observations on the Monthly and Seasonal Spatial average and Spatial trends of CAPE over Bangladesh for 40 years at 0000 UTC and 1200 UTC. Our analysis indicates that the increasing trend CAPE over Bangladesh may be liable for the increased frequency of extreme events. From March to May, the most significant CAPE values were observed in Bangladesh's southwest and southern part. The higher increasing trend of CAPE value has been demonstrated in April, which is more prominent in the northwestern part. The seasonal variation CAPE values vary from 800 J/kg to 3000 J/kg from pre-monsoon to post-monsoon over the southern region of Bangladesh. The highest CAPE value has been found in Barisal and Chattogram, the southern and southeastern parts of Bangladesh, and the lowest CAPE value has been observed in Rangpur and Sylhet. The findings of this research will effectively improve the forecasting of lightning and thunderstorm activity in Bangladesh.

Advanced pattern techniques in weather and climate science

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This presentation discusses two examples of the use of advanced pattern techniques in weather and climate science. Firstly, optimal mode decomposition (OMD) is employed for linear inverse modelling. The OMD technique determines a low-rank approximation to a high-dimensional dynamical system in terms of a linear empirical model; a set of patterns and a system matrix are identified simultaneously by maximising the explained predictive variance. The method is exemplified on a quasi-geostrophic atmospheric model with realistic mean state and variability as well as the ENSO. Considerable improvements in prediction skill are observed compared to the traditional approach based on principal components or dynamic mode decomposition (DMD). Secondly, the method of principal prediction patterns (PPPs) is explored. Here, pairs of patterns are determined in the space of predictors and the space of predictands, respectively, and linked in a predictive manner. We also discuss nonlinear extensions of the two techniques by including nonlinear functions of predictors into the PPPs or by combining the techniques with a clustering or nearest-neighbour approach.

Optimal transport for the multi-model combination of sub-seasonal ensemble forecasts

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We propose to explore ensemble forecasts and their combination from the perspective of a probability space. Recognizing ensemble forecasts as discrete probability distributions allows us to work directly in the probability distribution space and to reformulate Multi-Model Ensemble (MME) methods as barycenters. Indeed, the barycenter of a collection of distributions (or the ensemble forecasts here) is the distribution that best represents them with respect to a given distance. It can thus be seen as their combination, and so used to build MMEs. In fact the well-known “pooling” method (that is the concatenation of the different ensembles members) is equivalent to the barycenter with respect to the L2 distance. The barycenter can then be extended to other distances. In particular, we consider the Wasserstein distance which corresponds to the cost of the optimal transport between two distributions. It has interesting properties in the distribution space, such as the possibility to preserve the temporal consistency of the ensemble members, and lead to very different MME’s distribution. Moreover, barycenters allow us to easily build weighted-MMEs by giving different weights to the input distributions. The weights have an important impact on the skill of the MMEs. Thus, in order to obtain the best possible MME’s performance, we estimate the optimal weights from the data using cross-validation.

These two barycenters are applied to the combination of the models from the subseasonal-to-seasonal (S2S) project’s database. As a proof-of-concept, we first start with the combination of two models, namely the European Centre Medium-Range Weather Forecasts (ECMWF) and the National Center for Environmental Prediction (NCEP) models. The performance of the two barycenter-based MMEs are evaluated for the prediction of weekly 2m-temperature during European winter. We show that the two MMEs are generally able to perform as well or better than both the single-models. However, the best combination method depends on the metric and so has to be chosen according to the intended application. We then extend the barycenter approach to the combination of more models, of which we will discuss preliminary results.

El Niño prediction based on online change-point detection in high-dimensional correlation structure

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We concentrate on the changes in correlations and show that well before an El Nino episode the correlations tend to increase first and then decrease sharply. We use this robust observation to forecast El Niño development in advance. The problem of change point detection in the correlation structure of streaming high-dimensional data is explored, with minimum assumptions posed on the underlying data distribution and correlation structure. New detection procedures are proposed and theoretical evaluations of these proposed methods are conducted in terms of average run length and expected detection delay. This is the first time that an online change point detection procedure is used to predict El Niño events. Our method yields hit rates above 0.85 and false-alarm rates smaller than 0.1, based on high-quality observational data.

Extracting latent variables from forecast ensembles and advancements in similarity metric utilizing optimal transport

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This study presents a novel methodology for extracting latent variables from high-dimensional sparse data, particularly emphasizing spatial distributions such as precipitation distribution. This approach utilizes multidimensional scaling (MDS) with a distance matrix derived from a new similarity metric, the Unbalanced Optimal Transport Score (UOTS). UOTS effectively captures discrepancies in spatial distributions while preserving physical units. This is similar to mean absolute error however it

considers location errors, providing a more robust measure crucial for understanding differences between observations, forecasts, and ensembles. Probability distribution estimation of these latent variables enhances the analytical utility, quantifying ensemble characteristics. The adaptability of the method to spatiotemporal data and its ability to handle errors suggest its potential as a promising tool for diverse research applications.

The dynamics of persistent hotspells in European summers

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Persistent summer weather can result in extreme events with enormous socio-economic impacts; recent summers in Europe have notably demonstrated this. The dynamics that cause persistent surface weather, as well as its potential changes under anthropogenic climate change, are the subject of active scientific debate (e.g. Lorenz et al. 2010, Pfleiderer et al. 2019, Röthlisberger et al. 2019, Ali et al. 2021). Although summertime atmospheric dynamics is receiving increasing attention, our understanding of the mechanisms involved in the formation of persistent weather conditions in summer remains incomplete. This study investigates the drivers responsible for making some spells of extreme surface temperature more prone to lasting longer than others.

The study uses the ERA5 reanalysis dataset (Hersbach et al. 2020) to take advantage of its high spatiotemporal resolution and relatively long temporal coverage from the 1950s up to today. Starting from an impact-based definition of persistent hot conditions for different European regions, we characterise their persistence by looking at the associated circulation patterns and surface conditions. These regions in Europe were obtained through a clustering technique that considers the spatial co-occurrence of persistent temperature extremes. Through a comparison of long-lived (persistent) and short-duration events, we discern significant dynamical differences and regional variations that shed light on the common ingredients and mechanisms influencing the persistence of extreme heat events in summer. Results show that dry soil spells increase the likelihood of persistent hotspells, with this link being strong at longer timescales for Soutwestern Europe than for Central/Western Europe, where more intense land-atmosphere feedbacks during the event itself are key to extend the spell duration. That said, the atmospheric flow still needs to exhibit stationary or recurrent behaviour for the surface persistence to establish itself, for instance through blocking, large-scale Rossby wave breaking, or generally a less transient evolution of the flow - although recurrent Rossby wave packets are also seen to play a role.

A deeper investigation into the dynamical processes controlling persistent surface conditions over Europe in summer is essential for improved predictability at the sub-seasonal to seasonal (S2S) timescale, and it holds significant relevance for risk preparedness (White et al. 2017). Results from the study aim to advance the discussion on summer dynamics, S2S weather persistence and climate impacts.

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A new method for correcting model biases in decadal forecasts

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The field of near-term climate prediction has grown significantly since the pioneering studies made in the framework of EU-funded ENSEMBLES project (2004-2009). This quick development is in part due to the large scientific and socio-economic interest generated by these climate predictions. The inclusion of decadal predictions in the recent phases of the Coupled Model Intercomparison Project (namely CMIP5 and CMIP6) and the production and publication of real-time decadal prediction have helped to their rapid progress. Bridging the gap between seasonal predictions and longer-term climate projections, decadal predictions can provide climate information from interannual to decadal timescale (1-10 years) and have the potential to feed key climate services that support government and industry sector users to make decisions in our rapidly changing climate.

While the potential of near-term prediction for useful applications has been demonstrated, the scientific community have also highlighted a number of outstanding research questions and challenges in the climate prediction field. The drift problem related to model systematic errors is one of the major challenges in decadal prediction. Model drifts systematically occur when the model is initialized from the observations, which is a climate state away from the climate model attractor. Although some progress has been achieved, systematics biases are still present in decadal prediction systems. These need to be corrected from the forecasts before skill assessment. Finding a good method of forecast bias correction is a crucial issue, as in many cases the danger of removing the biases is also to remove the signal to be predicted. In this study we introduce a new bias correction method for decadal forecasting inspired by the Model Output Statistics (MOS) technique, which is routinely used in numerical weather prediction at Météo-France. MOS is a statistical technique that consists of a multiple linear regression between observations and predictions. What is interesting is that it can be adapted to each particular case and allows us to get deeper insight into the physics behind the predictability. In the framework of the H2020 IMPETUS4CHANGE project, the MOS method has been applied to decadal predictions performed by Earth System Models for two particular cases: ocean temperature in the North Atlantic and surface temperature in Europe. It is shown that MOS can improve the prediction skill compared to other drift correction techniques that are used as standard.

Probabilistic forecasting of cloud base height and visibility using Quantile Regression Forests, based on NWP and observation features

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We have applied Quantile Regression Forests (QRF) to generate probabilistic forecasts of weather conditions associated with Low Visibility Procedures (LVP) at Schiphol airport (Amsterdam, the Netherlands). LVP are determined by combined thresholds of cloud base height and (runway) visibility. Forecasts of these conditions are critical for airport operations, as they inform operational planning, with the potential of minimizing meteorologically induced disruptions.

Using a dataset of 5 years of hourly data, we have performed a forward feature selection and optimized QRF's hyperparameters for this specific application, and evaluated the model's performance for different forecast lead times and different classes of cloud base height, (runway) visibility and LVP conditions. Hereby, LVP forecasts were obtained by combining separate models for cloud base height and (runway) visibility, and applying a Schaake shuffle approach for restoration of the dependencies between these parameters.

The verification revealed consistent positive Brier Skill Scores (BSS) for the three most common LVP classes: Marginal, A and B. Although the skill was not always positive for the more extreme LVP classes C and D, we argue that also for these conditions forecasters might derive valuable indications from the forecast system.

We demonstrate the operational utility of the system with an example, also illustrating the support of interpretability through the use of SHAP (Shapley Additive exPlanations) values. Our results underscore the potential of QRF for probabilistic forecasts of meteorological conditions, for aviation and other purposes.

Evaluation of high resolution regional model (COSMO) used in marine weather forecasting over the Nigerian coast- Gulf of Guinea.

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Deficiency in sea states prediction is challenging especially in a dynamically complex coastal area as the equatorial part of the North Atlantic Sea – the Gulf of Guinea. To compensate for this challenge, a non-hydrostatic limited–area atmospheric model - COnsortium for Small scale MOdel (COSMO) from the German Weather Service adopted by the Nigerian Meteorological Agency, designed for both operational and numerical weather prediction (NWP), was employed in marine weather forecasting along the entire inshore and onshore areas of Nigeria. The variables taken from the output of the COSMO viz-a-viz Wind speed, SST, swell and significant wave height (SWH), particularly under stormy conditions are studied. The performance of the COSMO model was evaluated for extreme (Storm) and calm conditions while its simulations are compared with observations by using the most common skill scores (Bias, RMSE…..). The results indicated that there is mostly reasonable agreement between observations and simulations for the marine parameters used. The correlations between the observation and the forecast variables are generally greater than 0.9. The bias is generally >15% for the SWH with >20% for the Wind speed. The obtained results indicate that COSMO is able to partially reproduce the observed extreme events characteristics and suggest that COSMO-Model has the potential for marine weather forecasting. Potential shortcomings of the model were discussed as well.

Keywords: Weather Forecasting, COSMO, NWP, coastal waters, Evaluation

The Influence of Solar Activity on Snow Cover over the Qinghai–Tibet Plateau and Its Mechanism Analysis

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Using global ocean vertical temperature anomaly data, we identified that a significant response of the sea temperature anomaly (STA) to the solar radio flux (SRF) exists. We found that the STA exhibited a significant correlation with Asian summer and winter precipitation, among which the response from the Qinghai–Tibet Plateau (the QTP) was particularly noticeable. Based on NCEP/NCAR reanalysis data, the latent heat flux (LHF) anomaly, which plays a key role in winter precipitation in China, especially over the QTP, showed a significant response to the SRF in the Pacific. The results demonstrated the bottom-up mechanism of impact of solar activity (SA) on the plateau snow through sea–air interaction. Meanwhile, a top-down mechanism was also present. When the SRF was high, the stratospheric temperature in the low and mid-latitudes increased and the temperature gradient pointed to the pole to strengthen the westerly wind in the mid-latitudes. The EP flux showed that atmospheric long waves in the high altitudes propagated downward from the stratosphere to the troposphere. A westerly (easterly) wind anomaly occurred in the south (north) of the QTP at 500 hPa and the snowfall rate over the QTP tended to increase. When the SRF was low, the situation was the opposite, and the snowfall rate tended to decrease. The model results confirmed that when total solar irradiance (TSI) became stronger (weaker), both of the solar radiation fluxes at the top of the atmosphere and the surface temperature over the QTP increased (decreased), the vertical updraft intensified (weakened), and the snowfall rate tended to increase (decrease) accordingly. These conclusions are helpful to deepen the understanding of SA's influence on the snow cover over the QTP.

Improving sub-seasonal wind-speed forecasts in Europe with a non-linear model

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The maintenance, deployment, management, and energy supply-demand balance of systems involving wind power systems may be facilitated by the use of skillful wind forecasts. Forecasting wind speeds for sub-seasonal periods (two to six weeks) remains challenging. However, at these time scales, the predictability of atmospheric fields involved in large-scale dynamics tends to be better than for surface fields, suggesting a potential for improving wind speed probabilistic forecasts by leveraging information from the former. Research by Goutham et al. (2022) improved surface wind speed forecasts by applying a linear regression model to "downscale" information from forecasts of the 500 hPa geopotential height (Z500). Building on their work, our study investigates whether non-linear supervised-learning models, especially Convolutional Neural Networks (CNN), can surpass linear models in predicting sub-seasonal wind speeds in Europe for boreal winters.

Specifically, the proposed framework uses a supervised-learning model, Linear Ridge (LR) or CNN, to regress weekly-mean surface wind speeds from dynamic forecasts of Z500. The dynamical ensemble forecasts of surface wind speed from the European Centre for Medium-Range Weather Forecasts (ECMWF) serve as benchmarks for comparison. We first assess the skill of a deterministic version of these supervised-learning models, utilizing ERA5 reanalysis data to regress wind speed from Z500. It is found that the CNN is, on average, more skillful than LR with respect to the mean squared error (MSE) due to its non-linearity. Subsequently, the same models (without retraining) are applied to the sub-seasonal forecasts from the ECMWF covering the boreal winters from 2015 to 2022, with the same variables and member by member. The MSE of the ensemble mean, the Continuous Ranked Probability Score (CRPS) and the Spread Skill Ratio (SSR) are used to compare the skills of the forecasts. Again, the results show that the CNN performs better than the LR. Yet, this is in part explained by the fact that the deterministic supervised-learning models are under-dispersive due to the fact that they explain only a fraction of the target variable variance. Introducing random perturbations to represent the stochasticity of the unexplained part from the signal helps prevent this issue and shows that the CNN performs better than the LR only the first weeks while the LR's performance converges towards that of CNN after three weeks, and the forecasts from the LR and the CNN are both more skillful than the dynamical forecasts, even though no information about the dynamical wind forecasts is used. Thus, (1) stochasticity is key when applying supervised-learning models to regress the probabilistic evolution of meteorological fields from input forecast fields and (2) the improvements brought by nonlinear supervised-learning models depend on the lead time. Further investigation is needed to determine in which situations (case studies, input variables...) nonlinear models remain more skillful at the sub-seasonal lead times.

Goutham, Naveen, et al. "Statistical Downscaling to Improve the Subseasonal Predictions of Energy-Relevant Surface Variables." Monthly Weather Review 151.1 (2023): 275-296.

Deep-Learning Weather Prediction: Case Studies and Model Deficiencies

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The forecast accuracy of deep-learning-based weather prediction models is improving at an impressive speed, leading authors to speak of a "second revolution in weather forecasting". With a multitude of methods being developed and few physical guarantees on the deep-learning models' predictions, there is a need for a thorough evaluation of these new methods. While this need is partly fulfilled by benchmark datasets, it is possible that summary scores hide information on the performance during impactful extreme events or that the skill on multivariate impact variables degrades because of misrepresented dependencies between variables predicted by the forecasting systems. We compare deep-learning prediction models (GraphCast, PanguWeather, FourCastNet) and ECMWF's HRES system in three case studies: the record-shattering June 2021 Western North America heatwave, a humid heatwave in South Asia in April of 2023, and the winter storm in North America in February 2021, including analyses on impact metrics that combine multiple predicted variables. We stress the potential of case studies for building public trust as well as discovering unknown model deficiencies and argue that model developers should put a stronger focus on impact-relevant metrics and variables.

Human against the machine - how does a modern multi-model ensemble seasonal forecast compare to the traditional SARCOF consensus outlook?

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The concept of Regional Climate Outlook Fora (RCOF) such as the Southern African SARCOF is built around the so-called consensus forecast methodology. That methodology is a subjective in nature combination of empirical statistical and hybrid forecast, and expert opinion sourced from the region's forecasters yielding a simplified tercile forecast, and it has not essentially changed since the inception of RCOFs in the mid-1990s. The approach is currently being slowly phased out and replaced by purely numerical processing of the output of multi-model ensemble (MME) of dynamical, global forecast models, used in an objective seasonal forecast (OSF) framework. But is the dynamical forecast clearly advantageous over the consensus forecast? A purely mechanistic comparison of forecast skill between the two approaches reveals limited differences, strongly conditional on the choice of skill measure. The consensus forecast has low reliability, and is built to be conservative (i.e. close to climatological probabilities) which, in theory, constrains its utility compared to the MME forecast. However, a naive interpretation of the SARCOF consensus forecast as indicative of the direction of anomalies proves surprisingly skillful, exceeding skill of dynamical models. Additionally, while the MME forecast process focuses on data, the consensus forecast process has a potential to capitalize on its emphasis on capacity and confidence building, power relations, trust and relationships between climate information producers and stakeholders. The future of seasonal forecasting in the region thus appears to be a transformation of the consensus process to comply with OSF principles rather than adoption of mechanistic processing of global MME products.

Session 04: Weather/climate forecasting (poster presentations)

Weather/climate forecasting, predictability and forecast evaluation

Verification of extreme wet and dry cases in Brazil predicted by ECMWF S2S model

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Extreme conditions of wet or dry conditions produce social and economic impacts in several regions of Brazil. Predictions in the time- scale of 2 weeks are very important to establish actions of monitoring and warnings. The Subseasonal to Seasonal (S2S) project provided hindcasts that have been very useful to verify the ability of models in predictions at this time-scale. In a previous study, we analyzed the observed extreme wet and dry cases in the Southeast and South regions of Brazil and the predictions of the ECMWF model for those cases. The model could represent very well the precipitation patterns and the associated global and regional atmospheric features. Now, in this new study, we analyzed the extreme precipitation predicted by the ECMWF model two weeks ahead, and verified the observations of those cases. The six more extreme wet and dry cases were selected in the regions of Southeast, South, Central-West and Amazon Brazil during the period of 1999-2010. For verifications, GPCP precipitation data and ERA5 reanalysis were used. We discuss about the predictability in these regions and the atmospheric features associated.

Statistical downscaling of long-term summer temperature forecasts for Czechia

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Dynamical forecasts use full three-dimensional climate models to simulate potential changes in the atmosphere and ocean over the next few months based on current conditions. The ensembles of simulations provide probabilistic weather scenarios that indicate the likelihood of a given period being wetter, drier, warmer, or colder compared to the seasonal average. The added value of various downscaling approaches for seasonal forecasts is a topic of frequent debate. This work focuses on statistical downscaling, which is based on empirical relationships derived between a local observed predictand of interest (summer temperature in this case) and one or several suitable model predictors from global seasonal forecasting systems.

Unlike tropical regions, seasonal predictability in Europe remains limited. This study analyses the seasonal forecast systems available in the Copernicus Climate Change Service (C3S) archive, which provide near-surface air temperature data at 1° to 1° spatial resolution. This study examines the statistical downscaling of summer air temperature forecasts for Central Europe from two weather forecast systems: the European Centre for Medium-Range Weather Forecasting (ECMWF) SEAS5.1 system and the Météo-France 8 (MF) system.

The study analyses the period 1993-2016, which is the longest hindcast period common to all systems, and the domain of the Czech Republic in Central Europe (47-52°N, 11-20°E). To perform statistical downscaling using the neural network method in STATISTICA software, we tested air temperature and sea surface pressure from global forecast models as predictors. The reference data used in this study are gridded E-OBS observational air temperature data sets.

Subseasonal and Seasonal drivers of European winter weather

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Progress in weather and climate predictions strongly depends on an improved causal understanding of the climate system. Sources of predictability are expected in teleconnections, referring to a spatially distant forcing (e.g. enhanced tropical sea surface temperatures) influencing regional climate. For European winter weather, several of such climate modes such as the El Niño–Southern Oscillation (ENSO), the Quasi-Biennial Oscillation (QBO), the Madden–Julian Oscillation (MJO) and the stratospheric polar vortex (SPV) have been described. However, their combined influence on European weather likely involves non-linearities which are not well understood and quantifying their contributions from data remains challenging. Here I will discuss how the seasonal drivers ENSO and the QBO can modulate the influence of the SPV and the MJO on European weather. I will focus on conditions associated with cold temperatures, and low precipitation, that is, conditions which have been linked to high impacts. More generally, I argue that a causal design helps to interpret data, improves our understanding of teleconnections and may serve as a conceptual framework to better assess 'windows of opportunities' for subseasonal and seasonal predictions.

Seasonal Forecast of precipitation during winter season Using Climate Predictability Tool (CPT) over Ethiopia

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Abstract

The early warning of the climate seasonal forecast is significant. It can effects the country's risk management preparedness and its socio-economic sectors such as its energy administration, agricultural management, health, tourism planning , disaster forecasts and protection, water resource management, Information, and food security. A long-range forecast for Ethiopia is conducted with the latest version of the Climate Predictability Tool (CPT). Therefore, a reliable seasonal forecasting technique is presented for taking adaptation measures for sustainable management of agriculture, water resources in Ethiopia. Climate Predictability Tool (CPT), developed by the International Research Institute of University of Columbia is made use of making seasonal weather forecasts for Ethiopia. It uses Canonical Correlation Analysis, in which predictors and predictands are involved in making forecasts using the Model Output Statistics technique. The model is trained with 30 years of rainfall data retrieved from Meteorological observatories in Ethiopia, sea surface temperature, zonal wind speed and mean sea-level pressure Geopotential height of reanalysis data. Climate Predictability Tool seems to be a better tool for predicting rainfall of the northern part Ethiopia Surface Temperature as a predictor. ROC score showed good score, first, for below normal category (0.81) followed by above normal category (0.65), normal category, the low ROC score is given (0.5).

Operational seasonal prediction over Europe using multiple scenarios from a multi-model ensemble forecast

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Seasonal prediction uses ensemble forecasting to sample the distribution of possible climate outcomes in the upcoming term, given the slowly-varying constraints on the atmosphere. Thanks to freely-accessible data such as that of the Copernicus Climate Change Service (C3S), this can be even be done in multi-model mode, by combining ensemble seasonal forecasts from various modeling centers. However, translating the multi-model distribution into meaningful information is a challenge climate services are often faced with, due to the high dimensionality of the data, i.e the necessity to take into account the ensemble spread across several grid points and several co-varying variables simultaneously.

In order to overcome this issue, we propose to design a new product that consists in grouping the multi-model ensemble members into several competing scenarios, defined using a clustering algorithm. The role of the clustering algorithm is to summarize the forecast uncertainty by highlighting the main discrepancies between the members, irrespective of the data source. However, the number of possible clustering options is huge: the scenarios may differ depending on the algorithm itself, but also on the climate variables used for clustering, and on various data pre-processing choices. Here, we present our approach to determine a relevant clustering procedure for seasonal forecast scenarios of 2-m temperature and precipitation over Europe (29.5°W-40.5°E; 30.5°N-70.5°N).

The scenarios defined from this procedure are routinely produced every month for experimental purposes, as part of the Météo-France real-time seasonal forecast bulletin. We illustrate their outcomes on recent case studies. These case studies highlight how useful scenarios are to forecasters by refining the ensemble analysis beyond the usual seasonal forecast diagnostics that are ensemble mean and tercile probabilities.

Dynamic-statistical downscaling method for annual precipitation prediction in Yangtze River Basin and its application

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Based on the station data, reanalysis data and dynamic climate model hindcast data, a dynamic-statistical downscaling prediction method of annual precipitation anomaly in the Yangtze River Basin and its application skill are discussed by using the empirical orthogonal decomposition (EOF) iteration and interannual increment method. Results show that based on the annual scale circulation field of reanalysis data, a statistical downscaling prediction scheme for annual scale precipitation anomaly increment over the Yangtze River Basin is established. The average anomaly correlation coefficient (ACC) of 26-year hindcast test can reach 0.6, which proves that the scheme has high predictability. A dynamic-statistical downscaling prediction scheme of annual precipitation anomaly increment is further established by using the annual scale circulation predicted by the model. The average ACC is 0.42, showing a high hindcast skill. The skill is much better than that of the directly output precipitation of the model. By analyzing the factors affecting the skill of annual precipitation prediction, it shows that when the annual average SST anomaly in equatorial central and eastern Pacific is negative, the prediction skill is higher, and the average ACC is more than 0.5. Under the cold water background of La Nina development year or La Nina duration year, more eigenvectors are selected by EOF iteration, which are incorporated into the multi-scale atmospheric circulation information as the prediction signal, and the prediction skill of annual precipitation anomaly is improved.

Session 05: Statistics for climate models (oral presentations)

Statistics for climate models, ensemble design, uncertainty quantification, model tuning

Constraining Regional Precipitation Projections by Benchmarking Model Performance

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We introduce a dynamic, yet standardized, benchmarking framework that can be used to assess model skill in simulating various characteristics of rainfall. Benchmarking differs from typical model evaluation in that it requires performance expectations to be set a priori. This framework has innumerable applications to underpin scientific studies that assess model performance, inform model development priorities, and aid stakeholder decision-making by providing a structured methodology to identify fit-for-purpose model simulations for climate risk assessments and adaptation strategies. While this framework can be applied to climate model simulations at any spatial domain, we demonstrate its effectiveness over Australia using high-resolution, 0.5° x 0.5° simulations from the CORDEX-Australasia ensemble. We first show how the framework can be used to identify fit-for-purpose simulations from a full ensemble based on historical model performance. Then, we showcase how benchmarking historical model performance can be leveraged to reduce uncertainty in regional precipitation projections. To achieve this, we detail a comprehensive quantitative and qualitative assessment of model dependencies and implement model-as-truth experiments to quantify future model performance.

Uncertainty characterisation for time series from ensembles of climate projections

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Ensembles of climate model simulations underpin much of our understanding of the climate system, and in particular the potential evolution of future climate in response to different scenarios of socioeconomic development and the associated greenhouse gas emissions. No climate simulator (e.g. GCM or RCM) represents the real climate system perfectly, however; and ensemble outputs contain structured variation reflecting simulator inter-relationships, as well as shared discrepancies between the simulators and the real climate system. This structure must be accounted for when using ensembles to learn about aspects of the real climate system, especially when defensible assessments of uncertainty are needed to support decision-making. In this talk we describe a statistical framework for addressing this problem, in situations where the quantities of interest are time series with a single value per year. The approach uses a state-space representation of the real-world time series structure and of the simulator:reality discrepancies, using energy balance model dynamics to obtain a physically plausible representation of anticipated trends. The work is motivated by, and illustrated using, future climate projections for the United Kingdom for which two contrasting ensembles (UKCP18 and EuroCORDEX) are considered, each with different structures and properties: in this case, the approach is shown to reconcile the substantial differences between the original ensemble outputs, in terms of both of the real-world climate of the future and the associated uncertainties. Another example looks at uncertainties in the dates of global temperature threshold exceedance, based on the CMIP6 ensemble.

Huge Ensembles of Weather Extremes using the Fourier Forecasting Neural Network

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Studies of low-likelihood high-impact extreme weather and climate events would benefit from massive ensembles to capture particularly rare and severe instances of these phenomena in a warming world. However, generating such massive ensembles, of e.g. 1000 members, has proven to be exceptionally expensive using traditional weather and climate models operating at sufficiently high resolution. We describe how to bring the power of machine learning (ML) to replace traditional numerical simulations for short week-long hindcasts of extreme weather, an application where ML is demonstrably fit-for-purpose in terms of accuracy and fidelity. The ML algorithm FourCastNet (FCN) is based on Fourier Neural Operators and Transformers, which have proven to be efficient and powerful in modeling a wide range of chaotic dynamical systems, including turbulent flows and atmospheric dynamics. FCN has been shown to be highly scalable on HPC systems based on GPUs. FCN and similar emulators can now generate massive ensembles of 1,000- to 10,000-member hindcasts using orders-of-magnitude less computational resources than traditional numerical models.

We discuss our progress using statistical metrics for extremes adopted from operational NWP centers to show that FCN is sufficiently accurate as an emulator of these phenomena. We also show how to construct huge ensembles through a combination of perturbed-parameter techniques and a variant of bred vectors to generate a large suite of initial conditions that maximize growth rates of ensemble spread. Furthermore, we demonstrate that these ensembles exhibit a ratio of ensemble spread relative to RMSE that is nearly identical to one, a key measure of successful short-term NWP systems. We conclude by applying FCN to severe heat waves in the recent climate record.

Filling the GCM/RCM matrix

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The first CMIP5-based Euro-CORDEX ensemble is the largest GCM-RCM ensemble produced, and may remain so for some time. But how close is it to a hypothetical full matrix, given that still only two thirds of the possible GCM-RCM combinations in the matrix have been simulated?

With a method developed during the PRINCIPLES project we analyse this question. An ANOVA technique with period (scenario), GCM, and RCM choices as dimensions of variation is used to fill the matrix holes, and a comparison is made of various quantities between a direct ensemble mean and a "democratic" mean over a filled matrix.

Differences are quite small compared to spatial variation, as expected. However, the emulated full-ensemble averages are much closer to an expected full-ensemble average than the direct non-emulated average. The emulated values for winter temperature are roughly 5 times closer to the target than a direct average over sea, where GCMs are the main determinants of temperature, and around 1.2 times better over land.

Using a full 5x4 sub-matrix we use bootstrapping to explore how the results deteriorate as more and more simulations are removed; it is possible to set up equations describing the error as a function of ANOVA parameters.

Tuning Earth System Models Without Integrating to Statistical Equilibrium

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Earth System Models (ESMs) are critical tools for understanding climate dynamics, yet their effectiveness depends on accurately parameterizing sub-grid scale processes. Tuning these sub-grid scale parameterizations is a task complicated by the large computational expense of running ESMs. Traditional tuning algorithms, notably those based on Kalman Inversion, implicitly rely on models having reached statistical equilibrium. However, achieving such equilibrium in ESMs is a formidable challenge, particularly given the ocean's decadal to centennial time scale. Our work introduces a novel algorithm capable of yielding accurate parameter estimations without requiring the simulations to attain statistical equilibrium. This method models time series as outputs of Vector Autoregression with Exogenous Variables (VARX) processes, but with parameters depending on ESM parameters. This approach is applied to the Community Earth System Model version 2 (CESM2) and produces accurate parameter estimations from perturbation runs as brief as two years, despite the presence of climate drift. This approach potentially opens new avenues for model calibration without the need to integrate to statistical equilibrium.

Recent and Projected Changes in Climate Patterns in an extended Middle East and North Africa Region

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The arid and semi-arid regions of northern Africa and southwest Asia have been expanding in the last several decades with their impacts aggravated by the rapid population growth, and they are likely to become even more extreme in a warming climate. We investigate the changes in atmospheric circulation and how they are linked to variations in clouds, moisture, dust and radiation, for an extended Middle East and North Africa (MENA). This is achieved through a combination of observational and reanalysis datasets for the present climate, and the projections of a multi-model ensemble (MME) constructed using ten models that participated in the sixth phase of the Coupled Model Intercomparison (CMIP6) project for the future climate.

Observational and reanalysis datasets reveal a northward shift of the convective regions over northern Africa in summer and an eastward shift in winter in the last four decades, with the changes in the location and intensity of the thermal lows and subtropical highs also modulating the dust loading and cloud cover in the extended MENA region. Reanalysis data shows a steeper nighttime compared to daytime temperature increase over northeastern Africa and the Arabian Peninsula in particular in the summer months, which will likely further exacerbate the mugginess in a region where the combination of heat and humidity at times exceeds the threshold for human habitability.

The CMIP6 MME gives skillful predictions when compared to in-situ measurements, and generally captures the trends in the ERA-5 data over the historical period. In a warming climate, the seasons' length in the extended MENA region are projected to change typically by up to 2 days, suggesting the warming is likely to be felt uniformly throughout the year. The subtropical highs are projected to migrate poleward by 1.5º, consistent with the projected expansion of the tropics.

Using rare event algorithms to understand the statistics and dynamics of extreme events

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Extreme climate events have major impacts on human societies and ecosys- tems. The most detrimental events are often extremely rare, with return time of centuries or even millennia. Studying these events in the context of climate change is crucial to help adaptation efforts globally. Yet the study of these extremely rare events is extremely challenging due to the lack of data. Indeed, such events have likely not been observed in the instrumental period. An alternative is to use a global climate model to simulate these extremely rare events. However, this comes at a huge computational cost : gathering good statistics on centennial events would require to run a few thousand years of simulation.

Rare event algorithms have recently been introduced in the field of climate science to tackle this difficulty. By concentrating the computational effort on the trajectories most susceptible to lead to the extreme event of interest, they allow for the sampling of extremely rare events at a much lower computational cost than standard simulations.

In this study, we demonstrate the accuracy of a rare event algorithm in estimating some statistics of interest for extreme events. We run a rare event algorithm to sample extreme heatwave seasons in a heatwave hotspot of South Asia, using the intermediate complexity model Plasim, and compare the outcome of the algorithm against an extremely long – 8000 years – control run. This comparison allows us to demonstrate that the algorithm exhibits high precision in the estimation of extreme return levels and of various composite statistics: composite maps conditioned on centennial heatwave seasons estimated from the algorithm, are in very good agreement with the ones from the 8000-year long control simulation. Our results suggest that extreme heatwave seasons in the studied region are associated with a quasi-stationary atmospheric wave-pattern stretching from the North Atlantic towards South Asia. We also show that the algorithm correctly estimates the intensity-duration-frequency statistics of subseasonal heatwaves occuring within centennial heatwave seasons.

Rare event algorithms, thanks to their precise estimates of the dynamics and statistics, can be used for various applications. These include attribution studies, understanding mechanisms leading to extreme events, and exploring what extremely rare events could be in the future.

Beyond Multi-Model Means: Leveraging Local Model Strengths for Superior Climate Projections

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Numerous methods have been proposed to combine individual climate models and extract a robust signal from an ensemble, including the Multi-Model Mean (MMM) and the weighted MMM. These methods typically apply a global weighting to the models, overlooking the fact that certain models may excel in specific regions. This observation suggests that a method acknowledging the superior regional performance of individual models could significantly enhance climate projections derived from model ensembles.

To date, the Graph Cut optimization method (Thao et al., 2022) stands out as the sole technique effectively leveraging the local capabilities of different models across multi-decadal periods to produce global projections. This method involves selecting the most suitable model for each grid point while also ensuring the spatial consistency of the resulting fields. Despite its promising results, surpassing other ensemble combination techniques, it is restricted to optimizing for a single variable, thereby causing inconsistent model selection across variables in multivariate scenarios. This leads to a loss of the multivariate relationships encoded in models. Furthermore, this technique was limited to multi-decadal averages, and is thus unable to capture the distributional characteristics of climate variables, including extreme events.

Here, we introduce significant enhancements to the Graph Cut optimization method, allowing for the combination of distributions of daily means while preserving multivariate relationships, thus better capturing the complete span of climate dynamics. By employing the Hellinger distance to assess model performance, we can identify, at each grid point, the model that most accurately represents the joint distribution of target variables (e.g., temperature, pressure, and precipitation), minimizing the emergence of unrealistic discontinuities in the combined fields. Although every Graph Cut optimization produces a deterministic map where each grid point is assigned to one model, there exists a large number of solutions that have equivalent performance. By initializing the optimizations stochastically, we generate a range of analogous model combinations. For each grid point, we then proportionally combine the distributions of models based on their frequency of appearance, thereby weighting the models' contributions in accordance with their relative performance at both local and global scales. Compared to the original method, the resulting projections offer a more realistic representation of extremes and compound events.

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Constrained CMIP6 future climate projections over the Euro-Mediterranean region based on a circulation patterns approach

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As the Euro-Mediterranean region has been pointed out as a hotspot for both warming and drying signals, there is an increasing need for improved climate indicators for better-informed decision-making in the context of climate change. The present work builds on the design of a process-based evaluation framework for climate simulations, in which a classification of atmospheric circulation patterns (CPs) is used as a tool for climate diagnosis and performance ranking to get better model ensembles.

In the first step, CPs are defined using daily mean sea level pressure (SLP) through a clustering procedure combining data reduction through empirical orthogonal functions and Ward's hierarchical classification. The ERA5 reanalysis during 1950-2022 was considered as the reference to evaluate the historical simulations of a set of 24 CMIP6 global climate models (GCMs), constructing the CPs with SLP and analyzing their link to surface variables including precipitation (PR) and maximum and minimum temperatures (TX and TN, respectively).

In the following step, model performance is quantified based on multiple metrics for the spatial and temporal reproduction of the SLP patterns and the associated surface conditions in ERA5, allowing a ranking of the best-performing GCMs. GCMs manage to reproduce the annual cycle of the CPs frequency, with a dominant summer CP enhancing warm and dry conditions. In this aspect, the best-performing models include MPI-ESM1-2-LR, EC-Earth3-CC, and MRI-ESM2-0. However, the correct timing of this pattern and the transitional CPs (that is, during the autumn and spring seasons) are often misrepresented, such as in GFDL-ESM4 and NorESM2-LM. The analysis of the surface patterns related to the different CPs presents good model performance, better for TX and TN than for PR, particularly in the transition seasons, for which the GCMs spread in their skill score increases.

In this sense, the EC-Earth3-Veg, EC-Earth3-CC, and GFDL-CM4 models show the best scores, whereas INM-CM5-0, KIOT-ESM, and NorESM2-LM have lower skills. By blending both the spatial and temporal features of the CPs, the EC-Earth3-CC, EC-Earth3-Veg, GFDL-CM4, and MRI-ESM2-0 arise as the best-performing GCMs over the Euro-Mediterranean region.

Finally, this model ranking is used to construct multiple model ensembles, considering different weighting strategies. Results from this assessment show that the uncertainty in future projections of extreme climate indices ─including the expected increases in the frequency of warm days and dry spells─ can be reduced by selecting specific subsets of GCMs, according to the ranking established with the CPs framework.

Overall, models have different performances depending on the aspect considered, reinforcing the need for a complete process-based model assessment. This strategy is flexible enough to be replicated for independent sub-regions within the Euro-Mediterranean and to focus on different CPs (such as the ones most related to specific climate hazards) according to specific user needs. In this way, we can constrain future projections and reduce model uncertainty, coming up with coherent climate information at a regional scale.

Calibration with unknown discrepancy

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In order to calibrate the input parameters of an expensive simulator (whether via Bayesian calibration or history matching), it's important to account for model discrepancy, and ignoring or mis-specifying this can affect inference about the inputs x. However setting this discrepancy may be difficult, particularly if the model output is high-dimensional, and it may be challenging to directly elicit its form from an expert. To remove this prior requirement, we reframe the calibration problem as searching for informative (about reality) simulations. Instead of using a discrepancy-dependent distance metric, we combine an emulator of the expensive simulator with a model representing the expert's judgement about particular model simulations, rather than over the discrepancy directly. As with the history matching framework, we iteratively remove parts of the input parameter space that are inconsistent with or uninformative about reality. Over several iterations, we explore and refine not ruled out space, guided by expert judgement over what informative simulations look like, and identifying regions of the input space that lead to model output consistent with this judgement.

Simulating extreme weather events with high-resolution large climate model ensembles and neural networks

Peter WATSON

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Multi-thousand member climate simulation ensembles are a highly valuable tool for studying extreme events and how they are being affected by climate change, but are usually only possible at very coarse model resolutions. We will present results made using distributed computing to produce very large ensembles of global atmospheric simulations at high (60km) resolution in the Weather@Home project, which gives a greatly improved representation of the synoptic weather systems that drive extremes. Results include producing large ensembles of extremes conditioned on Met Office climate simulations and examining changes in extreme events under future climate change scenarios.

It would also be highly valuable to downscale the simulations to impact-relevant scales. Conventional statistical downscaling methods struggle to realistically represent spatial variability. We will show results from applying a large stochastic neural network-based model to produce realistic rainfall predictions at sub-10km resolution for the UK. The model is trained to emulate the Met Office UK convection-permitting model, with 2.2km resolution, which is normally too expensive to use to study extreme events. It will also be shown that this machine learning method can succeed at simulating extreme events, with up to at least ~100 year return periods. Issues related to evaluating machine learning models' extreme event simulations will be discussed as well.

Together, these advances open the possibility of producing realistic projections of extreme rainfall events at impact-relevant spatial scales.

Session 05: Statistics for climate models (poster presentations)

Statistics for climate models, ensemble design, uncertainty quantification, model tuning

Characterising spatial structure in climate model ensembles

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We present a methodology that is designed for rapid exploratory analysis of the outputs from ensembles of climate models, especially when these outputs consist of maps. The approach provides a hierarchical partitioning of variation, first using analysis of variance (ANOVA) techniques to identify components associated with ensemble structure (e.g. to quantify the proportion of variation associated with the choice of global climate model, regional model or emissions scenario) and subsequently decomposing these first-stage components into dominant spatial modes of variation which we call ensemble principal patterns (EPPs). The partitioning is unique for balanced ensembles in which all combinations of factors, such as GCM and RCM pairs in a regional ensemble, appear with equal frequency. We also provide easily-implemented suggestions for handling unbalanced ensembles, that are equally applicable in other areas where ANOVA methods are used. Applications include the selection of small representative subsets of ensemble members for use in impacts studies, and the diagnosis of modes of variation that can be linked to specific model formulations or parameter perturbations. The approach is illustrated using outputs from the EuroCORDEX and UKCP18 regional ensembles for the United Kingdom.

Session 06: Statistical and machine learning (oral presentations)

Statistical and machine learning in climate science

Unraveling individual and joint effects of large-scale climate modes and surface weather features on streamflow in the Murray River, Australia

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Considerable effort has been expended on finding linkages between regional hydroclimate and large-scale climate variability modes on decadal time scales. Most of these studies have investigated the influence of modes as a set of independent individuals rather than as a system of possibly interacting variables. Moreover, the impacts of interactions between modes and local-scale weather features are rarely explored or placed in a modeling framework capable of unravelling the complexities of the hydroclimatic system. This study examines the influence of climate modes and surface weather features on monthly streamflow in the Murray River Basin, Australia, over a 124-year period. A Bayesian network analysis is used to extract the key modes and surface weather features and quantify the directions and strengths of cross-variable relationships. Block bootstrap and expanding window methods are used to ascertain the sensitivity of the model structure and parameter estimates to background variability and over subsets of the study period. It is found that flow antecedent conditions, subtropical ridge intensity and average zonal sea level pressure (SLP) gradient have a direct and robust effect on Murray River flow. The type of influence (direct or indirect) exerted by the Indian Ocean Dipole was sensitive to the temporal ordering of information in the historical hydroclimatic series and background variability. Moreover, the initial state of the hydroclimatic system was found to be defined by the average zonal SLP gradient and lag-1 indices describing the Indian Ocean Dipole and Southern Annular Mode. The selected Bayesian network explained some 78% of the total variance in the streamflow series. This result indicates that the network has high explanatory power.

Using AI to estimate the dynamical contribution to European temperature variability.

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Europe is one of the fastest-warming regions of the world and temperatures of recent years have been systematically higher than best estimates of the forced response simulated by CMIP6 models. This may be due to internal variability favoring warm situations, or it may indicate that the simulated forced response is underestimated.

At intra-seasonal to inter-annual time scales, variations in European temperatures are primarily linked to the variability of North Atlantic atmospheric dynamics. The temperature T for a given day and year can be written as the sum of the forced response μ (the non-stationary climate normal), the effect of the dynamics D (or weather pattern) and a residual.

This study aims to estimate the contribution of dynamics to temperature variations (the D term). We investigate and compare two methods: the traditional circulation analogues method and Artificial Intelligence, through a deep neural network (U-NET). To test these methods, we use a perfect model framework, based on the MIROC6 large ensemble of 50 transient simulations. Ten members are chosen for model evaluations and the 40 others for training.

In the circulation analogue method, the temperature anomaly (T- μ) of a given day between 1950 and 2022 is reconstructed with temperature anomalies observed during similar atmospheric situations that occurred in the 40 training members at the same period of the year. As for the U-NET network, we estimate the function f in the equation (T- μ)=f(X), where X is the sea level pressure anomaly. Our network is trained on the 40 training members with sea level pressure as input and T- μ as output.

Using a RMSE criterion to confront the two methods, we find that AI significantly outperforms circulation analogues to reconstruct temperature variations. This improved estimate of the dynamical contribution to temperature anomalies opens up several prospects. In particular, we can remove this part of internal variability from observed temperatures to facilitate the estimation of the forced response, which is useful for both climate change quantification and observational constraint methods.

Enhancing local climate study through RCM-Emulator: Downscaling a large ensemble of GCM simulations for extreme event analysis

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In the realm of climate science, understanding the evolution of extreme events and quantifying associated uncertainties are pivotal for informed decision-making and policy formulation. This presentation introduces the application of Regional Climate Model (RCM)-Emulator techniques as a robust approach to downscale a large ensemble of near-future Global Climate Model (GCM) simulations. By harnessing RCM-Emulator, we aim to bridge the scale gap between coarse-resolution GCM outputs and localized climate phenomena, facilitating a detailed examination of extreme events.

RCM-emulators represent a hybrid downscaling approach that utilizes a statistical framework to learn the downscaling function embedded within a given RCM. This approach leverages existing RCM simulations to understand the relationship between predictors describing daily atmospheric large-scale circulation and high-resolution variables of interest, thereby overcoming the stationarity assumption inherent in traditional statistical downscaling methods by learning the relationship across different climates. Additionally, the efficiency of machine learning enables the downscaling of very large ensembles of GCM simulations.

In this presentation, we employ the emulator introduced in Doury et al., (2022, 2024) to downscale a substantial ensemble of GCM simulations. The emulator is trained over western Europe using historical and RCP85 EURO-CORDEX simulations (1951-2100) performed with the ALADIN63 regional climate model driven by CNRM-CM5. The ensemble being downscaled comprises

30 members for each of the SSP126, SSP245, SSP370, and SSP585 scenarios for the period 2015-2039, totaling 120 simulations all performed with CNRM-CM6.

Following a presentation on the emulator construction, we investigate the probability of occurrence and intensity of localized extreme events in this large ensemble of high-resolution "emulated" simulations.This work contributes to illustrating the potential of RCM emulators in advancing our understanding of the evolution of local climate and specially extreme events including a better quantification of uncertainties.

Higher-order internal modes of variability imprinted in year-to-year California streamflow changes

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Climate internal variability plays a crucial role in the hydroclimate system, and this study quantifies its predictability on streamflow in California using historical observations, climate simulations, and various machine learning models. The findings demonstrate that while 5% of the year-to-year variability in seasonal peak streamflow can be attributed to the well-known climate variability indices, the explained variance surpasses 30% when higher-order empirical orthogonal functions of these indices are retained in the analysis. Notably, the results highlight the significant influence of the 5th empirical mode of the Pacific North American pattern and of the Pacific Decadal Oscillation in shaping the streamflow variability, which is consistent across all the ML models. A deeper investigation reveals a clear and monotonic quasi-linear response of streamflow to these dominant patterns, emphasizing the substantial role played by higher-order internal modes of variability in molding regional hydroclimate systems, which contributes to bridging the gap between the well-known variability domains and local climate systems.

Filling gaps in historical extremes using Artificial Intelligence

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Existing datasets of observed extremes often have gaps in the spatial fields; these are especially prevalent before the middle of the 20th century. Using the CMIP6 ensemble as a training set we present a novel AI method to reconstruct extreme indices (warm and cool days and nights) over Europe, resulting in complete land coverage for 1901-2018. We show how this approach outperforms traditional gridding techniques (e.g. kriging or angular distance weighting), and results in temporal coverage outside of the range covered by most of the recent reanalysis products (e.g. ERA5). Using the 1911 heat wave and 1929 cold spell over Europe, we show how these reconstructed fields more closely match contemporaneous reports on the impacts of these events than the existing HadEX3 dataset. Being able to better characterise historical extremes enables improved understanding of recent extremes, and more informed and effective climate risk management and policies.

Detection and Characterization of Future Climate Extremes with Deep Learning

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In recent years, climate extremes have become a growing concern. According to the Intergovernmental Panel on Climate Change (IPCC), these events could vary significantly in frequency, intensity, and duration in many regions. Our aim is to characterize these changes based on carbon emission scenarios, using simulation data from the Coupled Model Intercomparison Project (CMIP6). Daily global data for each realization of a climate model requires a huge amount of computing power.

To detect extremes and process large geospatial data sets, we propose a novel method: a Variational Auto-Encoder (VAE), which is used for anomaly detection in various fields. In 2020, Sinha et al. [1] implemented a VAE to detect avalanches in satellite images. She too dealt with an unsupervised anomaly detection problem that involved numerous unlabeled pictures of both normal and abnormal categories. Auto-Encoders were also used to detect and analyze precipitation extremes (Murakami et al., 2022 [2], Huang et al., 2023 [3]).

The model is trained on a dataset of various images, including rare anomalies. It learns to compress and reconstruct images without any knowledge of their abnormality. Although it can reconstruct normal images well, it struggles with unusual samples, resulting in high reconstruction error.

In our study, the model is trained for each season using historical simulations of a specific climate variable (e.g. temperature) in a given geographical zone. The reference period 1850-1900 is used as an analogy to pre-industrial times. The model is then applied to projection data until 2100 for the same location and variable. The reconstruction errors are post-processed as time series to statistically characterize the events (frequency, intensity,…). The results are validated with several members (realizations) of the same climate model, and compared with analytical indices over a historical sample.

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Global-scale evaluation of classifications methods for atmospheric circulation

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Circulation classifications (CCs) represent a popular approach to describe synoptic-scale atmospheric circulation and its links to surface and environmental variables. The increased availability of datasets and computational resources has greatly heightened the usage and variety of CCs methodologies. In line with this advancement, a need for evaluations of classification methods and their various parameters was recognized. However, the current understanding of such evaluations remains incomplete. Here, we present a global-scale evaluation of up to five different CCs methods (Jenkinson-Collison, Grosswettertypes, Lund method, Principal Components and K-means), taking into account different configurations of them, by means of a metric measuring the impact of atmospheric circulation on multiple climate variables (2-meter Mean, Maximum, and Minimum Temperature, Total Precipitation, 10-meter Wind Gust, and Total Cloud Cover). We reveal the method with the strongest links region by region, covering the entire globe. We examine the inter-seasonal variability of these links and the influence of the methodology configuration on our findings. These results aim to assist researchers regarding methodological choices in the execution of future studies related to CCs, and enrich our comprehension of atmospheric circulation, ultimately improving our capacity to identify and study regions with significant climatic interplays.

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Keywords: Circulation classifications, global-scale evaluation, atmospheric circulation, climate variables.

Stochastic emulation of weather radar images time-series using generative AI

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Stochastic rainfall generators (SRG) aim to emulate synthetic rainfall that reproduces as closely as possible the statistical signature of rain observations. This involves a first step of statistical learning of the probability density function of rainfall from observations, and a subsequent stage of sampling this pdf to generate synthetic rainfall. Different statistical models have been proposed in the past for stochastic rainfall generation, each model focusing on a specific aspect of rain statistics: random fields to simulate space-time dependencies, fractal models to preserve scaling properties, or point-processes to account for clustering within rain fields. Recently, generative AI has been successfully applied to generate synthetic images and textures for various applications. In the field of rainfall modeling, Deep Generative Models of Rainfall (DGMR) have shown promising results in nowcasting rainfall from weather radar images and in downscaling satellite precipitation images. The main difference between DGMR and traditional SRG is that DGMR replace the parametric statistical model of traditional SRG by a deep neural network. This innovation is believed to enable the generation of rain fields with more complex and realistic space-time patterns.

This contribution explores the potential of generative AI for stochastic rainfall generation. The challenge in this experiment with DGRM is to generate synthetic rainfall without conditioning on past observations (as in nowcasting) or at coarse resolution (as in downscaling). The objective is to emulate realistic space-time rain fields at high resolution, as is observed by weather radars (10 min in time and 1km in space). We design a deep neural network dedicated to the stochastic generation of high resolution space-time rain fields, and propose a strategy to train this network from weather radar images. The generator has a fully convolutional architecture, which allows to extend the space-time window. It is trained using adversarial learning. The performance of the model is assessed on a 40 x 40 km2 test area located in central Germany. When evaluating the realism of emulated rainfall, we concentrate on the reproduction of key features of high resolution rainfall such as intermittency, advection-diffusion behavior, and the statistical distribution of rain intensities. The ability of generative AI to reproduce the natural variability of rainfall observed in radar images will be tested and discussed.

Analysis of extreme-temperature events over the Southern Africa region: Synoptic systems of heat waves and extreme hot days using Self-Organizing Maps

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This study evaluates the inter-annual variability and trends in extreme temperature indices across the Limpopo River Basin in Southern Africa, with a specific focus on heat wave and extreme hot events and their associated atmospheric circulations. Extreme weather events pose a considerable threat to livelihood, health, agriculture, and economy due to their severe impacts. The purpose of this research is to strengthen the understanding of these trends and their causes in a highly climate-vulnerable region of Southern Africa. This should help inform scientists, decision-makers, and stakeholders regarding the risks of extreme weather events, and raise public health awareness of heat wave risk. In the analysis of extreme events, a statistical tool developed by the Expert Team on Climate Change Detection and Indices performs a statistical analysis of climate indices at individual stations. This statistical tool enabled for the definition, detection, and analysis of climate indices in a standardized way, making it possible to compare results of various places and obtain coherent climate trends. Thereafter, the Self-Organizing Maps methodology was employed to investigate and visualize the atmospheric circulations associated with the regional heat wave and extreme hot events during austral summer. The trend analysis of climate indices revealed a warming and less cooling local climate, with increases in the percentage number of days that formed part of the sequential heat wave events, increases in the percentage number of extreme hot days/nights, and rapid decreases in the percentage number of extreme cold days/nights. It was detected that heat wave and extreme hot events were characterized by dominant high-pressure systems existing alone and

co-existing with a mid-latitude low pressure. More interestingly, the associated atmospheric circulations trends were not correlating to the observed increasing frequencies in heat waves and extreme hot days, and this aspect indicates potential areas of further research to understand other contributing factors to the observed trends in hot extremes.

Multi-Model Ensemble Projection of Global Precipitation and Temperature Changes Utilizing machine learning

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Based on multi-model ensemble simulations within the Coupled Model Intercomparison Project Phase 6 (CMIP6) and CMA's first-generation global atmospheric reanalysis (CRA40) dataset, we evaluate four distinct multi-model ensemble schemes: a simple arithmetic mean, a rank-based weighting, linear regression, and nonlinear random forest algorithm (from the category of machine learning). By comparing these schemes, the optimal ensemble scheme is subsequently selected for multi-model constrained projection. For total precipitation, average temperature, maximum temperature and minimum temperature, our findings demonstrate that random forest algorithm can effectively enhances the ability in capturing spatial climate characteristics and largely reduce the simulation deviation. Utilizing the identified optimal ensemble scheme, it is found that most regions will experience a significant increase in precipitation except for northern South America, western Australia and southern Africa at the end of the 21st century, with a maximum increase of more than 30%. While the temperature shows an overall increase, particularly in the northern Hemisphere.

Effect of Climate Change on Temporal and Spatial Variability of Vulnerability and Flood Hazard

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Flood is one of the most important natural disasters with a growing trend compared to other disasters. Therefore, it is necessary to understand the flood and its causes and aggravating factors, as well as to identify indicators of flood vulnerability in each region. This study is intended to determine areas with flood probability and to examine the current and future vulnerable indicators under different climatic scenarios in the Tajan watershed. To conduct this research, the HadGEM2 model was used to study climate change. The output of different scenarios of climate changes entered the L-THIA model and the model was implemented. Then, using the output of the L-THIA model, climatic, physical, hydrological, and flood points related to the Tajan watershed, a flood probability map using three machine learning models including Random Forest (RF), K-Nearest Neighbor (KNN), and Bayesian Generalized Linear Model (LGB) was prepared. To update the information and assess the temporal variability related to vulnerability, and vulnerable indicators in economic, social, policy, and physical dimensions in areas with high flood hazard susceptibility a questionnaire was completed in two periods before 2006 and after 2006 due to more accurate statistical information. A survey of the annual time series trend of precipitation data in both scenarios RCP2.6 and RCP8.5 showed that according to Kendal Z statistic, this trend is negative at Kordkhil station and is not significant at the level of 0.05, but is positive and significant at Kiasar station. Also, the results of climate data in the L-THIA model showed that runoff depth for the future RCP2.6 climate scenario is higher than the RCP8.5 climate scenario. After preparing the layers affecting the flood, the RF model was used due to the area under the curve (AUC) more (0.91) to prepare the flood probability map. The vulnerability was then assessed in areas with a high probability of flooding. The results of vulnerability criteria showed that the average difference of all four criteria in both statistical periods in all sub-watersheds except sub-watersheds 10 (Khalkhil), 19 (Tellarem and Crossep), and 23 (Dinehsar and Jafarabad) is significant. Also, the results of the study of vulnerability indicators show the improvement of indicators in different sub-watersheds increases the score of individuals to each indicator and increases the resilience of society against floods in the period 2006-2016.

MITIGATING BIAS IN CLIMATE PROJECTIONS OF EXTREME PRECIPITATION OVER WEST AFRICA USING MACHINE LEARNING

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This study investigates the intricate dynamics of precipitation patterns in West Africa, a region crucial for water resources, rain-fed agriculture, and climate-related disaster prediction. Climate change, coupled with increased greenhouse gas emissions, amplifies the complexity of extreme precipitation and temperature events, underscoring the need for accurate predictions. Extreme weather events impact various sectors, leading to food insecurity, reduced agricultural yields, and heightened risks of diseases. West Africa, particularly vulnerable due to its growing population and limited adaptation measures, faces increased susceptibility to heavy rainfall events. To enhance climate predictions, the study leverages the integration of Global Climate Models (GCMs) with Machine Learning (ML), a transformative tool in meteorology. The application of Machine Learning (ML) in weather prediction is evolving with reliable data and efficient computing. The study employs a robust dataset, including daily observations from Climate Hazards InfraRed Precipitation with Station Data (CHIRPS) and 14 Coupled Model Intercomparison Project Phase 6 (CMIP6) models simulations, analyzing five precipitation indicators defined by the Expert Team on Climate Change Detection and Indicators. Results showcase the varying abilities of models, with certain CMIP6 models like EC-Earth3-CC and EC-Earth3-Veg-LR outperforming others with root mean square error ranging from 25.69 to 70.5 and 26.83 to 71.74 and correlation coefficient ranging from 0.25 to 0.74 and from 0.24 to 0.76 respectively. The Machine Learning driven integration, particularly the ML_Model, emerges as a resilient tool, reducing structural model uncertainty with root mean square error ranging from 0.99 to 27.07 and correlation coefficient ranging from 0.85 to 0.95. The analysis extends to consecutive dry days and consecutive wet days, heavy precipitation frequencies, and daily intensities, revealing the strengths and limitations of different models. The ML_Model consistently aligns with observations, highlighting its potential for accurate climate predictions. Projected future scenarios under both SSP2-4.5 and SSP5-8.5 emission pathways indicate a general decrease in precipitation indices with

increase in dry days from 5 to 9 days and daily intensities from 2 to 10mm, notably impacting the Savannah and Guinea regions. This study stresses the importance of addressing drought in West Africa and identifies Machine Learning as a key tool in refining climate projections. The projected decrease in extreme precipitation occurrences raises concerns, necessitating further research on their potential consequences for both human society and ecosystems.

Identification of hydrometeorological drivers of forest damage in Europe

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Extreme meteorological events can induce significant damage to vegetation and ecosystems. In particular, heat and drought events are projected to become more frequent in a changing climate. It is therefore crucial to predict the frequency and the occurrence of such extremes.

We here focus on forest damage in Europe, defined as negative anomalies of the normalized difference vegetation index (NDVI). Compound drought and heat wave events are known to trigger low NDVI events in summer. A dry summer combined with moist conditions during the previous autumn can also have a negative impact. Hence, the goal of our study is to find, among all the hydrometeorological variables available as output from the S2S forecasts in the ECMWF model, the most relevant ones to predict forest damage. For this purpose, we apply a LASSO regression and a Random Forest procedure to identify the compound hydro-meteorological conditions leading to low NDVI events at the S2S timescale. We train the models using ERA5 and ERA5-Land reanalysis datasets for the explicative variables. These variables include temperature, precipitation, dew point temperature, surface latent heat flux, soil moisture, and soil temperature. Several space and time aggregations are considered in order to find the optimal scales and most relevant combinations of variables to predict low NDVI events.

Generative Modelling for Multivariate Downscaling via Proper Scoring Rules

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To complement computationally expensive regional climate model (RCM) simulations, machine learning methods can predict the high-resolution RCM data from low-resolution global climate model (GCM) input. Instead of merely targeting the conditional mean of the RCM field given the GCM data, more recent works are based on generative adversarial networks or diffusion models and aim to learn the full conditional distribution. In this spirit, we present a novel generative model that relies on statistical tools from forecast evaluation. To achieve this goal, we use a simple neural network architecture that predicts Fourier coefficients of the high-resolution fields for multiple variables jointly (temperature, precipitation, solar radiation and wind). The loss function of our model is a proper scoring rule, more specifically the energy score, the multivariate analogon of the CRPS. It measures the discrepancy between the model's predictive distribution and the RCM's true distribution. The score is minimised if both distributions agree. Our generative model is trained on multiple GCM-RCM combinations from the Euro-Cordex project. Evaluating the multivariate and spatially high-dimensional output of the machine learning model is challenging, hence we discuss possible benchmarks and metrics. Furthermore, we show how the framework can be augmented to perform a bias-correction task: With a modified loss function, it is possible to generate data from the observational distribution, for example resembling gridded E-OBS data. To summarise, our work presents a machine learning method that allows us to generate multivariate high-resolution climate data, and can be extended flexibly to include further variables or downscale and bias-correct future projections.

Identifying probabilistic weather regimes targeted to a local-scale impact variable

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Weather regimes are recurrent and persistent large-scale atmospheric circulation patterns that modulate local impact variables such as extreme precipitation. In their capacity as mediators between long-range teleconnections and these local extremes, they have shown potential for improving sub-seasonal forecasting as well as long-term climate projections. However, existing methods for identifying weather regimes are not designed to capture the physical processes relevant to the impact variable in question while still representing the full atmospheric phase space.

Here, we propose two novel machine learning methods, abbreviated as RMM-VAE and CMM-VAE, for identifying probabilistic weather regimes targeted to local-scale impact variables. Building on variational inference and a variational autoencoder architecture, the methods develop a statistically coherent model for combining non-linear probabilistic dimensionality reduction using a neural network with probabilistic clustering of the latent space using a mixture model, and a prediction task.

The new methods are applied to identify circulation patterns over the Mediterranean region targeted to precipitation over Morocco and compared to Principal Component Analysis (PCA), Canonical Correlation Analysis (CCA), and an existing alternative variational autoencoder architecture, combined respectively with k-means clustering.

Our results show that the new methods identify clusters with higher predictive skill of the target variable compared to PCA and CCA, while also outperforming these two methods in reconstructing the atmospheric phase space. Furthermore, the targeted clusters identified by the new methods maintain a higher cluster robustness and persistence compared to other targeted approaches, i.e. the alternative machine learning architecture and CCA.

The ability of the new methods to identify targeted weather regimes that maintain other desirable properties such as persistence that contribute to their predictability at sub-seasonal timescales highlights their potential benefit for use in various climate applications. Our findings also demonstrate the trade-offs involved in targeted clustering which can inform future method development in this area.

Random Forest Based Tropical Cyclone Detection

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Even though tropical cyclones (TCs) are well documented from the moment they materialise to the moment they evanesce, many physical processes governing them are not resolved by global circulation models (GCMs). Thus, the simulation and the projection of future changes in TCs' characteristics remain challenging [Knutson et al., 2019 ; Knutson et al., 2020]. In particular, due to the low spatial resolution of most GCMs, studying simulated tropical cyclones is difficult because they are hard to detect [Russotto et al., 2022]. Deterministic cyclone detection schemes are available [Bourdin et al., 2022] but their results are subject to the spatial resolution of the simulations and usually need numerous variables that are not always available in the models. In this study, the ability of a random forest approach to detect TCs is explored, with a limited number of variables in coarse-resolution data-sets. Through this approach, the detection problem becomes a binary supervised classification problem of zeros (non TCs) and ones (TCs).

Our first analysis is based on the observation data of 613 cyclones occurring in Tropical Atlantic over the 1980-2021 period and circulation variables such as mean sea-level pressure, relative vorticity at 850 hPa, Geopotential thickness 300-500 hPa, Total column water vapour and wind speed at 10m extracted from the ERA5 reanalysis. Preliminary results show potential for detection of tropical cyclone which is the first step for their attribution in climate change context.

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From climate to weather reconstruction with inexpensive neural networks

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Understanding atmospheric variability is essential for adapting to future climate extremes. Key ways to do this are through analysing climate field reconstructions and reanalyses. However, producing such reconstructions can be limited by high production costs, unrealistic linearity assumptions, or uneven distribution of local climate records.

Here, we present a machine learning-based non-linear climate variability reconstruction method using a Recurrent Neural Network that is able to learn from existing model outputs and reanalysis data. As a proof-of-concept, we reconstructed more than 400 years of global, monthly temperature anomalies based on sparse, realistically distributed pseudo-station data.

Our reconstructions show realistic temperature patterns and magnitude reproduction costing about 1 hour on a middle-class laptop. We highlight the method's capability in terms of mean statistics compared to more established methods and find that it is also suited to reconstruct specific climate events. This approach can easily be adapted for a wide range of regions, periods and variables. As additional work-in-progress we show output of this approach for reconstructing European weather in 1807, including the extreme summer heatwave of that year.

Session 06: Statistical and machine learning (poster presentations)

Statistical and machine learning in climate science

Short-term Prediction of Extreme Sea-Level at the Baltic Sea Coast by Random Forests

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We have designed a machine-learning method to predict the occurrence of extreme sea-level at the Baltic Sea coast with lead times of a few days. The method is based on a Random Forest Classifier and uses sea level pressure, surface wind, precipitation, and the prefilling state of the Baltic Sea as predictors for daily sea level above the 95% quantile at seven tide-gauge stations representative of the Baltic coast.

The method is purely data-driven and is trained with sea-level data from the Global Extreme Sea Level Analysis (GESLA) data set and from the meteorological reanalysis ERA5 of the European Centre for Mid-range Weather Forecasting. These

records cover the period from 1960 to 2020 using one part of them to train the classifier and another part to estimate its out-of-sample prediction skill.

The method is able to satisfactorily predict the occurrence of sea-level extremes at lead times of up to 3 days and to identify the relevant predictor regions. The sensitivity, measured as the proportion of correctly predicted extremes is, depending on the stations, of the order of 70%. The proportion of false warnings, related to the specificity of the predictions, is typically as low as 10 to 20%. For lead times longer than 3 days, the predictive skill degrades; for 7 days, it is comparable to a random skill.

The importance of each predictor depends on the location of the tide gauge. Usually, the most relevant predictors are sea level pressure, surface wind and prefilling. Extreme sea levels in the Northern Baltic are better predicted by surface pressure

and the meridional surface wind component. By contrast, for those located in the south, the most relevant predictors are surface pressure and the zonal wind component. Precipitation was not a relevant predictor for any of the stations analysed.

The Random Forest classifier is not required to have considerable complexity and the computing time to issue predictions is typically a few minutes. The method can therefore be used as a pre-warning system triggering the application of more sophisticated algorithms to estimate the height of the ensuing extreme sea level or as a warning to run larger ensembles with physically based numerical models.

Incorporating physical knowledge to emulate the parameterizations of the IPSL model

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Atmospheric general circulation models include two main distinct components: the dynamical one solves the Navier-Stokes equations to provide a mathematical representation of atmospheric movements while the physical one includes parameterizations representing small-scale phenomena such as turbulence and convection (Balaji et al., 2022). However, computational demands of the parameterizations limit the numerical efficiency of the models. The burgeoning field of machine learning techniques opens new horizons by producing accurate, robust and fast emulators of parts of a climate model. In particular, they can reliably reproduce physical processes, thus providing an efficient alternative to traditional process representation. Indeed, some pioneering studies (Gentine et al., 2018; Rasp et al., 2018) have shown that these emulators can replace one or more parameterizations that are computationally expensive and so, have the potential to enhance numerical efficiency.

Our research work aligns with these perspectives, since it involves exploiting the potential of developing an emulator of the physical parameterizations of the IPSL climate model, and more specifically of the ICOLMDZOR atmospheric model (for DYNAMICO, the dynamic solver using an icosahedral grid - LMDZ, the atmospheric component - ORCHIDEE, the surface component). The emulator could improve performance, as currently almost half of the total computing time is given to the physical part of the model.

We have developed two initial offline emulators of the physical parameterizations of our standard model, in an idealized aquaplanet configuration, to reproduce profiles of tendencies of the key variables - zonal wind, meridional wind, temperature, humidity and water tracers - for each atmospheric column. The results of these emulators, based on a dense neural network or a convolutional neural network, have begun to show their potential for use, since we easily obtain good performances in terms of the mean of the predicted tendencies. Nevertheless, their variability is not well captured, and the variance is underestimated, posing challenges for our application. A study of physical processes has revealed that turbulence was at the root of the problem. Knowing how turbulence is parameterized in the model, we show that incorporating physical knowledge through latent variables as predictors into the learning process, leading to a significant improvement of the variability.

Future plans involve an online physics emulator, coupled with the atmospheric model to provide a better assessment of the learning process (Yuval et al., 2021).

Separating Internal Variability from Anthropogenic Forcing Using Artificial Intelligence

Delphine TECHER, **Anne DURIF, Laurent TERRAY**
Cerfacs, France

Classical statistical methods for climate change detection and attribution rely on the spatial structure of the climate response to anthropogenic forcing in climate models. This technique provides a scaling factor to adjust the magnitude of the forced response to observations. It leads to an estimate of natural variability from simulation ensembles with constant external forcing [1]. The use of deep learning methods in climate science helps to directly estimate the climate response to external forcing using simulations from Earth System Models.

To isolate internal variability, which is considered as noise, from the forced response, Bône et al. [3] applied a neural network, originally designed for image segmentation, for denoising. The neural network proved to be more efficient than traditional statistical methods for surface air temperatures.

We develop a new methodology, using a denoising neural network, first for annual temperature. This deep learning model is based on the ForceSMIP database. The ForceSMIP (Forced Component Estimation Statistical Method Intercomparison Project) is an international project that uses climate model ensembles to develop and assess statistical methods for isolating the forced response from individual realizations of the climate system [2]. The project provides numerical climate model simulations that include both natural and anthropogenic external forcings.

We compare this technique to more traditional statistical methods (linear trend, Empirical Orthogonal Functions, …) and identify their respective advantages and disadvantages.

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Improving probabilistic forecasts of extreme winds by training post-processing models with weighted scoring rules

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Accurate forecasts of extreme winds are of high importance for many applications. Such forecasts are usually generated by ensembles of numerical weather prediction (NWP) models, which however can be biased and have errors in dispersion, thus necessitating the application of statistical post-processing techniques. In this work we aim to improve statistical post-processing models for probabilistic predictions of extreme winds. We do this by adjusting the training procedure used to fit ensemble model output statistics (EMOS) models – an often-used post-processing technique – and propose estimating parameters using the so-called threshold weighted continuous ranked probability score (twCRPS), a proper scoring rule that puts special emphasis on predictions over a threshold. We show that training using the twCRPS leads to improved extreme event performance of post-processing models for a variety of thresholds. We find a distribution body, distribution tail trade-off where improved performance at probabilistic predictions of extreme events come with worse performance at predictions of the distribution body. However, we introduce strategies to mitigate this trade-off based on weighted training and linear pooling. Finally, we consider some synthetic experiments to explain the training impact of the twCRPS and derive closed-form solutions of the twCRPS for a number of distributions, giving the first such collection in the literature. The results will enable researchers and practitioners alike to improve the performance of probabilistic forecasting models for extremes and other events of interest.

Multi-model Ensemble Prediction of Summer Precipitation in China Based on Machine Learning Algorithms

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The development of machine learning (ML)provides new means and methods for accurateclimate analysis and prediction. This study focuses on summer precipitation prediction using MLalgorithms. Based on BCC CSM1.1,ECMWF SEAS5,NCEP CFSv2, and JMA CPS2 model data,we conducted a multi-model ensemble(MME) prediction experiment using three tree-based MLalgorithms: the decision tree(DT), random forest(RF), and adaptive boosting (AB) algorithms.On this basis,we explored the applicability of ML algorithms for ensemble prediction of seasonalprecipitation in China, as well as the impact of different hyperparameters on prediction accuracy.Then,MME predictions based on optimal hyperparameters were constructed for different regions ofChina. The results showed that all three ML algorithms had an optimal maximum depth less than 2,which means that, based on the current amount of data, the three algorithms could only predictpositive or negative precipitation anomalies, and extreme precipitation was hard to predict. Theimportance of each model in the ML-based MME was quantitatively evaluated.The results showedthat NCEP CFSv2 and JMA CPS2 had a higher importance in MME for the eastern part of China.Finally, summer precipitation in China was predicted and tested from 2019 to 2021.According to theresults, the method provided a more accurate prediction of the main rainband of summer precipitationin China.ML-based MME had a mean ACC of 0.3, an improvement of 0.09 over the weighted averageMME of 0.21 for 2019-2021, exhibiting a significant improvement over the other methods. This showsthat ML methods have great potential for improving short-term climate prediction.

ANOMALY DETECTION IN DAILY TEMPERATURE FIELDS IN EUROPE USING VAEs: A new climate change attribution approach

Pablo Gabriel ZANINELLI GARCÍA[1], David Barriopedro Cepero[1], Marie Drouard[1], José Manuel Garrido-Pérez[2], Jorge Pérez-Aracil[3], Soledad Collazo[2,4], J. Emmanuel Johnson[1]

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Extreme event attribution involves quantifying the impact of climate change on specific extreme events (EEs). Understanding the degree to which climate change contributes to EEs is crucial due to the vulnerability of society and ecosystems to such occurrences, particularly the increased frequency and intensity of heatwaves in various regions globally. Consequently, the scientific community has directed efforts towards attribution analysis and the development of novel techniques for its investigation. However, attribution studies employing machine learning (ML) methods to analyze temperature EEs remain limited in the specialized literature.

Traditionally, unconditional attribution studies compare the probability of an event occurring today with its likelihood in the pre-industrial era, enabling the determination of the increased likelihood and severity of an event due to climate change. Nonetheless, classical methodologies face limitations such as the challenge in understanding the connections between the physical processes underlying extreme events and anthropogenic influences, as well as the inability to identify new trends associated with these influences. In addition, preprocessing of the raw data often involves temporal/spatial averaging to diminish noise, fitting it to a parametric distribution, and selecting a covariate to ascertain the impact of climate change.

The CLImate INTelligent (CLINT) project aims to address some of these limitations by designing ML algorithms to enhance classical attribution methodologies, focusing on three European hotspots in Spain, Italy, and the Netherlands. Within this context, this study presents an initial attribution analysis for summer heatwaves concentrated in the Iberian Peninsula, utilizing deep learning techniques such as anomaly detection with variational autoencoders (VAEs).

A VAE, an unsupervised method comprising two neural networks—one for encoding and the other for decoding information—is employed. The VAEs are trained using natural climate forced experiments integrated in the context of the Detection & Attribution Model Intercomparison Project (DAMIP), developed in the framework of CMIP6, allowing for the detection of variabilities and trends present in historical runs but absent in pre-industrial simulations. The influence of climate change on a specific temperature EE can be linked to the autoencoder anomaly associated with that EE.

The outcomes of this novel AI attribution methodology are compared with classical approaches, revealing promising results.

Session 07: Long term D&A and emergent constraints (oral presentations)

Long-term detection and attribution and emergent constraints on future climate projections

Time of Emergence Analysis in Climate Science

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Examining emergence of climate change signals relative to background variability is relevant to climate change impacts and has become a popular tool. However, different methods are used and there has not yet been a comprehensive review and analysis of the state of this area of climate science. Here, we perform a review and determine the next steps for this field.

Increases in atmospheric greenhouse gas concentrations due to human activities is resulting in our climate changing and emerging from the background variability expected under natural variability alone. This new state, and its departure from what is natural for the local climate, has many potential impacts on society and the environment. The time of emergence (ToE) of a new climate has been observed in many different variables, such as temperature, precipitation, sea ice and extreme weather events. To estimate the time of departure from the natural climate state, many different methods are used - Kolmogorov Smirnov test, signal-to-noise ratio, and probability ratio.

In this research, we summarise the previous literature and compare the time of emergence across variables. We also explore how different methodological choices may impact the time of emergence. We then also explore the time of emergence for several new variables, including climate extremes. This research also summarises all the best knowledge on how far the clime has emerged, on the global and local level for multiple variables, from its natural state. We also provide guidance on best practices for future time of emergence research.

A Statistical Review on the Optimal Fingerprinting Approach in Climate Change Studies

Song Xi CHEN

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\abstract{We provide a statistical review of the ``optimal fingerprinting" approach presented in Allen and Tett (1999) in light of the severe criticism of McKitrick (2021).

Our review finds that the ``optimal fingerprinting" approach would survive much of McKitrick (2022, CD)'s criticism by enforcing two conditions related to the conduct of the null simulation of the climate model, and the accuracy of the null setting climate model. The conditions we proposed are simpler and easier to verify than those in McKitrick (2022).

We provide additional remarks on the residual consistency test in Allen and Tett (1999), showing that it is operational for checking the agreement between the residual covariance matrices of the null simulation and the physical internal variation under certain conditions. We further provide the reason why the Feasible Generalized Least Square method, much advocated by McKitrick (2022), is not regarded as operational by geophysicists.

Detection and attribution of urbanization forcing on urban and regional hot extremes

Yang CHEN

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Cities are home to more than 50% of the world's population and emit at least 70% of global greenhouse gases. Understanding how cities impact, and are impacted by weather and climate extremes is fundamental to actionable planning. However, urban-scale extremes have seldom been the focus of formal detection and attribution analysis. The widely-employed 'urban minus rural' in observation leaves the quantification of urbanization forcings incomparable to model-based attribution of large-scale forcings, due to data and method differences.

We developed a stepwise detection and attribution method that incorporated the urbanization forcing into the fingerprinting framework, with multi-collinearity amongst forcing agents accounted for and avoided. Applied to urban compound hot extremes (day-night sustained heat) across Eastern China, the new method shows that in the frequency increase of 1.76 days decade-1 over 1961–2014, fingerprints of urban expansion and anthropogenic emissions are both detectable, and their attributable fractions are estimated at 0.51 (urbanization), 1.63 (greenhouse gases) and -0.54 (other anthropogenic forcings) days decade-1 respectively. The urbanization forcing, however, remans too weak to be detected in the observed regional increase including both urban and rural events.

The new framework also holds promise in detecting and quantifying other regional-specific anthropogenic forcings on extremes, such as irrigation and deforestation/afforestation.

Moving from empirical emergent constraints to more robust Bayesian statistics: a case study on land surface drying

Hervé DOUVILLE

Météo-France, France

Emergent constraints based on a single metric are increasingly used to constrain future responses of the Earth system to global warming, and global warming itsef is increasingly used to scale regional climate change. Yet, strong relationships between observables and future climate across an ensemble of climate models can arise from common structural model assumptions with few degrees of freedom or from a few outliers, and scaling of climate change by global warming is much less efficeint across models than across emission scenarios. In this presentation, we will showcase how basic Bayesian statistics can lead to more reliable observational constraints than classic emergent constraints and how improved Bayesian methods can further narrow projections by combining several observational constraints. We will also illustrate how the observed historical global warming can be misleading, if not considered jointly with other, more directly relevant observations. Finally, we will highlight how such methods can be also useful to derive more plausible storylines regarding future climate.

Detection and attribution of climate change using paleoclimate observations directly

Michael EVANS[1,2], Jörg FRANKE[4], Andrew SCHURER[2], Feng ZHU[5], Lucie LUCKE[2], Dylan JONES[2], Paul VALDES[3], Gabrielle HEGERL[2]

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We describe an initiative to perform detection and attribution of climate variability and change by simulating paleoclimatic proxy observations using realistically forced climate and data models. This includes improvements to the isotope-enabled version of the HadCM3 AOGCM, aggregation of stewarded paleoclimatic proxies from Past Global Changes (PAGES) initiatives, and the parameterization and validation of intermediate complexity proxy system models. By modeling the observations directly, we leverage process and causal understanding of the ways in which environmental information is encoded in paleoclimatic observations without the assumptions required by their inversion to climatic variables. We also sample and propagate forcing, process, parametric and observational uncertainty in the framework. First results suggest substantial but realistic uncertainty in detecting and attributing spatiotemporal patterns in both temperature and moisture. We are eager for interaction with the IMSC community to identify emergent constraints on the future from attribution of observed variations over the past 2000 years (Common Era).

The Detection and Attribution Model Intercomparison Project: CMIP6 highlights and plans for CMIP7

Nathan Gillett[1], Isla Simpson[2], Gabi Hegerl[3], Reto Knutti[4], Dann Mitchell[5], Aurélien Ribes[6], Hideo Shiogama[7], Daithi Stone[8], Claudia Tebaldi[9], Piotr Wolski[10], Wenxia Zhang[11]

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The Detection and Attribution Model Intercomparison Project (DAMIP) coordinates single forcing climate model simulations for detection and attribution analysis and other applications. DAMIP simulations were carried out with fifteen climate models as part of CMIP6, and these simulations were used in at least 270 published articles, including long-term detection and attribution studies and extreme event attribution studies. These simulations were also used directly in at least five chapters of the Working Group I contribution to the IPCC Sixth Assessment Report, and they underpinned the estimate of anthropogenic attributable warming highlighted in the Summary for Policymakers of that report, and quoted directly in the UNFCCC Glasgow Climate Pact. For CMIP7, natural-only, well-mixed greenhouse gas-only, and aerosol-only simulations have been proposed as fast track DAMIP simulations. New simulations proposed for CMIP7 will allow tests of the assumption that the responses to forcings add linearly which underpins most detection and attribution analyses, and will support attribution to emissions, accounting for the effects of carbon cycle feedbacks. This talk will present key DAMIP results from CMIP6, and will discuss novel aspects of the CMIP7 version of DAMIP. Comments and suggestions regarding the CMIP7 DAMIP experimental design will be welcomed.

Observational Uncertainty is Necessary for Assessing Time-of-Emergence

Jonah Krammer SHAW[1], Nathan JL LENSSEN[2]

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The emergence of forced climate trends above internal climate variability is a critical statistic used widely in climate science, including IPCC reports, for quantifying the impact of human activities on global and regional climate. The time of emergence of climate signals is scientifically important in understanding changes to the climate system as well as critical for climate adaptation efforts. An emergent trend in annual surface temperature, as investigated here, indicates that a region is experiencing a novel climate that may require adaptation. Many studies have calculated time of emergence for annual mean surface temperature trends with IPCC AR6 concluding that trends have emerged everywhere over the non-Antarctic land surface. While the signal-to-noise method used by the IPCC represents the state-of-the-art in time to emergence calculations, uncertainty in the observed trends is not included in their analysis. Here, we present a novel application of two historical surface temperature observational uncertainty ensembles to show that properly accounting for observational uncertainty delays time of emergence in nearly all regions. While most regions see a delay of only a few years, regions with low trends and high internal variability show delays on the order of decades.

Reconciling the "hot model" problem in climate projections

Chao LI[1], **Francis Zwiers**[2]

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Climate models participating in phase 6 of the Coupled Model Intercomparison Project (CMIP6) generally exhibit higher climate sensitivity than their earlier counterparts, leading to concern about their reliability in projecting future climates for adaptation and resilience planning. The level of global warming approach partially overcomes this concern by assessing climate change impacts based on the characteristics of impact relevant variables in climate simulations from different models during periods that are centered on specified levels of warming. With this approach, emissions scenario and climate model uncertainty is transformed into uncertainty concerning the timing of occurrence of future levels of warming. This uncertainty is relatively small for modest levels of additional warming, and adaptation planning where opportunities to remake adaptation decisions concerning a given system recur every 2-4 decades. This seems adequate for near- and medium-term adaptation planning but is less satisfactory for adaptation decisions with long time horizons, such as when designing infrastructure that is expected to be in service for the rest of this century. In these cases, users tend to be driven to developing plans that are conditioned on a choice of emissions scenario, and thus are faced with climate model uncertainty that is manifested, in part, through the wide range of climate sensitivities seen in CMIP6. Here we present a practical method to reconcile this "hot model" problem in the time-based climate projections by the CMIP6 climate models by conditioning the entire Earth system projections for future periods on the IPCC's assessed warming projections accounting for uncertainties in the assessed warming for future periods. This allows individuals from the broad community studying climate change using the CMIP6 models to deliver consistent and comparable assessments of changes in different aspects of the Earth system, while at the same time guaranteeing consistency of the assessments with observational evidence on the sensitivity of the climate system to carbon dioxide emissions.

Observationally constrained attribution and projection of warming in Canada

Tong LI, **Francis ZWIERS**, **Xuebin ZHANG**

Pacific Climate Impacts Consortium, University of Victoria, Victoria, British Columbia, Canada

Detection and attribution research helps us understand the factors responsible for past climate change, while projections inform us what the future climate will look like. Both fields depend on the output of Earth System models (ESMs), but there is still a wide uncertainty range in the simulated externally forced response. From the Bayesian perspective, observational records can be used to reduce the uncertainty of changes projected by ESMs, as an update of model simulated information that is treated as a prior distribution. In this sense, the observational constraint approach can be used in treating both the attribution and future projection problems. Regional-scale climate is increasingly important because of its greater relevance for climate change adaptation planning and implementation. The lower signal-to-noise ratio in smaller regions, as well as the intricate connection between regional and global-scale information implies that observational constraints at regional scales need to be carefully investigated, which includes finding an efficient strategy to use the available information at the regional scale. In this talk, we give the case of the application to Canada and its sub-regions, discuss the most effective way of applying observational constraints in both past attributed and future warming projections, show the results from the best estimate, also compare with the unconstrained ensemble simulation.

Accounting for Pacific climate variability increases projected global warming

Yongxiao LIANG[1], **Nathan Gillett**[1], **Adam Monahan**[2]

[1]Environment and Climate Change Canada; [2]University of Victoria

Observational constraint methods based on the relationship between the past global warming trend and projected warming across climate models were used to reduce uncertainties in projected warming by the Intergovernmental Panel on Climate Change (IPCC). Internal climate variability in the eastern tropical Pacific associated with the so-called pattern effect weakens this relationship, and has reduced the observed warming trend over recent decades. Here we show that regressing out this variability before applying the observed global mean warming trend as a constraint results in higher and narrower 21st century warming ranges than other methods. Whereas the IPCC assessed that warming is unlikely to exceed 2°C under a low emissions scenario, our results indicate that warming is likely to exceed 2°C under the same scenario, and hence that limiting global warming to well below 2°C will be harder than previously anticipated. However, the reduced uncertainties in these projections could benefit adaptation planning.

Relating observational constraints and data assimilation

Aurélien RIBES, **Octave TESSIOT**, **Saïd QASMI**

CNRM, Université de Toulouse, Météo France, CNRS, France

Observational constraints provide estimates of past, present and future climate change, by combining numerical model data and observations, while taking into account their respective uncertainties. These methods have gained in importance in recent years, through their use in AR6, both for projections and attribution, and the widening of their scope of application to more and more variables and to regional scales.

First, I'll describe the Kriging for Climate Change (KCC) method, which was introduced 4 years ago and has been used for many applications since then. It is a Bayesian statistical method, in which climate models are used to provide an a priori distribution of climate change, which is subsequently constrained by observations in a posterior distribution.

Second, beyond this conventional description of the method, I will focus on new features, in particular the relationship with data assimilation, and discuss similarities and differences with numerical weather prediction (NWP) data assimilation. Our technique can be seen as an Ensemble Kalman filter applied to a range of CMIP models. Unlike in NWP, all historical observations are assimilated in a single step in KCC, i.e., there is no iteration and no re-run of the models. This difference stems from the fact

that, while the coupled ocean-atmosphere system is chaotic, it is considered deterministic in terms of forced climate response -- the only quantity of interest for observational constraints.

Finally, I will show recent results illustrating the added-value of continuously updating (as new observations become available) climate projections constrained by observations, at the both global and regional scales. Our findings also suggest that observational constraints provide robust estimates of the current amount of warming, and so can be used to characterize the current state of the climate system.

An emergent constraint approach for making climate projections of Antarctic sea ice area decay

David Stephenson[1], Caroline Holmes[2], Tom Bracegirdle[2]

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Climate models project that Antarctic Sea Ice Area (SIA) will decline substantially in forthcoming decades due to anthropogenic greenhouse gas emissions. However, the projections from different climate models differ widely from one another so it is not evident how one should combine these projections to make inference about what might happen in the real climate.

This study proposes a simple three parameter emulator model for SIA decay that is capable of representing both linear and exponential decay. The model provides good fits to 36 CMIP6 model simulations of February SIA for 1950-2100 when forced with the ssp585 projection scenario. Two of the parameters in the emulator model, the initial SIA and the rate of linear decay, are found to exhibit a strong positive correlation across the model fits.

This emergent relationship can be usefully exploited to make a more certain inference about how SIA is likely to decline. The resulting prediction from CMIP6 under the SSP585 scenario has an initial decreasing trend consistent with the rate of rapid decline recently noted in the observations.

Granger causal inference for climate change attribution

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We present some recent advances in using Granger causal inference methods to attribute regional trends in climate variables. Instead of using climate models to create factual and counterfactual simulations of the world with and without forcing factors, we introduce the notion of “statistical counterfactuals” using only observed climate data. We draw a connection between the statistical covariates and the “betas” often used in linear regression analyses of climate model output. As an example, we use a multi-variate attribution analysis of mean and extreme precipitation over the United States to illustrate the strengths and weaknesses of this alternative and complementary approach to climate change detection and attribution.

Anthropogenic influence on temperature change in China over the period 1901-2018

Hong YIN

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Human influence on regional warming since 1901 has received little attention because of limited data during the early period. This study investigates the relative contribution of different external forcings to observed annual, summer and winter warming in China over the period 1901-2018. First, four observational datasets were compared to validate data representativeness, particularly during the early 20th century. Observed temperature changes were then compared with outputs from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) and Phase 6 (CMIP6) based on an optimal fingerprinting method. Generally, both generations of climate models were able to reliably reproduce long-term warming in China over the period 1901-2018; however, they slightly underestimate the amplitude of annual and winter temperature increases. The observed annual warming of 1.54 °C from 1901 to 2018 was more rapid than the global mean and was mostly attributable to the anthropogenic forcing signal. The three-signal detection analyses, including greenhouse gas (GHG), anthropogenic aerosol (AA), and natural external (NAT) forcings, indicated the detectable and distinct influence of GHG and AA signals on annual, summer and winter temperatures during 1901-2018. For annual mean temperature, the GHG and AA contributed to 2.06 °C [1.58 °C to 2.54 °C] and □0.45 °C [□0.17 °C to □0.73 °C] of observed change, respectively. The GHG signal was detectable from individual CMIP6 models and thus was indicative of the robustness of this influence. While during 1951–2018, GHG and AA were simultaneously detected in the summer temperatures based on the CMIP6 models; here, the AA cooling effects offset approximately 25% of GHG-induced warming.

Detecting human influence on precipitation in Canada

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There is overwhelming evidence of human influence on global climate system including on total and extreme precipitation on global and continental scale. Yet, the same cannot be said on regional scale. This study compares observed and model-simulated precipitation in Canada during 1949-2018 using generalized linear requestion with parameters being estimated based on estimation equation. Overall, we robustly detected precipitation response to anthropogenic forcing for Canada as whole and for Northern Canada. But it is more difficult to separate precipitation responses to greenhouse gases, aerosol and natural external forcing and it is also difficult to quantify human influence on the observed changes in precipitation in Canada. The presentation will report on these findings and discuss sensitivity testing and suggests reasons for any differences.

Reducing the uncertainty of projected changes in extreme precipitation

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Climate change detection and attribution research is providing a growing body of evidence that human induced climate change has intensified extreme, damaging, precipitation events over the past half century. Global climate model projections of future climate change indicate that further intensification will be part of our future across most of the globe. The magnitude of the projected changes in intensity and frequency remains largely uncertain, however, which inhibits effective and cost-efficient adaptation actions required to maintain resilience. Emergent constraint methods used by climate scientists seek to reduce this uncertainty by combining information from historical observations and climate model simulations of historical and future changes in what is effectively, a missing data imputation problem. This talk describes recent research that uses such methods to successfully constrain projected changes in extreme precipitation intensity. While future observations are not available, cross validation that uses climate simulations of the future as a proxy for observations substantially increases confidence in the constrained projections. Cross-validation shows that constraints based on observed global mean temperature change can reasonably be expected to provide projections of the future characteristics of extreme precipitation with substantially reduced bias and uncertainty compared to raw, unconstrained projections.

Session 07: Long term D&A and emergent constraints (poster presentations)

Long-term detection and attribution and emergent constraints on future climate projections

Projected Global Temperature Changes after Net Zero are Small but Significant

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The global mean temperature has been found to continue to evolve even after the abrupt cessation of emissions. The multi-model mean change in the global mean surface air temperature after 50 years has been found to be -0.07˚C, with a multi-model range between -0.36˚C to 0.29˚C. This is a small change and may be only due to internal variability, rather than a significant meaningful change in the global average temperature.

We demonstrate that the global mean changes after the cessation of emissions are indeed significant compared to natural variability in most models. We also analyse global mean precipitation changes after net zero, and find that changes are only significant in models that warm after net zero. We also demonstrate that post-net zero temperature changes have implications for the remaining carbon budget. The possibility of further global warming post-net zero adds to the evidence supporting more rapid emissions reductions in the near term.

Attribution of long-term trends in the Western Mediterranean: exploring regional aspects

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Global warming is not homogeneous. The observed warming in the Western Mediterranean (WM) region during the last decades is expected to continue and grow larger than the global mean, which is why it has been pointed out as a climate change hotspot. But even within a relatively small region such as the WM, spatial and temporal climate variability can lead to a variety of extreme weather and climate events that may exacerbate the countries' vulnerabilities. In this regard, the regional extremes and events that have been studied are geographically uneven. Many highly impactful extreme weather events have not been studied in the event attribution framework, which is the case for many WM events.

This study focuses on the detection and attribution of long-term trends of temperature and precipitation in the WM region, using a climate regionalization that considers the region's climatic heterogeneity. The research aims to establish a framework for future attribution studies on regional extreme events.

The regionalization process involved the utilization of monthly temperature and precipitation data from ERA5 during 1950-2020. Employing empirical orthogonal functions, a pre-filtering procedure was performed, retaining 90% of the variance. Subsequent to this, a non-hierarchical K-Means clustering was performed. A sensitivity analysis was conducted to determine the optimal number of groups, considering the internal representativeness of each group and the seasonal differences between groups.

This regionalization allows for a sectorized diagnosis and analysis of the recent and long-term trends observed in the WM region in different seasons of the year. Using a statistical approach, an estimate of return periods and the range of deviation with respect to the expected natural variability of a group of selected climatic extremes was obtained.

Finally, a preliminary attribution analysis was conducted on selected temperature and precipitation time series derived from the classification process. This analysis considered data from the Detection and Attribution Model Intercomparison Project (DAMIP) climate simulations to disentangle the contributions of different external factors to the climate system.

Contrast of emergent constraint on western North Pacific subtropical high between CMIP5 and CMIP6

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The western North Pacific Subtropical High (WNPSH) is a key circulation system controlling the summer monsoon and typhoon activities over the western Pacific, but future projections of its changes remain hugely uncertain. Here we investigate the projection uncertainty using pair of models in CMIP5 and CMIP6 under a high emission scenario. The leading modes of uncertainty of projected WNPSH between CMIP5 and CMIP6 are similar, but sources of the uncertainty in historical simulation are different, which is central-eastern Pacific sea surface temperature (SST) in the former whereas tropical North Atlantic SST in the latter. The physical mechanisms that impact the future projection of WNPSH are also different, which may result from the reduced cold-tongue biases in CMIP6 models. Constrained WNPSH based on Pacific and Atlantic SSTs show opposite results, that is strengthening in the CMIP5 while weakening in the CMIP6. The distinct constrained results indicate the dependence of emergent constraint on model ensembles, leading to new uncertainty of projection.

Quantifying Earth's historical feedback using statistical learning on sea-surface temperature patterns

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How much future climate will warm depends on the precise pattern of ocean warming, with different warming patterns initiating different radiative feedbacks: a phenomenon known as the pattern effect. The observed sea-surface temperature (SST) warming pattern over recent decades is markedly different from what most coupled climate models simulate, yet there is no assessment so far as to how large the difference in the SST patterns is when assessing the pattern's direct contribution to Earth's energy balance. We develop a statistical-learning method which quantifies the SST pattern's direct contribution to the energy balance. Given an observational SST data set, we show that the model is able to accurately quantify SST-induced variability in Earth's energy imbalance. Using the results from the statistical model, we derive an alternative estimate of Earth's feedback parameter without the need of atmosphere-only prescribed-SST runs. Our estimate is mostly in line with previous feedback quantifications over the historical period. However, after 1980 our estimate diverges from existing quantifications and does not show the increasingly negative Earth feedback obtained by calculation via atmosphere-only runs. This result could provide insight in the type of SST patterns responsible for annual versus decadal variability. Understanding this discrepancy is still an open question and is currently being investigated with the help of novel atmosphere-only simulations.

Detection and attribution, optimal fingerprinting, atmospheric climate models, and Aoteaora New Zealand

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Detection and attribution of multi-decadal trends over Aotearoa New Zealand (NZ) requires climate models capable of producing the relevant meteorological processes in a maritime region with large topographical variation. The current generation of coupled ocean-atmosphere climate models are not up to the task. Instead, we use large ensembles of three atmospheric climate models with sufficient resolution over NZ. The models are run under two scenarios: one driven by observed radiative and ocean surface conditions; a second driven by naturalised versions of those conditions, e.g. with greenhouse gases at circa year-1850 levels and sea surface temperatures cooled accordingly. Rather than impose our own regionalisation, we throw the full spatial details of annual averages into standard optimal fingerprinting code. We find that large ensembles using atmospheric models can be a powerful resource in identifying the anthropogenic signal in regions where the signal is heterogeneous, and that good old optimal fingerprinting still has a few new tricks up its sleeve.

Progress in the detection and attribution of regional climate change

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Modern approaches to the detection and attribution of anthropogenic climate change were formulated two decades ago, when the first relevant climate model simulations were performed. Since that time, there has been considerable progress in observational product development, climate model development (including representation of forcings), and the addition of two more decades of data. How has this progress influenced detection and attribution conclusions at regional scales? In this talk we update a largely automated system for assessing the human role in regional climate trends. This update includes a more detailed consideration of a priori confidence in the ability of observational products and climate models to reproduce variations and processes at small spatial scales. Using this updated system, we assess the role of anthropogenic climate change in observed temperature and precipitation trends in terrestrial regions around the world, evaluating how progress has been made in detection and attribution over national and subnational scales.

Impacts of natural and anthropogenic forcings on historical and future changes in global-land surface air temperature in CMIP6–DAMIP simulations

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Detection and attribution of climate change are essential for understanding past, present, and future climate changes arising from either natural, unforced variability or in response to changes in natural and anthropogenic forcings. Considering larger land warming than oceans, we furtherly investigated the historical change and future projection of the global land-surface air temperature under natural and anthropogenic forcings based on observations from the Climatic Research Unit gridded Time Series (CRU-TS) and all available model simulations from the Detection and Attribution Model Intercomparison Project (DAMIP) in the sixth phase of the Coupled Model Intercomparison Project (CMIP6). The results show that the increase in the global land-surface air temperature can be largely attributed to human activities. The effect of anthropogenic forcing (ANT) can be robustly detected and separated from the response to the natural external forcing (NAT) since about 1970–1990s. The greenhouse gases (GHG+, including the response to well-mixed greenhouse gases, ozone and land-use change) is the primary contributor to anthropogenic climate warming, and the effect of GHG+ can be clearly detected and successfully attributed to the observed temperature increases. The ANT contributes a robust warming trend of 0.1–0.2 °C per decade for global landmass during 1951–2020, along with a stronger warming in 2011–2020 (relative to 1901–1930) of 1.0–1.6 °C. These attributable warming largely encompass the observed warming trend of ~0.18 °C per decade in 1951–2012 and the observed warming of 1.59 °C in 2011–2020 (relative to 1850–1900) for global landmass reported in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and Sixth Assessment Report (AR6), respectively. The observed warming changes since 1951 or recent decade are primarily attributed to the GHG-forcing. The anthropogenic warming is projected to increase by 3–6 °C for most of global landmass under the SSP2-4.5 scenario, especially in the high latitudes of the Northern Hemisphere by the late of 21st century, along with an increase in the mean and widespread flattening of the probability distribution functions (PDFs) of temperature anomalies. In contrast a cooling effect of ~0.7°C in 2011–2020, the anthropogenic aerosols (AA) forcing is projected to cool the global land by around 0.6°C by the late of the 21st century.

Session 08: Single weather events (oral presentations)

Attribution and analysis of single weather events

Arctic marine heatwaves forced by greenhouse gases and triggered by abrupt sea-ice melt

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Since 2007, unprecedented marine heatwave events are occurring over the Arctic Ocean. Here we use extreme event attribution technique and identify the fraction of the likelihood of Arctic marine heatwaves magnitude (intensity, duration, and cumulative heat intensity) that is attributable to greenhouse gas (GHG) forcing. Results reveal that Arctic marine heatwaves are primarily triggered by an abrupt sea-ice retreat, which coincides with the maximum downward radiative fluxes. Up to 82% of the sea surface temperature (SST) variability over the shallow Arctic marginal seas, where marine heatwaves are prone to occur, can be explained by net accumulation of seasonal surface heat flux in the ocean. Event attribution analysis demonstrates that the 103-day long 2020 event -- the most intense (4 °C) recorded so far in the Arctic -- would be exceptionally unlikely (< 1% occurrence probability) in the absence of GHG forcing in terms of both intensity and duration. However, for moderate events, with an intensity in the range of 0.5 °C to 1 °C, GHG forcing emerges as a sufficient cause (with 66% to 99% probability). This suggest that if GHG forcing continues to increase, along with the expansion of first-year ice extent, events with moderate intensity will very likely consistently reoccur.

The long-term SST detection results clearly shows the emergence of a GHG signal in the observed 3 °C ocean warming (1996-2021) over the shallow Arctic marginal seas where marine heatwaves are prone to occur. The fact that marine heatwaves are superimposed on a GHG-induced systematic SST warming confirms the marine heatwave attribution results, and implies that the Arctic region will face increasingly frequent and intense extreme SST events, which will exacerbate climate change impacts in the Arctic, and cause Arctic sea ice extent to shrink even faster in the near future, especially given the continued increase in GHG emissions.

A simple hybrid method to translate past weather events into the future climate

Julien BOÉ
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When an extreme weather event occurs, in addition to the question "what role did climate change play in this event", another common question is "what would such an event be like in a warmer future climate". Here, we present a simple hybrid numerical-statistical approach for translating past weather events into the future climate and apply it to extreme temperature events.

First, a conditional approach with dynamical adjustment is used to assess the role of large-scale atmospheric circulation in the temperature anomalies of observed extreme events over Europe, using the ERA5 reanalysis.

The dynamical adjustment method is based on constructed analogues. It consists of constructing synthetic analogues of the large-scale circulation pattern responsible for an extreme event by the optimal linear combination of large-scale circulation patterns occurring in a training set. The same set of weights is then applied to the corresponding temperatures to evaluate the temperature anomaly due to large-scale circulation during the extreme event.

The temperature anomalies that an identical large-scale circulation pattern would produce in the future climate can be estimated using a similar approach. To do this, the constructed analogues for observed extreme events are estimated using regional climate simulations over Europe as a training set, first for the historical period, then for the future period of interest.

Following this methodology, for a selection of observed extreme temperature events defined in terms of intensity and spatial extent, we first assess the observed circulation-induced temperature anomalies and compare their magnitude across events. Then, after evaluating the ability of the regional climate model to capture the dynamical component of the observed extreme events, we quantify the temperature anomalies that would be associated with these events in a warmer future climate.

How extreme were daily global temperatures in 2023?

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Global temperatures were exceptionally high in 2023, with an annual average near 1.5°C above pre-industrial levels. Every month from June to December set a new record, and September even shattered the previous record by about 0.5°C. These warm anomalies result from both the long-term warming trend (forced component) and the internal variability: in particular the onset of an El Nino episode in mid-2023 after several years of La Nina provided ideal conditions for a remarkably hot year. However the amplitude of the 2023 anomalies surprised the community and raised questions about a possible acceleration of the global warming or underestimation of the forced component.

Here we analyze global temperatures of 2023 using a methodology for monitoring single extreme weather events. We first estimate the non-stationary daily normals of global temperature and disentangle the contributions of forced component and internal variability at the daily scale. We show that a 'normal' year 2023 (e.g. without El Nino) would already have broken the previous annual record of 2016. Then we assess the rarity of the 2023 anomalies over various time windows and compare it with other years. We find that the most extreme event of 2023 is the second half of September, and that this episode ranks among the most extreme of the entire global temperature series. We have developed an interactive application to monitor daily global temperatures in real time, and we will include the start of 2024 in the analysis if relevant.

The unprecedented spatial extent and intensity of the 2021 summer extreme heatwave event over the Western North American regions

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A record-breaking heatwave event occurred in western North America in the summer of 2021. Previous studies on a similar event's uniqueness and return period are typically estimated based on extreme value analysis and statistics of selected stations or area-mean temperature data. The extreme statistics results are no longer valid if moved to another location. Further, the detailed evolution of spatial extent and intensity through its duration is not quantified and compared to other historical heatwave events to claim its rarity and severity. By applying an event detection and tracking algorithm to heatwaves, we first construct an archive for all the events over the region since 1979 based on daily maximum temperature data from reanalysis. It documented the daily mean temperature anomalies, affected areas, and durations of all individual heatwave events. It is, therefore, possible to objectively compare and rank the magnitudes of all historical heatwave events by examining the total integrated effects from the intensity, impact region, and duration. With the global mean warming background increase of about 0.4 ◦C from 1979–2000 to 2000–2021, we found that the mean integrated magnitude and size of the top 100 heatwave events increased significantly by 155 ± 88%. The dominant relative contributions to this integrated severity measure increase are +78 ± 39% from the mean affected area, followed by +54 ± 21% from duration and +7 ± 4% from the intensity. With the above analyzed general historical increasing trend of heatwave event metrics, the severity of the 2021 summer heatwave over the region was due to a combination of its record-breaking event-mean spatial coverages (2090383 km^2), highest normalized daily maximum temperature anomalies and long duration (11 days, in the top 4% of all heatwave events). This integrated severity measure of the event was more than double that of any other historical heatwave event and about 17 times larger than the mean severity of all heatwave events over the region.

Forensic attribution of the extreme rainfall in Pakistan in 2022 to anthropogenic climate change

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In 2022, Pakistan experienced extreme dry heat in early spring, followed by devastating record-breaking flooding during summer. Both of these events caused severe impacts across agriculture, health and infrastructure, and taken together led to extreme economic impacts. Both events were studied using probabilistic event attribution by the World Weather Attribution group (Otto et al., 2023; Zachariah et al., 2023). The hot dry March-April period, extreme 5-day rainfall over the southern provinces of Baluchistan and Sindh, and elevated 60-day monsoon rainfall over the Indus basin, were all found to have become more likely and intense (to varying degrees) due to the influence of anthropogenic climate change (ACC). These univariate definitions were intended to capture the impacts of the events as closely as possible in a rapid study timescale. However, the impacts of extremes are most often experienced (or at least amplified) due to compound effects of multiple extremes across space and time (Zschesichler et al., 2020). A formalised methodology for attributing compound events has recently been developed using a multivariate framework (Zscheischler and Lehner, 2022). This approach can provide greater insight into changing drivers of risk and can be tailored to particular aspects – such as the drivers of impacts or causal factors – to answer specific questions. To this end, we build on the initial univariate analyses of extreme in Pakistan in 2022 by investigating two multivariate ways of characterising the event. First, flooding during the event was driven (meteorologically speaking) by the combination of saturated soils across the Indus basin and extreme pulses of rainfall in southern Pakistan. To focus on impacts, we therefore consider the co-occurrence of both the extreme rainfall events as characterised in past studies. Second, to consider the causal drivers in greater detail, we consider a multivariate analysis of the hot spring period, which resulted in a 'thermal low' over the region, followed by a wet monsoon season over the Indus basin. This combination of events could also compound across time, leading to elevated impacts for the agricultural sector, further highlighting its importance. Finally, in order to provide greater insight into the changes in risk going forwards, the likelihood and attributable signal of all of these events are assessed at the present day and across three shared socioeconomic pathways scenarios. Taken together, this analysis provides an array of estimates of the influence of ACC on different drivers of the event at present and across different scenarios. In doing so, it allows comparison of the relative changing drivers and could inform adaptation and mitigation efforts going forwards.

Causal Attribution of Arctic Extreme Fire Weather Events to Anthropogenic Forcings

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As an imprint of its rapid climatic transformation over the last two decades, the pan-Arctic region has experienced increasingly extreme fire events. However, a systematic and regionally comprehensive assessment of the recent extreme fire events in the pan-Arctic and the role played by human emissions is still pending. In this study, we employ an extreme event-attribution framework to assess the extent to which anthropogenic forcings affect the magnitude (intensity, area burned) and frequency of extreme fire events in the pan-Arctic region. We use large ensemble simulations run with the Community Earth System Model version 2 (CESM2) capable of isolating individual external climate forcings. Our initial analysis indicates that the presence of anthropogenic greenhouse gases throughout the last two decades was necessary to enable the observed extreme fire events in the Arctic. Moreover, it substantially raised the risk of high-latitudes being exposed to dangerous fire-weather conditions. We further explore the underlying mechanisms that drive changes in extreme fire-weather risk. We identify the relative contribution of maximum temperature, precipitation, relative humidity, and surface wind speed on the changes in extreme fire-weather risk.

A quasi-operational event attribution system for hot extremes in Canada

Nathan Gillett[1], Elizaveta Malinina[1], Megan Kirchmeier-Young[1], Yongxiao Liang[1], Karen Garcia Perdomo[1], Xuebin Zhang[2]

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In recent years, hot extremes in Canada have had major impacts on ecosystems and society, with the western Canada heatwave of 2021 causing the death of more than 600 people, and heatwaves in early 2023 being associated with the start of that year's exceptional fire season. In Canada, as elsewhere, there is a desire for quantitative information on the contribution of anthropogenic climate change to the probability of occurrence of observed extreme events, including heatwaves, to inform rebuilding and recovery efforts, and to improve public understanding of climate change impacts. Such information is much more impactful if it is available days after an event, rather than months or years later. This talk will describe the development and application by Environment and Climate Change Canada of a prototype quasi-operational probabilistic event attribution system for hot extremes which runs automatically on a daily basis, and provides estimates of return periods and risk ratios for one- and three-day hot extremes over sub-regions of Canada shortly after they occur. Observed events are characterized using ERA5 reanalysis, and risk ratios are calculated based on GEV fits to CMIP6 simulations of the present-day climate compared to simulations of an 1850-1900 base period. This talk will discuss the sensitivity of results to factors such as whether a stationary GEV is used, or one in which GEV parameters depend on global mean temperature, as well as methods to account for differences in variability between models and observations. It will end by discussing the next steps in the development of the system, including plans for a complementary system using high resolution atmosphere-only simulations conditioned on observed sea surface temperatures.

Anthropogenic Contribution to the Unprecedented 2022 Mid-Summer Extreme High-Temperature Event in Southern China

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This study aimed to investigate the role of anthropogenic forcing in the unprecedented extreme high-temperature event that occurred in southern China during mid-summer 2022 based on a dynamic adjustment methodology. It is worth noting that CPC only provided data from 1979 to the present, but longer time series data may have an impact on the recurrence period and attribution of this EHT. Our analysis revealed that 60.6% of the 2022 EHT is attributed to anthropogenic climate changes in southern China. These results were further supported by the FAR estimated through GEV fitting, implying the suitability of dynamic adjustment methods for detecting and attributing extreme weather events and assessing the contribution of anthropogenic forcing to climate change. Nevertheless, further investigation is warranted to explore the influence of external forcing on internal variability and the role of internal variability in response to external forcing. This would provide deeper insights for a more accurate attribution of extreme events.

Exploring unprecedented hot-dry events in Aotearoa New Zealand

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To understand the risks associated with climate extremes in a warming world, one of the most powerful sources of information comes from observational data associated with past events. Yet, we know the relative rarity of historical weather events can often be effectively random and heavily influenced by multiple sources of internal variability. In this study, we demonstrate a statistical framework to quantify the relative rarity of past meteorological drought events around Aotearoa New Zealand, exploring an extensive range of drought onset periods, spatial footprints, and event durations. Using several case studies, we show which regions are statistically overdue for a record-breaking meteorological drought and which past events were statistically exceptional across multiple regions. In addition, we examine the coincident occurrence of unprecedented hot events in the historical record, and quantify plausible hot-dry compound events which could occur under current and future warming scenarios across different regions in New Zealand.

Translating historical extreme weather events into a warmer world

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A new reanalysis-based approach is proposed to examine how reconstructions of extreme weather events differ in warmer or cooler counter-factual worlds. This approach offers a novel way to develop plausible storylines for changes in some types of extreme event that other methods may not be suitable for.

Here, we re-run the 20th Century Reanalysis (20CRv3) system to produce improved and plausible reconstructions of certain historical extreme weather events by adding newly rescued pressure observations. We then translate these events into a warmer world by increasing the SSTs used as reanalysis boundary conditions and assimilating the same pressure observations. This approach represents the same extreme weather patterns but in a warmer world with physically consistent changes to the atmospheric state.

As proof-of-concept, we apply this approach to a severe windstorm that occurred in February 1903. This event, known as Storm Ulysses, produced stronger winds than any other more recent event for parts of the UK. The translated reconstruction produces even higher wind speeds and increased rainfall, suggesting that this storm would be more damaging if it occurred today rather than 121 years ago. We expand this proof-of-concept to examine a wider range of historical extreme weather events in multiple regions.

Anthropogenic Influence on 2022 Extreme January–February Precipitation in Southern China

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The precipitation in January–February 2022 in Southern China was the second largest since 1961. Anthropogenic influence reduced the likelihood of extreme events like 2022 by about 50% (55%) in HadGEM3 (CMIP6). Analyses of single forcing experiments using CMIP6 model ensembles demonstrate different roles of changes in GHG and AA in J–F precipitation over SC with GHG forcing inducing an increase and AA forcing inducing a decrease. However, the magnitude of AA-induced precipitation decrease is larger than that of GHG-induced increase, leading to the reduced likelihood of the J–F precipitation event similar to that of 2022 in SC by the combined effect of anthropogenic forcing.

Global warming contribution to the long-lived super typhoon Hinnamnor: Role of warm surface water over the East China Sea

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In early September 2022, a tropical cyclone (TC) Hinnamnor struck South Korea. Hinnamnor was the first super typhoon that maintained its strong intensity near 30°N. Unlike typical TCs, Hinnamnor re-strengthened while moving northward. The sea surface temperature (SST) remained above 29℃ in the East China Sea (ECS) during 2022 August-September (AS), and this corresponds to the warmest record among the years when strong TCs having similar tracks affect South Korea. This study quantifies anthropogenic influences on the increase of SST and subsurface ocean heat content over ECS during AS 2022 using multimodel simulations from the Coupled Model Intercomparison Project phase 6 (CMIP6) historical (ALL) and historicalNat (NAT) experiments, respectively. An observational analysis using selected 16 TCs shows that warmer SST and sub-surface water over ECS are significantly associated with stronger landfall intensity and the maximum intensification latitude. Based on the observed relationship, we compare the probability of warm SST and sub-surface temperature over ECS between ALL and NAT runs. Results indicate that the 2022-like warm surface water has become at least five times more likely due to human activities. Further, this warm surface ocean is expected to become normal around 2030 under Shared Socioeconomic Pathways (SSP) 2-4.5 scenarios, implying much higher chances of Hinnamnor-like super typhoons affecting East Asia while maintaining their intensities up to higher latitudes.

Contribution of External Forcing and Internal Variability to Recent Extreme Rainfall Trends in the Horn of Africa

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From October 2020 to Jan 2023, Horn of Africa experienced five consecutive failed rainy seasons, resulting in the worst drought in 40 years. Subsequently, in October and November 2023, the region experienced extreme rainfall, leading to widespread flooding. The events resulted then followed extreme rainfall in October-November 2023 that caused widespread flooding. This led to adverse impacts such as reduced food production, water security, economic output, biodiversity loss, and increased human morbidity and mortality. The interaction between atmospheric warming and sea surface temperature (SST) changes in the Indian and Pacific oceans, driven by rising global surface temperatures, exacerbates precipitation extremes in the Horn of Africa. Remote teleconnections, namely the El Niño– Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), exert a dominant influence on interannual variability over the region. The drought years concluded with successive La Niña conditions while the flooding occurred during a positive phases of IOD and ENSO (El Nino). We employed various climate models and observations to assess changes in 24-month rainfall (2021-2022), and seasonal rainfall; both the (March-April-May, MAM) 'long rains' and (October-November-December, OND) 'short rains' in 2022, and consecutive 5-day and 30-day in November 2023. In order to examine the effect of the IOD and ENSO phases alongside that of increasing GMST, we extend the nonstationary model to accommodate the oceanic indices as additional covariates. Our findings reveal that positive phases of IOD and ENSO (El Niño) contribute to heavy rainfall during the October-November-December season in the wider Horn of Africa. Furthermore, climate change-induced changes in Pacific SSTs intensify the drought-inducing effects of La Niña, making La Niñas events more intense and hazardous over Horn of Africa. Our results also show a decline in rainfall during MAM and an upward trend during OND, which is attributable to climate change

Keywords: Climate change, attribution, drought, Horn of Africa, multiple covariates

Attribution of area burned and other fire season characteristics: an example from the 2023 Canadian wildfire season

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Canada experienced an extreme wildfire season in 2023, with the almost 15 million hectares burned more than doubling the previous record based on satellite-era observations. Many provinces/territories across the country set local records for area burned as well. The fire season started early and high fire weather conditions lasted for several months. We use a probabilistic event attribution framework to analyze several characteristics of the fire season, including the extreme fire weather, start and length of the fire season, and measures of the spatial extent of the high fire risk. We also develop simple statistical models to predict the area burned and investigate changes in the likelihood/magnitude. This presentation will discuss method considerations when extending event attribution beyond the typical fire weather index.

Extreme event attribution of the unprecedented heat event of August 2023 in Barcelona (Spain). Observed and projected intensity and exposure under global warming.

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The study analyses observed time series of temperatures from 1920 onwards and numerical simulation data from CESM1 to investigate the unprecedented heatwave that occurred in August 2023. The study examines historical changes in the intensity of such events, their expected future changes under scenarios of +1.5°C, +2°C and +3°C warmer worlds, and the future exposure of populations to these events. The findings indicate a significant increase in both minimum and maximum observed temperatures for similar heatwave to the one occurred in August 2023. The study also emphasises the impact of observed global warming on the intensification of heat events, over the impact of urbanisation. Additionally, after examining the role of natural variability in temperature changes we concluded that global warming is the primary factor driving the increase in heatwave intensity. Regarding the frequency of such kind of events, we pointed out that extreme heat events, similar to the August 2023 heatwave, will become more frequent and likely with global warming. This will expose a larger portion of the population to dangerous heat levels highlighting the importance of limiting global warming to 1.5°C to mitigate the impacts on urban populations. In conclusion, this research contributes to the understanding of the effects of global warming on urban heatwaves, particularly in Mediterranean cities such as Barcelona. It emphasises the need for targeted local adaptation strategies and global efforts to limit warming, highlighting the critical need to address the challenges posed by urban heatwaves in the context of climate change.

Probability estimation for long return period hot extremes using a large ensemble of model simulations

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Accurately estimating the probability of hot extreme events with long return periods is crucial for understanding the impacts of climate change. In particular, using event attribution to determine the change in likelihood of an extreme event due to anthropogenic forcing requires robust estimates of the event probability. Increasing demand for event attribution results in an operational context further strengthens the need for reliable methods. Estimates of the probability of hot extremes are commonly derived by fitting samples of annual maxima to generalized extreme value (GEV) distributions. A large ensemble of climate model simulations offers a large sample of extremes to evaluate the goodness of fit within a model-simulated climate and to quantify the impact of method choices on the estimation of return periods and risk ratios for very rare events. We discuss how the fit of annual maxima affects the estimation of return periods and risk ratios and how we can improve the goodness of fit for long return period hot extremes at the regional level.

The 2021 heatwave was less rare in Western Canada than previously thought

Elizaveta MALININA, **Nathan Gillett**

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The 2021 Pacific Northwest heatwave resulted in record temperatures observed across the Canadian provinces of British Columbia, Alberta and Saskatchewan as well as the US states of Washington and Oregon. Previous studies of extreme temperatures over predominantly rectangular regions covering parts of Oregon, Washington and British Columbia have estimated return periods of 200–100 000 years, generally based on data since 1950, with some analyses suggesting that the event would have been considered impossible based on statistical fits to pre-2021 data. Consistently with those studies, we estimate a return period of 1152 (126-∞) years for the 2021 event averaged over British Columbia, based on a generalized extreme value distribution (GEV) with a location parameter a function of global mean surface temperature fitted to 1950–2021 ERA5 data, However, we show that this return period is reduced to 236 (52-∞) years when the analysis period is extended back to 1940, using newly-available ERA5 data, owing to an extreme heatwave observed in 1941. While the 1941 event was 1.7 °C cooler than the 2021 event in British Columbia, it was a rarer event relative to the cooler climatology of the time, with an estimated return period of 735 (135-∞) years. Over this longer period, we also find that almost all CMIP6 models underestimate variability in annual maximum temperatures over British Columbia and overestimate it over other regions, in particular Saskatchewan.

While the 2021 event was an unprecedented and extremely intense heatwave whose likelihood was much increased by human-induced climate change, our results indicate that this event was not as rare as previously thought in Western Canada. Hence, as the climate continues to warm, the recurrence of such a heatwave in the coming decades is not as unlikely as suggested by previous analyses.

Synthesis of multi-model attribution results - Formally combining different lines of evidence in extreme event attribution

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Event attribution methods are increasingly routinely used to assess the role of climate change in individual weather events. In order to draw robust conclusions about whether changes observed in the real world can be attributed to anthropogenic climate change, it is necessary to analyse trends in observations alongside those in climate models, where the factors driving changes in weather patterns are known. Here we present a synthesis method, developed over eight years of conducting rapid event attribution studies, to combine attribution results from multi-model ensembles and other lines of evidence in a single framework to draw probabilistic conclusions on the overarching role of human-induced climate change in individual weather events.

The Effect of a Short Observational Record on the Statistics of Temperature Extremes

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In June 2021, the Pacific Northwest experienced a record-breaking heatwave event. Return levels estimated based on observations up to the year before the event suggested that reaching such high temperatures should not have been possible in the current climate. We assess the suitability of the prevalent statistical approach by analyzing extreme temperature events in climate model large ensemble and synthetic extreme value data. We demonstrate that the method is subject to biases, as high return levels are generally underestimated and, correspondingly, the return period of rare heatwave events is overestimated, especially if the underlying extreme value distribution is derived from a short historical record or in a changing climate. Furthermore, analyses triggered by an extreme event suffer from additional selection bias introduced by the implicit stopping rule. We also discuss an alternative approach to non-stationary return level and endpoint uncertainty estimation, using localized profile likelihood.

Human influences on spatially compounding flooding and heatwave events and future increasing risks

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Attribution of high-impact weather events to anthropogenic climate change is important for disentangling long-term trends from natural variability and estimating potential future impacts. Up to this point, most attribution studies have focused on univariate drivers, despite the fact that many impacts are related to multiple compounding weather and climate drivers. For instance, co-occurring climate extremes in neighbouring regions can lead to very large combined impacts. Yet, attribution of spatially compounding events with different hazards poses a great challenge. Here, we present a comprehensive framework for compound event attribution to disentangle the effects of natural variability and anthropogenic climate change on the event. Taking the 2020 spatially compounding heavy precipitation and heatwave event in China as a showcase, we find that the respective dynamic and thermodynamic contributions to the intensity of this event are 51% (35–67%) and 39% (18–59%), and anthropogenic climate change has increased the occurrence probability of similar events at least 10-fold. We estimate that compared to the current climate, such events will become 10 times and 14 times more likely until the middle and end of the 21st century, respectively, under a high-emissions scenario. This increase in likelihood can be substantially reduced (to seven times more likely) under a low-emissions scenario. Our study demonstrates the effect of anthropogenic climate change on high-impact compound extreme events and highlights the urgent need to reduce greenhouse gas emissions.

Relative contributions of anthropogenic forcing and internal variability in southeast Australia's multi-year (2017-2019) drought and future prospects

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A large region of southeast Australia received the lowest three-year rainfall during the 2017-2019 period, resulting in an unprecedented meteorological drought, known as the Tinderbox Drought. The cool season (April-September) rainfall declined was just 46% of 1901-1960 average over the Tinderbox Drought region. On analysing the observed rainfall records since 1900, we found that occurrence of a decline of this magnitude due to internal variability alone was exceptionally unlikely. We analysed outputs from CMIP5 and CMIP6 climate models under different forcing conditions to quantify the relative contribution of anthropogenic forcing and internal variability to the observed 2017-2019 cool season rainfall reduction and to estimate the likelihood of the extremely dry and wet multi-year rainfall changes over the coming century under different emission pathways. According to the climate models, the Tinderbox-type Drought is an extremely unlikely event under the preindustrial conditions, but the likelihood of its occurrence is being increased from near impossible to extremely unlikely by the anthropogenic forcing in the current climate. This suggests that the Tinderbox Drought was made more likely by the anthropogenic climate change, but still remains an extreme event in the context of the present climate. By the end of this century, the likelihood of the extremely dry 3-year period is estimated to be 20 (5) times more likely under the highest (lowest) emission scenario than that during the preindustrial climate. In contrast, the likelihood of extreme wet 3-year period tends to be lower than that of preindustrial climate under all scenarios towards the end of the 21st century.

A large ensemble illustration of how record-shattering heat records can endure

James RISBEY

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The record-shattering hot day in the Pacific Northwest in June 2021 is used to motivate a study of record-shattering temperature extremes in a very large hindcast ensemble. The hottest days in the Pacific Northwest in the large ensemble have similar large scale and synoptic patterns to those associated with the observed event. From the perspective of a fixed location, the hottest ensemble days are acutely sensitive to the chance sequencing of a dry period with a precisely positioned weather pattern. These days are thus rare and require very large samples (tens of thousands of years) to capture. The enduring nature of record-shattering heat records can be

understood through this lens of weather `noise' and sampling. When a record-shattering event occurs due to chance alignment of weather systems in the optimal configuration, any small sample of years subsequent to the (very unlikely) record event has an extremely low chance of finding yet another chance extreme. While warming of the baseline climate can narrow the gap between more regular extremes and record-shattering extremes, this can take many decades depending on the pace of climate change. Climate models are unlikely to capture record-shattering extremes at fixed locations given by observations unless the model samples are large enough to provide enough weather outcomes to include the optimal weather alignments. This underscores the need to account for sampling in assessing models and changes in weather-sensitive extremes. In particular, climate models are not necessarily deficient in representing

extremes if that assessment is based on their absence in undersize samples.

Global emergence of unprecedented lifetime exposure to climate extremes

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Climate extremes such as heatwaves, river floods, droughts, crop failures, as well as aspects of wildfires and tropical cyclones are increasingly attributable to anthropogenic climate change. Yet how this translates into unprecedented levels of extreme event exposure in one's lifetime remains unclear. Here we show that many of today's youth will experience unprecedented exposure to extremes during their lifetimes. For each event type above, the share people facing unprecedented lifetime exposure is projected to at least double from 1960 to 2020 birth cohorts under current mitigation policies aligned with a global warming pathway reaching 2.7 °C above pre-industrial temperatures by 2100. In a 1.5 °C pathway, 47% of people born in 2020 will experience unprecedented lifetime exposure to heatwaves. If global warming reaches 3.5 °C by 2100, this rises to 93% of this birth cohort. For the same cohort and warming pathway, 29% will live with unprecedented exposure to crop failures and 15% to river floods. Likewise, for tropical cyclones, when limiting cohort estimates to regions experiencing this geographically constrained event, this fraction nearly doubles from 10 to 19%. Our results overall call for deep and sustained greenhouse gas emissions reductions to lower the burden of climate change on young generations

Simulating the Western North America heatwave of 2021 with analogue importance sampling

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During the summer of 2021, the North American Pacific Northwest was affected by an extreme heatwave that broke previous temperature records by several degrees. The event caused severe impacts on human life and ecosystems, and was associated with the superposition of concurrent drivers, whose effects were amplified by climate change. We evaluate whether this record-breaking heatwave could have been foreseen prior to its observation, and how climate change affects North American Pacific Northwest worst-case heatwave scenarios. To this purpose, we use a stochastic weather generator (SWG) with empirical importance sampling. The SWG simulates extreme temperature sequences using circulation analogues, chosen with an importance sampling based on the daily maximum temperature over the region that recorded the most extreme impacts. We show how some of the large-scale drivers of the event can be obtained form the circulation analogues, even if such information is not directly given to the SWG. We conclude that such a hot event was hardly possible in the 20th century, and that climate change made such an event possible in the present conditions.

Session 08: Single weather events (poster presentations)

Attribution and analysis of single weather events

Recent developments from World Weather Attribution

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The World Weather Attribution (WWA) approach to probabilistic attribution assumes a nonstationary distribution for the weather extreme of interest, which either shifts or scales with global mean surface temperature. This nonstationary distribution is used to estimate the expected change in the expected frequency of exceedances of a threshold, or in the intensity of similar events. We introduce a new R package (available from GitHub) designed to allow users to quickly carry out WWA-style analyses and synthesise the results from observations and climate models. We illustrate the use of the package with examples from recent studies, highlighting the importance of including other relevant modes of variability – such as ENSO or the Indian Ocean Dipole – in the statistical model, along with other innovations to the basic WWA methodology.

Multiple attribution analysis for heat wave events in Argentina in the summer of 2022/23 using the analogue technique

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In the austral summer of 2022/23, Argentina experienced an unusually hot season. The occurrence of multiple heat waves during this season could be attributed to various factors operating on different time scales. On the synoptic scale, anticyclonic anomalies were necessary for these events to occur. On the interannual scale, the region experienced an extremely dry summer due to the third consecutive La Niña year. Finally, on longer time scales, these events occurred in the context of climate change, where global temperatures are increasing. The aim of this study is to investigate the contribution of these processes to the maximum temperature (TX) anomalies recorded during four heat waves (HWs) in the summer of 2022/23 in Argentina, using the analogue method. Attribution analysis shows that the presence of a quasi-stationary anticyclone at mid-atmospheric levels raises TX anomalies by up to ~2°C as compared to a random flow under current climate conditions. We also observe that such events are more likely to develop under dry soils due to the strong soil-atmosphere coupling in the region, producing TX anomalies more than 1°C higher than what would be obtained under wet soil conditions. Climate change also contributes to these more intense HWs. The analogue exercise shows that the TX anomalies recorded in the current climate are between ~0.5 and 1.2°C warmer than those recorded in the period 1951-1980 under anticyclonic conditions similar to those recorded during the HWs. In summary, we find that atmospheric circulation, soil moisture deficits, and climate change, along with their complex interactions, significantly contributed to amplifying the TX anomalies recorded in the HWs during the warm season of 2022/23 in Argentina.

Towards compound extreme event attribution: hot and dry events in Belgium

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Compound weather and climate events refer to combinations of multiple weather and climate rivers and/or hazards that lead to potentially large impacts. Not only will single extreme events become more frequent in the future, but there will also be a higher likelihood of high-impact compound events. Extreme events are more likely to occur simultaneously, leading to increased damage and impact on the territory. Extreme Event Attribution (EEA) is an emerging field in climate sciences. One of the goals is to describe whether and how the probability of an event depends on climate change. Extreme event attribution typically focuses on univariate assessments, often leading to an underestimation of the risks and actual damages attributable to climate change. While compound weather and climate events can result in significant socioeconomic consequences, their attributability to climate change remains largely unexplored. Here, we present a compound event attribution study assessing the change in probability of having co-occurrent hot and dry events in Belgium with and without climate change.

Perils, pitfalls, and proposals for extreme wind attribution based on the example of the 2022 Hurricane Fiona

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In late September 2022, the Atlantic Hurricane Fiona transitioned to a post-tropical cyclone making a landfall in the Canadian Maritime provinces, setting a new national lowest pressure record and causing more than 800m CAD in insured damage, making it the most expensive storm of its kind in Canadian history. While the landfall of Fiona in Canada was associated with precipitation, a commonly used variable in event attribution, most destruction associated with the event was caused by high winds. This talk describes an event attribution of extreme windspeed using CMIP6 high resolution atmosphere model (HighResMIP) simulations and ERA5 reanalysis data, including a discussion of the choice of the appropriate windspeed frequency and variable for the analysis along with the method we used to address these issues. Based on our best estimate using ERA5 data, the maximum hourly windspeed associated with Fiona was approximately a 1 in 100 year event in Atlantic Canada. HighResMIP simulations exhibit a statistically significant increase in the probability of extreme maximum windspeeds in the Maritimes in the current climate (2008-2037) in comparison to the climate of 1950-1979, indicating that human-induced climate change has increased the probability of extreme windspeeds, like those observed in post-tropical storm Fiona, in Atlantic Canada.

On the storyline and likelihood for spatially compound flood-heat-flood events based on ensemble boosting

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In September 2023, an unprecedented flood-heat-flood compound extreme attacked Iberian Peninsula, Northern France/German, and Greece, accompanied by a low-high-low pressure system showing up alternatively over Europe. These extremes have caused severe consequences for the local economy and ecosystems, and the impacts are even more aggravated due to its spatiotemporal synchronization. However, given the lack of long homogeneous climate observations, it is challenging to access how intense spatially compound extremes could get and what the physical drivers are, and to quantify their likelihood in the future or even in the present climate. To this end, this study applies the ensemble boosting method, a model-based approach with slightly perturbed atmospheric initial conditions to efficiently generate large samples of storylines in climate simulations. We first evaluate whether the model can reproduce analogues of the spatially compound extreme in September 2023 and compare the occurrences with those from randomly shuffling series, then re-initialize these events to analyze how this event could have evolved and whether it could have become even more intense. If so, this method can be further used to generate worst-case scenarios and help make emergency plans ahead.

Disentangling the Contribution of Greenhouse Gases and Aerosols to Estimates of Regional Heatwave Return Periods

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Heatwaves represent some of the most impactful extreme weather events, with profound implications for ecosystems, human health, and economies globally. Accurately attributing the changes in their occurrence probabilities, intensity, and duration is crucial for effective climate change adaptation strategies. A common practice of calculating heatwave return periods relies on extreme value statistics with a covariate on global mean surface temperature to parametrize instationarity. However, local temperature trends over the last decades are influenced, partly substantially depending on the region, by anthropogenic aerosol emissions (AER). AER trends can both counteract and amplify the warming effect of greenhouse gases (GHG), hence significantly altering regional climate dynamics and thermodynamical processes and, consequently, the return periods of extreme temperature events. In our study, we used several state-of-the-art single forcing large ensemble climate model simulations from the CMIP6 archive to analyse the regional effects of AER vs. GHG on estimates of heatwave return periods. By examining extreme temperature changes as a function of GHG and AER, we aim to disentangle the effects of these forcings on regional heat extremes. The single forcing large ensemble simulations with their large sample size are used in a model-as-truth experimental setup to evaluate return period estimates from individual ensemble members against the entire ensemble. Our findings indicate that regional aerosol trends have a considerable influence on the return periods of heatwaves. This study underscores the importance of incorporating regional aerosol trends into attribution studies to improve the estimation of return periods.

Probabilistic attribution analysis and future risk assessment of the extreme meteorological conditions associated with the 2022 Euro-Mediterranean wildfires

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In the summer of 2022, an unprecedented condition of wildfires swept across the Euro-Mediterranean region. Between late July and early August, an exceptionally high number of wildfire events resulted in a record-breaking extent of burned area. While considerable public concern about the impact of climate change on meteorological conditions conducive to wildfires has grown significantly, the limited number of wildfire attribution studies, along with the scarcity of observational data, has made it challenging to draw reliable collective conclusions for future forest management strategies.

Here, we present a probabilistic event attribution analysis of extreme 'fire weather' at ten individual locations across the Euro-Mediterranean region where such conditions coincided with extreme wildfires during summer 2022. Initially, we provide an overview of the meteorological anatomy of the summer 2022 event, including satellite-derived detections of individual fires. We apply an established statistical methodology to quantify trends in fire weather extremes. Annual fire weather maxima derived from both the observational record and 50-member ensemble of the Canadian Earth System Model version 5 (CanESM5) are fitted to extreme value distributions and scaled to global mean surface temperature. A comparison of extreme distributions representative of present, past and future climates is expressed probability ratio form following non-parametric bootstrapping. The results show an overall increase in likelihood of approximately 80% during the last century, with further increases of 60% and 80% approximated under 1.5°C and 2.0° global warming levels respectively. Our findings complement the positive trends in observed extreme fire weather shown in recent work and clearly underline the importance of combining individual attribution studies further with future risk assessment.

Impact of anthropogenic climate change on the frequency and intensity of extreme events in France in the context of conditional attribution

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Anthropogenic climate change (ACC) is one of the most demanding challenges facing our society. The intensification and increased frequency of many extreme events due to ACC are among the most impactful aspects. Notably, energy production is a crucial sector that has been compromised by extremes: extreme weather is recognized as a primary cause of wide-area electrical disturbances worldwide [Panteli and Mancarella, 2015]. Therefore, it becomes important to estimate how ACC and particularly changes in extreme events impact the energy sector to build a more resilient society and ensure future energy production.

This work focuses on the assessment of extreme events impacts on nuclear facilities in France. To do so, we use the ClimaMeter tool [Faranda et al. 2023], which is designed to provide context for extreme events in relation to ACC. ClimaMeter's approach focuses on the dynamics associated with extreme events and looks for weather conditions similar to those characterizing the event of interest, the so-called circulation analogues [Yiou, 2014]. It enables to evaluate significant evolutions over time of the event's dynamics and of the associated meteorological hazards, and attribute them to ACC. We use ClimateMeter to study extreme events of different kinds for which nuclear facilities have reported impacts and perform the attribution of these events to ACC.

This work aims to deepen our understanding of ACC impacts on extreme events in France and improve the knowledge needed to characterize the meteorological hazards considered in nuclear safety.

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Comparison of Results from Different Event Attribution Techniques for an Attribution Service

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The Australian Climate Service serves the Australian community to reduce its climate risk and draws on a suite of methods to explain the drivers of extreme weather and climate events. The reason to have a suite of methods is two-fold: firstly, to have additional contextual information - different methods can provide e.g. likelihood vs extremity, and secondly to draw greater certainty from using methods that have different sources of uncertainty and levels of conditioning. Including a range of methods in this way will help provide a useful and robust attribution service.

However, with the use of more than one event attribution method comes the question of how to compare and communicate results that may not always align. Here we present attribution results from each of the methods and compare them. We will address questions around how each result (and uncertainty) can be compared to those from other quite different approaches. Given known associations, results from different methods (e.g. describing the influences from large-scale modes of variability such as ENSO) may also provide greater confidence in the results from other methods (e.g. enhanced precipitation due to very warm nearby waters). The extensive range of event attribution methods will also be considered – are there other methods that should also be included to make a complete suite for an attribution service?

Attribution of extreme weather events over Germany

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Deutscher Wetterdienst, Germany

Since 2019, Deutscher Wetterdienst (DWD) is actively developing a quasi-operational workflow for probabilistic extreme weather event attribution studies for Germany-affecting events. This quasi-operational approach contains analysis of observations and climate model data for temperature and precipitation. The primary objective is to automate as many steps as possible to communicate a statement for recent extreme events within days or weeks after it has occurred. In addition, this allows to attribute smaller extreme events with lower impacts.

A current field of research is the development of a fitting synthesis tool to combine the results of the different observation and climate model data sets to get a final statement for the investigated variable of different chosen extreme events. This synthesis has a huge impact on the given statement and communication after the extreme events. Depending on the approach and uncertainty the synthesis can lead to different results while relying on the same model output. Here it is crucial to find a consistent procedure which can be used for the different types of extreme events to get comparable attribution results.

This poster will focus on the attribution workflow at DWD, recent attribution studies like the flooding in Lower Saxony in December 2023 and state-of-the-art synthesis approaches.

An attribution atlas for Aotearoa New Zealand

Dáithí A. STONE[1], David Frame[2], Luke Harrington[3], Greg Bodeker[4], Trevor Carey-Smith[1], Sam Dean[1], Nathanael Melia[5], Suzanne Rosier[1], Belinda Storey[6]

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We present a product that summarises the current understanding of the human role in recent extreme weather over Aotearoa New Zealand. The basic format is of an underlying table of assessments details, supporting a series of national maps with various layers running from detailed documentation of evidence, to summaries of evidence, to summaries accompanied by relevant maps of vulnerability. We describe how this product has been developed, translating a colleciton narrow quantitative studies into a general qualitative synthesis. We also discuss how the altas is intended to be used as well as experience in using it as a communication tool.

Session 09: EVA methods and theory (oral presentations)

Extreme value analysis methods and theory for climate applications

Flood risk modelling using geometric extreme value theory

Ioannis Papastathopoulos[1], Lambert De Monte[1], Ryan Campbell[2], Haavard Rue[3]

[1]University of Edinburgh, United Kingdom; [2]Lancaster University; [3]King Abdullah University of Science and Technology, Saudi Arabia

Extreme value theory (EVT) is a branch of probability and statistics concerned with the estimation of the probability (and the characterisation of the behaviour) of rare events of possibly unobserved magnitudes. This presentation will briefly discuss a new Bayesian methodology from the recently emerging "geometric" EVT framework and then focus on applications to the modelling of 1) extremes of river flows in rivers Pang and Windrush, both tributary to the Thames in England, and of 2) ocean level heights in relation to dyke design in Newlyn, England, both in the context of flood risk assessment.

The approach exploits new theory results for the limiting distribution of the radial part of a radial-angular decomposition of a multivariate random vector of interest, and for the distribution of directions in the multivariate space—the angular part—along which radial extremes occur. The proposed statistical inference methodology offers great flexibility in modelling various dependence structures and enables a coherent inclusion of uncertainty sources in the modelling procedure. Joint work with Ioannis Papastathopoulos, Ryan Campbell, Håvard Rue.

An appraisal of the value of simulated weather data for quantifying coastal flood hazard in the Netherlands

Cees DE VALK, Henk van den Brink

Royal Netherlands Meteorological Institute, Netherlands, The

With recently updated safety norms, assessment of flood safety in the Netherlands requires return values for coastal sea level and surface stress for a wide range of return periods up to 10M years. Estimates from measurements are highly uncertain, as we will demonstrate.

A possible solution could be to replace measurements by simulated weather datasets much larger than a typical measurement record. However, systematic errors can easily outweigh any gains in precision.

Piecing together elements from extreme value theory, physics and evidence from data, we argue that even as stress from present-day weather prediction models may be too high or too low, these data are suitable for estimating the shape of the upper tail of the distribution function of stress, and that this extends to simulated data of water level along the Dutch coast.

As scale and offset can be estimated with sufficient precision from relatively short measurement records, we estimate return values from a combination of simulated data from the SEAS5 seasonal ensemble forecast archive of ECMWF and surge/tide modelling (at least for shape) and measurements (for scale/offset), assess their uncertainties, and discuss strengths and limitations of the approach and prospects for further exploiting simulated weather data to assess flood risk.

Asymmetric dependence in hydrological extremes

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In the last decades, increasing attention has been put on the study of complex extreme events generated by the intercorrelation of multiple variables. Extreme events at regional scale, such as floods, droughts, or heatwaves, can be caused by the interactions of climate/hydrological variables, or can be influenced and amplified by large scale climate patterns such as the El Niño-Southern Oscillation. Compound climate or weather events are complex events generated by multiple variables (or hazards) that interact across multiple spatial and temporal scales. An example of flooding due to a compound event is the occurrence of heavy precipitation on saturated soil or on frozen ground. Similarly, the cooccurrence of heavy precipitation and storm surge increases the coastal flooding probability . Temporal and spatial clustering of precipitation is shown to increase the flood risk in several case studies around the world .In all these examples is important to study and model correctly the dependence and causality relationship among extremes. Extremal dependence describes the strength of correlation between the largest observations of two variables. It is usually measured with symmetric dependence coefficients that do not depend on the order of the variables. In many cases, there is a natural asymmetry between extreme observations that cannot be captured by such coefficients. An example for such asymmetry is large discharges at an upstream and a downstream stations on a river network: an extreme discharge at the upstream station will directly influence the discharge at the downstream station, but not vice versa. Simple measures for asymmetric dependence in extreme events have not yet been investigated. We propose the asymmetric tail Kendall's τ as a measure for extremal dependence that is sensitive to asymmetric behaviour in the largest observations. It essentially computes the classical Kendall's τ but conditioned on the extreme observations of one of the two variables. Our results show that there is important structural information in the asymmetry that would have been missed by a symmetric measure. Our methodology is an easy but effective tool that can be applied in exploratory analysis for understanding the connections among variables and to detect possible asymmetric dependencies.

A statistical test for changes in compound extreme events

Sebastian ENGELKE[1], Philippe NAVEAU[2], Chen ZHOU[3]

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Many effects of climate change seem to be reflected in the frequency and severity of extreme weather events. The most serious climate-related disasters are often caused by compound events that result from a combination of several drivers. Detecting changes in size or frequency of such compound events requires a statistical methodology that efficiently uses the largest observations in the sample. We propose a simple, non-parametric test that decides whether two multivariate distributions exhibit the same tail behavior. The test is based on the entropy, namely Kullback--Leibler divergence, between exceedances over a high threshold of the two multivariate random vectors. We study the properties of the test and further explore its effectiveness for finite sample sizes. We apply the method to test whether the extremal dependence structure of certain compound events has been affected by climate change.

Conditional Decomposition Approach for Modeling Multivariate Extreme Events

Whitney HUANG

Clemson University, United States of America

The class of max-stable models is commonly used for modeling multivariate and spatial extremes. Despite recent advancements in its model construction and implementation, a fundamental limitation persists in incorporating timing information for extreme events due to the "component-wise maximum" data selection process. Such a limitation can lead to inaccurate assessments of multivariate and spatial extreme risk. In this talk, I will present a conditional approach to model multivariate extremes, aiming to capture extremes under the event level by conditioning on the timing and the corresponding vector values when at least one variable is extreme. The proposed approach shares some similarities with the conditional extreme value models developed by Jonathan Tawn and his collaborators, but with a different treatment for modeling the conditional distribution of the concomitant variable(s) given that the conditioning variable is extreme. Specifically, the conditional distribution function is modeled by a composition of distribution functions where an extreme value base distribution is enriched by a conditional beta distribution. Simulated examples and an application of bivariate concurrent wind and precipitation extremes will be used to illustrate the proposed approach.

Robust extreme value analysis by semiparametric modelling of the entire distribution range

Frank KWASNIOK

University of Exeter, United Kingdom

Traditional extreme value analysis based on the generalised extreme value (GEV) or the generalised Pareto distribution (GPD) suffers from two drawbacks: (i) Both methods are wasteful of data as only block maxima or exceedances over a high threshold are used and the bulk of the data is disregarded, resulting in a large uncertainty in the tail inference. (ii) In the peak-over-threshold approach the choice of the threshold is often difficult in practice as there are no really objective underlying criteria. Here, two approaches based on maximum likelihood estimation are introduced which simultaneously model the whole distribution range and thus constrain the tail inference by information from the bulk data. Firstly, the bulk matching method models the bulk of the distribution with a flexible exponential family model using polynomial, spline or trigonometric basis functions, and the tail with a GPD. The two distributions are linked together at the threshold with appropriate matching conditions. The method becomes insensitive to the choice of the threshold. Secondly, in the extended generalised Pareto distribution (EGPD) model for non-negative variables the whole distribution is modelled with a GPD overlaid with a transition probability density which is again represented by an exponential family. Appropriate conditions ensure that the model is in accordance with extreme value theory both for the lower and upper tail of the distribution. This approach completely avoids the choice of a threshold. The methods are successfully exemplified on simulated data as well as wind speed and precipitation data. Compared to the classical GEV and GPD analyses, the new techniques provide more accurate estimates of extreme quantiles with a smaller uncertainty associated to them.

Development of a global empirical-statistical framework for the probabilistic assessment of wildfire risk in a changing climate

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As major natural hazards, wildfires pose a significant risk to many parts of the world. The occurrence of extensive fires in both hemispheres in recent years has raised important questions about the extent to which the changing nature of such incidents can be attributed to human-induced climate change. Offering reliable answers to these questions is essential for communicating risk and increasing resilience to major wildfires. However, the scarcity of wildfire attribution studies, combined with limited observational records and the complexity of representing fires by different models, poses a challenge in establishing robust and unified conclusions to better inform future forest management strategies.

Here, a globally applicable framework is developed to better understand and quantify how wildfire risk is responding to a changing climate. The framework is based on an empirical-statistical methodology, facilitating its application to 'fire weather' extremes from both observational records and the latest generation of global climate model ensembles from CMIP6. We assess trends in extremes in the Canadian Fire Weather Index (FWI) using extreme value distributions, fitted with both annual maxima and peaks over a pre-defined threshold, and scaled to global mean surface temperature. Particular attention is given to the sensitivity of the eventual findings to the spatial scale of the event, the way in which (extreme) fire weather is defined and the climate models used in the analysis. As part of a global analysis, a series of maps are constructed detailing the change in likelihood of fire weather extremes, defined by both intensity and duration, throughout the world's fire-prone regions, as a result of rising global temperatures. Both observation- and model-based analyses reveal an increase in likelihood of at least twofold across many parts of the world, with considerable regional and inter-model variation. The conclusions drawn from this work provide a platform to guide future analysis of fire weather events, in addition to facilitating reliable recommendations for wildfire response and enhancing resilience in the face of climate change.

Linear regression for mutlivariate extremes with application to climate sciences

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Linear regression is an ubiquitous topic in statistics. It is taught in all introductory courses in statistics and it has been applied to most known research fields. Its popularity is due to the simplicity of the problem at hand and the elegant properties of the solution. The basic problem is to establish a possible linear relationship between a random variable of interest denoted Y and a set of so-called explanatory variables set, say X. Still, climatologists and hydrologists do not have a simple regression tool to find linear relationships in multivariate extremes. Leveraging recent results concerning the multivariate generalized Pareto distribution, we propose a framework to treat the question of finding the optimal regression parameters when (Y, X) follows a generalized Pareto distribution.A fast algorithm is also derived and apply to climate extremes problems, in partciular compounds events.

Integration of physical bound constraints to alleviate shortcomings of statistical models for extreme temperatures

Robin NOYELLE, Yoann ROBIN, Philippe NAVEAU, Pascal YIOU, Davide FARANDA

LSCE, France

Heatwaves have devastating impacts on societies and ecosystems. Their frequencies and intensities are increasing globally with anthropogenic climate change. Statistical models using Extreme Value Theory (EVT) have been used for quantifying risks of extreme temperatures but recent very intense events have cast doubt on their ability to represent the tail probabilities of temperatures. Using outputs from a large ensemble of a climate model, we show that physics-based estimates of the upper-bound of temperatures in the mid-latitudes are 3–8°C higher than suggested by EVT-based models. We propose a new method to bridge the gap between the physical and statistical estimates by forcing the EVT-based models to have an upper bound coherent with the bound provided by the instability of the air column. We show that our method reduces the underestimation of tail risks while not deteriorating the performance of the statistical models on the core of the distribution of extreme temperatures.

Simulation of Extreme Events in Climate Models with Rare Event Algorithms

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The study of extreme events is one of the main areas of application of numerical climate models. Events like heat waves, floods or wind storms, as well as state transitions related to tipping elements of the climate system, can have huge impacts on human societies and ecosystems. Studying rare events and transitions on a robust statistical basis with complex numerical climate models is however computationally extremely challenging, as very long simulations and/or very large ensembles are needed to sample a sufficient number of events to have a reliable statistics. This problem can be tackled using rare event algorithms, numerical tools designed to reduce the computational effort required to sample rare events in numerical models. These methods typically take the form of genetic algorithms, where a set of suppression and cloning rules are applied to the members of an ensemble during the simulation, in order to oversample trajectories leading to the events of interest. Here we show recent applications of one of these algorithms to three different classes of events: 1) heat waves and warm summers in the Northern hemisphere, 2) extremes of Arctic sea ice reduction, and 3) the weakening and collapse of the Atlantic Meridional Overturning Circulation. We show how the rare event algorithm allows to efficiently sample events where the persistency of a specificic quantity is a key element of the dynamics of the extreme or transition. This allows to estimate return values for events with return times up to hundreds of thousands of years, with computational costs two to three orders of magnitude lower than what would be needed with direct numerical simulations. We compare the results with estimates based on Extreme Value theory, and we analyse the physical and dynamical properties of the trajectories leading to the extreme events. Finally we discuss how these results open the way to further applications to a wide range of problems, including seasonal to decadal predictions and climate change attribution.

What are the hottest events between now and the end of the century?

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Anthropogenic climate change is increasing the frequency of extreme heat waves, which can cause significant environmental, human, and material damage.

An important type of heat wave is the humid heat wave, where high temperatures are combined with high humidity. When these two variables are simultaneously high, the ability of humans (and other living organisms) to cool themselves by sweating becomes difficult - if not impossible - as the air is already saturated with water. This leads to significant excess mortality due to hyperthermia.

The method published in [1] uses Bayesian analysis to estimate the laws and statistics of extreme events. The statistical synthesis of climate model ensembles (CMIP6) serves as a prior of reality, which is then constrained by ERA5 observations. We thus obtain the statistics for extreme events between 1850 and the end of the 21st century, as they correspond to observations over the observed period, and to models compatible with observations over the rest of the period.

This method was originally developed for the attribution of extreme events. We extend it to the multi-scenario case (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) and use it to estimate the statistics of the strongest events (in terms of maximum temperature and heat-index [2]) likely to occur by the end of the century over India and Europe.

[1] Y. Robin and A. Ribes, "Nonstationary extreme value analysis for event attribution combining climate models and observations," Adv. Stat. Climatol. Meteorol. Oceanogr., vol. 6, no. 2, pp. 205–221, Nov. 2020, doi: 10.5194/ascmo-6-205-2020.

[2] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, and B. Tinz, "Comparison of UTCI to selected thermal indices," Int. J. Biometeorol., vol. 56, no. 3, pp. 515–535, May 2012, doi: 10.1007/s00484-011-0453-2.

Modeling moderate and extreme urban rainfall at high spatio-temporal resolution

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Precipitation modeling is of great interest for flood risk analysis, especially when considering urban environments. Our study focuses on the use of rainfall measurements from the Montpellier Urban Observatory rain gauge network over four years, capturing precipitation at a high spatial and temporal resolution. We combine this dataset with the COMEPHORE radar reanalysis data from Météo France, which allows us to extend our analysis over a longer period but with a less fine spatio-temporal resolution. In our modeling approach, we simultaneously consider moderate and intense rainfall events by using the Extended Generalised Pareto Distribution (EGPD) to avoid explicit threshold selection, which is often difficult in extreme statistics, and to reduce the complexity of parameter estimation. In addition, we model the spatio-temporal dependence by integrating advection through a spatio-temporal Brown-Resnick process. We use indices of extreme autocorrelation to show the variability between pairs of locations and temporal lags. By contrasting our dependence model with a simpler separable model, we will highlight the importance of including advection.

Session 09: EVA methods and theory (poster presentations)

Extreme value analysis methods and theory for climate applications

Optimizing the process of ensemble boosting using tailored iterative algorithms

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ETH Zurich, Switzerland

The extreme record year 2023 showed not only unprecedented global mean warming, but also a number of exceptional extreme events such heatwaves, droughts, floods and wildfires. Since the probability of such unprecedented record-shattering extremes increases with the rapid rate of warming, there is a crucial need for analyzing the underlying processes leading to these events and quantifying potential intensities of events in the coming decades.

Here, we evaluate how the process of ensemble boosting (Gessner et al. 2021 and Gessner et al. 2022) can be optimized with respect to time and computational resources. Ensemble boosting consists in re-initializing the most extreme simulated events in an intermediate-size initial condition ensemble, thus efficiently sampling very extreme states of the model climatology. However, several of its parameters – like the selection of events to boost, the number of boosted cases per event and the exact timing of the re-initialization – have so far been determined somewhat arbitrarily.

Since the desired outcome of the ensemble boosting process depends on the research question posed, these parameters can be tuned to achieve tailored results. Here, we explore how an iterative algorithm, choosing where to boost next based on previous boosted events, can find optimal configurations of parameters for efficient boosting. The resulting boosted events can then be analyzed to interpret the underlying mechanisms of each unfolding extreme event. This can, in turn, inform how different parameter tuning could result in differently driven heatwaves.

Large Scale Influence on Extreme Precipitation

Felix S. FAUER, Henning W. Rust

Freie Universität Berlin, Germany

Extreme precipitation and flooding events in middle Europe lead to high death tolls and huge existential and financial losses. Evaluating how the probability of such events changes with respect to climate change can help preventing casualties and reducing impact consequences. We create Intensity-Duration-Frequency (IDF) curves which describe the major statistical characteristics of extreme precipitation events (return level, return period, time scale). They provide information on the probability of exceedance of certain precipitation intensities for a range of durations and can help to visualize how extreme the event for different durations is. We modeled the underlying distribution of block maxima with the Generalized Extreme Value (GEV) distribution. Maxima from different durations are used and enable a model that can evaluate different time scales. All durations are modeled in one single model in order to prevent quantile-crossing and to assure that estimated quantiles are consistent.

The influence of climate change is included by letting the GEV parameters depend on the variables NAO, temperature, humidity, blocking and year (as a proxy for climate change). We found an increase in probability of extreme precipitation with year and temperature, while the effect of the other variables depends on the season. Since it is easier to project average values than to

project extremes, we use the relations between average large-scale covariates and extreme precipitation to create future IDF-relations based on climate projections and the projected average large-scale values. This poses some challenges because the polynomial dependencies of the past might not hold for an extrapolation into the future. Furthermore, we plan to add a spatial component to the model that enables the usage of data from several neighboring stations in one model and interpolate to ungauged sites. This will be the basis for investigating how gridded data sets can be used to complement the station-based approach. One focus will lie on the challenge of dependence between neighboring grid points.

Attribution of global fire weather extremes using UK Earth System Model

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In recent years, the occurrence of a series devastating wildfire events around the world has raised considerable public concern about how climate change is altering meteorological conditions conducive to such events. The relative scarcity of wildfire attribution studies, coupled with the limited observational record, has added to the difficulty of developing reliable collective conclusions for future forest and wildland management strategies. Recent work has discussed the uncertainties and sensitivities associated with the choice of meteorological indicator to represent fire weather and the validation of climate model ensemble in the context of extreme event attribution, but the value of linking the attribution of wildfire events with future risk assessment has not yet been fully explored.

As a part of the TerraFIRMA project, funded by the UK's National Centre for Earth Observation, this study will continue employing a well-established probabilistic framework based on extreme value theory to present the findings of wildfire attribution. Advanced models of the coupled Earth system, particularly focusing on the UK Earth System Model (UKESM; including a new configuration of UKESM2) will be utilized, with the use of transformational Earth Observation (EO) data and techniques in the model to address Earth system science. Fire weather extremes, represented by Canadian Fire Weather Index (FWI) and its new developments, are fitted to advanced statistical models (e.g. generalized extreme value distribution and generalized Pareto distribution) and scaled to the global mean surface temperature. Probability ratios are used to quantify the influence of rising global temperatures on the changing frequency of FWI extremes for past, present and future climates. Through this approach, the study aims to deliver attribution analysis results at a global scale and for a series of recent high-impact wildfires, conducting reliable assessments of the risks and impacts of future climate change. This will aid in understanding the societal and environmental impacts of global climate change, along with providing robust information on mitigation options to limit its effects to stakeholders.

Validation study for modeling extreme precipitation using a Bayesian hierarchical framework

Alexander Lee RISCHMÜLLER, Benjamin Poschlod, Jana Sillmann

University of Hamburg, Germany

This study investigates extreme precipitation events using a 50-member large ensemble from the Canadian Regional Climate Model (CRCM5). For the period 1980-2019, this results in 2000 annual maxima samples enabling us to derive "true" effective return levels from the empirical data. We create 100 random subsets of 41 years with the aim to estimate tail extremes and reproduce the effective return levels. Our analysis utilizes four distinct statistical models to estimate the generalized extreme value (GEV) distribution parameters for extreme precipitation events across various durations and localities. As baseline model, we devise the standard GEV using L-moments estimated separately for each duration and locality (GEV-Lmom). Additionally, we apply a duration-dependent approach with fixed shape parameter over durations with parameter estimation via maximum likelihood estimation (dGEV-MLE). As a novelty, we introduce two Bayesian hierarchical GEV models, with the first (dGEV-BHM-1) employing a fixed shape parameter across localities and a hierarchical approach over durations, and the second (dGEV-BHM-2) adopting a hierarchical shape parameter across both durations and localities. . Our findings reveal that BHM-1 significantly reduces relative error in 100-year return levels when physical characteristics across localities are consistent. While the static GEV-Lmom model shows the best goodness-of-fit (GoF) among all models, BHM-1 outperforms other duration-dependent models in terms of GoF, suggesting its potential as a robust approach for constructing intensity-duration-frequency (IDF) curves. This research highlights the critical importance of choosing suitable modeling techniques that align with the physical characteristics of the study area. Borrowing information across durations and localities plays an important role, underscoring its significance in enhancing the accuracy and robustness of estimating tail extremes.

The social psychological attribution of event attribution

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The past decade has witnessed the growth of a new field of research diagnosing the human role in specific extreme weather events. As with many touted climate services, the motivations for event attribution research appear myriad, including supporting international climate justice, domestic climate justice, public awareness, and climate understanding. But what is actually motivating the research? We report on a social psychology attribution analysis of a collection of almost 200 event attribution studies, examining properties of the topics, results, authorship, and funding, including trends over the past decade. Amongst other findings, we conclude that so far the implicit purpose of event attribution research has been to inform mitigation policies, and not to inform adaptation or loss and damage policies.

Session 10: Changes in extremes (oral presentations)

Changes in extremes including temperature, hydrologic, and multi-variate compound events

Heat waves trends and patterns in West Africa: definitions and drivers

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Heat waves increasingly capture global attention due to their severe impacts on humans, health, ecosystems, and economies. In recent years, there has been an increasing interest in studying heat waves due to their potential intensification under global climate change. While various regions worldwide have received substantial attention for their heat waves, research in Africa has been relatively limited, despite its vulnerability to such extreme occurrences. West Africa particularly remains in the shadows of discourse surrounding heatwaves. This situation is compounded by the absence of a well-defined threshold for characterising heat waves in West Africa, underscoring the necessity for an approach tailored to the region's context. In this study, we explored the dynamics of heat waves in West Africa using different heatwave indices. In this study, we inventory heat wave events across West Africa over 40 years using several widely used heat wave definitions. We consider the expression of these different definitions in West Africa, and we further examine the prevailing meteorological dynamics associated with each. The results of this study will offer valuable insights into the frequency, intensity, duration, and spatial distribution of heat wave events. These findings can inform policymakers, urban planners, and public health authorities in developing targeted strategies to mitigate the impacts of heat waves and enhance the region's adaptive capacity.

Designing life levels of Extreme Temperature by 2100

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In a context of climate change, design levels for environmental extremes have to be redefined.

This work describes a new Bayesian methodology to design life levels in a non-stationary context, with an application to extreme temperature excess by 2100 at a local scale.

The usual risk indicator, the annual return level, is only defined in a stationary context. Since it's defined as a level corresponding to an annual probability of excess, its value can't be defined for a period of interest. It is necessary to select another risk indicator able to cover an entire time period. The Equivalent Reliability, which defines the probability of the maximum event during the period, was chosen because its probability of excess over a period is the same as the total probability of excess over a period for a stationary return level (Liang 2016 et Hu 2018).

The method used to estimate the Equivalent Reliability is adapted from the statistical method by Robin and Ribes (2020). A generalized extreme value distribution is used, where the non-stationarity in the parameters is given by a covariate, the European annual mean temperature, as a proxy of climate warming. To estimate the parameters, this Bayesian framework uses a prior based on Global Climate Models output which is then constrained using local meteorological observations. An estimation of the posterior parameters' distributions was produced using the No-U-Turn Sampler MCMC algorithm implemented in Stan (Holman 2014).

The predictive estimate, including uncertainty over the parameters' full distribution, was adapted to Equivalent Reliability. It accounts for a larger range of possible extreme values than the median estimate, while providing a unique value fit for design calculation.

An application was done on the Rhone Valley on France over the period 2050-2100.

Non-stationarity of the multi-temporal severity of meteorological drought in France

Juliette BLANCHET

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Droughts are recurrent phenomena that present a large variety of time patterns making rather difficult the assessment of their rarity and their non-stationarity.

This study analyzes how meteorological drought events build and persist across time and how these persistence has changed since 1950 in France. We consider the concept of "rarity curve" proposed in previous works allowing to analyze drought persistence over a continuum of durations. The approach is purely statistic, assuming that drought consequences depend on the probability of non exceedance ("rarity") of antecedent rainfall accumulations. In order to cover a large spectrum of "memory effects", we consider a continuum of accumulation periods ranging from a few weeks to several years. The rarity curve of a given year displays the most severe rarity values encountered during the year as a function of the various accumulation periods (256 values ranging from 4 to 260 weeks in our case).

We use a k-means algorithm to classify the different years into typical drought situations from continuous drying to continuous wetting over the antecedent five years. Assessing the non-stationarity in the frequency of the clusters allows studying how drought persistence in France has changed since 1950.

Extreme Temperature Indices Based on Satellite Land Surface Temperature Data

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Research shows that climate change is making extreme temperature events more likely. This work examines the potential use of satellite land surface temperature (LST) to augment information obtained from 2-metre air temperatures (T2m) measured at weather stations to monitor and characterise temperature extremes. The World Meteorological Organisation's (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI; now discontinued) and Expert Team on Sector-specific Climate Indices (ET-SCI) previously defined a number of extreme temperature and precipitation indices based on T2m measurements at weather stations (https://climpact-sci.org/indices/). These 'Climpact' indices have been used by the Intergovernmental Panel on Climate Change (IPCC) to establish how the frequency and duration of extreme events is evolving in a changing climate. However, their analysis is restricted to regions that are well-observed in situ, therefore leaving large parts of the global landmasses unassessed.

This study uses data from weather stations and the European Space Agency Climate Change Initiative for LST (LST_cci; https://climate.esa.int/en/projects/land-surface-temperature/) project to assess the consistency between LST and T2m for a selection of Climpact temperature indices. Satellites are not able to record the T2m but can be used to estimate the LST by measuring infrared (IR) or microwave (MW) radiation emitted from the Earth. Studies show that LST and T2m are often well coupled and that the temperature signals present in T2m data are also evident in the satellite LST record. Therefore, the hypothesis is that extreme temperature indices based on LST should show similar patterns and trends to those derived from T2m. The results of the study show that the LST and T2m are generally in good agreement for the value-based indices (correlation r ~ 0.96), e.g. monthly maximum value of daily maximum temperature (TXx), monthly maximum value of daily minimum temperature (TNx), etc, and percentile-based indices (r ~ 0.7), e.g. monthly percentage of days when daily minimum temperature < 10th percentile (TN10p), monthly percentage of days when daily maximum temperature > 90th percentile (TX90p), etc. However, there are substantial differences for the threshold-based indices, e.g. number of frost days (FD), number of summer days (SU), etc. In this case, the number of threshold triggers can be very different for LST compared with T2m. Using Kernel Density Estimation and Logistic Regression, this work attempts to find LST thresholds that are triggered in similar proportions to the Climpact T2m thresholds. Both statistical methods show promise, improving the mean precision or mean recall for some indices. However, obtaining improved thresholds for LST is very challenging for indices with very few events (or triggers), e.g. ≤ 40. Work is ongoing to define a final set of 'Climpact-like' LST indices that could be used in conjunction with T2m to monitor global temperature extremes with fewer geographical gaps compared with using T2m data alone. In addition, the LST data could potentially provide information at a higher spatial resolution (e.g. <0.25°) compared to gridded T2m (e.g. 1.25° x 1.875°), enabling the use of extreme temperature indices data in a wider range of climate applications.

Assessing Precipitation Intensity-Duration-Frequency Curves under Climate Change in Local Scale Catchments

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Potential changes in frequency and intensity of precipitation are a big concern specially under climate change conditions. This research investigates these changes by focusing on their implications for the construction of Intensity-Duration-Frequency (IDF) curves used in climate projections and infrastructure development. The study reveals the challenges arising when evaluating the adequacy of historical IDF curves in accounting for the non-stationarity of extreme rainfall. This requires the design of infrastructure capable of withstanding both current and future climate conditions. The research provides insights into the IPCC climate report's evidence about the validity of the Clausius-Clapeyron (CC) relationship, which suggests a 7% increase in precipitation per 1-degree Celsius increase in temperature. It further offers guidelines for adjusting IDF curves to accommodate future climate conditions. The study calculates extreme daily precipitation changes alongside temperature changes and scaling factors for small urban catchments in Barranquilla, Colombia, a tropical region, revealing a sub-CC relationship. The research extends its scope to a comparative analysis with Champaign, Illinois-USA, an inland city in the north temperate zone, which adheres to the CC relationship. The study concludes that the generalized 7% correction factor may not be universally applicable, emphasizing the need for local parameter calculations. This highlights the importance of understanding regional climate variations and their impacts on infrastructure development in the face of climate change.

Scaling of climate extremes after net zero CO2 emissions

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To prevent continued warming, we must reach a state of at least net zero CO2 emissions along with reductions in other greenhouse gases. In response to the demand to reach net zero CO2 emissions, researchers have investigated climate evolution post-net zero using Earth System Models. Strides have made in understanding global and regional climate change after net zero, but there is limited understanding of how climate extremes might evolve after net zero CO2. In our work, we explore how changes in extreme temperature and precipitation scale with changes in mean state climate before and after net zero CO2 emissions using a collection of Earth System Models included in the Zero Emissions Commitment Model Intercomparison Project. Our work will also investigate whether or not there are significant changes in the mean, variance and higher order moments of regional mean state and extreme temperature and precipitation after transition to zero CO2 emissions at multiple cumulative carbon emissions levels.

Increasing frequency, intensity, duration and areal extent of extreme precipitation events in Japan since 1900

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Different spatial extents of heavy precipitation events can lead to either flash floods or river floods that generally cause either greater loss of life or loss of property, respectively. In the past, there have been plenty of studies on physical mechanisms leading to rainfall extremes and how climate change affects these events. Due to more moisture available in a warmer climate, it is often assumed that the extreme precipitation should increase similarly if strong dynamical forcing associated with rainfall extremes remains the same. However, if the circulations and dominant weather systems producing heavy rainfall change in the warming climate, there might be additional changing characteristics of extreme precipitation events that require further studies. Using a Japanese high-resolution 5-km daily precipitation product for more than 100 years based on gauged network data from 1900 (APHRO_JP V1207), we investigate how the frequency, intensity, duration, areal extent, and total accumulated rainfall volume associated with the most intensive daily precipitation events change through time from an event perspective. We first identify all the heavy precipitation incidents with an event tracking algorithm. Different thresholds are used to define heavy rainfall events and test the sensitivity of the result to the extreme event definition and thresholds. After archiving all the extreme rainfall events, it is possible to make a ranking for all the historical events by total rainfall volume. From the event archive, We find that both the frequency and total volume of extreme rainfall events have increased significantly in Japan since 1900. The main contribution to the volume increase is from the larger spatial extent in more recent decades. We will discuss the implication of the potential change in flash and river flood events as a function of the warming. With the information on the spatial and temporal evolution of extreme events, it is possible to further study the associated weather system and environmental conditions that fueled the precipitation extremes. Also how the convection-permitting climate model can capture the observed characteristic of extreme rainfall from an event perspective can be examined further in detail.

Dependence of daily precipitation extremes on the temperature in China from observation to projections

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Previous studies showed that extreme precipitation in China has intensified due to global warming. Assuming relative humidity stay constant, the Clausius–Clapeyron (C-C) relationship indicates that global precipitation extremes increase with temperature at a rate of approximately 7% /°C, while it is also noted that the scaling rate is highly spatial heterogenous, and uncertain whether the binning scaling rates will remain constant in the future climate. Therefore, we investigated the dependency of daily precipitation extremes (P99, P90, and P75) on the temperature using both stational data and examined the temporal consistency of the dependency with CMIP6 simulations. We found that the peak structure and sub C-C scaling (0%/°C-5%/°C) were dominant in China. The scaling rates exhibited a “sub C-C, C-C like or super C-C, negative C-C” trend from southeast to northwest over China. The negative scaling of precipitation extremes in the western part of the northwest has been attributed to the dry temperate continental climate; insufficient moisture under high temperatures decreases extreme precipitation intensity. We further found that the binning scaling rates have stability in the future but with a large increasing trend (more than 30%) in southeast China from the 2060s and beyond under the SSP5-8.5 scenario. Our study may provide the possibility to constrain future extreme precipitation predictions with C-C scaling.

Constraining decadal variability regionally improves near-term projections of hot, cold and dry extremes

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Hot, cold and dry meteorological extremes are often linked with severe impacts on the public health, agricultural, energy and environmental sectors. Skillful predictions of such extremes could therefore enable stakeholders to better plan and adapt to future impacts of these events. Such extremes are affected by anthropogenic climate change and modulated by different modes of climate variability. Here, we use a large multi-model ensemble from the CMIP6 and constrain these simulations by phasing in the decadal climate variability with observations. Hot and cold extremes are skillfully predicted over most of the globe, with also a widespread added value from using the constrained ensemble compared to the unconstrained full CMIP6 ensemble. On the other hand, dry extremes only show skill in some regions with results sensitive to the index used. Still, we find skillful predictions and added skill for dry extremes in some regions such as Western North America, Southern central and Eastern Europe, Southeastern Australia, Southern Africa and the Arabian Peninsula. We also find that the added skill in the constrained ensemble is due to a combination of improved multi-decadal variations in phase with observed climate extremes and improved representation of long-term changes. Our results demonstrate that constraining decadal variability in climate projections can provide improved estimates of temperature extremes and drought in the next 20 years, which can inform targeted adaptation strategies to near-term climate change.

Which regions are at risk for breaking precipitation records in the (near) future?

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Changes in the occurrence of record-breaking weather and climate events in a changing climate are highly societally relevant. An increasing occurrence rate of record-breaking events does not only mean more frequent extreme events, but also ever more intense extreme events. Since record breaking events are by definition unprecedented, they are more likely to exceed the levels infrastructure and emergency plans are designed for, and thus to incur significant damage and losses. For this reason, it is important to quantify the behaviour of record breaking in a changing climate for impact-related variables such as temperature, precipitation, wind, and drought.

We analysed the response of precipitation record breaking to climate change as simulated by climate models (CMIP6). Using extreme value distributions and analytical probabilities, we determine the theoretical evolution of record-breaking probabilities in our present and future climate. Our approach allows us to separate the effects of trends in the mean (distribution shift) and trends in variability (distribution widening/narrowing) on the changing record breaking probability, and we show that variability plays a large role for precipitation record breaking.

In addition, we compare theoretical precipitation record-breaking probabilities between 1950 and the present based on climate model simulations to the observed record breaking in the real world. Using quantile mapping, we identify regions where natural variability seems to have obscured the influence of climate change on record breaking. A measure of time-aggregated record-breaking probability, combining the time between records and the levels of the records, allows us to identify regions with extraordinarily low observed record breaking rate and levels given the theoretical expectation. These regions are at high risk for future record breaking.

Joint assessment of trends in the bulk and extreme precipitation using non-stationary extended generalized Pareto distribution

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Quantifying the impact of climate change on precipitation, particularly extreme precipitation events, is a challenging task due to the scarcity and high variability of such events. Current methods based on extreme value theory (EVT), which only consider a small portion of the available data, have limitations in modeling the bulk of the distribution. This has implications for water resources management, urban water supplies, and hydropower. To address these limitations, Naveau et al. (2016) proposed the Extended Generalized Pareto distribution (EGPD), which models the entire non-zero precipitation range and is consistent with EVT in both lower and upper tails. While the EGPD has been widely used to model precipitation in various regions, its application has mostly been limited to a stationary framework. This study aims to explore the potential of a non-stationary version of the EGPD to model both the bulk of the precipitation distribution and the extremes. The non-stationarity is accommodated by allowing the EGPD parameters to be parametric functions of relevant explanatory variables. The proposed model is applied to precipitation datasets in Switzerland, a region where long-term warming of twice the global average has already been experienced.

Unprecedented regional trends in extreme weather until 2040, even under strong mitigation

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Climate change is causing a range of weather phenomena to move outside the range to which people and ecosystems are adapted. Much attention has been given to absolute changes, such as average temperatures or changes to the return values of extreme events, with global warming. However, the rate of change, and how that compares to the rates of change experienced in the preindustrial climate, i.e. the amount of change we have previously experienced over a short time period, is also an important determinant of impacts, and yet has not been given as much attention. In particular, as climate extremes are responsible for a disproportionate share of impacts, society can be expected to be particularly vulnerable to high rates of change of extremes – especially when multiple hazards increase at once.

Using large ensembles of climate model simulations, we examine rates of change of temperature and precipitation extremes, both separately and combined, over the next twenty years (2021-2040) and compare with 20-year rates of change in the pre-industrial (PI) period. We consider regional scales, due to their increased relevance to the experience of people and ecosystems compared to global mean changes. We find that large parts of the tropics and subtropics, encompassing 70% of global population, are expected to experience unprecedented (>2 standard deviations of PI 20-year trend variability) joint rates of change in temperature and precipitation extremes combined over the next 20 years, under a high emissions scenario, dropping to 20% under strong emissions mitigation. This is dominated by temperature extremes, with most of the world experiencing unusual (>1 standard deviation) rates relative to the pre-industrial, with the clearest changes in low latitude regions, due to their small variability in temperature extremes. These tend to be low-income countries that are particularly vulnerable to the impacts of climate change. Unusual changes in rates also occur for precipitation extremes in northern high latitudes, South and South-East Asia and equatorial Africa. In low emission scenarios, the rates of change tend to flatten out in subsequent 20-year periods, but accelerate in the highest emissions scenarios.

Notably, we find that rapid reductions of anthropogenic aerosol emissions over the next twenty years in low emissions scenarios, mostly occurring over Asia, lead to accelerated co-located increases in warm extremes due to the compound effects of surface warming from greenhouse gas warming and loss of cooling from atmospheric aerosols. Indian summer monsoon precipitation is also affected.

These findings have important implications for climate policy, decision making and near-term adaptation strategies. However, despite the emerging signal of rapid 20-year rates of change, spread amongst ensemble members is nevertheless large, particularly in the mid to high latitudes, meaning that in the near-term, trends of the opposite sign are still likely for precipitation extremes, and are rare but not impossible for temperature extremes. This is also an important consideration to take into account when communicating these, and other, results on near-term decadal rates of change.

Compound climate events: can climate simulations be improved by bias correction?

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Some combinations of climate events, which are not necessarily devastating when isolated, can have devastating effects when they occur simultaneously or successively within a short period. These extreme climate events, called compound events (Zscheischler et al., 2020), correspond to interactions between climate variables presenting patterns of spatio-temporal and inter-variables dependencies.

To better understand their evolution in a climate change context, climate models, such as those involved in the "Coupled Model Intercomparison Project Phase 6" (CMIP6, Eyring et al., 2016), are used to get simulated data of a future climate. Due to numerical issues (discretization effects, low spatial resolution) or physical issues (parametrizations), climate models exhibit various biases in their marginal, spatial and inter-variable properties, which necessarily affect the representativeness of compound events. The outputs of the climate models need to be bias corrected with statistical methods (François et al., 2020).

In this work, the effect of some bias correction methods on the return period is assessed on two specific extreme compound events. The first one occurred in July 2021 over the Belgium-Germany boundary and involves daily precipitation and accumulated precipitation used as proxy for soil moisture (Mohr et al., 2022) The second one occurred in late spring 2016 over France and involves accumulated precipitation over two different areas: the Seine and Loire basins (Van Oldenborgh et al., 2016).

Using the extreme value theory, bivariate parametric models have been estimated for these two compound events, for ERA5 data (Hersbach et al., 2020) and 10 CMIP6 models. The return periods of these two events have been calculated and compared over a reference period between ERA5 and the simulations. A univariate bias correction method, CDF-t (Vrac et al., 2012), and some multivariate bias correction methods have been applied to the simulations, and the return periods have been compared, as well as their evolution until 2100. It is shown that bias correction methods lead to more accurate return periods over the historical period, while consistency between corrected and raw simulations in terms of future climate changes is not necessarily guaranteed.

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Understanding correlation of wind and precipitation annual aggregate severity of European cyclones

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The yearly cost of wind and flooding from European cyclones frequently reaches billions of euros. This study has investigated the correlation between wind gust and precipitation annual aggregate severity arising from extra-tropical cyclones over the Europe-Atlantic region using ERA5 reanalysis from 1980-2020.

Simple annual aggregate severity indices have been constructed by aggregating exceedances above chosen damage thresholds of wind gust speed maxima and precipitation totals for all storms in a year. At low thresholds, there is a strong positive correlation between wind and precipitation aggregate severity, likely induced by the common dependence on the total number of storms.

However, at higher thresholds, where the severity indices are expected to be a better reflection of wind and flood losses, negative correlations start to appear especially over western Europe. A correlation of -0.22 is observed between aggregate severity indices over France at thresholds of 20 m/s and 20mm. Furthermore, regions that experience positive correlation at these thresholds exhibit negative correlation values for sufficiently high thresholds.

This suggests that aggregate wind and flood losses in Europe should not be assumed to be either independent or positively correlated, and that there is a potential for risk diversification.

A statistical framework has been developed to better understand the negative correlation occurring at high thresholds. By treating collective risks as random sums, the framework uses the mean and variance of storm intensities and counts to model the correlation. Considering within and between year variance improves the framework and reflects how atmospheric conditions can lead to stormier or calmer years. The overall trend of the correlation being more positive over the ocean and closer to zero (and negative) over land is well captured by the framework.

A multi-variate measure of climate change emergence

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The emergence of a climate change signal relative to background variability is a useful metric for understanding local changes and their consequences. Studies have identified emergent signals of climate change, particularly in temperature-based indices with weaker signals found for precipitation metrics. In this study, we adapt climate analogue methods to examine multivariate climate change emergence. We use seasonal temperature and precipitation observations and apply a sigma dissimilarity method to analyse the multivariate time of emergence. We use this method to demonstrate that large local climate changes may already be identified in low-latitude regions. The multivariate methodology brings forward the time of emergence by several decades in some low-latitude locations. We observed particularly large departures from an early-20th century climate subsequent to El Niño years. The latitudinal dependence in the emergent climate change signal means that lower-income nations have experienced earlier and stronger emergent climate change signals than the wealthiest regions. Analysis based on extreme indices finds weaker signals and less evidence of emergence, but is hampered by lack of long-running observations in equatorial areas.

Regional climate change for East Asia and Europe based on homogenized daily observations

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Two datasets entitled "Homogenised monthly and daily temperature and precipitation time series in China during 1960–2021" and "Homogenised monthly and daily temperature and precipitation time series in Greece during 1960–2010" were developed based on MASH and Climatol method through the cooperation between China and Greece. These datasets provide the homogenised monthly and daily mean (TG), minimum (TN), and maximum (TX) temperature and precipitation (RR) records since 1960 at 366 stations in China and 56 stations in Greece. For China, the regional mean annual TG, TX, TN, and RR series during 1960–2021 showed significant warming or increasing trends of 0.27°C (10 yr)−1, 0.22°C (10 yr)−1 , 0.35°C (10 yr)−1, and 6.81 mm (10 yr)−1, respectively. Most of the seasonal series revealed trends significant at the 0.05 level, except for the spring, summer, and autumn RR series. For Greece, there were increasing trends of 0.09°C (10 yr)−1 , 0.08°C (10 yr)−1, and 0.11°C (10 yr)−1 for the annual TG, TX, and TN series, respectively, while a decreasing trend of –23.35 mm (10 yr)−1 was present for RR. The seasonal trends showed a significant warming rate for summer, but no significant changes were noted for spring (except for TN), autumn, and winter. For RR, only the winter time series displayed a statistically significant and robust trend [–15.82 mm (10 yr)−1]. The final homogenised temperature and precipitation time series for both China and Greece provide a better representation of the large-scale pattern of climate change over the past decades and provide a quality information source for climatological analyses.

Based on above two homogenized daily temperature and precipitation datasets, the temporal and spatial variations of 26 extreme temperature and precipitation indices for China and Greece since 1960were comparatively analyzed. Also, their association with atmospheric circulation types was evaluated using multiple linear regression. Extreme precipitation, intensity, and short-term heavy precipitation increased, while persistent heavy precipitation has decreased since 1960 in China. Short-term heavy precipitation has also shown an increasing trend in Greece, though total precipitation and persistent heavy precipitation decreased there between 1960 and 2010. Extreme cold events have tended to decrease, and extreme warm events have increased in both countries, a fact that can be attributed to global warming. For comparison, climatic warming in China was mainly seen in the half year of winter, while the extreme indices relevant to cold seasons such as FD0 and ID0 presented a small trend in Greece. The observed changes in many climatic indices, including RX5day and WSDI in China and R20MM, RX5day, CDD, PRCPTOT and FD0 in Greece, could be partly explained by those of the main large-scale circulation types in the corresponding regions. The significant multiple correlation coefficients of the main circulation types were up to 0.53 for RX5day and 0.54 for WSDI in China, and 0.74 for PRCPTOT and 0.71 for R20MM in Greece. The relationships between climatic indices and circulation types were closer in Greece than in China, especially for the precipitation indices.

Projections of Diverse ENSO Teleconnections with Extremes in CMIP6 models

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El Niño-Southern Oscillation is the dominant source of climate variability globally, with wide-ranging impacts on weather, climate, ecosystems, agriculture, and economies through its atmospheric teleconnections. The most devastating impacts of El Niño and La Niña events are felt through extreme weather events. The atmospheric response to ENSO, and its resulting impacts, can differ significantly depending on the location within the tropical Pacific where the event peaks, typically characterised by the location of maximum sea surface temperature (SST) variability. As a result, two distinct types of El Niño (and La Niña) events have been defined: Eastern Pacific (EP) and Central Pacific (CP). Despite the significance of this distinction, limited work has been done on understanding the impact of these diverse ENSO events on extremes.

In this study, we explore diverse ENSO teleconnections with extremes in the observational record as well as in global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6). We assess each of the model's ability to simulate ENSO diversity and its associated teleconnections using two established methodologies from the existing literature. One method uses SST anomalies from defined "boxes" within the tropical Pacific to derive two new indices distinguishing EP and CP events. The other method uses the first and second leading empirical orthogonal functions (EOF) to formulate an E-index and C-index for event identification. Our analysis examines projected regional changes to the teleconnections under future emissions

scenarios using the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report references regions. It also explores the sensitivity of results to the choice of method when defining ENSO events.

Systematic overview of circulation contributions to observed summer heat trends

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Heat waves are weather extremes for which the direct influence of global warming is especially pronounced and well understood. Besides this thermodynamic forcing, as for other weather extremes, there are a number of additional effects that could contribute to trends in heat extremes on the local and regional level. For instance, heat extremes strongly rely on favorable large scale atmospheric circulation patterns. Internal climate variability, or forced changes in atmospheric circulation, could therefore considerably affect trends in heat extremes in relatively short, observed time series. Consequently, an observed trend in a given location is the result of multiple contributions including thermodynamic forcing in response to greenhouse gas and aerosol emissions, and changes in circulation patterns and soil moisture, which may be partly forced and/or modulated by internal variability.

However, it is unclear whether state-of-the-art climate models capture the magnitude of different components of heat trends correctly, in particular with respect to trends in atmospheric circulation. Here, we systematically decompose local trends in heat indicators into three components: the direct effect of rising global mean surface temperatures (GMT), the effect of atmospheric circulation and the effect of soil moisture. The analysis is based on a multivariate ridge regression that we validate by comparing nudged circulation experiments with similar large scale circulation variability but different GMT trajectories. The validation is important to test whether the statistical setup correctly disentangles circulation-induced trends from thermodynamic trends. Decomposing drivers of summer heat around the globe helps to identify regions, where a considerable portion of the observed trend is not attributable to thermodynamic forcing. Comparing this decomposition between observations and climate models helps to understand why regional differences in changes in heat extremes are not well reproduced by climate models.

Time and period of emergence of compound events in France

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Compound events (CE) are the combination of climate phenomena which, taken individually, are not necessarily extreme but whose (concurrent or sequential) composition can cause very strong impacts and damages. The typology defined by Zscheischler [1] highlights four types of compound events: multivariate, temporal, spatial and pre-conditioned. The understanding of their potential past and future changes and evolutions are of great importance and, thus, more and more research is being carried out on this issue ([2], [3], [4]). However, these questions are still rarely addressed over France, especially at high spatial resolution, even though they are necessary for the development of adaptation strategies.

The present study focuses on historical multivariate compound events (several events occurring at the same time and same location), like hot and dry events or extreme wind and precipitation events, and aims to detect past changes in probability of such events over France. ERA5 reanalyses [5] are then used on the 1950-2022 period. The first question that arises is: Where and when did these signals emerge in France? Are patterns forming? This issue is addressed through the analysis of “times” and “periods” of emergence, corresponding to moments when the change in probability of a specific CE is out of its natural variability [6]. The second question that comes up is: “What drives the emergence? What are the contributions of the changes in the marginal distributions and in the dependence structure to the change of compound events probability?” The study tries to answer this question thanks to the copula theory, allowing to decompose these different contributions. Copula functions are used to model bivariate joint probabilities, and are increasingly applied to hydroclimatic variables ([7], [8], [9]).

Depending on the intensity and the type of the compound, the results indicate that (1) maps of time of emergence show clear spatial patterns and (2) that the changes in marginal distributions play a much more significant role than the changes in dependence during the emergence. This work opens perspectives for future projects, such as investigating physical phenomena driving these patterns and more deeply understanding changes in dependence between the different climate variables. Then analyzing climate model ability to reproduce the results would enable the application of the methodology to attribution framework and a better assessment of the risks associated with past and future climate change.

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Assessing irreversible increase of hot/dry and hot/wet compound extreme events in a post-net-zero climate

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Compound climate events that result from multiple climate drivers and hazards provoke more severe socioeconomic risk than univariate events. Understanding compound events is necessary to prepare for damage caused by them. In this study, the irreversibility of hot/dry (HD) and hot/wet (HW) compound events are analyzed using 11 CMIP6 models simulated under the SSP1-1.9 scenario which assumes reaching a net-zero CO2 emission around 2050 and a negative emission after that. First, univariate events are defined as 5-day mean daily maximum temperature (hot) and 5-day cumulative precipitation (wet) exceeding corresponding thresholds (99th percentiles) obtained from the current period (2007-2026). In dry events, 1th percentile of 90-day cumulative precipitation is used as a threshold. Compound events are defined as those exceeding thresholds of both variables at least once within the same month. We compared frequencies of HD and HW compound events in the late 21st century (2080-2099) of SSP1-1.9 scenario simulations with those from the current period, when CO2 concentration is decreased back to the current level. The results exhibit that HD events are simulated over the northwestern part of South America and Africa regions while HW events are mainly found in Eurasia and North America in the current period. Regional analyses based on 25 SREX domains indicate more frequent HD events relative to the present period in several sub-regions over northern South America and Africa. In contrast, HW extremes are found to be irreversible to current states in Alaska, Canada, North Asia, and East Asia, despite recovered CO2 concentrations. Sensitivity tests based on the periods with the same global surface air temperature (GSAT) indicate that the irreversibility of HW is mainly due to the irreversible response of temperature. However, HD frequencies are found to be less associated with GSAT, indicating a potential influence of local land-atmospheric feedback.

Statistical modelling of extreme rainfall over Aotearoa New Zealand

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Extreme rainfall in New Zealand, and how best to characterise expected changes in those extremes as the climate warms, is investigated using very large ensembles of regional climate model simulations at five different ‘epochs' of climate change (pre-industrial, present-day, and three future states at 1.5, 2.0 and 3.0 degC above pre-industrial). Different constructs of non-stationary Generalised Extreme Value (GEV) models are explored to determine which provides the most accurate estimates of extreme rainfall for the minimum model complexity. The different GEV model constructs vary the number of parameters (location, scale and shape) that are assumed to vary as climate changes, summarised as a linear dependence on Southern Hemisphere mean land surface temperature. Non-stationarity is also explored a different way, with a stationary GEV fitted separately within each of the five 'epochs'. These different models are applied to annual maximum one-day rainfall at eight locations around the country, chosen to be broadly representative of the various rainfall regimes countrywide. In situations with fair but not enormous sample sizes, such as with long historical records, the model in which only the location and scale, but not the shape, parameters vary with warming has the tightest sampling uncertainty without introducing substantial bias. According to this GEV model, 1-in-100-year rainfall increases with warming at all eight locations, ranging from about 5%/degC in most of the country to 8%/degC in the north. The change arises from an increase in the location parameter, with only a proportional increase in the shape parameter, consistent with extreme rainfall increases dictated by anthropogenic increases in specific humidity.

On the atmospheric background for the occurrence of three heat wave types in East China

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Compared with daytime (occurring only in daytime) and nighttime (occurring only in nighttime) heat waves (HWs), daytime-nighttime compound HWs (occurring simultaneously in daytime and nighttime) are highlighted to exert much severer impacts especially on human health. However, the physical mechanisms underlying compound HWs are poorly understood. Based on the observed maximum and minimum temperatures and NCEP/ NCAR reanalysis data, this article addressed the physical processes for the occurrence of compound HWs in East China, where compound HWs occur most frequently across China. Comparisons with those related to daytime or nighttime HWs were also performed. The results indicate that the occurrences of three HW types are all associated with anticyclonic circulation anomalies from the upper troposphere to the lower troposphere, whereas their locations and intensities determine the configuration of atmospheric conditions for different categories of HWs. The resultant less (more) cloud cover and humidity as well as increased downward shortwave (longwave) radiation at the surface favor the warming of daytime (nighttime), conducive to the occurrence of daytime (nighttime) HWs. The combination of above conditions associated with daytime and nighttime HWs, which helps the persistence of high temperatures from daytime to nighttime, benefits the occurrence of compound HWs. In addition, nighttime and compound HWs occur with the northwestward extension of the western Pacific subtropical high (WPSH), while it stays in the climatological location for the occurrence of daytime HWs. Further investigation suggests that daytime (nighttime) HWs are accompanied with an upper-tropospheric meridional (zonal) wave train propagating downstream from western Siberia (the east to the Caspian Sea). In comparison, the

wave train related to compound HWs shares the mixed features of daytime and nighttime HWs, characterized by a meridional wave propagation from the Scandinavian Peninsula to East China and then a zonal propagation toward the western Pacific.

Future shifts in timing of regional extreme precipitation

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Despite the high confidence in the overall intensification of the hydrological cycle in response to global warming, future changes in the spatiotemporal distribution of extreme precipitation remain uncertain. We here explore how climate change affects the seasonality and timing of extreme precipitation, which potentially alters its impact on society, economy and ecosystems substantially. Extreme precipitation events are defined as an exceedance of the all-day 98th percentile of daily precipitation.

Most of the CMIP6 models capture the historical timing of extreme precipitation compared to the REGEN observational data. With climate change, we find distinct regional shifts in extreme precipitation across models. The most pronounced signal is a distinct shift of extreme precipitation from summer into the shoulder seasons, spring and autumn, or even into winter at latitudes between about 45°N and 75°N in Eurasia and northeast America. These regions, which are climatologically characterized by extreme precipitation predominantly occurring during the summer, are projected to experience a strongly reduced fraction of extreme precipitation in summer during the second half of the 21st century.

Synoptic analysis indicates a combined effect of limited moisture supply and weaker updrafts during the core summer extreme precipitation events. Further analysis is required to disentangle the relative role of thermodynamic and dynamic contributions to impact-relevant changes in seasonality of extreme precipitation.

Increasing overlap of USA - Australia fire seasons poses challenges for firefighting cooperation

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The USA and Australia are members of an international partnership that shares firefighting resources, including equipment and personnel. This arrangement is possible because these regions have historically had opposing fire seasons. Climate change is bringing more intense and longer fire seasons to both nations, which could result in a greater fire season overlap. This would pose challenges for cooperation by reducing the window during which each nation could afford to lend resources to each other, potentially impacting the overall firefighting capabilities of each country.

Here we investigate how the fire season lengths in eastern Australia and western North America have changed in the past and are projected to change in the future. We use the Canadian Fire Weather Index to characterise the fire season, and compute season length statistics using reanalysis data together with historical and future projection runs from four CMIP6 single model initial-condition large ensemble models. We focus on the potential for spatially compounding fire weather, quantified as the number of days in each year during which the fire seasons of the two regions overlap.

We show how the length of the fire season in these regions has changed, with consequences for the frequency and degree of overlap in any given year. Furthermore, we show that the interannual variability of overlap may be weakly related to the El Niño Southern Oscillation, despite this mode of variability’s asymmetric relationship with fire weather in the two regions. Finally, we highlight how this overlap is projected to change in the coming decades, and how this might impact the current agreements for sharing resources.

Session 10: Changes in extremes (poster presentations)

Changes in extremes including temperature, hydrologic, and multi-variate compound events

A storyline of the intense Mediterranean heavy precipitation event and storm Alex occurring in 2022 instead of 2020, with warmer sea surface temperatures

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We employ convection-permitting regional climate modeling to analyze the intense Mediterranean Heavy Precipitation Event (HPE) in October 2020 in the south-eastern French and north-western Italian Alpine region, post passage of extra-tropical storm Alex. Although this mountainous Mediterranean region has experienced other damaging HPEs in the past, the intensity of the HPE in 2020 is exceptional. More than 600mm in 24 hours and 90mm in 1 hour were recorded in the French Alpes-Maritimes region. In France, this HPE caused severe flooding and landslides, killing at least 10 people, and leaving hundreds of people homeless. This observed extreme event will serve as a crucial benchmark for studying natural hydrometeorological hazards and their evolution in the context of climate change.

Exploring the event's sensitivity to warmer sea surface temperatures (SSTs), we conduct modeling experiments for September-October 2020 in western Europe. An ensemble-based approach is developed to comprehensively assess local uncertainties purely driven by internal variability.

Using the CNRM-AROME model, we accurately reproduce the HPE and precursor storm Alex characteristics, including the observed sequence of extreme events and related regional to local impacts. Sensitivity experiments are then conducted with idealized and uniform 2K warming and cooling patterns added to the SSTs over the entire domain and the Mediterranean Sea solely, all other forcings kept identical and representative of the 2020 observed conditions.

We find that SST warming intensifies the HPE's extremeness and accumulated precipitation amounts in the Alpine region. This is accompanied by a shift of the most intense precipitation eastward. In contrast, the strengthening of storm Alex with SST warming has limited impact on the Mediterranean HPE. Our findings underscore the crucial role of Mediterranean warming, enhancing moisture and instability upstream, and fostering deep atmospheric convection over the mountainous coastal region.

A storyline analysis is conducted by investigating a plausible worst-case scenario where the timeline of extreme events in 2020 would occur two years later, in 2022, with warmer Mediterranean SST conditions. This modeling experiment suggests milder precipitation-related impacts in the French Alpes-Maritimes region but increased damage in Italy.

Future risk of hyperthermia in French Guiana: assessing extreme values of Heat Index with multi-model analysis

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The IPCC's sixth report describes future climate scenarios which show increased moist heat across the entire tropical belt. Heat, coupled with high humidity, can lead to hyperthermia, i.e. an increase in body temperature above thresholds dangerous to human health. In the most severe cases, it can be deadly, even for young and healthy people.

The ongoing development of Global Climate Models and downscaling methods, both dynamic (Regional Climate Models) and statistical ones, allows us to analyze moist heat in medium-resolved climate projections. Guiana, a French overseas territory, is a coastal and equatorial land located in South America. Unfortunately, this small territory is covered by very few grid points from global models.

Here we show the projections for French Guiana of a thermal comfort index, the NOAA Heat Index, determined from a statistical downscaling of CMIP6 global models. The Heat Index, the temperature felt by a human being, is computed from daily temperature and relative humidity data. A previous study revealed that maximum temperature and minimum relative humidity are the best daily indicators for Heat Index computation in French Guiana.

Due to the geographical characteristics of French Guiana, as well as modelling errors, raw simulated data show significant biases and an Intertropical Convergence Zone shifted too far southward during the boreal winter, resulting in a bad representation of the wet season in French Guiana. Consequently, and using quality-controlled long series of observations from three stations in French Guiana, we perform monovariate bias corrections adapted to take account of non-stationarity due to climate change. Extreme moist heat events are characterized by levels and return periods calculated with Generalized Extreme Value distributions.

The intensity and frequency of moist heat extremes expected in French Guiana could increase massively by the end of the 21st century. With apparent temperatures sometimes exceeding 50°C, particularly under the most pessimistic scenario in terms of greenhouse gas emissions (SSP5-8.5), such levels would raise the question of the future of Guyanese energy consumption, due to the increased use of air conditioning.

Projected Changes in Hot, Dry, and Compound Hot-Dry Extremes Over Global Land Regions

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The impacts of hot, dry, and compound hot-dry extremes are significant for societies, economies, and ecosystems worldwide. These events therefore need to be assessed in the light of global warming so that suitable adaptation measures can be implemented by governments and stakeholders. Here we show a comprehensive analysis of hot, dry, and compound hot-dry extremes over global land regions using 25 CMIP6 models and four future emissions scenarios from 1950 to 2100. Hot, dry, and compound hot-dry extremes are projected to increase over large parts of the globe by the end of the 21st century. Hot and compound hot-dry extremes show the most widespread increases and dry extreme changes are sensitive to the index used. Many regional changes depend on the strength of greenhouse-gas forcing, which highlights the potential to limit the changes with strong mitigation efforts.

Attribution of extremes in the terrestrial carbon cycle

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Policymakers rely on the estimation of the terrestrial carbon sink for the calculation of the national carbon budgets. To ensure that the remaining budgets are in line with the chosen climate targets, it is important that changes to the land carbon sink induced by forced climate change (or by internal climate variability) are detected and attributed. However, the detection of a trends is a challenging task due to the short observation period and the high interannual variability of the carbon sink. Because infrequent but large negative carbon flux anomalies can undo the carbon sequestration of several years, we address the issue by focusing on the attribution of these extreme events. To determine to what part a negative carbon sink anomalies are due to internal variability and to what part due to climate change, we perform counterfactual simulations with the Community Earth System Model 2 (CESM2). We use observed circulation patterns from ERA5 wind fields to nudge CESM5 under different CO2 and aerosol forcing, and land use scenarios. This allows to disentangle not only the effects of climate change from internal variability, but also to find the direct contribution of different facets of global change to the extent of carbon cycle anomalies. We further evaluate how the temperature and drought anomalies of the same circulation events have changed under climate change and how much each variable has contributed to the intensification of carbon cycle extremes. With this work we want to provide the framework for the attribution of near-term carbon flux anomalies which eventually could be used to update national carbon budgets.

Analyzing 23 years of warm-season derechos in France: a climatology and investigation of synoptic and environmental changes

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Derechos are severe convective storms known for producing widespread damaging winds. While less frequent than in the United States of America (USA), derechos also occur in Europe. The notable European event on 18 August 2022 exhibited gusts exceeding 200 km h-1, spanning 1500 km in 12 hours. This study presents a first climatology of warm-season derechos in France, identifying thirty-eight (38) events between 2000 and 2022. Typically associated with a southwesterly mid-level circulation, warm-season derechos in France generally initiate in the afternoon and exhibit peak activity in July, with comparable frequencies in June and August. Predominantly impacting the northeast of France, these events exhibit a maximum observed frequency of 0.65 events per year, on average, within a 200 km by 200 km square region. These characteristics are similar to those observed in Germany, with notable differences seen in the USA, where frequencies can attain significantly higher values. The study also examines synoptic and environmental changes linked with analogues of the 500 hPa geopotential height patterns associated with past warm-season derechos, comparing analogues from a relatively distant past (1950–1980) with a recent period (1992–2022). For most events, a notable increase in convective available potential energy (CAPE) is observed, aligning with trends identified in previous studies for southern Europe. However, no consistent change in 0–6 km vertical wind shear is observed in the recent period. These environmental shifts align with higher near-surface temperatures, altered mid-level atmospheric flow patterns, and often, increased rainfall. The role of anthropogenic climate change in these changes remains uncertain, given potential influences of natural variability factors such as the El Niño Southern Oscillation (ENSO) or the Atlantic Multidecadal Oscillation (AMO).

Record-breaking and record-shattering extremes in a warming climate

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Recent heatwaves on land, marine heatwaves, precipitation extremes, melt rates in glaciers, sea ice minima, and even monthly global mean temperature anomalies shattered previous observed records by large margins and reached intensities that many would have conceived impossible based on observations so far.

Here, we review the observed and projected occurrence of univariate and multivariate records in a warming climate in the context of theoretical considerations of record statistics. We identify the most extreme record margins in recent decades across different time scales and show that many of them relate to events with great impacts on society and ecosystems.

Based on different observational datasets and reanalyses, we demonstrate that the observed record ratio, i.e., the frequency of all-time daily records relative to the theoretically expected probability in a stationary climate, is now about 3–3.5 for hot records and 0.2–0.4 for cold records, respectively. The record ratio for hot records is even higher over oceans than over land. In 2023, the highest global average record ratio of 5 was reached for hot extremes over land. Also, the global occurrence of daily heavy precipitation records and agricultural drought records is 30-40% and 20%, respectively, higher than expected in a stationary climate.

We demonstrate how these observed and projected record ratios as well as their space and time dependence can be understood with theoretical statistical considerations and reproduced by statistical time series models. The ratio of the long-term drift relative to the residual variance determines most of the record characteristics and explains how the record probability varies in space and across different time scales. We show that both the warming rate as well as changes in the residual variance are important factors explaining changes in record probability and record margins. We further extend this framework also for multivariate records, e.g., in co-occurring heat and drought.

Future projections reveal that even a slowdown of the warming rate would imply a reduction of the record probability. Stabilizing global mean temperature results in a rapid reduction of record probability and of record margins of hot records. Record margins of heavy-tailed distributions, on the other hand, even increase with time in a stationary climate.

Spatial return levels for meteorological variables, in climate change context

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Predicting return levels for extremes meteorological variables is critical for anticipation and adaptation to climate change. We aim at providing spatial return level surfaces for meteorological variables that take into account non stationarity induced by climate change and spatial dependence.

We extend the return level concept, usually defined pointwise, to spatial surfaces. A period P return level surface is a surface that is exceeded by a spatio-temporal process simultaneously everywhere in the study domain with probability 1/P. By analogy with the univariate theory of excesses above a threshold, we use the recent results on convergence of l-excesses of regularly varying processes to l-Pareto processes for spatial exceedances defined by a risk function l over the study domain.

Non stationarity is modeled through a marginal transformation by extended Generalized Pareto function varying in time. The spatial dependence is assumed stationary, and its inference is performed indirectly, using as auxiliary model, a Gaussian random field, esay to infer. Then we use these results to simulate exceedances of the process under study, and derive the return level surface empirically from these simulations. We express the period P return level as the Expected Number of Exceedances during period P according to the non stationary distribution function. The methodology is experienced on simulations of stationary and non-stationary max-stable processes and climate data for Burkina-Faso and France. In a climate change context, it provides spatial scenarios of potential future extreme temperature surfaces over the country.

Cluster of storms and insurance impact

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Clusters of storms are defined as spates of several storms within a short duration and and limited spatial extent. They are examples of compound events. Storms are known to be among the costliest events for Insurance in Europe, with an average annual insured loss of $3.3 billion [SCOR, 2023]. The repetition of such intense wind and strong precipitation events is no exception to the rule. The emblematic winter of 1999, characterized by the succession of Lothar and Martin, remains the costliest event ever observed in France with an estimated loss of €17 billion [EEA, 2023]. Despite the important risk that represent such events, only few studies have focused on such compound events.

The major risk of such hazard are the precipitation and the wind which can result in more damage, when they are confined in time. Here, we present a Lagrangian approach to characterize clusters of storms and study the amount and distribution of rain associated to these events. This approach is based on the analysis of [Dacre, Pinto, 2020] using an absolute frequency metric. It produces a catalogue of 230 events with two European storms succeeding in less than 48h since 1959.

Recent literature on this subject assumes that the total precipitation scales to the product of the number of events by the precipitation of each events. However, a significant amount of precipitation is under-represented with this hypothesis. Beyond the scaling assumption, we propose a method to represent and evaluate the potential impact of precipitation in a cluster of storms. This is evaluated in a recent case study that occurred in France. The approach is first tested on the ERA5 reanalysis. We then propose an application on climate model simulations.

Emergence of climate change signals in a CMIP6 multi-model ensemble of extreme indices

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Climate and weather extremes are becoming more and more frequent due to the influence of anthropogenic climate change. Knowing when and where we can expect these effects to occur is essential for both climate change mitigation and developing adaptation measures. A range of 27 indices for climate extremes related to surface temperature and precipitation have been defined by the Expert Team on Climate Change Detection (ETCCDI), which allow for a more comprehensive understanding of the characteristics of different kinds of hazards. We investigate the time of emergence - meaning the earliest time at which the climate change signal for these indices can be detected from the noise of natural climate variability – by applying the Kolmogorov-Smirnov statistical test to compare climate distributions along a 250-year timeline.

For the first time, an ensemble of 21 CMIP6 models (including several with a large number of initializations) is combined with a model weighting scheme that accounts for both model performance and independence to provide robust ensemble statistics of the emergence of climate extremes and to explore the between-model variability. We present results from this comprehensive study for several ETCCDI indices across IPCC AR6 climate reference regions and highlight different patterns, in particular related to absolute- vs. percentile-based indices and maximum vs. minimum temperatures.

Detection and characterisation of the compound drought and heatwave event of spring-summer 2022 in the Adige River catchment (north-eastern Italy).

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The Adige River catchment (north-eastern Italy) is one of the most important river basins in Italy. With a drainage area of 12,100 km2 and a length of 409 km is a crucial water reservoir for a variety of economic activities in northeastern Italy, especially agriculture and hydropower production. Here, we present our recent results on the detection and characterisation of past compound drought and heatwave (CDHW) events in the Adige River catchment. We identified drought conditions on a monthly basis through the Standardized Precipitation Index (SPI) at 3-, 6- and 12-month scales. Heatwaves were defined as periods of at least three consecutive days with daily maximum temperature (TX) above the 90th TX percentile for the calendar day computed over a 31- day running mean. The concurrence of both conditions was defined as a CDHW event if it affected at least 60% of the catchment area. Different datasets were considered for the description of surface meteorological situation, including local station observations, the European observation gridded dataset E-OBS and the ERA5-Land reanalysis. E-OBS was preferred to ERA5-Land, which showed a larger underestimation of dry conditions and, in general, a lower agreement with station data. Starting from the list of detected CDHW events in the period 1980-2022, we identified the large-scale atmospheric patterns based on the ERA5 reanalysis that triggered such concurrence of drought and heat conditions. In order to better assess the contribution of climate dynamics in modifying the occurrence probability of impactful CDHWs, we estimated the frequency trend of circulation conditions like the ones which led to the extreme event of spring-summer 2022, using the flow-analogue method and ERA5 500 hPa geopotential height data since 1940. The results obtained provided a basis for unravelling the role of large-scale circulation and warming conditions in altering the characteristics of CDHWs and related impacts on the complex region of the Adige River catchment.

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Trends in severity of heat waves: an added value of three-dimensional (3D) insight

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Heat waves are among the most studied hazards in relation to climate change due to their adverse effects on society and ecosystems. They have been commonly investigated using near-surface temperatures, not taking into account their vertical temperature profiles. In this study, we employed a recently developed approach to the analysis of heat waves as three-dimensional (3D) phenomena to evaluate the added value compared to conventional two-dimensional methods. Heat waves were studied using the ERA5 reanalysis in several densely populated mid-latitudinal regions in both hemispheres during the 1979–2022 period. Temperature anomalies at 12 pressure levels (from 850 to 300 hPa) were employed in addition to near-surface (2 m) anomalies to define and characterize heat waves. Based on prevailing location of temperature anomalies in vertical cross sections, heat waves were classified into four types: near-surface, lower-tropospheric, higher-tropospheric, and omnipresent. We showed that the characteristics (mean and maximum lengths, predominant intra-seasonal occurrence) of heat waves' types and their links to land-surface dryness (analysed thought SPI and SPEI indices) varied among regions, which contributed to spatially heterogeneous heat waves' trends.

Assessment of recent trends in climate extremes over Kano State, Nigeria using statistical techniques

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Extreme weather and climate events are wicked and disastrous. Unfortunately, the impact of these events is worsened by climate change caused by the increasing emission of greenhouse gases (GHG) in major urban cities globally. Kano, a metropolitan city in Nigeria with a population of over 4.1 million, has been experiencing recurring compound extreme weather and climate events that have resulted in significant economic and social losses. Despite rapid population growth in Kano State, little has been done to monitor these extreme climate events. To investigate the past and current trends of temperature and precipitation extremes, I utilized ten core indices recommended by the World Meteorological Organization's Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) and the Expert Team on Sector-Specific Climate Indices (ET-SCI) using the CHIRPS 2 AFRICA and NASA POWER daily precipitation, minimum, and maximum temperature dataset from 1980 to 2021.

RClimdex software and the ET-SCI Compact 2 web-based application were used to calculate the ten selected extreme event indices. To evaluate the consistency and statistical significance of daily compound trends (temperature and precipitation), the homogeneity test, Mann-Kendall (MK), and Sen's slope non-parametric tests were conducted. Interestingly, the results indicate significant warming trends across Kano State for all temperature indices during the study period with a decrease in cool nights, an increase in warm days, and more frequent warm spells. These trends could exacerbate heat island intensities, trigger heat waves, and worsen bioclimatic conditions within urban areas. I will present stakeholders' and communities' roles in dealing with the impacts of compound events in Kano, Nigeria

Keywords: Extreme events, ETCCDMI, ET-SCI, RClimdex, Climate change, Kano State.

Frameworks for considering extreme weather risks in future climates given major uncertainties

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How can we best apply our science to predicting risks of extreme behaviour in a system as complex as the climate? It would be desirable to be able to represent all of our knowledge about the risks so that it can be applied to enable effective decision-making. Risk assessments often consider only the range of behaviour displayed by climate models, but a substantial part of the risk seems likely to be due to the possibility of the real world veering outside this range. It will be illustrated how implicitly ignoring this component would lead to risks being systematically underestimated, and how multi-model and initial condition large ensembles can be misleading. Other approaches such as storylines illustrate potential ways to think beyond numerical model simulations, but sometimes downplay the quantification of event risks. Given that we generally lack clear bounds on how severe extreme events can be, there seems to be an open question of what magnitude of events are sensible to consider. Leaving risks unquantified also does not satisfy decision analysis methods that seek to quantitatively trade off protection against extremes against other benefits. This presentation considers how we can go beyond counting events in simulations, using tools such as climate models to inform our future projections without being constrained to ignore possible outcomes that they cannot simulate, whilst also retaining as much quantitative knowledge about event risks as possible and acknowledging when ambiguities become very large. Frameworks from philosophy and decision analysis will be surveyed and it will be discussed how these may help to show a way forward in our climate prediction predicament. It will be suggested that climate science should aim to be pluralistic in the knowledge frameworks it considers, to be of use to the broadest possible range of decision making.

Causes of 2022 Atypical Meiyu in Lower Yangtze River Basin: Subseasonal Perspective and Its Predictions

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In 2022, an atypical "hot-and-dry" Meiyu occurred in the lower Yangtze River basin (LYRB). Consequently, early summer precipitation of LYRB hit a near record low since 2006, while temperature reached a record high since 1979. We show that the 2022 Meiyu featured an early onset and a three-stage back-and-forth swing through LYRB, with two meridional rainband shifts: a southward withdrawal in early June and a northward leap in late June. The early-onset was jointly induced by enhanced Western Pacific Subtropical High (WPSH), active Northeast China Cold Vortex and intensified Bay of Bengal Trough. Influenced by active phases of the Boreal Summer Intraseasonal Oscillation and the "Cold Vortex-Heat Dome" (CVHD) pattern in northern East Asia, the rainband withdrew southward in early June and maintained in South China. Entering late June, an enormous upper-tropospheric anomalous anticyclone formed over western East Asia and caused a sudden northward displacement of the East Asian summer westerly jet, leading to a northwestward extension of WPSH and an abrupt northward leap of the rainband. Typhoon Chaba (2022) further pushed WPSH northeastward and the rainband into North China, bringing an end to Meiyu during its dissipation in early July. Two eastward-propagating intraseasonal wave trains along the polar front and subtropical westerly jets play crucial roles in triggering CVHD pattern and forming the upper-tropospheric anomalous anticyclone. La Niña-related persist positive sea surface temperature anomalies on the south of Maritime Continent provided a stable background for the strengthened and riveted WPSH in the first two stages. Three subseasonal forecast models predicted rainband positions well in the first and third stage, but overestimated LYRB rainfall in the second stage, which may be associated with poor predictions of the two intraseasonal wave trains and CVHD pattern. These results highlight the cooperative effects of tropical and extratropical intraseasonal variabilities in extreme Meiyu events.

Session 11: Global to regional impacts (oral presentations)

From global change to regional impacts, downscaling and bias correction

Detection of Anthropogenic Impacts on Snowpack Variability in Western US.

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Snowpack in the Western US plays a pivotal role in regional water resources, supporting a wide range of socio-economic activities. Anthropogenic climate change is inducing shifts in temperature and precipitation patterns, introducing changes in snowpack variability across the region. This study utilizes the Variable Infiltration Capacity (VIC) hydrology model, driven by bias-corrected spatial disaggregated CMIP6 model simulations, to generate high-resolution snow water equivalent data. The analysis aims to discern the fingerprint of anthropogenic climate change on snowpack variability in the Western US. Through the utilization of a multi-model ensemble approach, we seek to elucidate robust signals from internal variability, providing valuable insights into the specific impacts of climate change on snowpack dynamics in this critical region.

Evolution of high-temperature extremes over the Euro-Mediterranean region and its impact on aircraft takeoff performance

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Extreme heat conditions negatively affect aircraft performances and airport's capacity and efficiency. An increase in the magnitude and in the frequency of high-temperature extremes due to climate change would impact aviation operations, with further socio-economic, environmental and even health consequences. The Mediterranean region is a major climate change "hotspot", specially concerned by the increase in high temperatures. This study assess the future impacts of rising high-temperature extremes on aircraft takeoff performance over the Euro-Mediterranean region. The problem is addressed as follows: 1) the future evolution of high-temperature extremes is studied from climate model simulations, and 2) the potential induced impacts are assessed in terms of the levels of pollutant emissions, in particular, of nitrogen oxides (NOx), and engine performance, and in terms of the aircraft's maximum carrying capacity at takeoff.

Before evaluating the potential impacts of future changes in high-temperature extreme events, the past and future evolution of these events over a list of major and regional airports is analysed from observations and climate model simulations and projections. The daily maximum near-surface air temperature (TX) in summer is used. First, the magnitude of extreme values observed in recent decades is characterized, and trends in summer TX percentiles are computed as well. The quantile regression method allows us to obtain the evolution of the shape of the Probability Distribution Function, in particular, the trends of the median and the extremes, and not only the mean trends like the most-commonly used Ordinary Least Squares regression method. A robust increase is generally found over the airports for all percentiles. Some airports experienced a stronger increase in the upper percentiles than in the median or in the lower percentiles, which may be particularly problematic for aviation, and other sectors as well. Second, climate models are evaluated in present climate in these terms over the airports. This is a crucial step for the further assessment of future climate projections and related impacts. Simulations performed with Regional and Global Climate Models (RCMs and GCMs) are considered in a multi-model ensemble approach. In particular, the Euro-CORDEX multi-RCM ensemble and the ensemble of driving GCMs from CMIP5 are used. The two ensembles are compared to each other. Results show that there is no generally prevailing added value in RCMs for the study of the magnitude of high-temperature extremes nor for their temporal trends at the airport scale, despite their higher spatial resolution. Third, the future evolution of summer TX extremes is assessed for different time horizons and different climate change scenarios. A robust increase of the order of few degrees Celsius is found in summer TX extremes in the future for all the airports (up to +3.2ºC in the near term and up to +8.5ºC in the long term, under the severe scenario), with larger changes projected by the GCMs over the same locations. Forth, biases in future climate projections are corrected before the evaluation of the impact on the aircraft takeoff. Both RCMs and GCMs ensembles are considered here, in order not to underestimate climate modelling uncertainties.

In the second part of the study, the potential future increase in the levels of NOx emissions is assessed using an industrial tool for analysing the engine performance and pollutant emissions. The input value for the ambient temperature is declared as the future magnitude of summer TX extremes over the airports, which was estimated from the climate projections. To the best of our knowledge, this is the first time that data from climate models are used as input to an engine emulator. A general increase is found in the levels of NOx emissions over the selected airports. It could lead to an increase in absolute NOx emissions at takeoff of the order of a few percentage points in future extreme events: up to nearly +4% and +6% by the near and medium term, respectively. The potential future decrease in aircraft's maximum carrying capacity induced by the future increase in summer TX is assessed for each airport, following an empirical law for degrading the Maximum TakeOff Weight (MTOW) curves in Aircraft Characteristics for Airport Planning. This empirical law was provided by AIRBUS for three different aircrafts representing long-, mediumand short-range couriers. The future reductions in MTOW are generally of the order of tones for the long- and medium-range aircrafts, which could result in weight restrictions corresponding to tens of passengers and/or in delays or cancellations. The short-range aircrafts would experience little to no impact on the MTOW.

Despite the robust positive trend found for the levels of NOx emissions and the MTOW limitations, there are large uncertainties in the magnitude of the impacts analysed here. They mainly arise from uncertainties in climate projections that would need to be narrowed for the design of adaptation and/or mitigation strategies in the future.

This work assessed some of the maximum potential impacts that climate change may have on General Aviation operations in the coming decades. It illustrates the magnitude of the negative effects that the increase in high-temperature extremes would have on aircraft takeoff performance in terms of pollutant emissions, engine performance and MTOW limitations. All this focused on one of the world's most sensitive areas to climate change: the Euro-Mediterranean region. Moreover, it highlights the positive feedback loop between the rising temperatures and the rising NOx emissions from aviation.

Aviation operations at Euro-Mediterranean airports will be likely impacted by the increase in high-temperature extremes in the future. Adaptation and resilience strategies should be designed and deployed. This would require collaboration with airlines, aircraft and engine manufacturers and other stakeholders.

Assessment of the performance of convolutional neural network based RCM-emulator in representing daily near-surface temperature over the complex terrain of Subtropical Chile

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In this work we apply a deep learning UNet-based regional model emulator, recently developed and thoroughly tested over a region centered over the Southern France (Doury et al., 2022), to the complex terrain of Subtropical Chile (26ºS-34ºS). The study region exhibits marked climate gradients associated with a decreasing influence of the Pacific Ocean from the coast to the inlands and with topographic effects of the Andes Mountains reaching 6000 m.a.s.l.

The emulator is trained using a 150-years simulation of the CNRM-ALADIN regional climate model (RCM) configured for the North-Central Chile at a 12km resolution and driven by the CNRM-ESM2-1 CMIP6 global climate model (GCM) under the historical and SSP5-8.5 scenarios over 1950-2100. The emulator performance is evaluated based on an independent CNRM-ALADIN simulation driven by the same GCM but under SSP3-7.0 (2015-2100). Three less sophisticated downscaling methods are used as benchmarks: (i) a simple interpolation to the target resolution with an elevation adjustment based on the lapse-rate from CNRM-ALADIN RCM; (ii) multiple linear regressions using the same predictors as UNet and (iii) constructed analogues.

The results show that the UNet emulator is able to accurately reproduce the high-resolution spatio-temporal variability and changes of the RCM-simulated near surface temperature over the complex terrain of subtropical Chile, although in most cases it tends to underestimate the cold and hot extremes. In general, the performance of the emulator is weaker a) in autumn-summer than in winter-spring, and b) over mountains above ~3000m.a.s.l. and over a narrow coastal strip than over more inland coastal regions and valleys, suggesting an important role of regional to local phenomena (e.g. near-costal SST, marine low clouds, snow cover etc.) controlling the near-surface temperature in these seasons/regions.

Motivated by practical applications, we further discuss advantages and limitations of two training strategies for predictors/predictand over the study region: RCM/RCM or so-called "perfect model framework" which uses predictors from the upscaled RCM and GCM/RCM which uses predictors from the driving GCM.

Selection of representative climate simulations by minimizing bias in average monthly temperature and precipitation: near-future climate change in Odesa, Ukraine

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A significant average difference between the observed and modeled precipitation in the warm months is registered in Odesa for 1970–2005. This difference is probably determined by complex orography and inappropriate parameterization methods for convective processes climate models. In the last 15 years (2006–2020), the average temperature has increased by about 1 °C in winter and by 2 °C in summer compared with 1970–2005. Considering decreasing precipitation during summer months, it seems that the climate of Odesa is moving towards the Mediterranean climate—warm to hot, dry summers and mild, moderately wet winters. The approach based on selecting representative simulations with minimum average bias and adjusting the choice to the present-day climate is described and applied for Odesa using data from the RCP8.5 scenario simulations of the EURO-CORDEX project and ERA5-Land reanalysis. The approach can be applied separately for monthly near-surface temperature and total precipitation, as well as jointly for these variables, and provides the satisfactory ability to select models for use in impact studies.

As for climate change in Odesa from the last decades of the 20th to the middle of the twenty-first century, its most prominent feature is the increasing temperature for all months and the decreasing precipitation during the summer months. The climate for the Ukrainian coast of the Black and Azov Seas in 1980–2016 was defined as BSk—arid, steppe, cold—giving precedence for climate type B over type D, despite precipitation being sufficient for a temperate climate, type C. Nevertheless, the temperature of the coldest month in 2006–2020 was just slightly below zero, i.e., very close to the climate class Cfa, and summer precipitation decreased significantly. Moreover, we can expect only positive values of monthly temperature in the near future. Thus, the climate in Odesa would be moving toward the Mediterranean one, Csa, if the decrease in summer precipitation proceeds.

If necessary, daily averages can be used instead of monthly ones, for example, to analyze wet days (precipitation sum equals or greater than 1 mm), the warm-spell duration index, etc. Best models can be selected from data for a specific period of the year, e.g., summer months, if an impact study is related to events or processes during the warm half of the year. Another approach to determining the weight coefficients is possible, for example, if winter atmospheric processes are more crucial for the impact study than summer ones. Finally, the proposed approach can be used as a preliminary step to select the best simulations before applying a bias correction technique. For the current study, when only 10% is selected from many simulations, we suppose the set of simulations is ready for use in impact studies.

Intercomparison of Statistical and Dynamical Downscaling for Reproducing Compound Hot-Dry Events

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Compound events are typically defined as either combinations of extreme events occurring simultaneously, or as combinations of events that are not themselves extremes but lead to an extreme event or impact when combined (Zscheischler et al., 2018). Among them, compound hot-dry extremes (episodes with co-occurring high temperature and low precipitation) have been shown to be amongst the most detrimental to society and ecosystems, impacting energy production, human health as well as agricultural systems. Thus, it is essential to have a spatially-detailed and reliable representation of such events, in order to inform mitigation and adaptation policies.

Statistical (SD) and dynamical downscaling (through regional climate models, RCMs) are the main two approaches used to bridge the gap between the coarse-resolution simulations provided by global climate models and the local-to-regional information needed for most practical applications. As opposed to RCMs, SD methods do not explicitly solve any physical process, and thus, inter-variable consistency is not granted. Therefore, in this work we assess the ability of the two approaches to reproduce compound hot-dry events.

We perform the intercomparison over the Iberian Peninsula, using a selection of representative SD methods which have been recently found to be suitable for the generation of climate change scenarios, and a set of RCMs available within EURO-CORDEX (at a 0.11º resolution). As observational reference, we employ the gridded dataset Iberia01 (Herrera et al. 2019), available at a 0.10º resolution.

The comparison of downscaling approaches is performed using the standardised dry and hot index (SDHI, Hao et al., 2018), which represents a severity measure of a compound hot-dry event by employing the standardised ratio of precipitation with respect to temperature for a given period. The standardisation makes the SDHI not sensitive to the potential biases in the marginal distributions of precipitation and temperature, allowing for a fair intercomparison between SD methods and RCMs.

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Diving into Deep Learning techniques for multi-site fire danger prediction through a pseudo-reality study.

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Weather-station measurements capture the local variability and extremes of weather phenomena better than gridded products, which often smooth out or underestimate them. Therefore, point observations are essential for many climate impact applications that depend on variables with high spatial heterogeneity, such as precipitation and wind. Consequently, weather-station measurements can provide more accurate estimates of the Fire Weather Index (FWI), a multivariate climate index vital for fire prevention, effective wildfire management, and climate-resilient planning. Thus, multi-site FWI Empirical Statistical Downscaling (ESD) applications are important for allocating resources efficiently, intervening early in high-risk areas, and identifying potential threats under climate change conditions. To this end, it is important to apply adequate downscaling techniques that preserve the spatial consistency of the predictions, the reproducibility of extreme events, and their extrapolation ability to future climate change scenarios, factors that are seldom combined in ESD model assessments. This study examines the performance of different Deep Learning (DL) ESD methods for predicting FWI in various locations across the Iberian Peninsula, exploring different topologies based on fully-connected neural networks (FCNNs) and convolutional neural networks (CNNs). We attempt to ensure the spatial consistency of the methods by integrating the covariance structure of the predictands into the FCNN and CNN output layers design, resulting in spatially consistent FWI predictions. Our assessment addresses multi-site spatial consistency, reproducibility of extreme events, and ability of extrapolation, providing a benchmarking experiment that includes two classical perfect-prog techniques (GLMs and Analogs) as reference. Furthermore, we intercompare the transferability and capacity of the models to preserve the climate change signal of the driving model by a pseudo-reality experiment using a regional climate model from the EURO-CORDEX simulations under the historical and future RCP8.5 scenarios for different Global Warming Levels (GWLs). We find that some CNN methods yield overall good results in cross-validation in the historical period, but most of them exhibit extrapolation problems in climate change conditions, altering the climate change signal of the model. Our results show that a careful tuning of DL models is required to ensure consistency of the predictions in all the validation aspects considered. Only then do novel DL methods emerge as a powerful tool for ESD application of fire danger.

Nearest-Neighbor Gaussian Process to Downscale Solar Forecasting at the Grid-Edge for Increased Situational Awareness

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Accurate solar irradiance prediction is essential for energy-efficient building heating/cooling systems with rooftop solar panels. Planning electricity usage in the face of outages, such as those caused by natural disasters like hurricanes, is difficult in regions with high solar irradiance variability, like Puerto Rico. This project aims to design a computationally accelerated method to downscale nationally available climate data, particularly solar irradiance, to forecast microclimate data for buildings in western Puerto Rico. Downscaling links low-resolution climate models to local-scale data. This project uses spatiotemporal data from nearby weather stations and global weather forecasts to design highly accurate building-local models in Puerto Rico. Low-power sensors, local computing resources, and an empirical downscaling method are used to quantify the relationship between global and local data. An effective (and parallelizable) nearest neighbor Gaussian process (NNGP), accelerated by a graphics processing unit (GPU), is used to achieve this at the grid-edge. Models developed from local and global climate data, each for a different season in Puerto Rico, forecast solar irradiance given the location, time, and date, resulting in more accurate microclimate data. The applicability of NNGP to embedded computers was validated using an NVIDIA Jetson Nano.

Distribution-based pooling for combination and multi-model bias correction of climate simulations

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For investigating, assessing and anticipating climate change, tens of Global Climate Models (GCMs) have been designed, each modeling the Earth system slightly differently. To extract a robust signal from the diverse simulations and outputs, models are typically gathered into multi-model ensembles (MMEs). Those are then summarised in various ways, including (possibly weighted) multi-model means, medians or quantiles.

In this work, we introduce a new probability aggregation method termed "alpha-pooling" which builds an aggregated Cumulative Distribution Function (CDF) designed to be closer to a reference CDF over the calibration (historical) period. The aggregated CDFs can then be used to perform bias adjustment of the raw climate simulations, hence performing a "multi-model bias correction". In practice, each CDF is first transformed according to a non-linear transformation that depends on a parameter alpha. Then, a weight is assigned to each transformed CDF. This weight is an increasing function of the CDF closeness to the reference transformed CDF. Key to the alpha-pooling is a parameter alpha that describes the type of transformation, and hence the type of aggregation, generalising both linear and log-linear pooling methods.

Focusing on climate models simulations of temperature and precipitation over Western Europe, several experiments are run in order to assess the performance of alpha-pooling against methods currently available, including multi-model means and weighted variants. A reanalyses-based evaluation as well as a perfect model experiment and a sensitivity analysis to the set of climate models are run. Our findings demonstrate the superiority of the proposed pooling method, indicating that alpha-pooling presents a robust and efficient way to combine GCMs' CDFs.

The results of this study also show that the CDFs pooling strategy for "multi-model bias correction" is a credible alternative to usual GCM-by-GCM bias correction methods, by allowing to handle and consider several climate models at once.

Bias adjustment of climate models: common pitfalls and a new Python package to address these through model comparison and evaluation.

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Statistical bias adjustment is commonly applied to climate models before using their results in impact studies. However, different methods based on a distributional mapping between observational and model data can change the simulated trends as well as the spatiotemporal and inter-variable consistency of the model and are prone to misuse if not evaluated thoroughly. Despite the importance of these fundamental issues, researchers currently lack the tools to compare different bias adjustment methods and evaluate their potentially distorting impact on different climate metrics. To address this, we developed ibicus, an open-source Python package which implements eight widely used bias adjustment methods in a common framework, further allowing for a comprehensive evaluation on user-defined and spatio-temporal climate metrics. Applying ibicus in a case study over the Mediterranean region using 20 CMIP6 global circulation models, we show that the most appropriate bias adjustment method is often use-case dependent, and that bias adjustment can alter core features of the climate model, for example, even trend-preserving methods can modify the climate change trend. Finally, we show that bias adjustment can alter and shift climate model ensemble spreads, which has implications for our understanding of uncertainty in future projections. We investigate the shift in ensemble distributions both in terms of marginal and multivariate aspects and discuss strategies to handle the implications of bias adjustment on our understanding of the uncertainty of future projections.

Session 11: Global to regional impacts (poster presentations)

From global change to regional impacts, downscaling and bias correction

Mapping local climate change : a methodology with regional warming levels as key intermediary

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Faced with the rapidly expanding volume of climate data, deriving relevant regional climate information is an increasingly difficult task. This task becomes particularly challenging when data are uncertain, contrasting, or even sometimes conflicting. We propose a simple-to-implement approach for mapping climate change at the local scale, based on (i) global observational constraints, (ii) regional observational constraints, (iii) pre-existing global and regional simulations.

The approach is to use regional warming levels, in a manner perfectly similar to the work done in the IPCC Sixth Assessment Report, but on a regional scale. Bias-corrected EURO-CORDEX climate projections are used to describe climate change at a given regional warming level. On the other hand, the CMIP6 projections in combination with observations are used to relate the regional warming level to the corresponding global warming level and its timing.

The approach is illustrated for metropolitan France, a region affected by problems of inconsistent climate data. First, the reference sets of climate projections underestimate recent warming. In addition, the regional models project a weaker warming than their driving global models. The proposed methodology makes it possible to revise upward the regional to global warming ratio without the need for new simulations. As a result, the level of warming in France and the associated impacts are arriving earlier than predicted by regional projections alone.

Ensemble bias correction of climate simulations: preserving internal variability

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Climate simulations often need to be adjusted (i.e., corrected) before any climate change impacts studies. However usual bias correction approaches do not differentiate the bias from the different uncertainties of the climate simulations: scenario uncertainty, model uncertainty and internal variability. In particular, in the case of a multi-run ensemble of simulations (i.e., multiple runs of one model), correcting, as usual, each member separately, would mix up the model biases with its internal variability. In this study, two ensemble bias correction approaches preserving the internal variability of the initial ensemble are proposed. These “Ensemble bias correction” (EnsBC) approaches are assessed and compared to the approach where each ensemble member is corrected separately, using precipitation and temperature series at two locations in North America from a multi-member regional climate ensemble. The preservation of the internal variability is assessed in terms of monthly mean and hourly quantiles. Besides, the preservation of the internal variability in a changing climate is evaluated. Results show that, contrary to the usual approach, the proposed ensemble bias correction approaches adequately preserve the internal variability even in changing climate. Moreover, the climate change signal given by the original ensemble is also conserved by both approach.

Semi-parametric, multisite precipitation weather generation using GAMLSS

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(Conditional) Weather Generators based on so-called Generalized Linear Models (GLMs) have proven successful in emulating the main properties of multisite daily precipitation for applications in the downscaling of climate models or hydrological impact assessments. It has however been found that they can have issues properly representing seasonality in the tails of the rainfall distribution: the highest quantiles of summer rainfall are underestimated whilst the ones of winter rainfall are overestimated (see Yang et al. 2005). This can be a problem for applications as it can lead to extreme rainfall being over- or underestimated.

In this work we extend upon the GLM framework and use Generalized Additive Models for Location Scale and Shape (GAMLSS) to model daily rainfall at a number of rain gauge locations. We show that GAMLSS models improve the representation of seasonal dependence in the tails of the distribution. We introduce strategies for model/covariate selection for both parametric and semi-parametric GAMLSS in the presence of unresolved spatial dependence using an adjusted Akaike information criterion and a bootstrap-based approximation to the Kullback-Leibler divergence. And finally, we introduce a new spatial dependence scheme based on a censored Gaussian copula that accounts jointly for intersite dependence in amounts and occurrence and can be used to simulate hypothetical rainfall values with correct spatial dependence structure.

Future Scenarios Projections of Temperature, Precipitation and Extreme Climate Indexes over Guangxi

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The performance of the BCC-CSM2-MR model in simulating climate characteristics over Guangxi was evaluated using the grid observation dataset. Additionally, climate change projections for Guangxi from 2021 to 2064 under different projection scenarios were studied. The evaluation results indicate that the model has a good simulation capability of historical temperature, precipitation and extreme climate indexes over Guangxi, and the temperature simulation is better than the precipitation simulation, with a certain deviation in the spatial distribution compared with the observation. Future scenarios projections suggest a significant linear upward trend in temperature, with the degree of warming increasing from the northwest to the east and south of Guangxi. Precipitation is expected to maintain its decadal oscillation characteristics and increase over the next 50 years. Overall, extremely high temperature is projected to rise and intensify, while the extremely low-temperature index is anomalously high. The extreme precipitation index is also expected to increase. These findings reveal a higher likelihood of increased high-temperature heatwave events, relatively fewer low-temperature events and the occurrence of more intense extreme precipitation in certain regions of Guangxi in the future. It is important to note that under the SSP2-4.5 scenario, Guangxi is likely to undergo winter droughts to some extent in the near term of the 21st century (2021-2040), and the northeastern region may face more severe extreme low temperatures in the mid-21st century (2041-2060). Flooding caused by extreme precipitation is more likely to occur in the northwestern region under the SSP5-8.5 scenario.

Session 12: Impact attribution (oral presentations)

Impact attribution: from source to suffering

Attributing damage costs to climate change in New Zealand floods

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Heavy rainfall from the 15th to the 18th of July 2021 caused significant flooding within Westport, a small rural town in New Zealand. Following the flood, 23% of the town's housing stock required repair to make it habitable. Insurers have paid out over $85 million in claims to date. With New Zealand having already warmed by about 1.1 degrees above preindustrial temperatures as a result of human-induced climate change, it is broadly understood that both the intensity and frequency of such heavy rainfall events have likely increased. This has been supported by numerous studies looking at the attributability of rainfall in extreme events in New Zealand.

Here we go further and consider different methods for estimating how much of the direct damage costs associated with the event might reasonably be attributed to anthropogenic emissions of greenhouse gases. In the first we use a hydrodynamic inundation model with gridded observational rainfall as input and validated with in-situ measurements of flood depths. We then use a range of methods to remove the contribution to the rainfall intensity that might be considered attributable to climate change (Stone et al. 2022), creating a 'counterfactual' rainfall event. This is used to simulate a number of counterfactual, or 'naturalised', floods as though there had been no anthropogenic emissions of greenhouse gases, while accounting for uncertainty in these estimates.

Using a building damage model for the 2021 Westport flood event we estimate direct economic costs from both the actual flood and the naturalised flood, and thus an associated attributable cost that is the difference between the two. We compare this to the attributable cost estimated from a previously published methodology based on the fraction of attributable risk (FAR) associated with the rainfall event (Frame et al. 2020). We also consider how the attributable cost behaves as we add further incremental warming, reflective of changes that might be anticipated in the future.

Storylines for heat-mortality extremes

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Recent heat extremes reached records far out of the observational temperature range. These extremes challenged the risk view of climate scientists on what could be physically possible within the current climate conditions. However, it is precisely such unprecedented events that pose a large risk to underprepared societies. To better anticipate and prepare for such potential extreme events, the climate risk community started producing storylines which are designed to draw potential and plausible worst-case scenarios without aiming to quantify their probability of occurrence.

The recent development of the ensemble boosting method allows investigating physically plausible extreme heatwaves by re-initializing a climate model with random round-off perturbed atmospheric initial conditions shortly before the onset of a great heat anomaly. This allows for creating storylines whilst ensuring physical consistency. However, so far these storylines were only used to estimate the pure physical climate extreme without the additional quantification of impacts on society.

In this study, we therefore aim to produce several storylines for potential worst-case heat-mortality scenarios. For that, we aim to combine ensemble boosted climate model output with methods from environmental epidemiology to quantify heat-mortality. Concretely, we model the empirical relationship between daily mean temperature and daily mortality counts by using quasi-Poisson regression time series analyses with distributed lag nonlinear models, which is a well-established approach in climate change epidemiology. We then combine these empirical temperature-mortality relationships with the bias-corrected extreme storylines that we developed by ensemble boosting a fully-coupled free-running climate model (CESM2).

The findings of this study have significant implications for societies, particularly in the context of public health policy development, to effectively respond to unprecedented but anticipatable heat extremes.

Projected shifts and dynamics in blue and green water resources availability

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A deep understanding of the dynamics of green and blue water resources is crucial for accurately estimating future water availability. Although projections of precipitation trends are robust in many regions, changes in precipitation partitioning into green and blue water fluxes present a significant source of uncertainty for water management. To quantify water partitioning dynamics, we introduce the Blue-Green Water Share (BGWS) metric. This metric utilizes monthly precipitation data, while monthly runoff and transpiration data serve as proxies of blue and green water fluxes. We investigate the output of fourteen CMIP6 models for the historical period and under the SSP-RCP scenario 3-7.0 to assess changes in BGWS under climate change. Here, we examine how and why the BGWS varies across different regions. Most importantly, primary drivers of the BGWS changes are attributed by applying a multiple regression analysis and computing the permutation importance of selected ecohydrological variables. We employ Elastic Net regularization to handle the multicollinearity among impact variables.

The results illustrate a strong regional dependency and interplay of the driving variables. However, clustering the variable importance demonstrates that BGWS changes in higher latitudes tend to be more dependent on temperature, while precipitation patterns dominate partitioning changes in the tropics. Several regions, including the Mediterranean, Northern South America, and Eastern Australia, show a substantial influence of vegetation alterations on the BGWS change, shifting the partitioning imbalance towards more green water flux. We discuss the varying variable importance based on the counteracting mechanisms of increased CO2 concentrations, altered growing seasons, and changed precipitation patterns. Our results highlight the importance of comprehensively understanding green and blue water dynamics in the context of water resources availability under a changing climate.

Tipping points in hydrology: an inquiry into Sahelian watersheds regime shifts with a dynamical model and past climate simulations

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The Sahel, the semi-arid fringe south of the Sahara, experienced severe meteorological droughts in the '70s-'80s. During these droughts, four watersheds of the Central Sahel (Gorouol, Dargol, Nakanbé, Sirba) may have experienced an hydrological regime shift leading to an increase in annual runoff coefficient (annual runoff normalized by annual precipitation).

To investigate these regime shifts, we introduce a lumped model that represents feedback between soil and hydrology at the watershed scale and annual time step using runoff coefficient as constraint for the state variable and precipitation as external forcing. For each watershed, calibration takes place as follows: one million simulations are run with observed precipitation as forcing; then we select an ensemble of 1000 simulations – and associated 1000 parameterizations – that best reproduce runoff coefficient observations. Every parametrization of these ensembles is bistable, i.e. the parametrized model exhibits two equilibrium states for some range of precipitation. Thus, based on the bifurcation diagram of each parametrization, we define two non-asymptotic regimes: a low and a high runoff coefficient regime.

Our results show that for each watershed the calibrated ensemble forced with observed precipitation reproduces the regime shift and captures the first order dynamics of the observed runoff coefficient. Most parametrizations of the ensemble have a runoff coefficient trajectory that belongs to the low regime in 1965 and to the high regime in 2014. We note that the drier watersheds are shifting first.

Then, the calibrated ensemble is forced with past climate simulations of precipitation. In this region, precipitation interannual-to-decadal variability is largely driven by variations of the interhemispheric Atlantic sea surface temperatures (SSTs) gradient. Our preliminary results surprisingly indicate that the historical patterns of SSTs did not make these regime shifts more likely than other counterfactual modes of variability of the Atlantic. To our knowledge, this is the first attribution study concerning the hydrological regime shift observed in the Sahel.

Quantifying Individual Contributions to eXtremes (QuICX)

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Probabilistic event attribution aims to quantify the role of anthropogenic climate change in altering the intensity or probability of extreme climate and weather events. It was originally conceived to calculate the costs associated with any increased likelihood of the meteorological event in question. However, only recently have such studies attempted to divide liability between polluting nations and ascribe a cost. Recent protests indicate a perception that older generations have the greater responsibility for climate change. In this paper, we examine how a portion of the cost of an event can be attributed to any individual person, according to their age and nationality.

We demonstrate that this is quantitatively feasible using the example of the 2018 summer heatwave in eastern China and its impact on aquaculture. A relatively simple technique finds sample individuals responsible for between 0.53 and 18.10 yuan, increasing with their age and their country's emissions over their adult lifetime since the first international consensus on carbon emissions was reached. This provides an illustration of the scale of such responsibilities, and how it is affected by national development and demographics. Such data can support decisions, at national and international levels, on how to fund recovery from climate impacts. It offers a simple quantitative approach for individuals to know their impact on the climate, or for governments to use in making policy decisions about how best to distribute costs of climate change.

Further to this, we are now extending the technique to cover all heatwaves worldwide, with a view to cover other classes of event too. The aim is to be able to indicate to individuals, companies and countries, their possible liability for the effect of their emissions on the climate. This could feed into insurance products, and might give context to governments about losses and damages due to climate change.

Extreme heatwaves in Europe 1950-2021: analysis of the links between meteorology, population, and impacts

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There is high confidence that heatwaves will become more frequent and more intense under the influence of climate change. Different definitions of heatwaves exist based on the statistical distribution of temperature, in general using thresholds and duration and extension criteria. If one observes the overlap between these definitions and the actual human and material damage produced by heatwaves, it appears that there is low consistency between the two. In other terms, a large amplitude heatwave in the physical climatological sense may not be equivalently as large in terms of impacts.

By crossing meteorological, demographic, and impact databases at the European scale, we developed indices to classify heatwaves and select extreme ones in terms of impacts. We also proposed a method to evaluate the classification abilities of these indices. We show that including demographic data in the indices is central to understand the links between meteorological conditions and observed impacts.

Aridification and its impacts on terrestrial hydrology and ecosystems over a comprehensive transition zone in China

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In China, the topography, climate, ecology, hydrology and human environment vary greatly from southeast to northwest, and a typical natural and social environmental transition zone (namely comprehensive transition zone) exists near the "Hu Huanyong line" that is a famous demographic dividing line in China, known as the Hu zone. Dry-wet climate changes in the Hu zone can have a significant impact on terrestrial ecosystems and hydrological conditions, ultimately affecting human-land relations. However, there is still a lack of clear understanding of environmental changes in the context of climate change in the Hu zone. Here, a quantitative analysis of climate change and its impact on terrestrial hydrology and ecosystems from 1951 to 2020 is presented. The results showed that there exists a significant drying trend in the Hu zone and a dramatic decrease in terrestrial water storage (TWS), indicating that the environment has become worse. Conversely, from the perspective of significant greening, the environment has improved. This contradiction is mainly due to climate change dominating the depletion of TWS, while the increase in vegetation greenness is more driven by human activities including agricultural management and ecological restoration, offsetting to some extent the negative impact of water scarcity on vegetation growth.

ASSESSMENT OF THE VULNERABILITY OF SENEGALESE FARMING HOUSEHOLDS TO CLIMATE CHANGE: INTEGRATED ASSESSMENT APPROACH AND MAPPING OF INDICATORS USING GEOGRAPHIC INFORMATION SYSTEMS (GIS).

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Due to their heavy dependence on rain-fed agriculture, sub-Saharan African countries are largely exposed to climate change. Sahelian countries, and particularly those in West Africa, are among the most affected by the recurrent effects of climate change, particularly long periods of drought. Climate change could exacerbate the vulnerability of agricultural households; whose livelihoods mainly depend on income from agricultural production. The theoretical literature is unanimous in considering that climate change increases the vulnerability of rural households (Barrett et al., 2007; IPCC, 2007; Agossou et al., 2012). However, there is a lack of knowledge on certain questions such as "Who is vulnerable?" », "What is the degree of vulnerability? », "What is the capacity to adapt? », "How is vulnerability distributed geographically? This misinformation from political decision-makers about the level of vulnerability of people and their priority needs poses a problem for the effectiveness of public investments. This research attempts to answer these questions to shed light on how agricultural households are affected by climatic events such as drought and floods. It maps a set of indicators and generates a vulnerability index, which could facilitate the intervention of political decision-makers on climate change issues. A sample of 668 agricultural households distributed in 33 communes and two different agro-ecological zones was studied using an integrated and spatial approach combining socio-economic indicators and institutional factors of households, biophysical variables linked to temperature, precipitation and climatic events (drought, floods), and other variables linked to accessibility to infrastructure and basic social services (roads, education, health, etc.), and environmental characteristics such as soil type, the slope and the vegetation. These cited indicators are grouped according to three sub-components of vulnerability, namely exposure, sensitivity and adaptive capacity of households, then a composite vulnerability indicator is calculated according to the definition of the Intergovernmental Panel on climate change (IPCC) and the methodology developed by Zébisch et al. (2021). The results of the research indicate that out of 33 municipalities studied, two (2) are in a very high level of vulnerability of around 0.61 to 0.70, six (6) are in a state of high vulnerability of 0.53 and 0.60 and six (6) others are in a moderate situation (0.46 to 0.52). These localities are highly exposed to climate change, including changes in temperature, precipitation, and events such as floods and droughts. They are also sensitive given their altitude, less conducive to the development of rice growing, and especially their fragility linked to a relatively dominant age group. Indeed, in these slightly more remote areas, the adaptation capacity of households remains low; Households are far from roads and health infrastructure and have limited access to agricultural credit, extension services and agricultural insurance and are therefore characterized by relatively low income levels. To this end, strengthening social capital through the development of extension services such as agricultural advice; strengthening human capital through education and training; the development of institutional capital through the development of basic social infrastructure, transport and credit institutions; as well as economic capital through the promotion of agricultural insurance, are fundamental policy measures to reduce the vulnerability of agricultural households and thus improve their resilience. The policy implications that emerge from this research provide an idea of the order of priority of adaptation policies in the different localities considered. The originality of this research is that it is being developed in a context where

countries need to produce solid scientific knowledge to justify their exposure to climate change so that the adaptation options that will be proposed can meet the requirements of the mechanisms of international financing as established by the guidelines of the Least Developed Countries (LDC) Expert Group which stipulates that the financing process for national adaptation plans (NAPs) must be based on sound scientific knowledge (LDC-2012) .

Keywords: Climate change, Vulnerability, Index method, Rice farmers, Senegal.

Forecast-based attribution of the mortality impact of the Pacific Northwest heatwave

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In June 2021, British Columbia experienced daytime temperature of 49.6 degrees and recorded 486 fatalities during the heatwave period, a 195% increase in the number of deaths compared to the same period in the past. This Pacific Northwest heatwave was well forecast ahead of time. Here, we use a novel operational forecast-based approach that synthesizes the storyline and probabilistic approaches for extreme event attribution. We take a step further to couple these forecast-based ensembles of present-day, pre-industrial and future climates with empirical temperature-mortality relationships for key cities in the region, in order to provide an attribution statement about the role of human-induced climate change on the mortality impact of this event. We examine the possibility of using alternative temperature-health models for impact attribution. This work represents the first forecast-based impact attribution study and our results will assist policymakers to make informed decisions on interventions and policies to prepare the public for “best case” and “worst case” scenarios.

Navigating Climate Change Health Impacts: Unveiling the Role of Behavioural Communication

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Abstract

This study delves into the intricate relationship between climate change and health, focusing on the pivotal role of behavioral communication in mitigating and adapting to the evolving health risks posed by a changing climate. As global temperatures rise and weather patterns become increasingly unpredictable, understanding the intersection of climate change and public health becomes paramount. The research employs a comprehensive approach to unravel the impact of climate change on health, emphasizing the influence of behavioural communication strategies in shaping adaptive responses. The attribution of health impacts to climate change involves tracing the complex chain from emissions to climatic variables, addressing the challenges posed by both climatic and non-climatic human influences. The study explores innovative methodologies to investigate health variables and assesses the efficacy of behavioural communication in bridging the gap between climatic phenomena and downstream health outcomes. Drawing on empirical evidence and case studies, this research utilizes Nigeria as a case study to highlight the unique challenges and opportunities presented in a developing country context. In pushing the limits of attribution research, this study examines behavioral communication as a catalyst for change, aiming to extend its impact downstream to ecosystems, agriculture, and various sectors of human society. The findings contribute valuable insights into the design of effective communication strategies that enhance public awareness, promote adaptive behaviours, and foster resilience in the face of climate-induced health challenges.

Keywords: Climate Change, Health Impacts, Behavioural Communication, Adaptive Responses, Nigeria.

Children disproportionally exposed to attributable heatwaves at low-latitude low-income countries

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Heatwaves are increasing in frequency, intensity, and duration, and represent the category of extreme event that is most easily attributable to anthropogenic warming. Yet how the spatiotemporal patterns of attribution outcomes link to population dynamics and demographic patterns is still poorly understood. Here we investigate whether children and young people are already being affected by a disproportionately greater number of attributable heat extremes, especially in the Global South. Using observations, reanalysis, and simulations of temperature changes available through the ISIMIP3b and CMIP6 projects, in combination with demographic data, we investigate whether temperature extremes emerge more clearly and consistently from the noise across low-income countries in lower latitudes, which have some of the youngest populations. We test the sensitivity of our findings to different definitions of a hot extreme and explore possibilities to increase the impact-relevance of our framework. Our anticipated findings could have implications for children and young people seeking redress from climate harms.

Impact Attribution - how did climate change affect wheat yields in northern Kazakhstan?

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Northern Kazakhstan is a major exporter of wheat, contributing to food security in Central Asia and beyond, but wheat yields fluctuate and low-producing years occur frequently. The most severe low-producing year in this century was in 2010, leading to severe consequences for the food security of wheat importing countries. To date, the extent to which human-induced climate change contributes to this is unclear.

In this session, we present the first attribution study for wheat production in northern Kazakhstan, which is at the same time one of the very first climate impact attribution studies for the agricultural sector in general. We quantify the impact of human-induced climate change on the average wheat production as well as economic revenues and on the likelihood of a low-production year like 2010. For this, we use bias-adjusted counterfactual and factual climate model data from two large ensembles of latest-generation climate models as input to a statistical subnational yield model. The climate data and the yield model were shown to be fit for purpose as the factual climate simulations represent the observations, the out-of-sample validation of the yield model performs reasonably well with a mean R2 of 0.54, and the results are robust under the performed sensitivity tests.

Our results show that human-induced climate change, and explicitly increases in daily-minimum temperatures and extreme heat, have had a critical impact on wheat production, decreasing yields between 2000 and 2019 by around 6.2 to 8.2% (uncertainty range of two climate models), increasing the likelihood of the 2010 low-production event by 2.1 to 3 times, and leading to economic losses of 119 to 158 million USD. The latest IPCC report assessed that climate change has today mixed positive and negative impacts on wheat production in Central Asia, but the results are stated with low confidence as studies are sparse in this region. This climate impact attribution study addresses this gap, finding clear indications for a negative influence of climate change, especially via temperature increases, on wheat production in northern Kazakhstan.

Acceleration of local warming damped in urban areas of the Global South

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Global warming is accelerating, and many parts of the world have also experienced accelerated warming in recent decades as greenhouse gas (GHG) emissions have risen. In this study, we investigate the regional variations in acceleration using gridded surface temperature data for 1850-2022. We use a modified Mann-Kendall trend test/Sen's slope analysis for highly autocorrelated data, along with regression analysis across different sample sizes to calculate regional warming acceleration rates. We find that, on average, regions with low Human Development Index (HDI) experienced much higher accelerated warming in comparison to regions with high HDI. However, regions of low HDI with a large population experienced slow acceleration in warming due to high local aerosol emissions. These results are consistent across different sampling lengths. Since aerosol negative forcing impacts are short-lived and localised, rapid future reduction of aerosol emissions without a concurrent reduction in GHG emissions could have major compounding impacts. Such a pathway, which is similar to some well-used 21st century scenarios, could expose a large fraction of the world's most vulnerable people to a sudden warming acceleration and impacts associated with increased heat stress. This study therefore highlights regions of high vulnerability, as clean-air policies become more widespread, which require targeted climate adaptation strategies to counter future accelerated warming.

Linking rising temperatures and mental health risks in India- Implications for attribution of climate-related impacts.

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India, with a population exceeding 1.4 billion, stands as one of the world's most populous and diverse nations. This diversity, evident in its geography, climate, and social structures influenced by factors like religion, ethnicity, and occupation, is considered pivotal to the country's development. However, this extensive population and diverse demographics also contribute significantly to mental health challenges and elevated suicide risks across all sectors of society. Adding to this challenge is a growing body of global evidence linking climate change-driven temperatures to increased physiological stress and mortality rates. Past studies in India have successfully demonstrated this linkage, notably within the farming community, showing a significant positive correlation between suicides and regional temperatures, particularly following prolonged heat and drought episodes associated with widespread crop loss. To better understand the quantitative links between heatwaves and physiological stress, it's crucial to utilize metrics like apparent temperature or "feels-like" temperature, which account for humidity. This metric offers insights into the combined effects of heat and humidity on both physiological responses and psychological well-being.

This study is conceived in two stages. In the first stage, Intensity-Duration-Frequency (IDF) and Intensity-Areal extent-Frequency (IAF) curves will be developed for selected heatwave hotspots in the country, based on observed datasets and climate models. The India Meteorological Department (IMD)'s experimental Heat Index (HI), which is used for impact-based forecasts is identified as the metric for quantifying heat stress. Copulas will be used for modelling the joint distributions between intensity and duration, and between intensity and areal extent. The heatwave frequency curves will thereafter be used for estimating the changing risk in humid heatwave with different intensities, durations and areal-extent, under global warming targets of 1.5degC and 2degC

above pre-industrial levels. In the next stage, probabilistic models will be developed for assessing suicides, conditioned on the heatwave descriptors, based on observed datasets. Such relationships will then be utilized for quantifying the expected change in likelihood of suicides above mean, to changes in heat stress conditions due to global warming. The findings of this study can inform targeted early warning systems, tailored interventions, and proactive strategies to mitigate the adverse impacts of heatwaves on mental health and reduce the risk of suicides, particularly in vulnerable communities.

Direct and lagged climate change effects intensified the widespread 2022 European drought

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In 2022, Europe faced an extensive summer drought with severe socio-economic consequences. By combining observations and climate model outputs with hydrological and land-surface simulations, we show that central and southern Europe experienced the highest observed total water storage deficit since satellite observations began in 2002, likely representing the highest and most widespread soil moisture deficit since 1960. While precipitation deficits primarily drove the soil moisture drought, global warming contributed to over 30% of the drought intensity and its spatial extent via enhancing evaporation. We reveal that 14-41% of the climate change contribution was mediated by the warming that started to dry out the soil before the hydrological year 2022, indicating the importance of considering lagged effects of climate change to avoid underestimating risks. Qualitatively similar effects were observed in river discharges. These results highlight that global warming effects on droughts are widespread, long-lasting and already underway, and that drought risk may escalate in the future.

Session 12: Impact attribution (poster presentations)

Impact attribution: from source to suffering

The impact of future sea-ice loss on temperature extremes and human mortality in Canada

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Extreme cold temperatures are associated with an increased risk of human mortality. Previous research has identified a strong warming signal in winter temperature extremes from future sea-ice loss at 2°C global warming above pre-industrial, particularly in eastern Canada. However, the impacts of these changes in temperature distribution have not yet been fully explored. Here, we will examine the impact of future sea ice loss on human mortality in Canada from extreme temperatures using the Polar Amplification Model Intercomparison Project (PAMIP) model ensembles, as well as a very large ensemble following the same protocol, and a statistical temperature-mortality model. The very large ensemble will allow us to analyse the extreme tails of the temperature distribution more fully. We will further explore the skill of the mortality model using various methods to determine city-wide or regional observed temperature, including interpolation and population-weighting techniques, which may have a considerable influence on the calculated relative risk of mortality from temperature exposure, particularly in larger regions with sparse populations.

ECMWF ensemble model specific humidity skill verification in the region of Vietnam

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In the context of an accelerated warming climate, outbreak episodes of diseases such as dengue fever are expected to increase in the near future, increasing health burden in areas like Vietnam. Because meteorological variables exert a great influence on dengue transmission, weather forecast data is key to model future dengue fever outbreaks and mitigate future damages. Previous research assessed the skill of the ECMWF ensemble model on precipitation and temperature over Vietnam, but they did not include specific humidity, which also plays an important role in vector-borne disease transmission. Hence, this study aims to assess the skill of ECMWF ensemble specific humidity in Vietnam, using ERA5 reanalysis for the evaluation for the period between the dates 2001-2020. The results obtained will provide more insight about the ECMWF skill in the medium-range forecast and help to establish Dengue-modelling warning systems.

Short Course on climate change detection and attribution with estimating equations

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This two-hour course will introduce the estimating equations approach to optimal fingerprinting described in Ma et al (2023) and will include hands-on exercises using the companion R package dacc. Participants will be expected to bring their own laptops and to have installed R and the dacc package in advance of the course.

Climate change detection and attribution has played a central role in establishing the influence of human activities on the climate. Optimal fingerprinting, a linear regression with errors-in-variables (EIV), has been widely used in detection and attribution analyses of climate change. The method regresses observed climate variables on the expected climate responses to the external forcings, which are measured with EIVs. The reliability of the method depends critically on proper point and interval estimation of the regression coefficients. The confidence intervals constructed from the prevailing method, total least squares (TLS), have been reported to be too narrow to match their nominal confidence levels. We propose a novel framework to estimate the regression coefficients based on an efficient, bias-corrected estimating equations approach. The confidence intervals are constructed with a pseudo residual bootstrap variance estimator that takes advantage of the available control runs. Our regression coefficient estimator is unbiased with a smaller variance than the TLS estimator. Our estimation of sampling variability of the estimator has a low bias compared to that from TLS, which is substantially negatively biased. The resulting confidence intervals for the regression coefficients have close-to-nominal level coverage rates, which ensures valid inferences in detection and attribution analysis. In applications to the annual mean near-surface air temperature at the global, continental, and subcontinental scales during 1951–2020, the proposed method led to shorter confidence intervals than those based on TLS in most of the analyses.

References:

Ma, S., T. Wang, J. Yan and X. Zhang, 2023: Optimal fingerprinting with estimating equations. J. Climate, 36, 7109-7122, https://doi.org/10.1175/JCLI-D-22-0681.1
Li Y, Chen K, Yan J (2023). dacc: Detection and Attribution Analysis of Climate Change. R package version 0.0-2, <https://CRAN.R-project.org/package=dacc>;.