Sensitivity of Alpine glaciers to anthropogenic atmospheric forcings

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Glacier of interest

Argentière glacier:

- Mont Blanc Range
- 2nd largest in France
- from 1550 to 3500m a.s.l.
- ~10km long
- many observations
- mean thickness loss = -25% since 1900

From there …

1860

… to there

2015

Study overview

General Circulation Model IPSL-CM6-LR :

➔ atmosphere-ocean coupling

➔ mesh size : ~150 km

Atmospheric Reanalysis

➔ reference data (S2M)

➔ mesh size : 40x15 km

Statistical correction

➔ Daily temperature and precipitation

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3D ice flow model

Surface Mass Balance model
Parameterized model

Observational Data
GLACIOCLIM observatory, proxies, …

Glaciological model
- Calibration
- Initialization

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Simulations

Analysis

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Climatology

Simulations → **Analysis**

3D ice flow model

Surface Mass Balance model
Parameterized model

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Glaciology

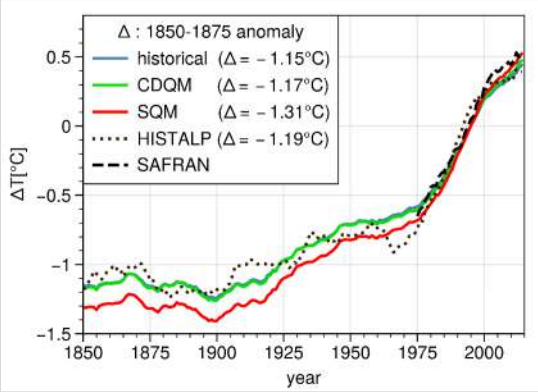
Statistical correction

Main goals:
- ➔ Downscaling
- ➔ Bias correction at daily timescale

Principle:
- monthly basis
- difference GCM vs. S2M reanalysis
- calibration with **historical mean** over **1975-2014**
- applied for all experiments and the whole period (1850-2014)

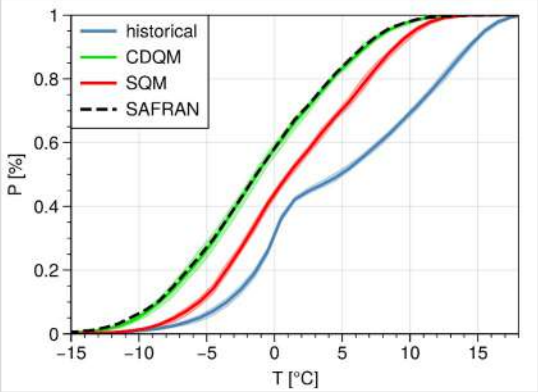
Tested methods :
- ★ Simple Quantile Mapping (SQM) ✗
- ★ Coupled Delta Quantile Mapping (CDQM) ✓

⚠ **Long-term tendencies overestimation**



30-year rolling mean of temperature anomaly, reference is the 1975-2014 average, Δ is the 1850-1875 mean anomaly

⚠ **Precipitation-temperature consistency : snowpack understated**



Precipitation cumulative distributive function relatively to 1°C-width temperature quantiles, solid line corresponds to the member mean and shade area to the member range

CDQM = delta quantile mapping for T (Cannon et al., 2015) **+ 2D conditional approach for P** (Piani et al., 2012)

Statistical correction

<u>Main goals:</u>
- ➔ Downscaling
- ➔ Bias removing
- ➔ Mean climatology and daily variability adjustment

<u>Principle:</u>
- monthly basis
- difference GCM vs. reanalysis
- calibration with **historical mean 1975-2014**
- applied for all experiments and the whole period (1850-2014)

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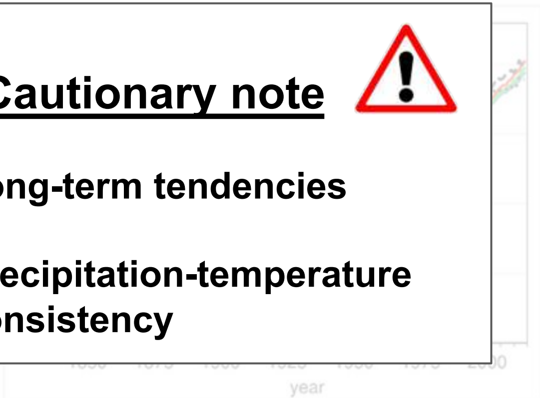

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⚠ Cautionary note ⚠

- ➔ **Long-term tendencies**
- ➔ **Precipitation-temperature consistency**

General Circulation Model outputs

Atmospheric forcing experiments

- ➔ retrospective simulations : 1850-2014
- ➔ *HIST*, *NAT*, *AER*, *GHG*

Ensemble modeling:

- ➔ 6 members per experiment

Statistical correction :

- Long-term temperature tendencies
- Precipitation-Temperature consistency

⇒ ***Coupled Delta Quantile Mapping***

experiment \ forcings	volcanic & solar	anthropogenic aerosol	greenhouse gases
HIST	X	X	X
NAT	X		
AER		X	
GHG			X

Climate adjusted data

Precipitation :

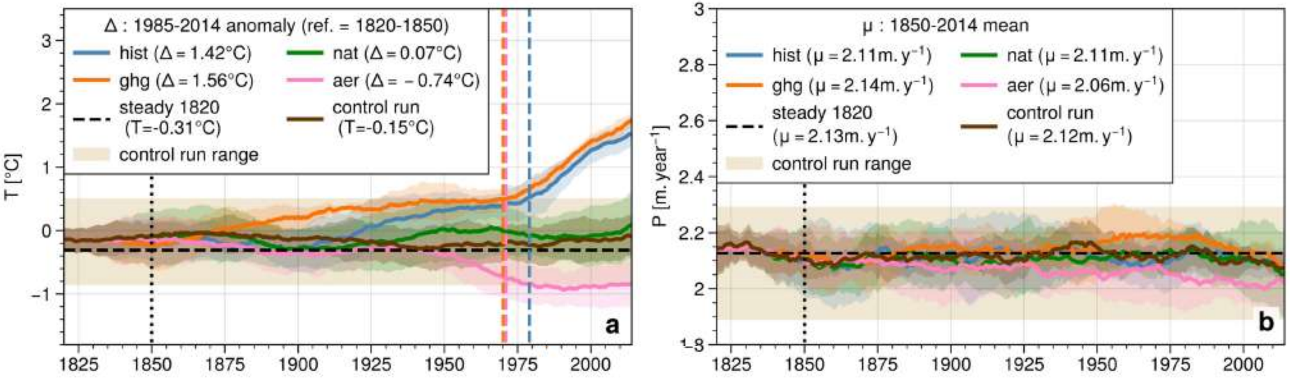
- no clear tendency
- variability dominates

Temperature:

- signals stronger than variability
- significance test ⇒ very likely (P>90%) :
  - *AER* cooler than *NAT* by 1971
  - *GHG* hotter than *NAT* by 1971
  - *HIST* hotter than *NAT* by 1979

Temperature

Precipitation

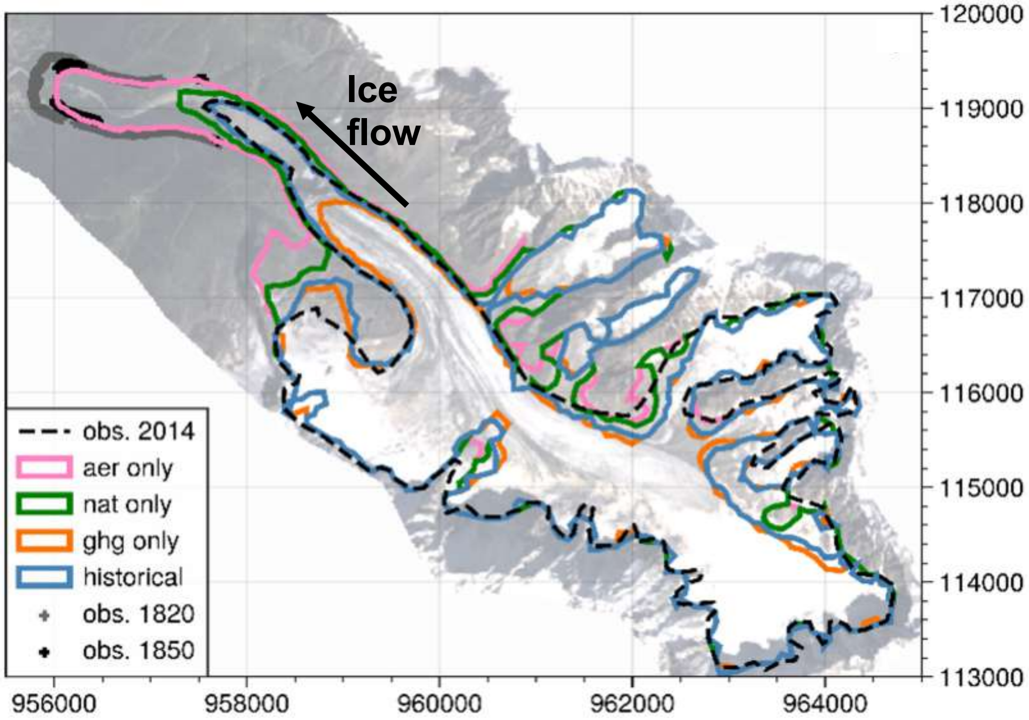


30-year rolling mean of (a) temperature and (b) precipitation. Solid lines are 6-member means, shades correspond to the 1-σ member range, vertical black lines show the spin up end, vertical coloured dashed lines indicate the year by which it is very likely (>90%) or unlikely (<10%) to have a lower value than in the natural forcings only experiment

Simulation results

Glacier shape:

- *AER* ⇒ close to 1850 moraine (cooling effect)
- *GHG* ⇒ strong glacier retreat (warming effect)
- *HIST* ⇒ close to 2014 observation (great retreat)
- *NAT* ⇒ lower retreat compared to *HIST* (end of Little Ice Age)

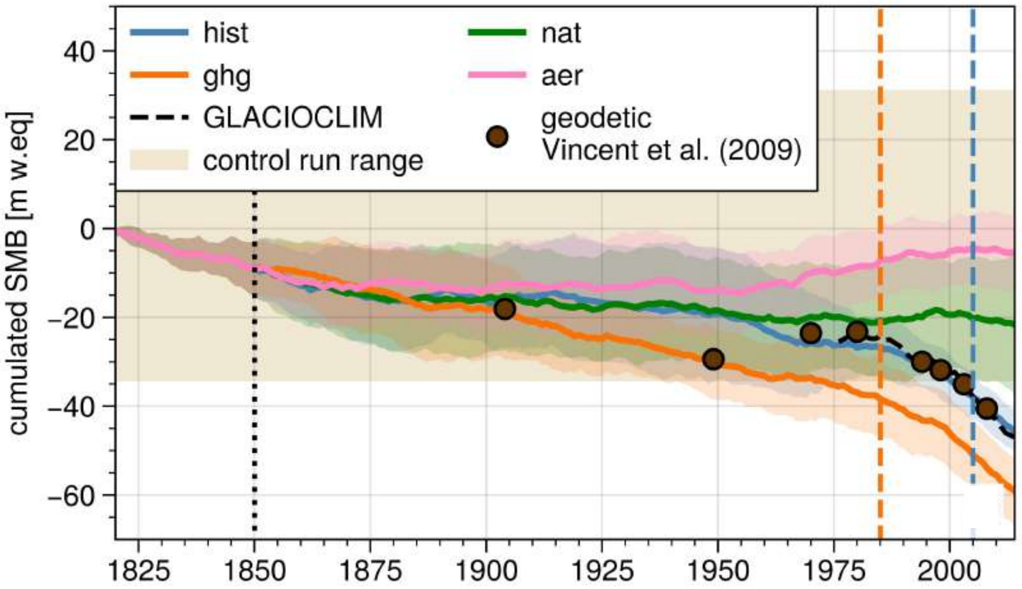


Glacier extent *for each experiment 6-member mean in 2014. Coordinates are given in meters in Lambert Centre France coordinates (EPSG:27562). Background picture is a Landsat 8 (band L1) georeferenced photograph taken on 03/09/2014, black dashed line is the corresponding glacier extent. 1820 and 1850 observations are from Protin et al. (2019)*

Simulation results

Cumulative Mass Balance (~volume):

- Topography independent variable
- Influence of internal variability
- *NAT* ⇒ mass loss and stabilization around *-20 m.w.eq*
- *AER* ⇒ loss before growth
- *HIST* ⇒ follow *NAT* before a great decrease, mass loss very likely stronger than *NAT* in 2008
- *GHG* ⇒ mass loss very likely stronger than *NAT* from 1987

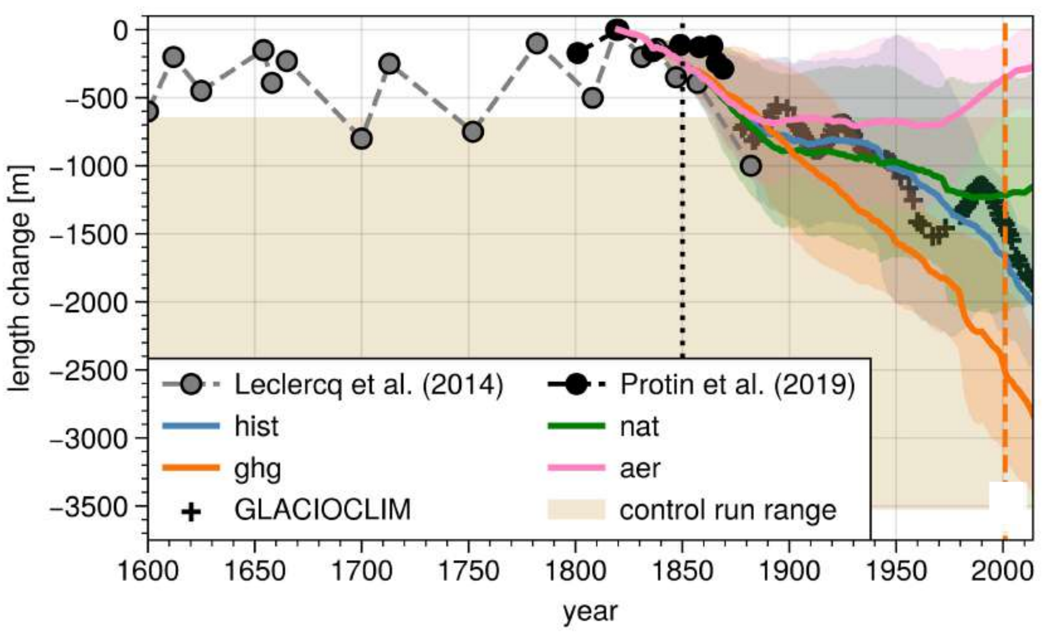


Cumulative Surface Mass Balance*, solid lines are 6-member means, shades correspond to the 1-σ member range, vertical black lines show the spin up end, vertical coloured dashed lines indicate the year by which it is very likely (>90%) or unlikely (<10%) to have a lower value than in the natural forcings only experiment. The darken yellow bands highlight the spread simulated in a 800 year control experiment based on constant natural forcing (A 1000 year experiment from which a 200 year spinup is excluded).*

Simulation results

Length change:

- Topography dependent variable
- Influence of internal variability
- Little Ice Age positions cannot be explained by internal variability
- ***HIST*** ⇒ still compatible with ***NAT*** in 2014!
- ***GHG*** ⇒ Not compatible with ***NAT*** from 2001



***Length change from 1820**, solid lines are 6-member means, shades correspond to the 1-σ member range, vertical black lines show the spin up end, vertical coloured dashed lines indicate the year by which it is very likely (>90%) or unlikely (<10%) to have a lower value than in the natural forcings only experiment; The darken yellow bands highlight the spread simulated in a 800 year control experiment based on constant natural forcing (A 1000 year experiment from which a 200 year spinup is excluded).*

Conclusion

Results:

- ➔ High sensitivity to atmospheric forcings
- ➔ Strong influence of internal variability at this time scale
- ➔ Attribution of mass loss to human activities in 2008 for SMB

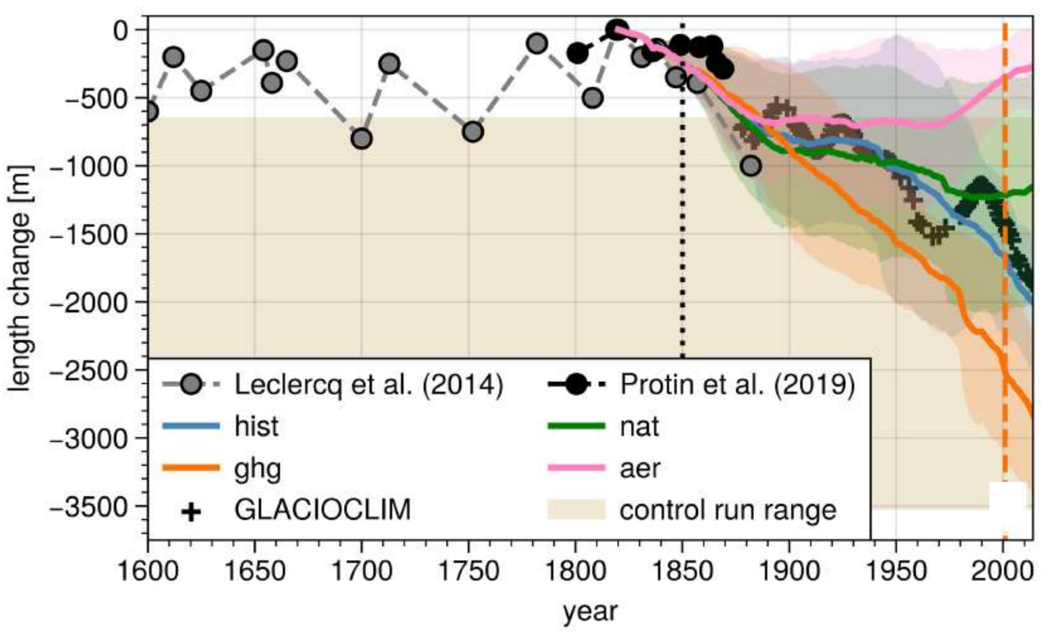
Discussion:

- ➔ generalizable to other glaciers ?
- ➔ aerosol effect on snow/ice albedo
- ➔ hypothesis on the statistical adjustment

Perspectives:

- ➔ multi-model approach
- ➔ application to other glaciers

Paper in rev.



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Thanks for your attention !

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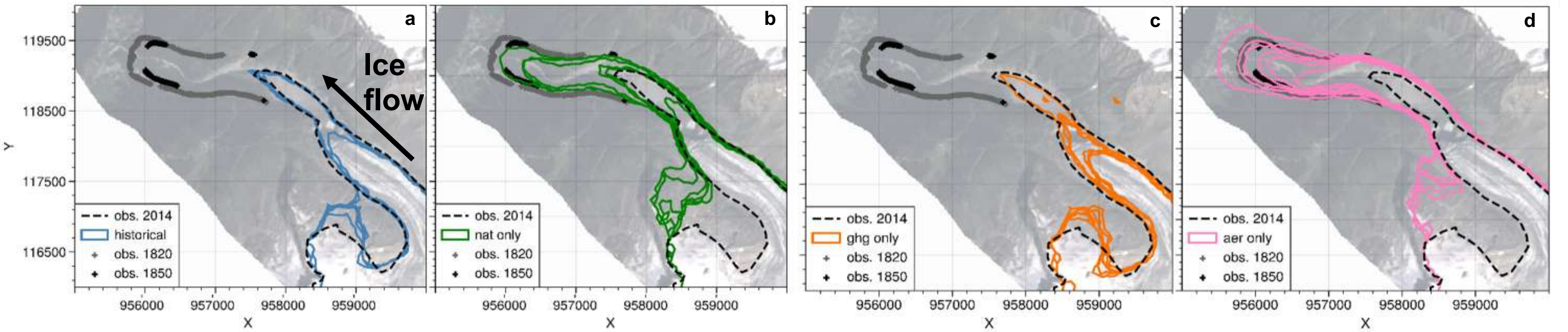
Simulation results



(a) Glacier extent for the individual (a) hist, (b) nat, (c) ghg and (d) aer members in 2014. Coordinates are given in meters in Lambert Centre France coordinates (EPSG:27562). Background picture is a Landsat 8 (band L1) georeferenced photograph taken on 03/09/2014, black dashed line is the corresponding glacier extent. 1820 and 1850 observations are from Protin et al. (2019)

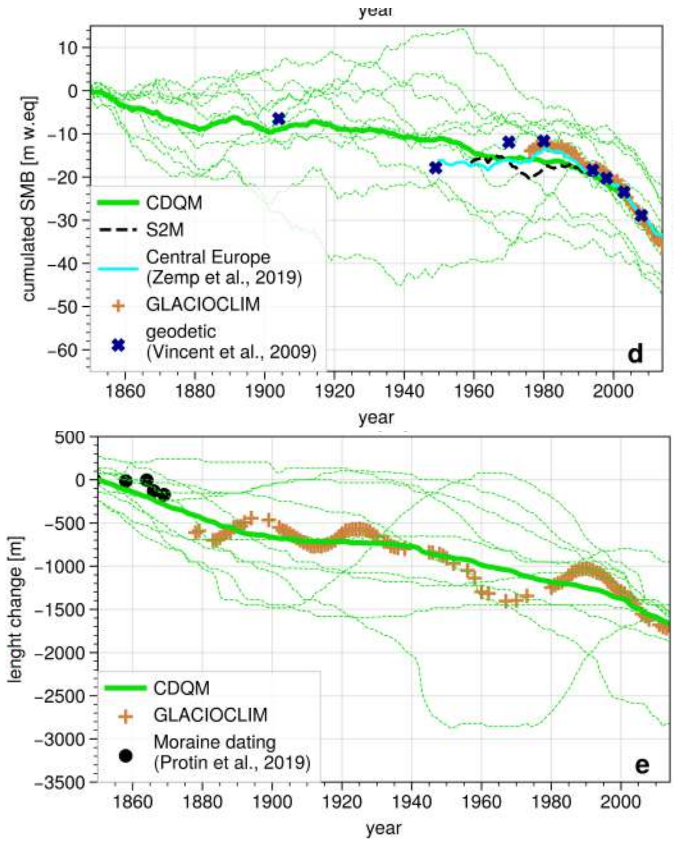
➔ ***HIST***
- close to 2014 observations
- strong retreat

➔ ***NAT***
- strong variability

➔ ***GHG***
- warming effect
- stronger decline than HIST

➔ ***AER***
- cooling effect
- close to 1850 observations
- variability

- ➔ Ensemble mean close to observations
- ➔ Large member spread

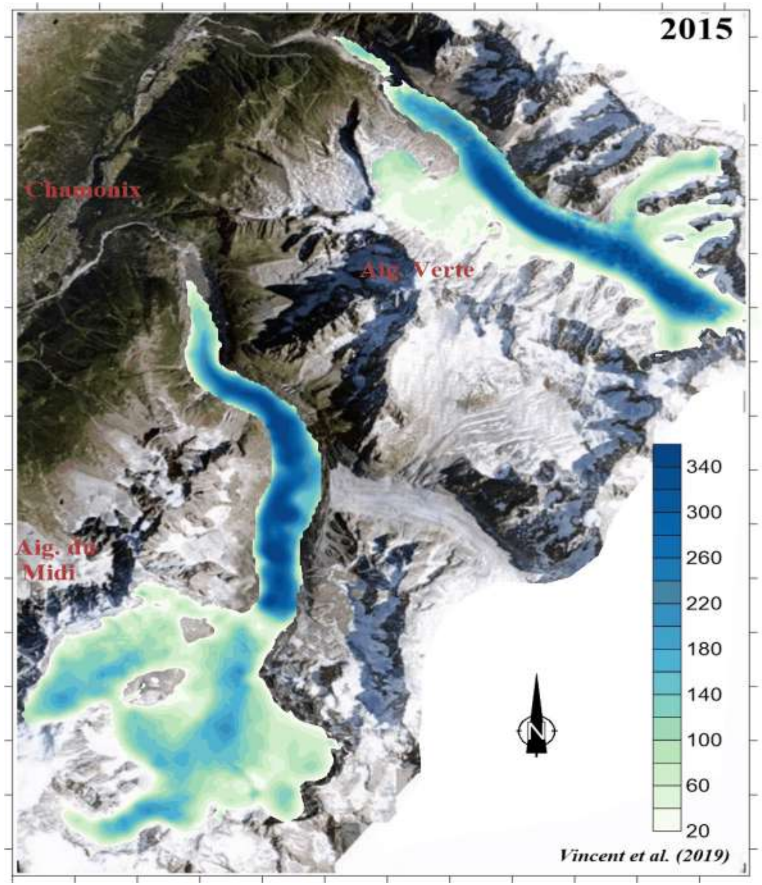


Surface Mass Balance

Glacier length change

Historical simulations

- ➔ Ensemble mean close to observations
- ➔ Large member spread



Argentière

Mer de glace

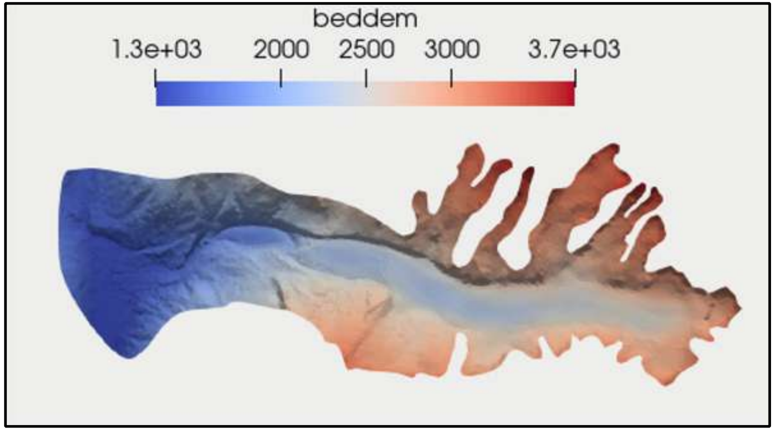
Glaciological model

3D ice flow model:
- ➔ Full-Stokes finite element solvers
- ➔ Refining meshing in front position
- ➔ Digital Elevation Model for bedrocks

Surface Mass Balance model:
- ➔ parameterized model (temperature-index)
- ➔ spatialization of T and P (each node)
- ➔ Accumulation : ***A=P if T<1°C***
- ➔ Melt derived from energy (*Oerlemans, 2001*)

Calibration :
- ➔ period 1975-2014
- ➔ observational data (*GLACIOCLIM*)

Initialization
- ➔ 1820 : stable state (*Protin et al., 2019*)
- ➔ 1820-1850 spin-up : initialize dynamics



Digital Elevation Model of Argentière glacier catchment