Modèles théoriques de l'interaction vent-vagues et des flux air-mer

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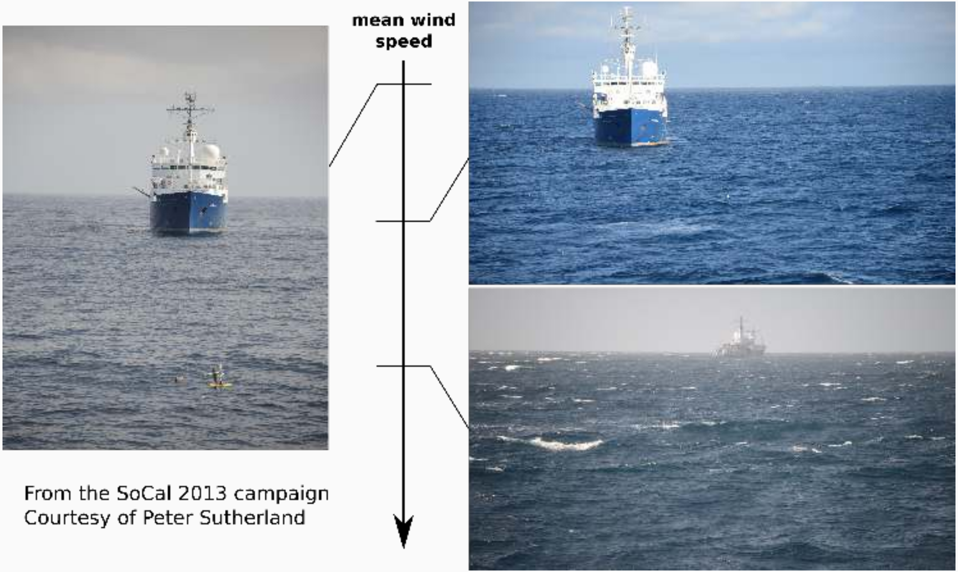
Outline

Introduction (I): the sea surface, a complex boundary



From the SoCal 2013 campaign
Courtesy of Peter Sutherland

Introduction (I): the sea surface, a complex boundary

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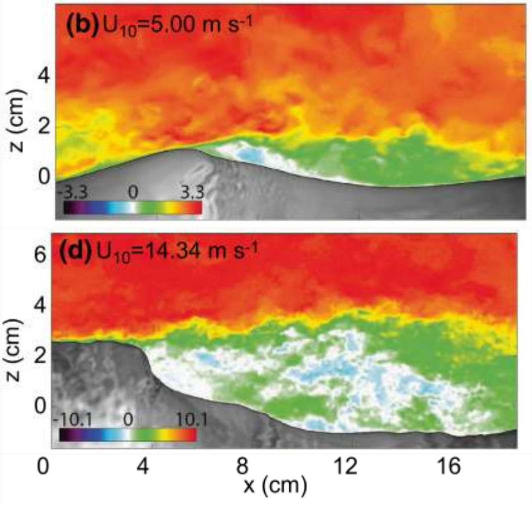
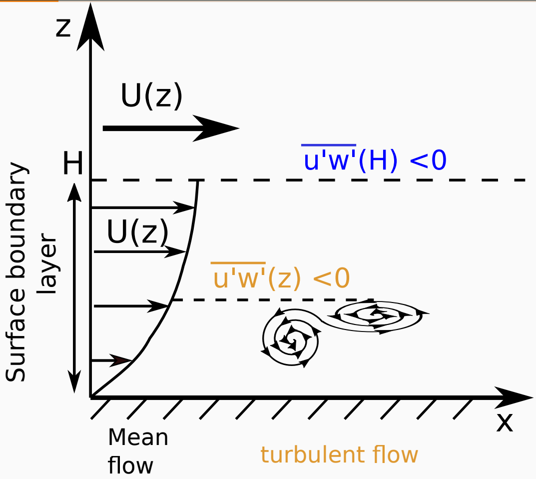


Laboratory measurements, *Buckley and Veron (2016)*

Introduction (II): turbulent momentum fluxes



- Reynolds decomposition:

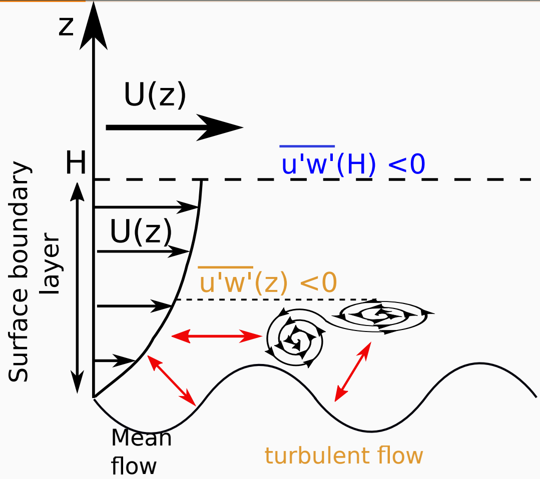
$$u = \overline{u} + u' = U + u'.$$

- Non-linear terms in NS: exchange of momentum mean flow ↔ turbulence

$$\frac{dU}{dt} = \cdots - \frac{d\overline{u'w'}}{dz}$$

- $-\overline{u'w'}(H) = u_*^2$: "surface" momentum flux (at the SBL top), parameterized in numerical models.

Introduction (II): turbulent momentum fluxes



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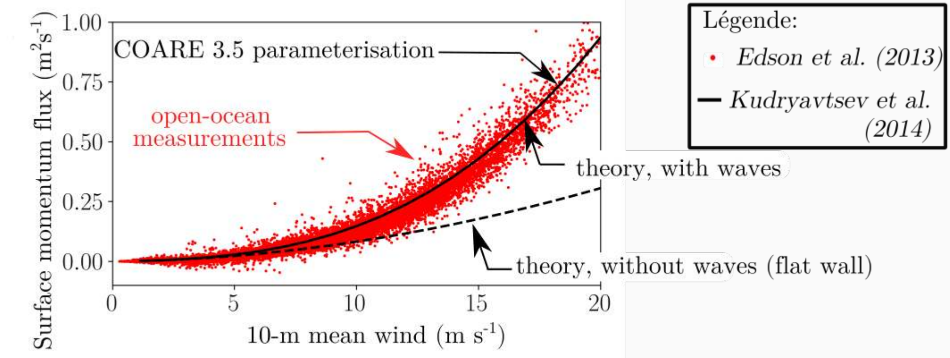
Surface momentum fluxes are impacted by the presence of waves

Surface momentum fluxes

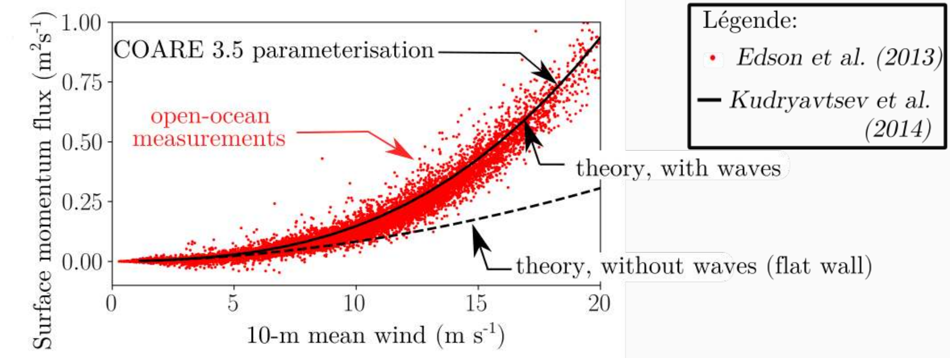


Open ocean data (dots) and best fit (solid black line), from *Edson et al. (2013)*.

Surface momentum fluxes are impacted by the presence of waves

Introduction (III): parameterization of momentum fluxes

Surface momentum fluxes

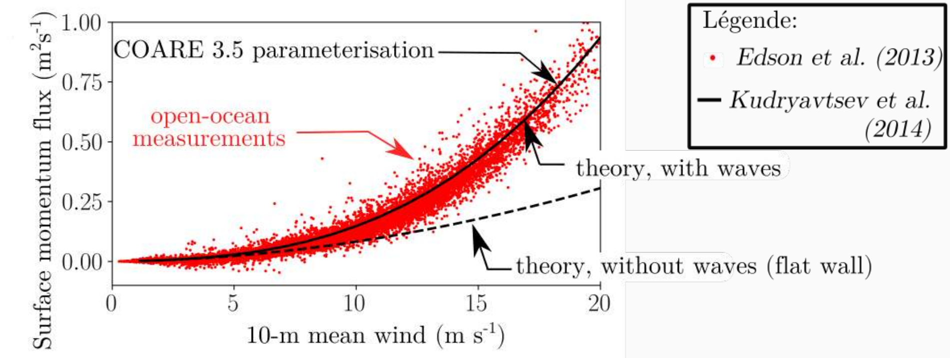


Open ocean data (dots) and best fit (solid black line), from *Edson et al. (2013)*.

The best fit is a parameterization of surface momentum fluxes

It represents a local equilibrium between wind and waves

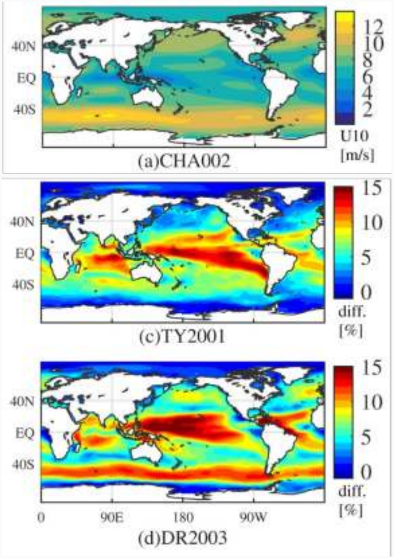
Surface momentum fluxes



Open ocean data (dots) and best fit (solid black line), from *Edson et al. (2013)*.

What part of this variability (for a given 10 m wind) results from wind and waves?
Is it underestimated? What are its driving parameters?

Introduction (IV): variability of atmospheric turbulence

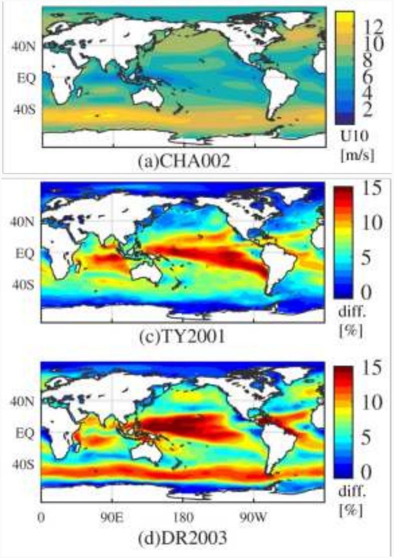


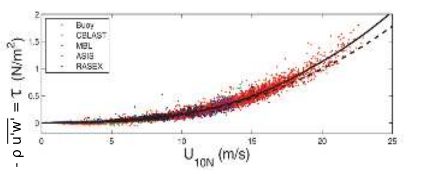
This variability has important consequences on planetary-scale atmospheric circulation

Left figure: *Shimura et al. 2017*
50-year averaged fields from an atmospheric model for different parameterizations of $\overline{u'w'}(H)$.

What are the limitations of such parameterizations?

Introduction (IV): variability of atmospheric turbulence





Parameterizations and measurements are **based on a theoretical description** of the local interaction between wind and waves

What are the limitations of wind-over-waves theoretical models?

Outline

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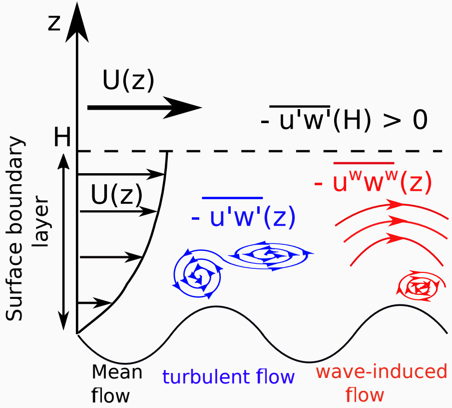


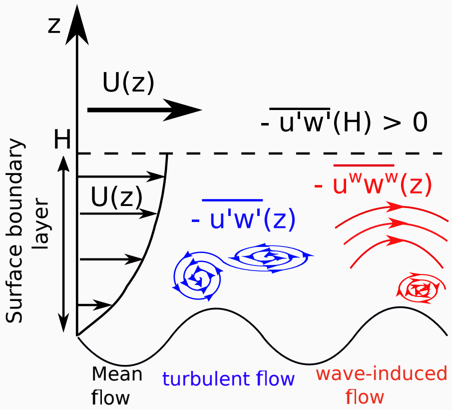
1. Define:
   - a Reynolds average $\bar{\cdot}$ filtering turbulent motions
   - a wave average $< \cdot >$ filtering wave-coherent motions.
2. Triple decomposition of atmospheric variables

$$u = U + u' + u^w$$

3. Momentum balance on the vertical direction with horizontal homogeneity and stationarity

Momentum balance in the wave boundary layer

$$<\overline{u'w'}>(H) = \underbrace{- <\overline{u'w'}>(z)}_{\text{Reynolds stress}} \underbrace{- <\overline{u^w w^w}>(z)}_{\text{wave-induced stress}}$$



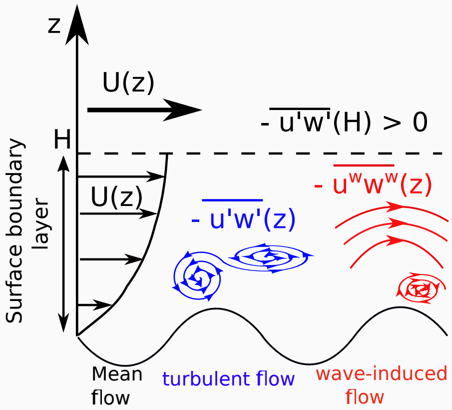
TKE balance in the surface boundary layer with waves

$$\underbrace{-<\overline{u'w'}>\frac{\partial U}{\partial z}}_{\text{mechanical prod.}}\underbrace{-<\overline{u^w w^w}>\frac{\partial U}{\partial z}}_{\text{wave production}}+\underbrace{\frac{g}{\theta_r}<\overline{w'\theta'}>}_{\text{buoyancy}}=\epsilon$$

where ϵ is TKE dissipation. Standard closure close to a wall:

$$\epsilon(z)\propto -z^{-4}<\overline{u'w'}>^3(\partial U/\partial z)^{-3}$$

Wind-over-waves models (II): TKE dissipation



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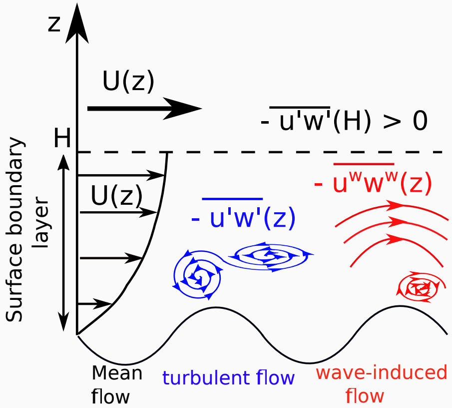

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What are the limitations of the representation of wave-induced stress ?

Wave induced stress depends on the wave growth rate: β

Limitations of wind-over-waves models (I): a complex wave life cycle

Wave induced stress depends on the wave growth rate: β

- Statistical description of the spectrum for short gravity wind-waves:

> wind input = dissipation by wave breaking

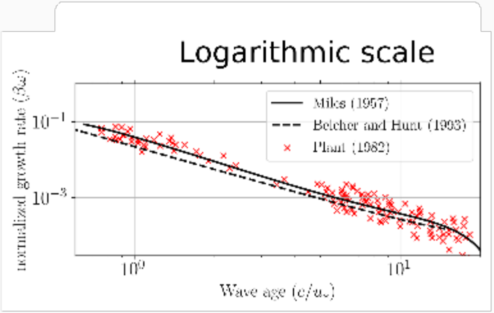
- wave growth depends on the life cycle of individual waves

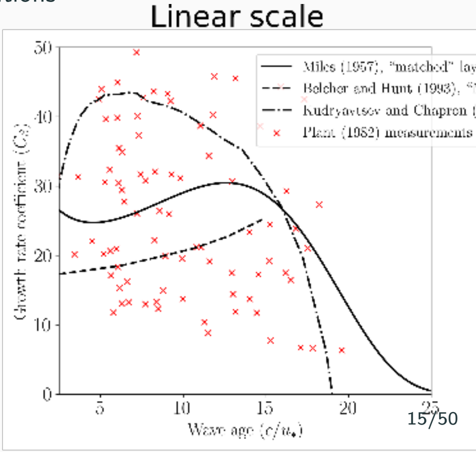
Ayet & Chapron, 2022

Limitations of Wind-over-waves models (II): wave growth representation

Wave induced stress depends on the wave growth rate: β

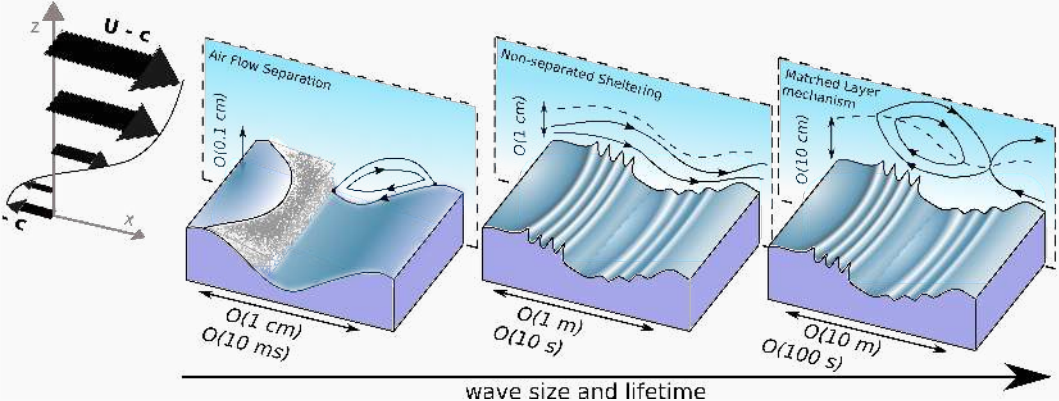
- Models of wave growth developed for single monochromatic waves
- Still a lot of uncertainties even for controlled lab conditions





Limitations of Wind-over-waves models (III): multiscale interactions

Multiscale both for turbulence and waves, potentially interacting



Ayet & Chapron 2022

Limitations of Wind-over-waves models (IV): Conclusion

Limitations of wind-over waves models due to wave-induced stress: no **explicit** representation of :

- wave growth and of the complex life cycle of non-stationary waves
- Multiscale interactions: both for waves and turbulent processes

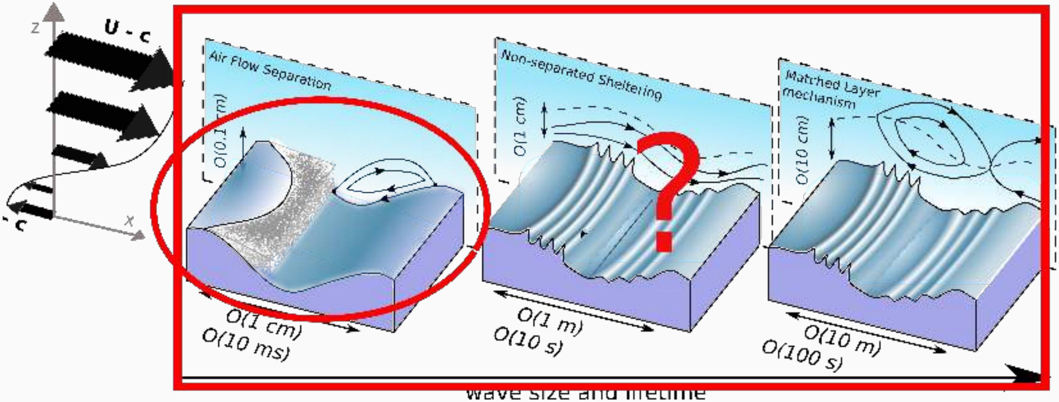
These processes are "hidden" in averaged theories: difficult to study the **sensitivity to external parameters**.

For more details, see the review Ayet & Chapron (2022)

Rest of the thesis:

Use a multiscale theoretical framework for atmospheric turbulence to improve the theoretical understanding of wind and waves

Questions addressed during this thesis



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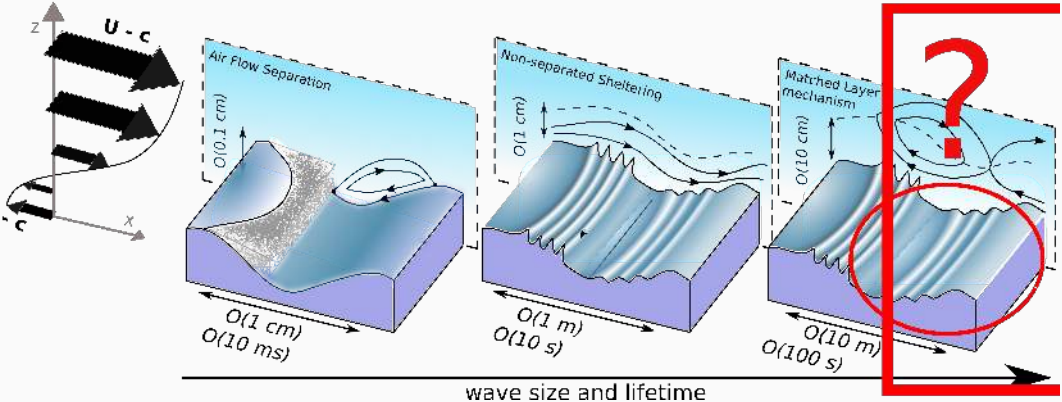
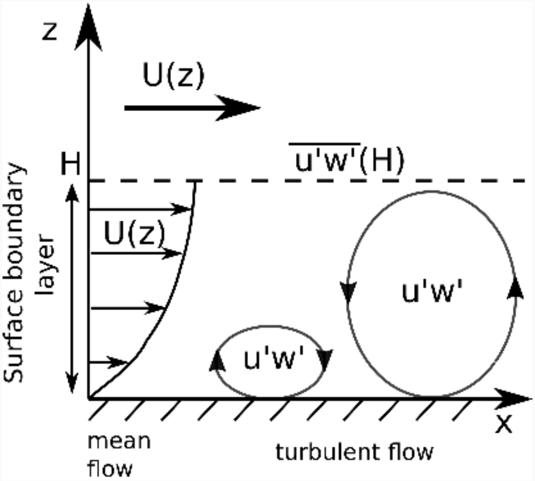


Outline

Turbulence description (I)

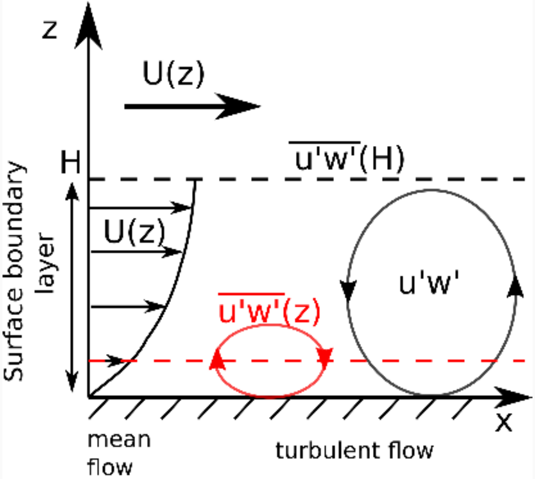


- Framework: *Gioia et al.* (2010); *Katul et al.* (2011).
- TKE balance whitout waves

$$\underbrace{-\overline{u'w'}}_{?}\underbrace{\frac{dU}{dz}+\frac{g}{\theta_r}\overline{w'\theta'}}_{\text{given}}=\epsilon$$

+ horizontal homogeneity and no subsidence

Turbulence description (I)



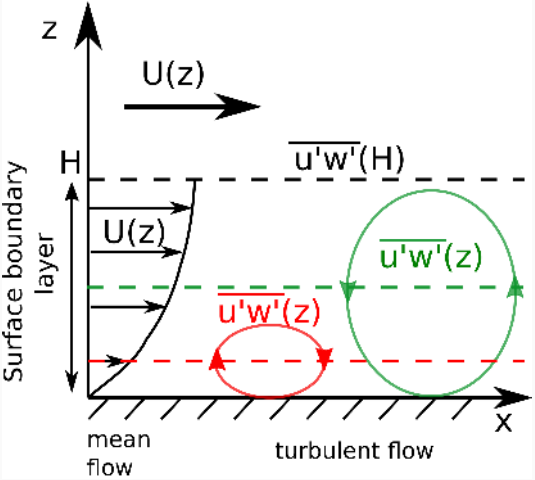
TKE balance

$$-\overline{u'w'}\frac{dU}{dz} + \frac{g}{\theta_r}\overline{w'\theta'} = \epsilon$$

Aim: get a closure for ϵ

Gioia et al. (2010) focus on the "most energetic turbulent structures at a given height": attached eddies (*Townsend* 1980)

Turbulence description (I)



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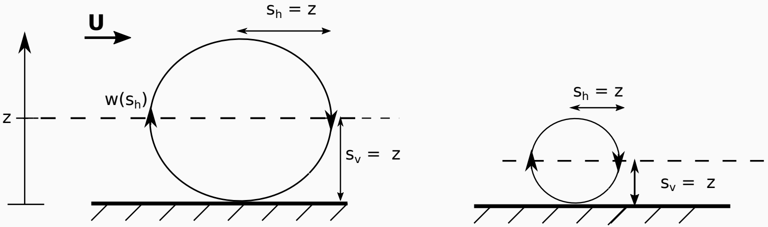
Turbulence description (II): TKE dissipation



TKE dissipation at height z, related to the shape of the most energetic turbulent structure

$$\epsilon(\mathrm{z}) \propto -\overline{u'w'}^3 \left(\frac{\partial u}{\partial z}\right)^{-3} \underbrace{s_v^{-3}(\mathrm{z}) s_h^{-1}(\mathrm{z})}_{\text{shape of the structure}} , \quad \text{with } s_v = z.$$

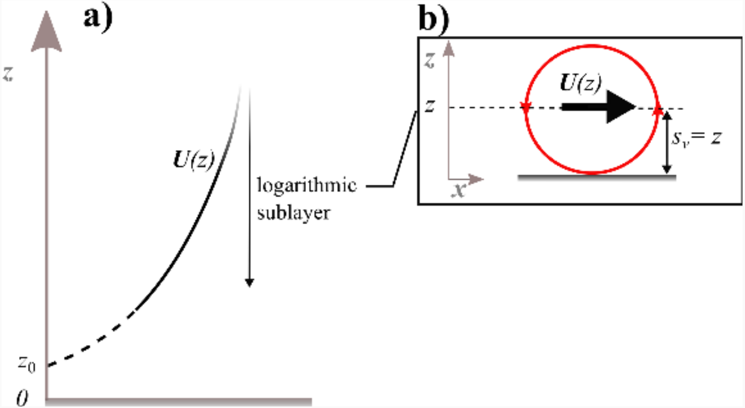
For neutral conditions, "isotropic" structures $s_h = s_v = z \longrightarrow$ log. profile.

The model is related to a spectral (multiscale) representation of turbulence.

Limitations of this model, see *Ayet & Katul 2020 GRL* and *Ayet et al. 2020 JGR atmospheres*

Outline

Effective parameter (I): turbulence model



Bonetti et al. (2017) extended the phenomenological model to rough surfaces

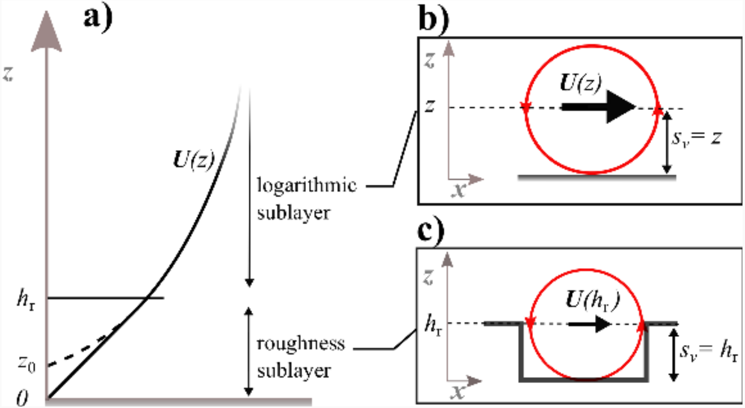
- A logarithmic layer

$$s_v = z \text{ for } z > h_r$$

- A roughness sublayer of height h_r in which

$$s_v = h_r \text{ for } z \leq h_r$$

Effective parameter (I): turbulence model



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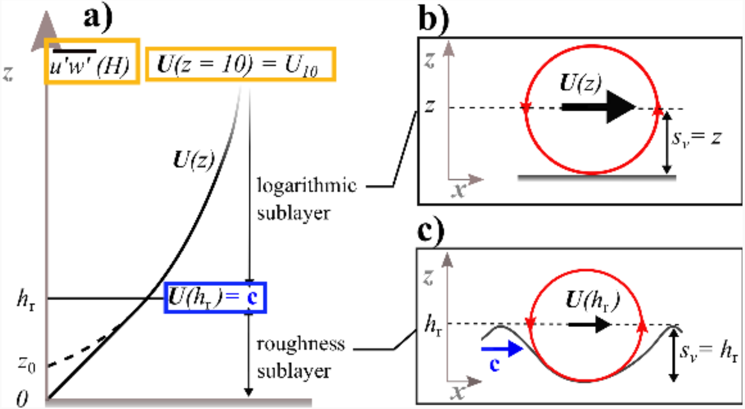
Effective parameter (II): extension above waves



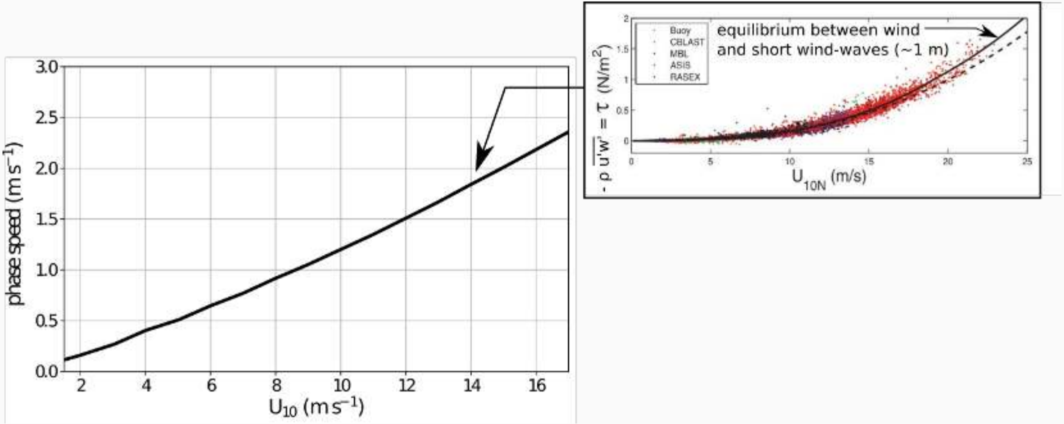
Ayet et al. (see ArXiv)

- **Hypothesis:** there exists a *representative speed* c associated to breaking waves that controls shear in the roughness sublayer
- **Conclusion:** $U(h_r) = c$

$$c \sim 2.5 \times u_*$$

  Similar to *Melville* (1977).
- c depends solely on bulk atmospheric data u_* or U_{10}.

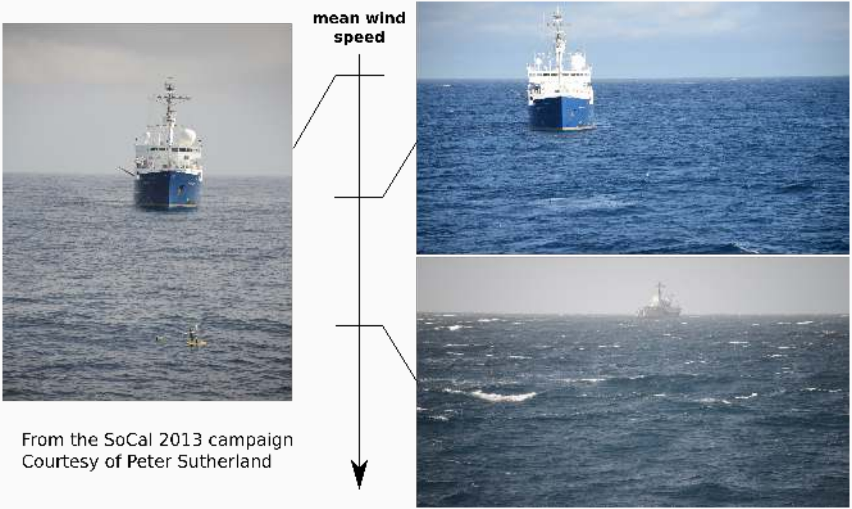
Effective parameter (II): extension above waves



The representative wave phase speed is that of short wind-waves (from cm to m)

Effective parameter (III): wave breaking measurements

Visually, changes in short (< 1m) wind-waves can reflect changes in wind (Beaufort scale).



From the SoCal 2013 campaign
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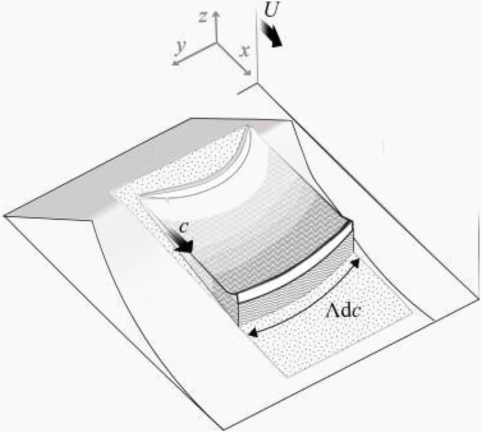
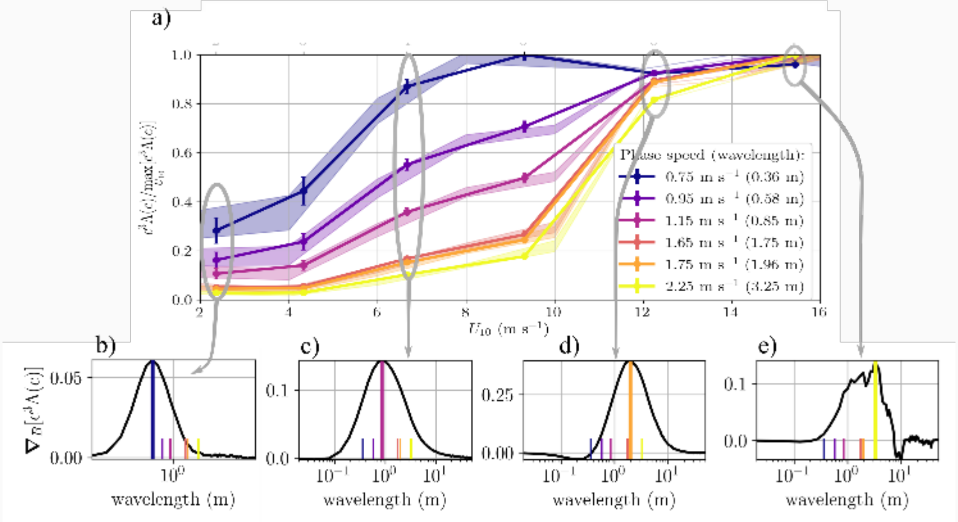
Effective parameter (III): wave breaking measurements

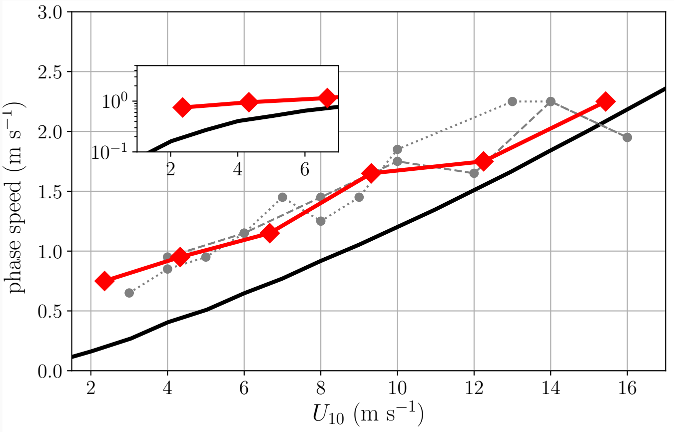


- $\Lambda(c)dc$: breaking fronts length / unit area / unit time at a given wave phase speed c (*Phillips* (1985))
- We use infrared measurements of $\Lambda(c)$ (*Sutherland and Melville* 2013, 2015) from open ocean field campaigns in the Pacific.

Analysis of the variations of $c^3\Lambda(c)$ with 10-m mean wind speed.



Effective parameter (IV): results



-black solid: Turbulence model **-red and grey**: Wave-breaking infrared measurements

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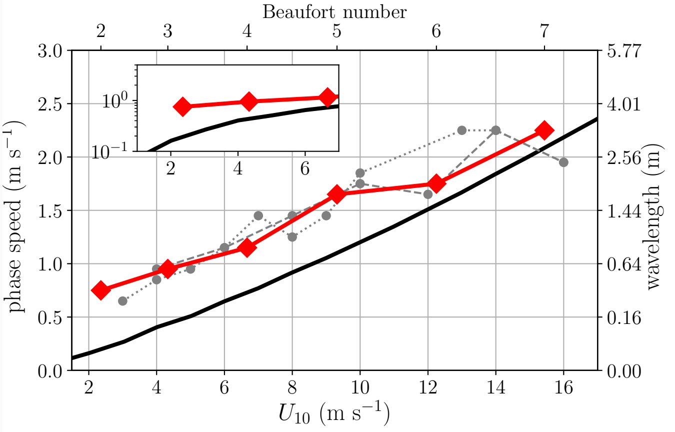

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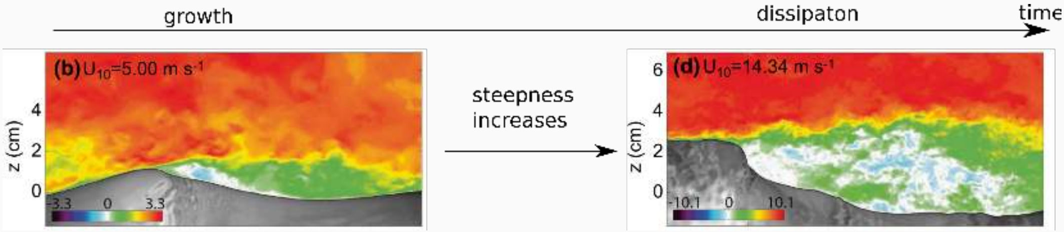
The speed of wave breaking fronts sets the wind-and-waves coupling

Ayet et al., (see ArXiv)

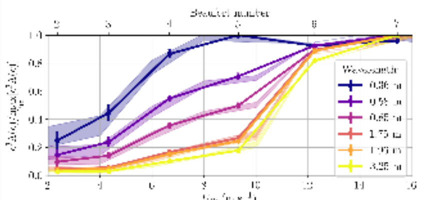
Why does this speed appear? An hypothesis



- wind creates a vortical layer and wind drift q :
  $q = 0.55u_*$
- Critical steepness for breaking: $s_c(c) = 1/2(1 - q/c)^2$
- Representative speed: $c \sim 5 \times q \longrightarrow$ drift-affected waves.

Saturation of Λ:

- increase in u_*
- decrease in s_c
- increase in wave breaking density



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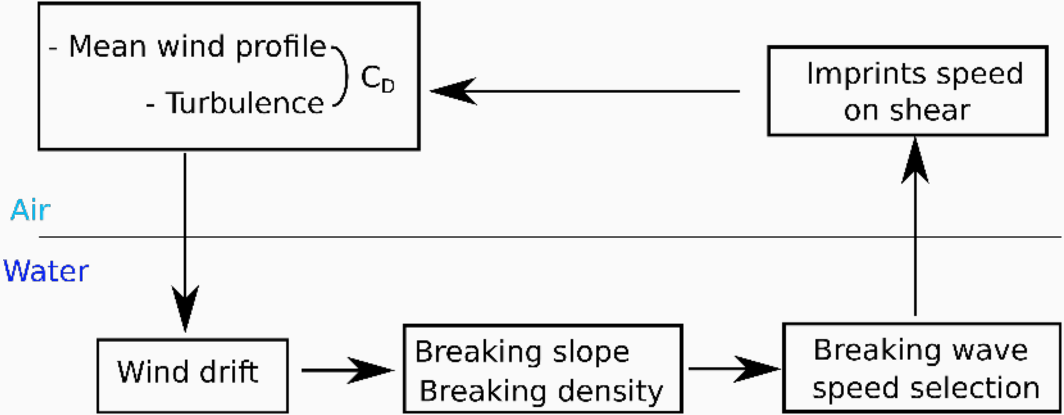

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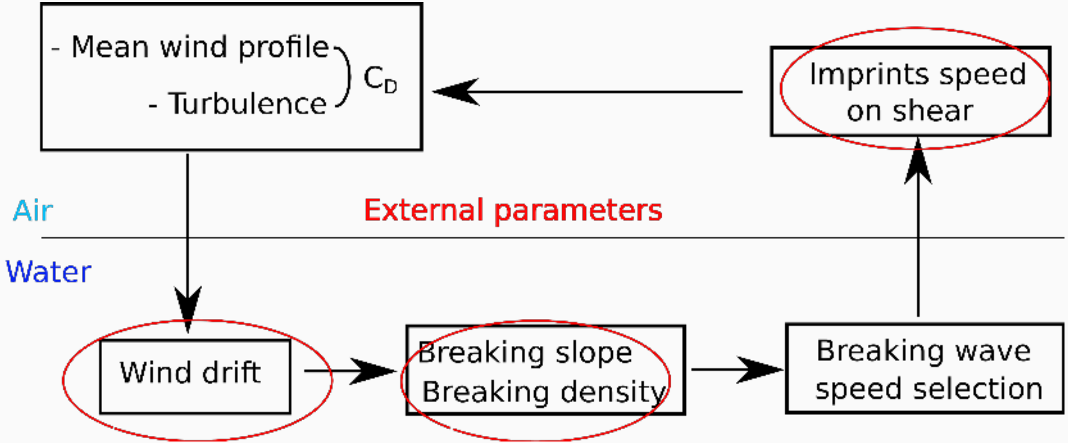

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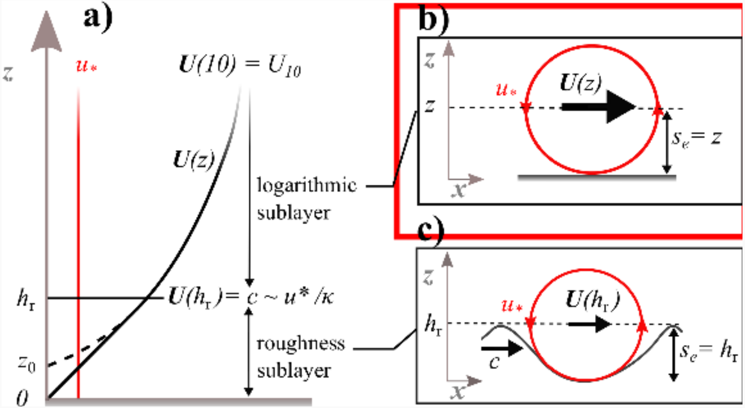
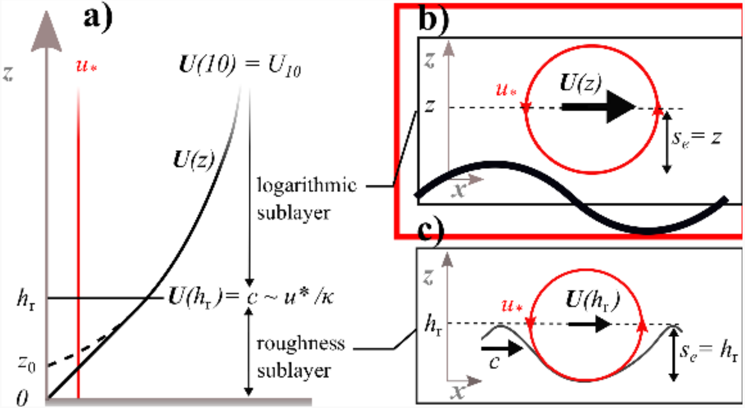


- The processes governing wave-turbulence interactions change with height
- **What happens to eddies in the logarithmic sublayer, when waves are included?**

Long wind-waves (I): motivation



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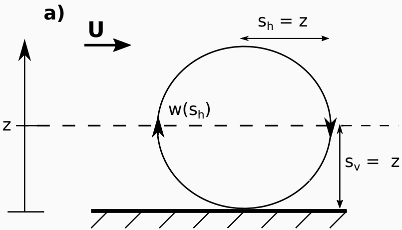
Long wind-waves (II): more on the turbulence model



TKE dissipation at height z, related to the shape of the most energetic turbulent structure

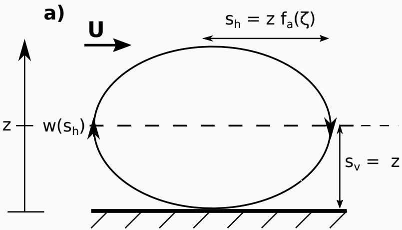
$$\epsilon(z) \propto -\overline{u'w'}^3 \left(\frac{\partial u}{\partial z}\right)^{-3} \underbrace{s_v^{-3}(z) s_h^{-1}(z)}_{\text{shape of the structure}} \;, \quad \text{with } s_v = z.$$

For neutral conditions, “isotropic” structures

$$s_h = s_v = z;$$

the logarithmic wind profile is recovered.

Long wind-waves (II): more on the turbulence model



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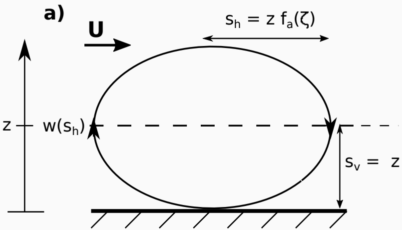
Katul et al. (2011): stability effects → "anisotropic" structures:

$$s_h = f_a(\zeta) s_v.$$

$\zeta = z/L$ is the stability parameter and L Obukhov's length. $\zeta > 0$ stable, $\zeta < 0$ unstable atmosphere.

Long wind-waves (II): more on the turbulence model



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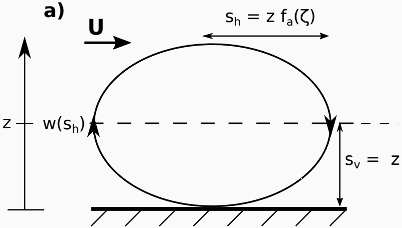
Katul et al. 2014 show that this model is consistent with MOST (flat wall)

Long wind-waves (III): inclusion of waves in the model



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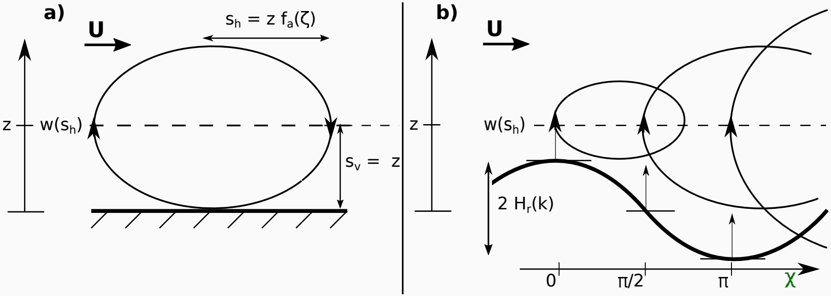
How do waves reorganize turbulent structures?

Long wind-waves (III): inclusion of waves in the model



For a monochromatic wave, depending on the phase χ between the turbulent structure and the wave,

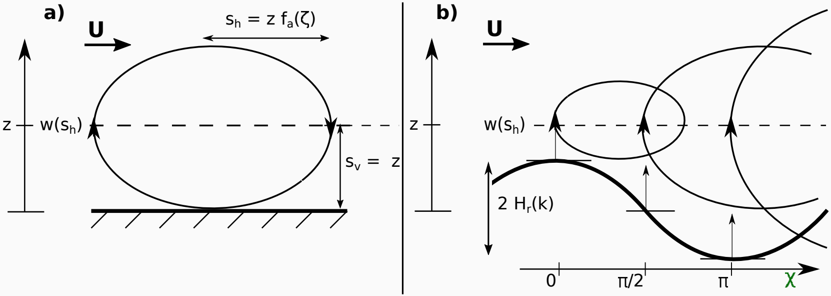
$$\tilde{s}_h(\chi) = f_a(\zeta)[z - H_r(k)\cos\chi)].$$

The mean eddy size reads:

$$s_h^w = \int p(\chi)\tilde{s}_h(\chi)d\chi$$

where $p(\chi)$ is the p.d.f. of each of the configurations.

Long wind-waves (III): inclusion of waves in the model



Result

$$s_h = \underbrace{z f_a(\zeta)}_{\text{stratification}} + \gamma \underbrace{[k^2 S(k)]^{1/2}}_{\text{long wind-waves!}}, \quad \text{with } k = \frac{\pi}{z}$$

γ depends on the strength of the modulation of short wind-waves by long wind-waves.

Rewritten as $s_h(z) = z f_a(\zeta) g_e(z, \gamma, k^2 S)$

TKE dissipation becomes

$$\epsilon = - < \overline{u'w'} >^{3} \left(\frac{\partial u}{\partial z}\right)^{-3} (\kappa z)^{-4} \underbrace{f_a(\zeta)^{-1}}_{\text{Stratification}} \underbrace{g_e(z, \gamma, k^2 S)^{-1}}_{\text{waves}}.$$

The mechanism depends on $k^2 S(k)$: **long wind-waves, of the order of 10 m**.

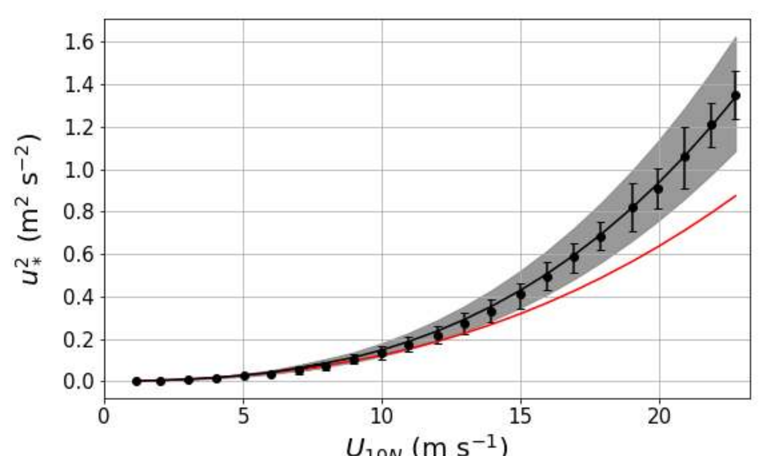
Turbulence Kinetic Energy equation

$$- < \overline{u'w'} > \frac{\partial U}{\partial z} - < \overline{u^w w^w} > \frac{\partial U}{\partial z} + \frac{g}{\theta_r} < \overline{w'\theta'} > = \epsilon$$

Long wind-waves more sensitive than short wind-waves to external parameters.

Long wind-waves (IV): result

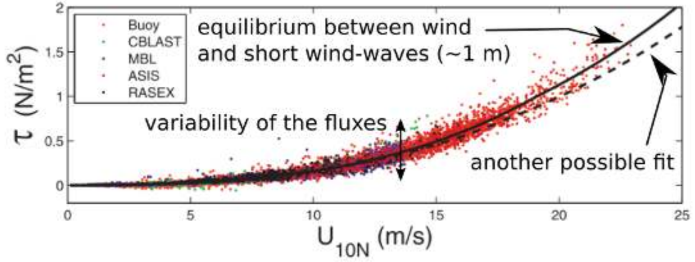
Long wind-waves more sensitive than short wind-waves to external parameters. (*Ayet et al.*, BLM 2020)

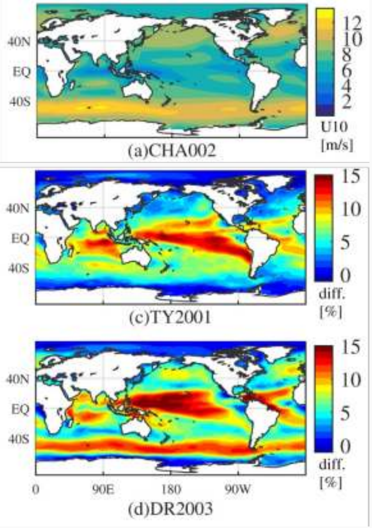


-bins: *Edson et al.* (2013) measurements
-solid black: COARE parameterization
-solid red: momentum fluxes whitout waves
-grey shadings: variations of TKE dissipation

Outline

Motivation: variability of surface momentum fluxes

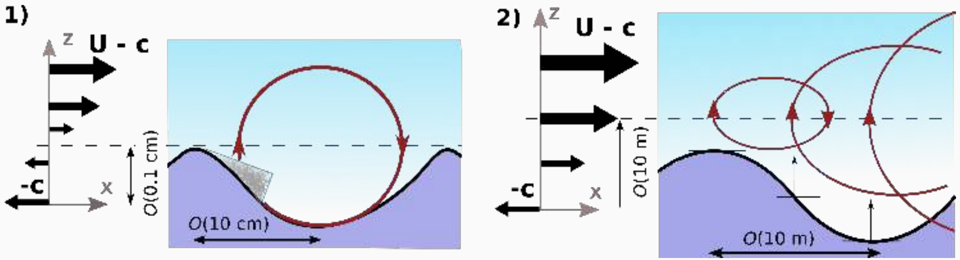




Approach: theoretical modeling

Conclusion

- Limitations of wave-induced stress/ wave growth in theoretical models: multiscale interactions and wave lifecycle (growth and breaking)
- There exists a breaking wave phase speed which describes the wind-over-waves equilibrium
- Long wind-waves affect TKE dissipation and introduce variability in momentum fluxes.
- The phenomenological model is linked to a spectral view of turbulence



Ayet & Chapron (2022)

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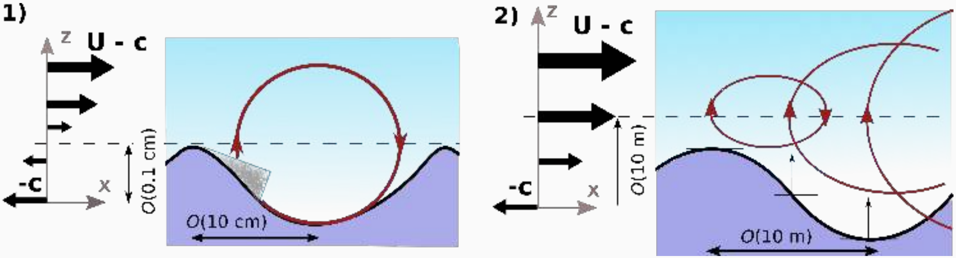

Ayet & Chapron (2022)

multiscale interactions and wave lifecycle (growth and breaking)

There exists a breaking wave phase speed which describes the wind-over-waves equilibrium

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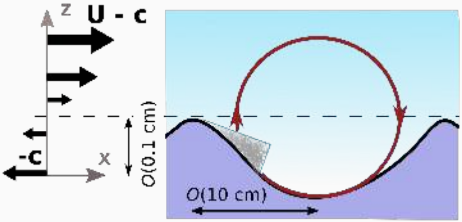

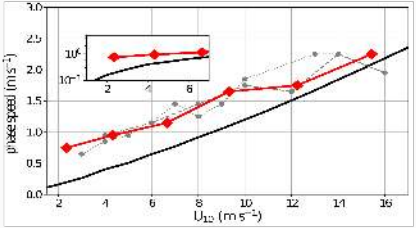

Ayet et al. ArXiv (submitted to JFM)

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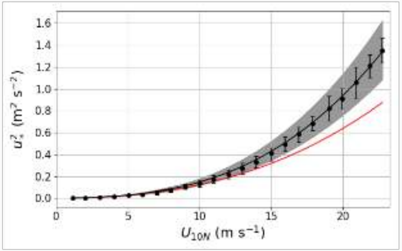

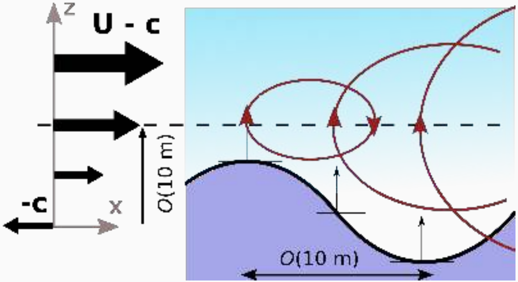

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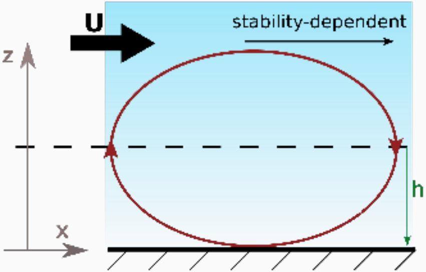
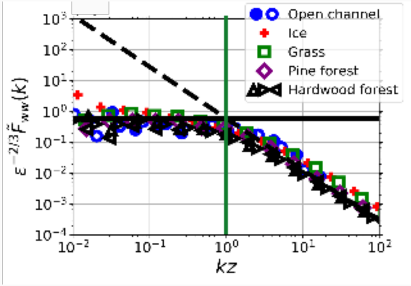




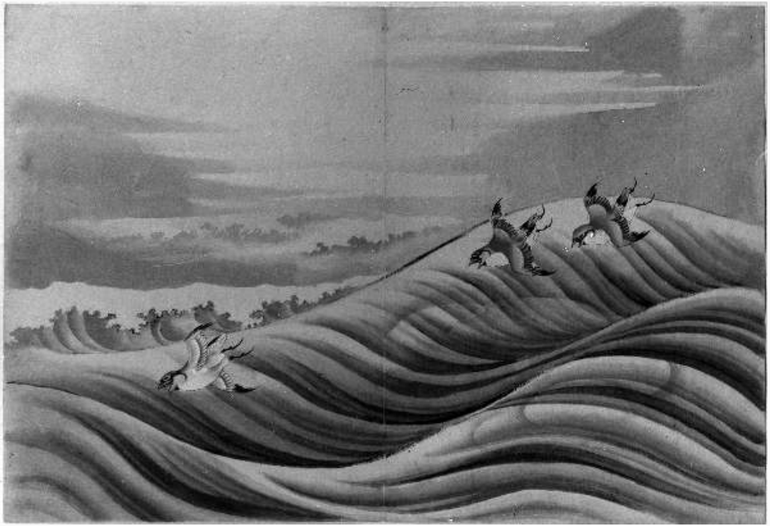
Perspectives

- Inclusion of the effect of currents on the wind-over-waves system through

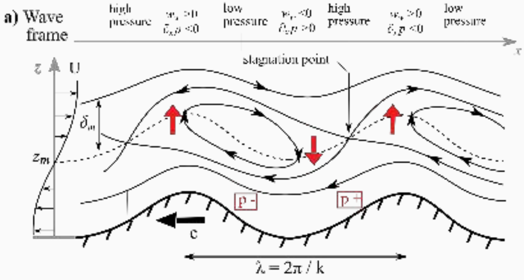
1. their effect on short breaking waves
2. their effect on long wind-waves

- Understand the effect of the averaging method on momentum fluxes.
- Build an emulator of wind-waves for satellite roughness measurements (SWOT)
- Towards a spectral description of the interaction between turbulence and wind-waves.

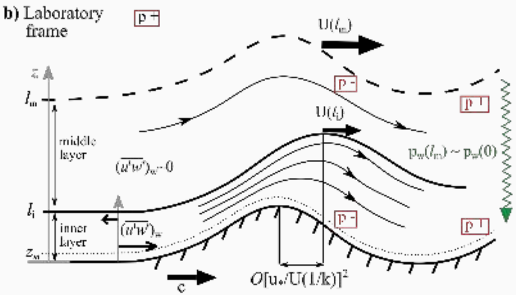
Thank you



Details on wave-induced stress (I)



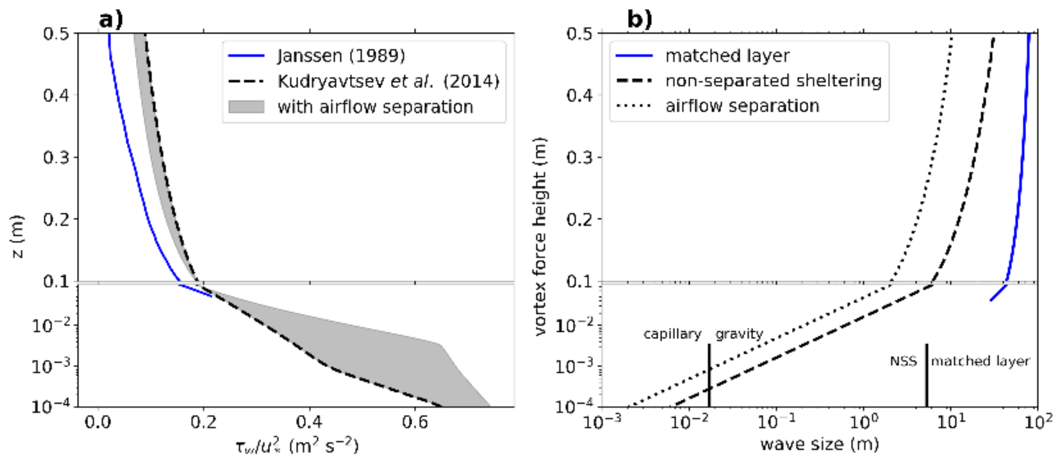
Critical layer mechanism: Miles (1957)
longer waves



Non-separated sheltering: Belcher and Hunt (1992)
shorter waves

- *Miles* (1957): no turbulence, definition of a critical layer.
- *Belcher and Hunt* (1993): for short waves, inclusion of $\overline{u'w'}^w = \overline{u'w'} - \langle \overline{u'w'} \rangle$.

Details on wave-induced stress (II)



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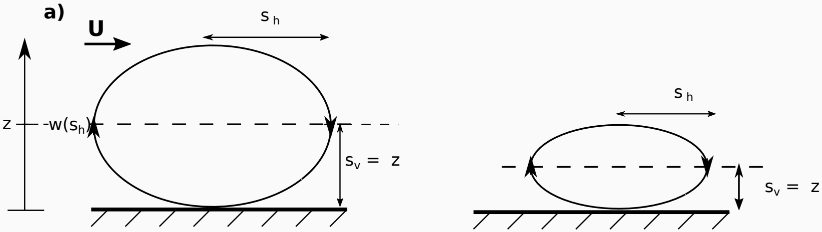
Details on the phenomenological model



1. Momentum fluxes are estimated from the shape of the turbulent structure (*Gioia et al.* 2010):

$$-\overline{u'w'}(z) = \kappa_T|w(x+2s_h) - w(x)|[u(z+s_v) - u(z-s_v)]$$

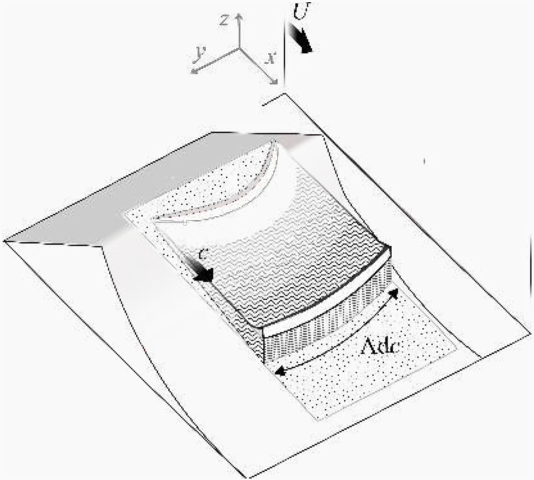
$$\sim \kappa_T|w(x+2s_h) - w(x)|\frac{du}{dz}\,2s_v, \text{ with } s_v = z.$$

   Structures are attached to the wall (*Townsend* 1980)

2. Kolmogorov's scaling for the structure function.

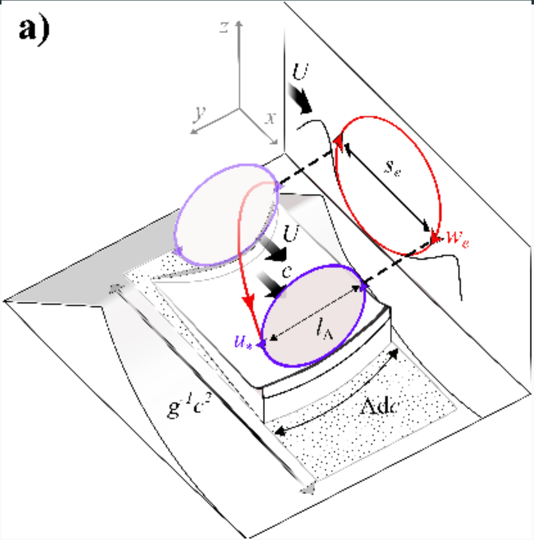
$$|w(x+2s_h) - w(x)| = (\kappa_\epsilon \epsilon s_h)^{1/3}.$$

Coupling between breaking waves and turbulence (I)



- $c^3\Lambda(c)$: volume of air/unit area/time entrained in the ocean by breaking waves *Deike, Lenain and Melville* (2017), *Deike and Melville* (2018)
- *Ericsson et al.* (1999): surface disturbances after a breaking crest have an isotropic spectra (with direct cascade)
- *Newell and Zackharov* (1992): $P \propto c_b^3$, the energy flow towards this cascade
- *Kudryavtsev et al.* (2014): this is related to the roughness generated by breaking waves.
- $c^3\Lambda(c)$ can be related to the energy flux controlling the roughness elements generated by breaking waves.

Coupling between breaking waves and turbulence (II)



- The transverse direction of breaking fronts leaves on imprint on turbulence l_Λ
- In a log layer, there exists a minimal l_Λ corresponding to the representative roughness element
- $c\Lambda(c)$: fraction of sea surface turned over by breaking fronts/unit time (*Phillips* 1985)
- $g^{-1}c$: lifetime of the breaking events (*Reul and Chapron* 2003)
- c: momentum of the breaker front.
- Those three processes are important in $c^3\Lambda(c)$.

Details on the wave-related physics (I)

Waves are characterized by their **directional spectrum** $S(k,\psi)$

k: wavenumber magnitude; ψ wavenumber direction

- Wind $\rightarrow$ waves: wind-waves growth rate (*Makin* 1999)

$$\beta(k,\psi) \propto \left[\frac{<\overline{u'w'}>(1/k)}{c(k)}\right]^2, \quad \text{for } U(1/k) < c$$

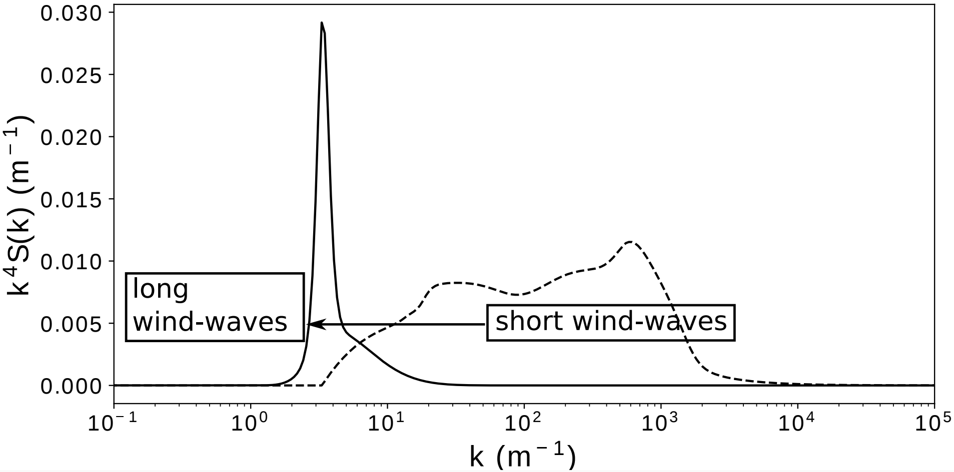
where $c = \sqrt{g/k}$ is the wave phase speed

- Waves $\rightarrow$ wind:

$$-<\overline{u^w w^w}> \propto \int \beta(k) k^4 S(k) dk$$

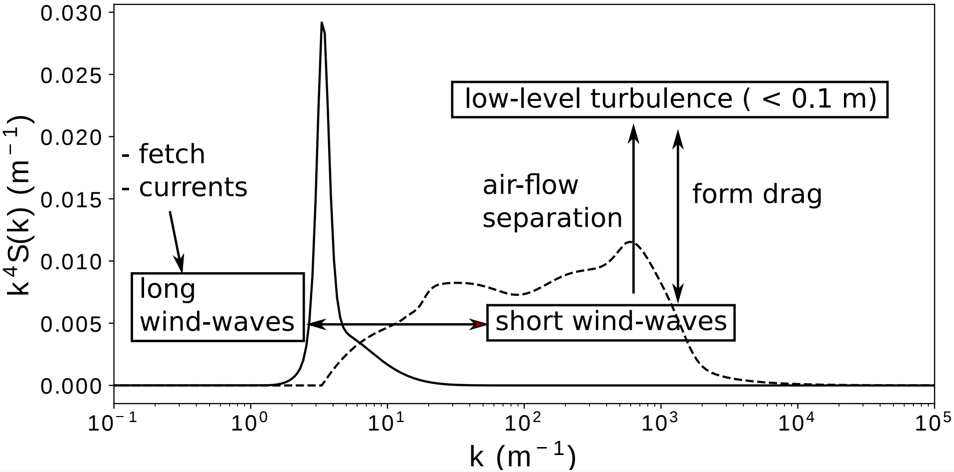
$k^4 S(k)$: relevant for **short wind-waves ($\leq$ 1m)**.

Details on the wave-related physics (II)



Example of the modeled saturation spectrum of a wind-wave field.

Details on the wave-related physics (II)



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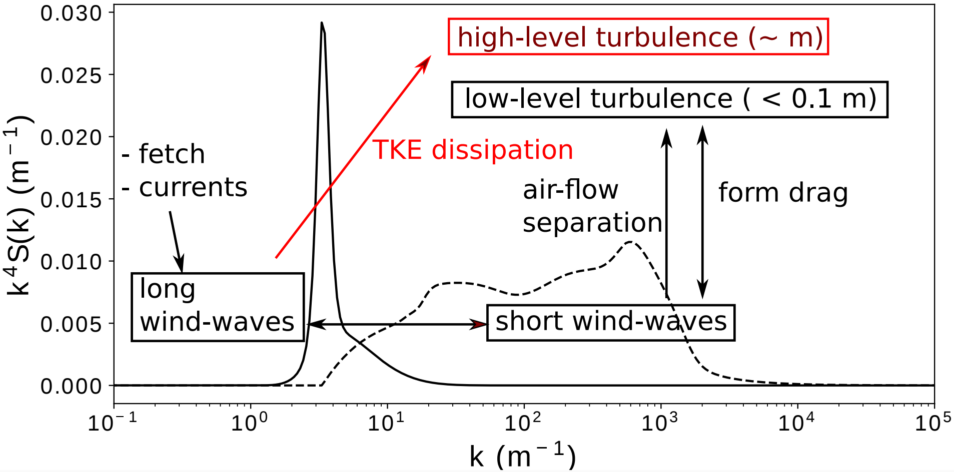


Example of the modeled saturation spectrum of a wind-wave field.

Heat fluxes (I)

Effect of wind-waves on heat fluxes

- Heat flux Q constant in the SBL (no "wave-induced stress")
- $Q = -\mathrm{Pr}^{-1}\frac{d\theta}{dz}$ where K is turbulence viscosity coefficient.

Results from *Kudryavtsev et al.* (2014)

Heat fluxes (II)

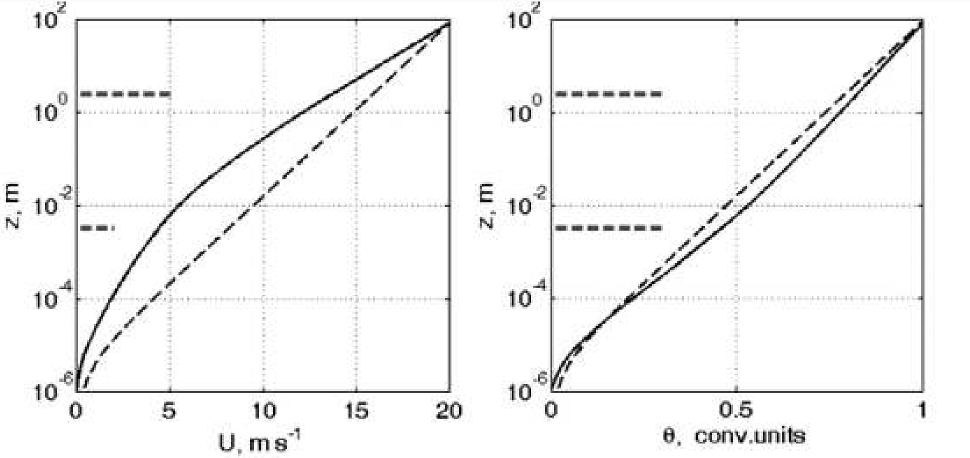


Figure 5. (left) The wind and (right) the air temperature profiles at 20 m/s wind speed at reference level $z = 100$ m. Dash lines show "reference" profiles when form drag is switched off (aerodynamically smooth surface). Solid lines show the full model calculations. Gray dash lines adjacent to the z axis indicate altitude of the impact of spectral peak wave (top line) and shortest breaking waves (bottom line) on the form stress.

Heat fluxes (III)

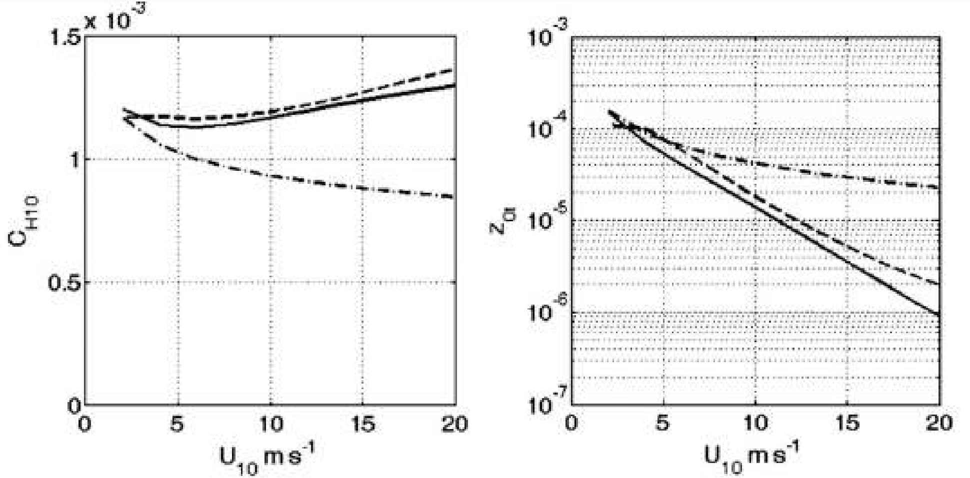


Figure 8. (left) Heat transfer coefficient and (right) the heat transfer roughness scale versus wind speed: dash lines show empirical dependences suggested by *Fairall et al.* [2003], COARE 3.0 data; dash-dotted lines are the heat transfer relations for the smooth surface (form drag is switched off); solid lines are the model calculations following (32) and (35).

Monin-Obkhov similarity theory (I)

Deine the dimensionless wind shear as

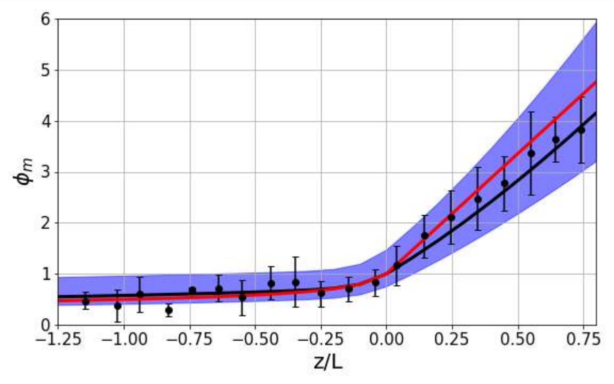
$$\phi_m = \frac{\kappa z}{u_*^l}\frac{\partial u}{\partial z}.$$

The TKE balance then reads

$$\phi_m^4 - (1-\alpha_c)^{-1/2}\zeta\phi_m^3 = (1-\alpha_c) f_a^{-1} g_e^{-1}.$$

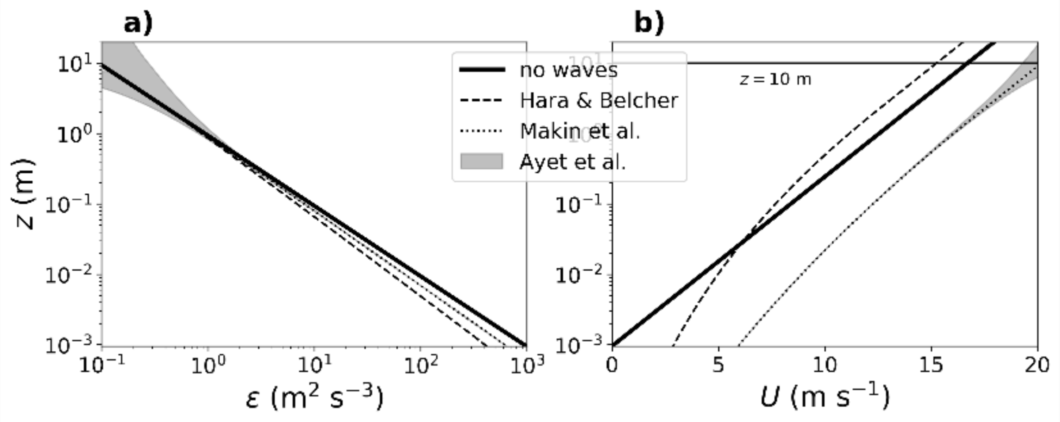
which generalizes the O'KEYPS equation

Monin-Obkhov similarity theory (II)

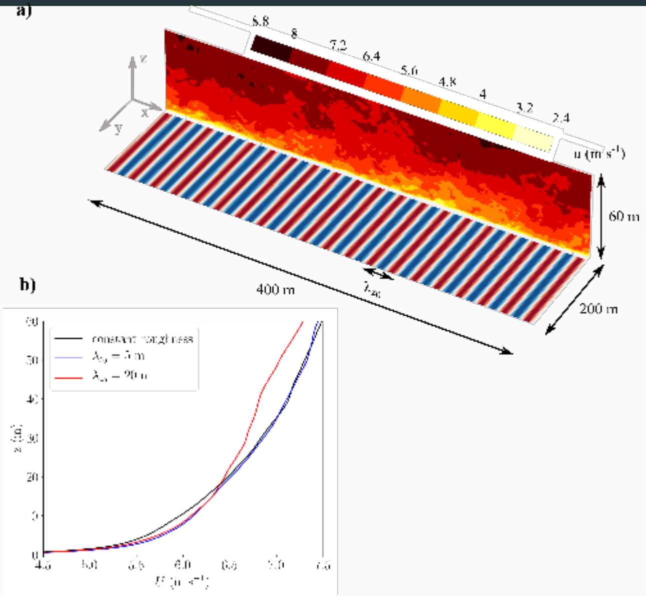


Dimensionless wind shear ϕ_m as a function of stability $z/L = \zeta$: wind-wave model (black line), Businger-Dyer parameterization (red line), and observations (black dots). The shadings result from variations of TKE dissipation.

Variation of TKE dissipation

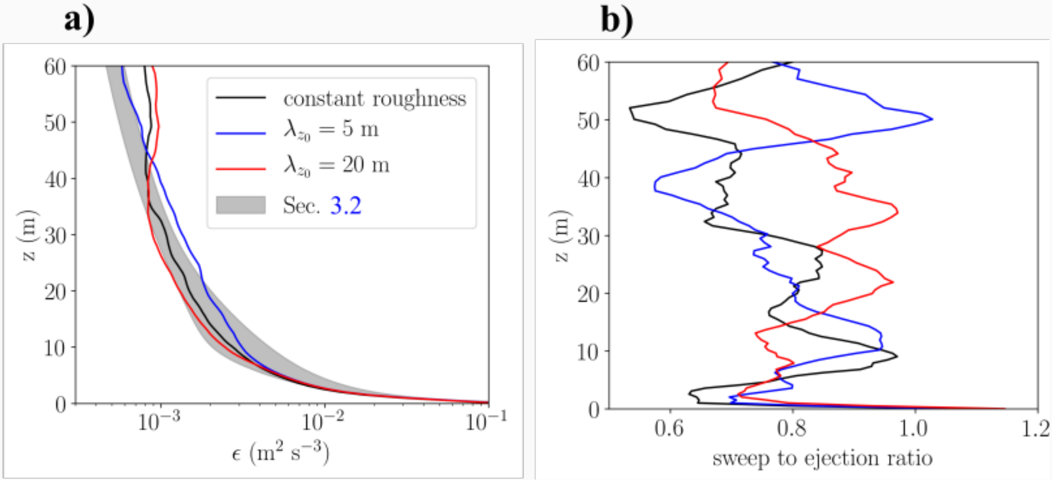


Numerical simulations (I)



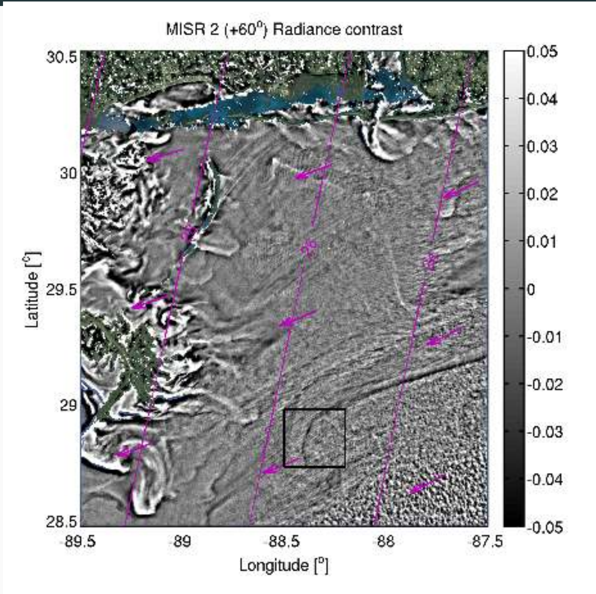
- Meso-NH, doubly-periodic box, pressure gradient flow, **resolution:** 0.5 m s^{-1}
- Mean wind of 6 m s^{-1}
- Momentum flux at first level: $\overline{u'w'}(z_1) = [\kappa U_{10} log(z_1/z_0)^{-1}]^2$
- Charnock parameterization: $z_0^m = \alpha_c[\overline{u'w'}(z_1)]^{1/2}/g$
- Periodic variations of z_0 of $\pm 75\%$ around its mean value z_0^m (following *Gent and Taylor* 1976).

Numerical simulations (II)



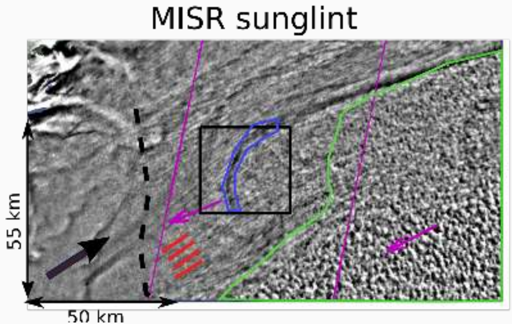
- λ_{z_0}: wavelength of the variation of z_0

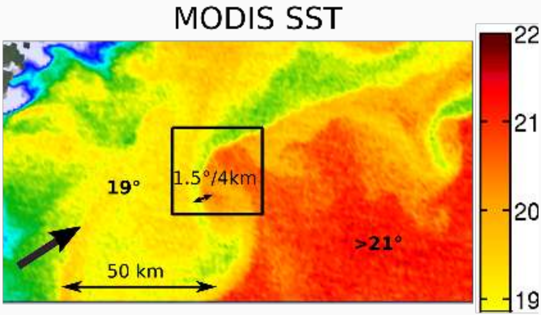
Variability of long wind-waves (I)



- Radiance contrast from the Multi-angle Imaging SpectroRadiometer (onboard Terra)
- Sensitive to modulation of the steppness of $\mathcal{O}(1m)$ *waves*, which are sensitive both to current divergence and wind stress variations on short timescales (30').

Variability of long wind-waves (II)

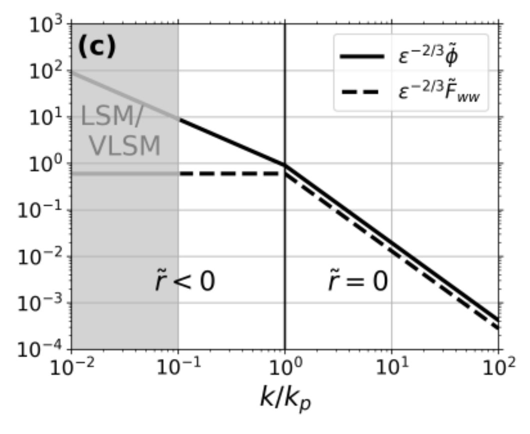




- Wind blows from cold to warm (**black arrow**)
- Current divergence associated with the sharp front impacts wave steepness
- Near-surface wind streaks downwind of the dashed boundary.
- Micro-scale convection .

See the classification of *Wang et al.* (Geoscience Data Journal, 2019)

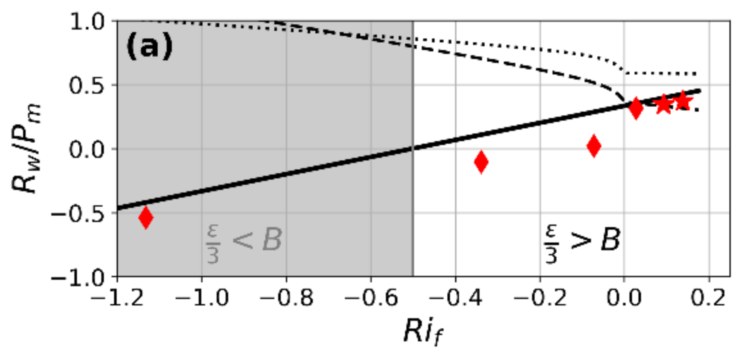
Idealized spectra



Idealized spectra used in the spectral budget

$$\frac{1}{2}\frac{\partial F_{ww}(k)}{\partial t} = 0 = B(k) + R_w(k) - T(k).$$

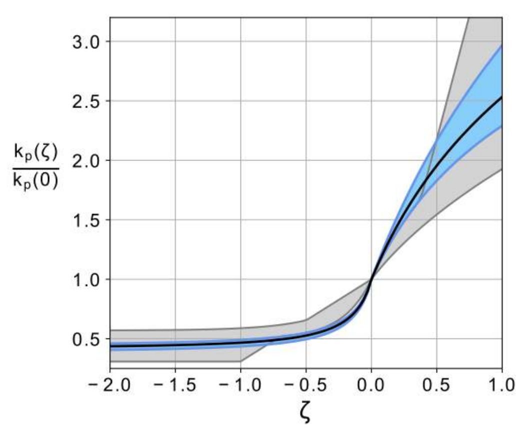
Return-to-isotropy in numerical models



Symbols are DNS and LES, solid line is the expected value from a budget, and dahsed line are the standard Rotta predictions.

From *Ayet et. al* JGR-a (2020)

Effect of measurement resolution of k_p



Alternative way to obtain k_p

$$-\overline{u'w'} = \int_{1/z_i}^{1/d_s} F_{uw}(s)ds.$$

where z_i is the BL height and d_s is the instrumental cutoff

- Grey shading: data
- blue shading: sensitivity to d_s in the model