Response of the Marine Atmopheric boundary layer to a SST front: insights from an analytical model

Alex Ayet[1,2] and Jean-Luc Redelsperger[1]
also with Bertrand Chapron[1], Guillaume Lapeyre [2], Louis Marié[1]

Clivar meeting, wind, waves and currents, Feb. 2020

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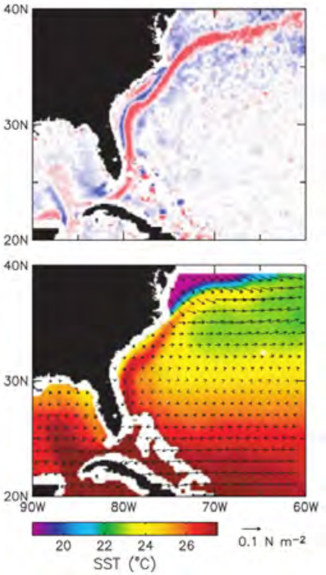
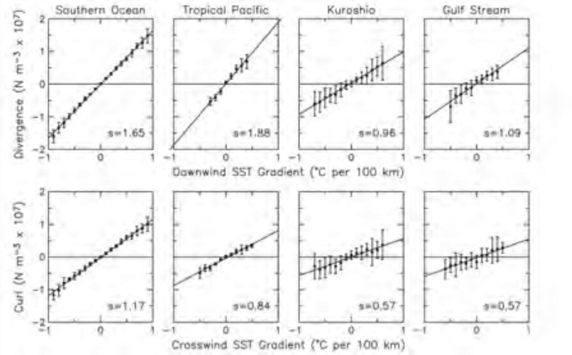
Outline

Introduction : Large scale interactions and wind divergence

4 year average of high-pass filtered wind stress curl

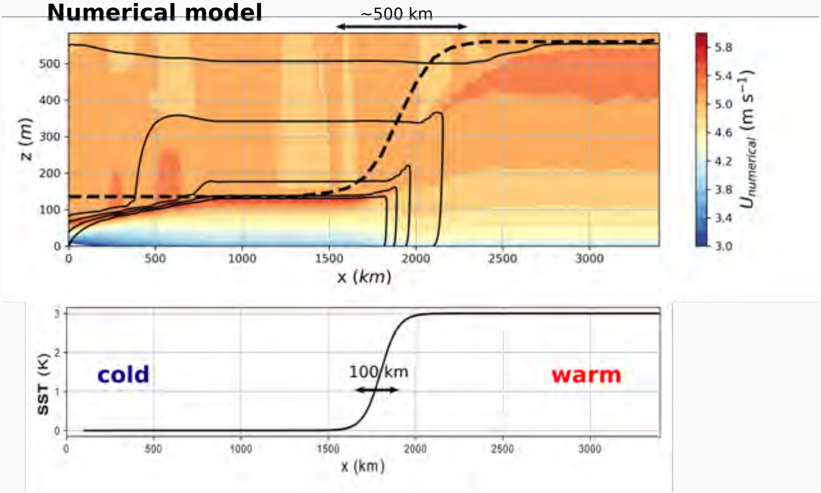




From *Chelton et al.* (2004).

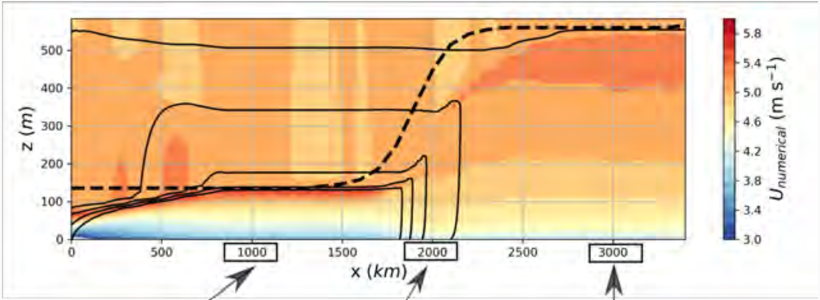
- Large scale interactions [spatial scales of $\mathcal{O}(100\text{km})$].
- Correlation between divergence/curl of wind stress and SST gradient.

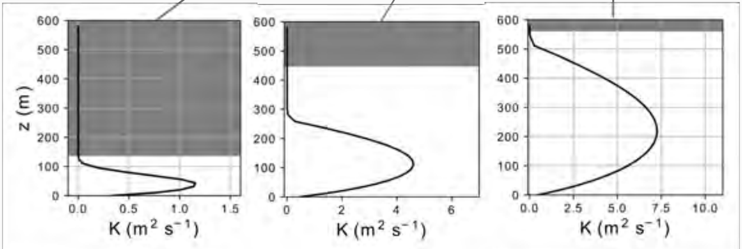
Large eddy simulation after 36h



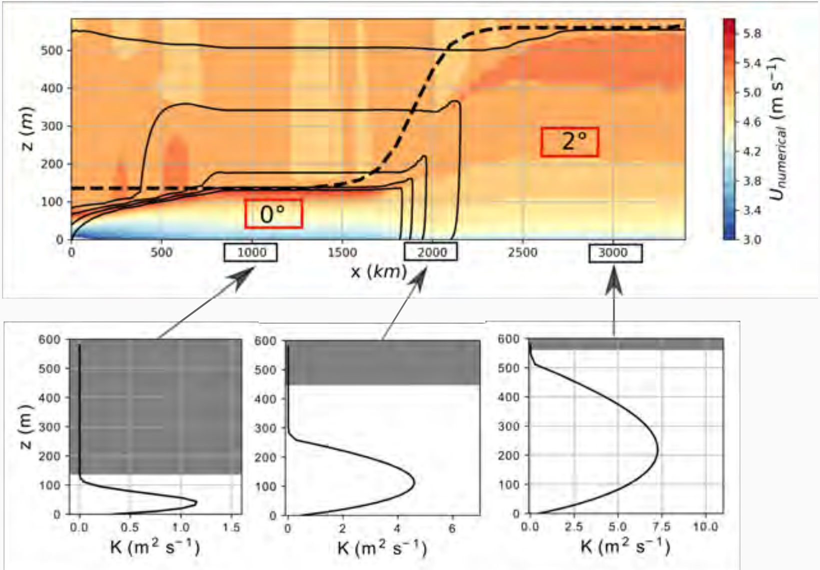
From *Ayet and Redelsperger*, QJRMS (2019)

Downward momentum mixing : $\nabla \cdot \boldsymbol{\tau} \propto \boldsymbol{U}_g . \nabla SST$

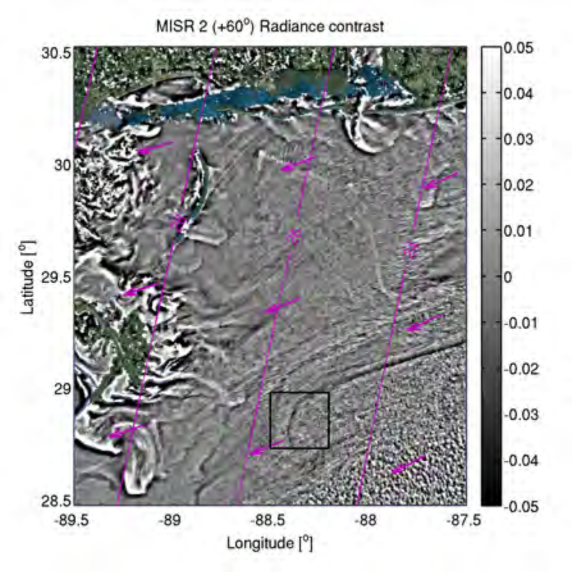




Pressure adjustment mechanism : $\nabla \cdot \overline{\boldsymbol{U}} \propto \Delta SST$

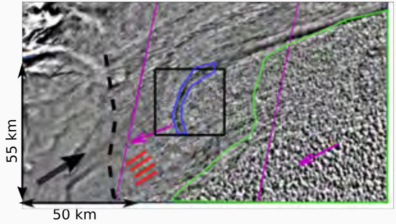


Introduction : Instantaneous features (I)

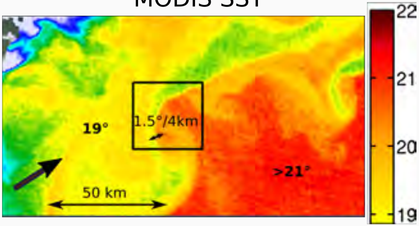


- Radiance contrast from the Multi-angle Imaging SpectroRadiometer (onboard Terra)
- Sensitive to modulation of the steppness of $\mathcal{O}(1m)$ *waves*, which are sensitive both to current divergence and wind stress variations on short timescales (30').

MISR sunglint



MODIS SST



- 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)

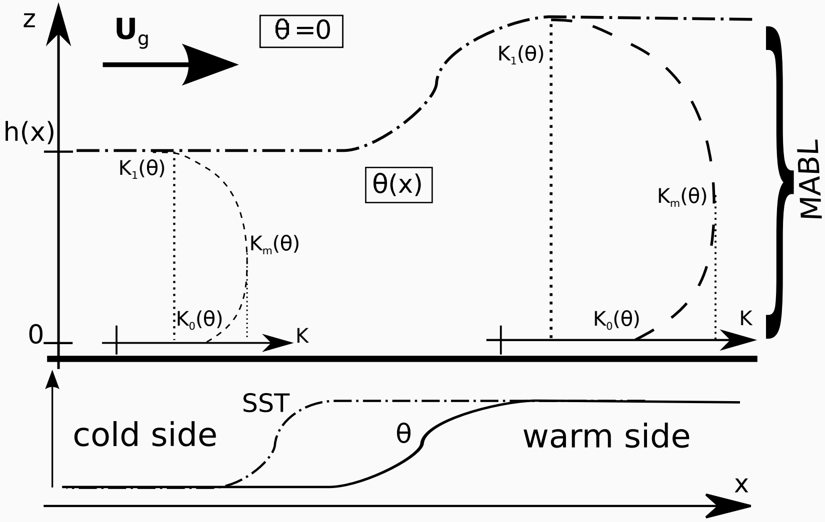
Boundary layer turbulence : $\mathcal{O}(10\text{km})$; SST front : $\mathcal{O}(1\text{km})$.

See also *Redelsperger et al.* (QJRMS, 2019) for recent LES over the sharp Ushant front

Outline

Outline

The model (I) : A simple toy problem



Ayet and Redelsperger (QJRMS, 2019)

The model (II) : momentum balance

Momentum balance

$$\underbrace{\partial_z \left[K \partial_z U\right]}_{\text{turbulent stress}} - \underbrace{ifU}_{\text{coriolis}} = \frac{g}{\theta_0}\left[\underbrace{(z-h)(\partial_x \theta + i\partial_y \theta)}_{\text{temp. gradient}} \underbrace{-(\partial_x h + i\partial_y h)\theta}_{\text{MABL height gradient}}\right]$$

- Advection is neglected : small Rossby number
- Simplistic bottom boundary conditions (no waves !)

$$U(x,h) = 0 \text{ and } U(x,0) = -U_g.$$

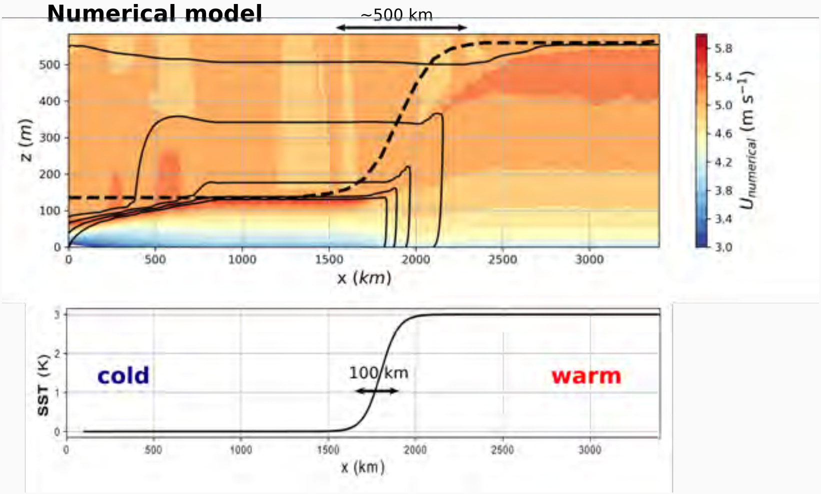
- Parabolic diffusion coefficient

$$K(x,z) = A(x) + B(x)\left[z - \frac{h(x)}{2}\right] + C(x)\left[z - \frac{h(x)}{2}\right]^2.$$

- Thermodynamical (h, θ) and turbulent (A, B, C) quantities are parameters of the model
- Analytical solution

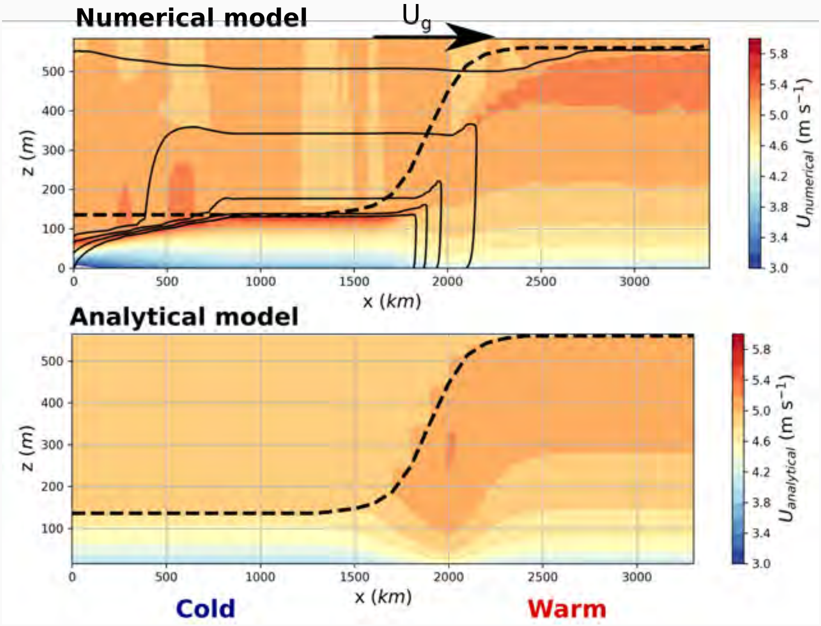
Outline

Comparison to a numerical simulation (I)

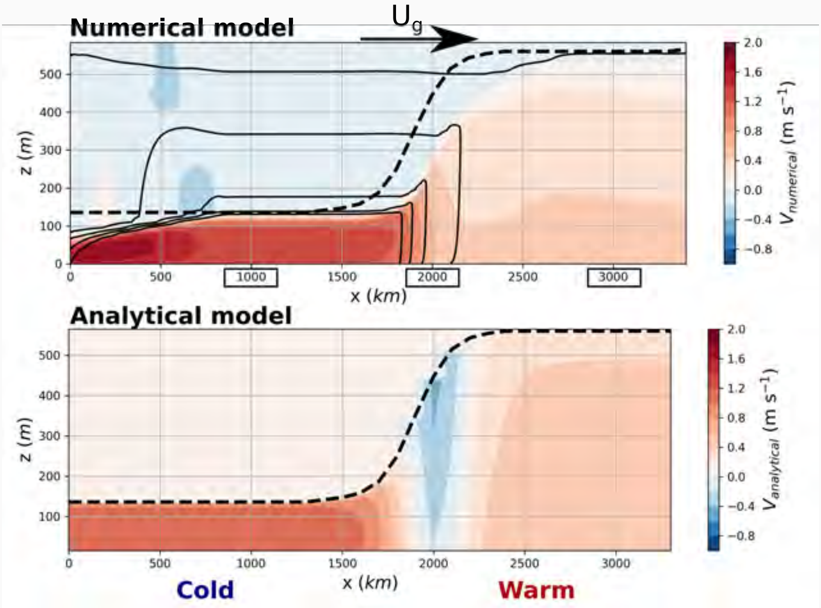


Large eddy-simulation : $U_g = 5$ m s^{-1}, $\Delta x = 1$ km, two-dimensional f-plane (45°N).

Comparison to a numerical simulation (II)

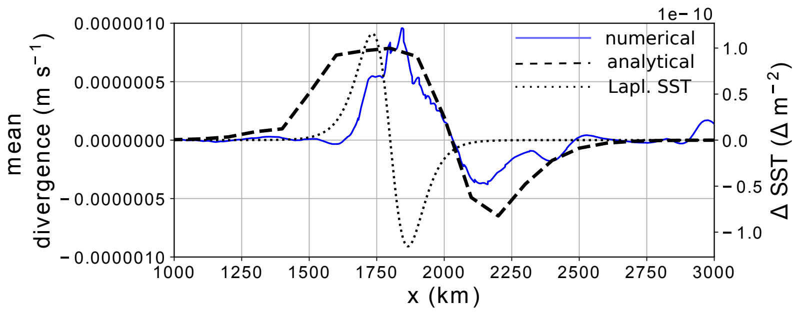


Comparison to a numerical simulation (III)



Depth-integrated wind divergence

$$\nabla \cdot \overline{\mathbf{U}} = \underbrace{\alpha_L \Delta\theta}_{\text{P. adjustment}} + \underbrace{\alpha_D \mathbf{U}_g . \nabla\theta}_{\text{mom. mixing}} + \cancel{\alpha_C (\mathbf{U}_g \times \nabla\theta)} + \cancel{\alpha_G (\nabla\theta)^2}$$



Depth-integrated wind divergence

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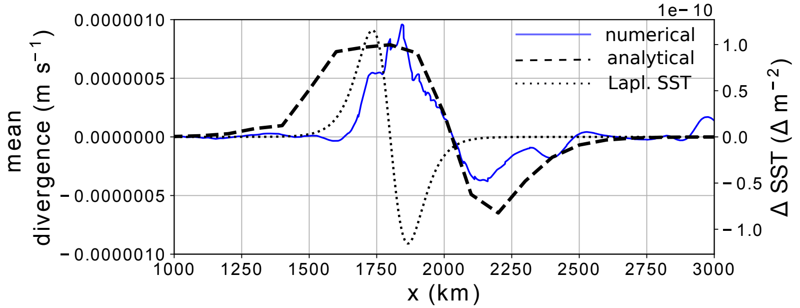


Insights from the analytical solution : wind divergence

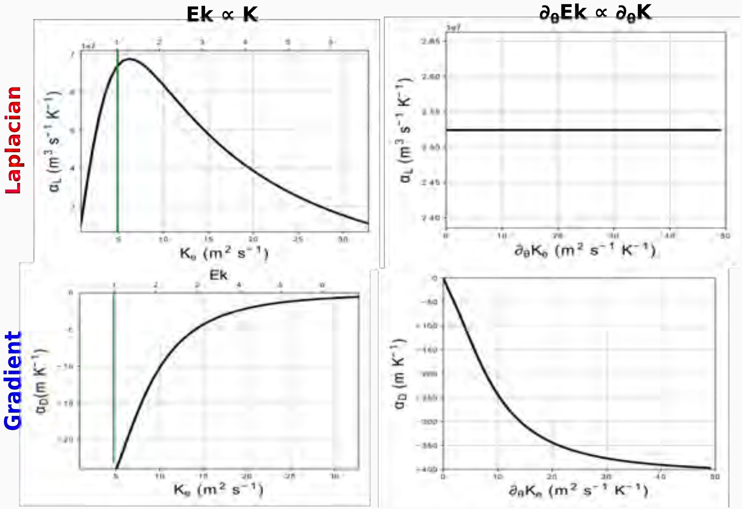
Depth-integrated wind divergence

$$\nabla \cdot \overline{\mathbf{U}} = \underbrace{\alpha_L \Delta\theta}_{\text{P. adjustment}} + \underbrace{\alpha_D \mathbf{U}_g . \nabla\theta}_{\text{mom. mixing}} + \cancel{\alpha_C(\mathbf{U}_g \times \nabla\theta)} + \cancel{\alpha_G(\nabla\theta)^2}$$

The analytical model further reveals that the wind divergence can be decomposed into a

- Scale-dependent part : $\Delta\theta \propto L^{-2}$; $\nabla\theta \propto L^{-1}$, with L the scale of the front
- Turbulence-dependent modulation : $\alpha_L, \alpha_D \propto F(K, \partial_\theta K)$
  - K : turbulence intensity
  - $\partial_\theta K$: adjustment of turbulence to SST variations

$$\nabla \cdot \overline{\mathbf{U}} = \alpha_L \Delta\theta + \alpha_D \mathbf{U}_g . \nabla\theta$$



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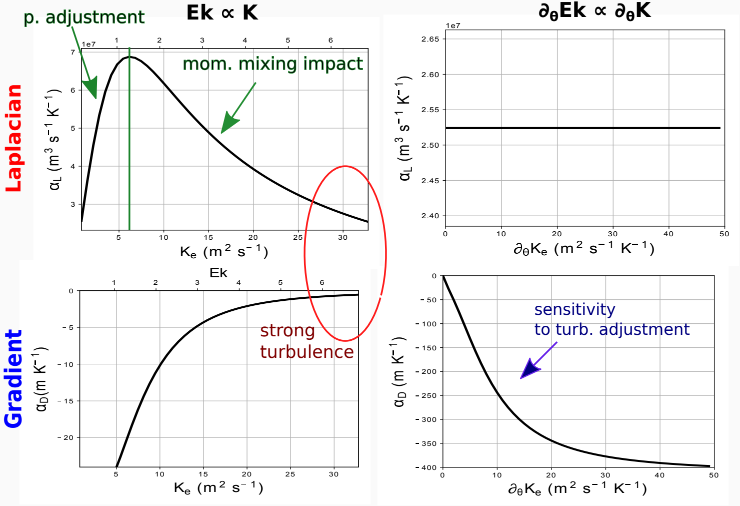

Insights from the analytical solution (II) : wind divergence

Different upwind turbulent conditions can lead to different responses : an illustration for different time and space scales

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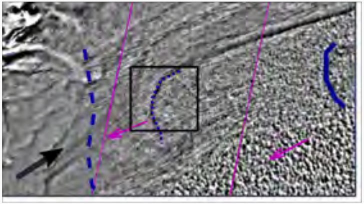
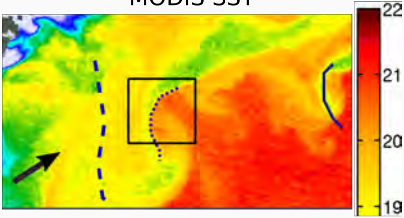
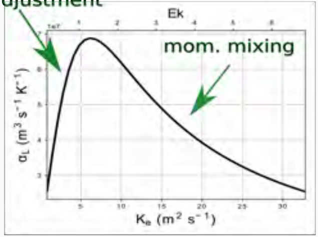
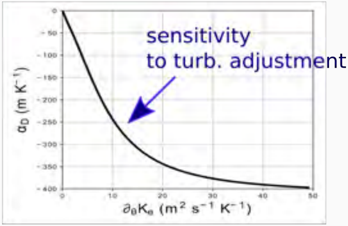


MODIS SST



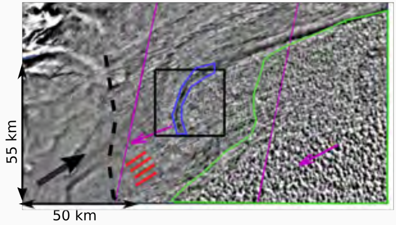
p. adjustment

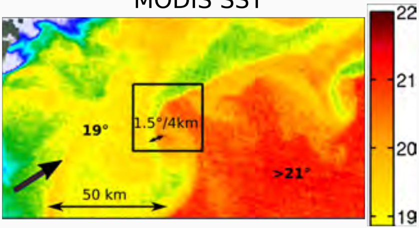




Outline

What about waves ? The chicken or the egg ?





Modulation of $\mathcal{O}(1\mathrm{m})$ waves, associated to surface stress

- Current divergence associated with the sharp front impacts wave steepness
- Near-surface wind streaks downwind of the dashed boundary.
- Micro-scale convection .

Are those wave variations associated to changes in the wind, in waves or both ?

How should wind-wave interactions be included in the picture ?

What about waves ? Wind-wave coupling (I)

Change the bottom boundary condition : $\tau = \rho C_D U_{10}^2$

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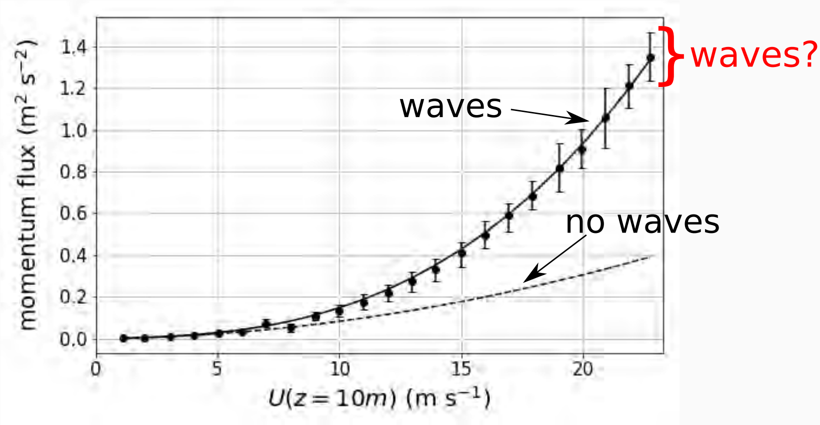
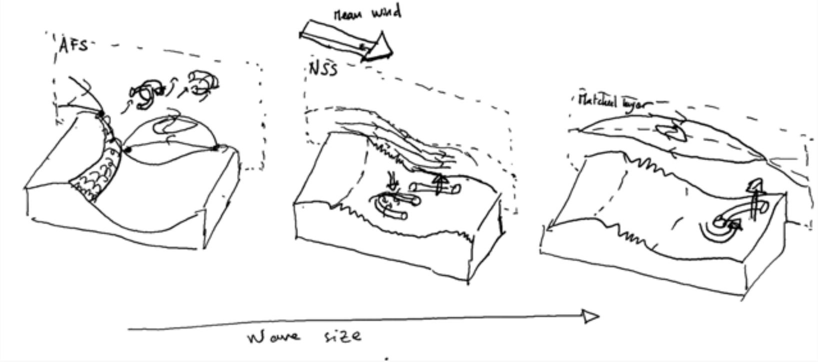
Change the bottom boundary condition : $\tau = \rho C_D U_{10}^2$



Measurements : *Edson et al.* (2013) ; Model : *Kudryavtsev et al.* (2014)

Surface stress is increased by short waves, with uncertainties

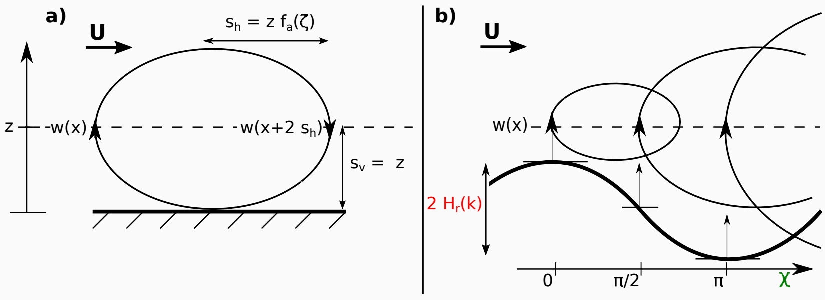
What about waves ? Wind-wave coupling (II)



Short waves (<1m) : Depending on wave scale, the coupling acts at different heights and intensities

AFS : air-flow separation (wave breaking) ; NSS : non-separated sheltering (*Belcher and Hunt 1993*) ; Matched layer : Miles' 1957 mechanism.

What about waves ? Wind-wave coupling (III)

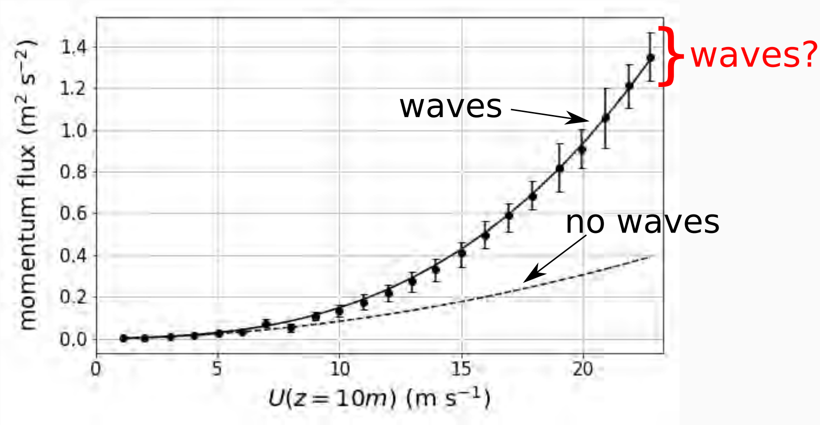


Long waves (∼10m) : could impact atmospheric turbulent structures by modulation of shorter waves.

From *Ayet et al.* (BLM, 2019), see also *Kudryavtsev and Chapron* (2016)

What about waves ? summary

the bottom boundary condition : $\tau = \rho C_D U_{10}^2$

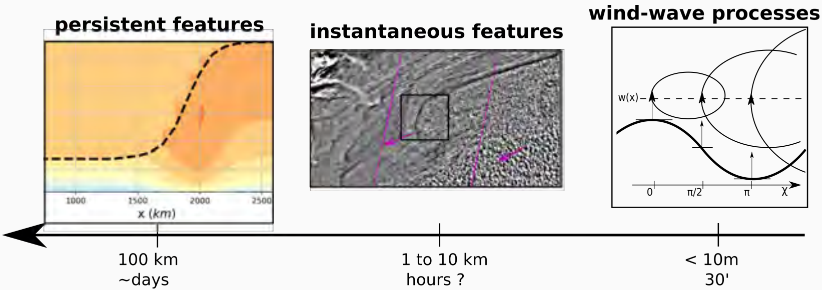


Surface stress is coupled to waves at scales $< (n \times 10)$ m

Sensitive to atmospheric turbulent conditions and currents

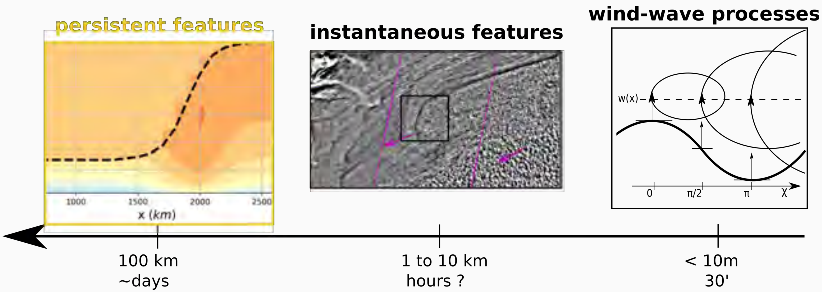
Outline

Conclusion



Simple case of a cold-to-warm front, at multiple scales

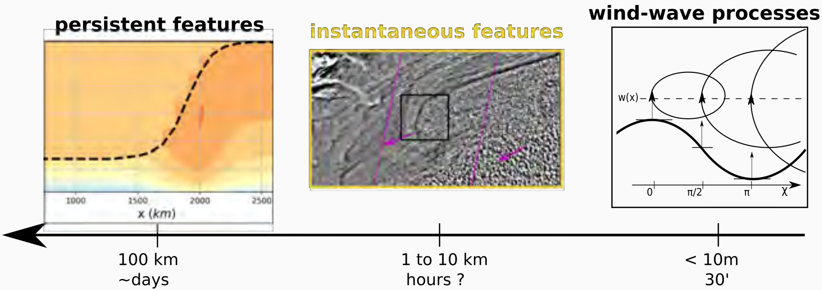
- Analytical model for the large scales, with low rossby number
- Instantaneous features reveal changes in turbulence associated to sharp fronts
- This changes are associated with wind-wave (and current) couplings, with uncertainties in their modelling



Simple case of a cold-to-warm front, at multiple scales

- Analytical model for the large scales, with low rossby number
  - A parabolic diffusion coefficient whose intensity is not related to the MABL height is essential to reproduce the numerical simulation
  - The analytical model reveals different responses of wind divergence to SST field derivatives, that depend on the dynamical regime and scale.

Conclusion



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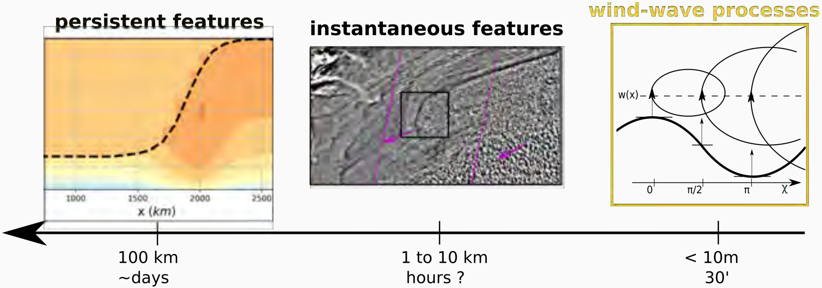

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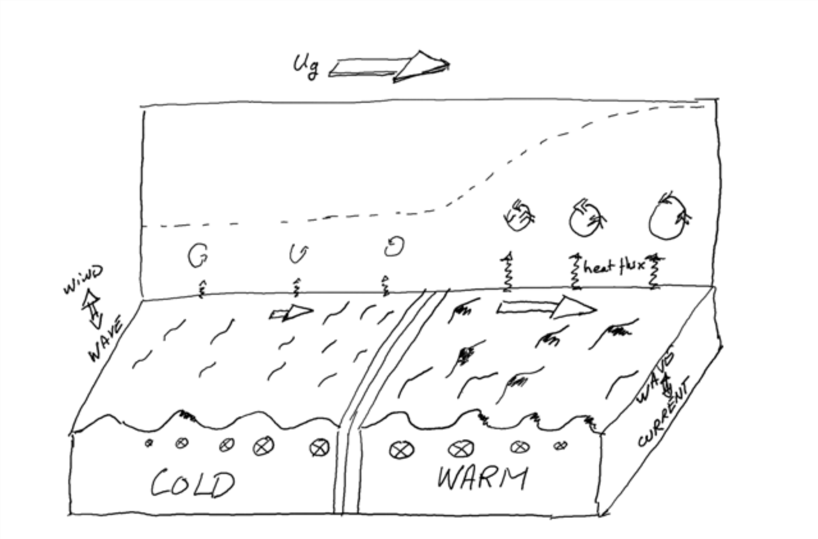
Conclusion : multiscale wind-wave-current interactions

Non-exhaustive summary of wind-wave-current interactions occuring for this toy problem.



Insights from the analytical solution : dynamical regimes

Dimensionless momentum balance

$$\underbrace{\mathrm{Ek}\ \partial_{z'}(K'\partial_{z'}U')}_{\text{turbulent stress}} - \underbrace{iU'}_{\text{coriolis}} = \underbrace{\mathrm{Pc}\ (z'-1)(\partial_{x'}+i\partial_{y'})\theta'}_{\text{pressure}}$$

$$\mathrm{Ek} = \frac{\text{mixing}}{\text{coriolis}} = \frac{l_e^2}{h^2} \propto \frac{\overline{K}}{h^2}$$

where l_e is the height of the Ekman Layer, $\overline{K}$ averaged turbulence diffusion.

$$\mathrm{Pc} = \frac{\text{pressure}}{\text{coriolis}} \propto \frac{h}{L}\frac{\Delta\theta}{U_g}$$

where L is the horizontal extension of the SST front, $\Delta\theta$ the relative temperature ($\sim$ SST) difference across the front.

Insights from the analytical solution : dynamical regimes

Ekman number

$$\text{Ek} = \frac{\text{turbulence}}{\text{coriolis}} = \frac{l_e^2}{h^2} = \frac{2\pi^2\overline{K}}{h^2 f}$$

where l_e the Ekman layer height $\rightarrow$ Ek$=1$ for an Ekman layer model