Ocean-Waves-Atmosphere Coupling

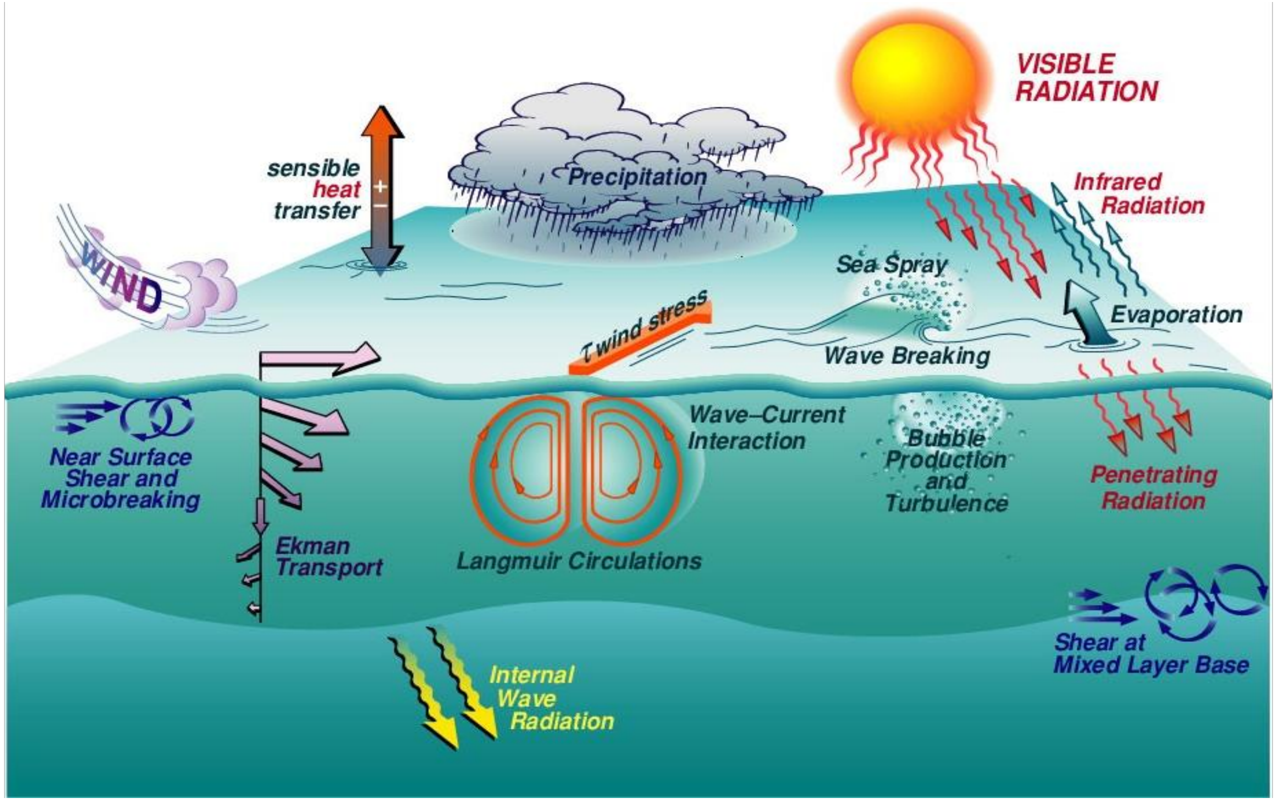
Outline

- Coupling: why?
- Ocean-Atmosphere coupling
- Ocean-Waves coupling
- Coupling in practice

Coupling: Why?

Coupling: why?

- Many coupling processes coexist at the air–sea interface
- Over a large spectrum of temporal and spatial scales
- They are key features in driving circulation in both fluids



Coupling: why?

- In an ocean model, part of these processes are generally either ignored, or parameterized through the bulk formulation of air-sea fluxes

$$H_s = \rho_a c_{pa} \overline{w'T'} = \rho_a c_{pa} C_h S(T_s - \theta)$$

$$H_l = \rho_a L_e \overline{w'q'} = \rho_a L_e C_e S(q_s - q)$$

$$\tau = \rho_a \overline{w'u'} = \cdot = \rho_a C_d S(u_{s1} - u_1)$$

with S=wind speed

=> considers SST, currents, wind speed, and transfer coefficients

- Several limitations arise:
  - Feedback to the wind profile and feedback loop is not accounted for
  - Bulk formulations are only valid under some conditions:

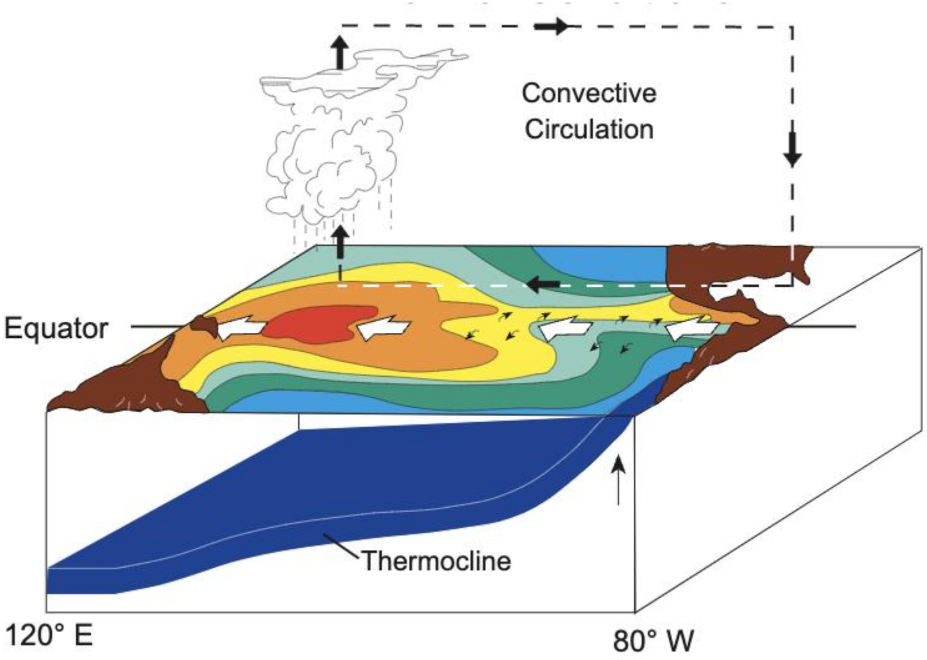
  - Moderate wind conditions (except for some formulations developed for high winds)
  - Fully developed waves
  - Relatively large spatial scales
  - Relatively low frequency O(day)

Ocean-Atmosphere coupling

Ocean-Atmosphere coupling

Strong 2-way **ocean-atmosphere** interactions

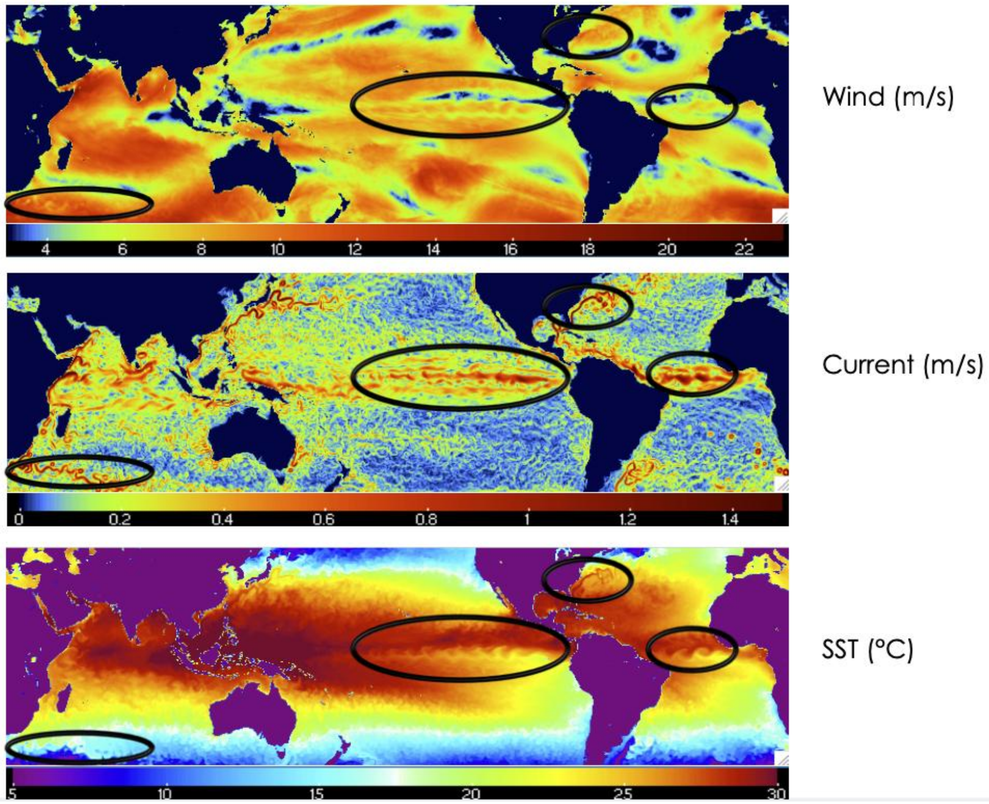
- in the tropics



Ocean-Atmosphere coupling

Strong 2-way **ocean-atmosphere** interactions

- at mesoscale



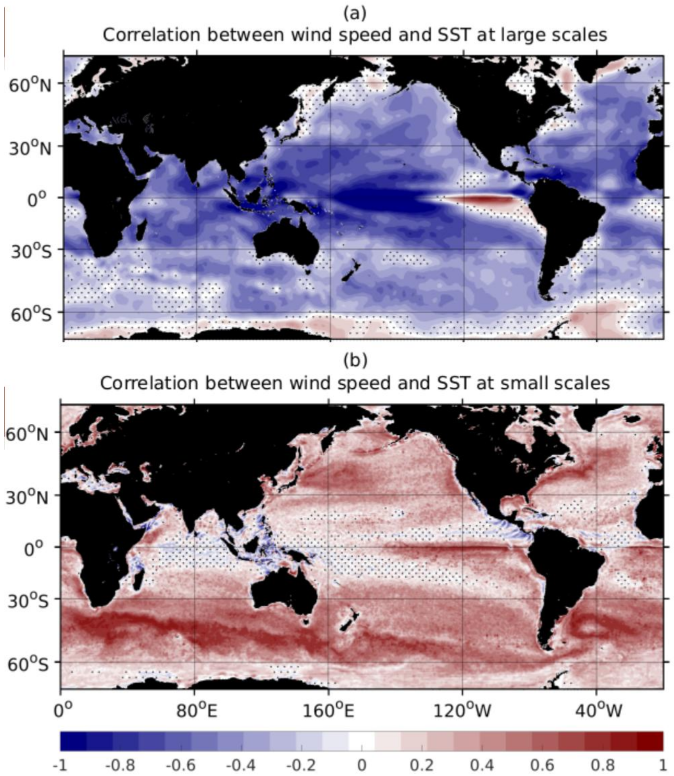
Ocean-Atmosphere coupling

Strong 2-way **ocean-atmosphere** interactions

- at mesoscale **Thermal feedback:**

While the atmosphere generally drives the ocean at the basin scale (e.g. more winds => lower SST => negative correl.),

the ocean drives the atmosphere at mesoscale
(e.g. warmer waters => enhanced winds => positive correl.)



* From Pasquero et al. [2020]

Ocean-Atmosphere coupling

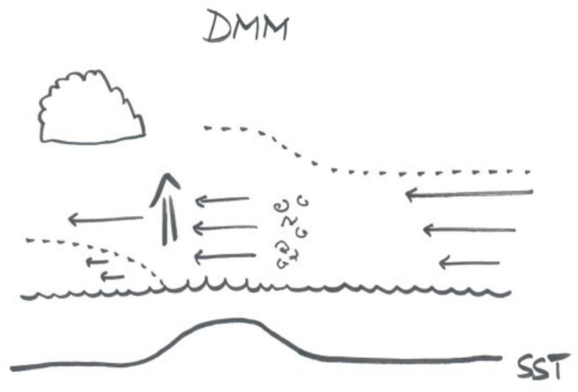
Strong 2-way **ocean-atmosphere** interactions

- at mesoscale **Thermal feedback:**

Donward Momentum Mixing - DMM

Involves the large eddies with the MABL, acting on the turbulent fluctuations of momemtum from the top of the MABL towards the surface

$\nabla \cdot \vec{u} = \alpha_{DM} \nabla SST$

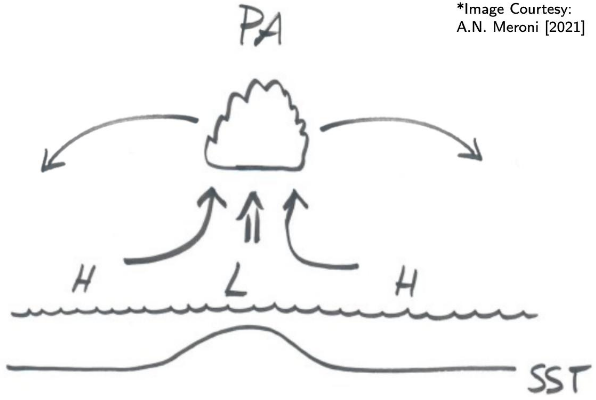


Pressure Adjustment - PA

A secondary circulation is forced by the divergence of the air-temperature gradient, itself driven by Sea Surface Temperature (SST)

$\nabla \cdot \vec{u} = \alpha_{PA} \nabla^2 SST$

*Image Courtesy: A.N. Meroni [2021]



Ocean-Atmosphere coupling

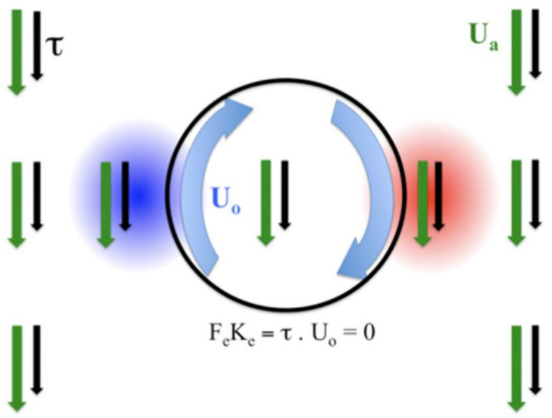
Strong 2-way **ocean-atmosphere** interactions

- at mesoscale **Current feedback:**

On one side:

Currents opposed to winds

=> negative wind work



a) No Current Feedback

On the other side:

Currents aligned with winds

=> positive wind work

* From Renault et al. 2016

Ocean-Atmosphere coupling

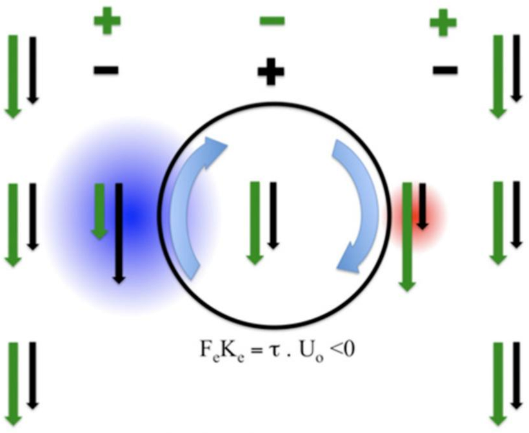
Strong 2-way **ocean-atmosphere** interactions

- at mesoscale **Current feedback:**

On one side:

Currents opposed to winds
=> **increased stress**
=> decreased winds

=> **more negative** wind work



c) Current Feedback to the Surface Stress and Wind

On the other side:

Currents aligned with winds
=> **decreased stress**
=> increased winds

=> **less positive** wind work

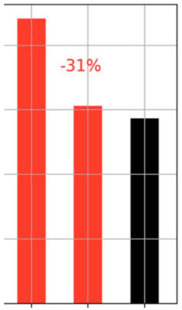
the impact of coupling is always negative

Ocean-Atmosphere coupling

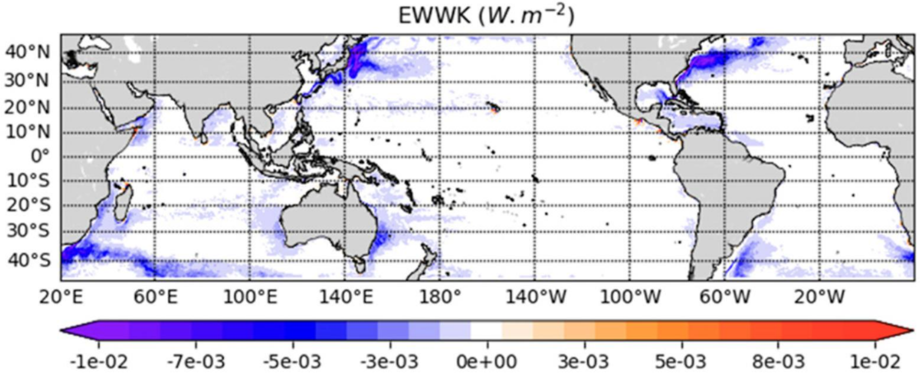
Strong 2-way **ocean-atmosphere** interactions

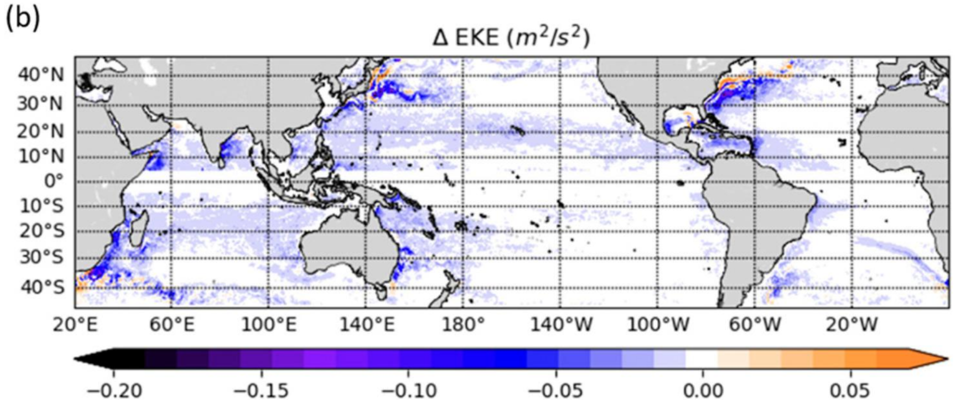
- at mesoscale **Current feedback:**

=> Negative eddy wind work
=> Decrease EKE (-30%)



* From Jullien et al. 2020





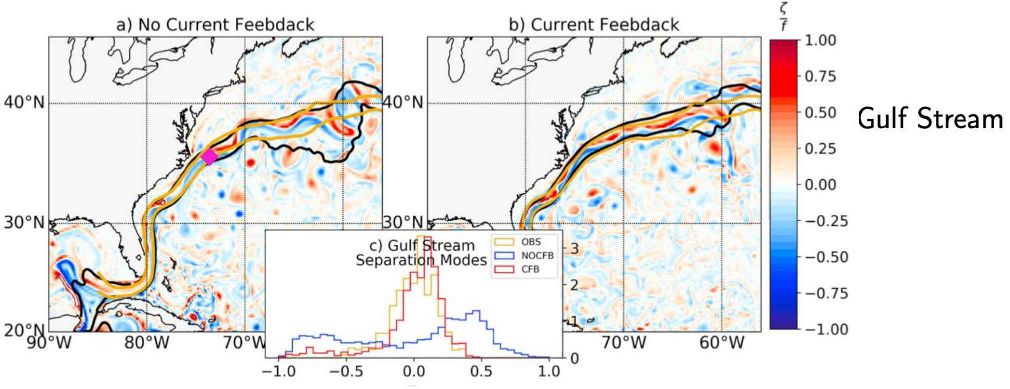
Ocean-Atmosphere coupling

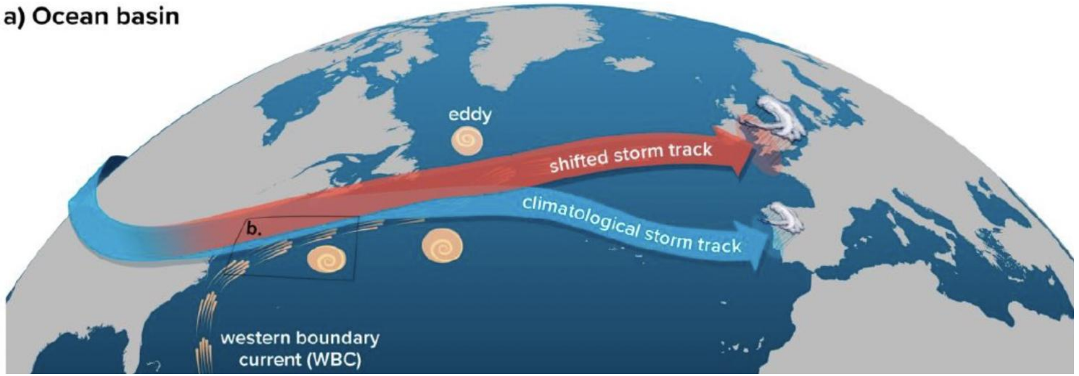
Renault et al. 2019

Strong 2-way **ocean-atmosphere** interactions

- at mesoscale **Upscaling effects**

=> Ocean total EKE
=> Boundary current separation
=> Storm tracks
...



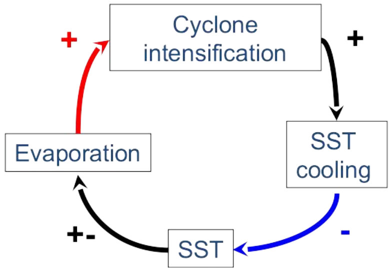


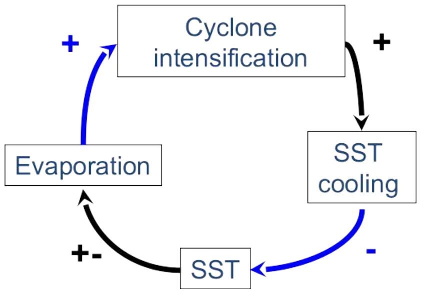
Ocean-Atmosphere coupling

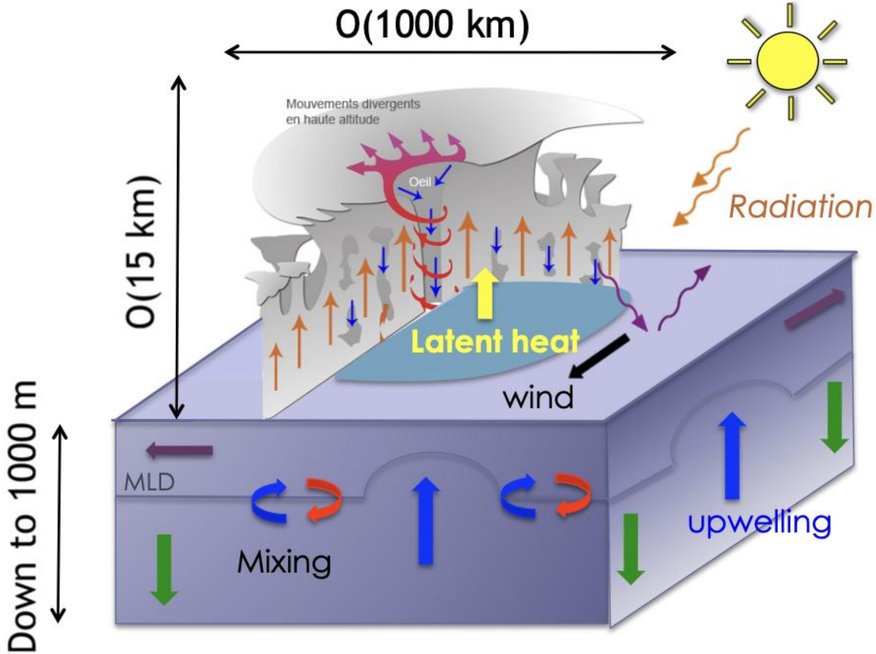
Strong 2-way **ocean-atmosphere** interactions

- in extreme events

=> Feedback controls TC intensity







Ocean-Waves coupling

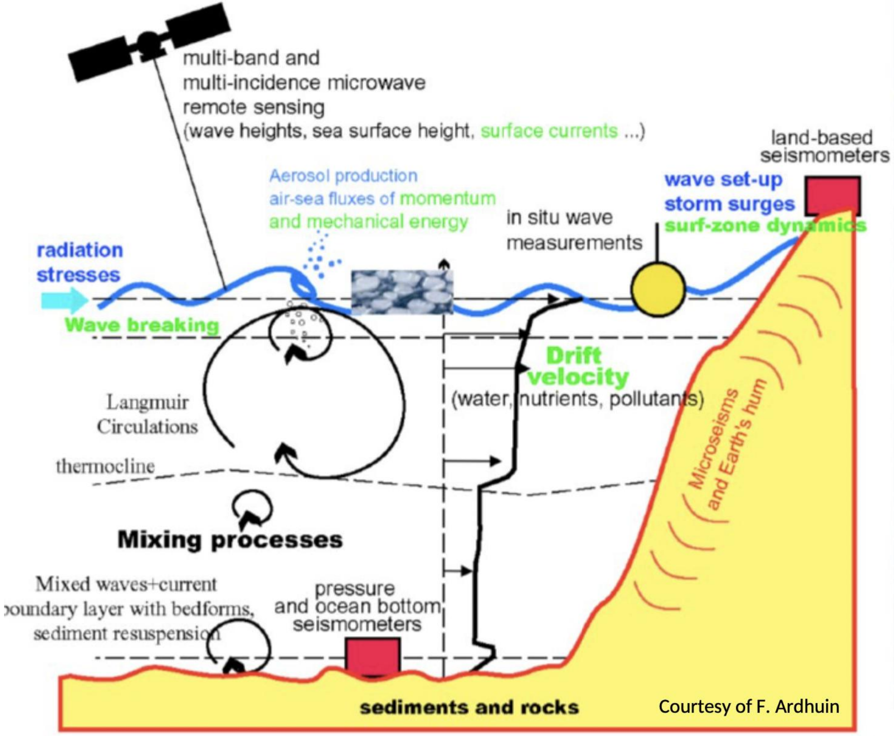
Ocean-waves coupling

Strong 2-way interactions between **waves and currents**

- Ocean circulation and mixing
- Air-sea fluxes
- Nearshore circulation and land-sea exchanges
- Sea ice
- Ocean crust (microseisms)

Applications:

- Remote sensing (hs, ssh, currents, winds...)
- Engineering (offshore and nearshore structures)
- Maritime transport
- Drifting objects and pollutants
- Biology

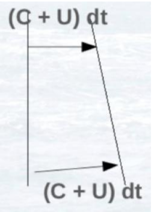


Ocean-waves coupling

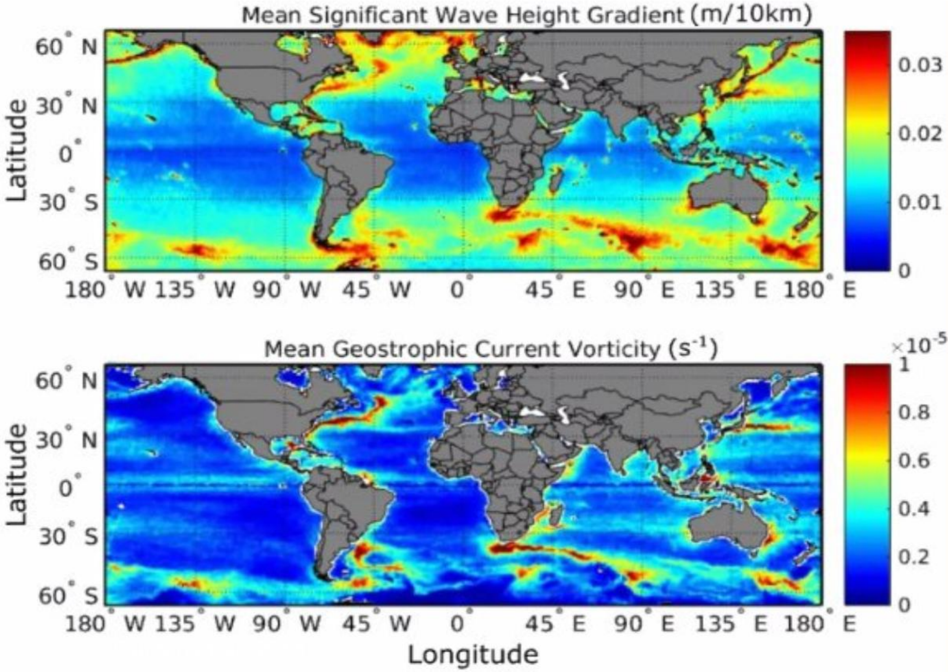
Strong 2-way interactions between **waves and currents**

- Currents => waves

Current gradients induce **refraction** of waves => change in phase velocity (c' = c + U) in the lateral direction (along the crests) causes variations in the **direction** and **height** of the waves



$$[Ec_g]_1 b_1 = [Ec_g]_2 b_2 \qquad a_2 = \sqrt{\frac{c_{g,1}}{c_{g,2}}}\sqrt{\frac{b_1}{b_2}}\, a_1$$



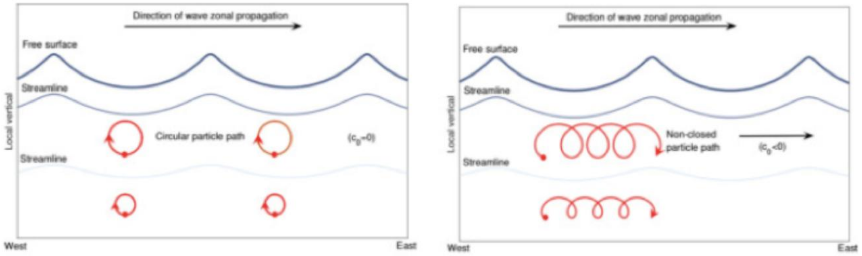
Ocean-waves coupling

Strong 2-way interactions between **waves and currents**

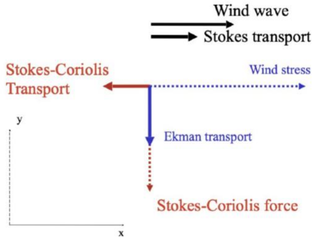
- Waves => currents

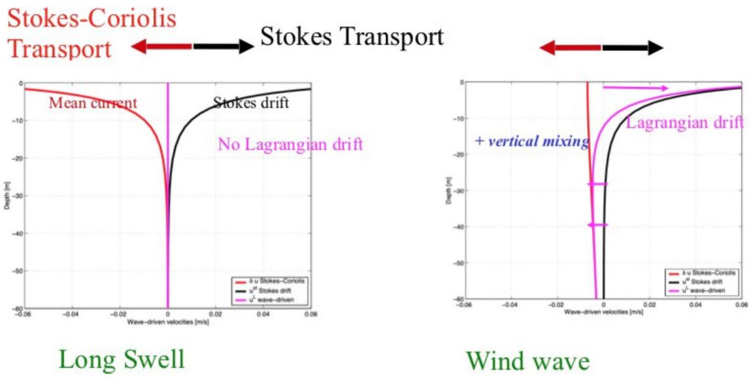
When waves are developing on an ocean with an **underlying current**, wave **orbitals are not closed** => this results in a **drift** that can be significant

In a vertical average, transport generated by the Stokes drift should be balanced by the mean flow, however... => when equilibrium state is not reached yet (e.g. young waves), there is a **residual Stokes transport**



(a) No underlying current: $c_0 = 0$ (b) Depth-invariant current $c_0 \neq 0$





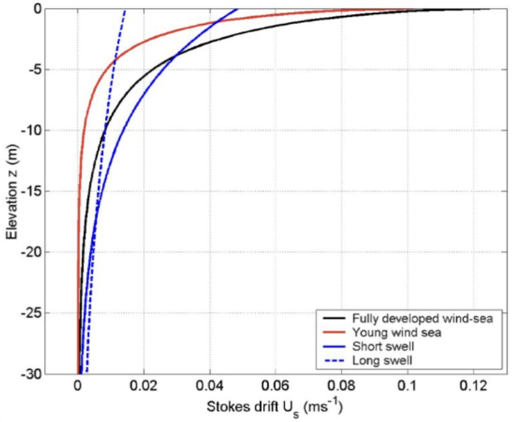
Ocean-waves coupling

Strong 2-way interactions between **waves and currents**

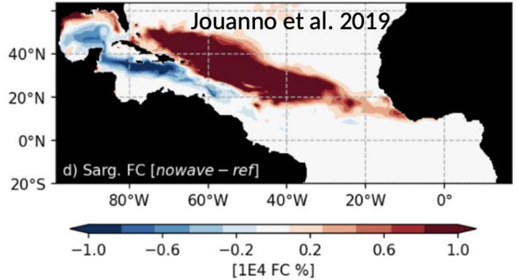
- Waves => currents

For a fully developed wind sea:
- surface: 1.2% U10 (Kenyon, 1969)
- up to 30% of the Ekman transport (McWilliams and Restrepo, 1999)
- affects depths of 10-40m

For swell, low Stokes drift on the surface.



Modification of tracer advection, particle advection

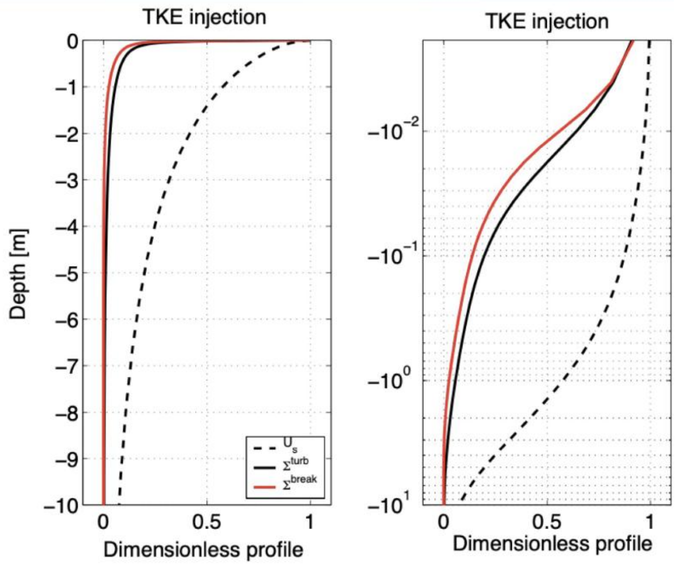


Ocean-waves coupling

Strong 2-way interactions between **waves and currents**

- Waves => mixing

TKE injection through wave breaking and wave-turbulence interactions => impact on MLD



Rascle 2007

Ocean-waves coupling

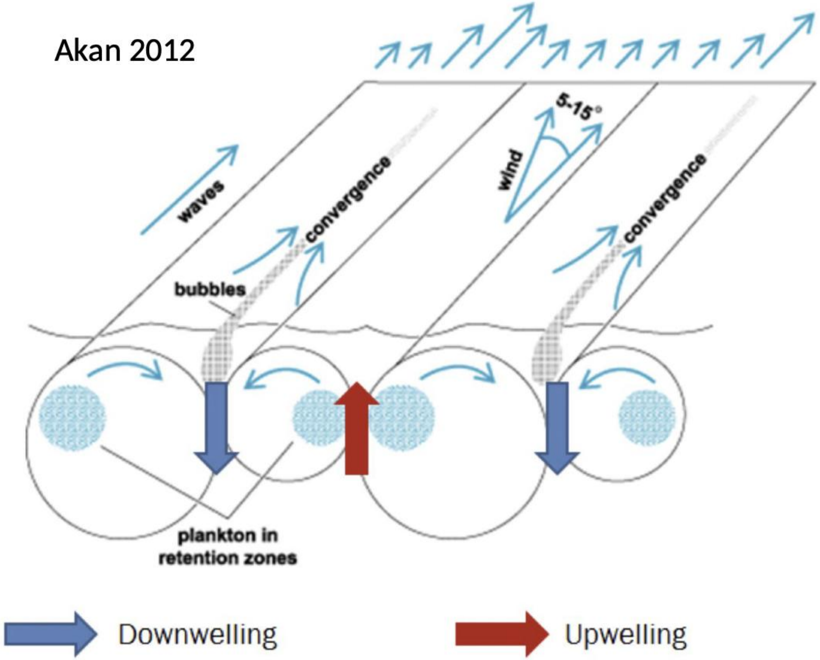
Strong 2-way interactions between **waves and currents**

- Waves => mixing

Langmuir circulation: interaction of the mean flow with the wave-averaged flow:

=> Stokes drift velocity stretches and tilts the vorticity near the surface. The production of vorticity in the upper ocean is balanced by downward (often turbulent) diffusion.

Akan 2012

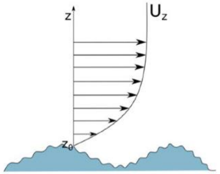


Ocean-waves coupling

Strong 2-way interactions between **waves and currents**

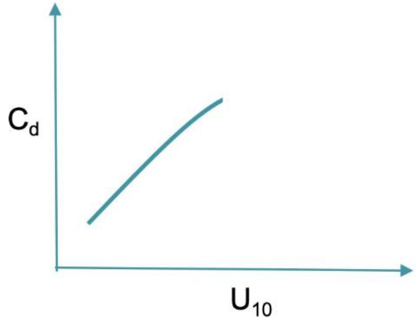
- Waves => air-sea fluxes

$$\tau = \rho_a \overline{u'w'} \longrightarrow \tau = \rho_a C_d U_{10}^2 = \rho_a u_*^2$$



$$C_d = \frac{k^2}{\left[\ln\left(\frac{z}{z_0}\right)\right]^2}$$

$$z_0 = \alpha \frac{u_*^2}{g} + 0.11 \frac{1.5 \times 10^{-5}}{u_*}$$



Ocean-waves coupling

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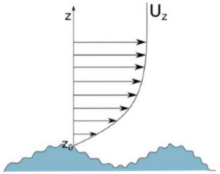


$$C_d = \frac{k^2}{\left[\ln\left(\frac{z}{z_0}\right)\right]^2}$$

$$z_0 = \alpha \frac{u_*^2}{g} + 0.11 \frac{1.5 \times 10^{-5}}{u_*}$$

$$\alpha = 0.0185$$ Charnock 1955

$$\alpha = 0.01\left(\frac{c_P}{U}\right)^{-1}$$ Smith et al. 1992

Liu et al. 2012

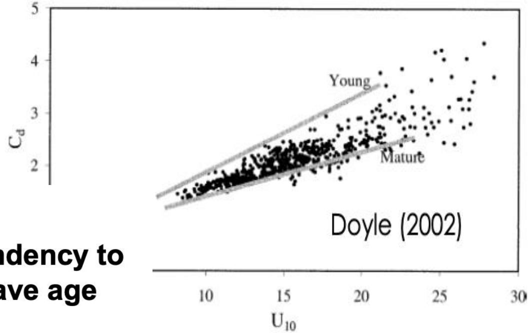
Li et al. 2016

$$\alpha = \begin{cases} (0.085\beta_*^{3/2})^{1-1/\omega}[0.03\beta_* \exp(-0.14\beta_*)]^{1/\omega}, & \beta_* < 35 \\ (17.6)^{1-1/\omega}(0.008)^{1/\omega}, & \beta_* \geq 35 \end{cases}$$

$\beta_* = c_p/u_*$

α_{ww3}

Dependency to the wave age



Ocean-waves coupling

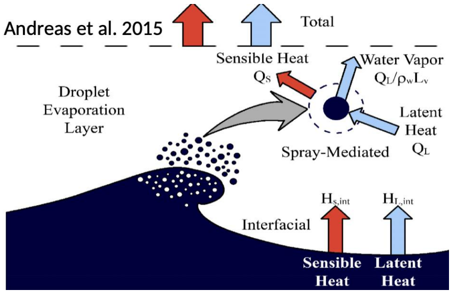
Strong 2-way interactions between **waves and currents**

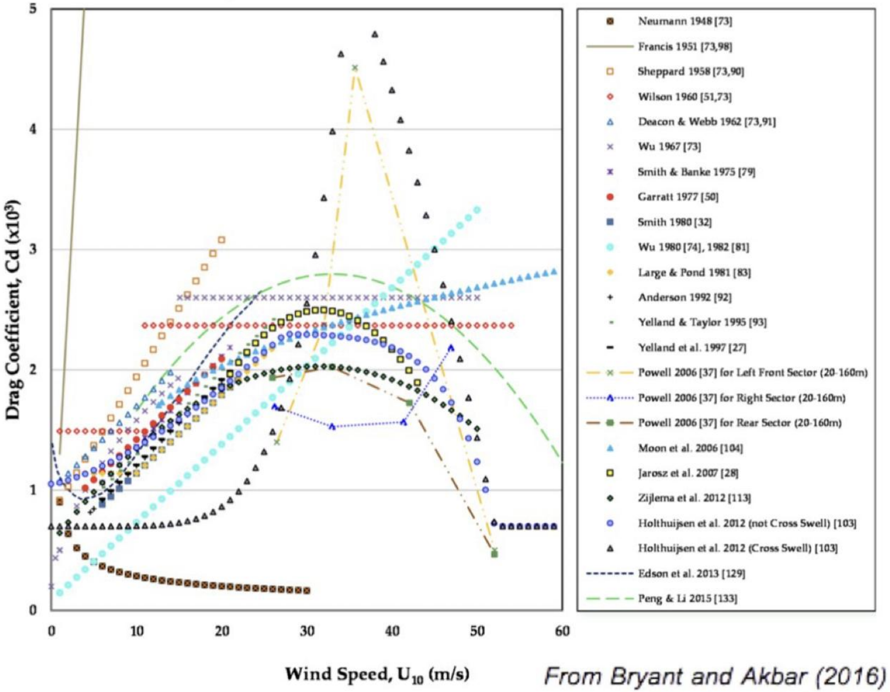
- Waves => air-sea fluxes

State of the art of existing parameterizations of the drag coefficient

=> work is still needed...

+ impact on the enthalpy coefficient...





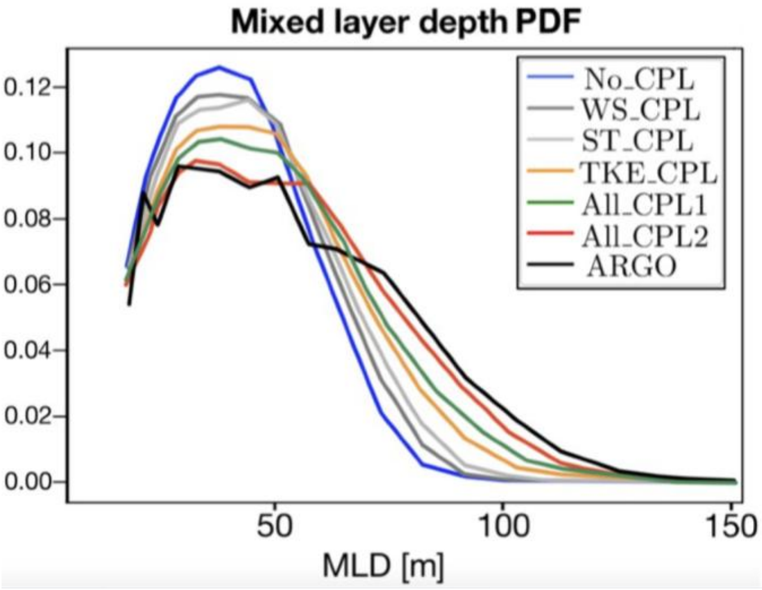
From Bryant and Akbar (2016)

Ocean-waves coupling

Strong 2-way interactions between **waves and currents**

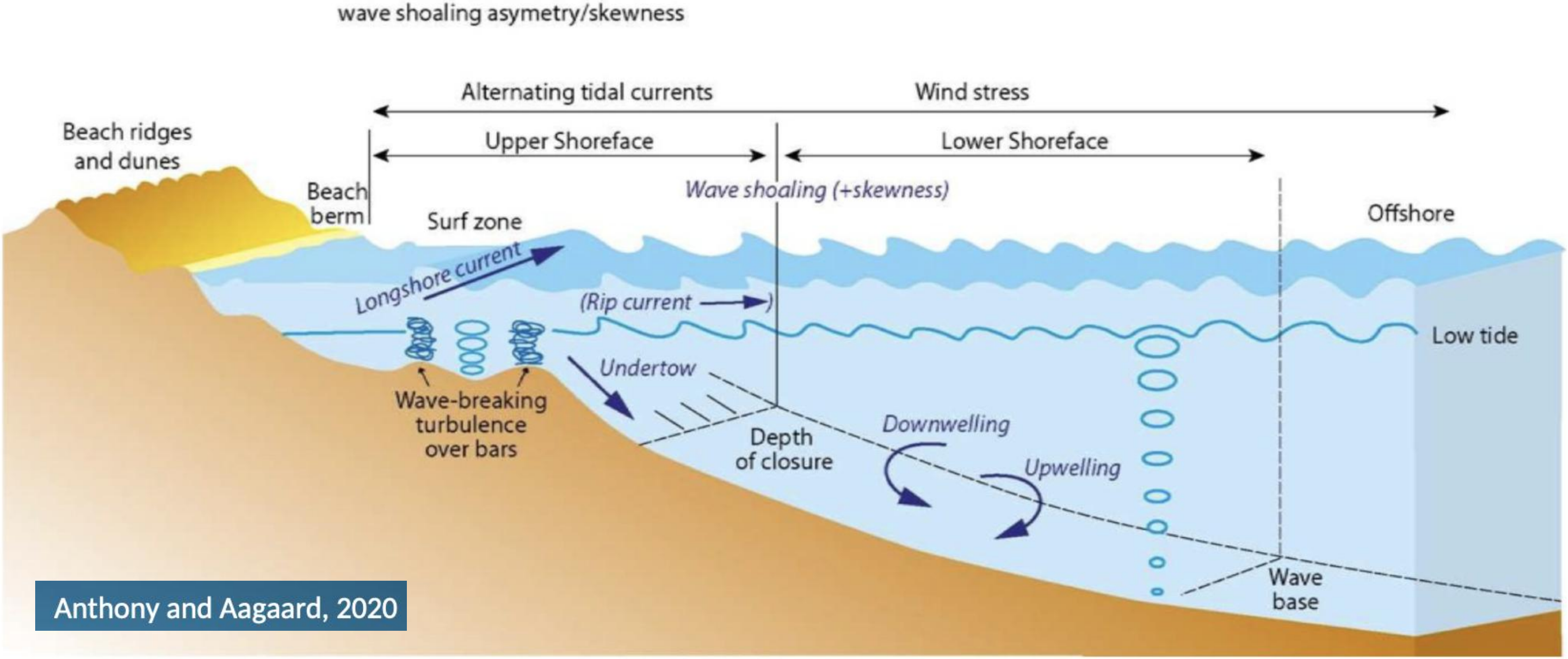
* From Couvelard et al. 2020

- ➢ TKE injection through wave breaking and wave-turbulence interactions => impact on MLD
- ➢ Langmuir circulation => impact on MLD
- ➢ Change in wind stress (drag) => impact on MLD
- ➢ Change in currents (Stokes) => impact on MLD



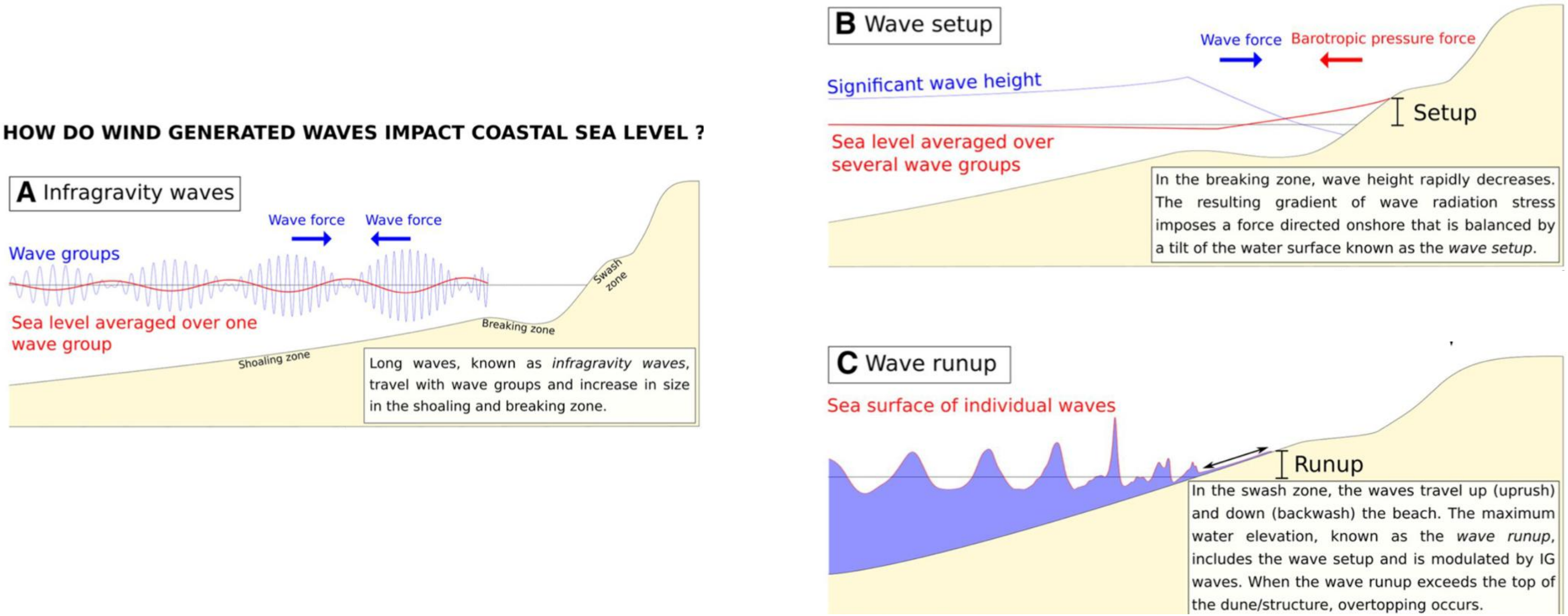
Near the shore...

Nearshore => Circulation is driven by the waves



Near the shore...

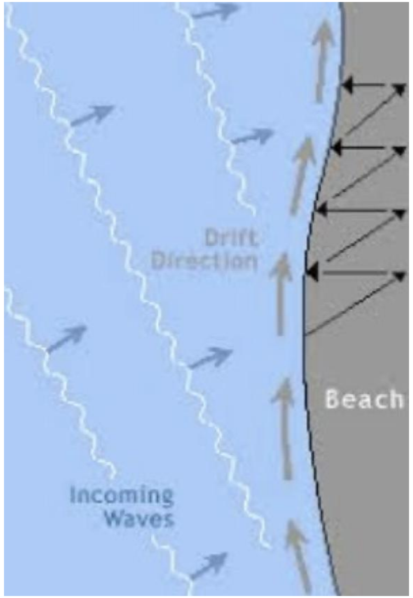
impact on **sea level**



Near the shore...

Longshore current

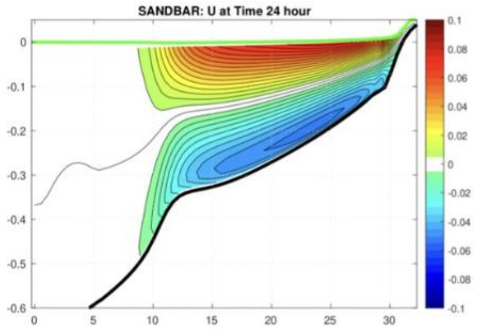
when waves break, a gradient in the wave force is induced
 => its component parallel to the shore is balanced by a longshore drift

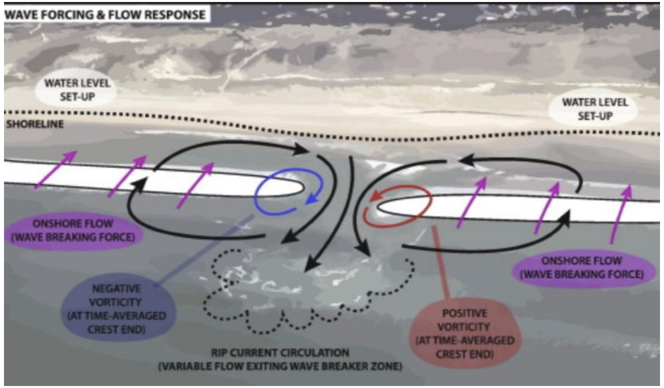


Near the shore...

Cross-shore circulation

- on-shore directed currents:
  – stokes drift
  – bottom streaming: wave stress in the wave bottom boundary layer
  – rollers: fraction of wave energy converted into rollers that propagate towards the shoreline
- off-shore directed currents: undertow
- Rip currents due to non-uniform bathymetry





Coupling in practice

Processes to be coupled

Ocean - Atmosphere

- SST feedback to heat flux computation in the atmosphere
- Current feedback to momentum and heat fluxes
- Water flux accounting for rainfall from the atmosphere
- Solar flux from the atmosphere

Wave - Atmosphere

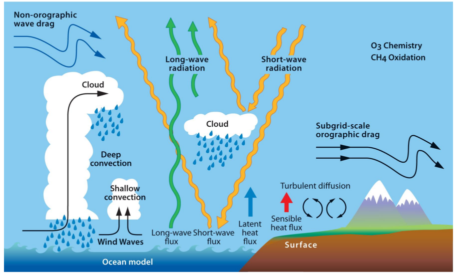
- Wind-wave growth
- Roughness evolution according to sea state
- Sea spray
- Swell feedback to the atmosphere

Ocean - Wave

- Impact of evolving water level on waves
- Impact of current on waves evolution (refraction, etc)
- Wave-induced circulation (stokes drift and transport, acceleration by breaking)
- Enhanced mixing due to wave breaking
- Wave-induced pressure effects
- Wave-induced additional diffusivity
- Wave-induced setup
- Surface and bottom streaming (wave-induced thin viscous boundary layer)
- Mass flux due to wave rollers

Models

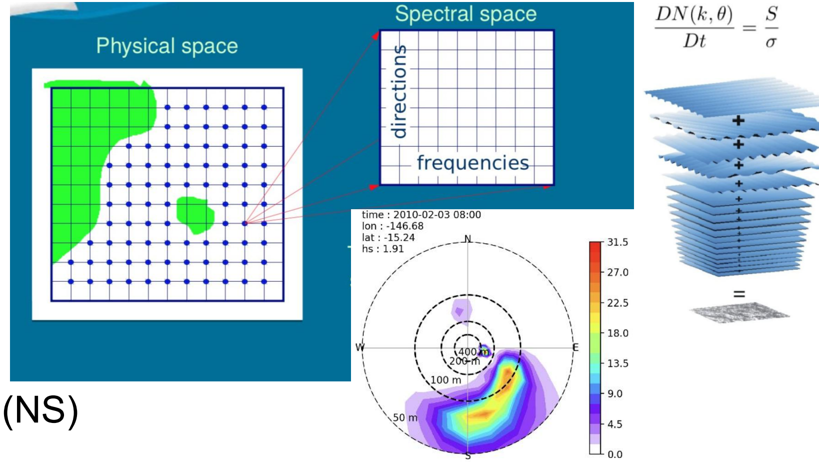
- **Atmospheric model**



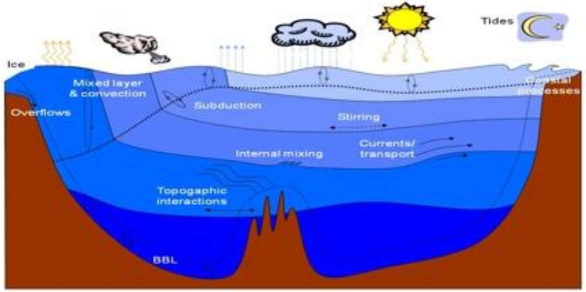
3 equations of motion (NS)
1 thermodynamic equation
Several continuity equations for water species
1 mass continuity equation

- **Wave model**

Equation of conservation of wave action



$$\frac{DN(k,\theta)}{Dt} = \frac{S}{\sigma}$$



- **Ocean model**

Momentum equations (NS)
Conservation of mass
Conservation of heat
Conservation of salinity
Equation of sate

How to couple

- **air-sea fluxes are directly provided** to CROCO (no bulk use in CROCO)
- CROCO **feedback** to the atmosphere or wave model: **SST, currents, sea level**
- for coupling with waves, equations are modified : **wave-averaged equations (vortex force formalism)**

$\xi^c = \xi + \hat{\xi}$ — ξ^c is a composite sea level,

$\phi^c = \phi + \hat{\phi}$ — ϕ^c absorbs the Bernoulli head $\hat{\phi}$,

$\vec{\mathbf{v}}_L = \vec{\mathbf{v}} + \vec{\mathbf{v}}_S$ — $\vec{\mathbf{v}}_L$ is the wave-averaged Lagrangian velocity, Stokes drift $\vec{\mathbf{v}}_S$

$\mathcal{F}^{\mathcal{W}}{}_u, \mathcal{F}^{\mathcal{W}}{}_v, \mathcal{F}^{\mathcal{W}}{}_C$: wave forcing terms (bottom streaming, breaking acceleration)

$\mathcal{D}_u, \mathcal{D}_v, \mathcal{D}_C$: diffusive terms (including wave-enhaced bottom drag and mixing)

$\mathcal{F}_u, \mathcal{F}_v, \mathcal{F}_C$: forcing terms

$$\frac{\partial u}{\partial t} + \vec{\nabla}.\left(\vec{\mathbf{v}}_L u\right) - f v_L = -\frac{\partial \phi^c}{\partial x} + \left(u_S \frac{\partial u}{\partial x} + v_S \frac{\partial v}{\partial x}\right) + \mathcal{F}_u + \mathcal{D}_u + \mathcal{F}^{\mathcal{W}}{}_u$$

$$\frac{\partial v}{\partial t} + \vec{\nabla}.\left(\vec{\mathbf{v}}_L v\right) + f u_L = -\frac{\partial \phi^c}{\partial y} + \left(u_S \frac{\partial u}{\partial y} + v_S \frac{\partial v}{\partial y}\right) + \mathcal{F}_v + \mathcal{D}_v + \mathcal{F}^{\mathcal{W}}{}_v$$

$$\frac{\partial \phi^c}{\partial z} + \frac{\rho g}{\rho_0} = \vec{\mathbf{v}}_S . \frac{\partial \vec{\mathbf{v}}}{\partial z}$$

$$\frac{\partial C}{\partial t} + \vec{\nabla}.\left(\vec{\mathbf{v}}_L C\right) = \mathcal{F}_C + \mathcal{D}_C + \mathcal{F}^{\mathcal{W}}{}_C$$

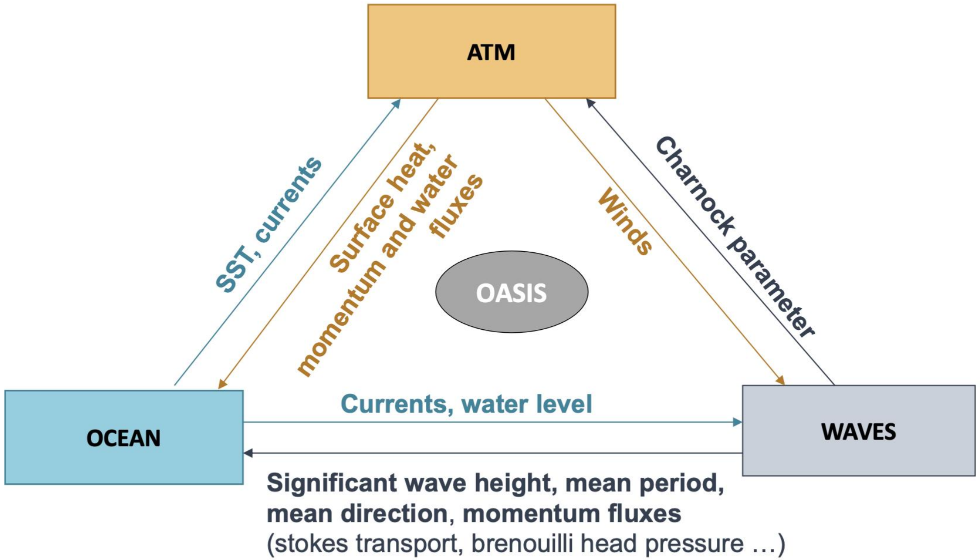
$$\vec{\nabla}.\vec{\mathbf{v}}_L = 0$$

$$\rho = \rho(T, S, P)$$

Various ways for coupling

- **Using several models and a coupler: here OASIS-MCT**

  => Full physics using dedicated models for each compartment (atmosphere, waves, ocean)



Various ways for coupling

- **Internal coupling / modules**

  WKB: Monochromatic wave model embedded in CROCO (no coupler):
  - propagation/refraction, based on conservation of action and wavecrests
  - no wave generation
  - only monochromatic boundary forcing
  - parametrizations for wave breaking and wave induced bottom drag

  => relevant for nearshore applications

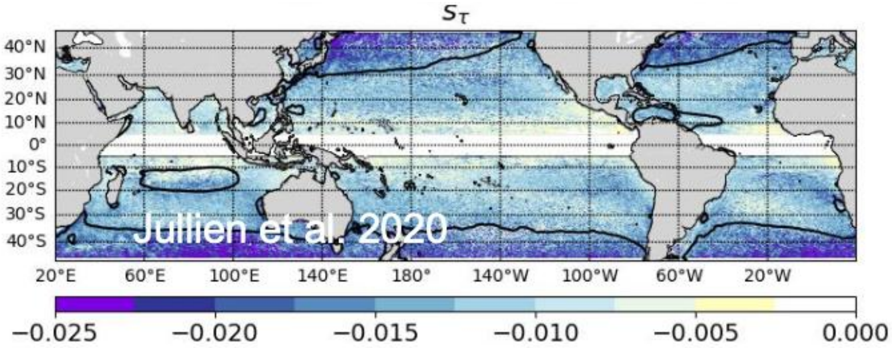
  => activated through cpp key

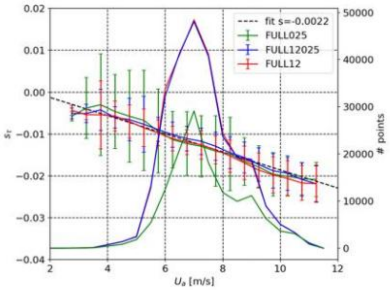
Various ways for coupling

- **Simplification / parameterization of coupling**

  Current feedback (CFB) parameterization:

  - Momentum flux: $\boldsymbol{\tau = \tau_a + s_\tau . U_o}$ ***with*** $\boldsymbol{s_\tau = -0.0029.|U_a| + 0.008}$
  - Heat fluxes (use of relative wind): $\boldsymbol{U_r = U_a - (1-s_w).U_o}$ ***with*** $\boldsymbol{s_w \approx 0.3}$





=> activated through cpp key

Various ways for coupling

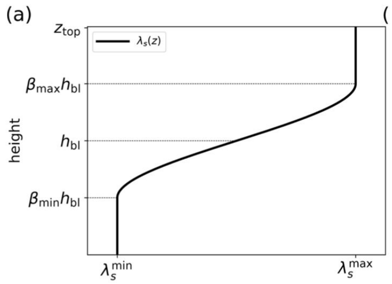
- **Simplification / parameterization of coupling**

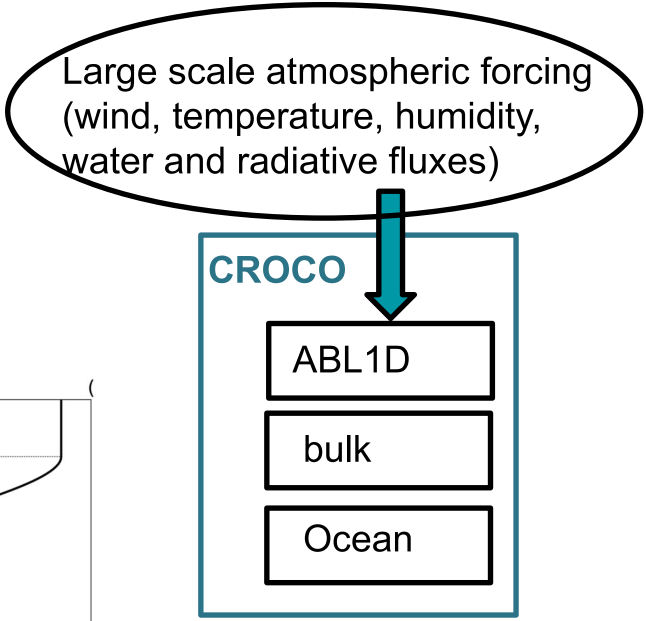
Atmospheric boundary layer (ABL) model (1D, work in process for 3D)

Hypotheses: - horizontal homogeneity
- no vertical advection
- transparent ABL (radiative and water fluxes imposed from the large scale model

=> compute turbulent diffusivity and viscosity
and compute the momentum and turbulent heat fluxes
=> Forced by a large scale model

$$
\begin{cases}
\partial_t u = +fv + \partial_z(K_m \partial_z u) + \lambda_m(u_{LS} - u) \\
\partial_t v = -fu + \partial_z(K_m \partial_z v) + \lambda_m(v_{LS} - v) \\
\partial_t \theta = \partial_z(K_s \partial_z \theta) + \lambda_s(\theta_{LS} - \theta) \\
\partial_t q = \partial_z(K_s \partial_z q) + \lambda_s(q_{LS} - q)
\end{cases}
$$





Other modules