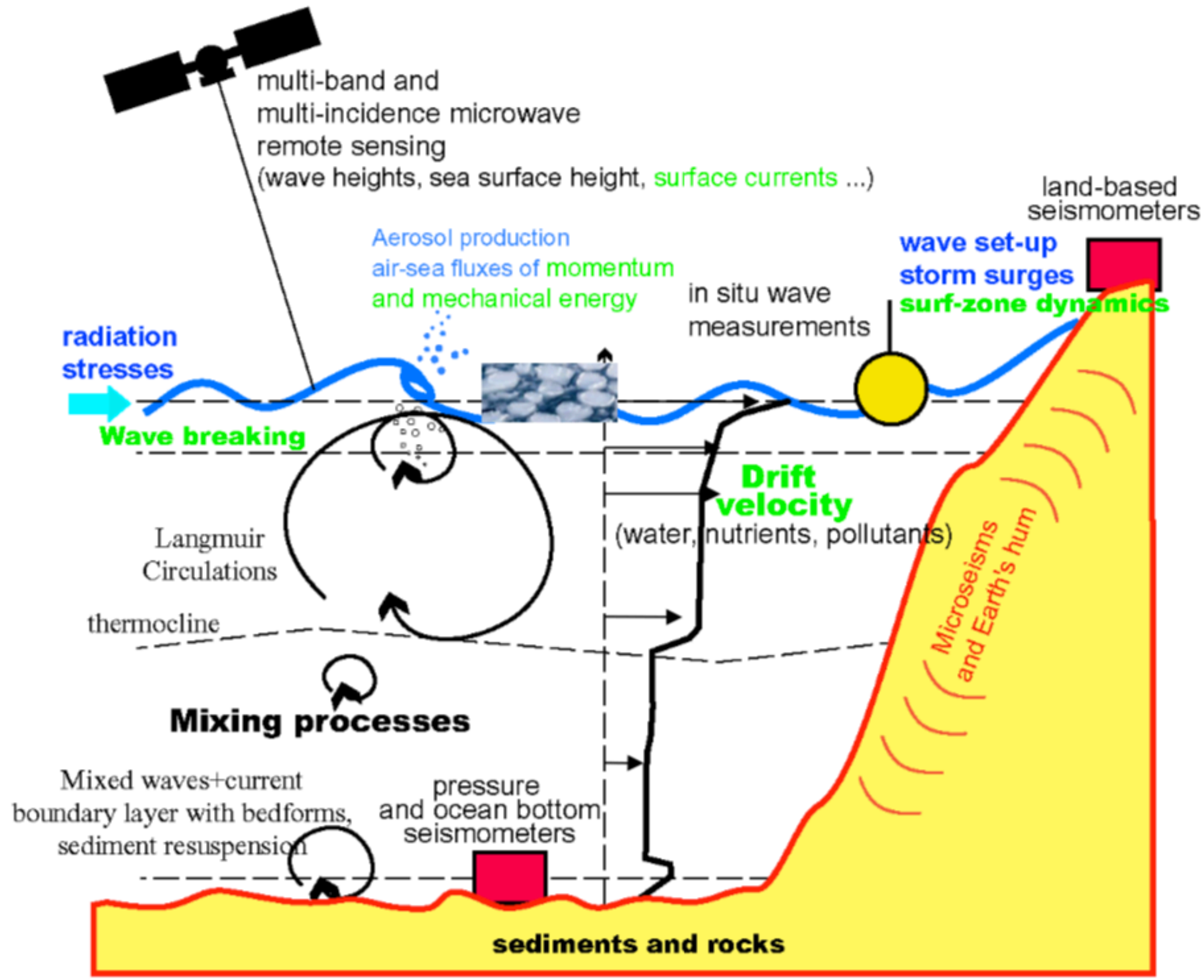
Introduction to WAVEWATCH III® and its coupling with CROCO

Swen Jullien
(with numerous inputs from F. Ardhuin)

Waves and sea states generalities

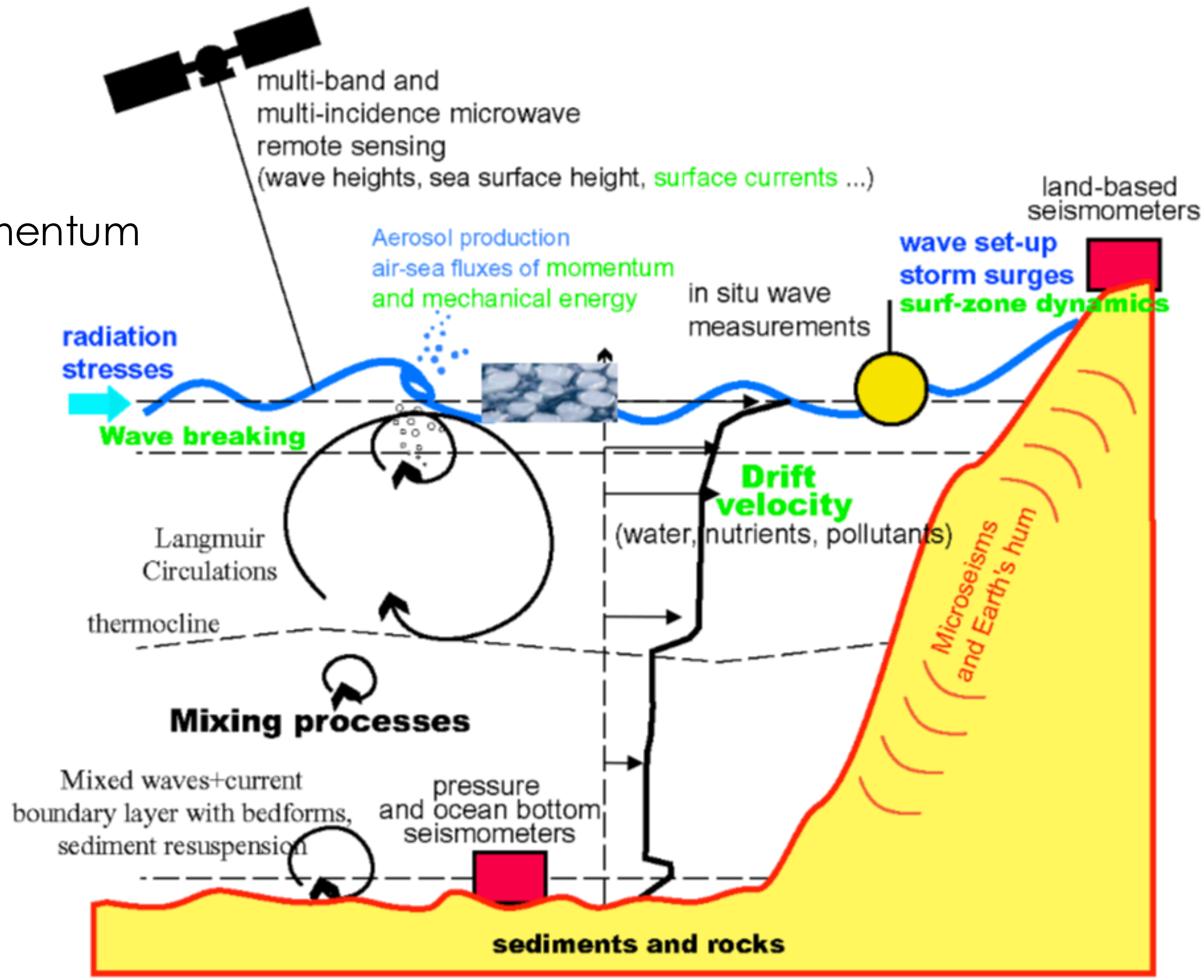


Waves and sea states generalities

Air-sea

- surface is not flat
- aerosol production
- air-sea fluxes of momentum
  and heat

- Remote sensing
  hs
  ssh
  currents
  winds

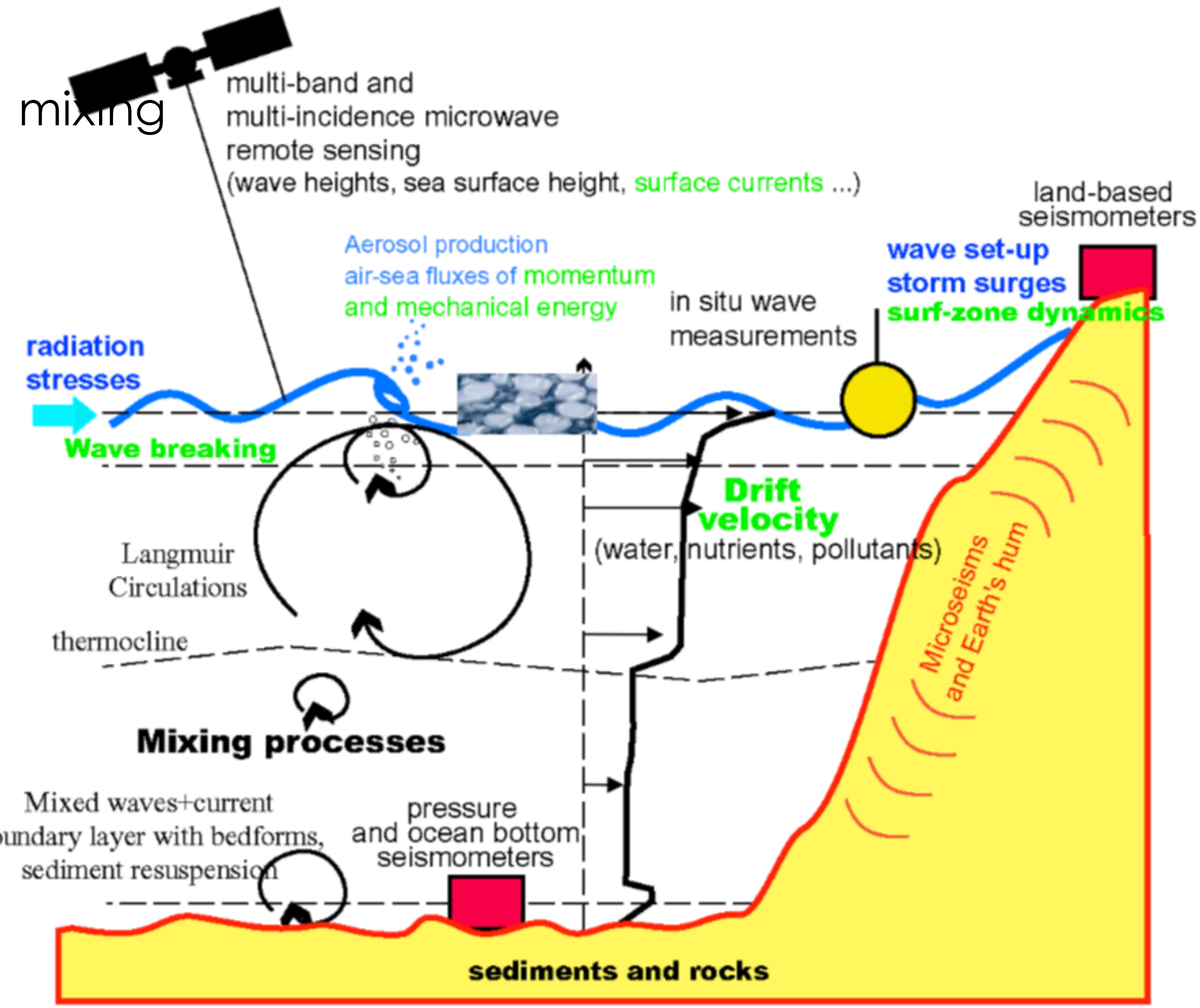


Waves and sea states generalities

Air-sea

Ocean circulation and mixing

- Stokes drift



Waves and sea states generalities

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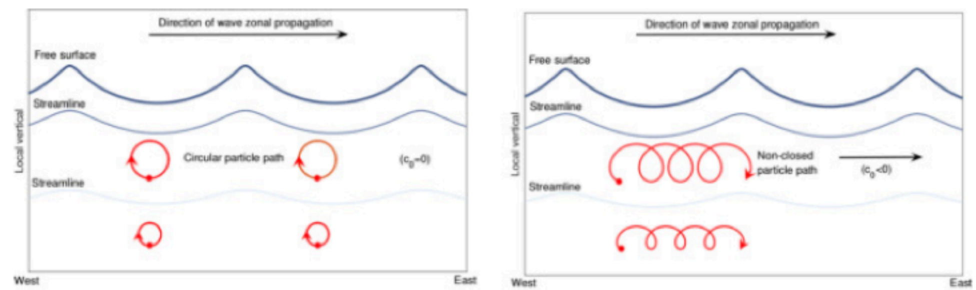
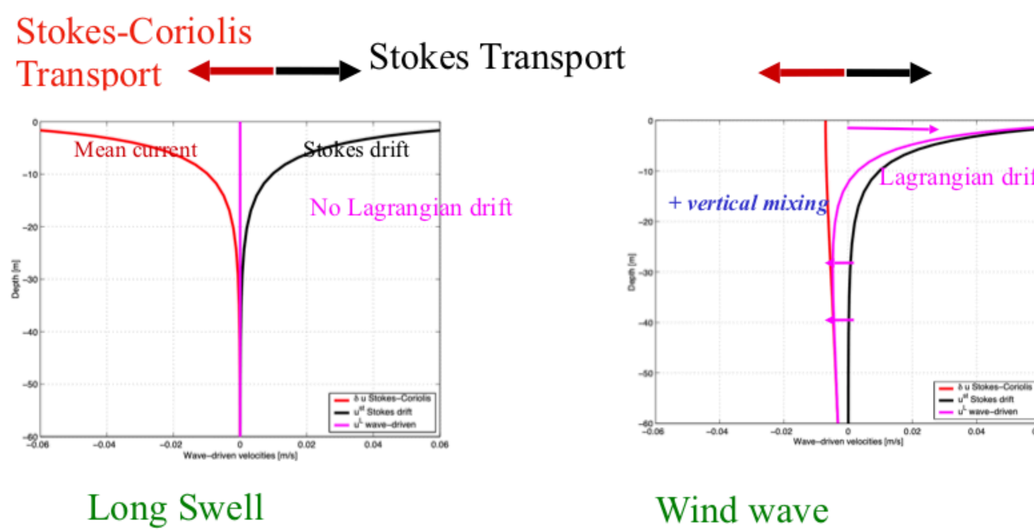


(a) No underlying current: $c_0 = 0$ (b) Depth-invariant current $c_0 \neq 0$

Stokes drift (residual) : orbital are not closed.
Transport up to 10m depth

Vertical average :
mean flow / stokes compensation
=>no wave induced transport
But potential drift



Waves and sea states generalities

Air-sea

Ocean circulation and mixing

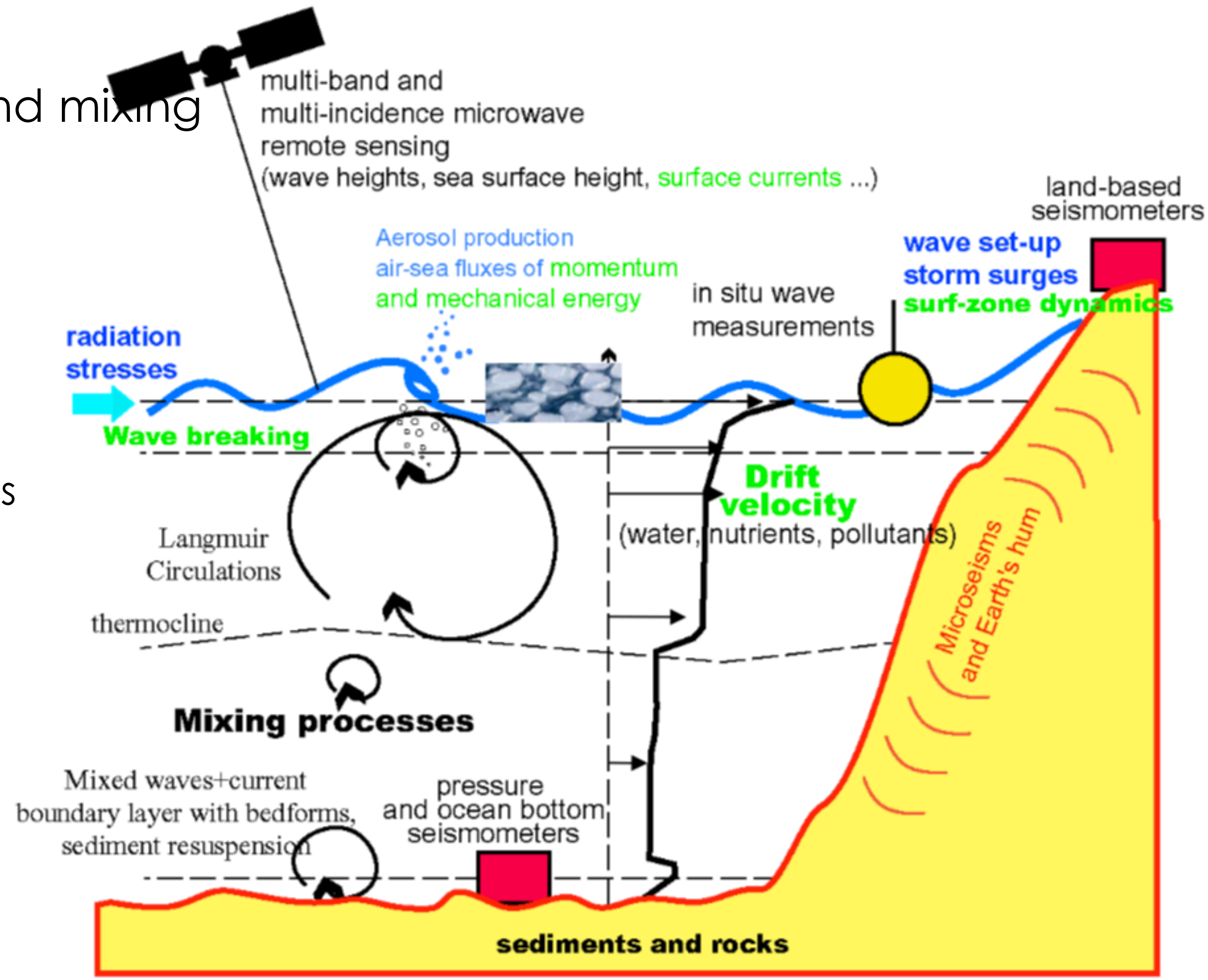
- Stokes drift
- Mixing: TKE injection

Through wave breaking and wave-turbulence interaction

- Langmuir circulations

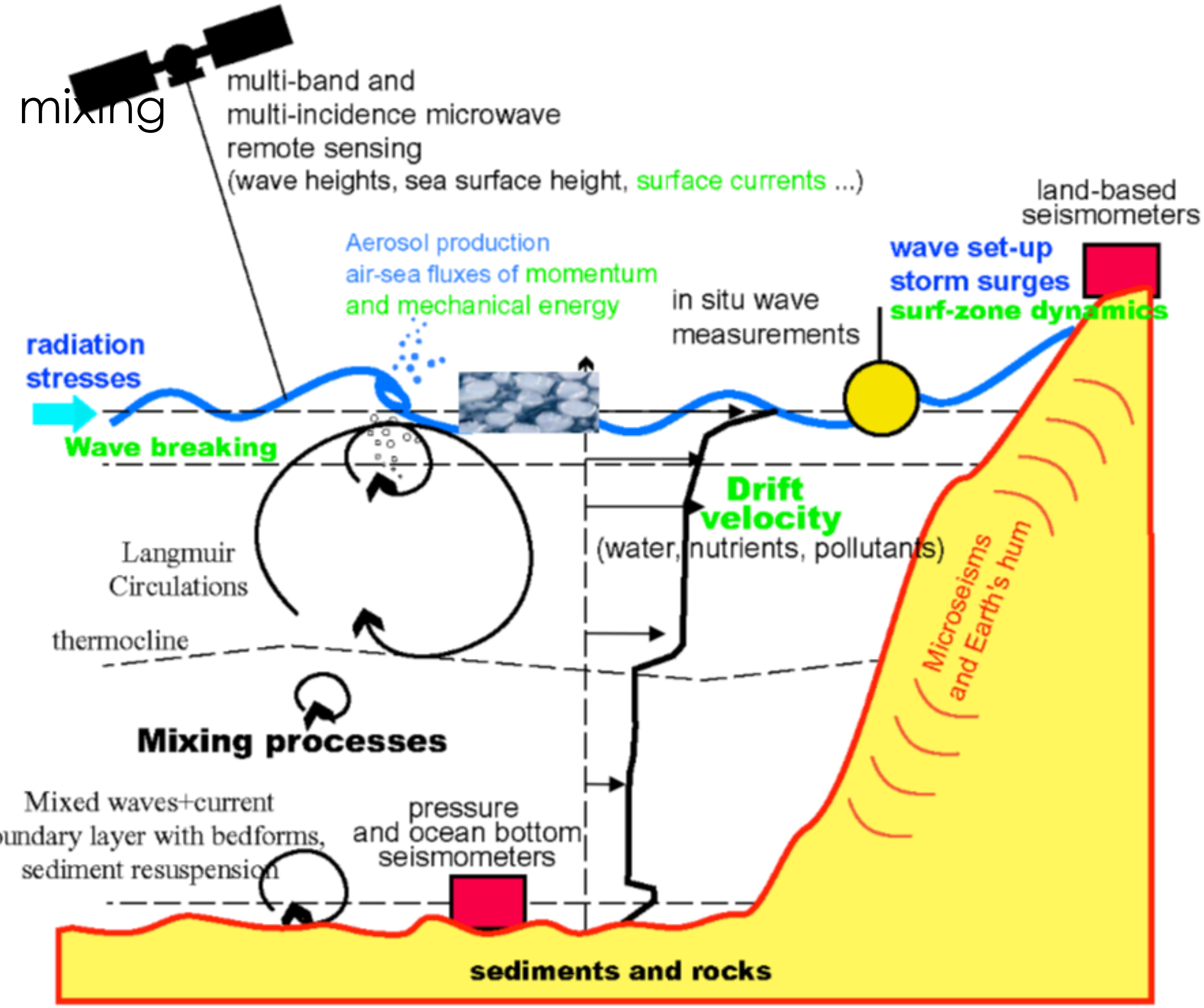
Impacts on:

- Biology
- Drifters
- Pollutants



Waves and sea states generalities

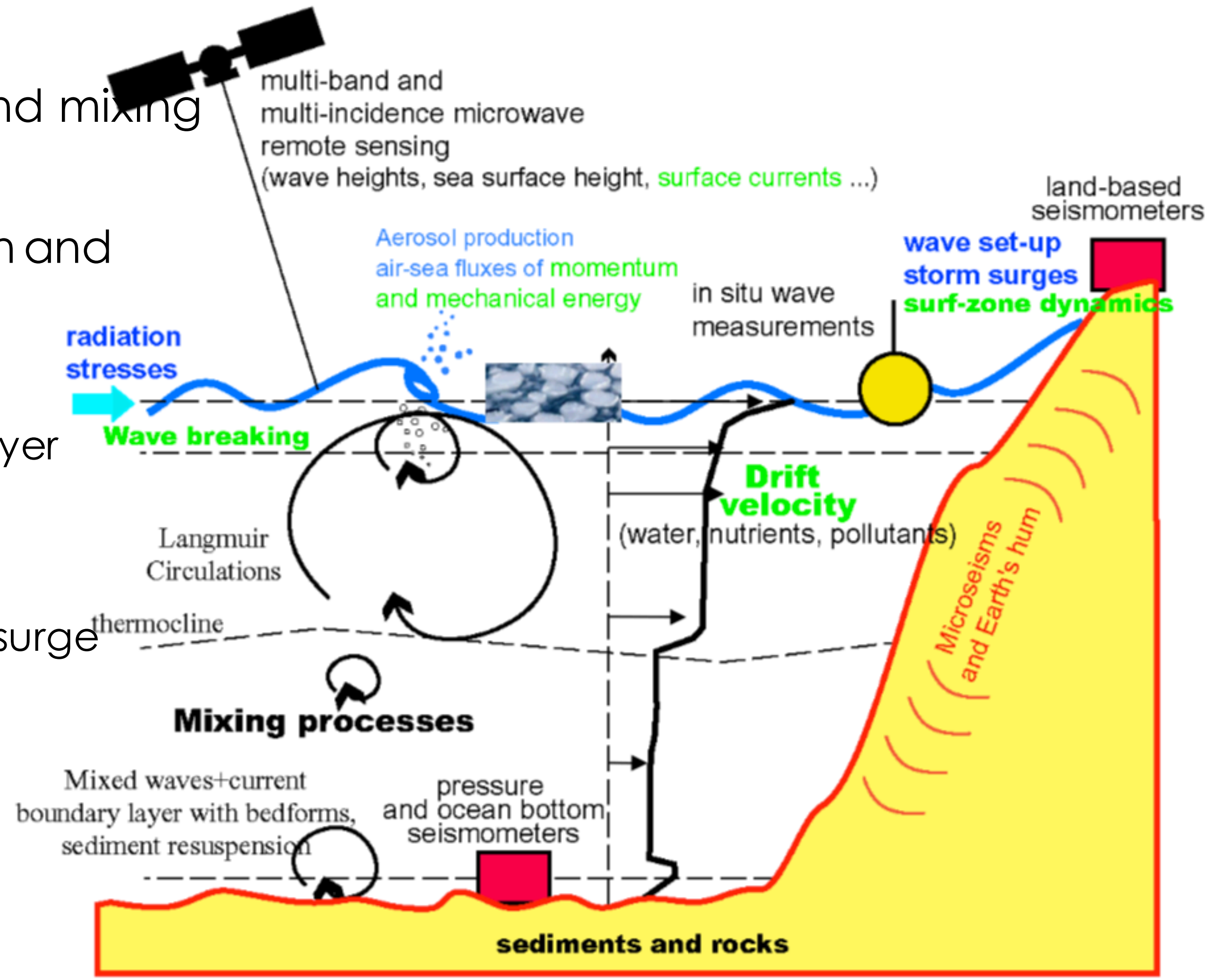
Air-sea
Ocean circulation and mixing
Ocean-ice



Waves and sea states generalities

Air-sea
Ocean circulation and mixing
Ocean-ice
Nearshore circulation and land-sea exchanges

- Surf-zone dynamics
- Bottom boundary layer
- Bedforms, sediment transport
- Wave set-up, storm surge



Waves and sea states generalities

Air-sea

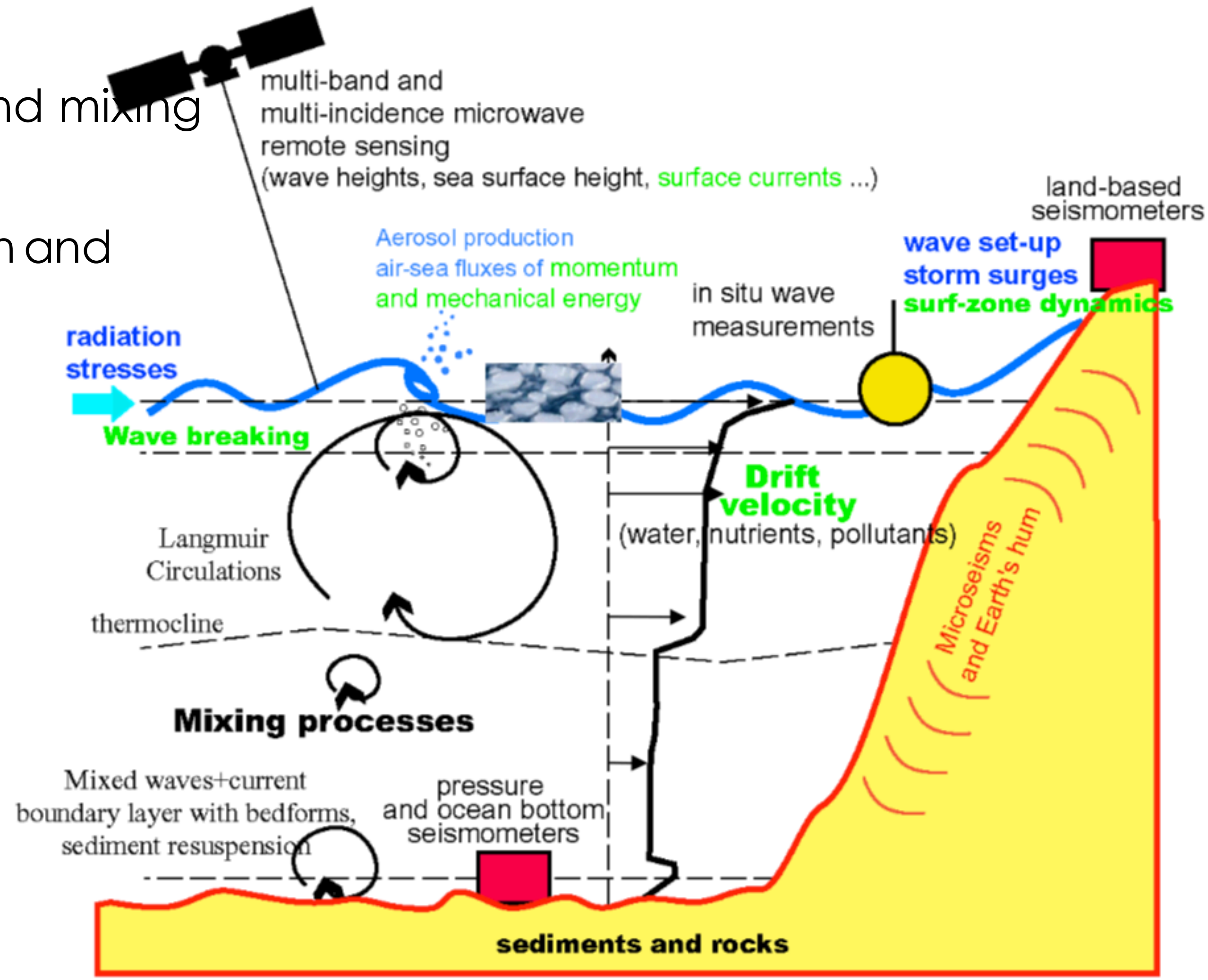
Ocean circulation and mixing

Ocean-ice

Nearshore circulation and land-sea exchanges

Ocean crust

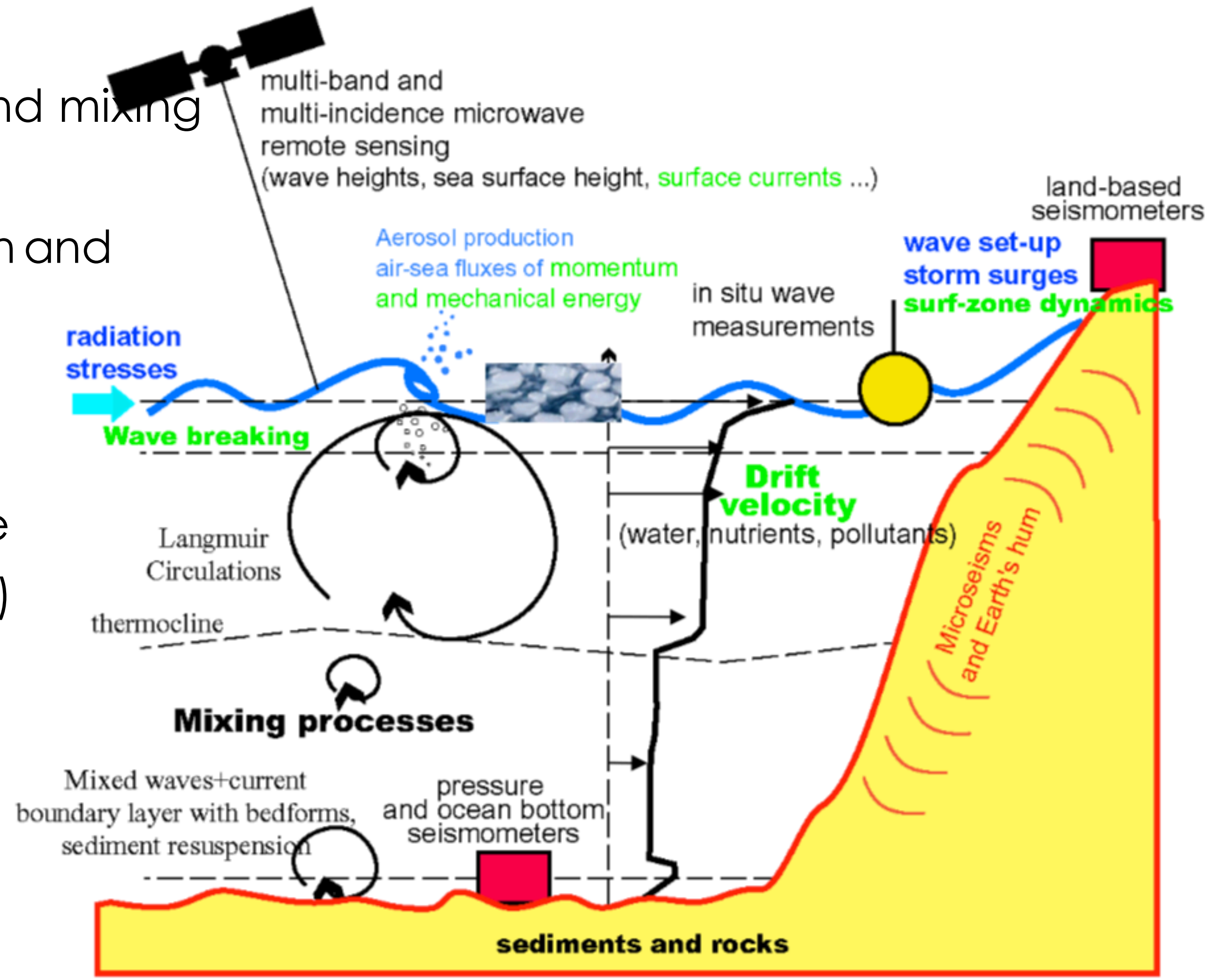
- microseisms



Waves and sea states generalities

Air-sea
Ocean circulation and mixing
Ocean-ice
Nearshore circulation and land-sea exchanges
Ocean crust

Engineering (offshore and littoral structures)
Maritime transport
Drifting objects and pollutants

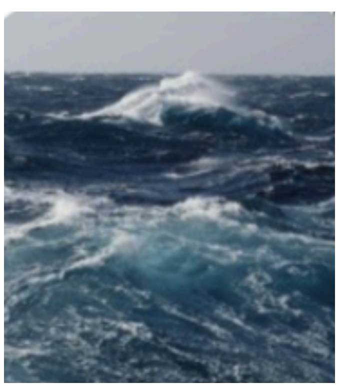


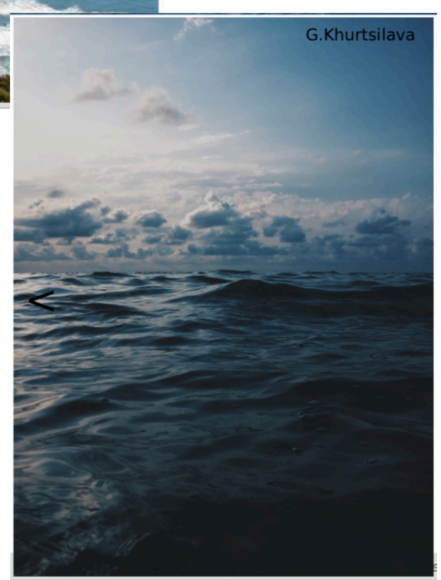
Waves and sea states generalities

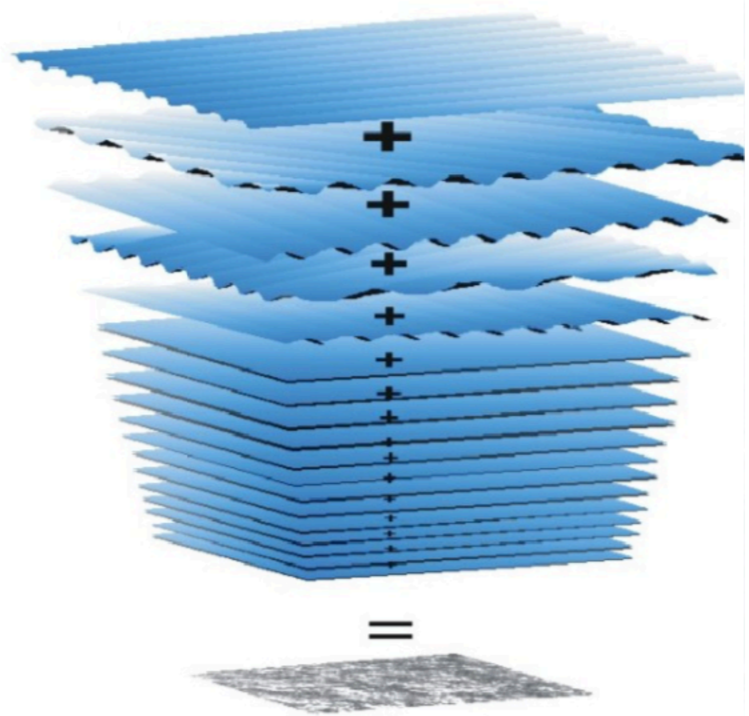
We think of waves as the large crests that we see at the sea surface…

But there are also short « wavelets » riding on the largest waves.

This collection of waves (long, short, tall, small…) is the « **sea state** »

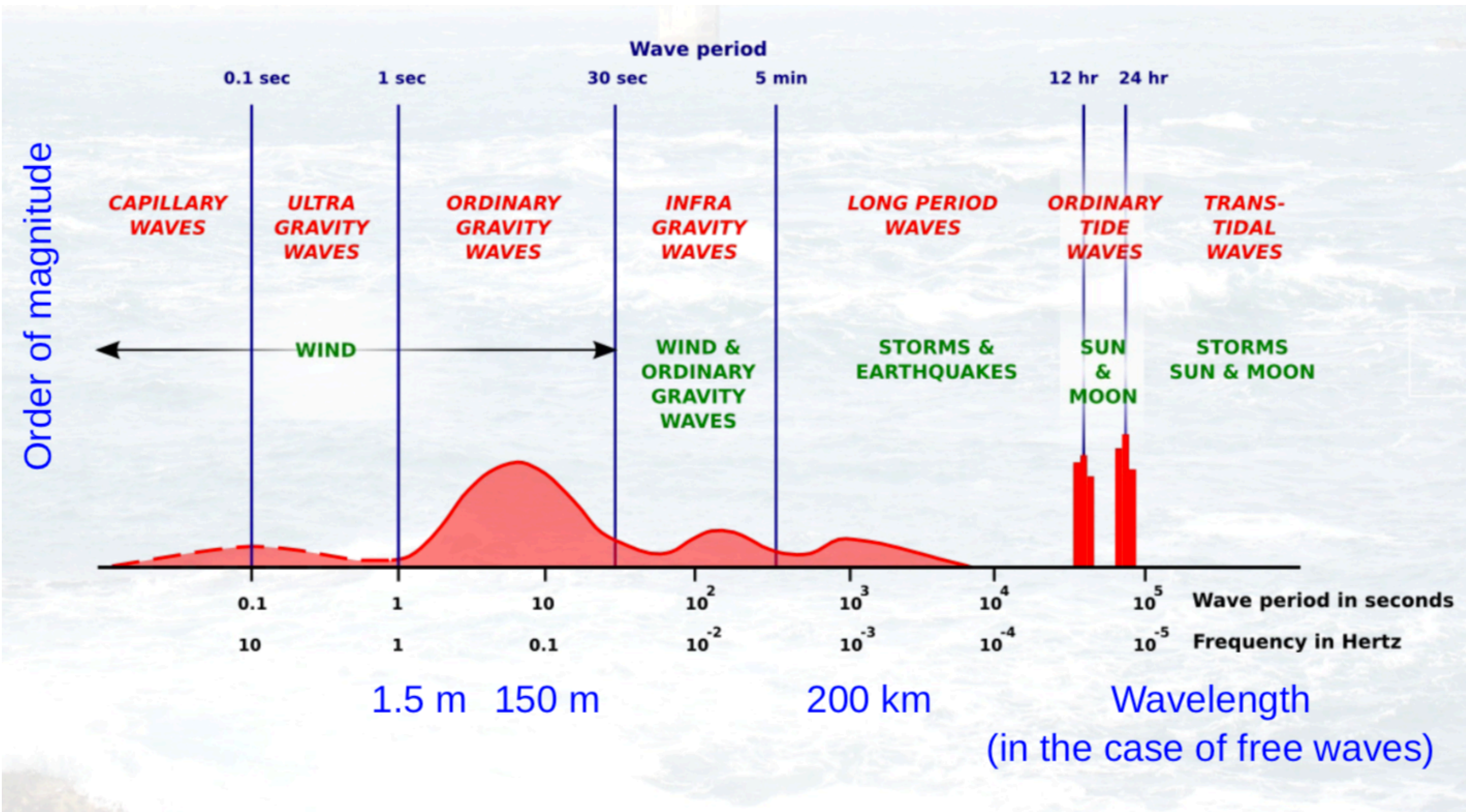






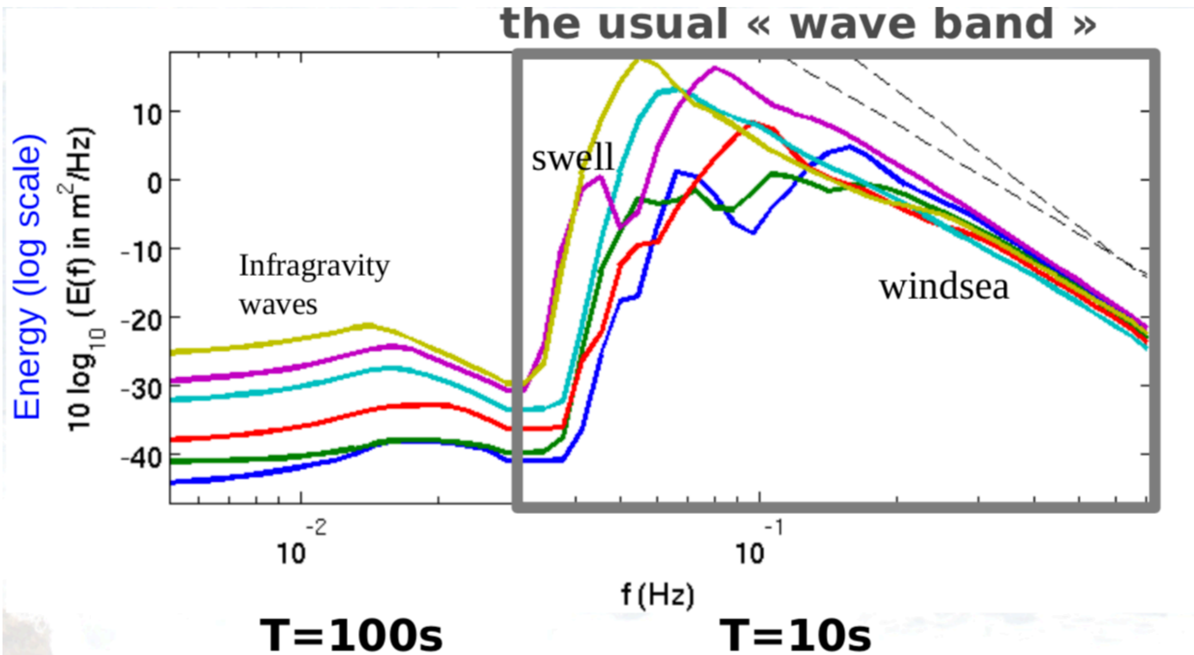
Waves and sea states generalities

Waves are characterized by the distance between 2 crests: the **wavelength**
And by the time between 2 crests passing a fixed point: the **wave period**



Waves and sea states generalities

Examples of power spectra of the surface elevation



The spectrum is a distribution of the variance across scales

$$\mathbf{E = \int E(f).df}$$

Definition of the significant wave height: **hs = 4 √E**

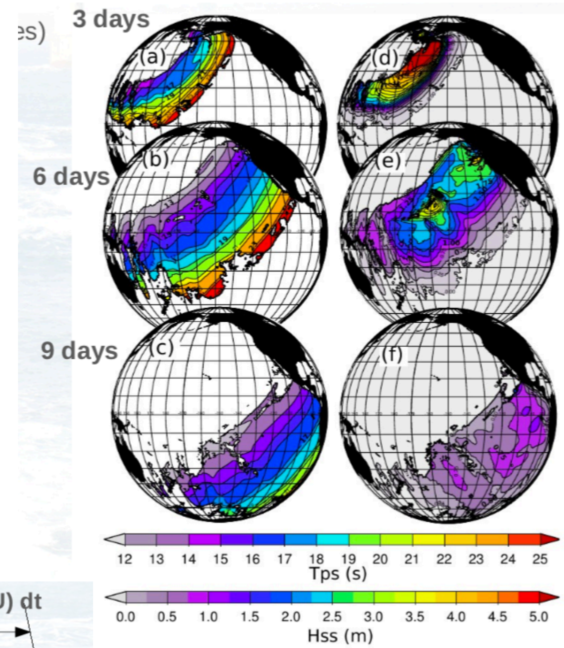
Waves and sea states generalities

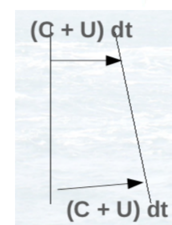
Wave energy propagate...
at the velocity Cg + U (group speed + current)...
Which is different for each spectral component !

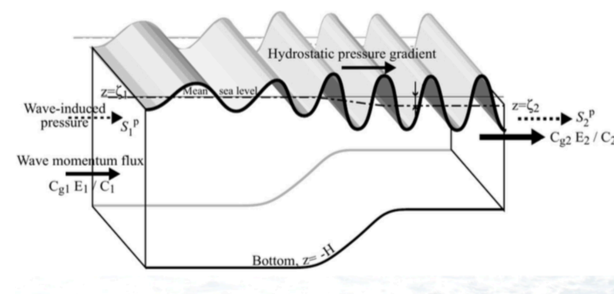
Waves turn...
following geodesics (great circles)
change in effective phase speed : C + U → **refraction**

Waves « shoal »...
If the velocity Cg + U converges...
then the energy density increases → wave heights go up
– Due to a change in water depth **: shoaling**
– Due to a change in current velocity

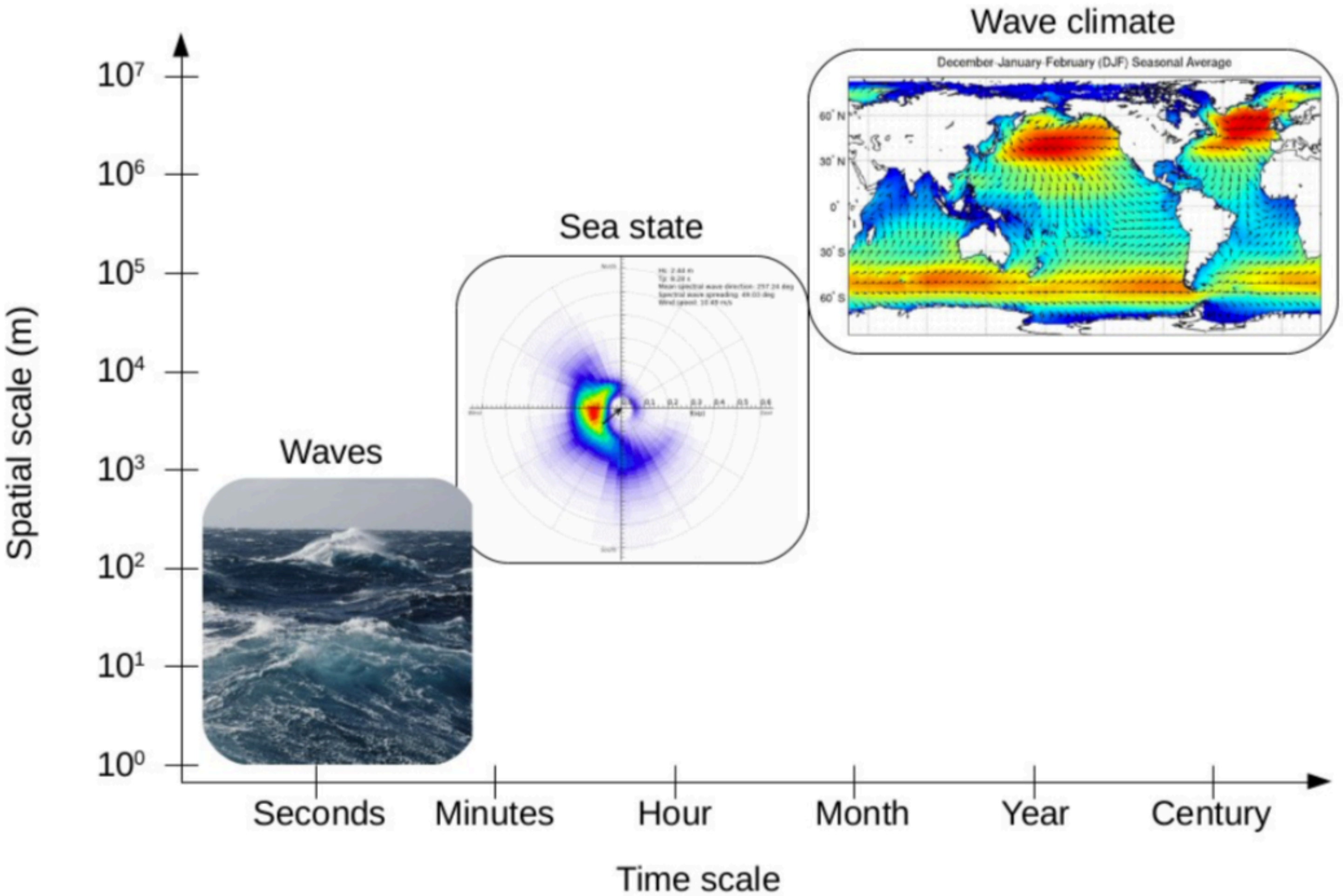
Steep waves break







Waves and sea states generalities

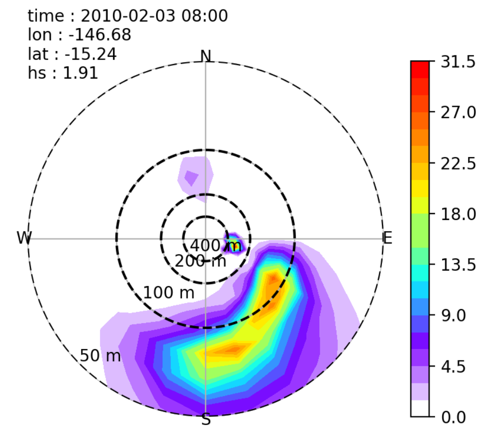


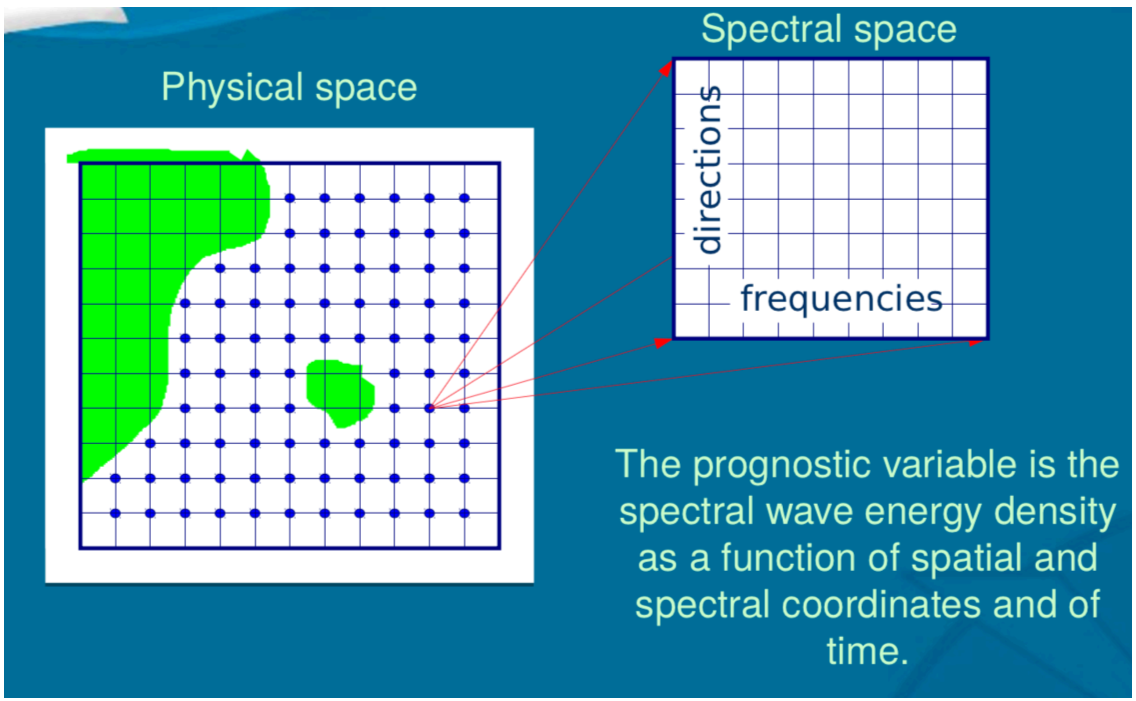
Modeling waves

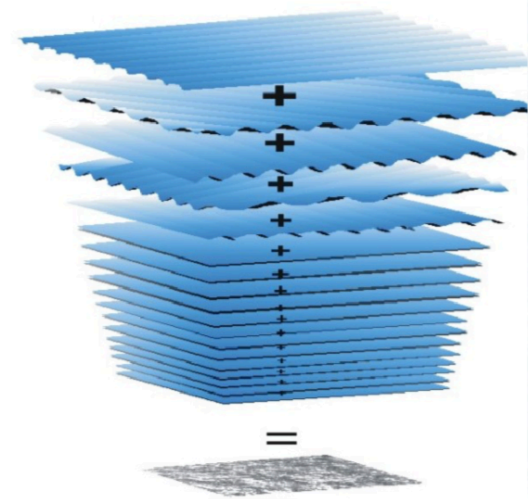
Wave modeling with spectral models (such as WAVEWATCH III)

-> Solve the equation of evolution of the wave spectrum

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







Modeling waves

Wave modeling with spectral models (such as WAVEWATCH III)

-> Solve the equation of evolution of the wave spectrum

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

where N(k, θ) is the wave density (or action) spectrum

And σ is the intrinsic frequency (i.e. observed in a frame of reference moving with the mean current)

Energy or Action? Action is a more general invariant than wave energy (e.g. in wave-current interactions there is exchange of energy with the current). The relation between action and energy spectra is given by:

$$F(f,\theta) = \frac{2\pi}{C_g} F(k,\theta) = \frac{2\pi}{C_g} \frac{N(k,\theta)}{\sigma}$$

Modeling waves

Wave modeling with spectral models (such as WAVEWATCH III)

-> Solve the equation of evolution of the wave spectrum

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

advection equation

source terms

$$\frac{\partial N}{\partial t} + \nabla_x \cdot \dot{\mathbf{x}} N + \frac{\partial}{\partial k}\dot{k} N + \frac{\partial}{\partial \theta}\dot{\theta} N = \frac{S}{\sigma} \,,$$

$$\dot{\mathbf{x}} = \mathbf{c}_g + \mathbf{U} \,,$$

$$\dot{k} = -\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial s} - \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial s} \,,$$

$$\dot{\theta} = -\frac{1}{k}\left[\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} + \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial m}\right] \,,$$

Hyperbolic equation with well-known solution methods

Modeling waves

Wave modeling with spectral models (such as WAVEWATCH III)

-> Source terms represent many different effects:

- Generation by the wind
- Non-linear evolution
- Dissipation due to breaking
- Dissipation due to bottom friction
- Scattering and reflection…

$$\boxed{S = S_{ln} + S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{db} + S_{tr} + S_{sc} + S_{ice} + S_{ref} + S_{xx}}$$

Sln = linear input term for model initialization to provide more realistic wave growth
Sin = atmosphere-wave interactions (usually positive but can also be negative in the case of swell
Snl = wave-wave interactions
Sds = wave-ocean interaction term that generally contains the dissipation
Sbot = wave-bottom interactions (shallow waters)
Sdb = depth-induced breaking (very shallow waters)
Str = triad wave-wave interactions
Ssc = scattering of waves by bottom features
Sice = wave-ice interactions
Sref = reflection off shorelines or floating objects such as icebergs
Sxx = eventual user-defined source term

Modeling waves

Wave modeling with spectral models (such as WAVEWATCH III)

-> The accuracy of wave models is a function of:

- forcing parameters (winds, currents, bottom, sea ice ...)

  -> Wind errors are among the main sources of wave errors

  -> Currents are important too and can create large differences. They can have effects on very small scale: wave height gradients are probably dominated by currents

- choice of parametrizations

  -> Source term parameterization tuning is complex

- model numerics

-> wave model validation mainly with hs from altimetry (and in situ buoys)

when going from Hs to E(f) to full spectrum to source terms ... we are talking about aspects of the wave model that are less and less validated...

Modeling waves

Wave modeling with spectral models (such as WAVEWATCH III)

-> Outputs of wave models

- Full spectra
- 1D spectral data : E(f)
- « bulk » parameters (scalar / vector): derived
    - from the spectrum (e.g. Hs, Tm0,-1 ...)
    - from the source terms (e.g. tauw, phioc ...)

WAVEWATCH III in practice

WAVEWATCH III (and most spectral models) do not solve the full density spectral evolution equation in once, but split it into 3 parts:

$$\begin{aligned}\frac{\partial N}{\partial t} &+ \text{advection} = 0\\ \frac{\partial N}{\partial t} &+ \text{refraction} = 0\\ \frac{\partial N}{\partial t} &= S/\sigma.\end{aligned}$$

Because the time scales (generation vs propagation are very different)

$\Rightarrow$ Different time steps for the different parts

DTG = global time step (each step is integrated over DTG)

DTX = time step used for advection, constrained by stability (CFL)

DTR = time step used for refraction and k-advection

DTS = time step used for source terms

WAVEWATCH III in practice

Practical rules for choosing time steps:

DTG: accuracy requires relatively small factor between DTX and DTG (say 2~3) as we do not want to propagate information over barely resolved bathymetry in overall time step

DTX: CFL criterion : information cannot jump stably over more than one grid box in one time step => DTX = 0.8 x dx/(g/fmin4pi) with fmin=0.0373 => 3-4 % of dx

DTR: refraction includes great-circle direction change, depth and current refraction, and current induced wavenumber shifts, refraction is filtered (limited) for stability, and reducing the refraction time step will reduce the use of filter. Generally kept large but best set at ½ DTG => need to check that lower DTR has no impact on the solution.

DTS: actually represents the minimum used DT, smaller minimum DT results in smoother and faster model. Generally used: 1- 10s

WAVEWATCH III in practice

WAVEWATCH III includes **many options** for numerics and parameterizations

-> The general options are chosen prior to compilation by setting the "**switch**" file *(similarly to cppdefs in CROCO)*. It includes the choice of:

- The propagation scheme (PR0-PR3 / UQ, UNO)
- The generation and dissipation parameterizations (ST1-ST6)
- The wave-wave interactions (NL0-NL3)
- The bottom friction (BT0-BT4)
- The sea ice treatment (IC0-IC3 / IS0 – IS2)
- The shoreline reflection (REF0-1)
- The interpolation method of the forcing fields (WNT0-2, WNX0-2)
- The use of coupling (COU / OASIS / OASOCM, OASACM)
- The use of netcdf4 library (NC4)
- The use of parallelization or not (SHRD or DIST, MPI)

```
F90 NOGRB NOPA NC4 TRKNC DIST MPI PR3 UQ FLX0 LN1 ST4 STAB0 NL1 BT4 DB1 MLIM TR0 BS0 IC0 IS0
 REF1 XX0 WNT0 WNX1 RWND CRT0 CRX1 COU OASIS OASOCM O0 O1 O2 O2a O2b O2c O3 O4 O5 O6 O7
```

WAVEWATCH III in practice

WAVEWATCH III includes **many options** for numerics and parameterizations

-> Then parameter adjustment is made through **namelists** when defining the model configuration in **ww3_grid.inp**

```
&MISC CICE0 = 0.25, CICEN = 0.75, FLAGTR = 4 /
&FLX3 CDMAX = 2.5E-3 , CTYPE = 0 /
&PRO3 WDTHCG = 4.00, WDTHTH = 4.00 /
&SIN4 BETAMAX = 1.33 /
&SDS4 WHITECAPWIDTH = 0.3 /
```

Here are a few references for numerics and parameterizations (other can be found in WW3 manual):

Tolman 2002, Ardhuin et al. 2010, Filipot et al. 2012, Babnin et al., Janssen et al. 1991 and updates, Hasselmann 1985, Battjes and Janssen 1978...

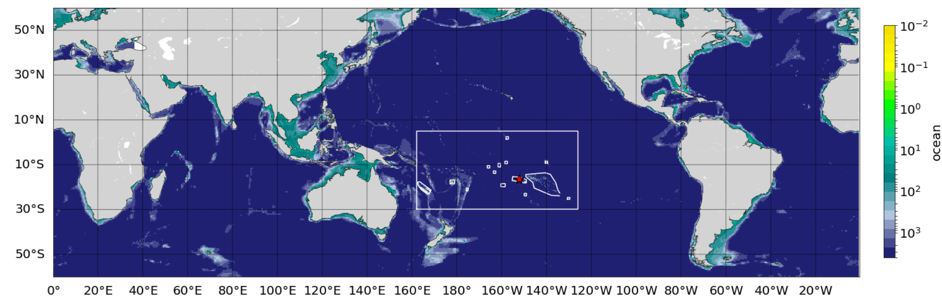
WAVEWATCH III in practice

WAVEWATCH III grids

WAVEWATCH III has multiple grid options

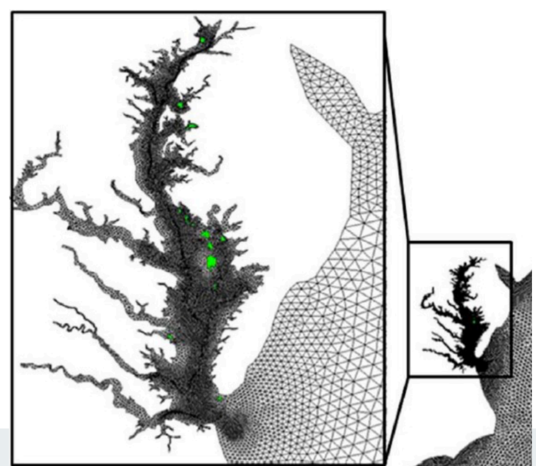
Structured grids:

- rectangular grids: RECT
- curvilinear grids: CURV



Multigrid option (for nesting higher resolution structured grids)

Unstructured grids: UNST



WAVEWATCH III in practice

WAVEWATCH III grids

WAVEWATCH III requires 3 grid definitions to run (1 necessary and two optional):

- bathymetry (necessary)
- land –sea mask (optional in some version, needed in multi-grid version of WWIII)
- obstructions (optional): to account for energy decay due to sub-grid blocking (e.g. unresolved islands…)

Two types of reference data are usually used to build the grids:

- global high resolution bathymetry dataset (e.g. ETOPO)
- global shoreline database in the form of polygons (e.g. GSHHS)

⇒ Algorithms are designed to meld the high resolution bathymetry with the shoreline database to develop the optimum grids within the **GRIDGEN** pre-processing framework

WAVEWATCH III in practice

WAVEWATCH III forcing
(water level, atmosphere, currents, ice, boundaries)

Atmosphere/currents/water level/ice forcings:

- not mandatory (but no atmospheric forcing means no wave generation and only propagation from the boundaries),
- can be set as constant,
- can be prescribed from external file or model (in the case of coupling)

(activation through flags in ww3_shel.inp)

Boundaries:

- WWIII can run with closed or open boundaries,
- Boundary data are therefore mandatory only for open boundary case,
- They are prescribed from wave spectra

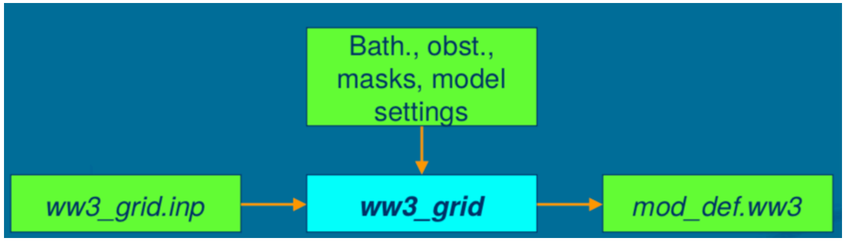
(activation with dedicated values (2) in the mask grid)

Initialization:

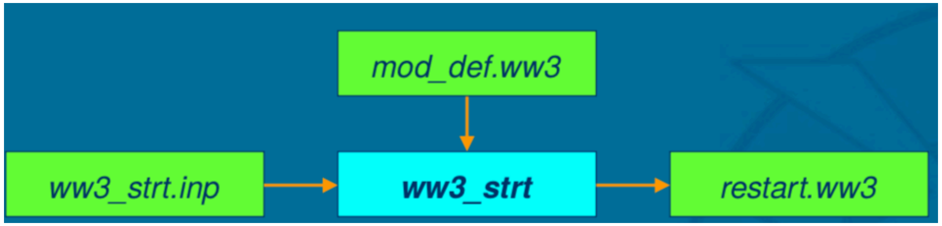
- May be set up from calm conditions
- Or from a prescribed idealized spectrum

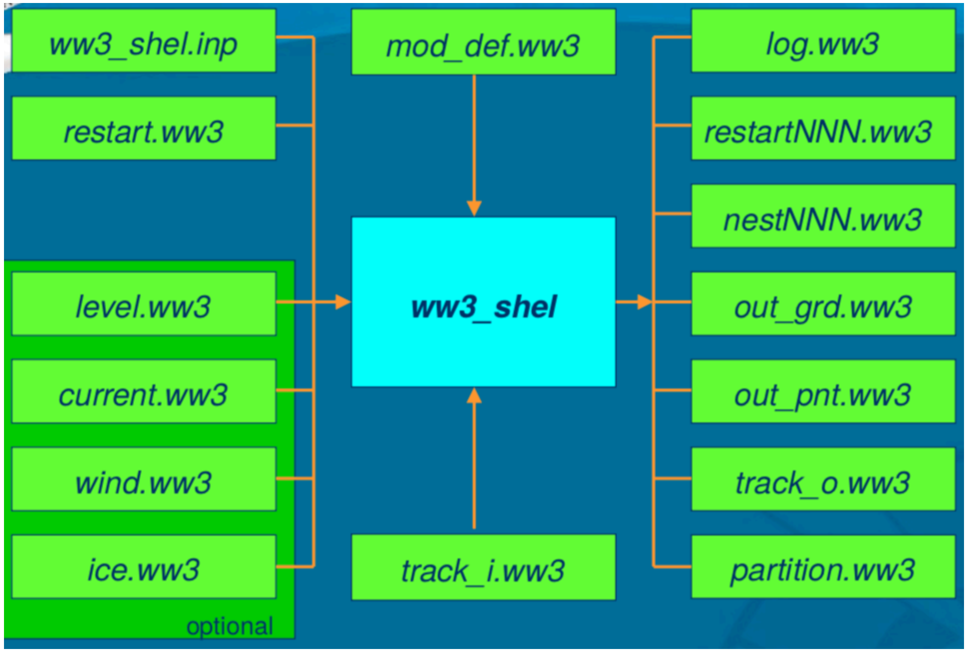
(using ww3_strt.inp)

WAVEWATCH III in practice



WAVEWATCH III workflow

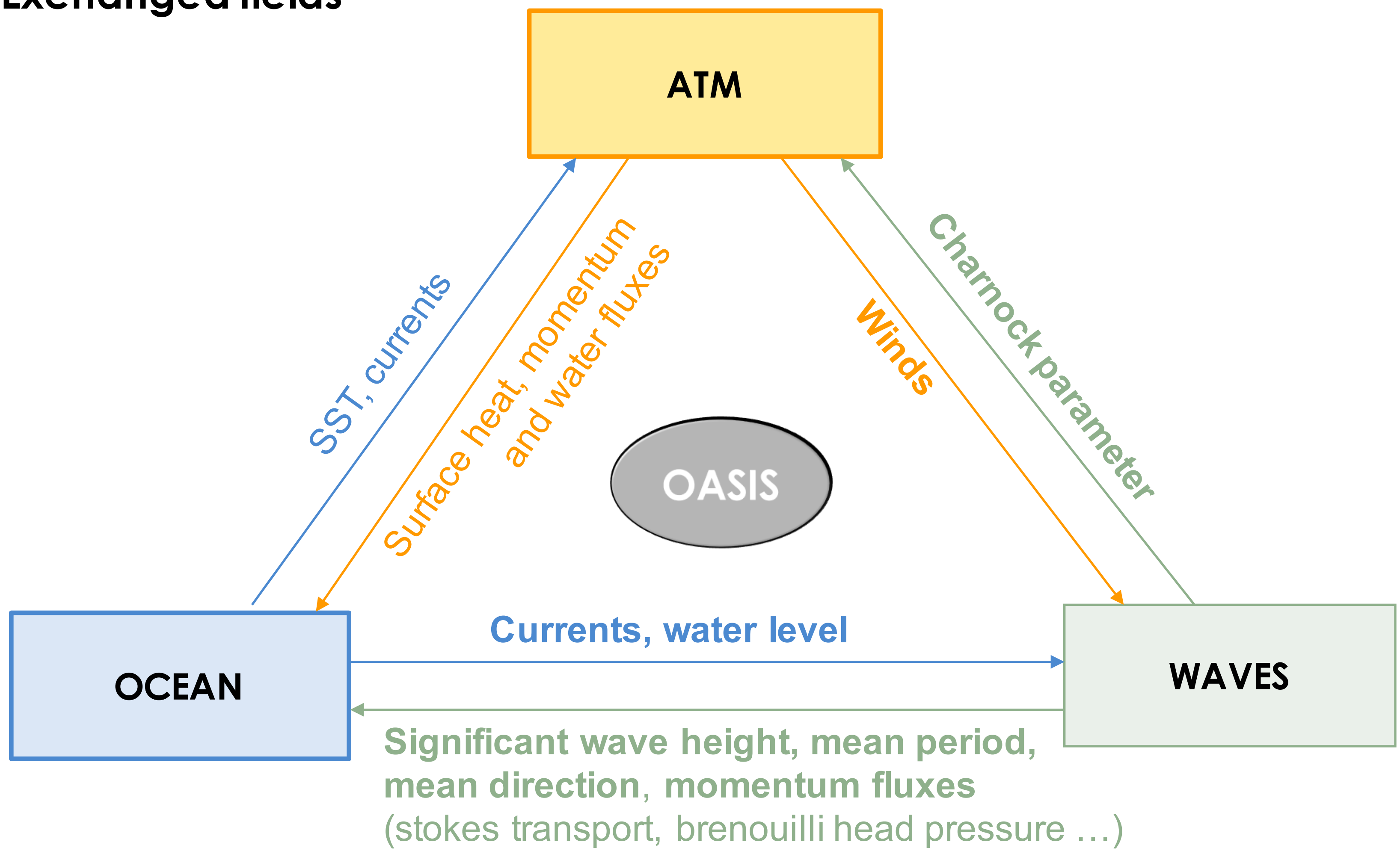




+ some utilities to prepare forcing files (w3_prnc), boundary files (w3_bounc), and transform output files to netcdf or ascii files (w3_ounf, w3_outp, w3_ounp…)

Coupling WAVEWATCH III with CROCO

Exchanged fields



Coupling WAVEWATCH III with CROCO

In practice

⇒ Activate **switches** associated to coupling for **coupled compilation**

COU OASIS OASOCM => ocean-wave coupling
COU OASIS OASACM => atmosphere-wave coupling

NB! MPI DIST switches are also mandatory, as OASIS uses MPI communications

⇒ In **ww3_shel.inp**: activate coupled flags to forcing fields:

```
C F    Water levels
C F    Currents
C F    Winds
```

And define the coupling time step and the coupled fields in:

```
$ Type 7 : Coupled fields
 20090101  000000  3600  20090201  000000
N
T0M1  OHS DIR TAW  TWO  ACHA
SSH CUR WND
```

NB! The coupling time step must equal the global time step (DTG, defined in ww3_grid.inp)

Coupling WAVEWATCH III with CROCO

In practice

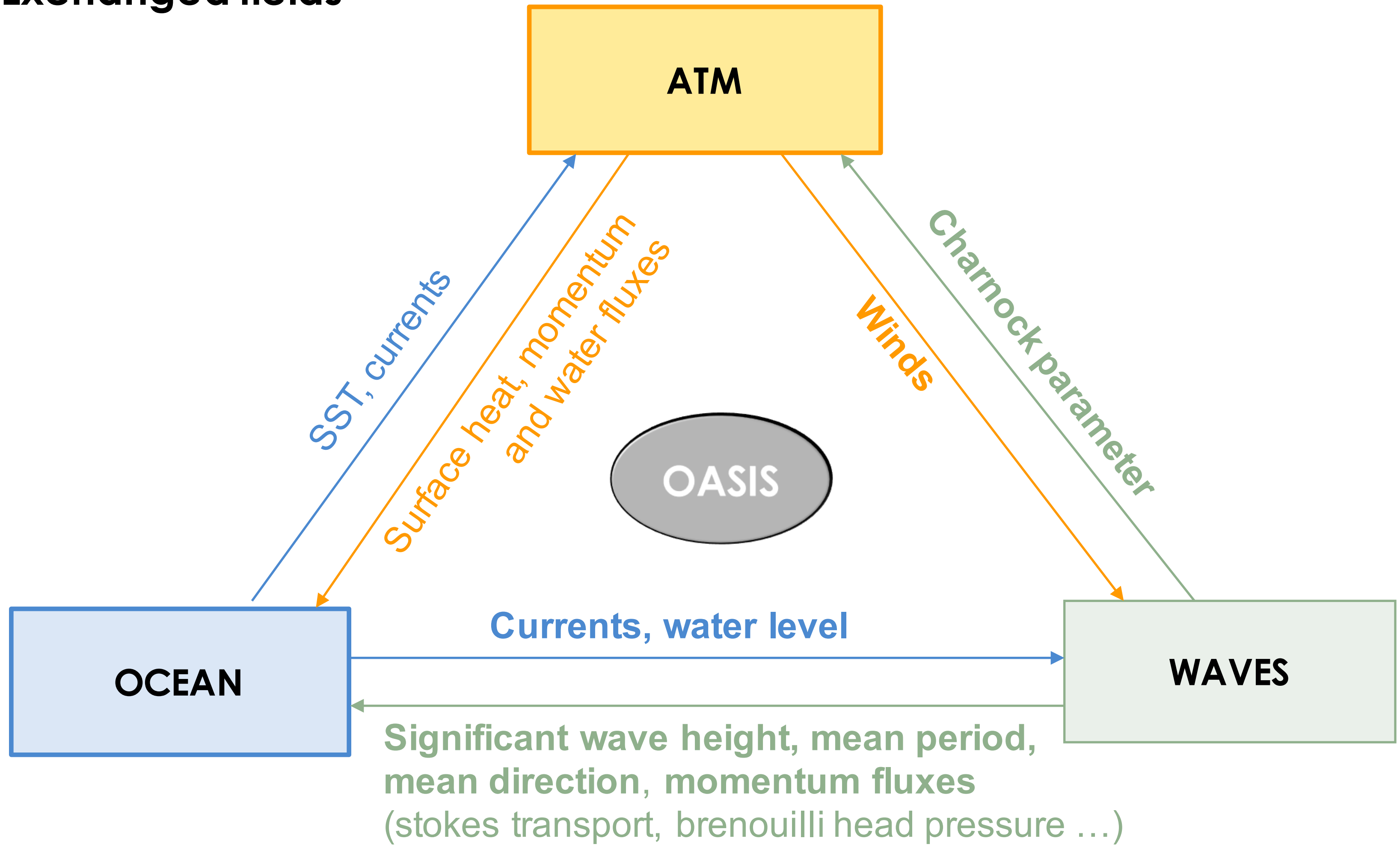
⇒ OASIS **namcouple** has to be set-up according to chosen fields to be coupled in WAVEWATCH III and CROCO

⇒ **w3_grid** has to be launched sequentially prior to launching the coupled run

⇒ **w3_shel** (renamed wwatch for the coupler) has to be launched together with croco executable through MPI command

Coupling WAVEWATCH III with CROCO

Exchanged fields



Coupling WAVEWATCH III with CROCO

Coupling: why?

- Waves are influenced by winds
- Waves are influenced by currents, water levels, bottom roughness
- Waves are influenced by sea ice

Feedbacks:

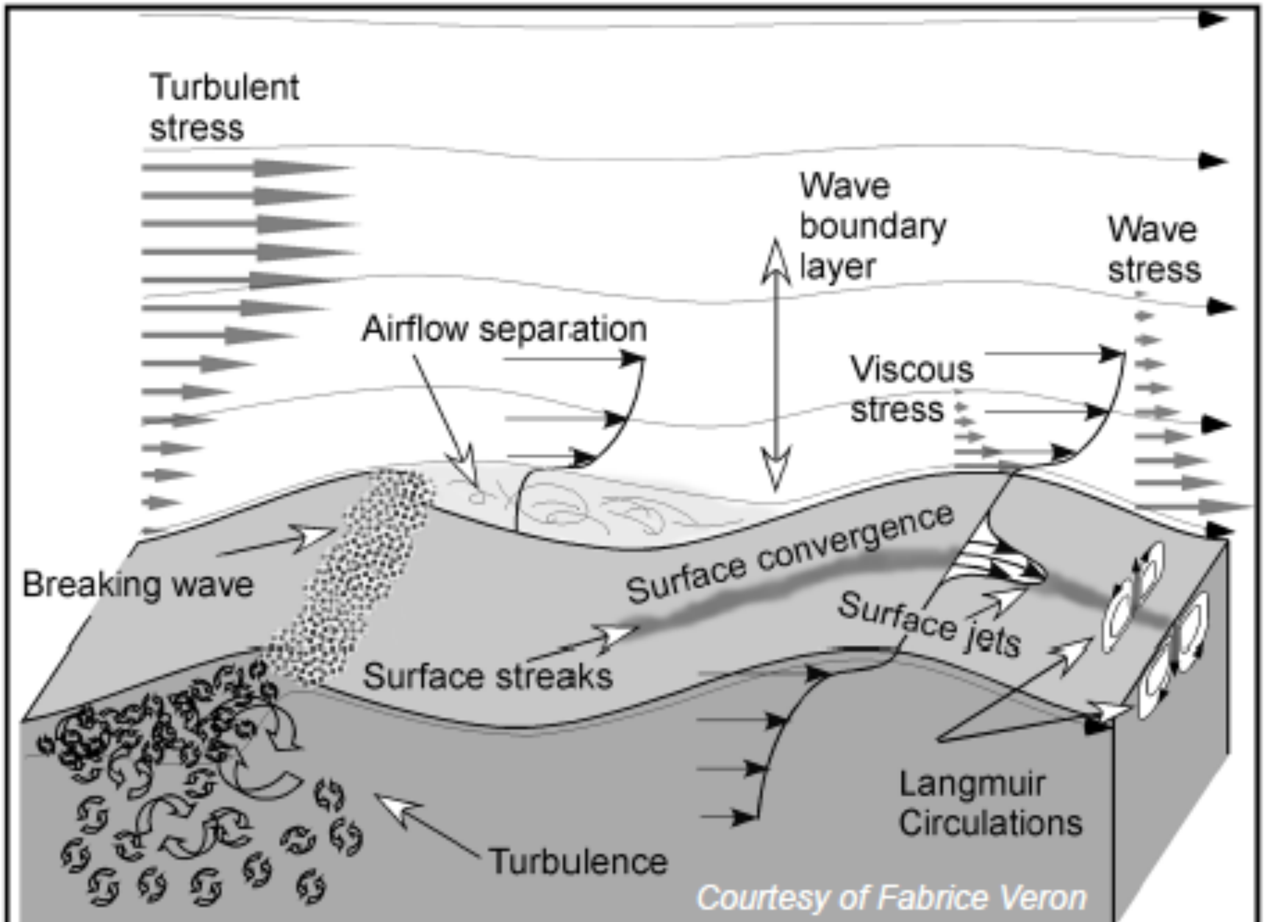
- the surface roughness (waves) modifies the wind stress
- Waves generate currents and modify water levels and bottom roughness
- Waves enhance the upper ocean mixing
- Waves break up the ice and push it around

- And such feedbacks have influence on waves

  $\Rightarrow$ **Need to couple**

Coupling WAVEWATCH III with CROCO

Coupling: why?



Coupling WAVEWATCH III with CROCO

Coupling: When does it matter?

-> Coupled feedbacks through the wind stress

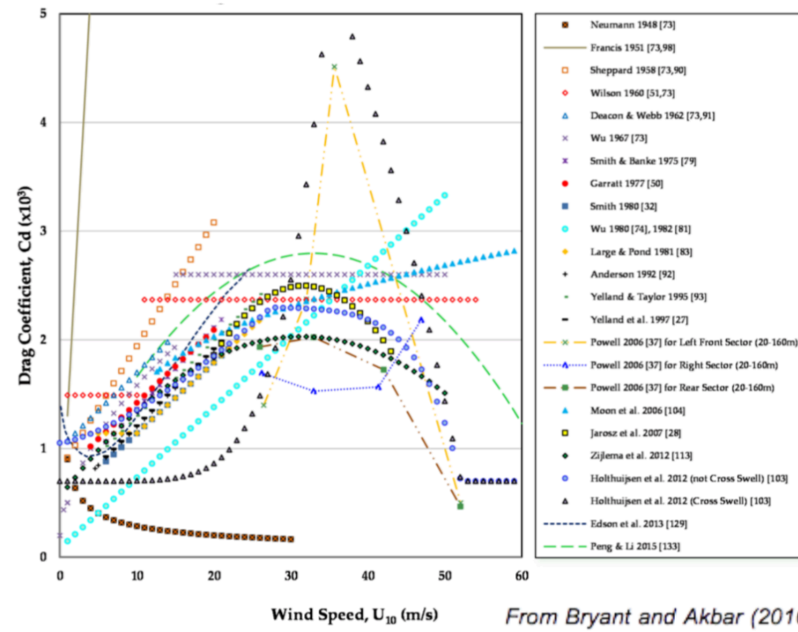
drag coefficient is dependent on the sea state, dependent on wave age

⇒ So basically it always matters

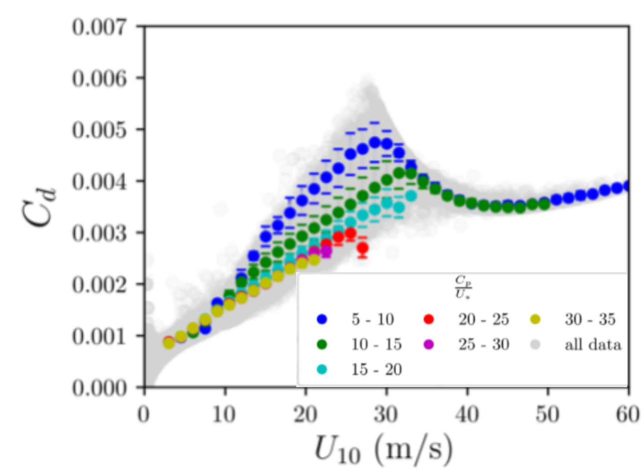
⇒ Notably when **mixed seas**

⇒ Lots of remaining uncertainties for high wind speeds, but certainly important for **extreme events**

⇒ **Coastal storm surge** modelling



From Bryant and Akbar (2016)



Coupling WAVEWATCH III with CROCO

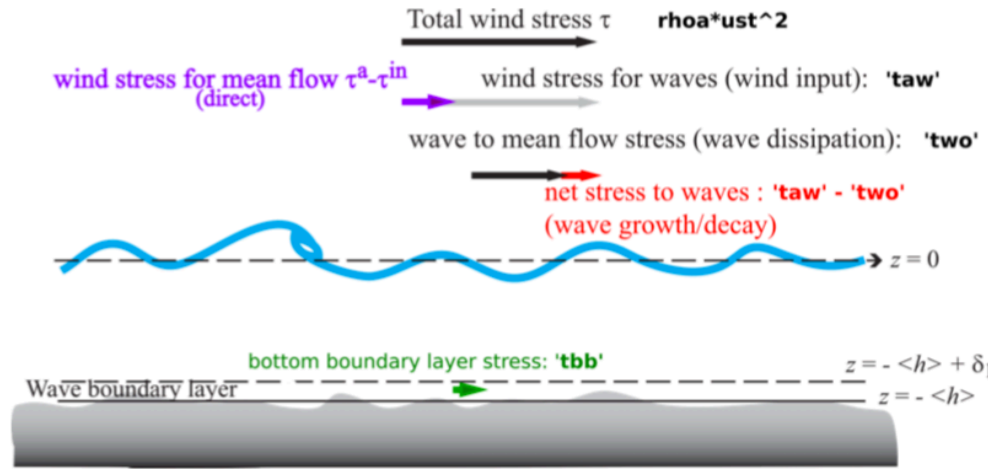
Coupling: When does it matter?

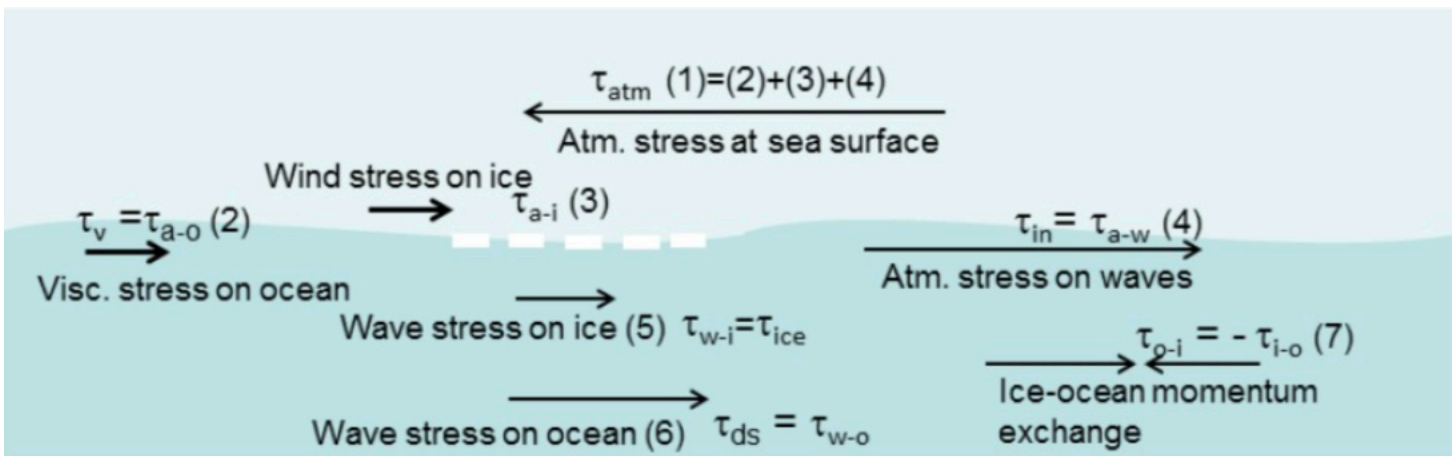
-> Fluxes computation

Wave-atmosphere

Wave-ocean

Wave-ice

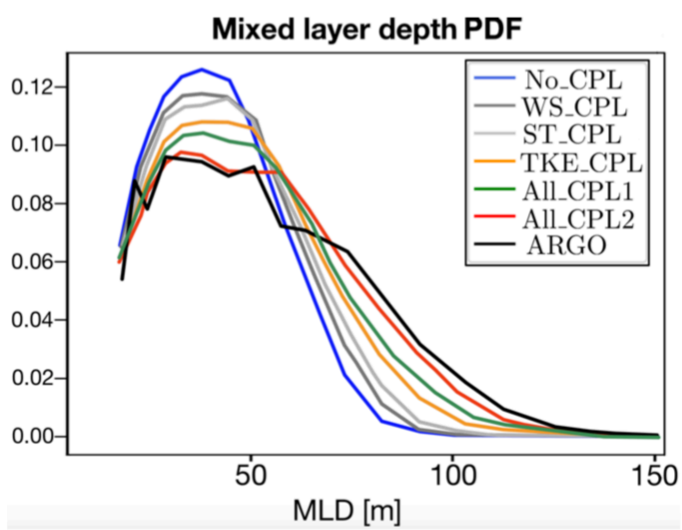




Coupling WAVEWATCH III with CROCO

Coupling: When does it matter?

-> Coupled feedbacks to mixing in the ocean



Couvelard et al. 2020

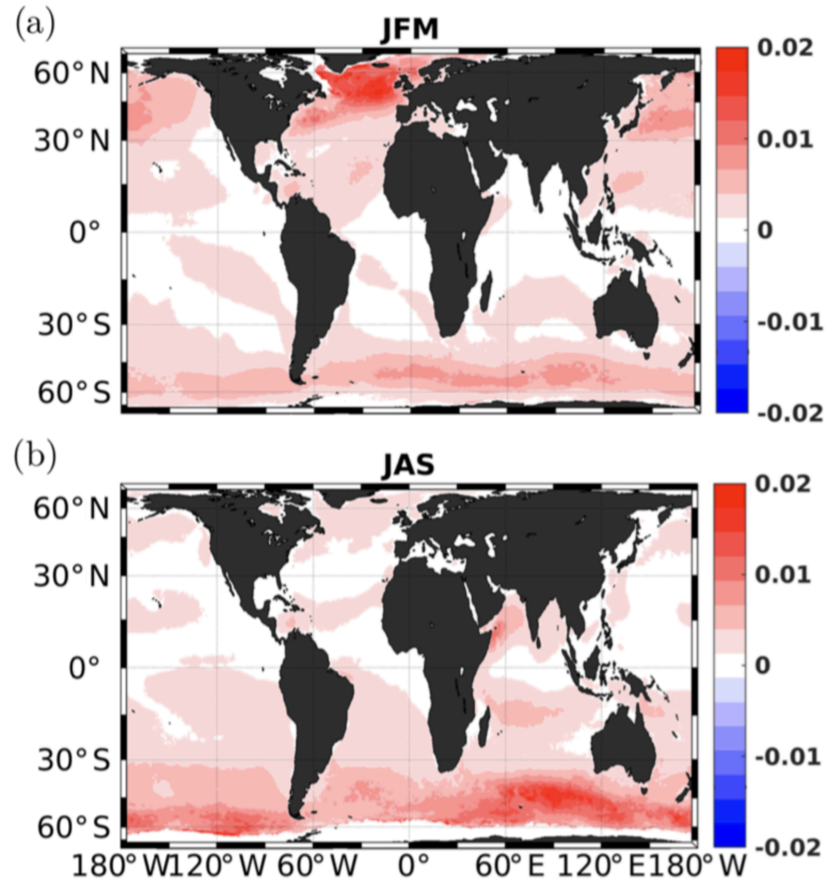
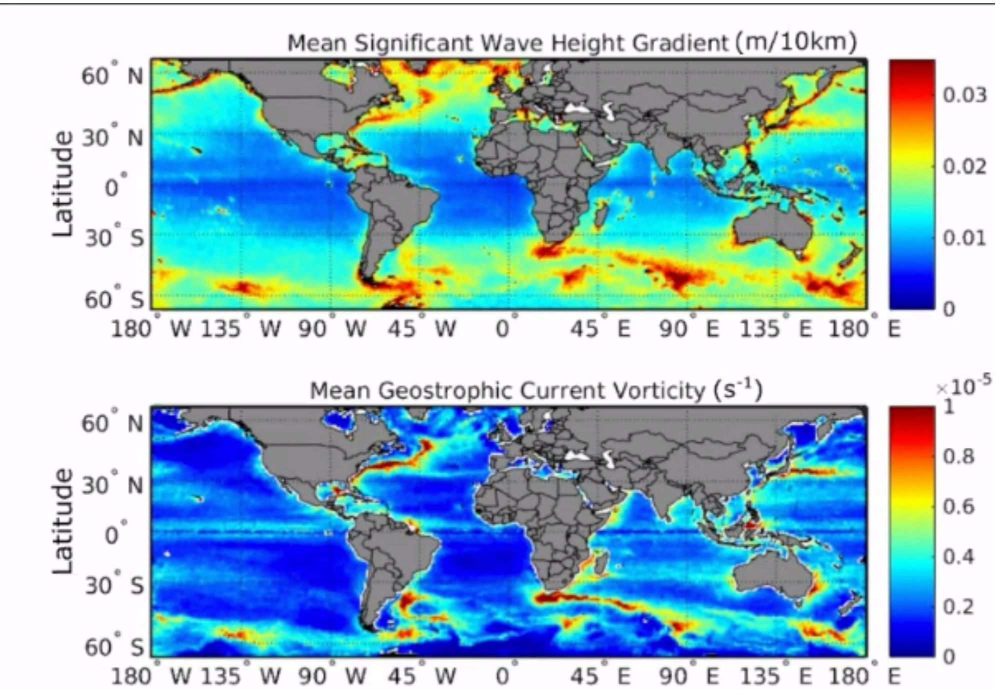


Figure 6. Seasonal difference of 1 m depth turbulent kinetic energy ($m^2\ s^{-2}$) between the coupled case (All_CPL2) and the uncoupled case (No_CPL). **(a)** January, February, and March (JFM); **(b)** July, August, and September (JAS).

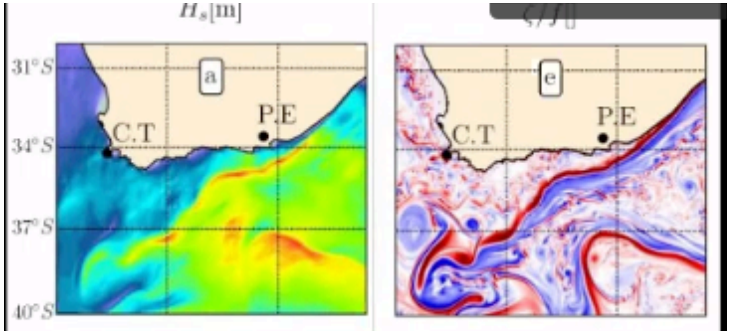
Coupling WAVEWATCH III with CROCO

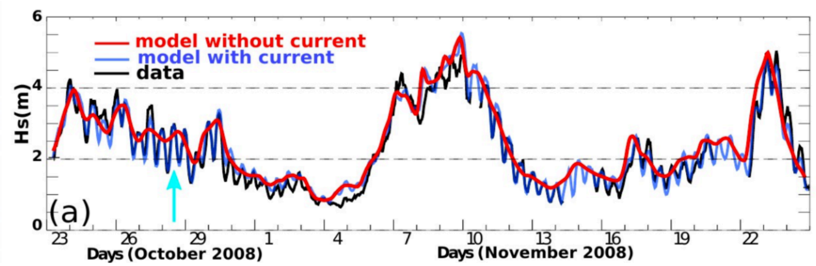
Coupling: When does it matter?

-> Over strong ocean current gradients



Quilfen et al. 2018





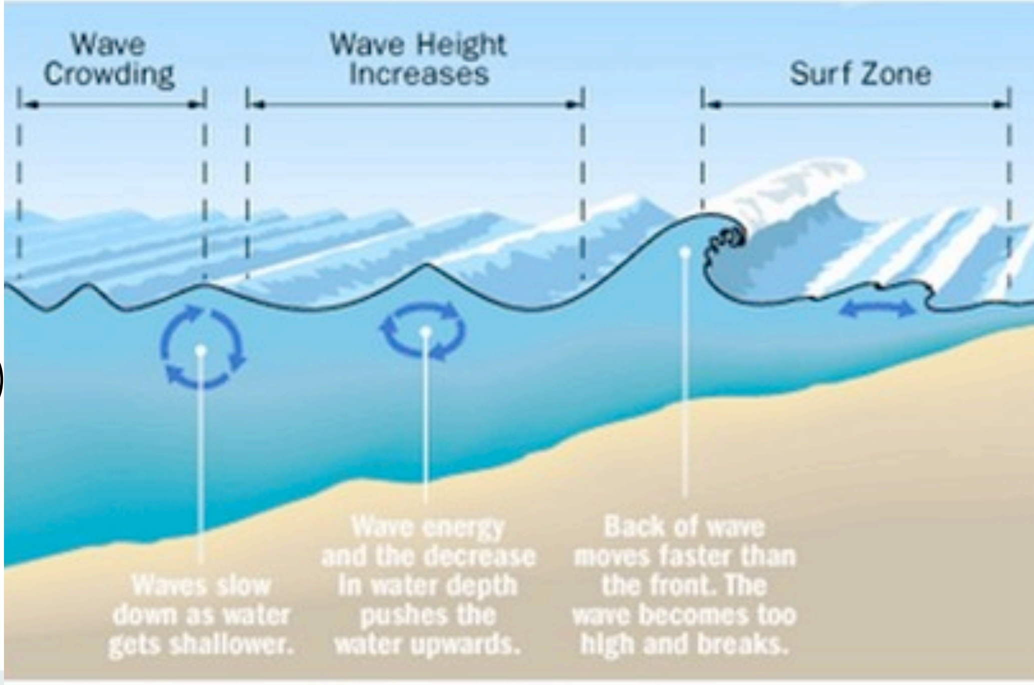
Coupling WAVEWATCH III with CROCO

Coupling: When does it matter?

-> Nearshore-dynamics:

Predominance of wave-induced circulation in littoral regions

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



A few links/references

Online documentation:

http://www.croco-ocean.org/documentation/

https://croco-ocean.gitlabpages.inria.fr/croco_doc/tutos/tutos.16.coupling.html

A few papers:

Ardhuin et al. 2010, 2017, … and many others

Marchesiello et al. 2015

Pianezze et al. 2018

Couvelard et al. 2020

Masson et al. 2022 (in prep)