GODAE OceanView International School

New Frontiers in Operational Oceanography

2-13 October 2017, Club Pollentia Resort, Mallorca, Spain.

New frontiers in ocean circulation modelling

Julien Le Sommer

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About me

Contact

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Field of expertise

- **ocean fine scale processes** : observations, modelling and scale interactions
- *modelling* : representation of fine scales in **ocean circulation models**
- *scale interactions* : impact of fine scales on **oceans' climatic functions**
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I'm involved in

- developping **NEMO** ocean model
- **SWOT** mission Science Team
- **CLIVAR** Ocean Model Devt Panel

I'm excited about

- open source / open data / reproducibility
- how to deal with the flow of data in geoscience

About the course

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Lecture #1 : Ocean circulations models : scope, usage and fundamentals.

- Thursday: 11:45-12:30

Lecture #2 : Representation of physical processes ocean circulation models

- Saturday: 9:45-10:30

Lecture #3 : Towards data-driven, probabilistic ocean circulation models

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Slides of the lectures :

also here : https://github.com/lesommer/2017-lectures-godae-ocean-view

Book chapter (with Eric Chassignet):

also here : https://github.com/lesommer/2017-book-chapter-godae-ocean-view

Textbooks :

- Griffies, S., 2004. Fundamentals of Ocean Climate Models. Princeton University Press.

- Lauritzen, P.H., Jablonowski, C., Taylor, M., 2011. Numerical techniques for global atmospheric models. Springer.

- Haidvogel, D.B., Beckmann, A., 1999. Numerical Ocean Circulation Modeling. World Scientific.

Review articles

- Griffies, S.M., Adcroft, A.J., 2008. Formulating the equations of ocean models, in: Hecht, M.W., Hasumi, H. (Eds.), Geophysical Monograph Series. American Geophysical Union, Washington, D. C., pp. 281–317.

- Griffies, S.M., Treguier, A.M., 2013. Ocean Circulation Models and Modeling, in: International Geophysics. Elsevier, pp. 521–551. doi:10.1016/B978-0-12-391851-2.00020-9

- Griffies, S.M., 2009. Science of Ocean Climate Models. in: Encyclopedia of Ocean Sciences (Second Edition)

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Topics covered

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Topics covered

- definition and scope of ocean circulation models
- landscape of ocean circulation models.
- range of usages of ocean circulation models
- physical hypotheses and governing equations
- boundaries, interfaces and forcings
- discretizing the primitive equations
- illustrations of current status/skill

Outline of Lecture #1

Part 1. Scope and applications of ocean circulation models

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Part 2. Physical formulation of ocean circulation models

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Part 5. Current skills of ocean circulation models

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Part 1. Scope and applications of ocean circulation models

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Part 4. Boundary conditions of ocean circulation models

Part 5. Current skills of ocean circulation models

Part 1.

Scope and applications of ocean circulation models

Scope of ocean circulation models

Ocean circulation modelling ?

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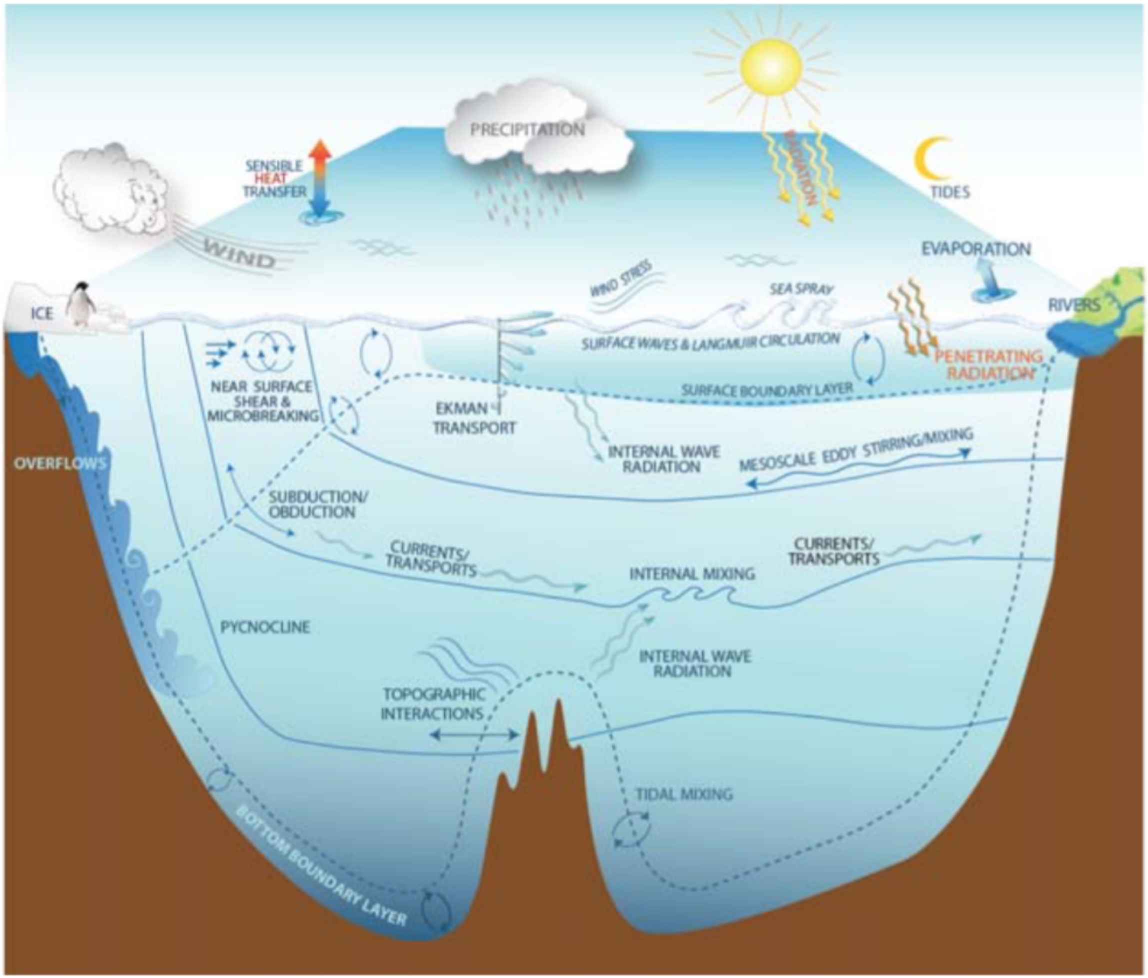
- a branch of **numerical modelling** focusing on the representation of the physical mechanisms governing the **evolution of ocean physical properties**, namely T, S, u, v, w

Variety of physical processes affecting ocean properties



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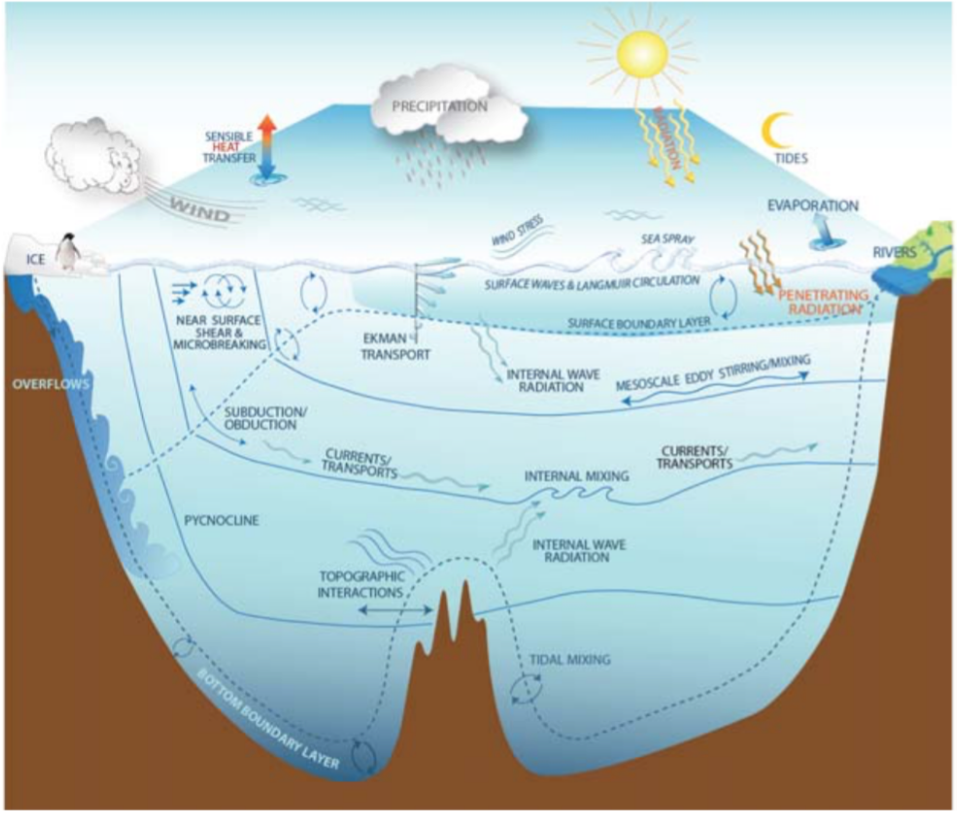

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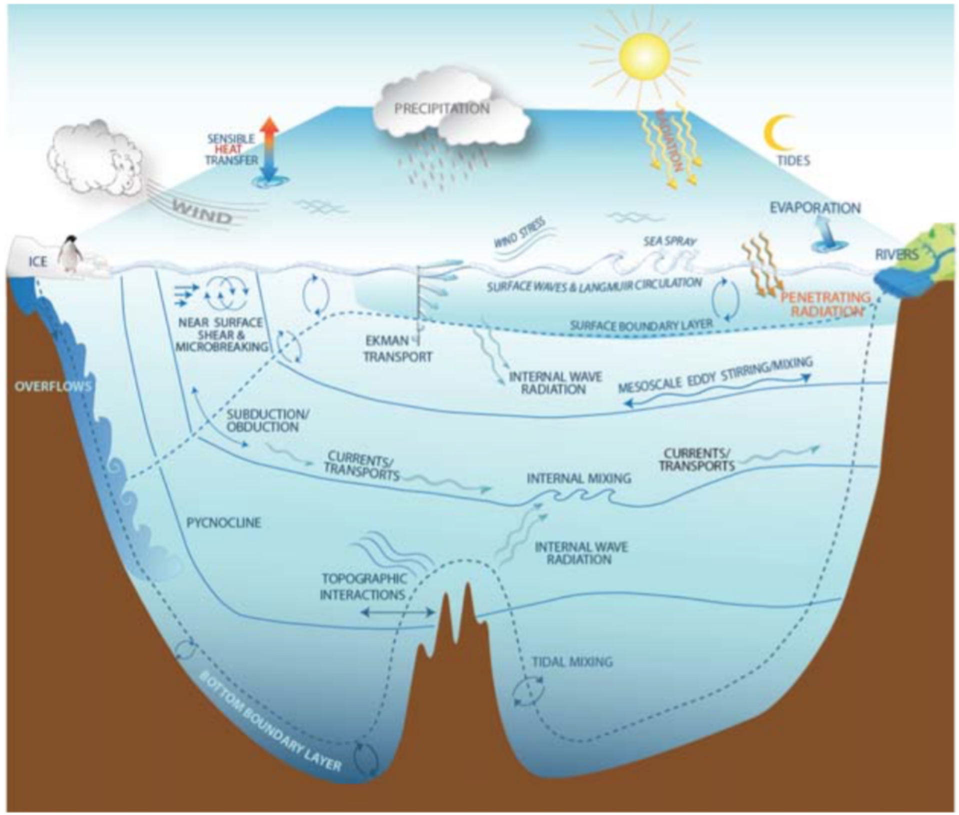

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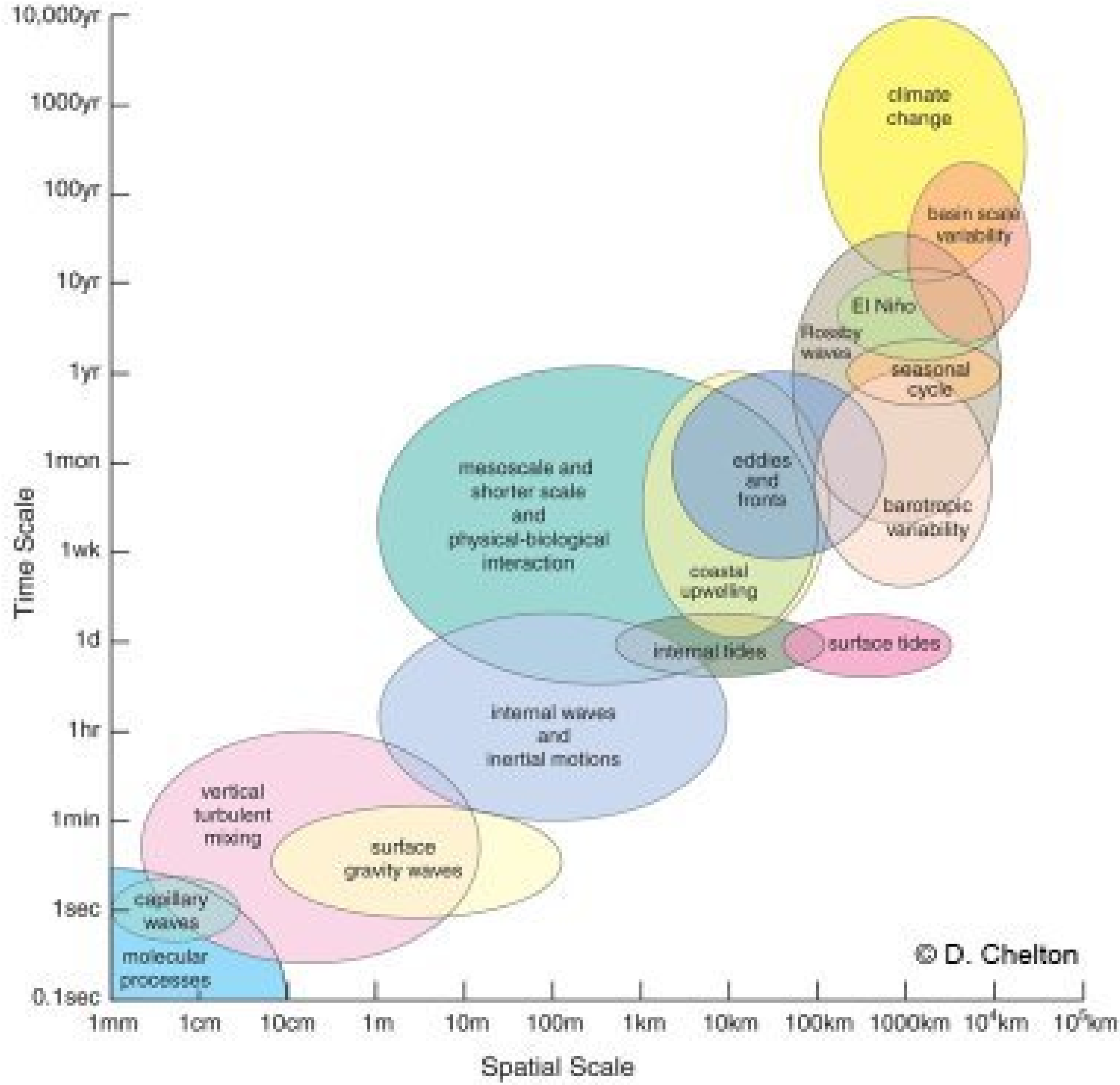
Physical understanding is pivotal to ocean circulation modelling.

Space and time scales of major ocean physical processes



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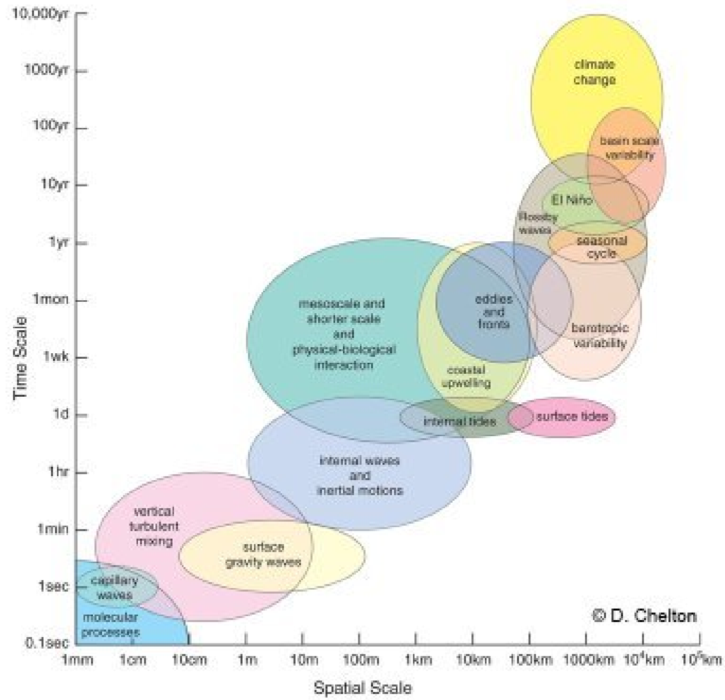

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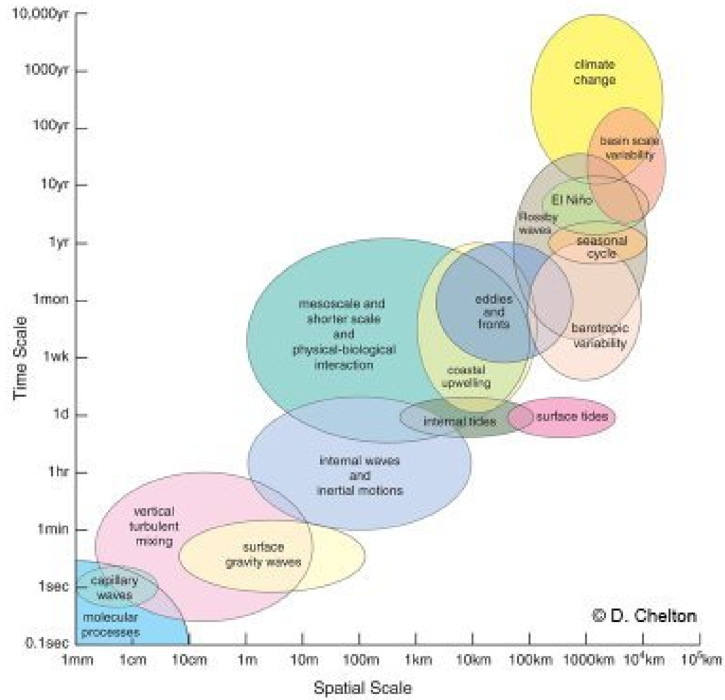

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a truncated description of the ocean state is required and will be required in the foreseeable future.

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    - in **realistic settings** at global or regional scale
    - or in idealized settings for **process studies**.

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- each code is the result of **5 to 10 years of development**;
- developping/maintaining/running ocean circulation models requires collaborations among **different people with different skills**.

The landscape of ocean circulation models

(Temptative) list of major ocean models (in 2017)

listing ocean circulation models that are **currently developped / supported / used** with published applications at **basin to global scale**.

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- POP (*US*)
- MPAS (*US*)
- NCOM (*US*)
- ROMS (*US/Fr*, $\times 3$)
- NEMO (*EU*)
- MPIOM (*Germany*)
- FESOM (*Germany*)
- OFES (*Japan*)
- MRI.com(*Japan*)
- LICOM (*China*)
- ...

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A fair **variety of ocean circulation models** with different horizontal grids, vertical coordinates and subgrid closures.

most of them (if not all) are freely available and distributed under **open source licences**.

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The previously listed ocean circulation models all have preferential **target applications** but the general trends is towards **seamless** modelling.

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- Ocean circulation models are used for **preparing satellite missions**.

Part 2.

Ocean circulation models : Physical formulation

Approximations to the Navier Stokes equation

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- **Incompressibility hypothesis** : assuming that sound waves propagate at infinite celerity, this allows to use longer time steps.

Primitive equations

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horizontal momentum equation

$$\frac{\partial \mathbf{U}_h}{\partial t} = -[(\nabla \times \mathbf{U}) \times \mathbf{U} + \frac{1}{2}\nabla(\mathbf{U}^2)]_h - f\,\mathbf{k} \times \mathbf{U}_h - \frac{1}{\rho_0}\,\nabla_h p + \mathbf{D}^{\mathbf{U}} + \mathbf{F}^{\mathbf{U}}$$

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conservation of heat

$$\frac{\partial T}{\partial t} = -\nabla \cdot (T\mathbf{U}) + D^T + F^T$$

Primitive equations

horizontal momentum equation

$$\frac{\partial \mathbf{U}_h}{\partial t} = -[(\nabla \times \mathbf{U}) \times \mathbf{U} + \frac{1}{2}\nabla(\mathbf{U}^2)]_h - f\,\mathbf{k} \times \mathbf{U}_h - \frac{1}{\rho_0}\,\nabla_h p + \mathbf{D}^{\mathbf{U}} + \mathbf{F}^{\mathbf{U}}$$

hydrostatic equation

$$\frac{\partial p}{\partial z} = -\rho\, g$$

incompressibility condition

$$\nabla \cdot \mathbf{U} = 0$$

conservation of heat

$$\frac{\partial T}{\partial t} = -\nabla \cdot (T\mathbf{U}) + D^T + F^T$$

conservation of salinity

$$\frac{\partial S}{\partial t} = -\nabla \cdot (S\mathbf{U}) + D^S + F^S$$

Additional equations

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Equation of state of sea water

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

with T is conservative temperature and S is absolute salinity (TEOS10).

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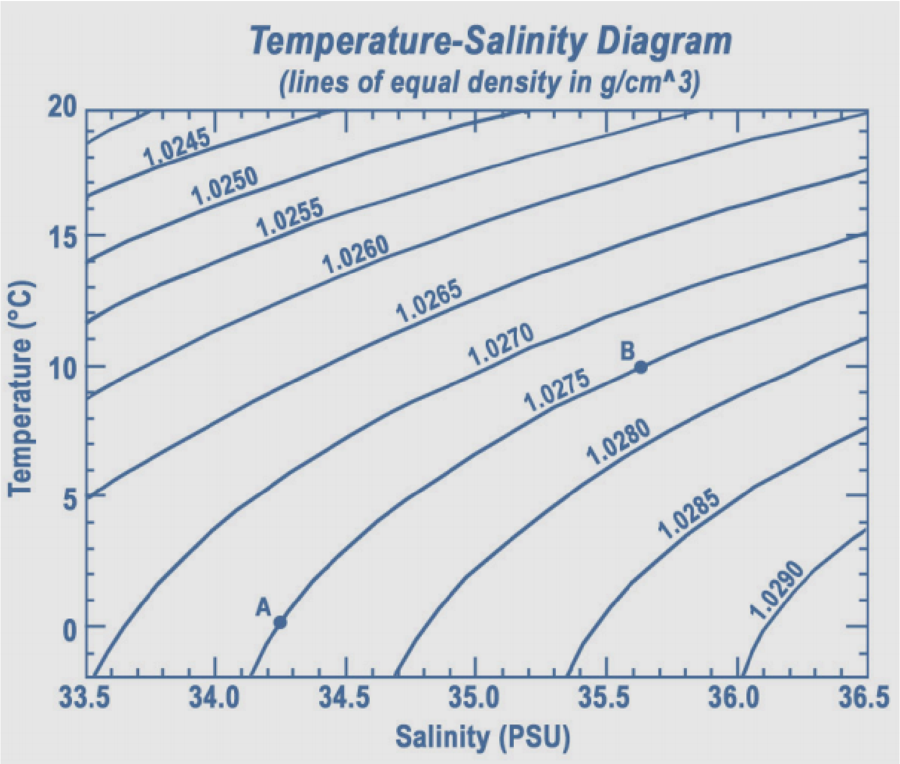

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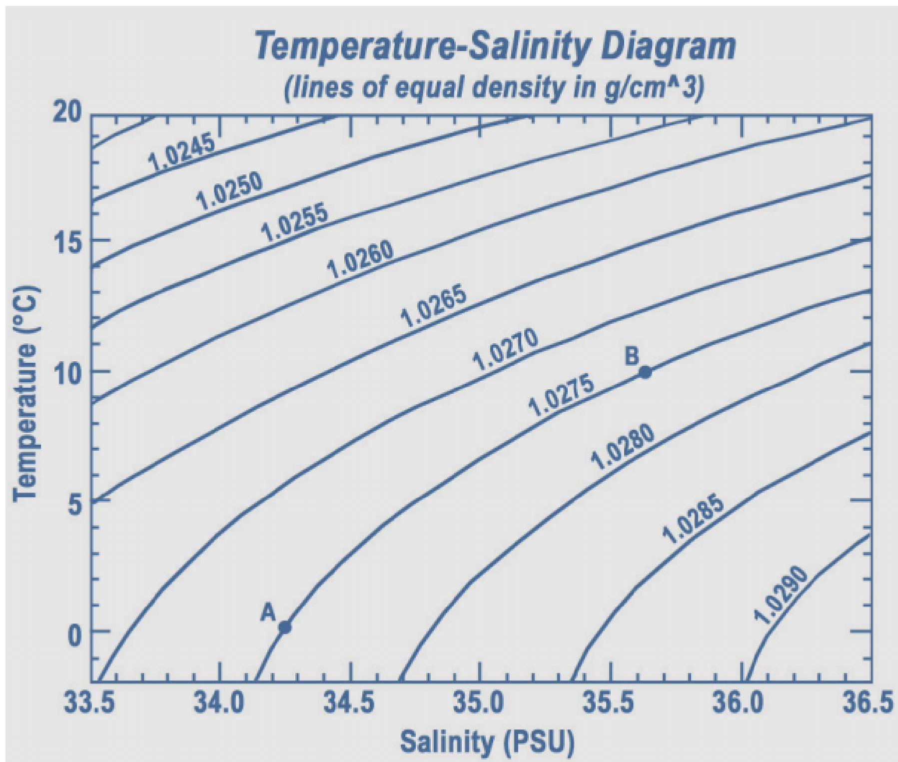

The equation of state is a strongly nonlinear at cold temperature and high pressure.

Additional equations

Additional equations

Surface boundary conditions

- kinematic condition :

$$\frac{\partial \eta}{\partial t} + \mathbf{U}_h \cdot \nabla \eta = w_{|surf} + E - P$$

(*most ocean circulation models no longer use the rigid lid approximation*)

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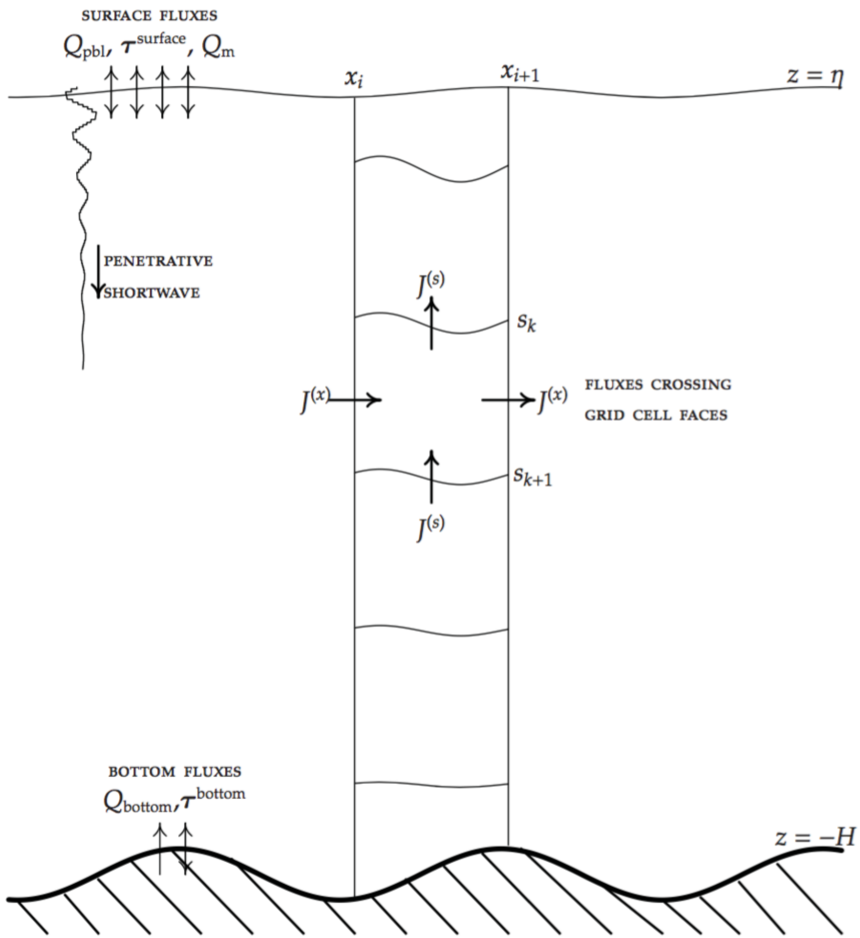
Part 3.

Ocean circulation models : Discrete formulation

Discretizing the primitive eqations



Basic idea is to cut the ocean volume into small boxes that exchange fluxes at their boundaries.

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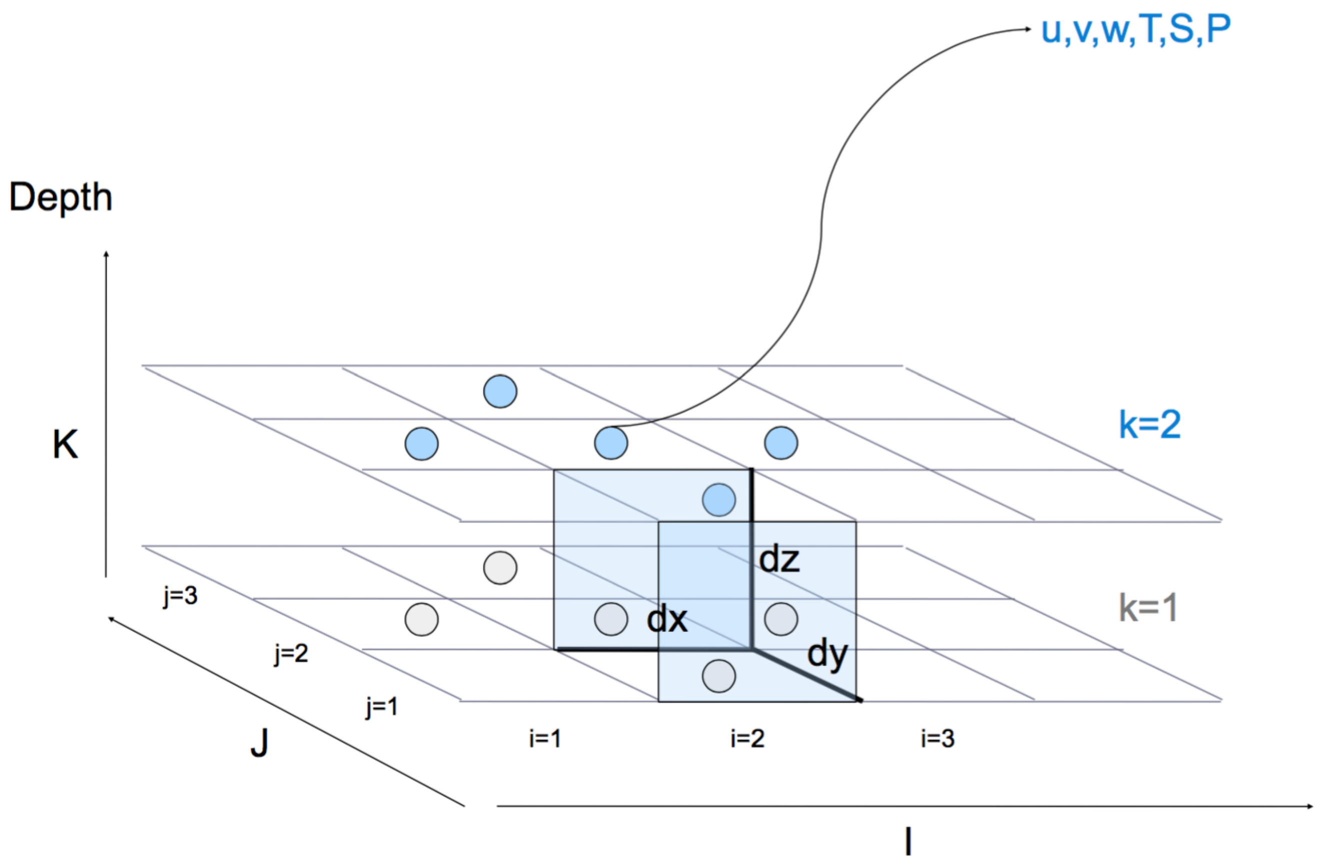

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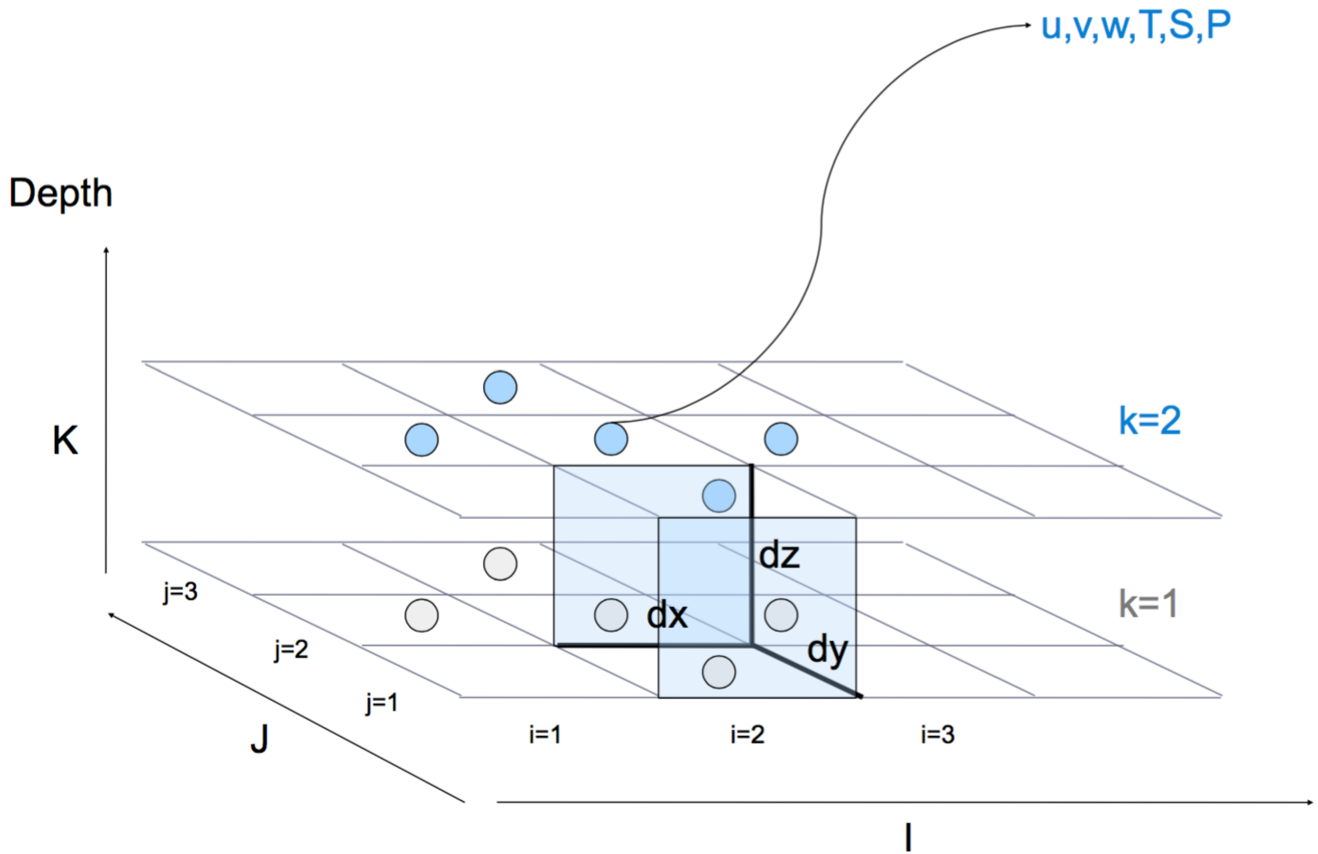

Note that there are several types of grids and several approaches for defining discrete approximations of continuous variables.

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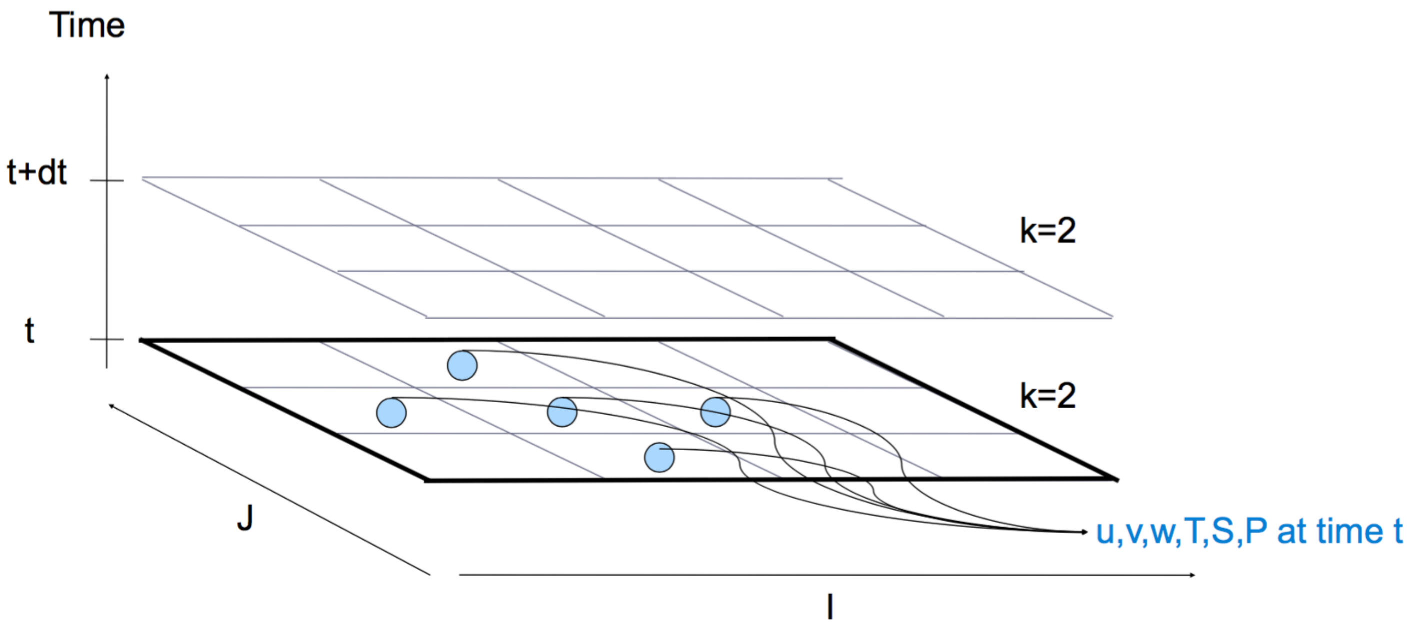

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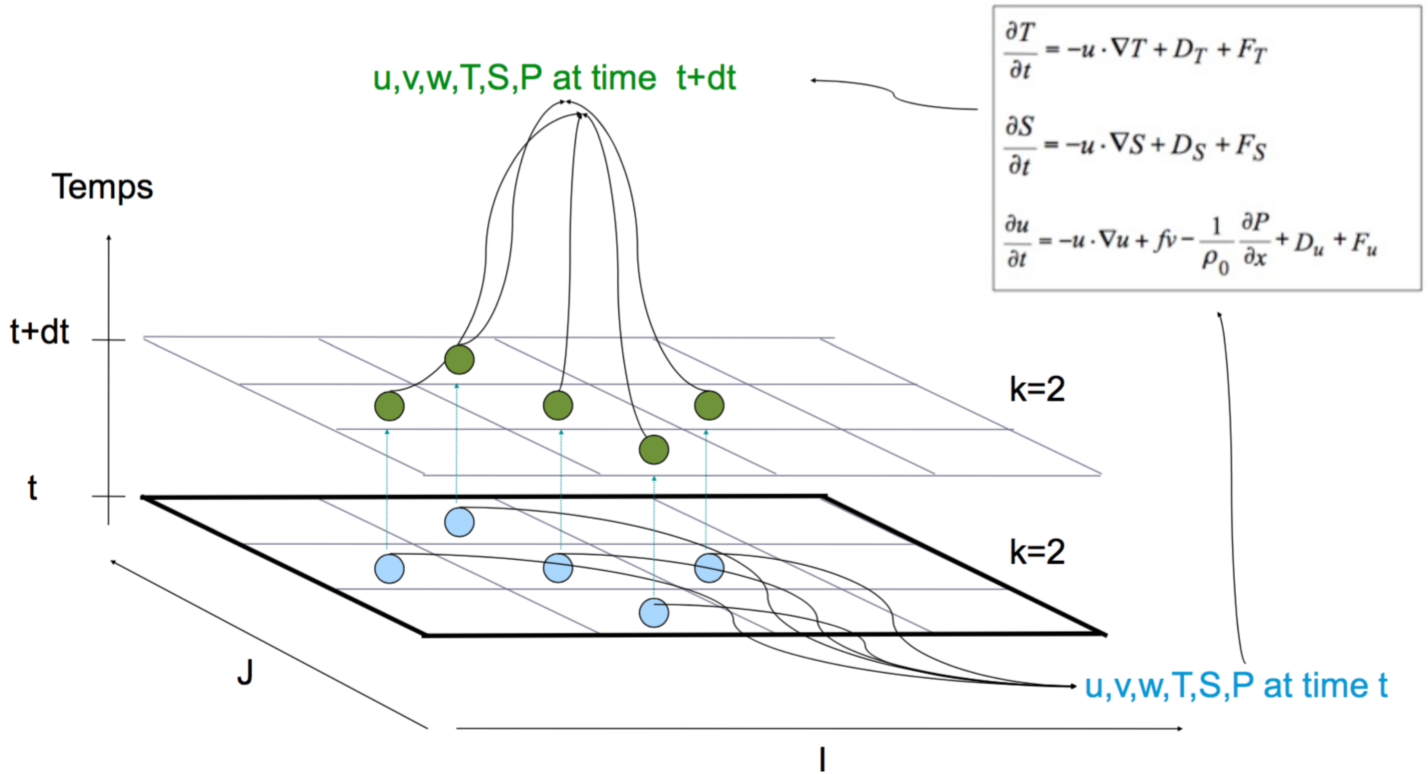

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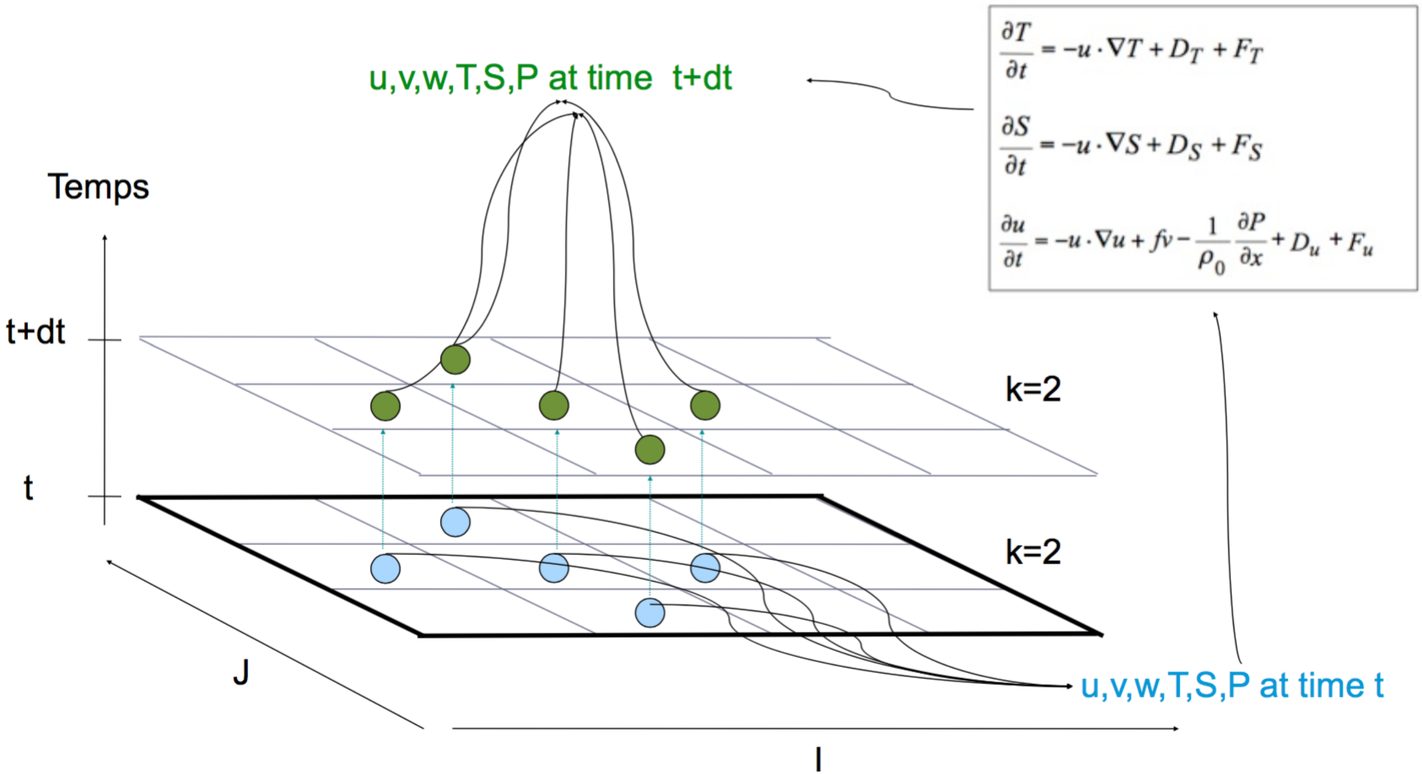

in practice,

$$\phi(x_i, t^{n+1}) = \phi_i^{n+1} + \text{error terms } E(\Delta x, \Delta t)$$

Numerical discretization schemes

How to guarantee that we get as accurate an answer as we wish, as long as we discretize our function finely enough in space and in time ?

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An approximate difference equation is **stable** if it has an upper limit (as $t \rightarrow \infty$) to the growth of the solution (or to errors introduced by round-offs).

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Order of accuracy of discretization schemes

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Using high orders schemes provides a good alternative to increasing resolution.

Part 4.

Ocean circulation models : Boundary forcing

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The boundary forcing and the mechanical energy dissipation are key to a good ocean model simulation.

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    - the **seasonal** cycle
    - **interannual** fluctuations (such as the NAO and ENSO).

Time scales of atmospheric forcing versus ocean dynamics

Atmospheric variability and oceanic variability are not occuring at the same space and time scale.

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0:00

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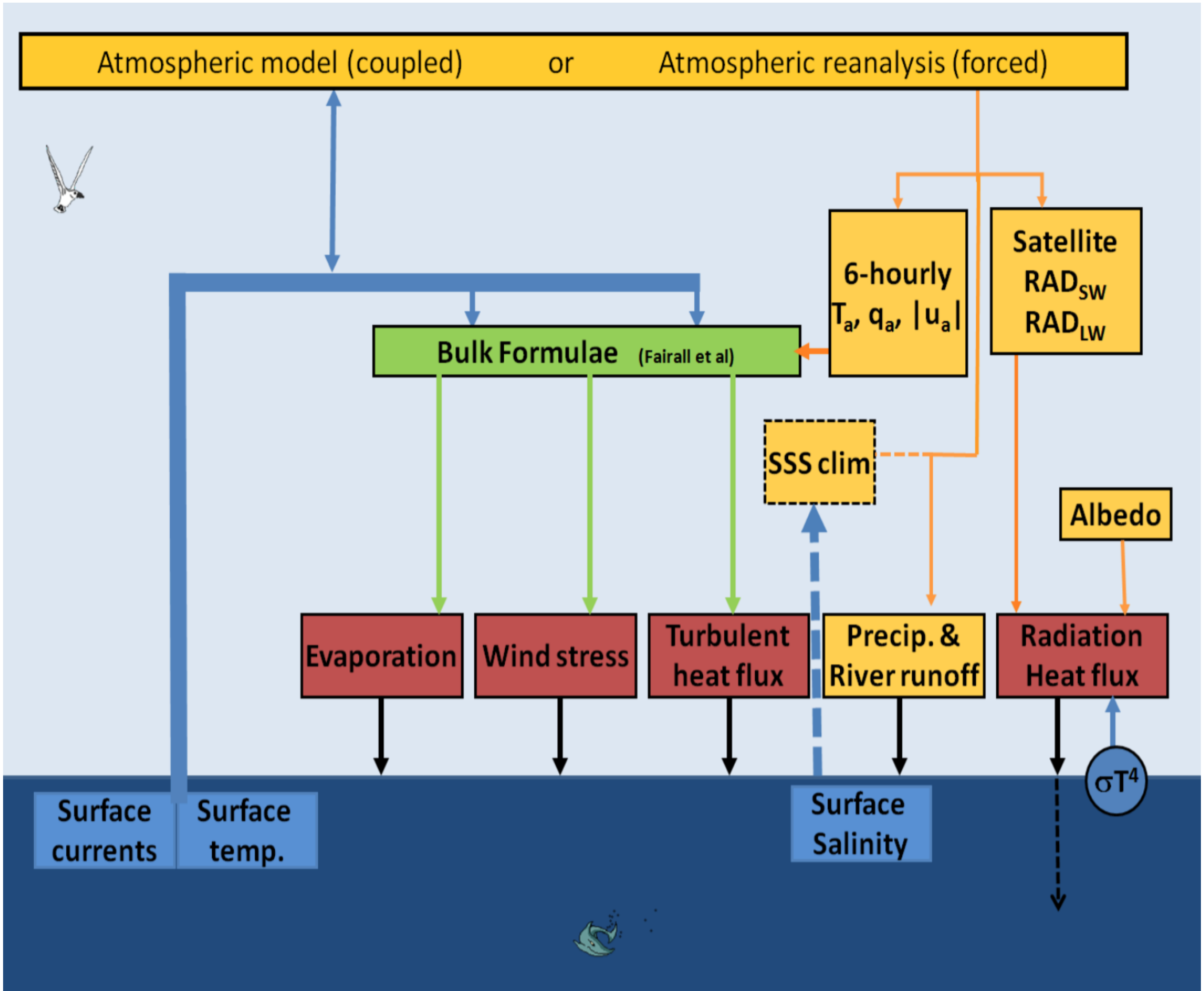
Surface fields that constrain ocean models should be used at high frequency (typically 3h)

Formulation of air-sea forcing in ocean models



Representation of high latitude freshwater forcing

Example : antarctic freshwater fluxes in ocean models

exemple :
glacial freshwater in NEMO
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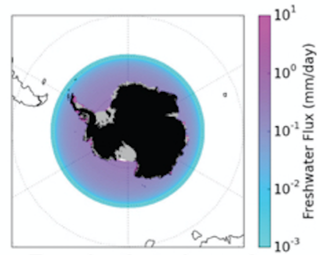
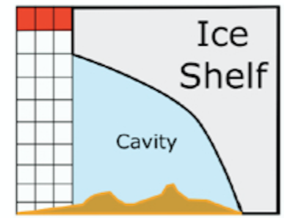


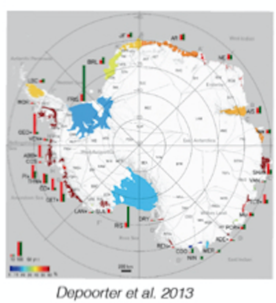
Evenly distributed flux < 60°S



Freshwater flux as a surface run-off

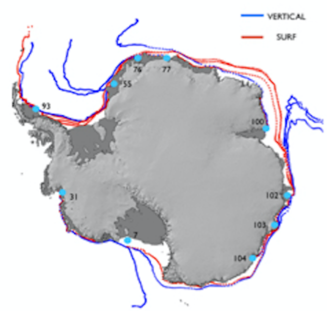
before 2015

now

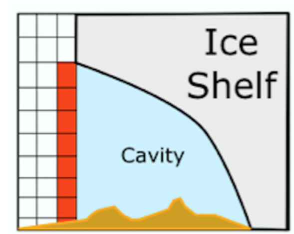


Calving: 1321Gt/yr
Basal melt: 1454Gt/yr

(Depoorter et al. 2013)



Lagrangian iceberg model (+ vertical)
(Merino et al. 2016)



Emulation of under-ice shelf overturning
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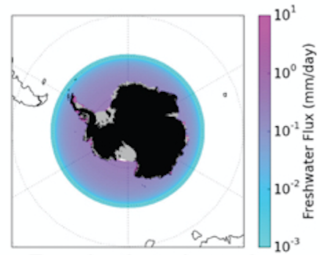

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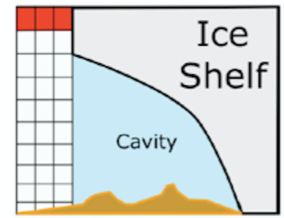

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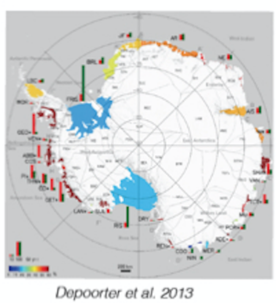

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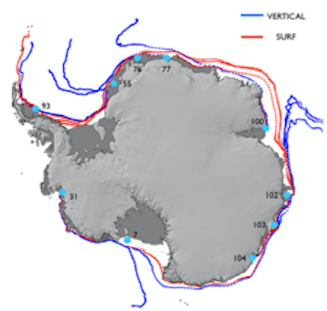

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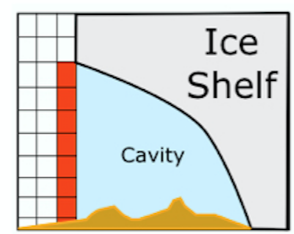

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Formulating the forcing function of ocean circulation models is a essential task that requires a lot of efforts (and crude hypotheses).

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- the **dynamical feedbacks from ocean state onto atmospheric properties** in the atmospheric boundary layer are not accounted for.

Part 5.

Ocean circulation models : current skills.

Mesoscale permitting cean circulation models

Surface currents in NEMO-ORCA12 (here coupled to IFS)

source : https://www.youtube.com/watch?v=Pl5QdYRP8qE

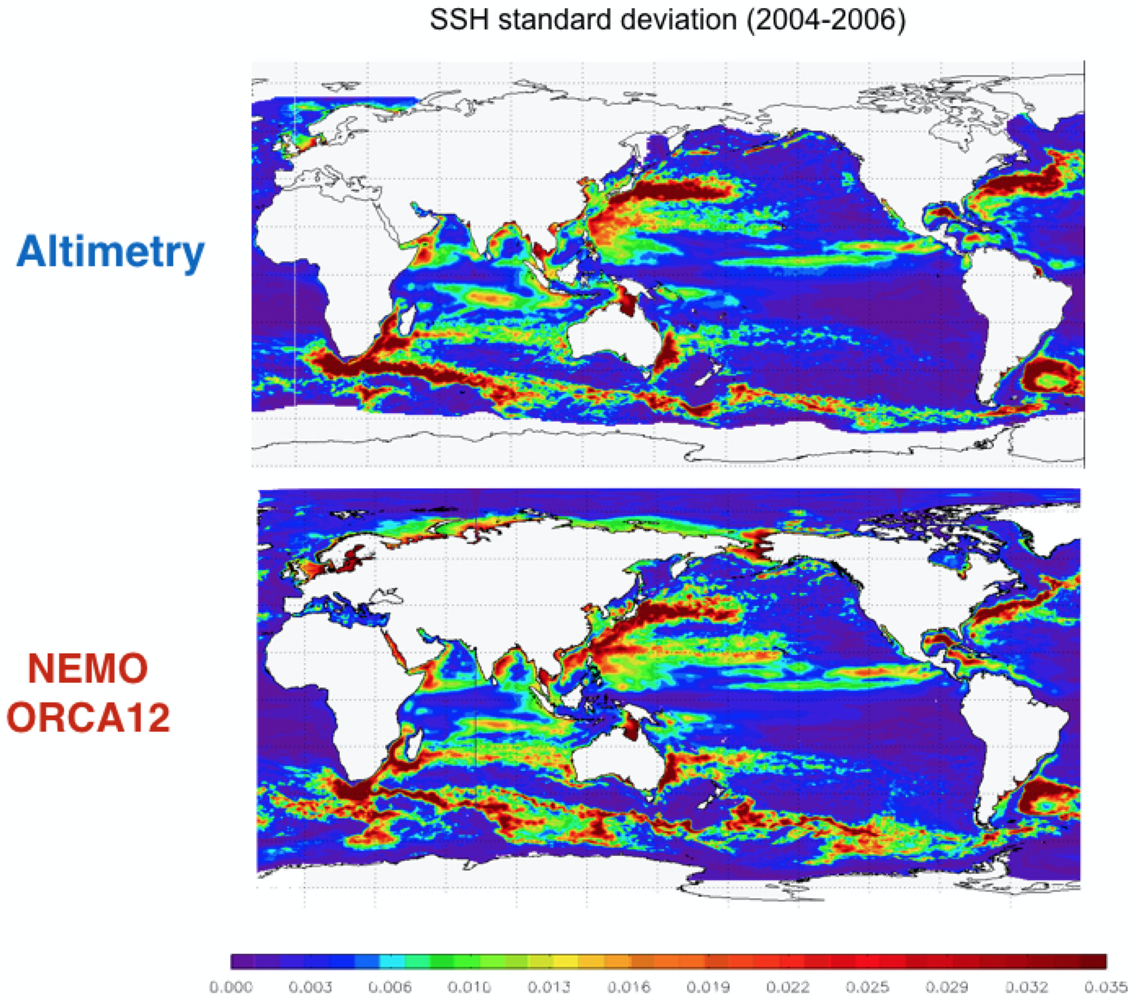
Mesoscale permitting ocean circulation models

Surface currents in ECCO2 reanalysis (MITgcm based)

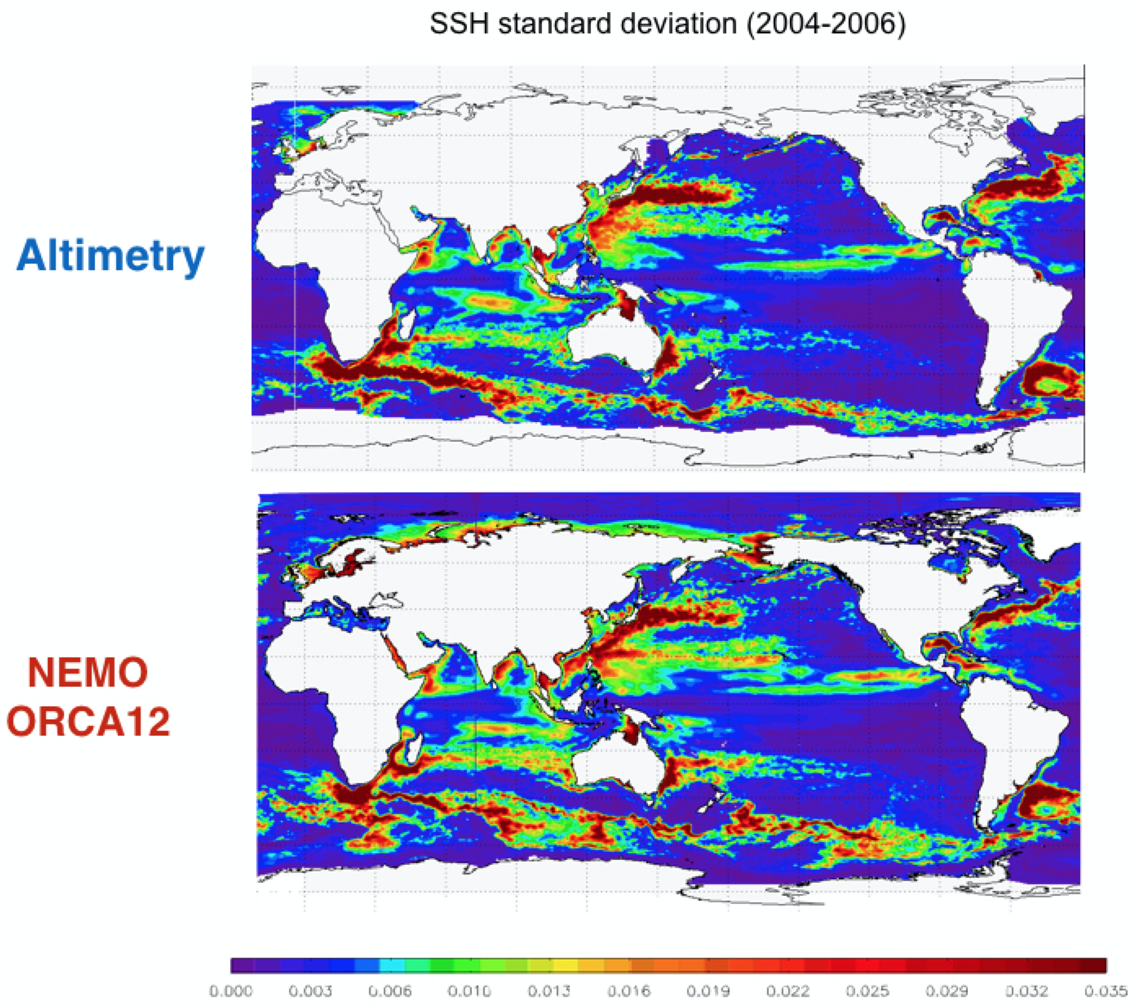
0:00

source : https://www.youtube.com/watch?v=iORUBN8KgZE

Mesoscale permitting ocean circulation models

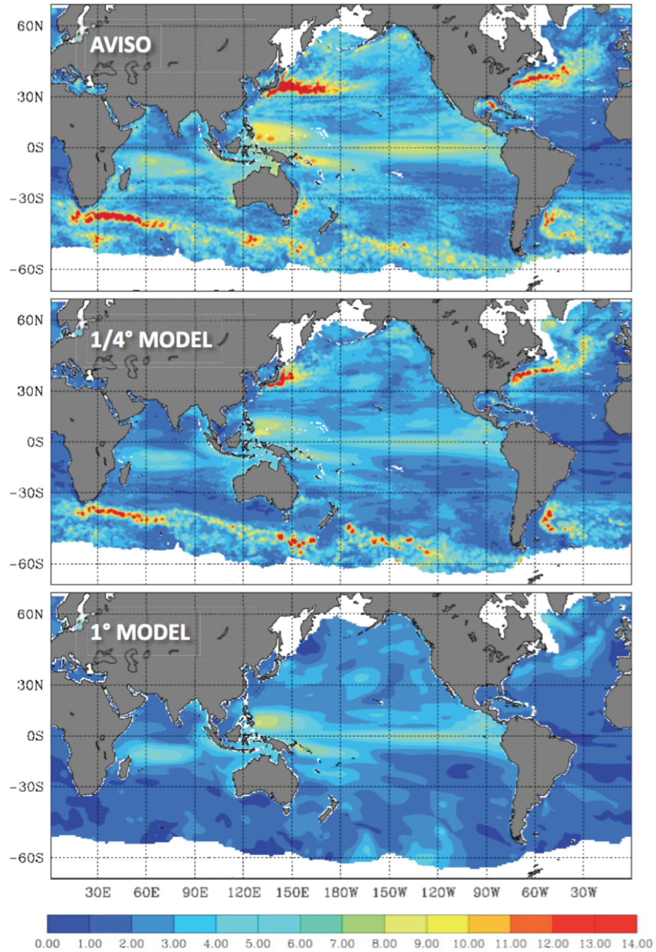


Mesoscale permitting ocean circulation models



O(10km) grid resolution models capture quantitatively SSH variance.

Impact of model horizontal resolution



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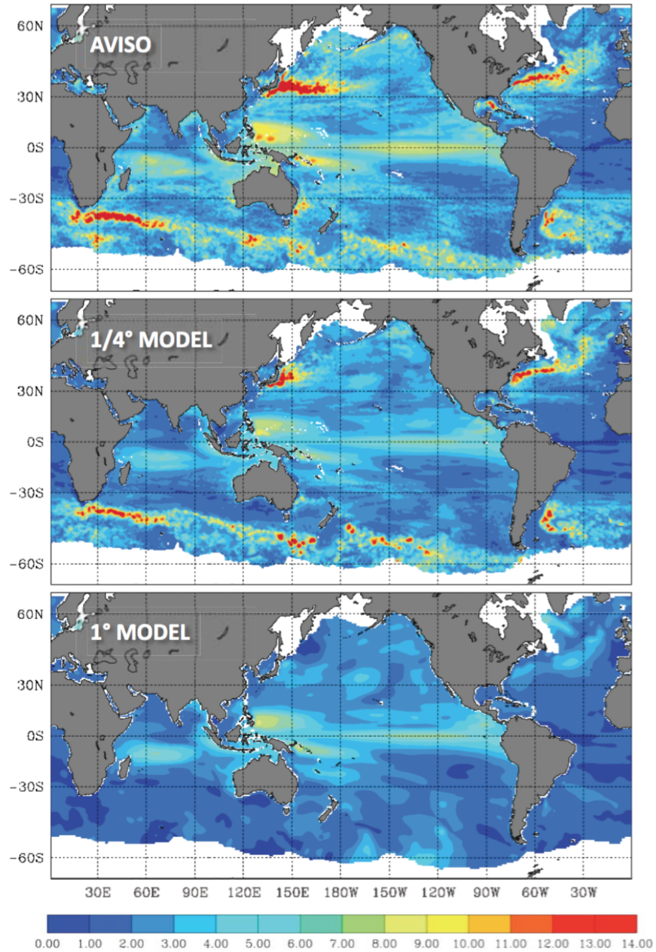
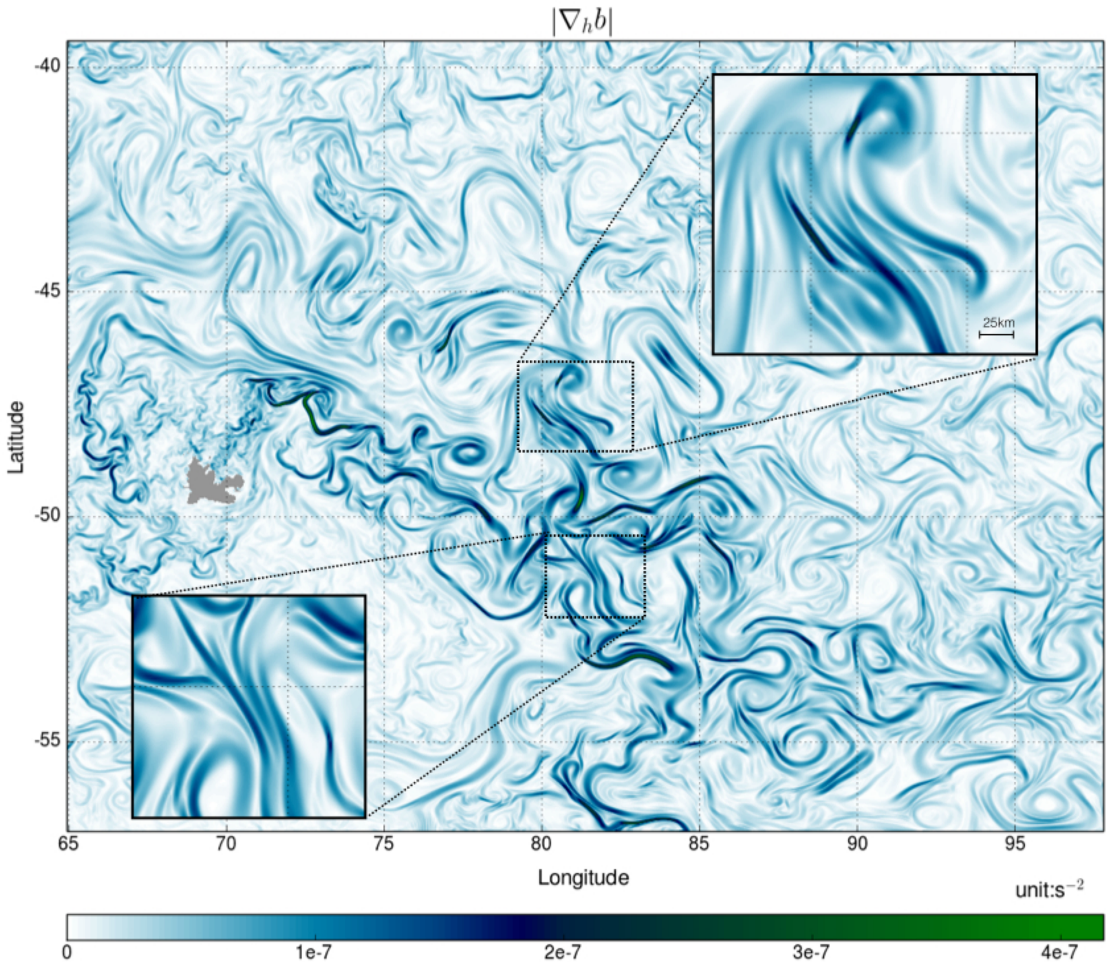


A regime transition between O(100km) and O(10km) grid resolution models due to the emergence of eddy variability.

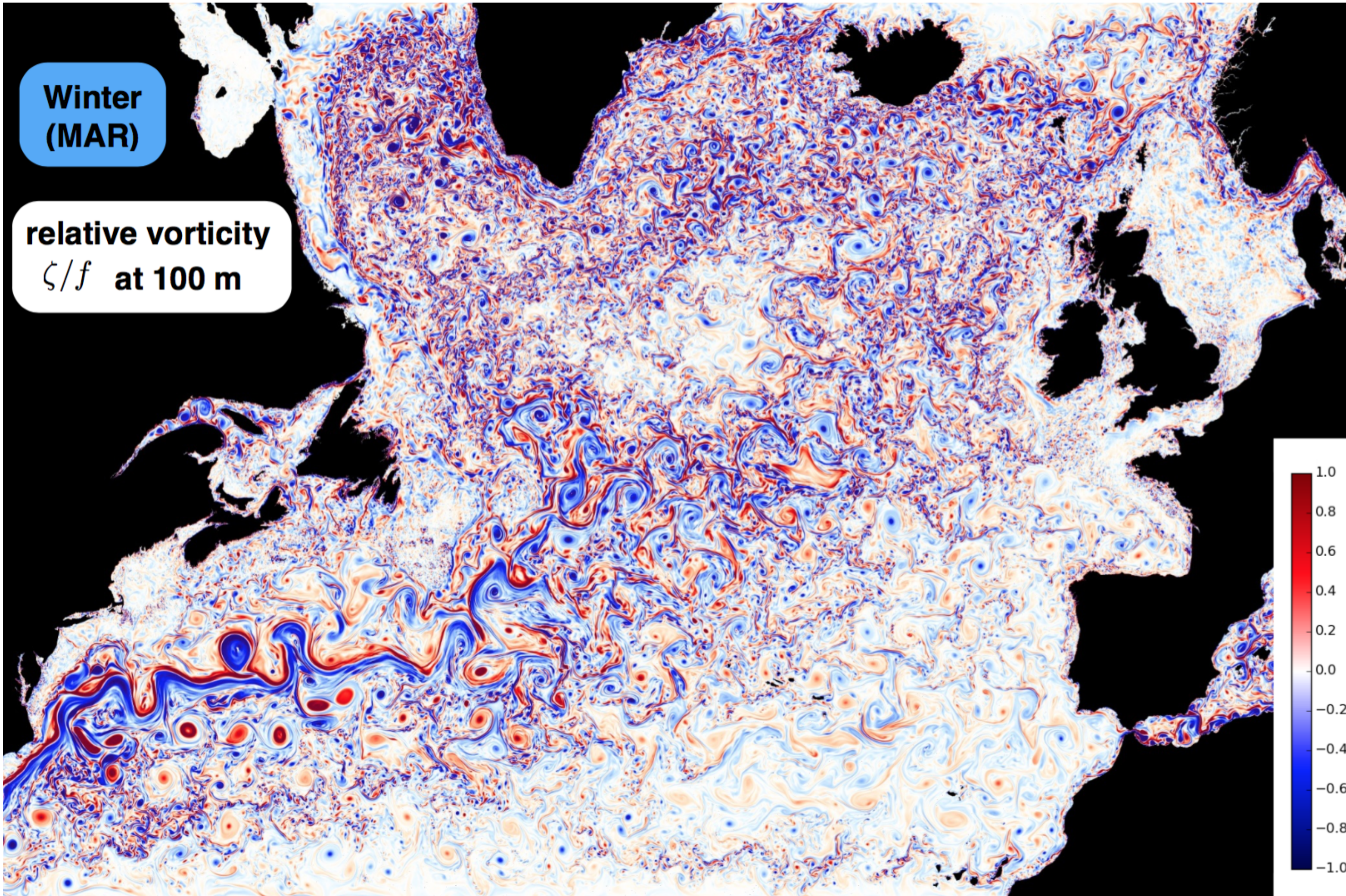
Submesoscale permitting ocean circulation models

Submesoscale permitting ocean circulation models



Higher resolution models can describe intense fronts at submesoscales
(here downstream Kerguelen plateau).

Submesoscale permitting ocean circulation models



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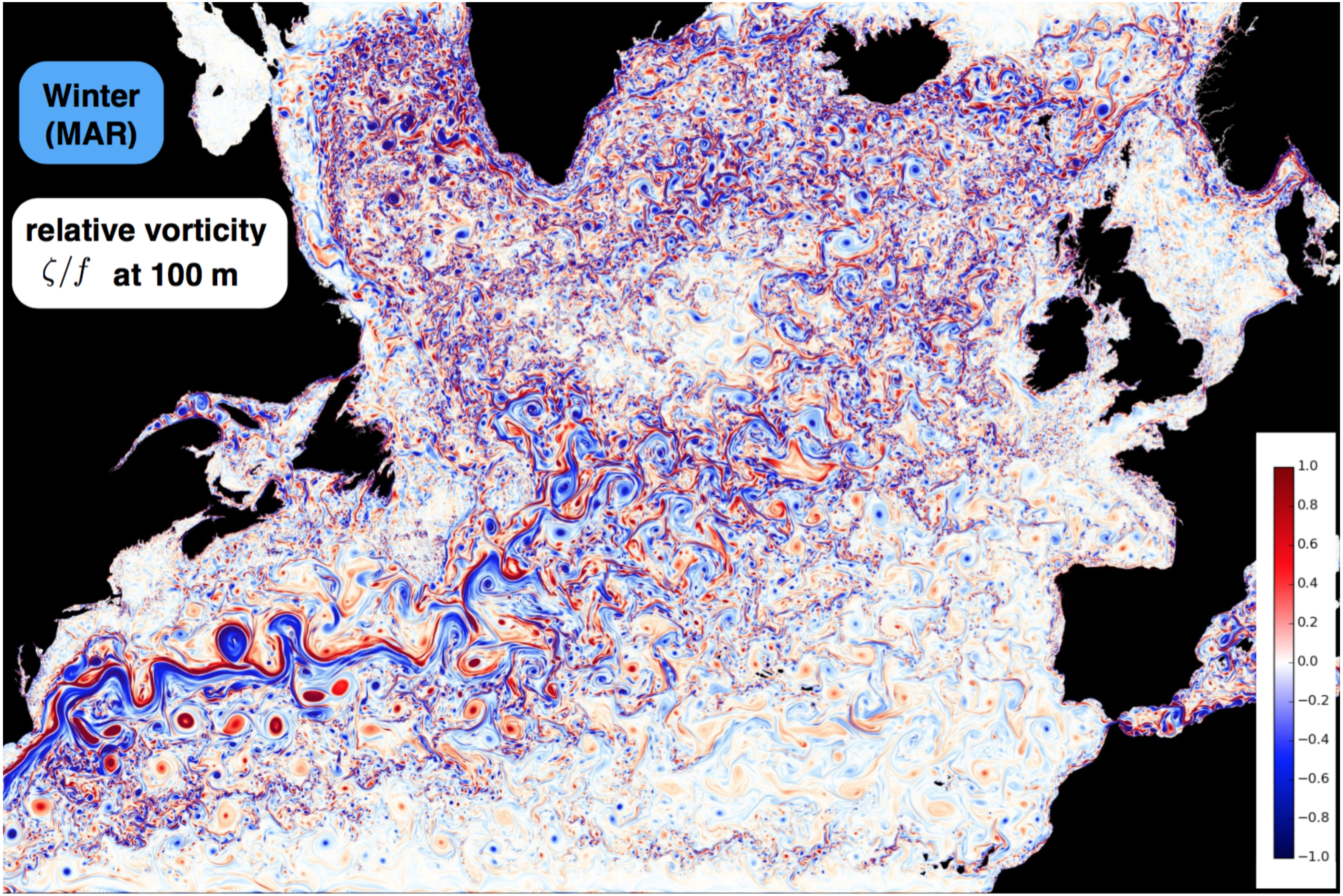
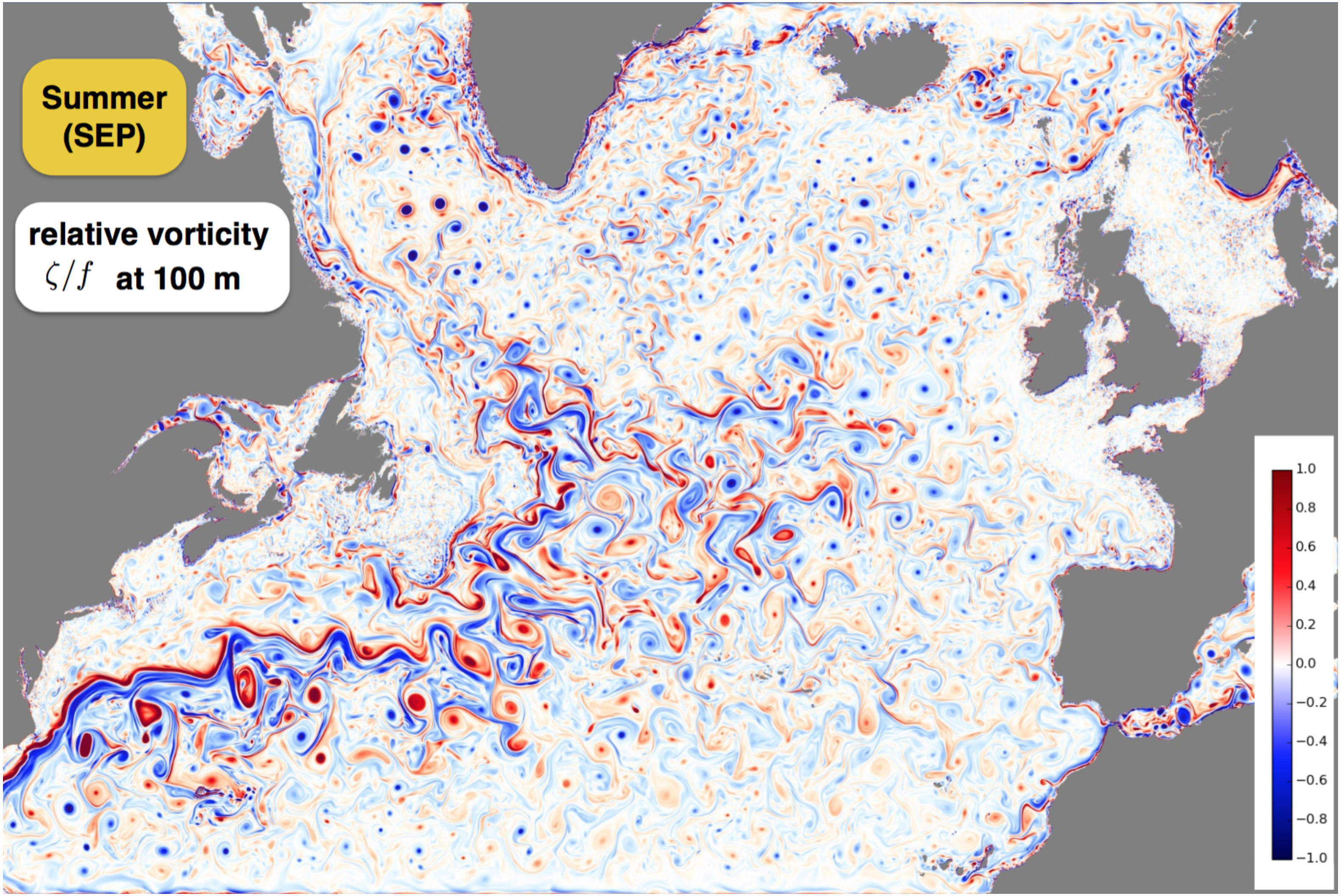


Kilometric resolution ocean models describe high Ro surface flows.

Submesoscale permitting ocean circulation models



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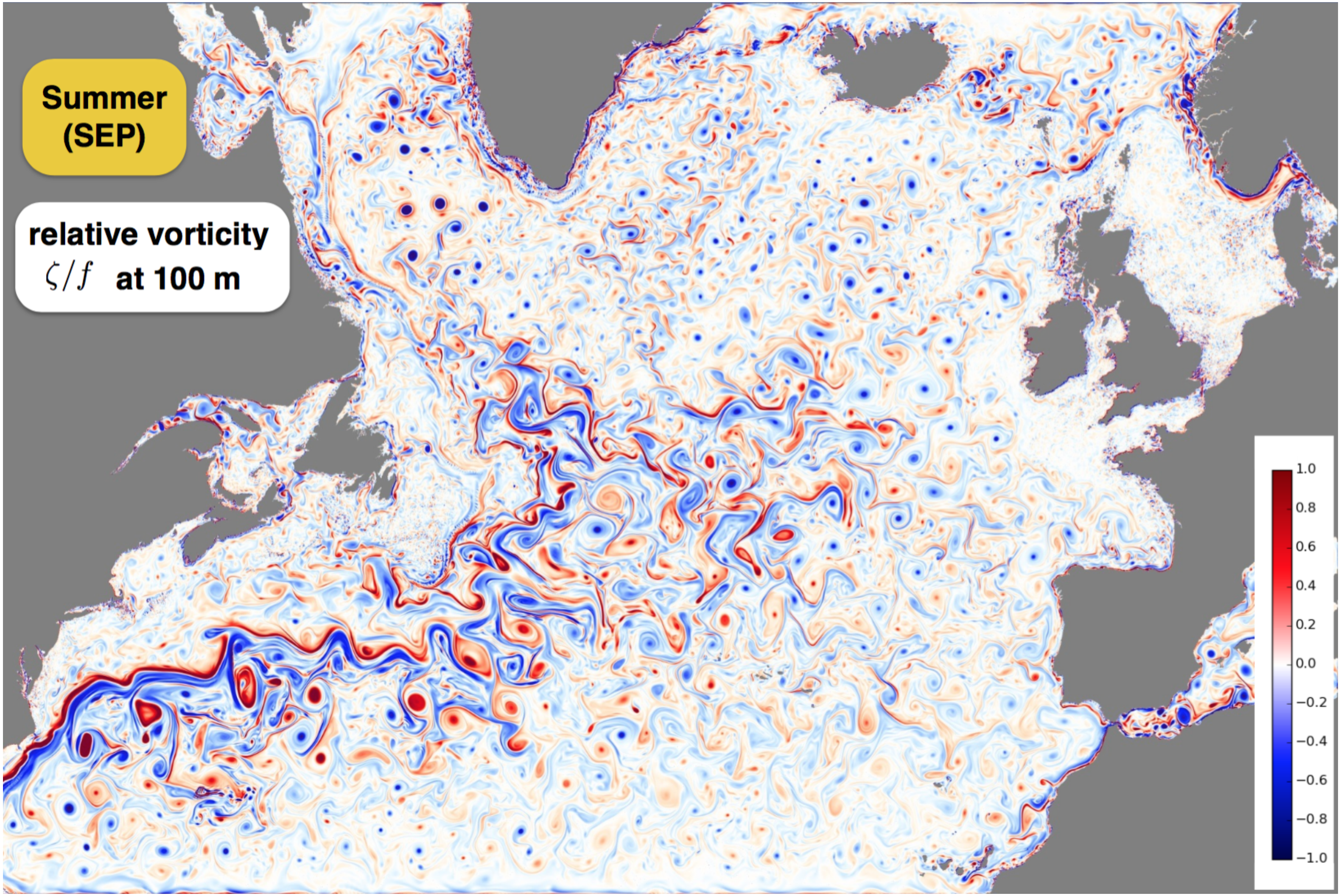
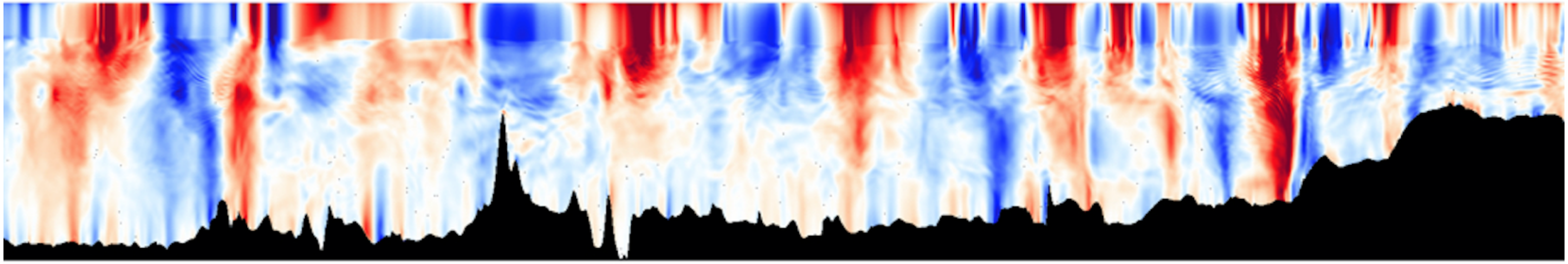
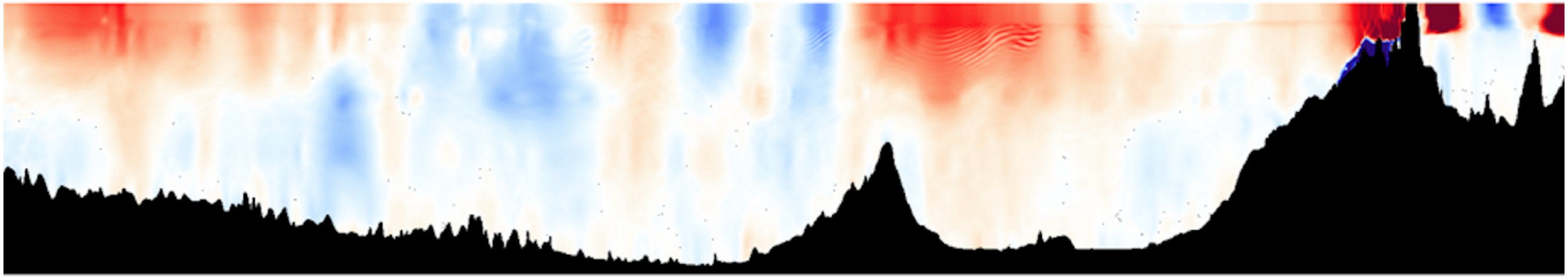


km resolution ocean models show the seasonality of submesoscales

Internal waves in ocean circulation models

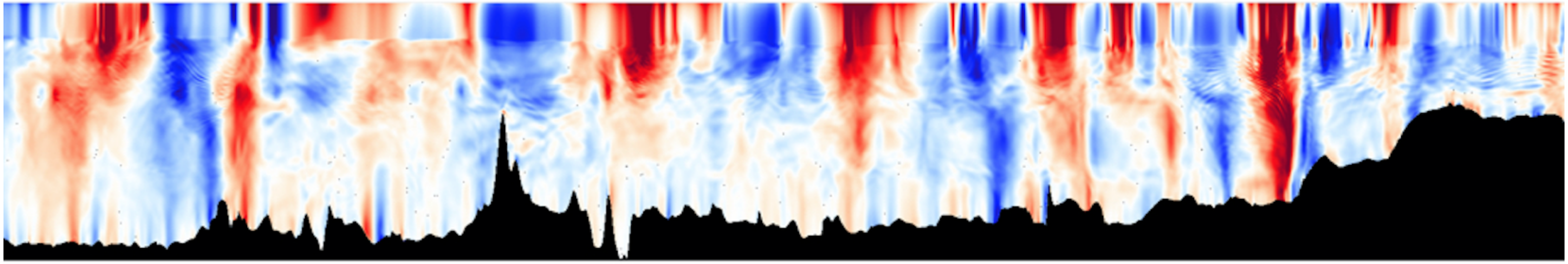


Zonal velocity,
section at 19°W (Island on the left)

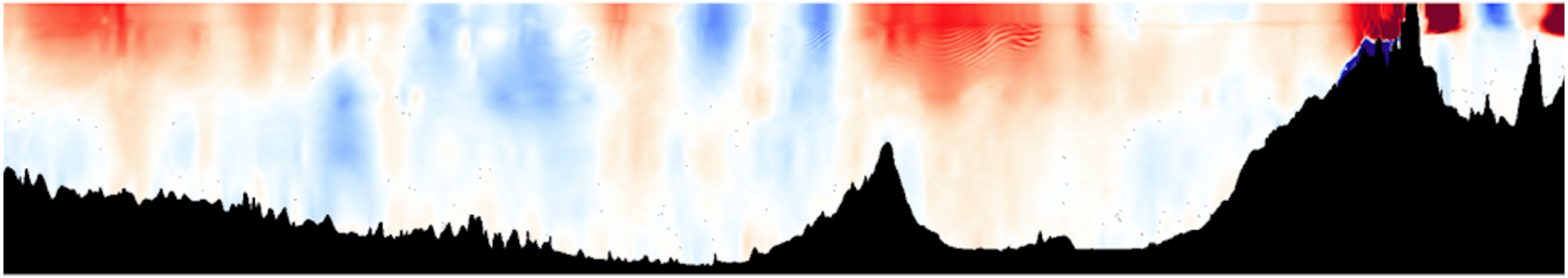


Zonal velocity,
section at 36°N (Gibraltar strait on the right)

Internal waves in ocean circulation models



Zonal velocity,
section at 19°W (Island on the left)



Zonal velocity,
section at 36°N (Gibraltar strait on the right)

With increasing resolution, ocean circulation models are now able to represent a fraction of the internal wave spectrum.

Wrapping-up Lecture #1

Ocean circulations models : scope, usage and fundamentals.

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- new frontier : **submesoscale-permitting modelling at global scale**.