GODAE OceanView
International School
New Frontiers in Operational Oceanography
2-13 October 2017, Club Pollentia Resort, Mallorca, Spain.

New frontiers in ocean circulation modelling

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About the lectures

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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

Lecture #1

Ocean circulations models : scope, usage and fundamentals.

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

Lecture #1

Ocean circulations models : scope, usage and fundamentals.

Ocean circulation models

- are based on **first principle physics**;
- are used for a **wide range of applications**;
- are a key **building block of operational oceanography**;
- require **group effort and collaborations** over long time scales.

We have also learned that :

- **subgrid closures are rate controling** components of ocean models;
- **numerical discretization is a key** aspect of ocean circulation modelling;
- besides the numerical kernel, **interfaces are also important** (forcing function, coupling interfaces, etc...)
- ocean models are now (arguably) **able to describe mesoscale motions at global scale**;
- new frontier : **submesoscale-permitting modelling at global scale**.

Outline of Lecture #2

Part 1. Resolved versus unresolved physics in ocean circulation models

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Part 2. Broadening the spectrum of resolved processes in ocean models

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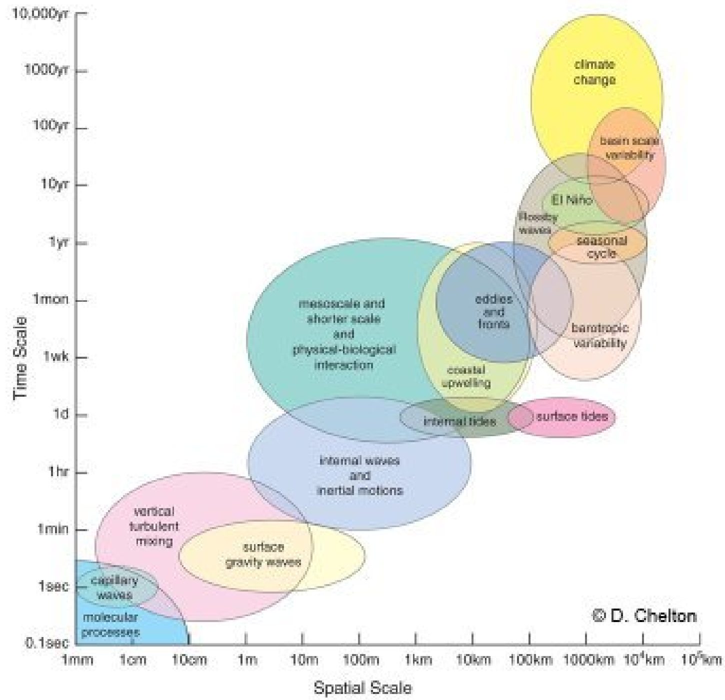
Part 4. Accounting for unresolved processes through model coupling

Part 1.

Resolved versus unresolved physics in ocean models

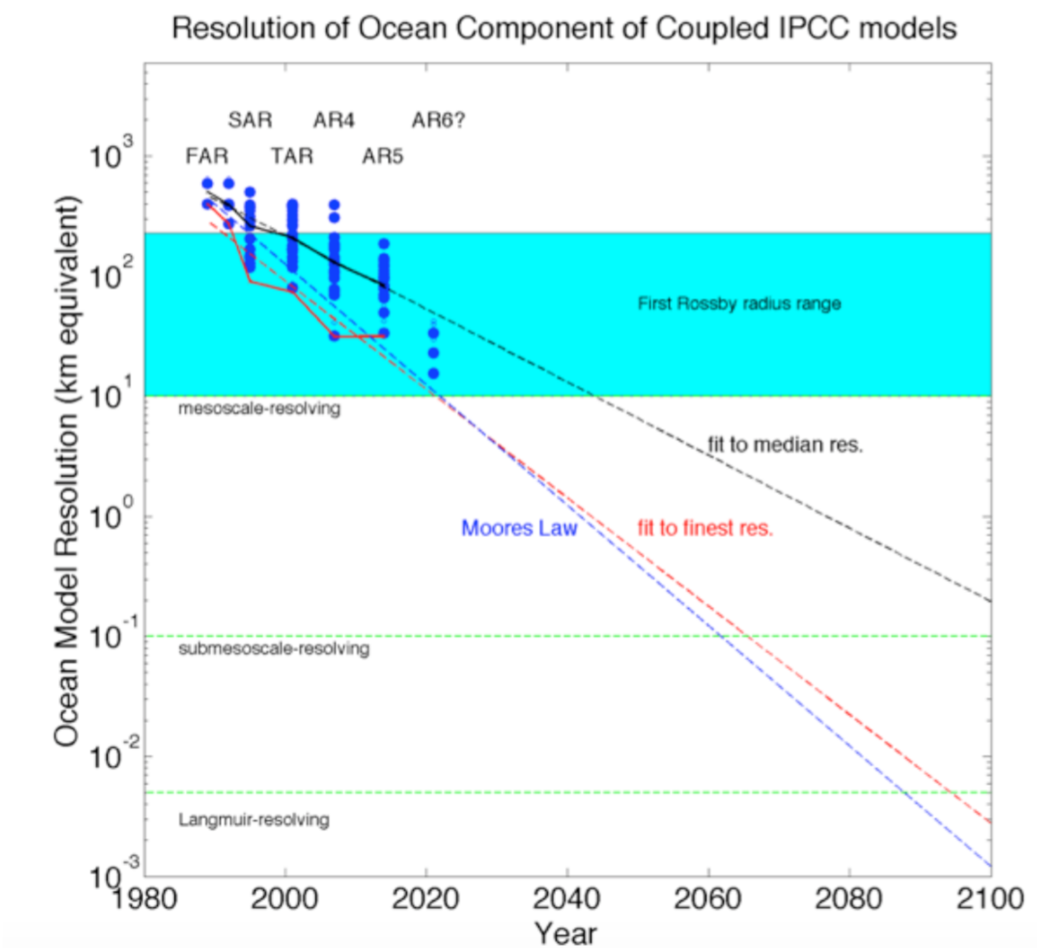
Space and time scales of major ocean physical processes



Resolving space into regions of dimension 10^{-3}m for an ocean with volume roughly $1.3\ 10^{18}$ m^3 requires $1.3\ 10^{27}$ discrete grid cells (roughly 10^4 times larger than Avogadro's number!) (*Griffies*).

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

Projection of the future evolution of model grid resolution



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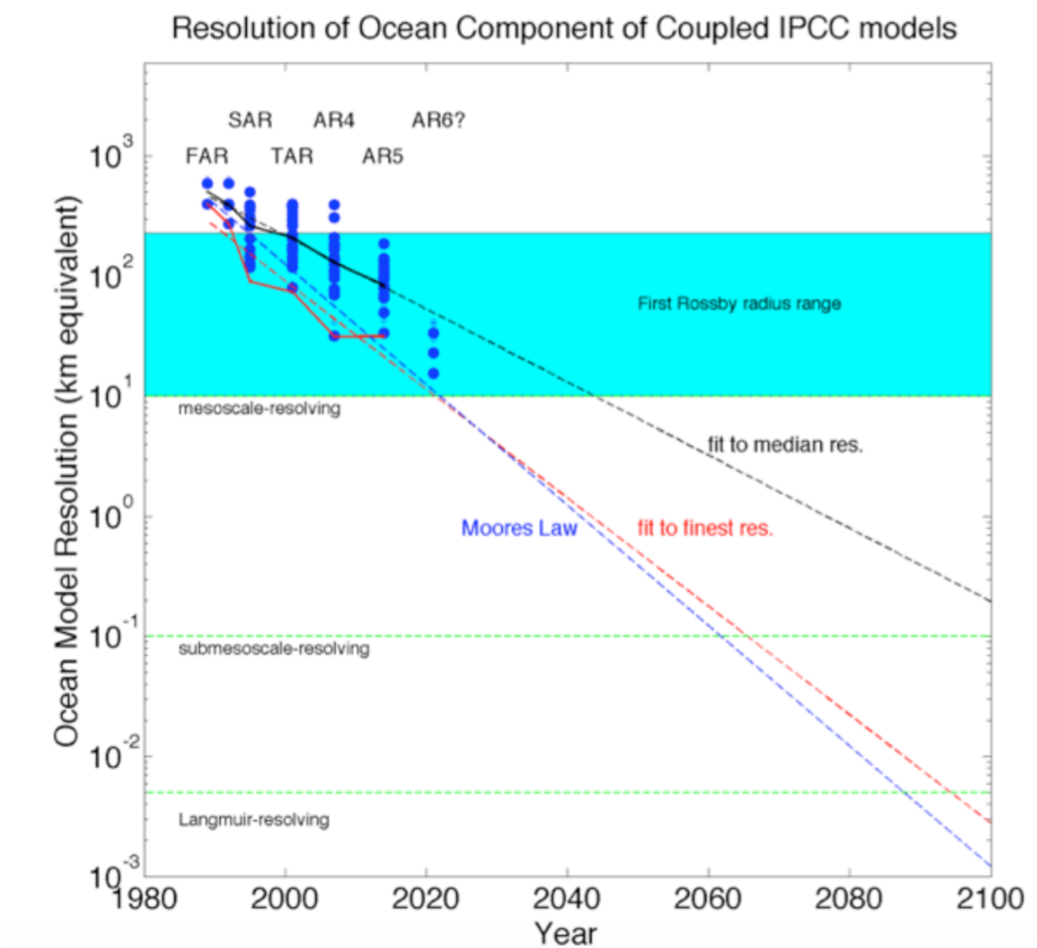
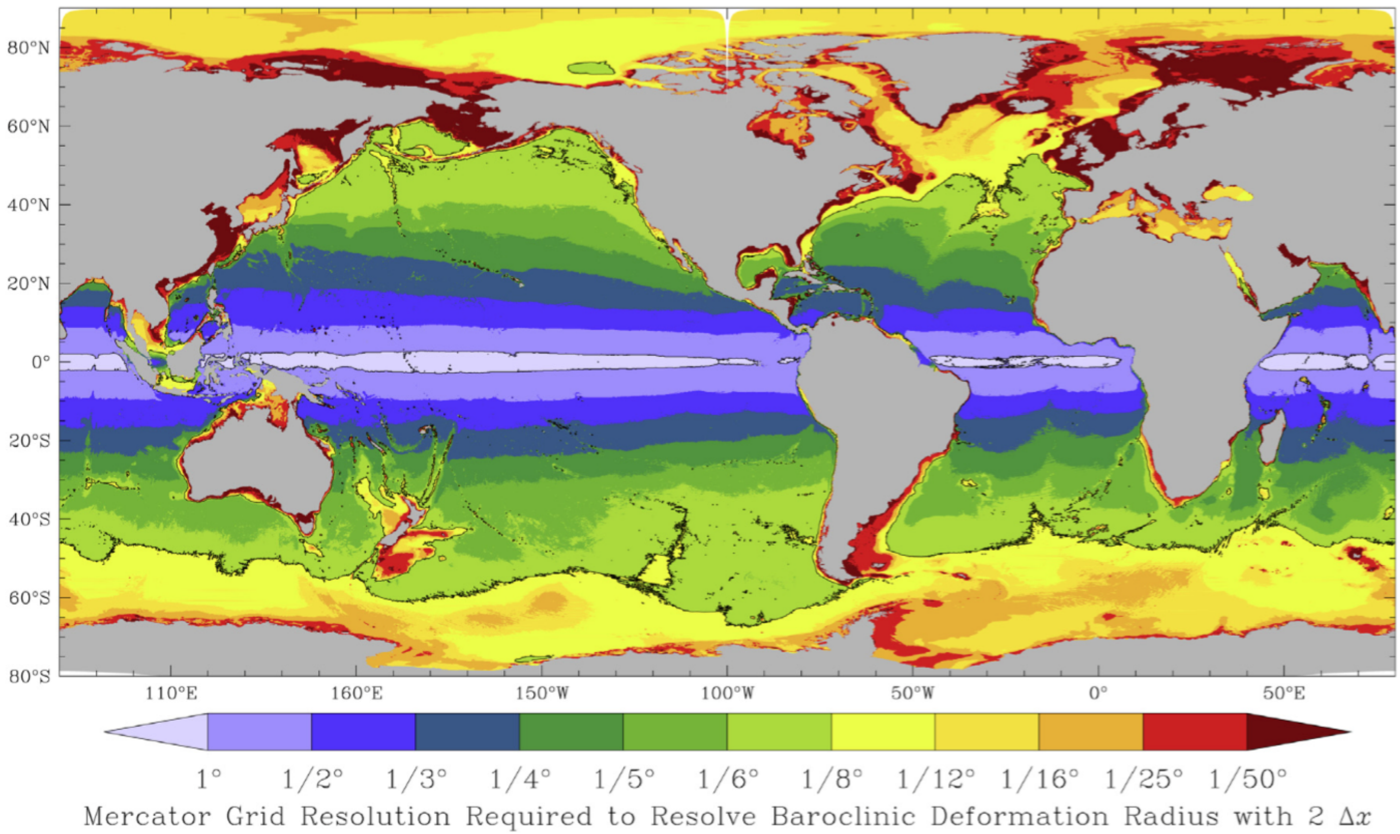


A large fraction of the **spectrum of oceanic variability will remain unresolved** in ocean circulation models in the foreseeable future.

Ability of model grids to resolve mesoscale processes

Horizontal resolution needed to resolve the first baroclinic deformation radius with grid points on a mercator grid (Hallberg et al. 2013).



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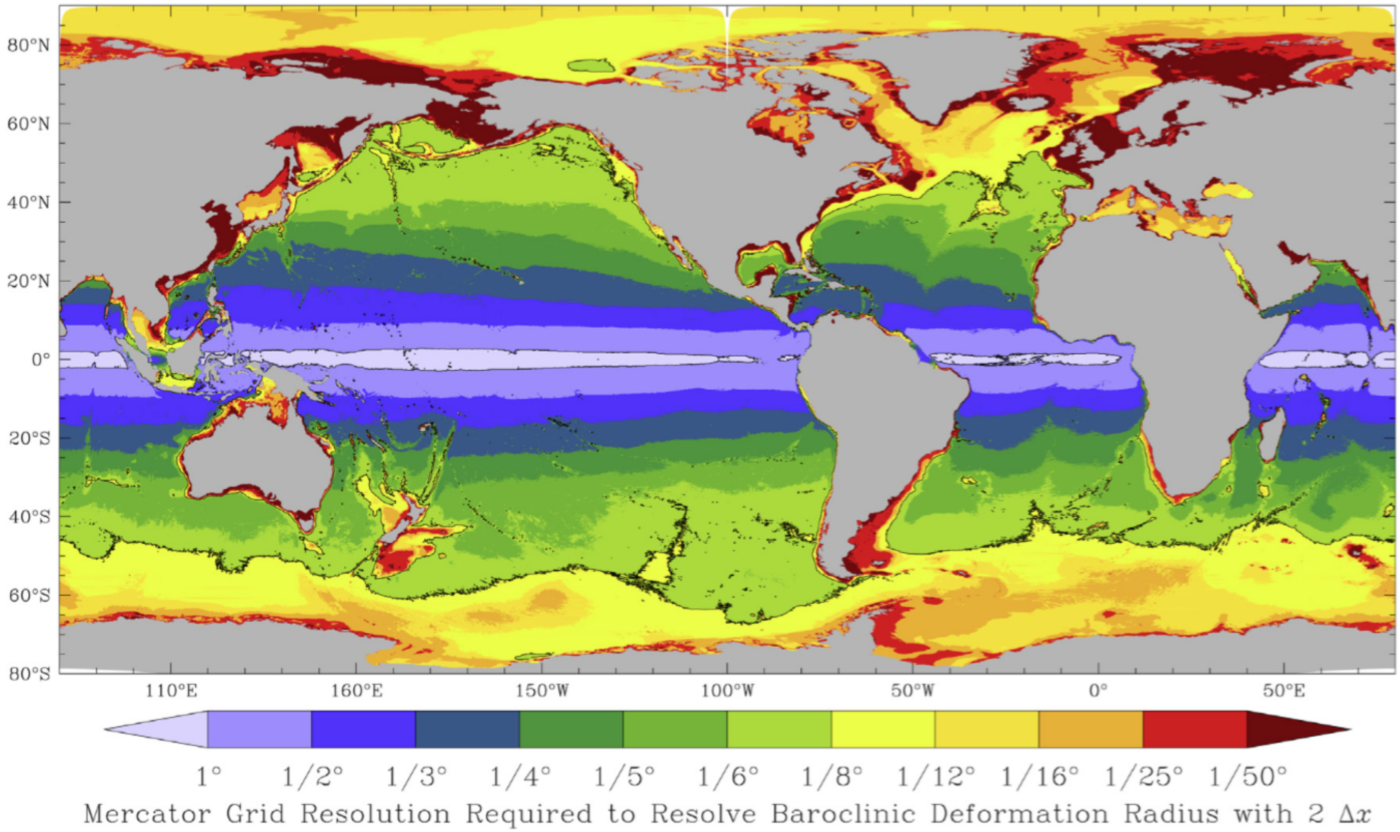

Actual mesoscale permitting modelling at global scale may require 1/50° horizontal grid resolution...

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- need for a **robust rationale** for designing optimally ocean model components of operational systems
- understanding of **what controls the potential spectrum of resolved process** in ocean circulation models besides the model grid resolution

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practical **rule of thumb** :

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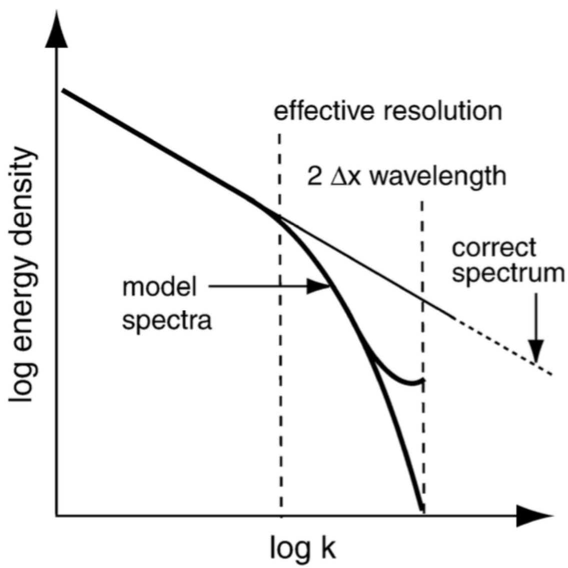

Skamarock et al. (2004)

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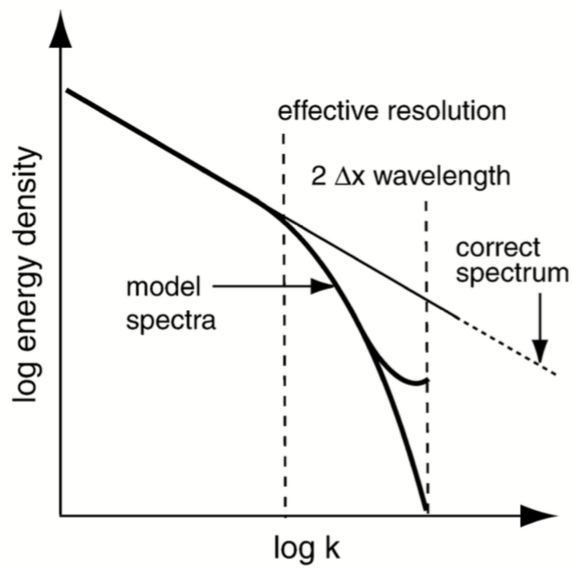

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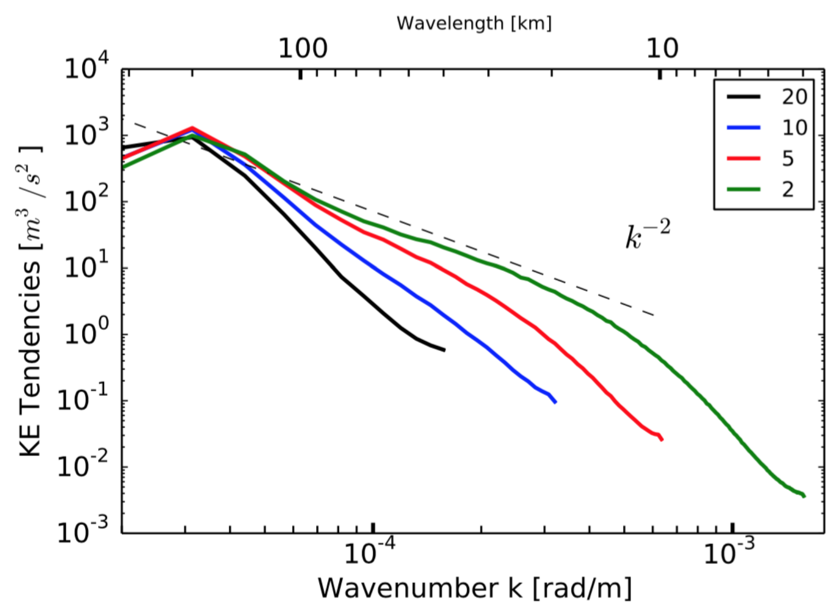

Soufflet et al. (2016)

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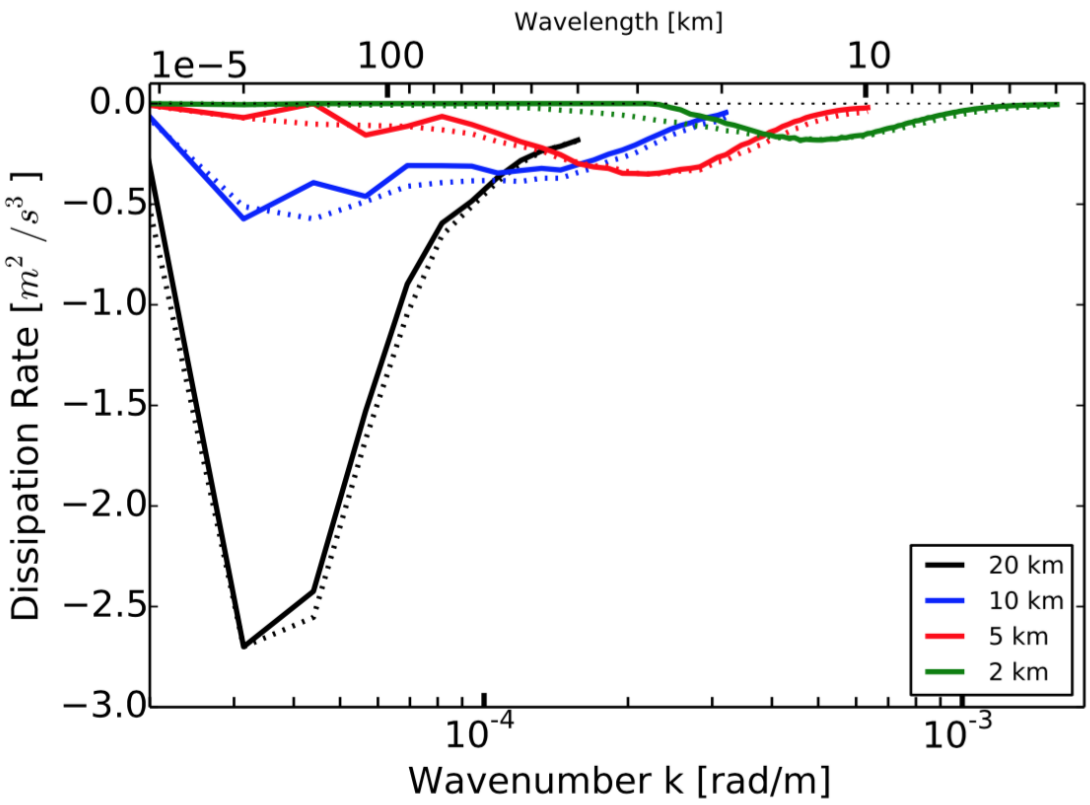

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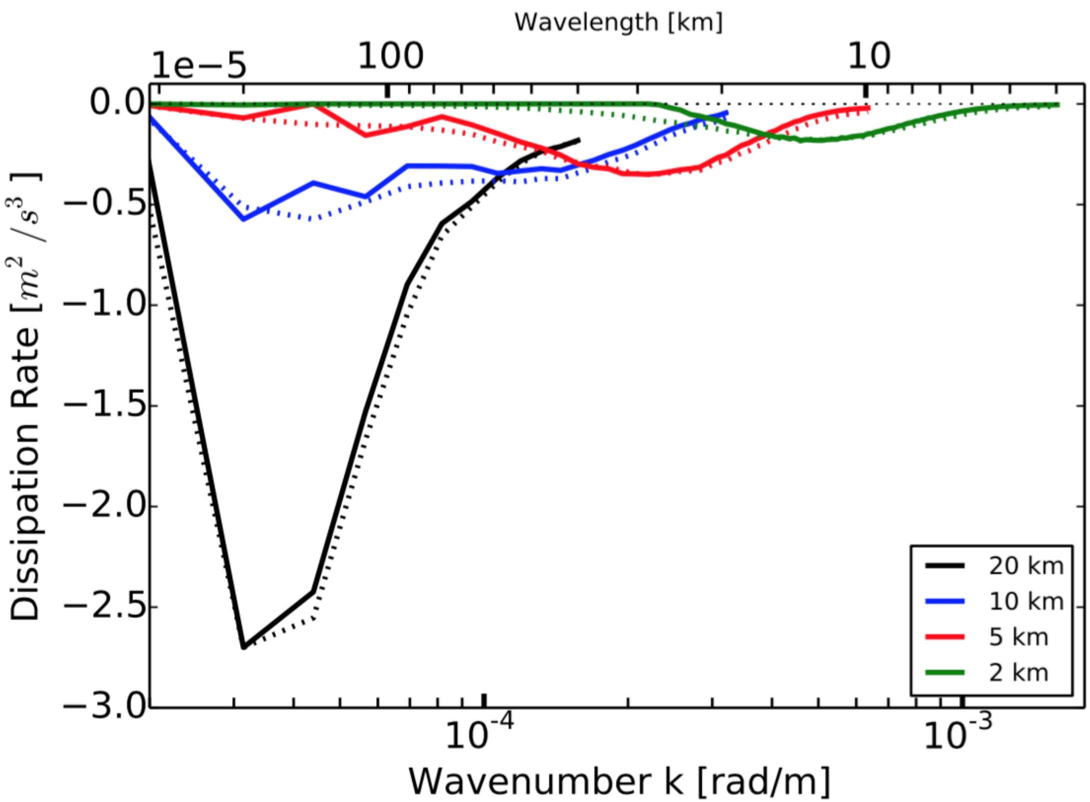

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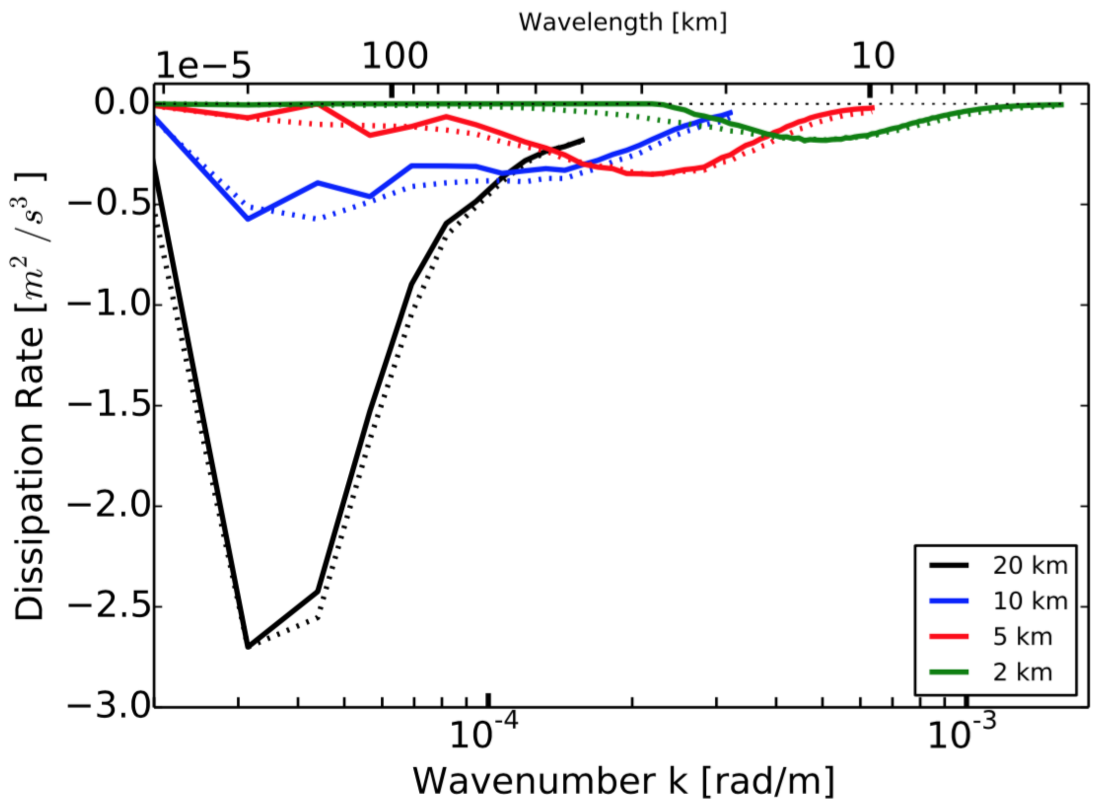

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under such conditions, typical effective resolution are **about 6 to 10 dx**.

Part 2.

Broadening the spectrum of resolved processes

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in practise, need to **trade-off between mimetic prop. and order of accuracy**

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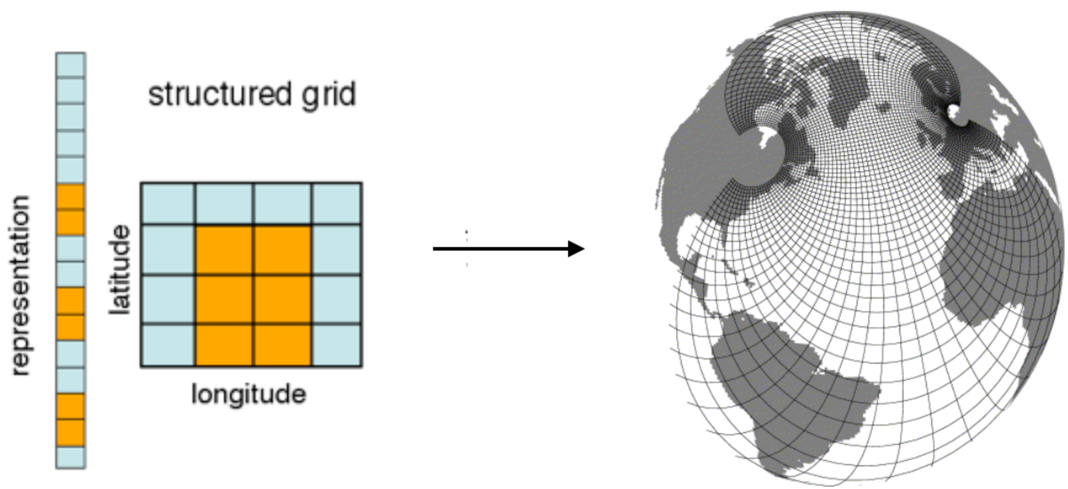

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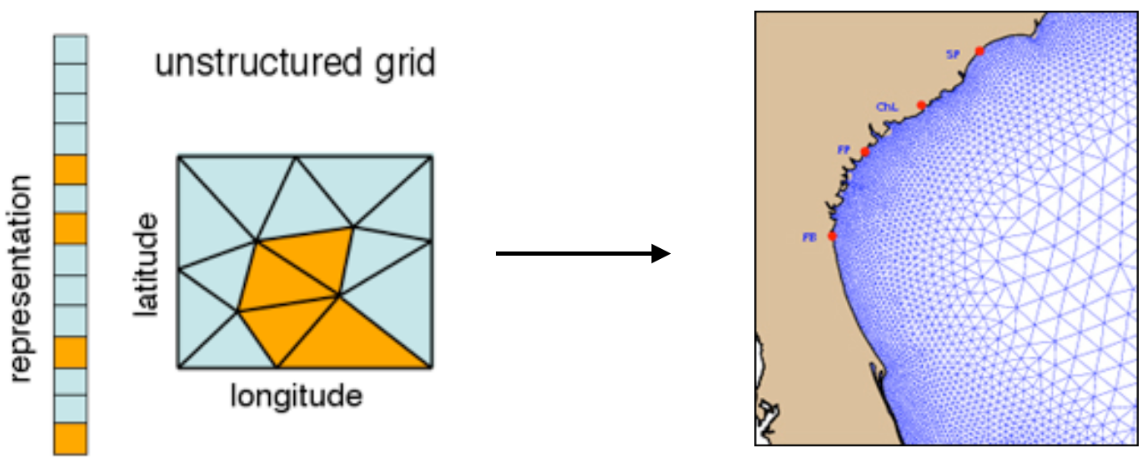

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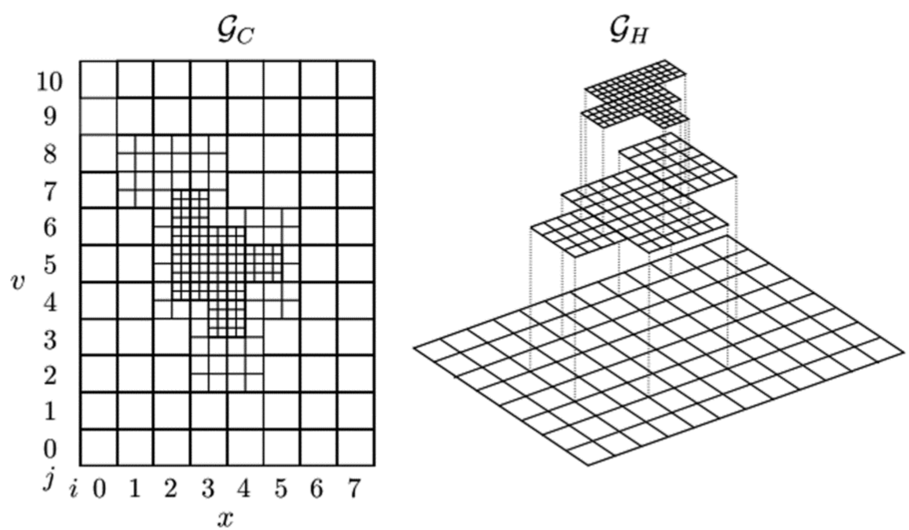

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Some open issues :

- the design of robust **discretization schemes** for large-scale ocean models on triangular or hexagonal meshes is **still challenging** (Danilov 2013).
- it is still **unclear how to optimally use the potential for mesh refinement** and mesh adaptativity of multiscale modelling approaches in large scale ocean circulation models.

Increasing effective resolution with improved usage of HPC

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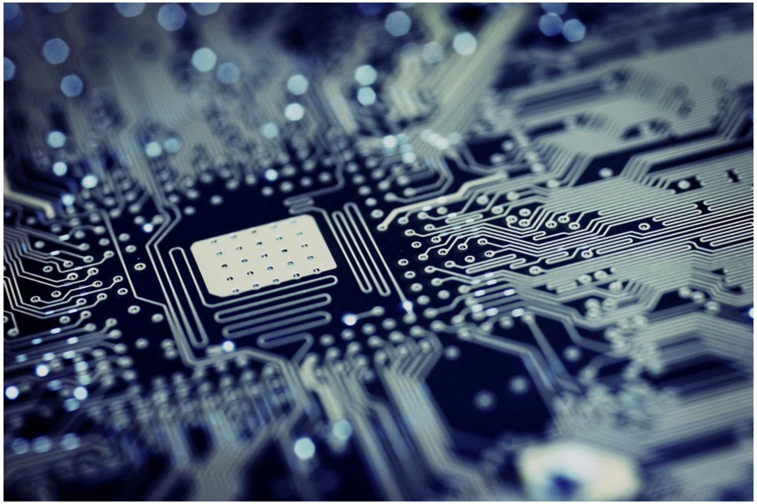

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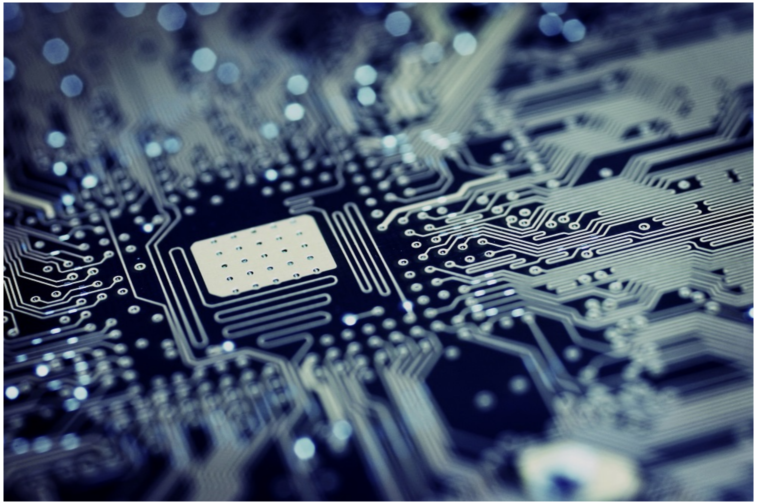

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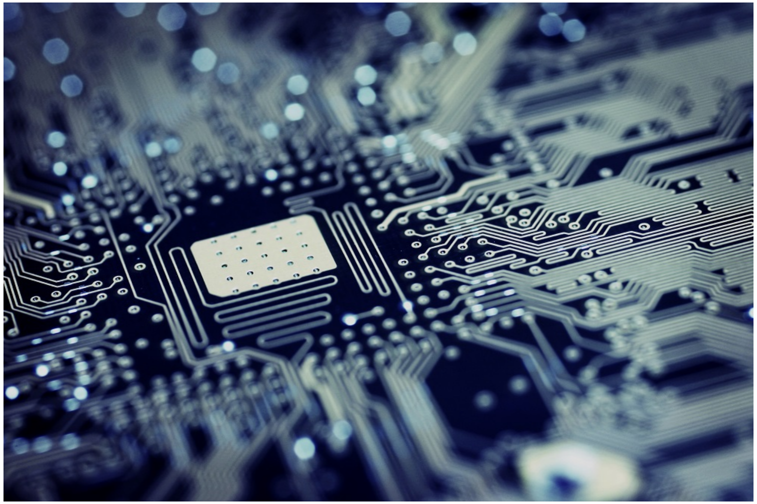

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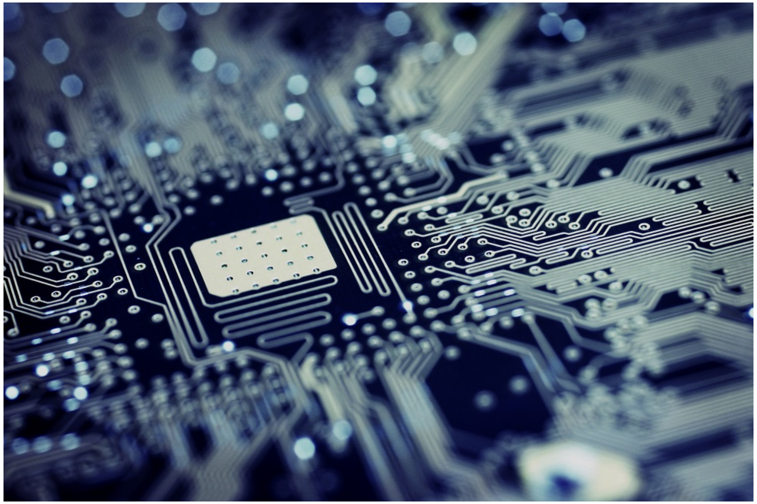

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- Over past decades, **computation have become cheaper** but **memory transfers are still expensive**
- Although modern HPC platforms can deliver a peak **performance in the Petaflop/s range**, most of the existing ocean circulation models are yet **unable to exploit this potential**

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- **innovative algorithms** for solving our PDEs : eg. parallelisation in time (eg : Parareal algorithm)

- this will require intense **collaboration between ocean modellers and computer scientists**

Part 3.

Accounting for unresolved processes through subgrid scale closures

Nonlinearity and subgrid scale closures

Primitive equation (PDEs)

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where :

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Caveats :

- it is not that easy to know how to relate $\mathbf{s}$ and $\bar{\mathbf{s}}$.
- it is usually assumed that $\bar{\mathbf{s}}$ is an averaged version of $\mathbf{s}$, but what average ?
- assuming that $\mathcal{M}$ is deterministic is strong assumption

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    - SGS closures for **processes in the Ocean Surface Boundary Layer**
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- the design of SGS closures associated with physical processes usually involves :
  - idealized process studies with models
  - realistic process studies with models
  - targeted field experiments at sea
  - lab experiments (probably more rarely now)

Approaches to designing subgrid scale closures (1/2)

- $\mathcal{N}(\bar{\mathbf{s}}) - \overline{\mathcal{N}(\mathbf{s})}$ contains a lots of terms involving a lot of different correlations among u, v, w, T, S

- The general approach is **not to focus on particular nonlinear terms** in the primitive equations but rather on **particular physical processes** (that may affect several terms)

- A rough classification of unresolved physical processes could be :

    - SGS closures for **balanced turbulence** (eddy closure)
    - SGS closures for **processes in the Ocean Surface Boundary Layer**
    - SGS closures for **interior mixing processes**
    - SGS closures for **Bottom Boundary layer processes**

- the design of SGS closures associated with physical processes usually involves :

    - idealized process studies with models
    - realistic process studies with models
    - targeted field experiments at sea
    - lab experiments (probably more rarely now)

- importantly, a SGS closure should always **target a particular ocean circulation model resolution** because the information at resolved scale depends on the model resolution.

Approaches to designing subgrid scale closures (2/2)

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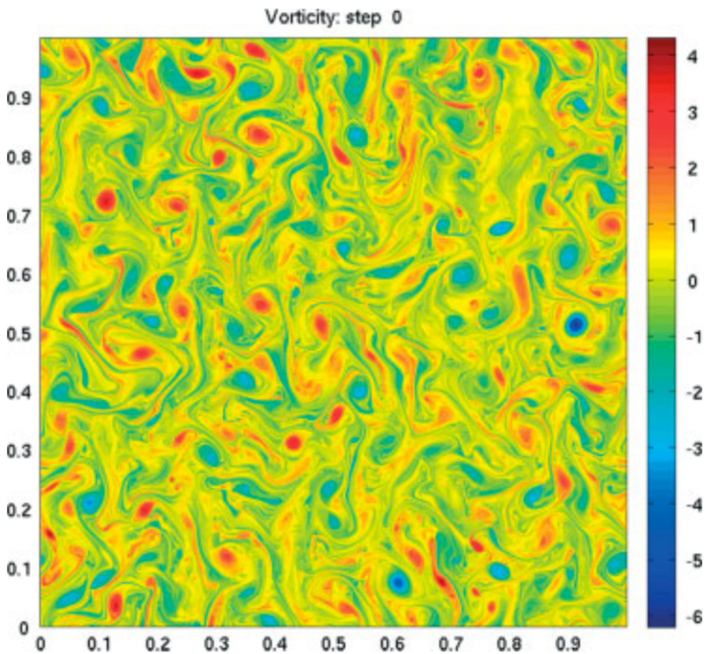
    - **functional closures** consider the bulk action of the subgrid terms on the resolved scales. example : Smagorinsly momentum closure
    - **structural closures** aim at estimating the best local approximation of the unknown SGS term by constructing it from the known structure of small-scale. example : closures defined by Taylor series expansion.

Example : the case for eddy energy backscatter (1/2)

•



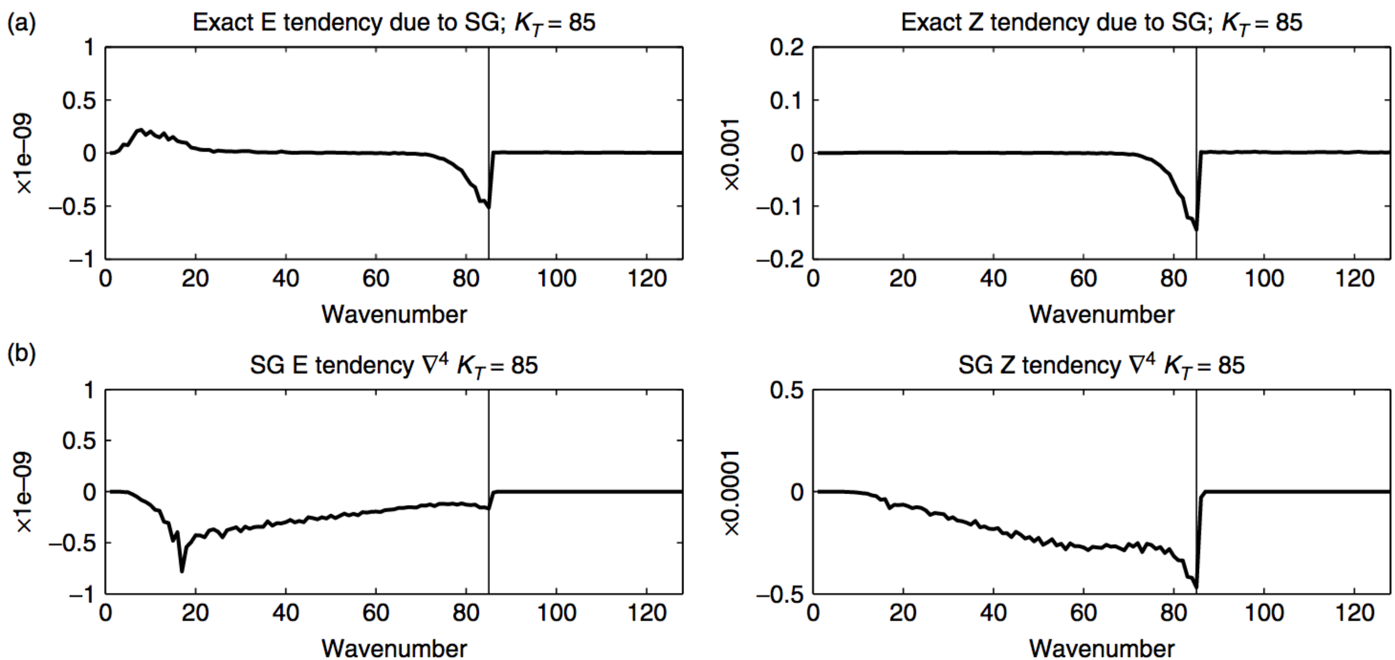
In two-dimensional turbulence, both energy and enstrophy are conserved :

$$E = -\frac{1}{2}\int \psi \zeta \, \mathrm{d}x \, \mathrm{d}y$$

$$Z = \frac{1}{2}\int \zeta^2 \, \mathrm{d}x \, \mathrm{d}y.$$

- remind that in 2D turbulence, **energy is transfered to large scales while enstrophy is transfered to small scale**.
- so in numerical simulation, **unresolved scale may exchange energy and enstrophy with resolved scales**

Example : the case for eddy energy backscatter (2/2)



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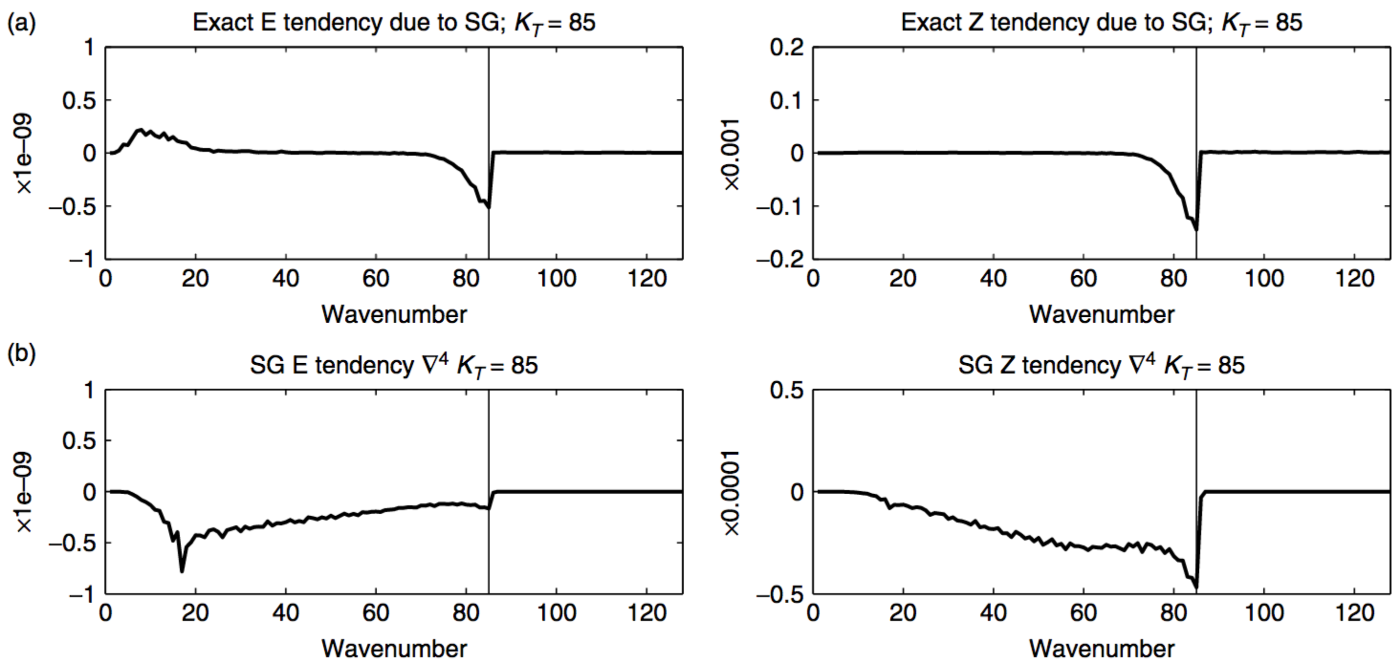

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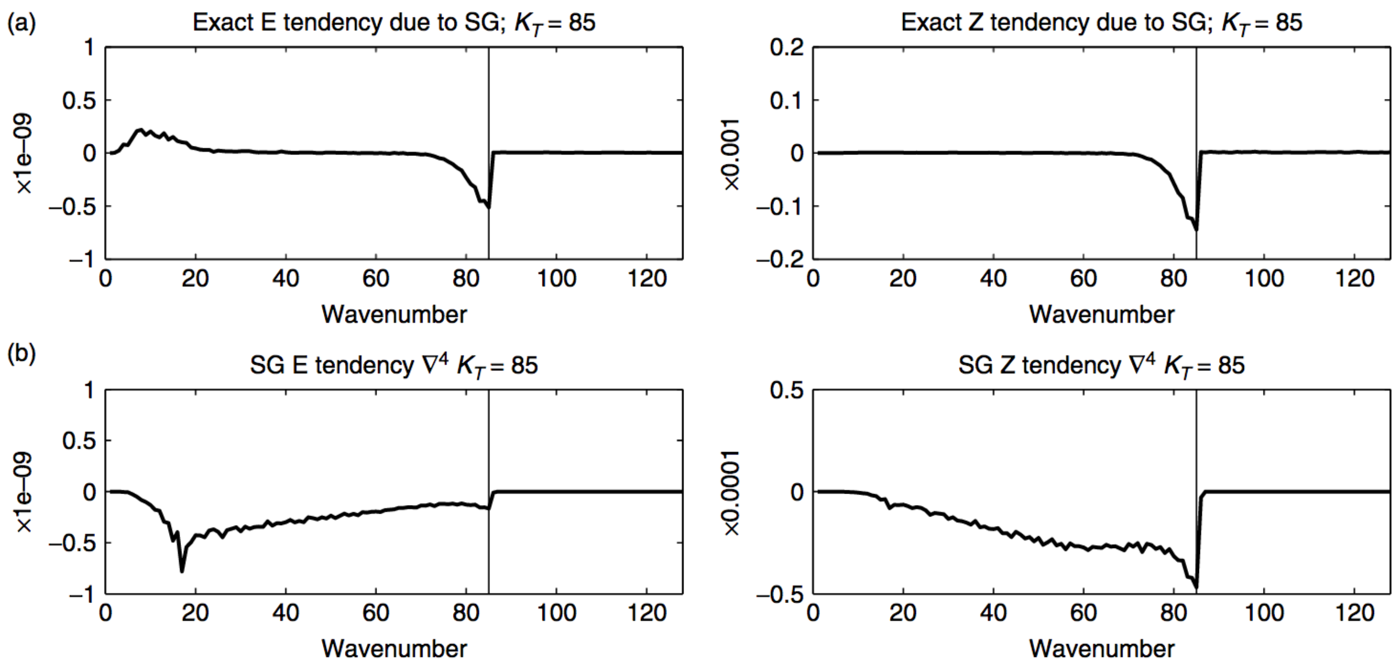

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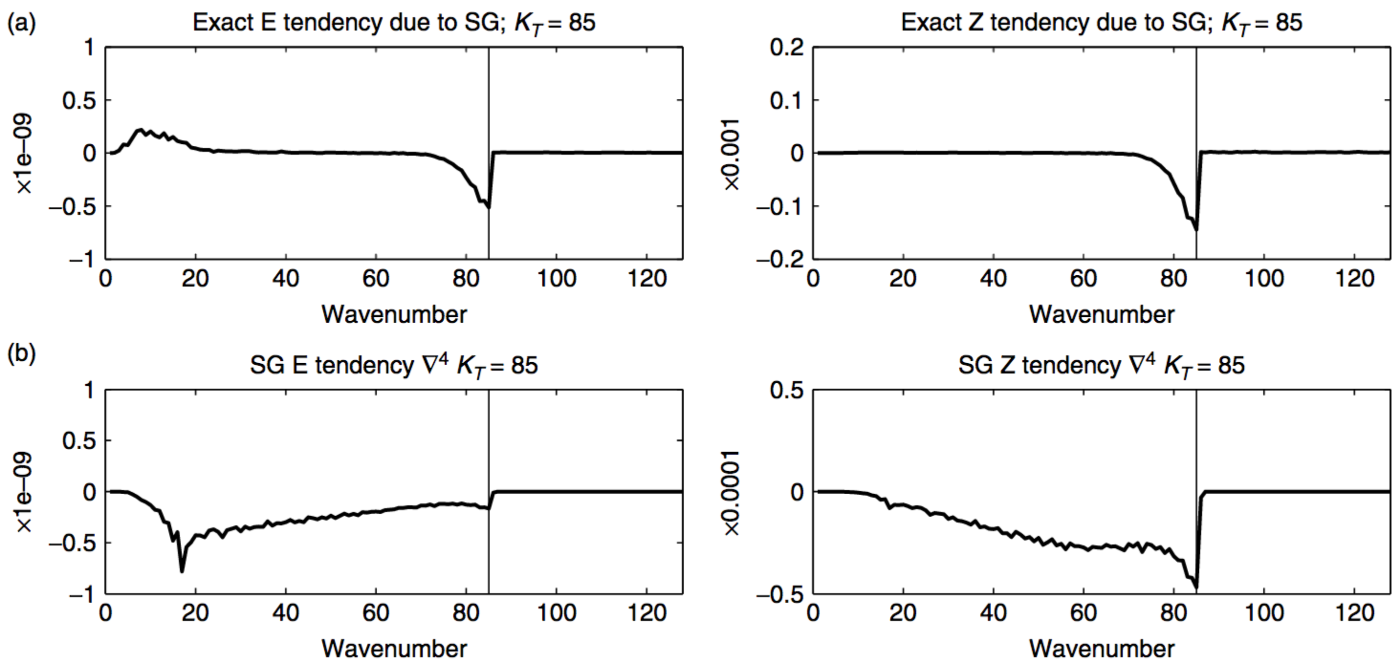

- Thurburn (2013) has made the case for **the need to take into account the backscatter of energy**:
- showing in particular **biharmonic viscosity is not accounting for this effect**.
- this has motivated the development of a number of different **closures for primitive equation models**

Part 3.

Accounting for unresolved processes through model coupling

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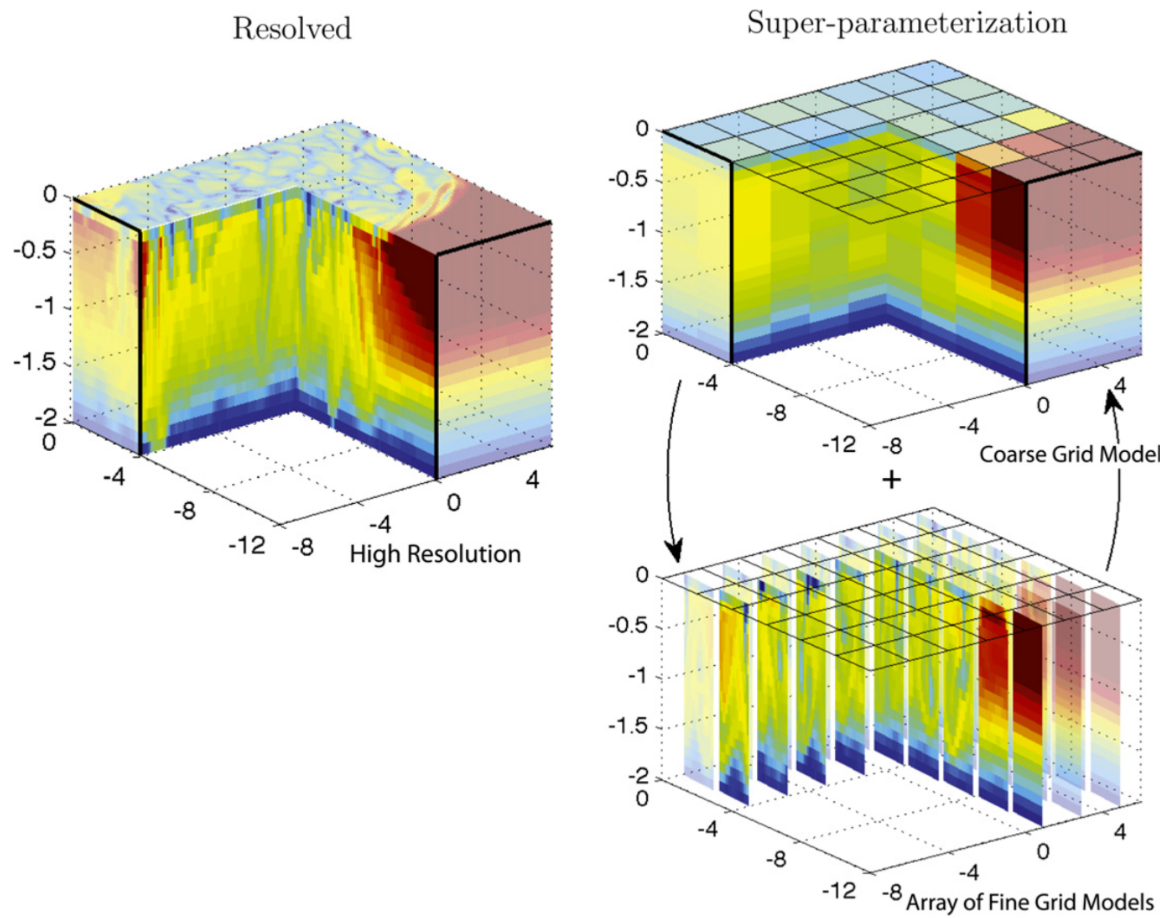
- in all the above case, ocean modellers are actually representing missig processes by coupling their ocean circulation models to third party process models.

Example 1: Superparameterization of deep convection.



Capmpin et al. (2013) have proposed to embed 2Dz non-hydrostatic models with an hydrostatic PE model in order to inprove the representation of the transport due to deep convective plumes.

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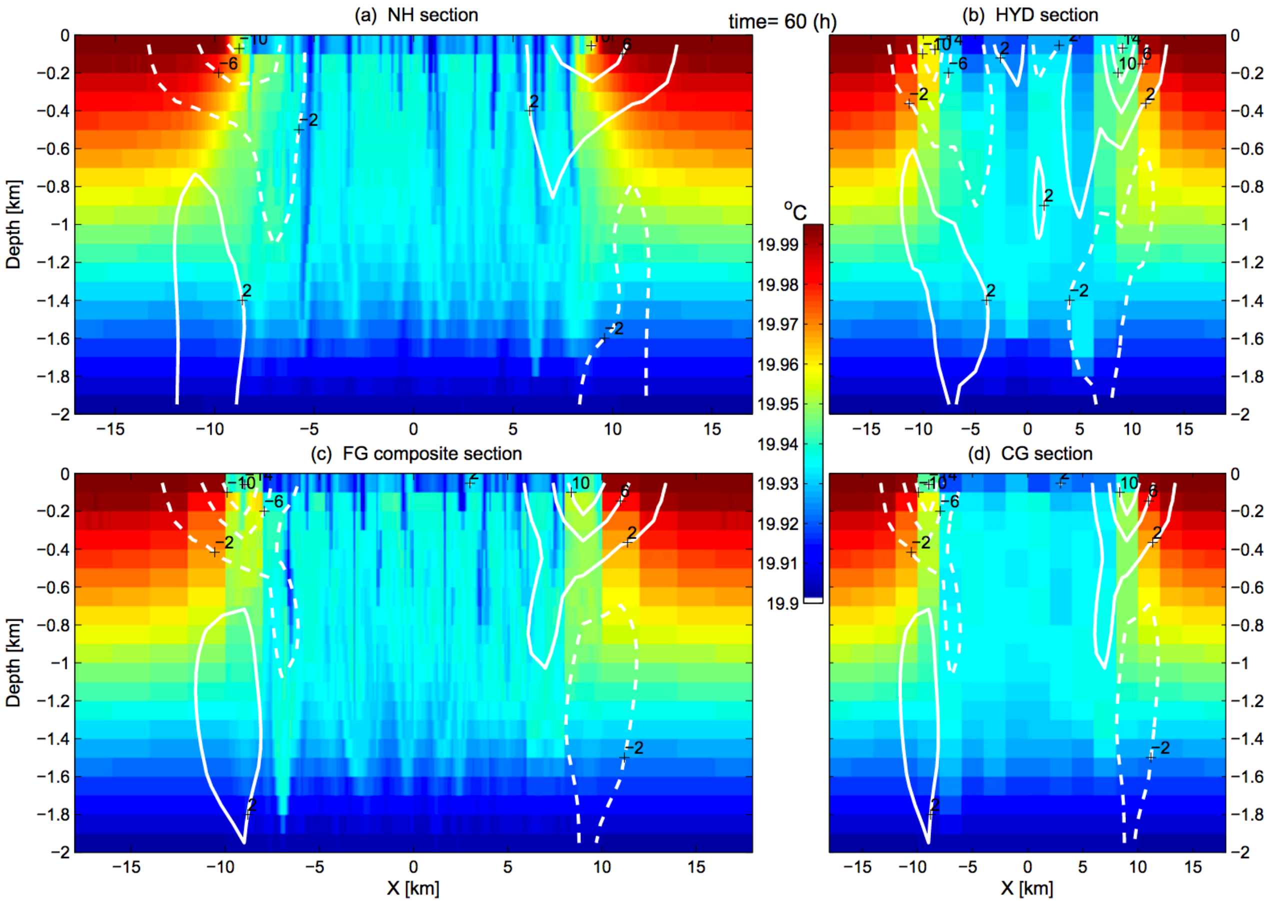
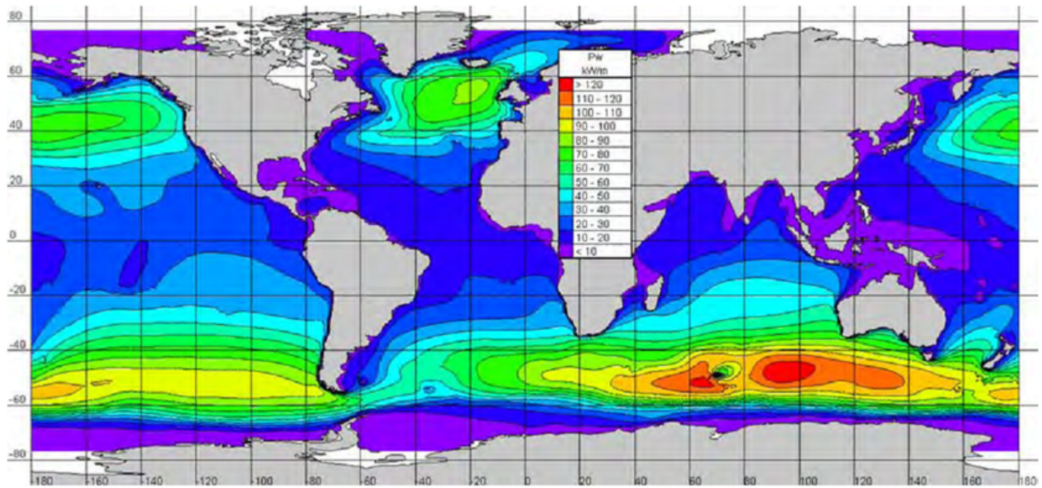


Campin et al. (2013)'s approach improves substancially the change in T, S in unstable condition with respect to classical convective adjustment scheme

Example 2: Coupling circulation models with wave models.

Global Distribution of Annual Wave Power Flux from WW3 Model (kW/m)



- surface wave affect OSBL processes in various ways : mixing, langmuir turbulence, air-sea fluxes, stokes drift...
- ocean surface waves are strongly affected by ocean currents;
- mature surface wave models exist because of the importance of wave forecasting for operations at sea;
- adequately accounting for the impact of surface waves on ocean circulation in models requires to couple circulation models with wave models

Side remark : implication for operational centers.

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- specific **data assimilation methods will be needed** for constraining simultaneously several independant model components in operational systems with data assimilation.
- more generally, this relates to the **question of the increasing complexity of operational systems** in the future.

Wrapping-up Lecture #2

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- Interaction with **computer scientist and applied mathematicians will be essential** to further increasing the range of scale resolved in ocean models (schemes, HPC, ...)
- the design of **SGS closures is a key activity** of ocean model design but (1) this is not an easy task (2) the problem is not that well posed (average ?, LES, RANS ?)

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- Interaction with **computer scientist and applied mathematicians will be essential** to further increasing the range of scale resolved in ocean models (schemes, HPC, ...)
- the design of **SGS closures is a key activity** of ocean model design but (1) this is not an easy task (2) the problem is not that well posed (average ?, LES, RANS ?)
- the **coupling with third party models** is likely to become a natural way for ocean circulation model to account for certain classes of physical processes