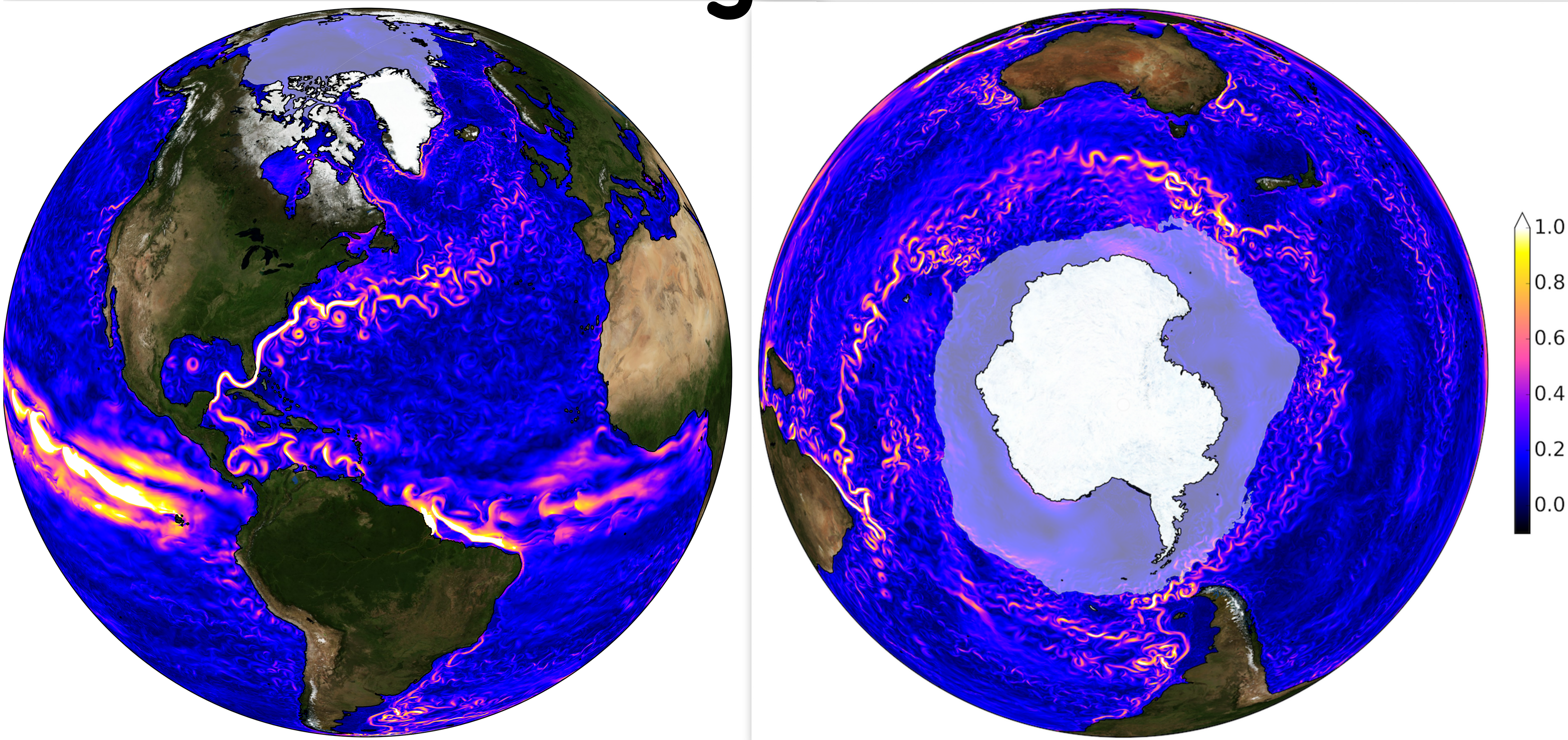
# A Brief Introduction to Modelling the Ocean




Andy Hogg (Australian National University) — with sincere thanks to Stephanie Waterman (University of British Columbia)

# What is an ocean model ?

a representation

in the form of

equations / computer code

describing

physical processes

of our understanding of how the ocean works.

# What is an ocean model ?

a representation

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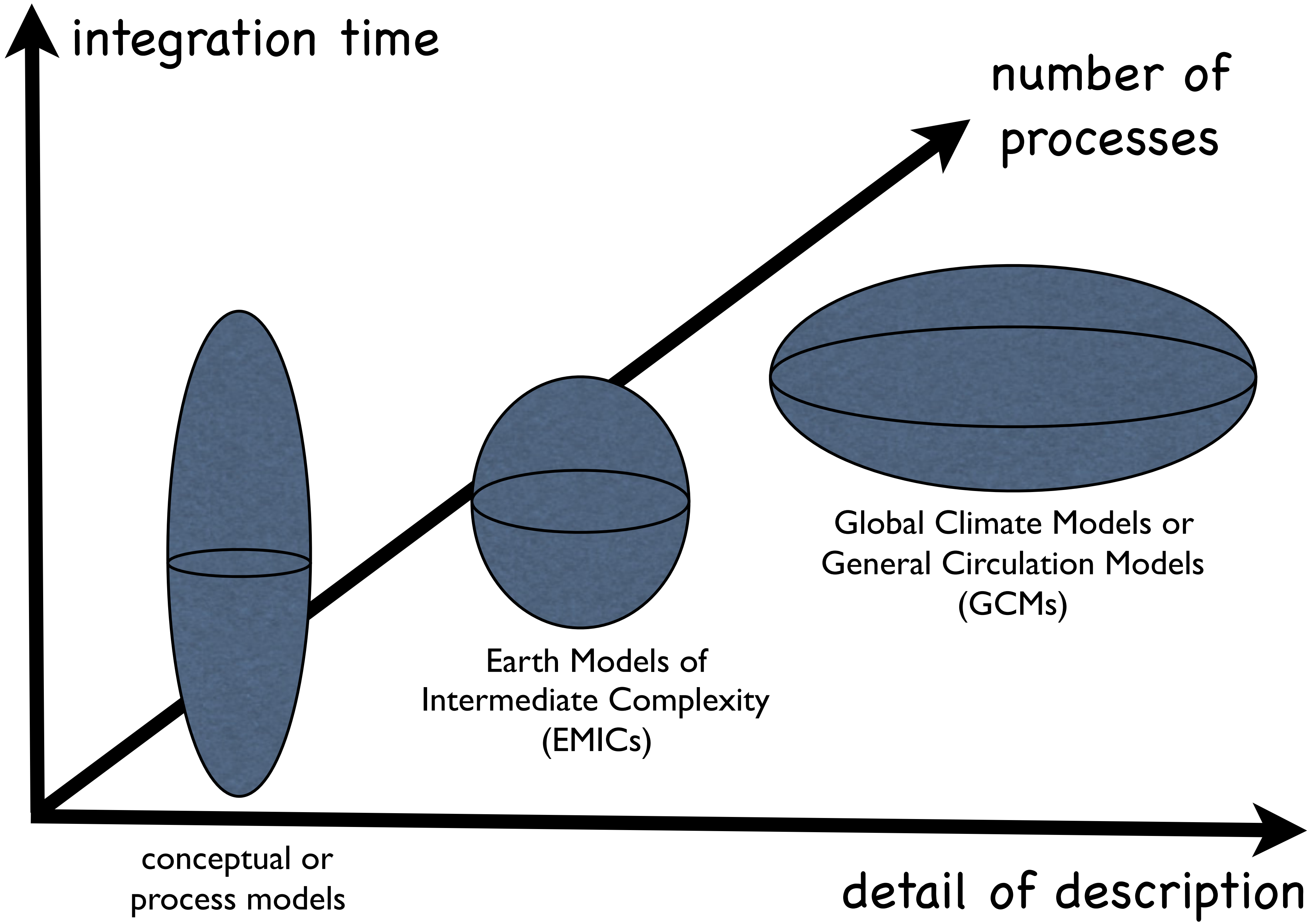
**physical processes**

of our understanding of how the ocean works.

- the exchange of energy, mass, and momentum between the ocean and external sources (e.g. radiation, evaporation, precipitation, river runoff, wind energy that creates waves or currents etc. etc.)
- ocean movement/dynamics including horizontal advection and vertical convection; and
- 3-dimensional mixing and dissipation processes at scales from molecular to ocean basin
- ...

# There are many types of ocean models...

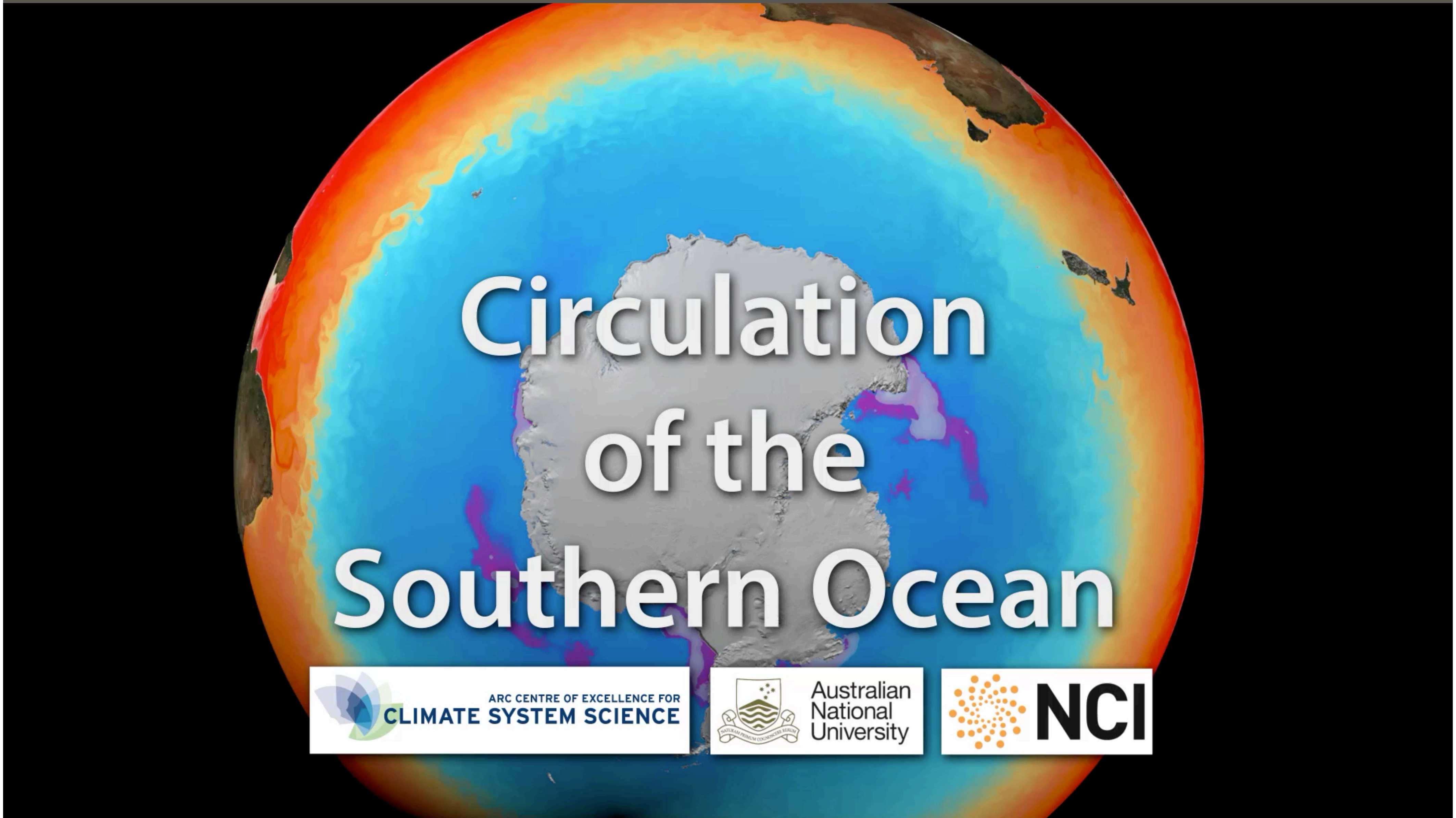



[Adapted from Claussen et al 2001]

# There are many ways to use ocean models...

- to consider future climate scenarios
- to make operational now-casts and forecasts
- to investigate ocean and climate processes
- to mechanistically interpret ocean observations
- ...

**Remember: All models are wrong, some are useful!**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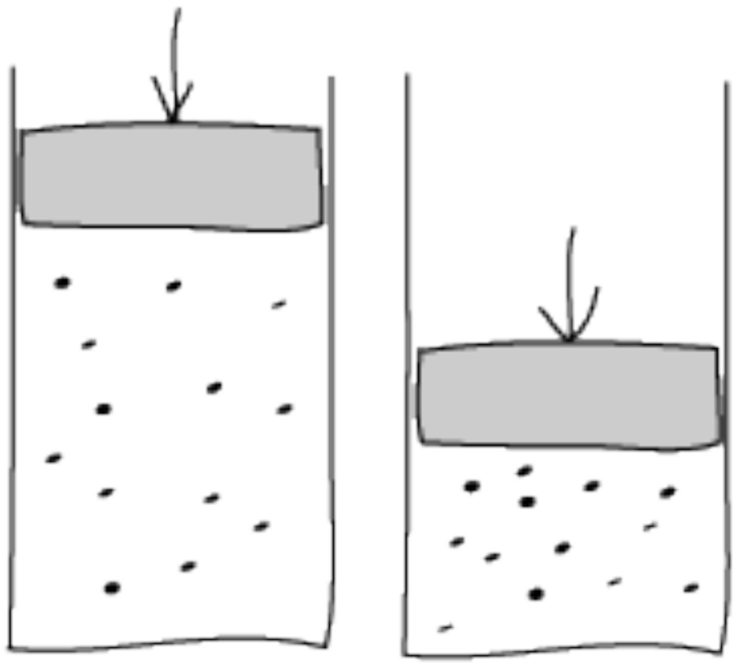
# Ocean vs. Atmospheric Models I

## 1. liquid vs. gas

- air is a compressible gas; seawater is a (nearly) incompressible liquid
- this relationship requires a fundamentally different equation of state:
  - atmosphere: ideal gas law (easy!)
  - ocean: density = fn(temperature, salinity,pressure) (hard!)
- **BUT** (in most applications) we can assume incompressibility (so water into a box = water out)



# Ocean vs. Atmospheric Models II

## 2. salinity vs. **humidity**

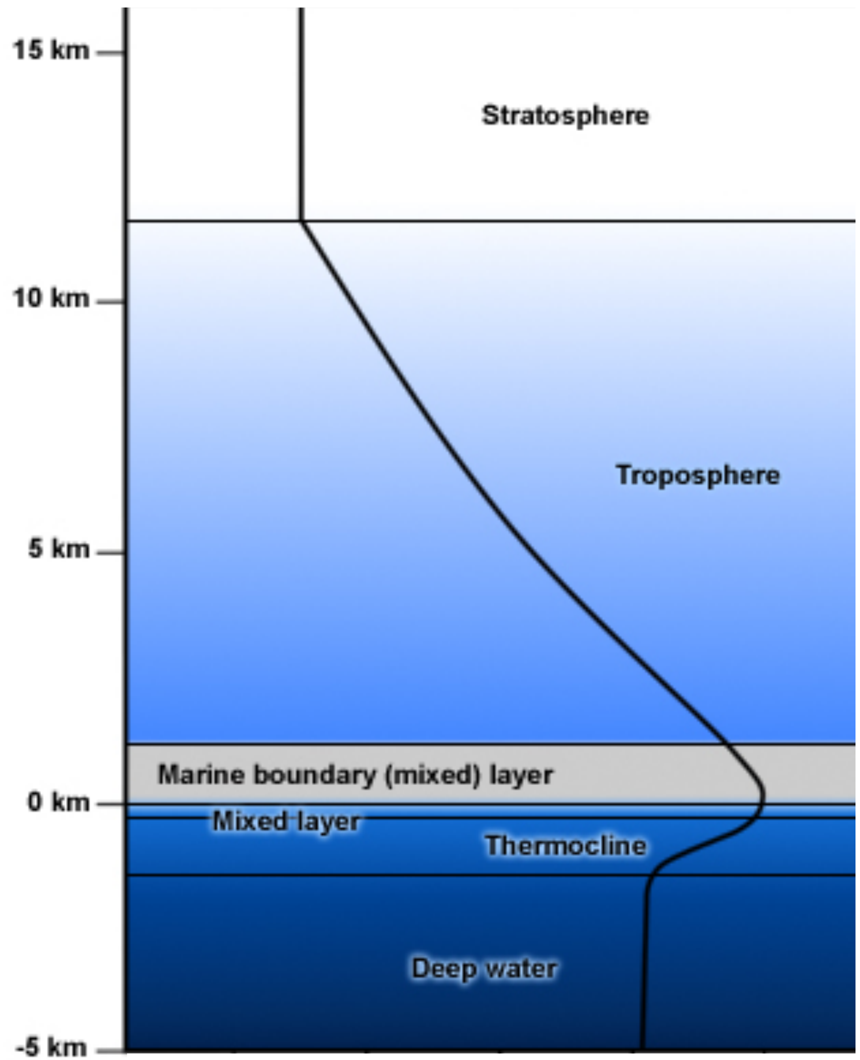
- seawater contains dissolved chemicals known collectively as "salinity"
- ocean models must account for the effects of salinity on density in an analogous way that atmospheric models must account for humidity


[http://en.wikipedia.org/wiki/File:IAPSO_Standard_Seawater.jpg#filelinks]

# Ocean vs. Atmospheric Models III

## 3. vertical structure

- the vertical structure of the ocean and atmosphere share both similarities and differences
- both have a well-mixed layer near the surface where most of the heating and cooling occurs
- **BUT** mixing occurs (to some degree) throughout the troposphere while the ocean is stratified below its thin mixed layer
- because the ocean is so stratified, ocean models can make assumptions about the dominance of horizontal processes over those in the vertical
- ocean modellers can benefit from vertical coordinate systems that exploit the fact that much of the action occurs in the near-surface mixed layer

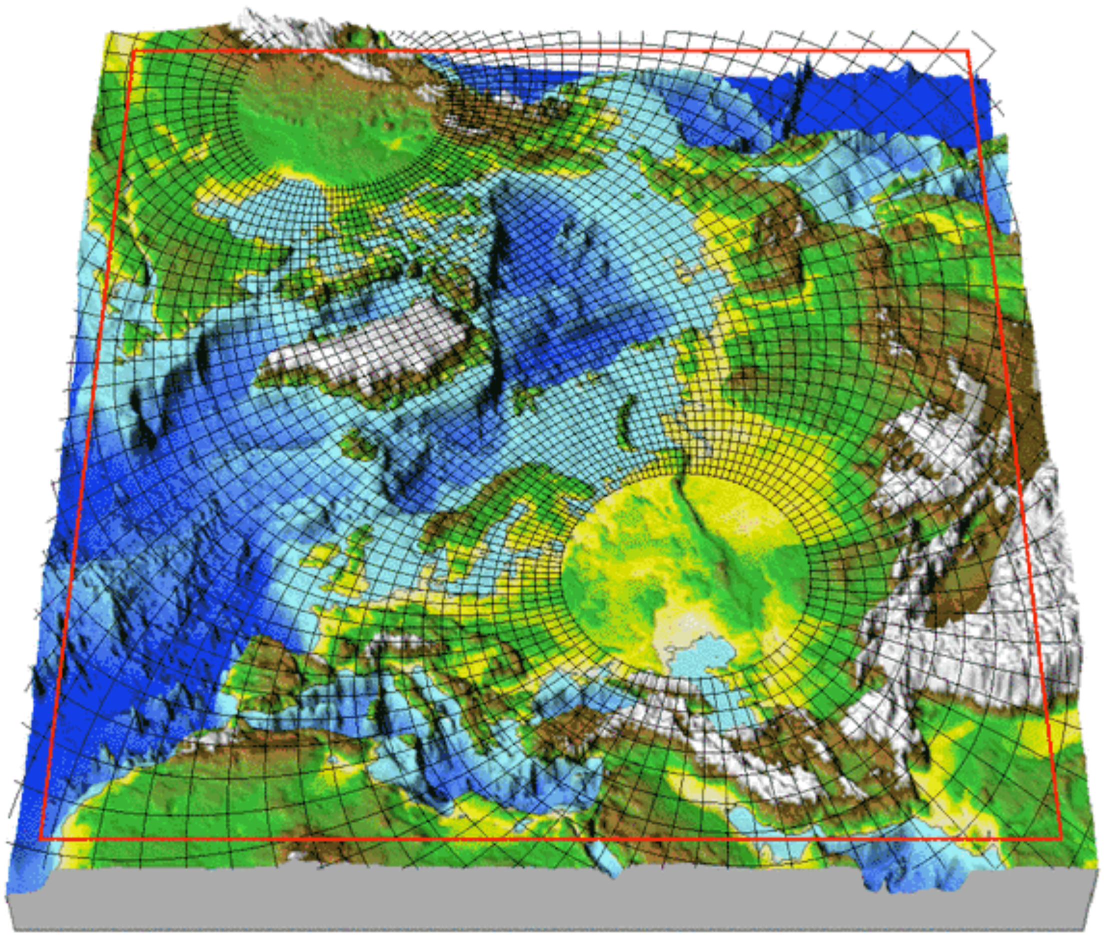



Temperature Profile: Seafloor to Stratosphere
[source: The COMET program]

# Ocean vs. Atmospheric Models IV

## 4. horizontal structure

- the atmosphere blankets the earth in a laterally continuous layer; it is pierced by (relatively) small mountain ranges
- the ocean is bounded on 5 of 6 sides by complex topography:
  - a series of irregularly shaped basins
  - fringed by narrow continental shelves
  - bottom bathymetry plays on O(1) role
- there are lateral boundary conditions: freshwater run-off from the continents that alters density and currents along the coast
- the need to resolve both horizontal and vertical processes along ocean margins plays a critical role the choice of horizontal and vertical co-ordinate systems

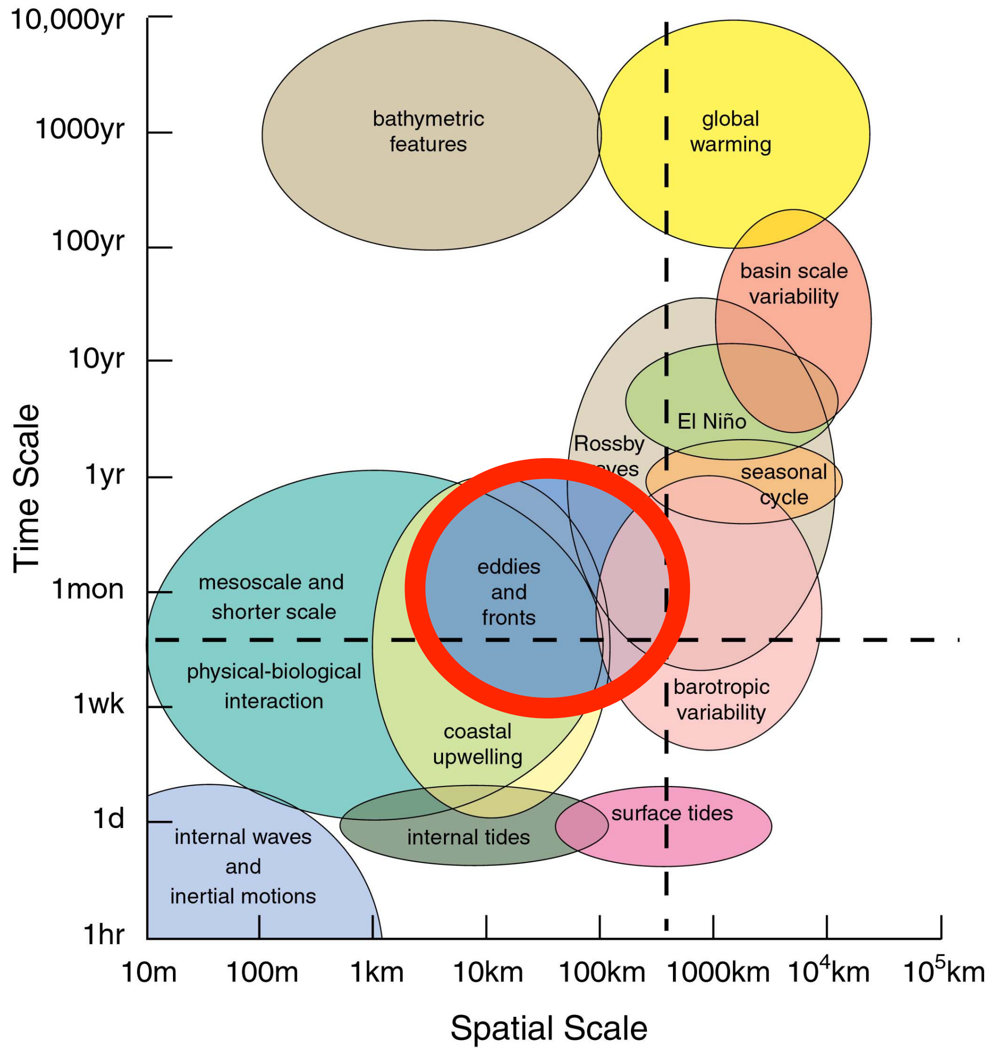


[courtesy of Maxim Nikurashin]

# Ocean vs. Atmospheric Models V

## 5. time and length scales of motion

- Atmospheric models are more expensive than ocean models **for a given grid size**
- **BUT** the energy-containing (geostrophic) scales in the atmosphere are much **larger** than those in the ocean
- this means we need to model the ocean at a finer resolution to resolve the same "types" of features
- also because the ocean interior is almost adiabatic (i.e. along-density surfaces) whereas the atmosphere is (relatively) well-mixed, the **equilibrium timescale** of the ocean is much s l o w e r
- to spin up a ocean model from rest: 1000 + years integration !!!



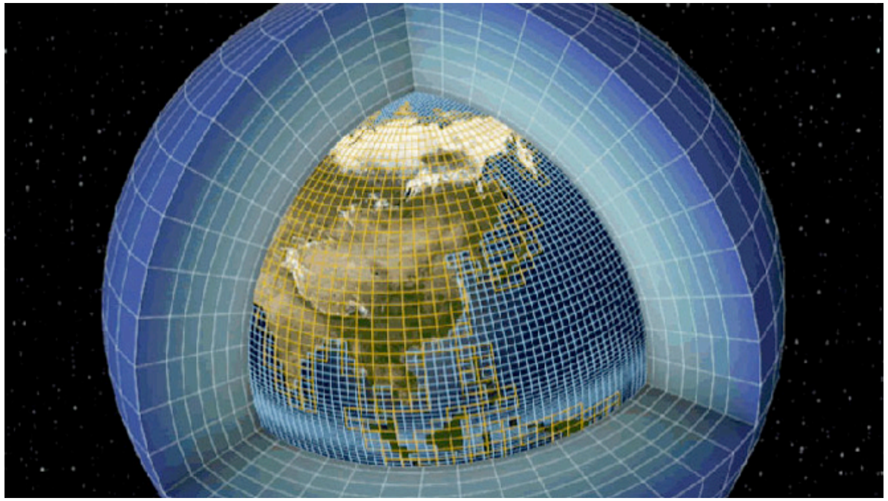

The space and time scales of various ocean phenomena.

[source: Chelton (ed) 2001]

# Ocean vs. Atmospheric Models

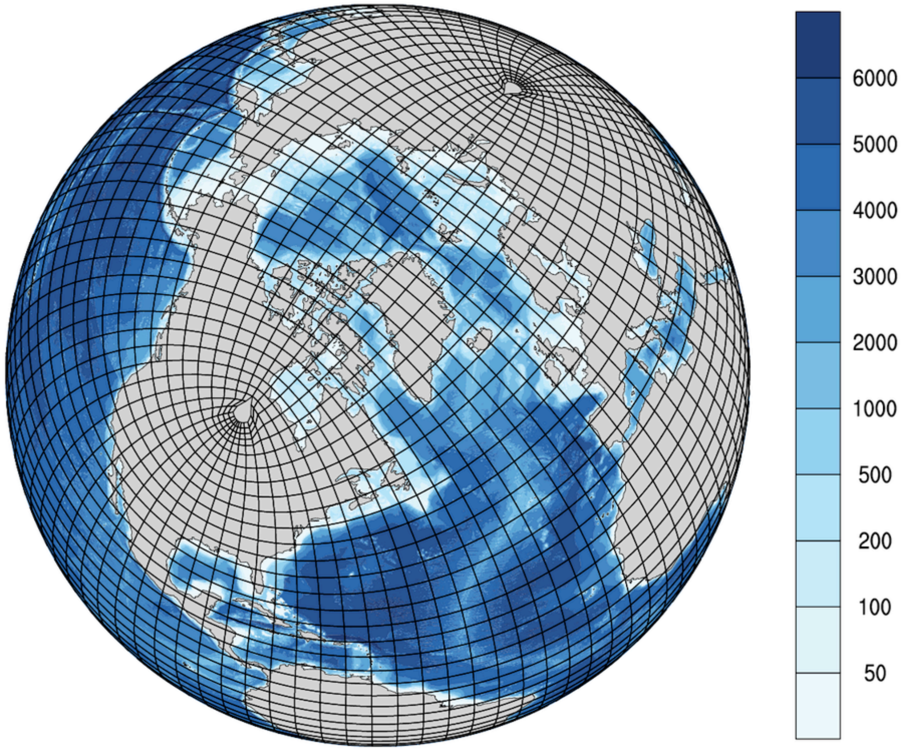
Ocean modellers have it both easy and hard compared to their atmospheric counterparts:

- the ocean is (nearly) incompressible: water in ~ water out
- the ocean is strongly stratified: horizontal processes dominate over vertical ones
- no change of state of seawater: just form ice when T < -1.8ºC



**BUT**

- domain geometry is complex
- lateral boundary conditions are required and poorly constrained
- the eddies are smaller
- the spin-up time is longer
- there are fewer observations for validation




[courtesy of Maxim Nikurashin]

# Ocean Model Ingredients I

1. the primitive (hydrostatic) equations

$$\frac{d\vec{u}}{dt} + f\vec{k} \times \vec{u} = -\frac{\nabla P}{\rho} + \vec{F} + \nu \nabla^2 \vec{u}$$ Horizontal momentum

$$\frac{\partial P}{\partial z} = -g\rho$$ Hydrostatic balance

$$\frac{\partial \rho}{\partial t} + \vec{u}.\nabla_H \rho + w\frac{\partial \rho}{\partial z} + \rho\left(\nabla_H .\vec{u} + \frac{\partial w}{\partial z}\right) = 0$$ Conservation of mass

$$\frac{dT}{dt} = \kappa \nabla^2 T + Q_T$$ Conservation of heat

$$\frac{dS}{dt} = \kappa_S \nabla^2 S + Q_S$$ Conservation of salinity

$$\rho = \rho(P, S, T)$$ Nonlinear equation of state

= 7 coupled equations in 7 unknowns: u, v, w, P, T, S, ρ

[courtesy of Sonya Legg]

# Ocean Model Ingredients cont.

2. boundary conditions
   - basin geometry
   - bottom topography
   - an atmosphere on top, especially via:

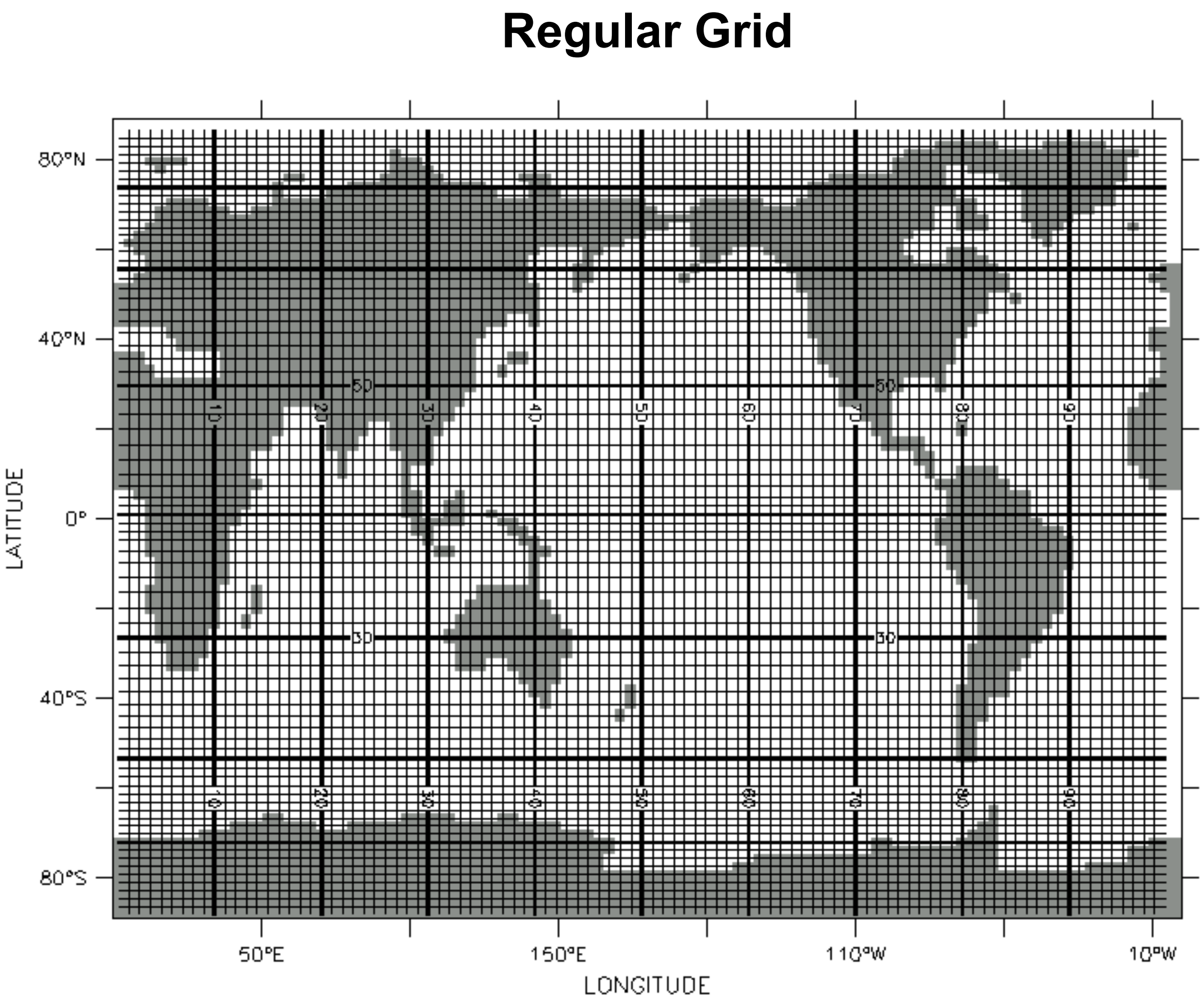
3. forcing fields
   - shortwave radiation, long-wave radiation, latent heat and sensible heat at the surface
   - evaporation and precipitation at the surface
   - land surface run-off at the margins
   - winds
   - tides

4. initial conditions (maybe from climatology i.e. the mean state or a previous already spun up model run)
   - initial temperature and salinity fields
   - initial velocity fields

# Ocean Model Practicalities I

## 1. the horizontal grid

- **regular grids** consist of regularly spaced lines
- on a spherical earth **CAN'T** have both uniform grid spacing **AND** straight lines
- in practice grids tend to be curvilinear and their internal spacing tends to vary
- regular lat-lon grids also have a problem at the poles where grid lines converge



# Ocean Model Practicalities I

## 1. the horizontal grid

- a cleaver solution: the **tripolar grid** = a circular grid laid over the Arctic polar region with two poles positioned over land

**Tri-polar Grid**

[Schopf 2005 after Murray 1996]

# Ocean Model Practicalities I

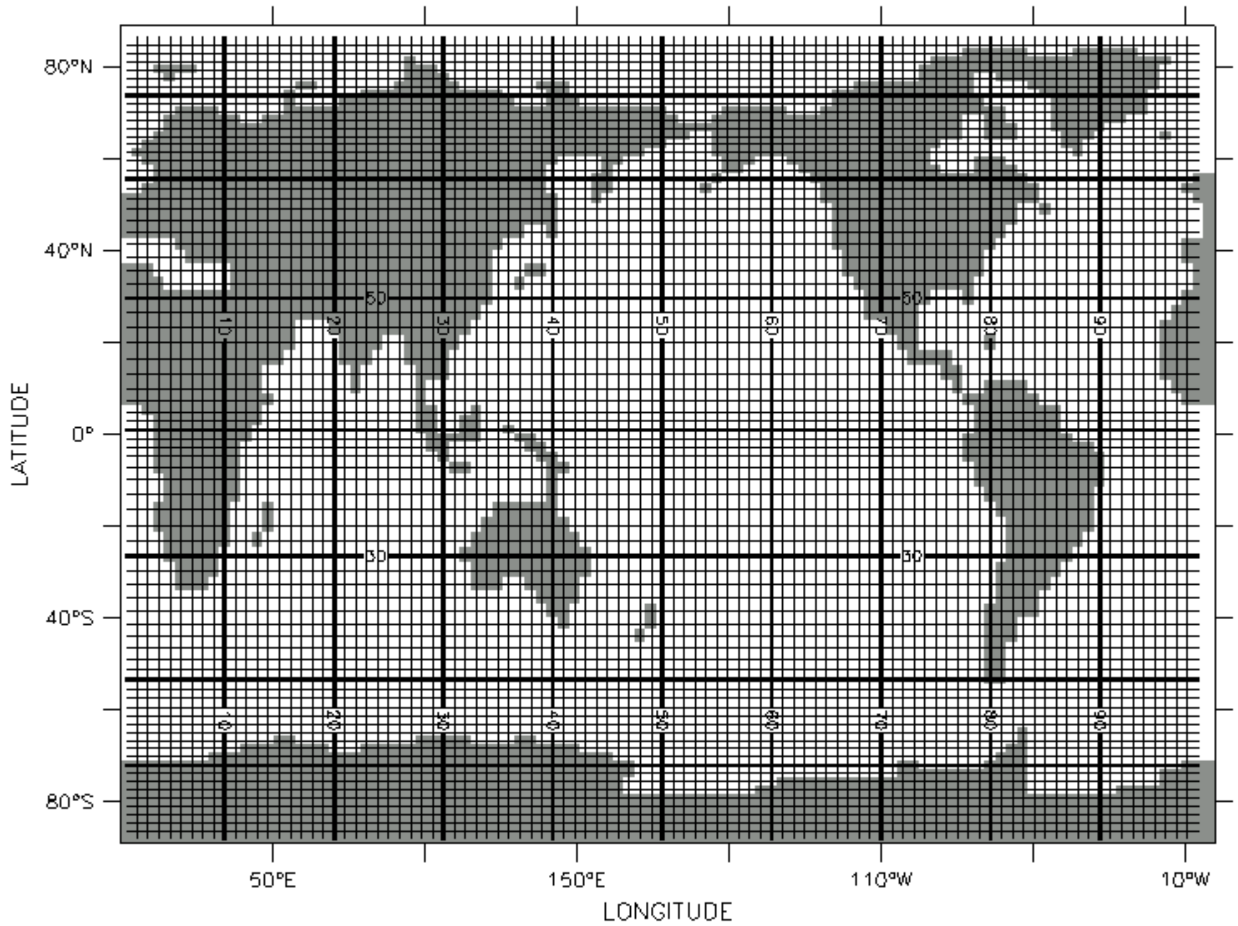
## 1. the horizontal grid

**regular grids:**

- are computationally efficient
- have (relatively) straightforward analysis algorithms
- have benefited from decades of research experience

**BUT**

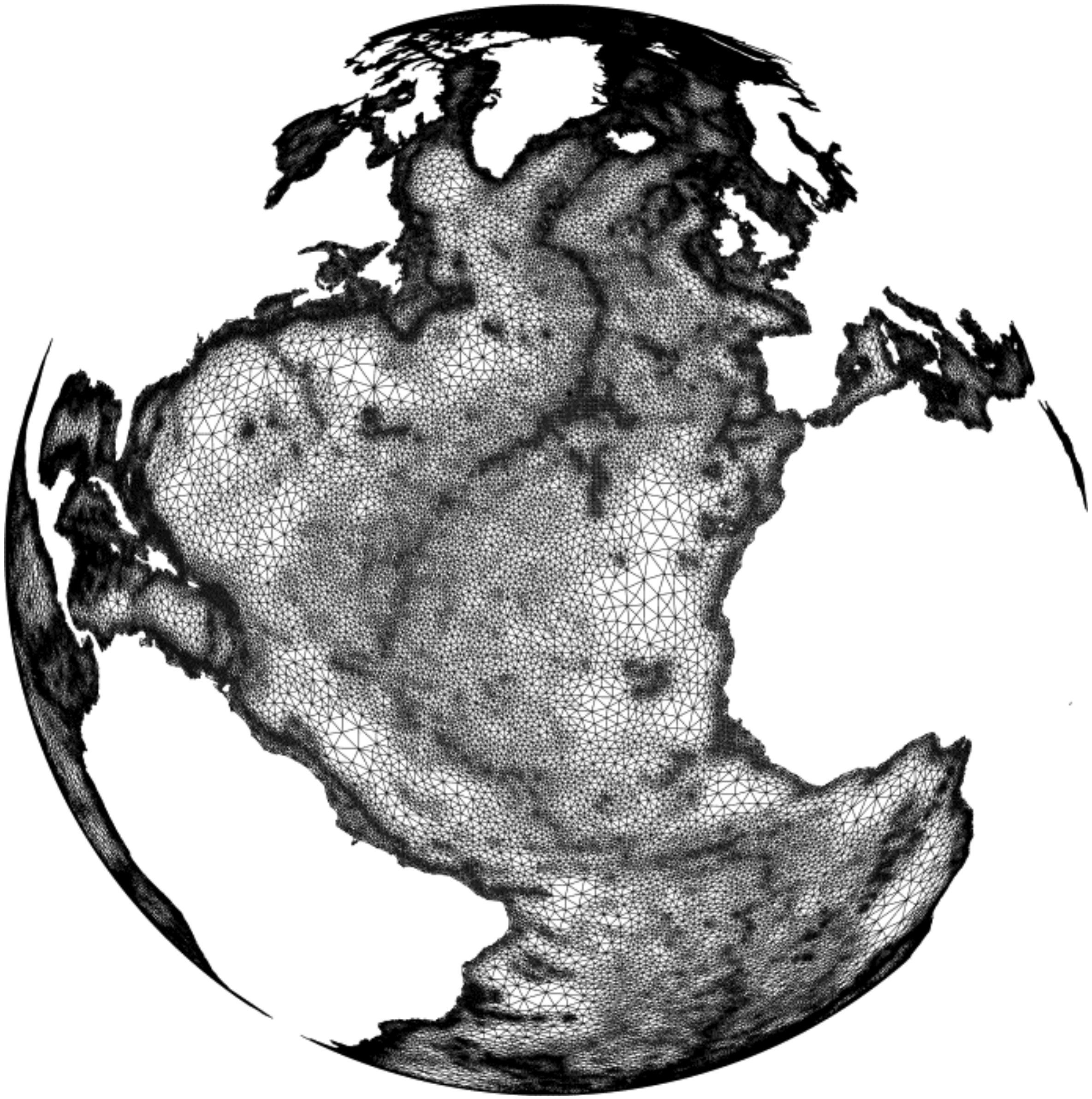
- (for a given latitude) have a fixed resolution: to increase resolution near the edge of an ocean basin (where you want it!) requires an increase of resolution everywhere including out in the middle of the ocean (where you don't!)



# Ocean Model Practicalities I

## 1. the horizontal grid

- **irregular grids** are designed to give you more freedom to put spatial resolution where you want it
- a common scheme is composed as a series of triangles = "**finite elements**"
- by varying the triangle size we can construct a non-uniform horizontal resolution over the computational domain



[Gorman et al, 2006]

# Ocean Model Practicalities I

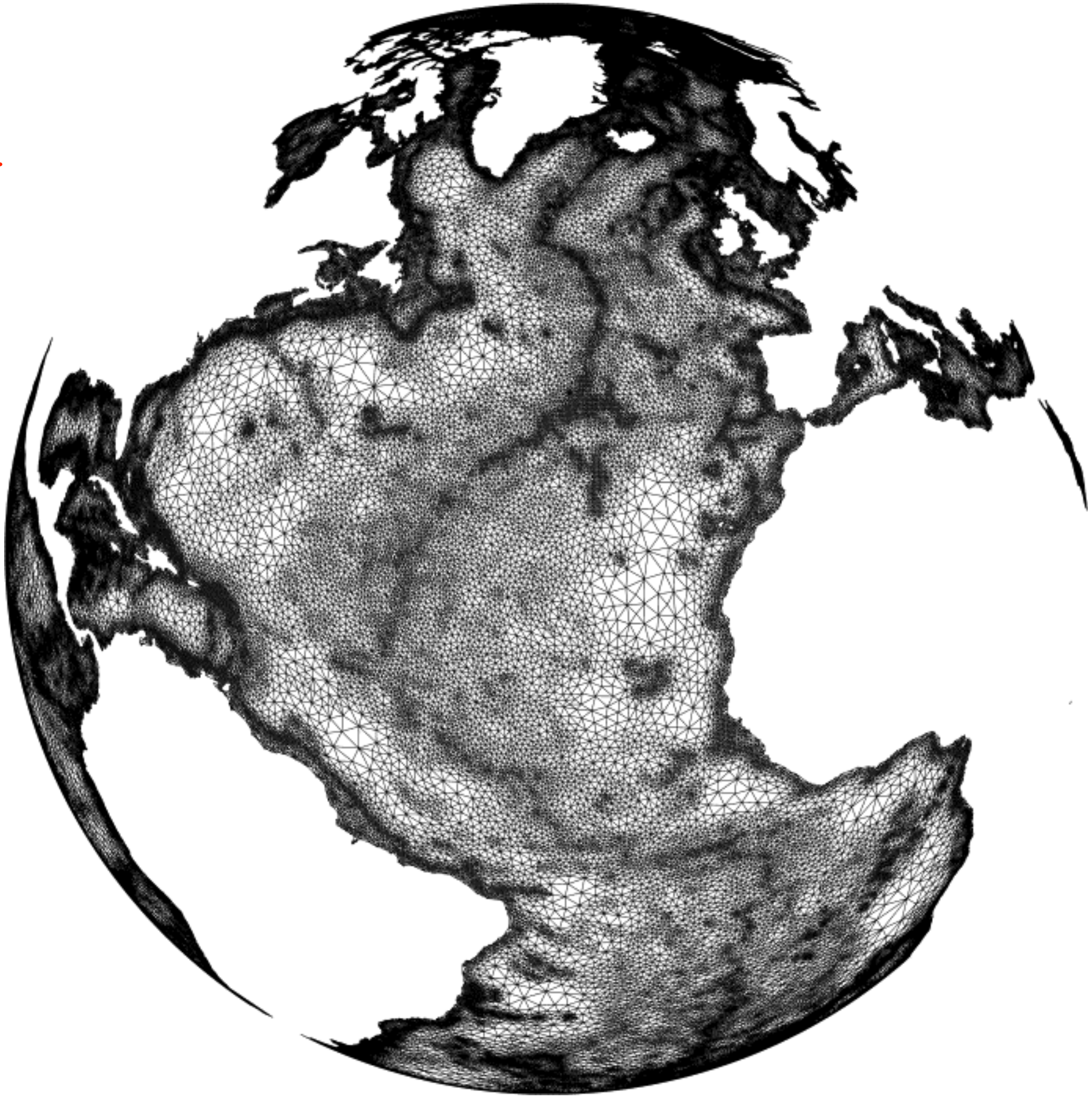
## 1. the horizontal grid

**irregular grids:**

- are efficient owing to the fact that resolution can be tailored to need as a function of space
- can accurately represent highly irregular coastlines and topography

**BUT**

- are complicated to configure
- have spatially variable resolution-dependent physics (e.g. viscosity and diffusivity coefficients)
- have spatially variable spurious diapycnal mixing
- tools to analyze are immature
- are computationally expensive

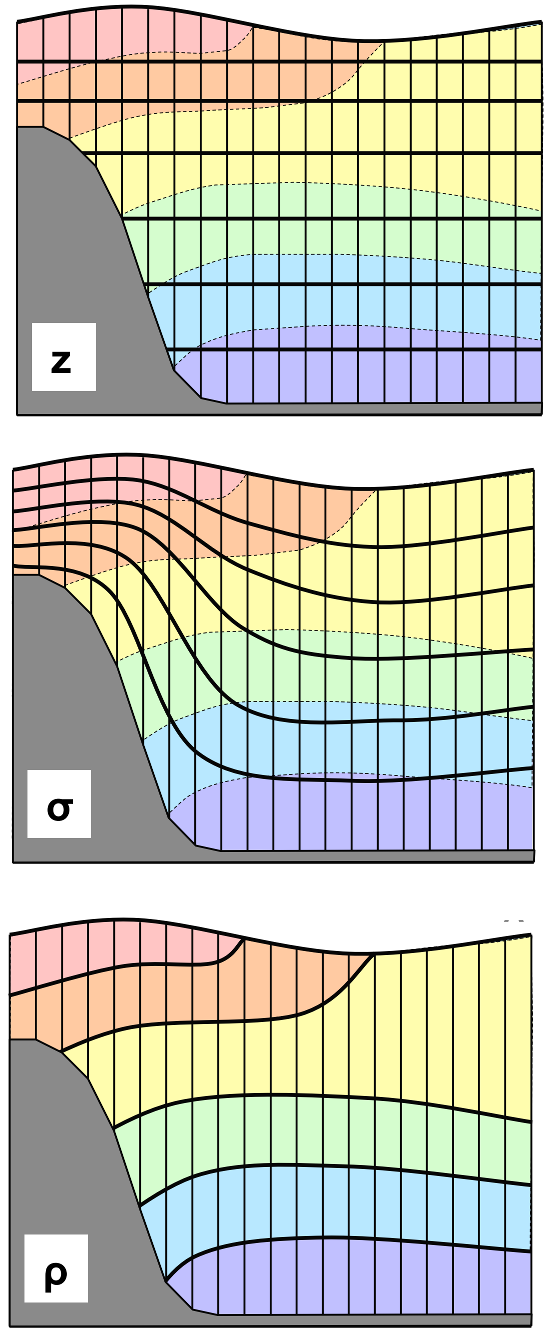


[Gorman et al, 2006]

# Ocean Model Practicalities II

## 2. the vertical grid

- the choice of the vertical co-ordinate system is loaded because:
  - the oceans are forced at the surface; most of the "action" occurs there
  - the oceans are strongly stratified
  - the oceans are ~ adiabatic in the interior
  - there is complex bottom bathymetry to deal with
- as a consequence there exist a number of approaches to choose from




[courtesy of Sonya Legg]

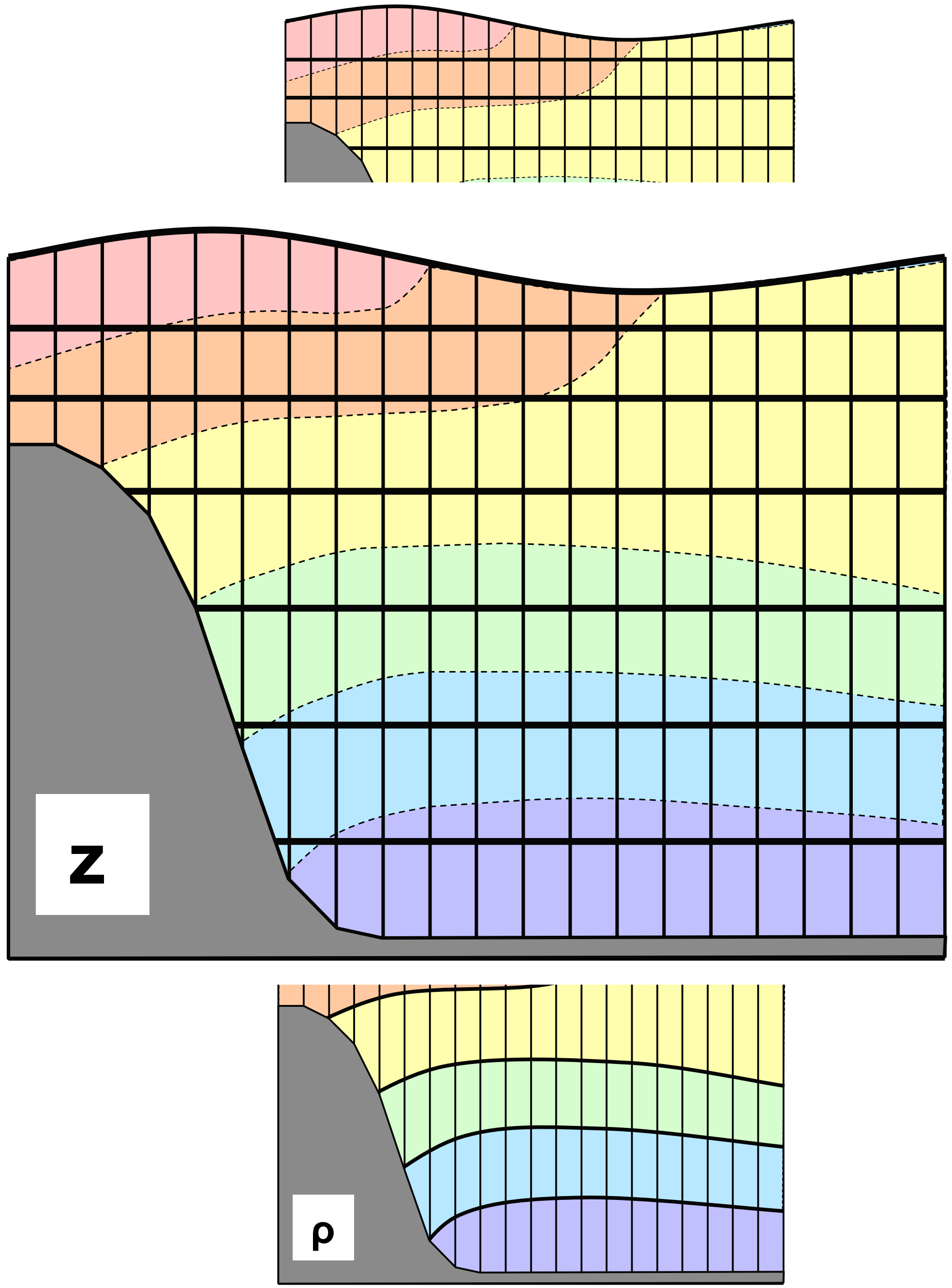
# Ocean Model Practicalities II

## 2. the vertical grid

### 1. absolute depth / z-coordinate system

- based on a series of depth levels
- common to add vertical resolution near the surface by decreasing the spacing between the levels in the upper ocean relative to the deep
- **ADVANTAGES:** simple to set up; computationally efficient; there are no pressure gradient errors
- **DISADVANTAGES:** increased vertical resolution near the lateral boundaries (i.e. on the continental slopes) requires the addition of grid cells throughout the basin; spurious diapycnal mixing associated with the numerical advection scheme

e.g. MOM5 (actually uses z*)




[courtesy of Sonya Legg]

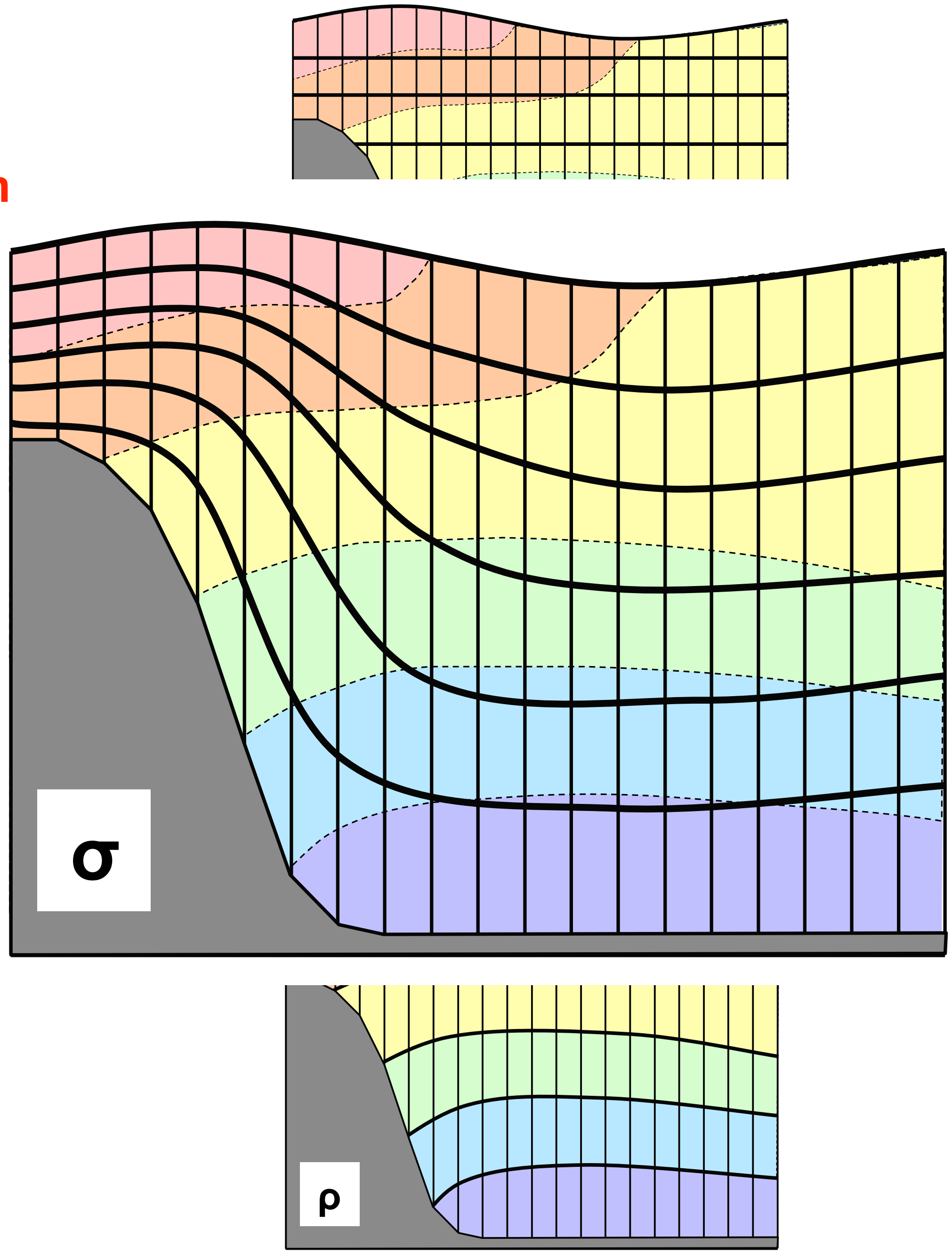
# Ocean Model Practicalities II

## 2. the vertical grid

### 2. “terrain following” / σ-coordinate system

- based on the fractional depth, scaled from 0 to 1:
  - 0.01σ level is 1% of the depth of the ocean
  - 0.5σ level is exactly half the depth of the ocean
  - 0.99σ level is at 99% of the depth of the ocean
- **ADVANTAGES:** mimics the bathymetry and allows high resolution near the sea floor regardless of depth or proximity to land
- **DISADVANTAGES:** pressure gradient errors; issues with spurious diapycnal mixing coming from the numerical advection scheme

e.g. ROMS, POM




[courtesy of Sonya Legg]

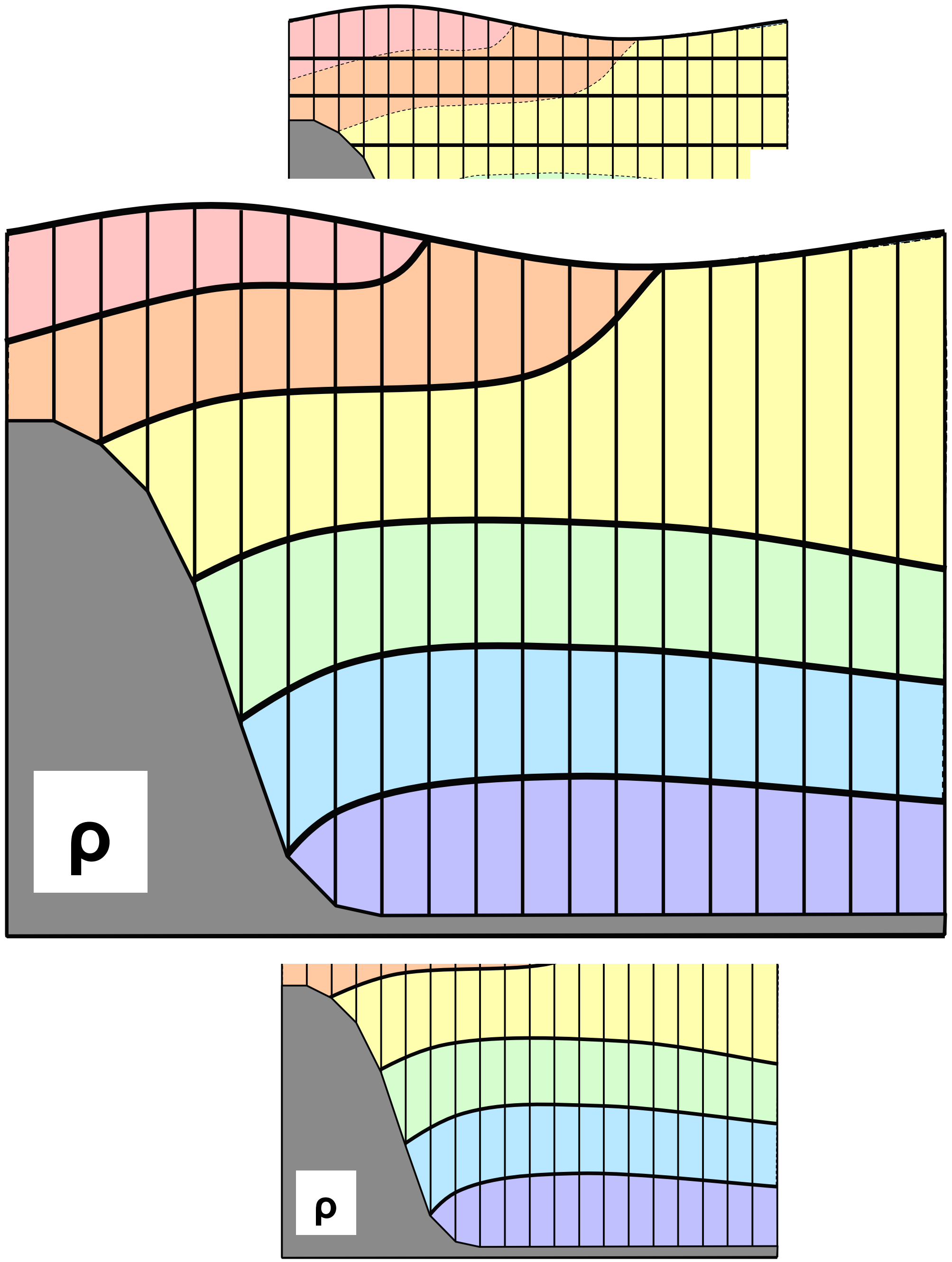
# Ocean Model Practicalities II

## 2. the vertical grid

**3. density (ρ) / "isopycnal" coordinate system ("layered models")**

- vertical grid defined by density surfaces
- exploits the fact that below the mixed layer, ocean currents generally flow along surfaces of equal density (flow is "adiabatic")
- **ADVANTAGES:** simple, "exactly isopycnal" (no spurious diapycnal mixing!)
- **DISADVANTAGES:** perform poorly where the ocean is less stratified (e.g. in shallow water); no resolution in an unstratified fluid; no mixed layer unless you tack one on; issues with entrainment

e.g. GOLD (precursor to MOM6)




[courtesy of Sonya Legg]

# Ocean Model Practicalities II

## 2. the vertical grid

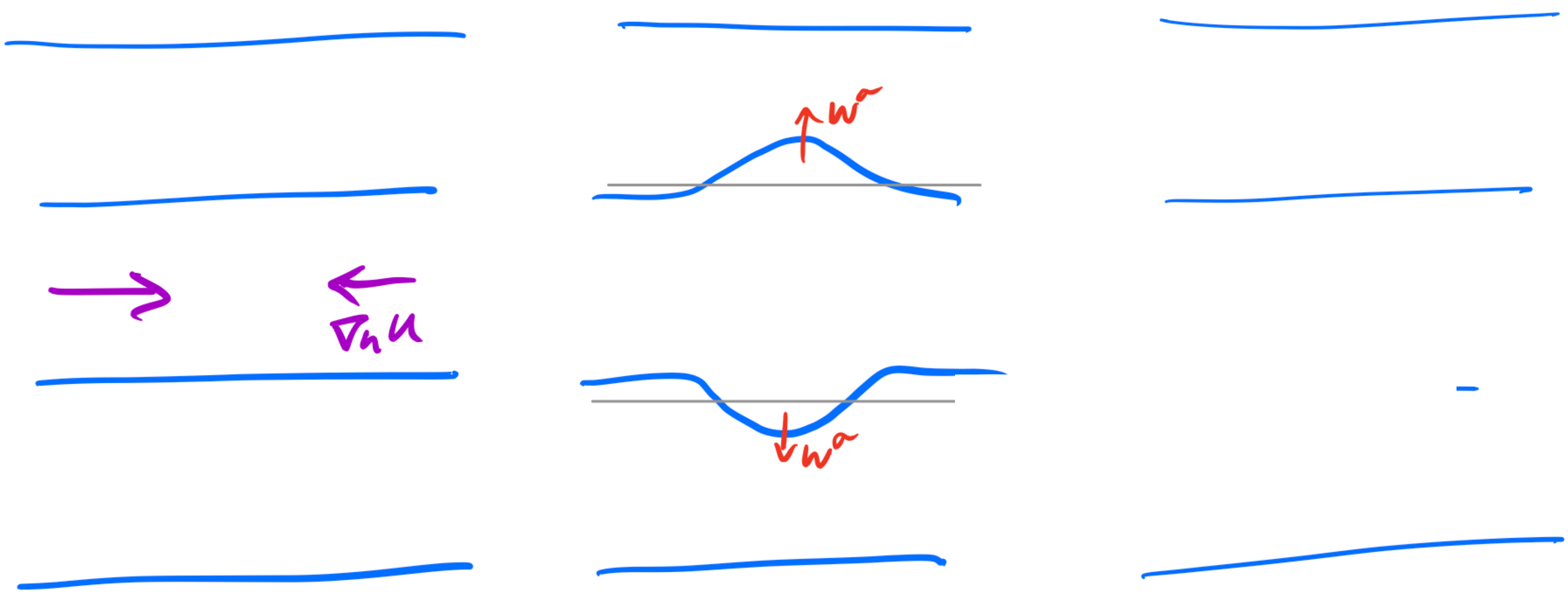
**4. Arbitrary Lagrangian-Eulerian**

- Configurable hybrid system
- Can use z near surface, terrain-following near bottom and isopycnal interior

**ADVANTAGE**: dynamically optimized coordinate system gives improved results;

**DISADVANTAGE**: it's new!!

e.g. MOM6

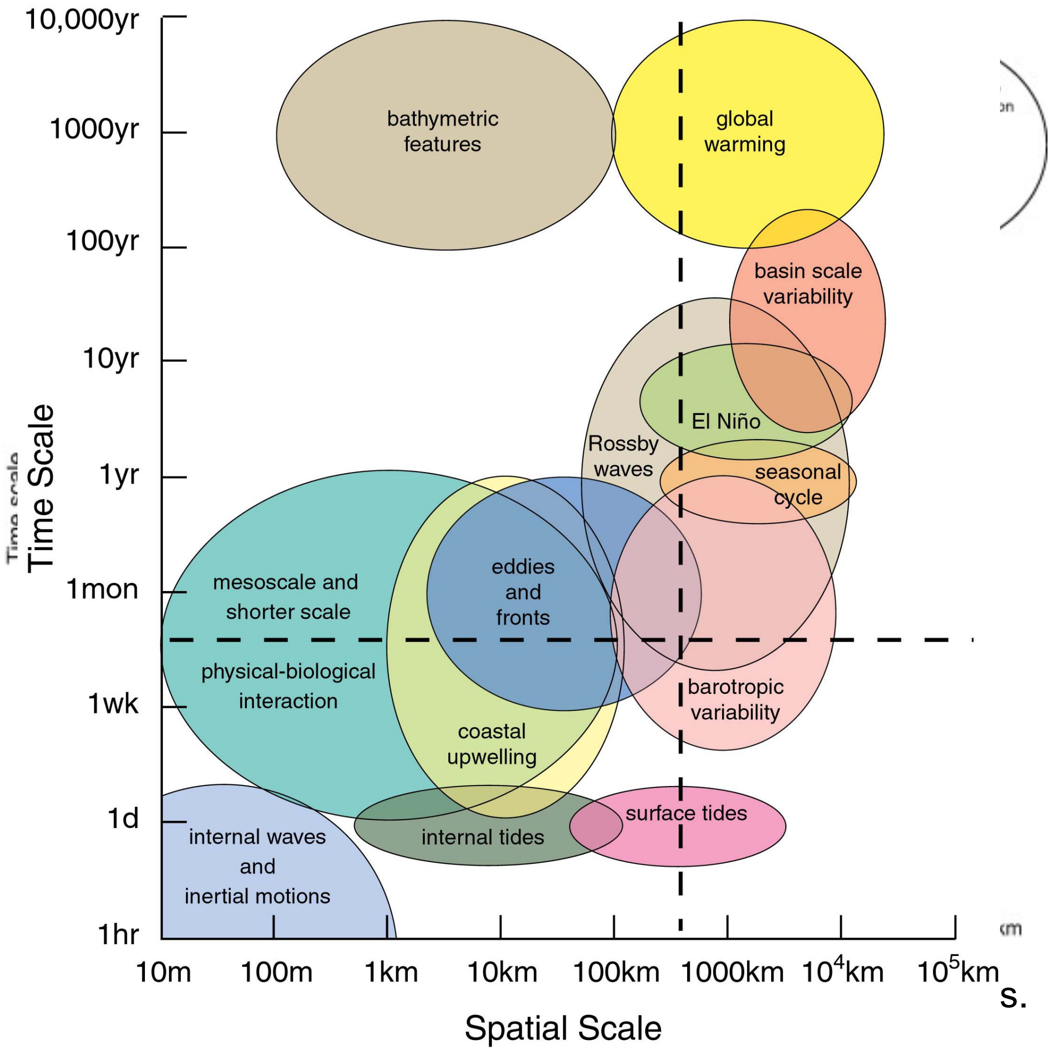


# Ocean Model Practicalities III

## 3. model resolution

**What are we trying to resolve?!?**

- like the atmosphere the ocean has "**multiple scale variability**" = a broadband of time and length scales that are important/on which motions exhibit variation
- further, processes include coupling across scales ("non-local interactions") and these scale interactions can have important effects
- the range of important time and space scales is immense: molecular (mm and seconds) to basin scale (10 000 km and 1000 years)
- multiple scale variability and scale interactions make ocean dynamics fascinating but very challenging to model!

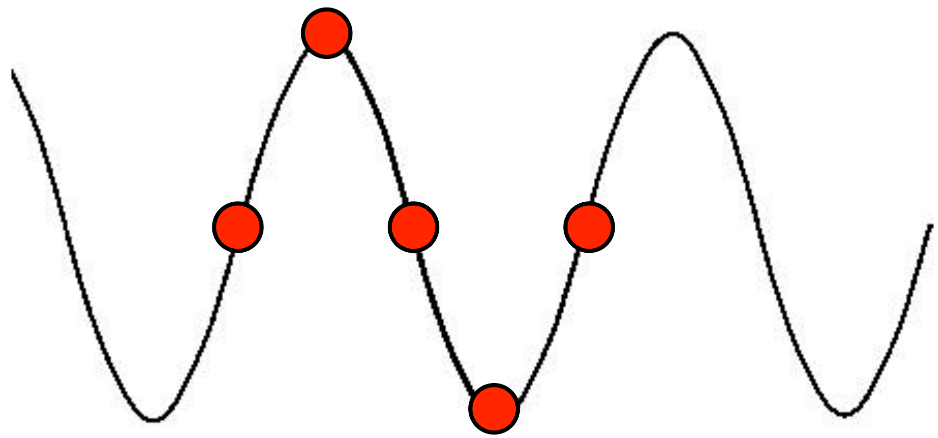



[adapted from: Chelton (ed) 2001 and Dickey and Chang 2001]

# Ocean Model Practicalities III

## 3. model resolution

- general principles of resolution are the same for both atmospheric and ocean models
- there are different rules of thumb: one is that it takes 5 grid points to accurately define a feature without aliasing
- this means **1/8°** global resolution with an average horizontal grid cell of **14 km** can accurately depict only features larger than **56 km**
- models with variable grid spacing have variable resolution - beware of resolution-dependent physics!
- resolution is not cheap - because of the CFL* condition, as we shrink the horizontal grid spacing we must add vertical layers and decrease the time step



*"every halving of the grid spacing requires roughly ten times as many computations"*

* no transport faster than one grid cell per time step!

# Ocean Model Practicalities III

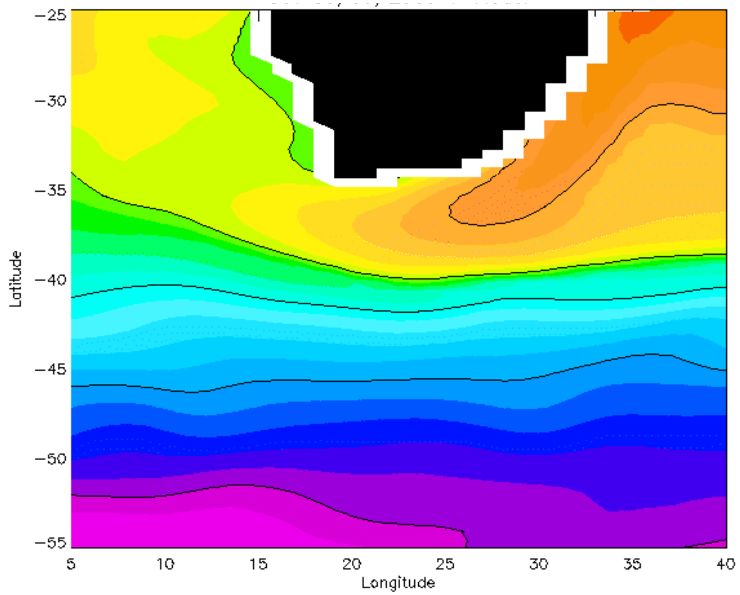
## 3. model resolution

- global ocean models often describe their horizontal resolution with respect to their ability to "**permit**" or "**resolve**" mesoscale (i.e. Rossby radius scale) eddies

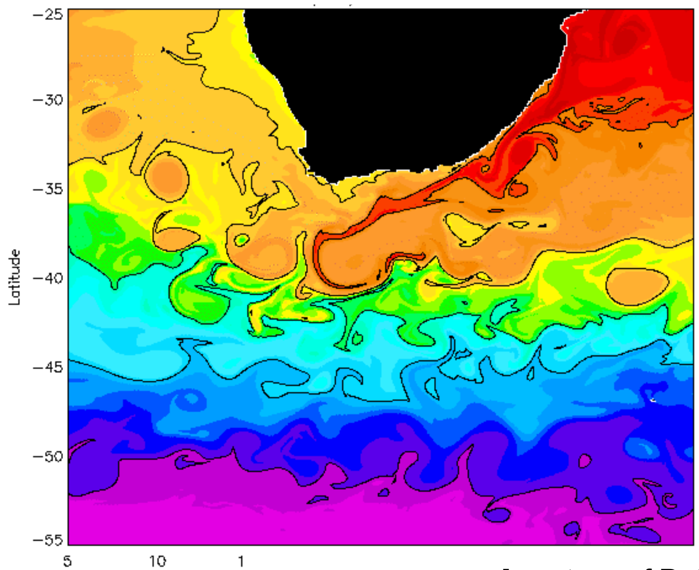
| resolution | lingo | meaning |
|---|---|---|
| ≥ 1° | "coarse" | no eddies |
| ~ 0.5° | "eddy-permitting" | some eddies |
| ≤ 0.2° | "eddy-rich" | eddies generate at realistic strength and rate |

- "**eddy rich**" does **NOT** mean all eddies are resolved or that all eddy effects of resolved eddies are acting !!!
- the spatial resolution of the ocean component of CMIP5 coupled models is 0.2° to 2°: from "coarse" (no eddies) to "eddy-permitting" (partially resolved eddy field)
- the effects of eddies need to be parameterized in coarse models (more later!); what to do in models that partially resolve the eddy field is an increasingly important question

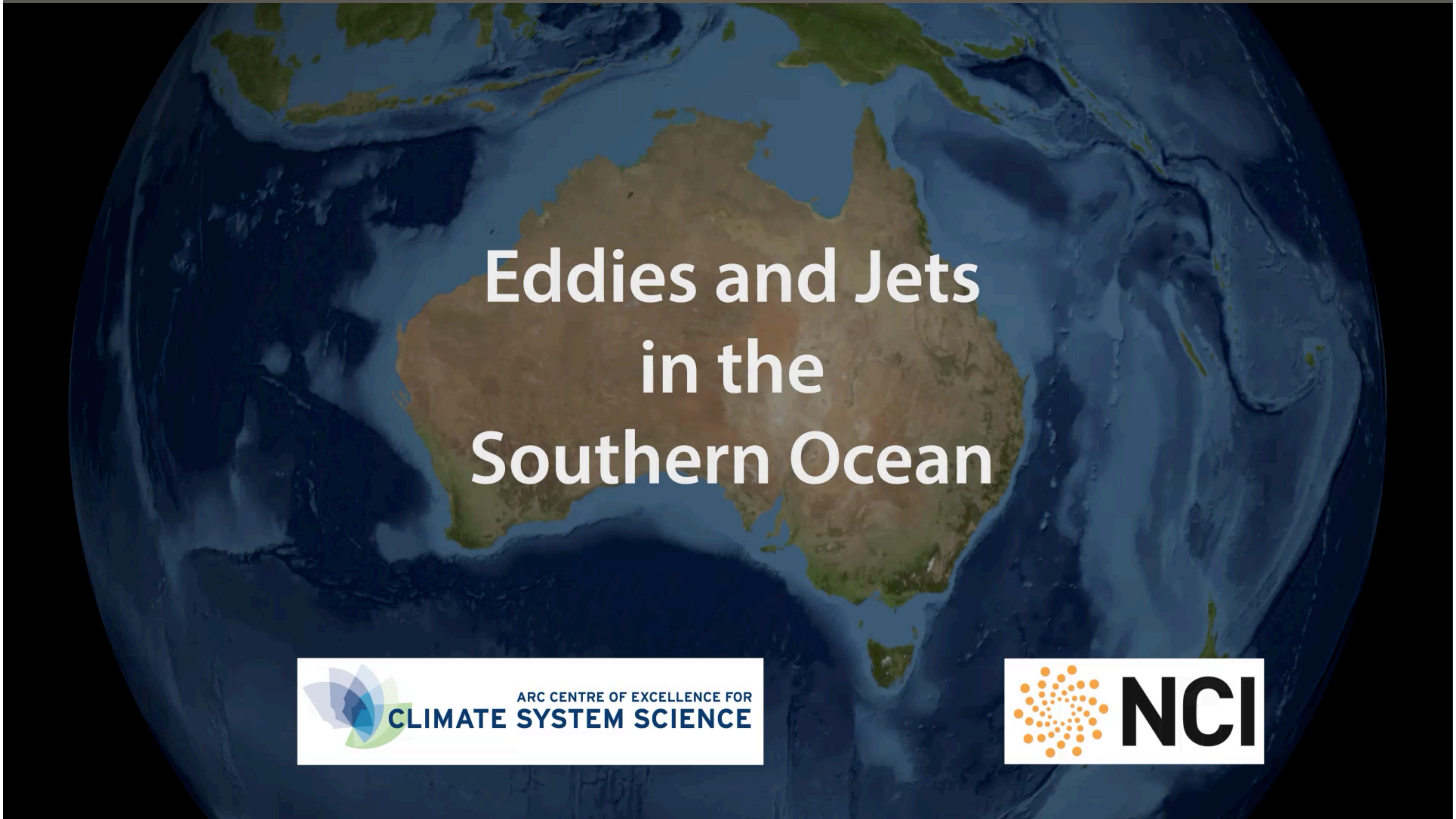
**1° "coarse resolution" model**




**0.1° "eddy-resolving" model**




[courtesy of Peter Gent]


Eddies and Jets
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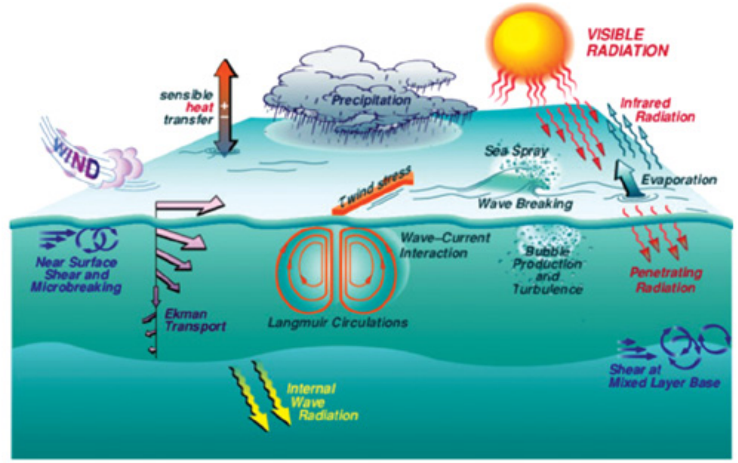
# Ocean Model Practicalities IV

## 4. parameterizations

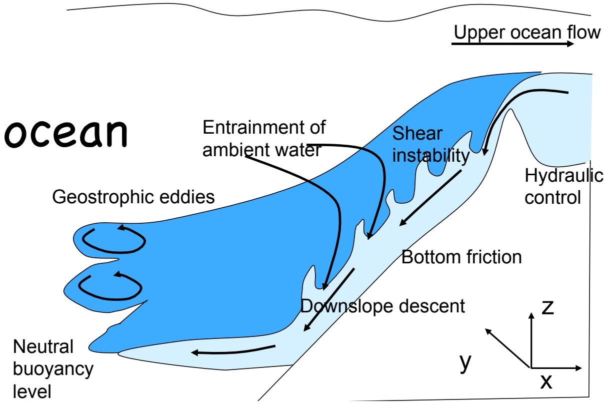
- processes need to be parameterized in a model for **2** main reasons:
  1. we won't spend the computational resources required to directly treat them because they are either too small or too complex;
  2. we don't understand it well enough to be represented by an equation

- processes commonly parameterized in ocean models include:
  - mesoscale eddy effects
  - submesoscale eddy effects
  - dense overflows
  - coastal processes
  - surface mixed layer processes
  - friction
  - sub-grid scale mixing
  - ocean-ice interactions

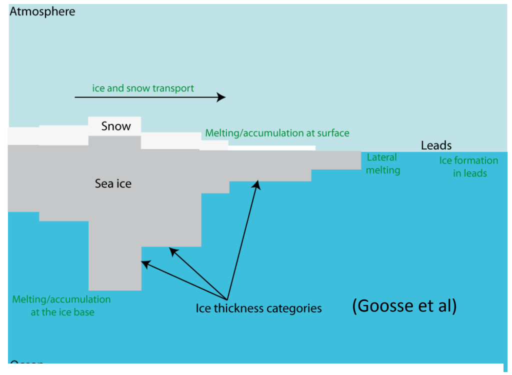
- low res models: the main problem is mesoscale eddies; high res models: submesoscale eddies (fronts and filaments), internal wave mixing, details of flow-topography interactions



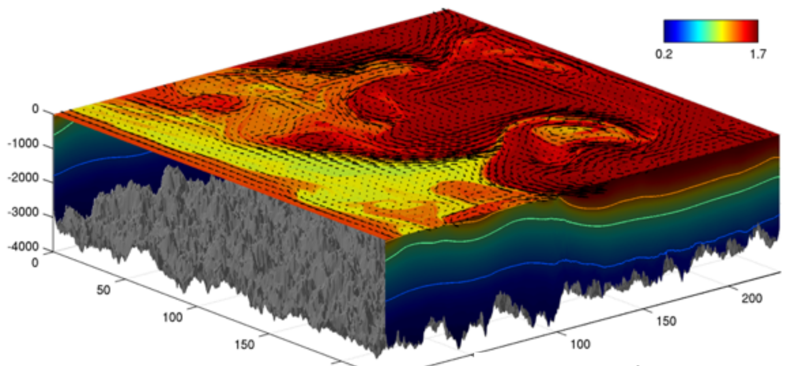

[courtesy of Bob Weller]




[courtesy of Sonya Legg]




[Goosse et al.]




[courtesy of Max Nikurahsin]

# Ocean Model Practicalities IV

## 4. parameterizations

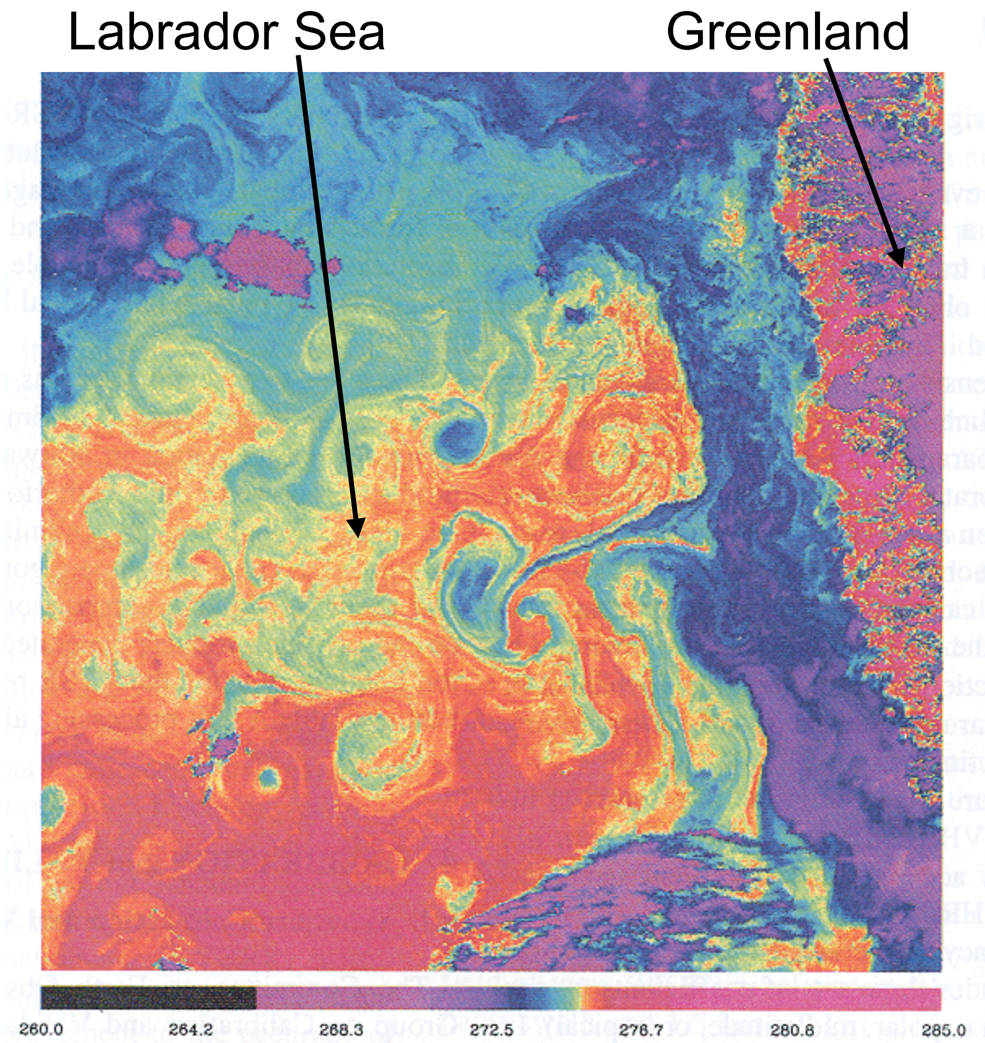
### 1. parameterizing mesoscale eddy effects:

- mesoscale eddy effects include:
  - mixing along isopycnals
  - restratifying / flattening isopycnals
  - non-local fluxes: transport by rings, Meddies
  - acting as a source of small scale noise/ variability
  - modifying air-sea fluxes
  - cascading energy to different scales
  - ...

- **critical** eddy parameterizations in coarse-resolution models are:

  1. **Along-isopycnal diffusion** (Redi)

  2. **Bolus transport** (Gent and McWilliams or "GM")




Sea surface temperature showing the eddy field in the Labrador Sea.

[Jourdain et al. 2008]

# Ocean Model Practicalities IV

## 4. parameterizations

**1. parameterizing mesoscale eddy effects:**

- mesoscale eddy effects include:
  - **mixing along isopycnals**
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  - non-local fluxes: transport by rings, Meddies
  - are a source of small scale noise/variability
  - modify air-sea fluxes
  - cascade energy to different scales
  - …

- **critical** eddy parameterizations in coarse-resolution models are:

  1. **Along-isopycnal diffusion** (Redi)

  = mixing of tracers (temperature, salinity *etc.*) along density surfaces

  2. **Bolus transport** (Gent and McWilliams or "GM")

$$-\nabla.\langle \vec{u}'\tau' \rangle = \nabla.\kappa_\rho \underline{\underline{K_{Redi}}} \nabla\tau$$

- $-\nabla.\langle \vec{u}'\tau' \rangle$: end result of mixing by eddies along density surfaces
- $\kappa_\rho$: isopycnal diffusivity
- $\nabla\tau$: large-scale (**resolved**) tracer gradient

where

$$\underline{\underline{K_{Redi}}} = \begin{pmatrix} 1 & 0 & S_x \\ 0 & 1 & S_y \\ S_x & S_y & |S|^2 \end{pmatrix}$$

- $\underline{\underline{K_{Redi}}}$: eddy diffusivity
- $S_x$, $S_y$: components of the (**resolved**) isopycnal slope

[see Redi, 1982]

[courtesy of Sonya Legg]

# Ocean Model Practicalities IV

## 4. parameterizations

### 1. parameterizing mesoscale eddy effects:

- mesoscale eddy effects include:
  - mixing along isopycnals
  - **restratifying / flattening isopycnals**
  - non-local fluxes: transport by rings, Meddies
  - are a source of small scale noise/variability
  - modify air-sea fluxes
  - cascade energy to different scales
  - ...

- **critical** eddy parameterizations in coarse-resolution models are:

  1. Along-isopycnal diffusion (Redi)

  2. **Bolus transport (Gent and McWilliams or "GM")**

  = represents the advective or transport effect of eddies by means of a "bolus" velocity

  - mixes "isopycnal thickness" to flatten density surfaces without mixing density (to mimic baroclinic instability)

$$-\nabla.\langle \vec{u}'\tau' \rangle = -\nabla.\langle \tau \rangle \vec{u}\,^*$$

end result of mixing by the "advective" effect of eddies

$$\vec{u}^* = \begin{pmatrix} u^* \\ v^* \\ w^* \end{pmatrix} = \begin{pmatrix} -\partial_z(\kappa_{GM} S_x) \\ -\partial_z(\kappa_{GM} S_y) \\ \partial_x(\kappa_{GM} S_x) + \partial_y(\kappa_{GM} S_y) \end{pmatrix}$$

"bolus velocity"

"GM eddy diffusivity"

components of the **(resolved)** isopycnal slope

$$\underline{\underline{K_{GM}}} = \begin{pmatrix} 0 & 0 & -S_x \\ 0 & 0 & -S_y \\ S_x & S_y & 0 \end{pmatrix}$$

[see Gent and McWilliams, 1990]

[courtesy of Sonya Legg]

# Ocean Model Practicalities IV

## 4. parameterizations

### 2. vertical mixing schemes

- when the ocean becomes statically unstable ($\rho_z > 0$ ) vertical over-turning should occur but cannot because we make the hydrostatic approximation (vertical acceleration is excluded!)
- so vertical mixing must be accomplished via a very large coefficient of vertical diffusion
- many models use the **K-Profile Parameterization** (Large et al., 1994)

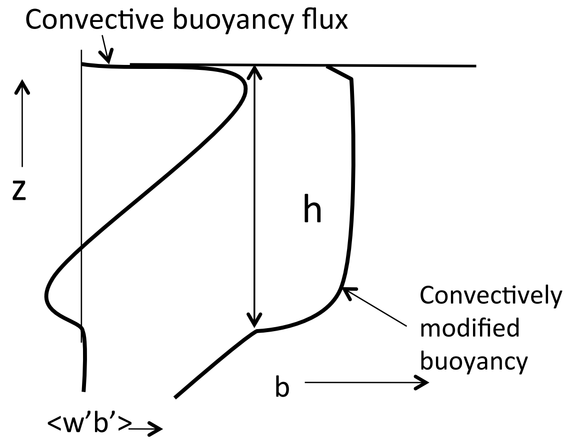
= large mixing in the upper ocean due to many processes (but dominated by wind) and very much weaker mixing in the deep ocean due to internal wave breaking and tides

$$\langle w'\tau'\rangle(d) = -\kappa_\tau\left(\frac{\partial\langle\tau\rangle}{\partial z} - \gamma_\tau\right)$$

end result of vertical mixing by eddies; eddy diffusivity; down-gradient diffusion; non local flux

$$\kappa_\tau\left(\frac{d}{h}\right) = hw_\tau\left(\frac{d}{h}\right)G\left(\frac{d}{h}\right)$$

mixed layer depth; vertical velocity scale; non-dimensional shape function




[courtesy of Sonya Legg]

# Ocean Models: The Future

**"The ideal ocean climate model has high enough resolution to resolve eddies and topography, zero numerical diffusion and is efficient enough to integrate for 1000s of years."**

## your challenges to solve:

- model biases and model drift
- projections of sea-level rise: most current GCMs are Boussinesq and must calculate the steric contribution to sea-level rise a-posteriori
- the realistic representation of mixing: how much, where? why?
- spurious mixing: models are too diffusive; in z-coordinate resolution models numerical mixing depends on resolution
- overflows
- getting the energy out of the mesoscale eddy field
- sub-mesoscale effects/parameterization
- mixed layer depth and dynamics
- effects of the internal wave field
- parameterizations for partially resolved eddy fields; resolution-dependent parameterizations
- ICE: dynamic ice-sheets and ice shelves, iceberg transport (lack of leads to cold-fresh bias around Antarctica!)
- ...

# Want to know more?


- MIT Open Courseware: "12.984 Atmospheric and Oceanic Modeling"
  http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-950-atmospheric-and-oceanic-modeling-spring-2004/index.htm
- Griffies, S M, 2004: Fundamentals of Ocean Climate Models, Princeton, NJ: Princeton University Press, 518 pp.
- Griffies, S M, C Böning, F O Bryan, E P Chassignet, R Gerdes, H Hasumi, A C Hirst, A M Treguier, and D Webb, 2000: Developments in ocean climate modelling. Ocean Modelling, 2, 123-192.
- Griffies, S M, and A Adcroft, 2008: "Formulating the equations of ocean models" In Ocean Modeling in an Eddying Regime, Geophysical Monograph 177, M. W. Hecht, and H. Hasumi, eds., Washington, DC, American Geophysical Union, 281-318.
- Griffies, S M, 2009: "Science of ocean climate models" In Encyclopedia of Ocean Sciences, 2nd edition, Elsevier, DOI: 10.1016/B978-012374473-9.00714-1.
- Griffies, S M, A Adcroft, A Gnanadesikan, R W Hallberg, M J Harrison, S Legg, C M Little, M Nikurashin, A Pirani, B L Samuels, J R Toggweiler, and G K Vallis, et al., 2010: Problems and prospects in large-scale ocean circulation models In Ocean Obs '09, 21-25 September, Venice, Italy, ESA Special Publication, DOI: 10.5270/OceanObs09.cwp.38.