An introduction to good old fashioned **Ocean Modelling**

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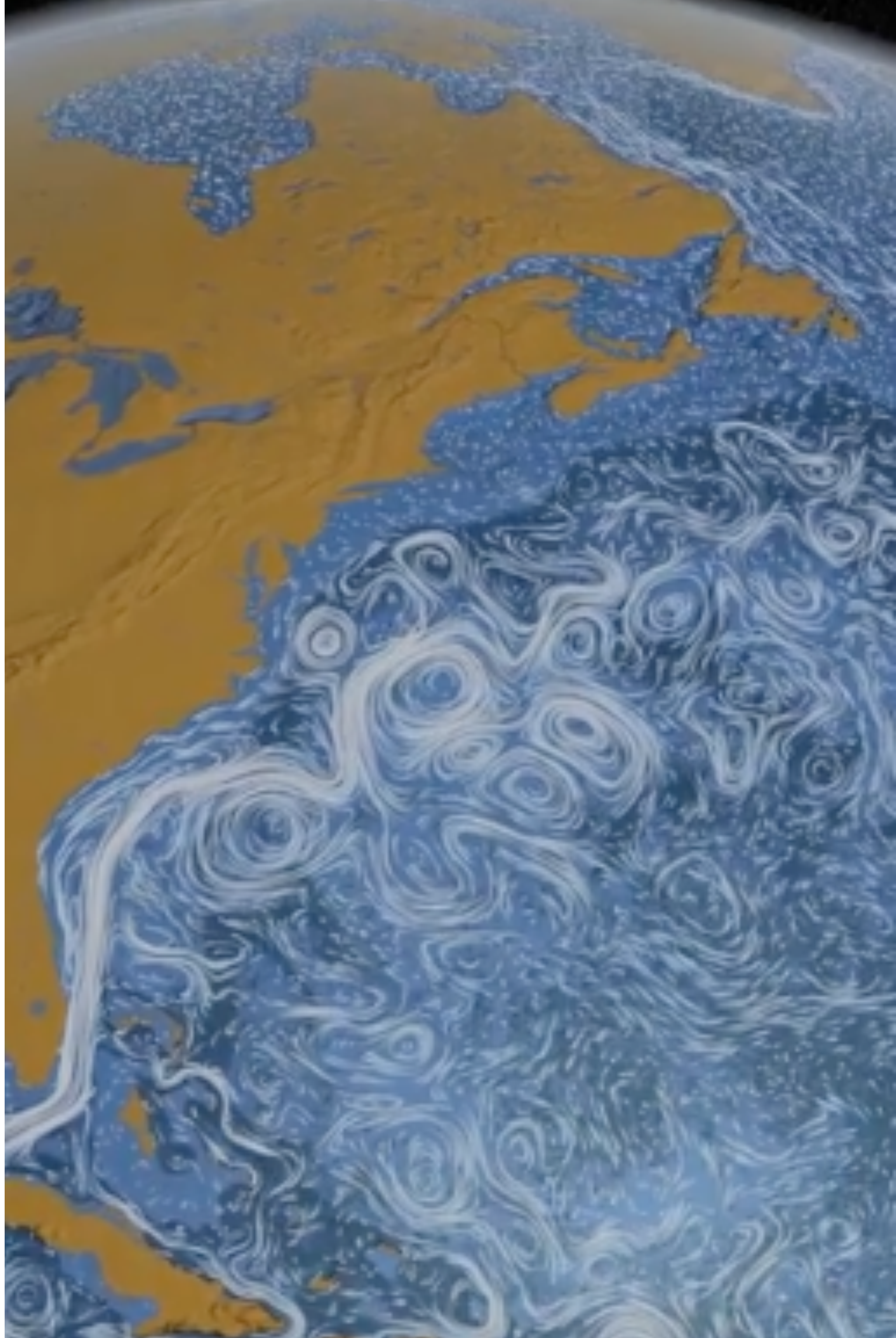
Slides based partly on material from Prof Arne Biastoch (GEOMAR - Kiel)

Utrecht University

Institute for Marine and Atmospheric research Utrecht



My own journey around the oceans

Utrecht University

BSc/MSc in (Climate) Physics (1999-2005)

PhD in physical oceanography (2005-2009): "*Assessing Agulhas leakage*"

UNIVERSITY OF MIAMI

Postdoc (2009-2011)

UNSW SYDNEY

Fellowship (2011-2015)

Imperial College London

Assistant professor (2015-2017)

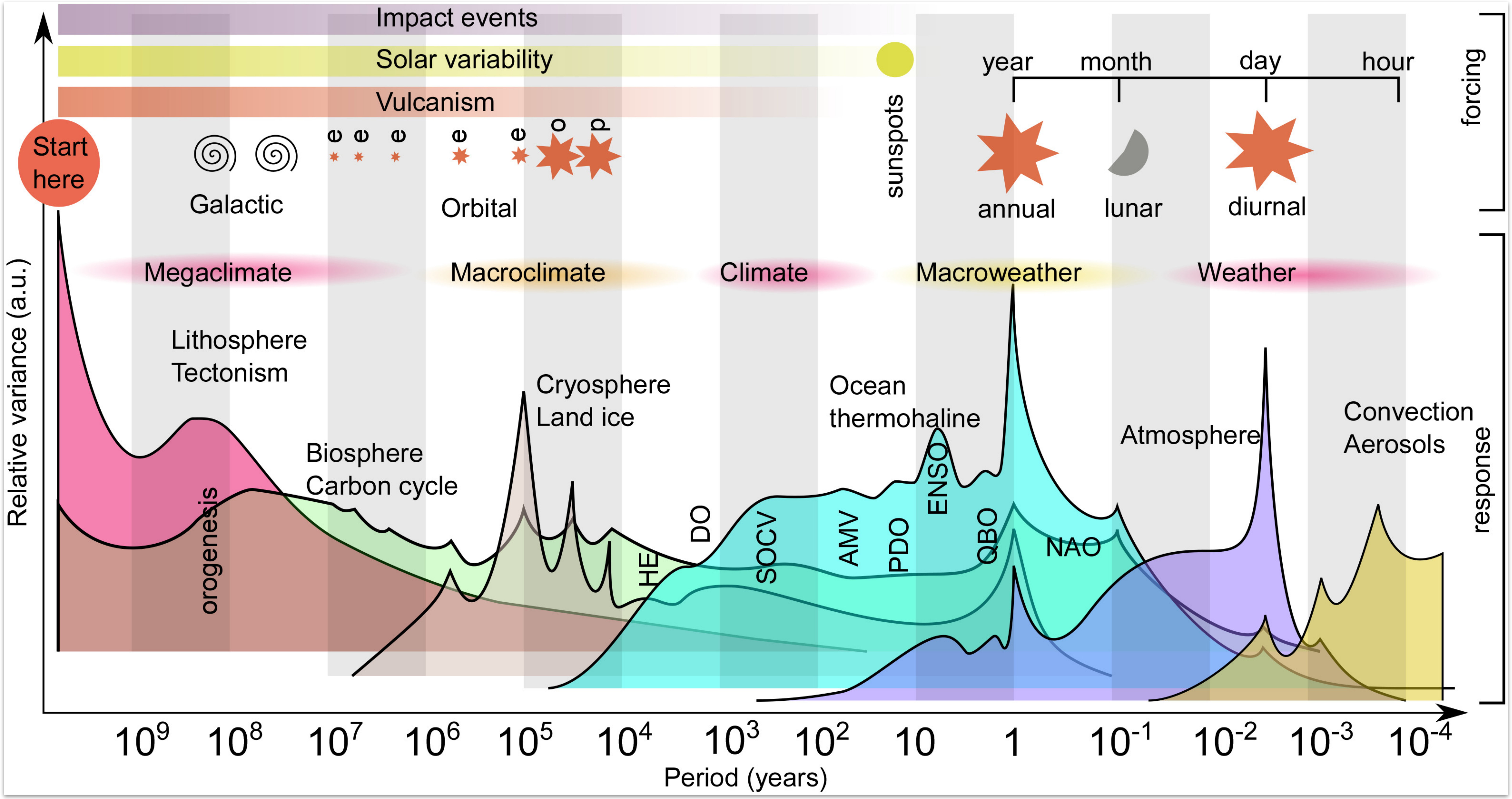
Utrecht University

Associate professor (2017-2021)

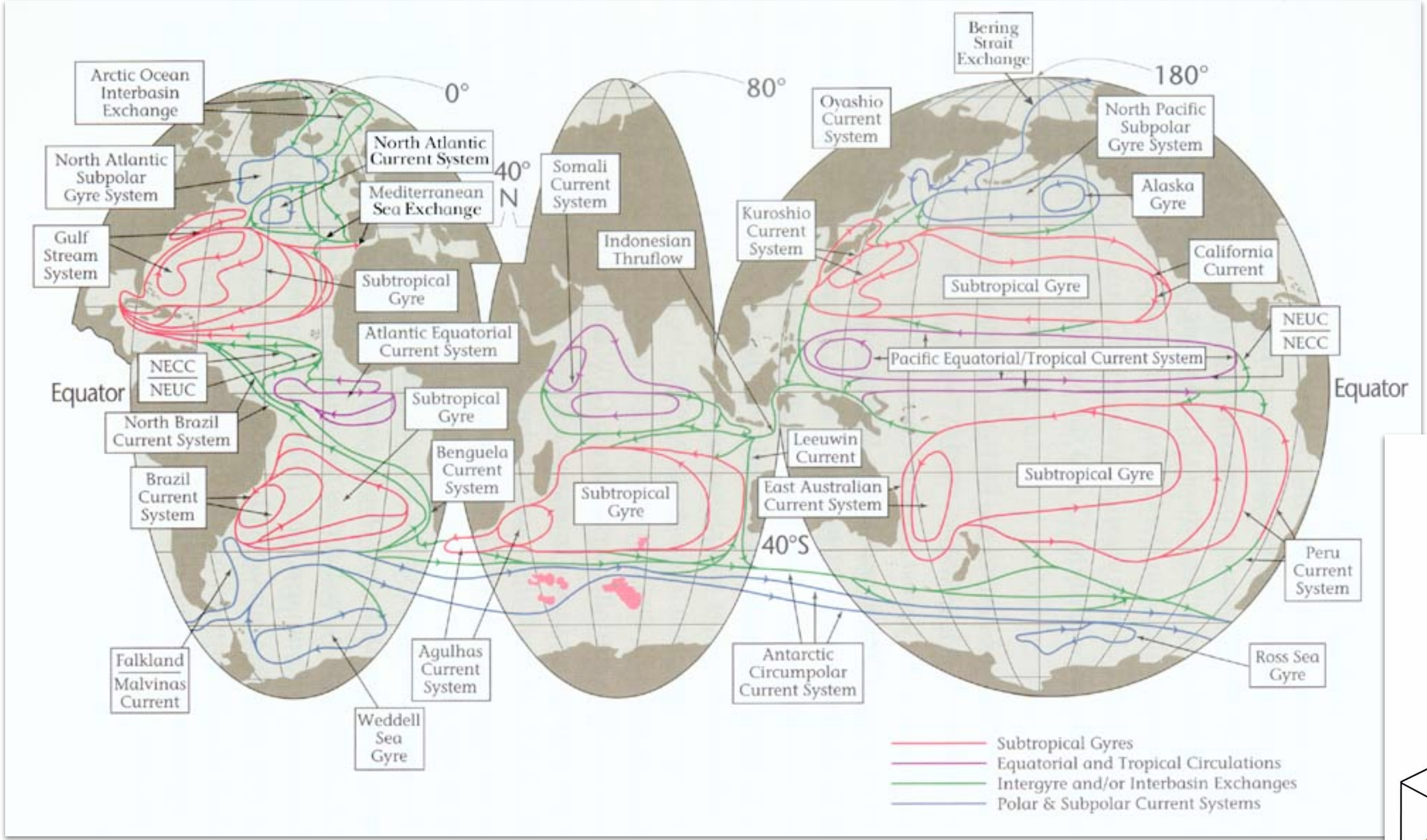
Full professor (2021-now)

Van der Heydt *et al* (2021) *Global and Planetary Change*

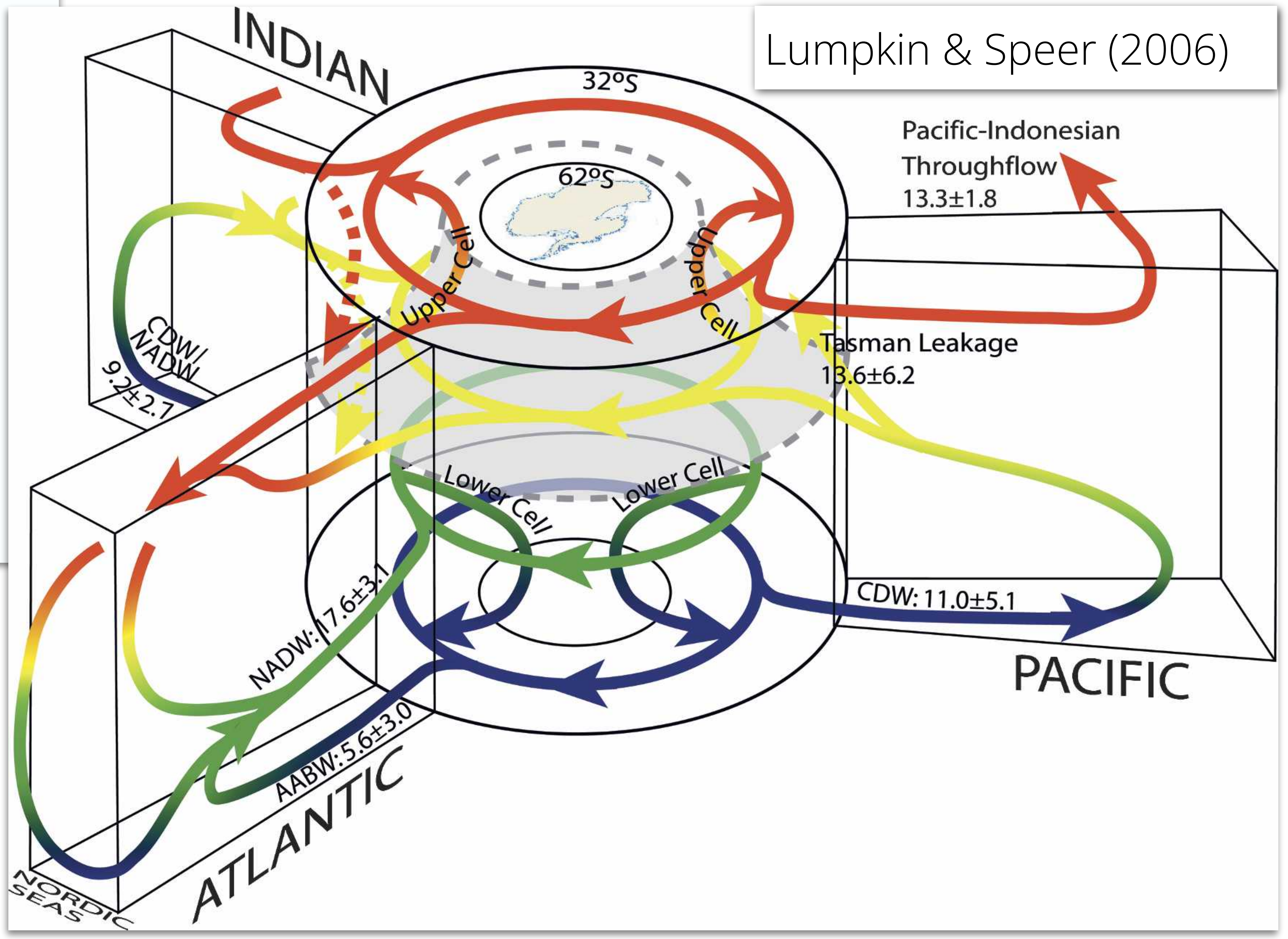
Why care about the ocean?



Cartoons of the ocean circulation



After Schmitz (1995) *Reviews in Geophysics*



Lumpkin & Speer (2006)

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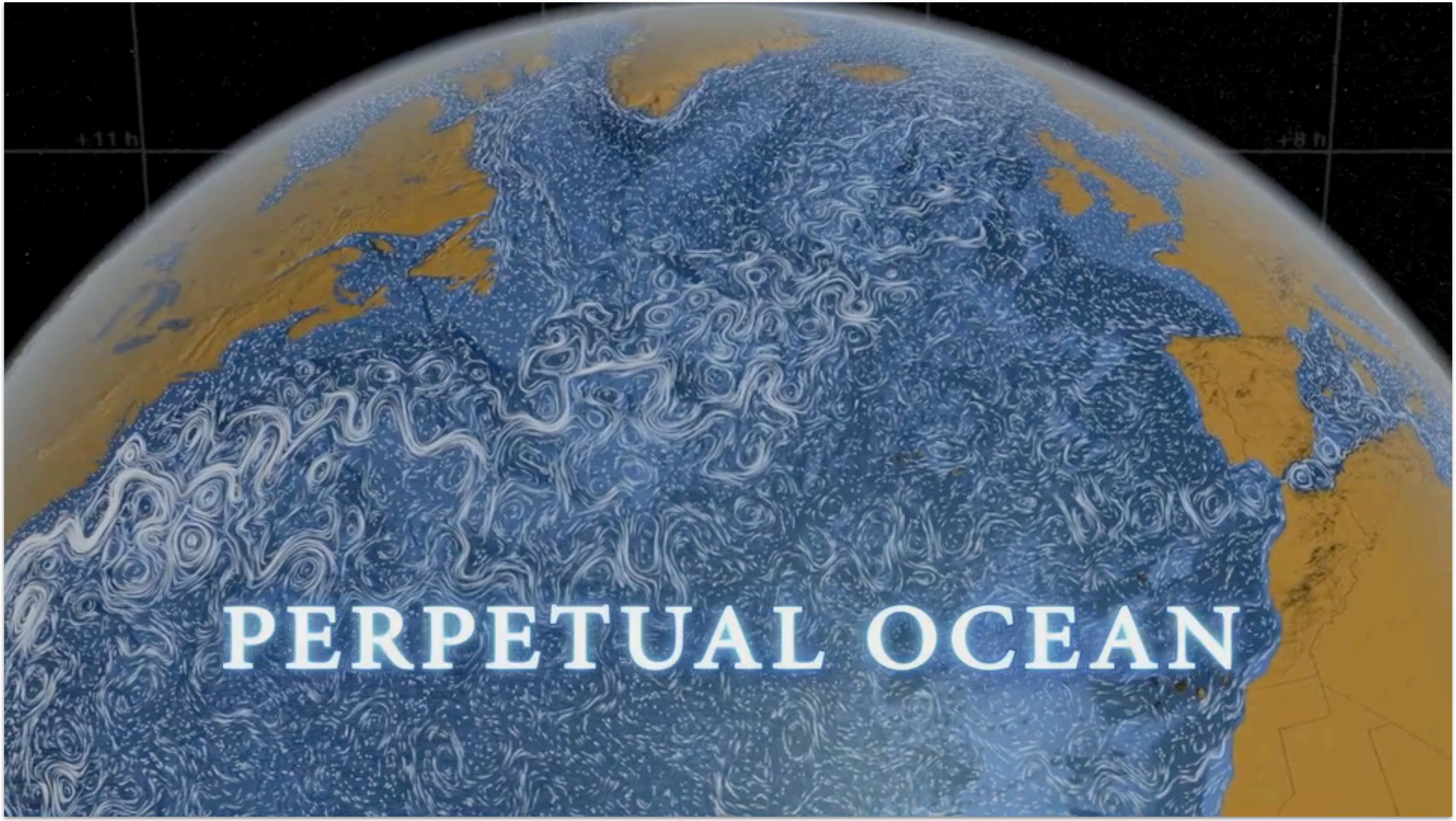
The ocean in motion



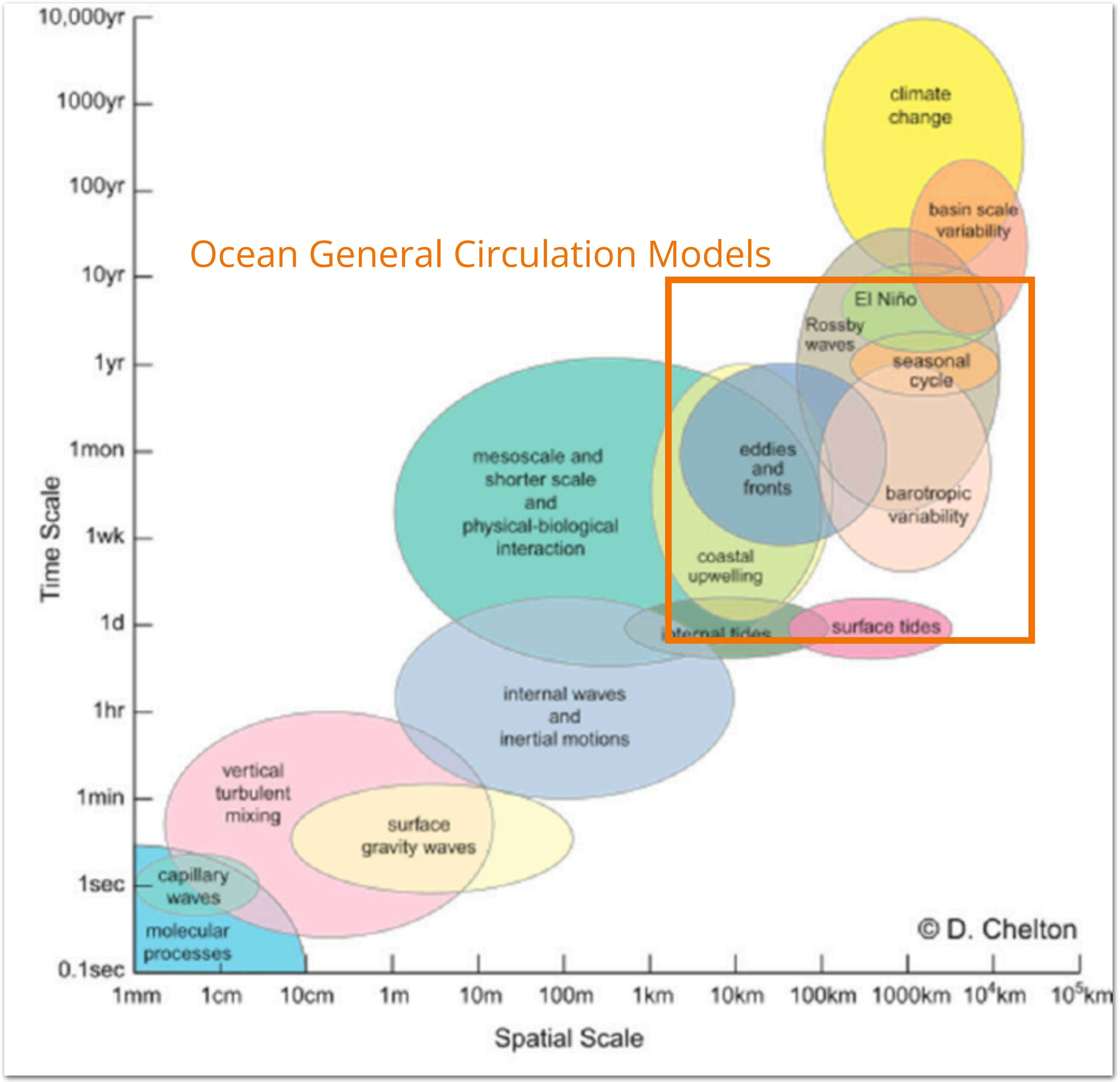
See https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=3827

When and why to use ocean models?

- Advantages
  - No need to go out and collect data; all data is available
  - Self-consistent (as long as no bugs)
  - Often best way to test hypotheses (“what would happen if New Zealand disappears?”)
- Disadvantages
  - Not the truth!
  - Need large teams to build ocean models, and even larger computers to run them

A tradeoff between spatial and temporal scales

- There is no one ocean model that can simulate anything from beach waves to climate change
  - Each problem requires its own ocean model



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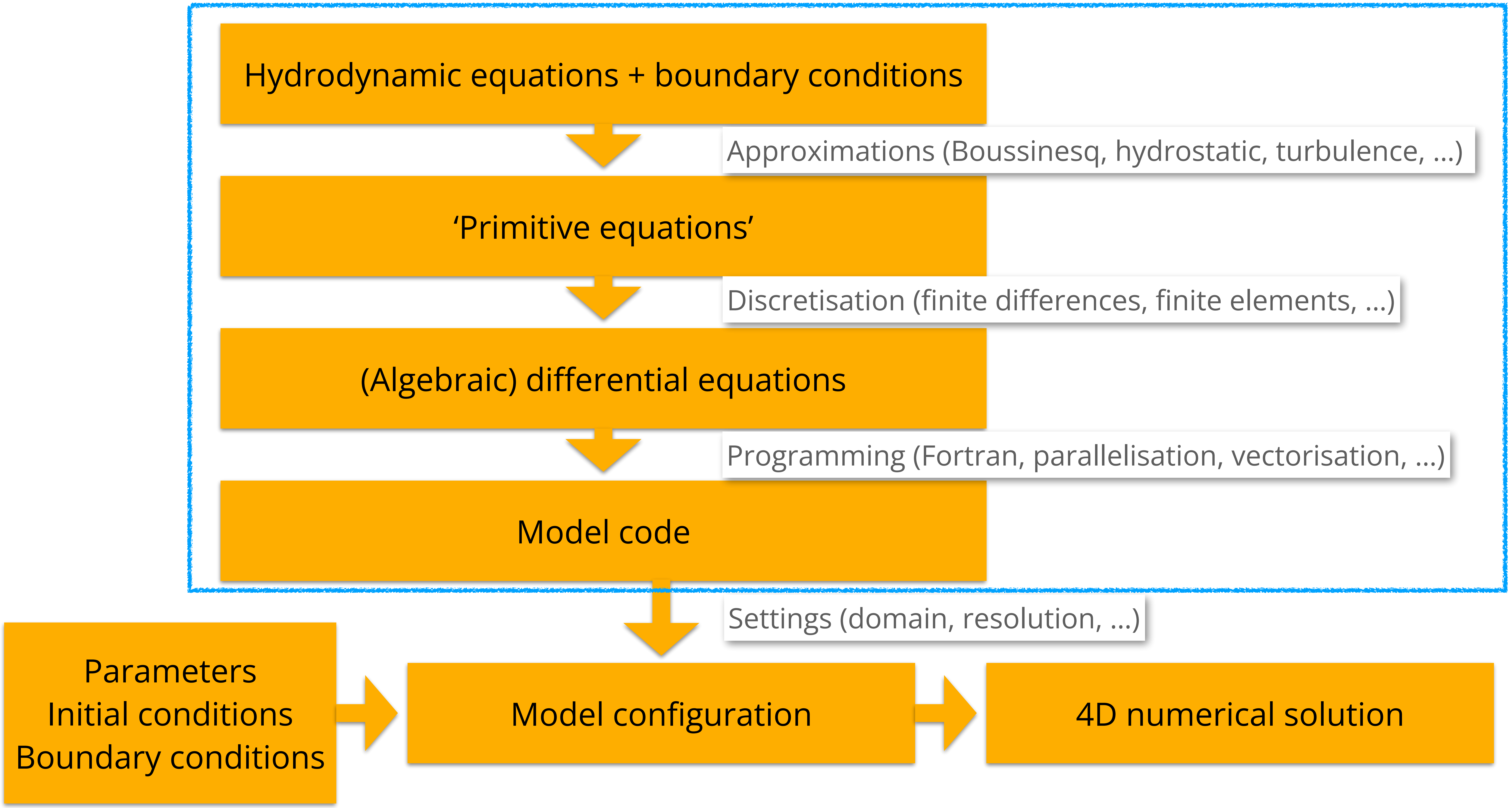
Basic ingredients of an ocean model



Ocean models follow physical principles

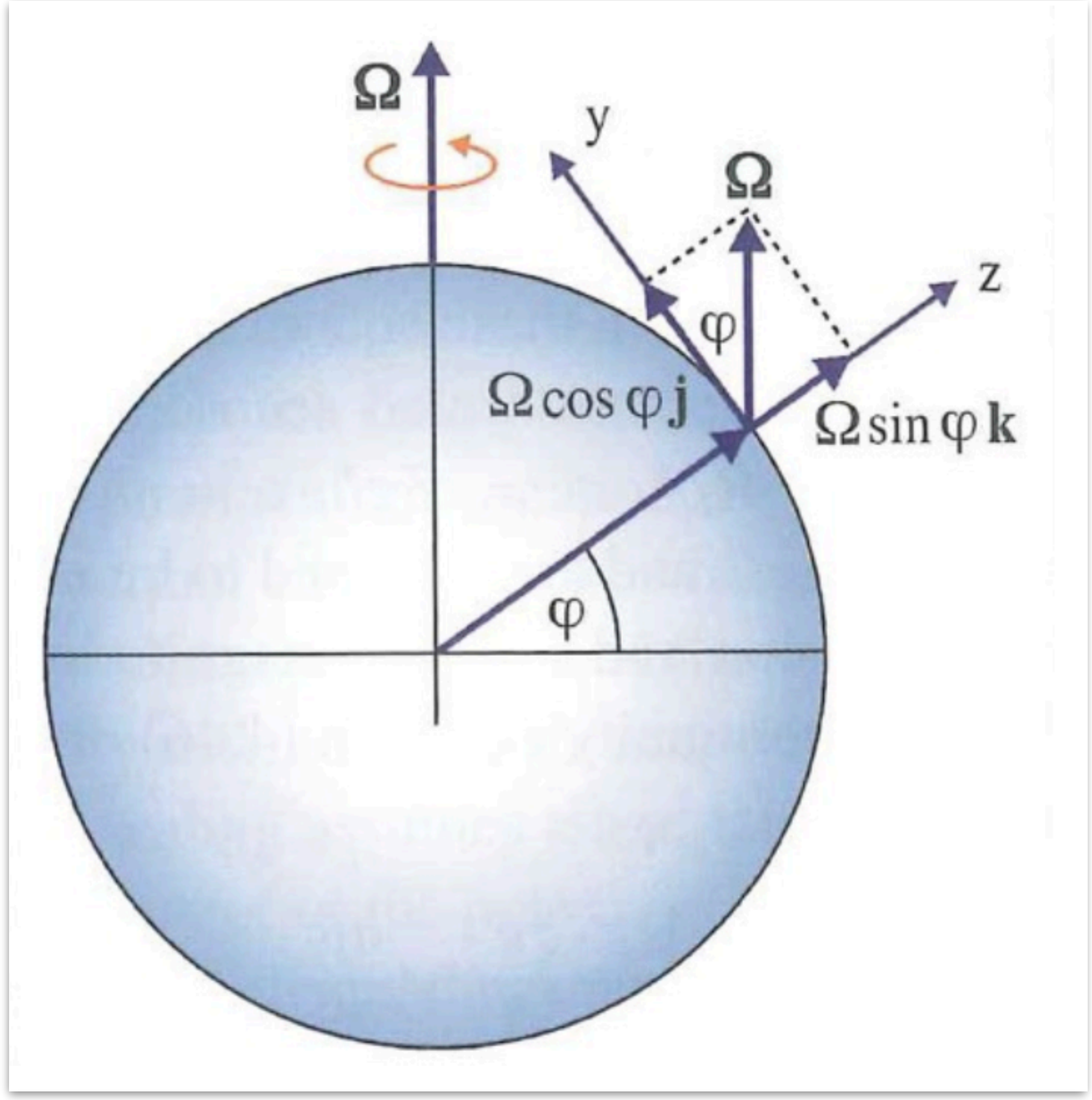
- Based on
  - Conservation of mass: $\frac{D\rho}{Dt} = -\rho\nabla \cdot \vec{u}$
  - Conservation of momentum (Navier-Stokes): $\rho\frac{D\vec{u}}{Dt} = -2\rho\overrightarrow{\Omega} \times \vec{u} - \nabla p - \rho\nabla\Phi + \mathscr{F}$
  - Conservation of salt: $\rho\frac{DS}{Dt} = \mathscr{G}_{\mathscr{S}}$
  - Conservation of heat: $\rho\frac{D\theta}{Dt} = \mathscr{G}_{\theta}$
  - Equation of state: $\rho = F(S, \theta, p)$

Some important approximations

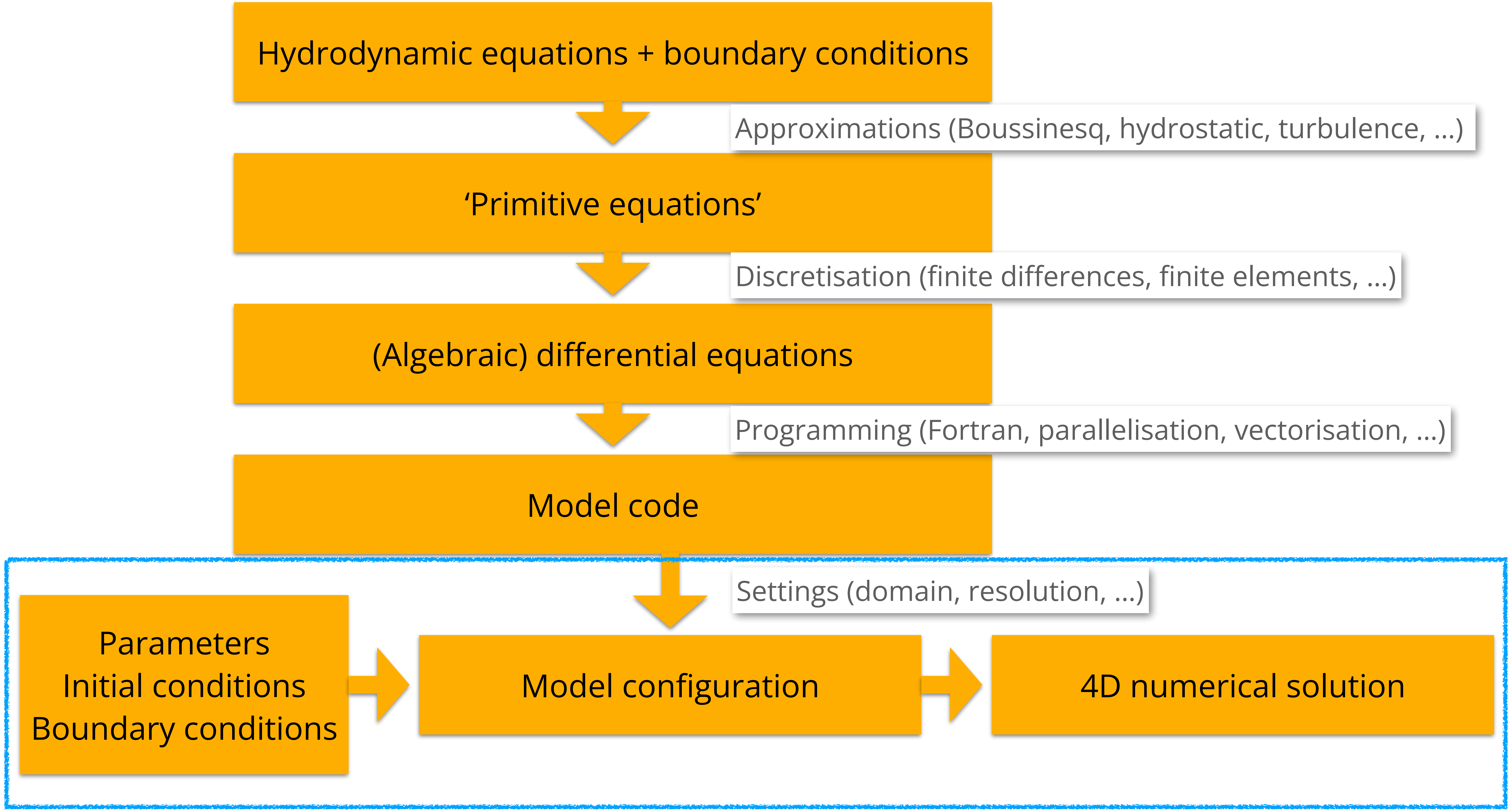
- Thin-shell/shallow aspect ratio approximation
- Hydrostatic approximation
  - No accelerations or friction in the vertical, balance between gravity and pressure gradient
- Boussinesq approximation
  - Density is (nearly) constant in the ocean. Can replace $\rho(\vec{x})$ with ρ_0 almost everywhere
    - Eliminates sound waves
    - Mass conservation becomes volume conservation

This yields the 'primitive equations'

- $\rho_0 \left(\frac{Du}{Dt} - \frac{uv}{a} \tan \varphi - fv \right) = - \frac{1}{a \cos \varphi} \frac{\partial \tilde{p}}{\partial \lambda} + \mathscr{F}_u$
- $\rho_0 \left(\frac{Dv}{Dt} - \frac{u^2}{a} \tan \varphi + fu \right) = - \frac{1}{a} \frac{\partial \tilde{p}}{\partial \varphi} + \mathscr{F}_v$
- $\frac{\partial \tilde{p}}{\partial z} = - g \tilde{\rho}$
- $\rho_0 \frac{D\tilde{S}}{Dt} = \mathscr{G}_{\mathscr{S}}$
- $\rho_0 \frac{D\tilde{\theta}}{Dt} = \mathscr{G}_{\theta}$
- $\tilde{\rho} = F(\tilde{S}, \tilde{\theta}, p_0)$



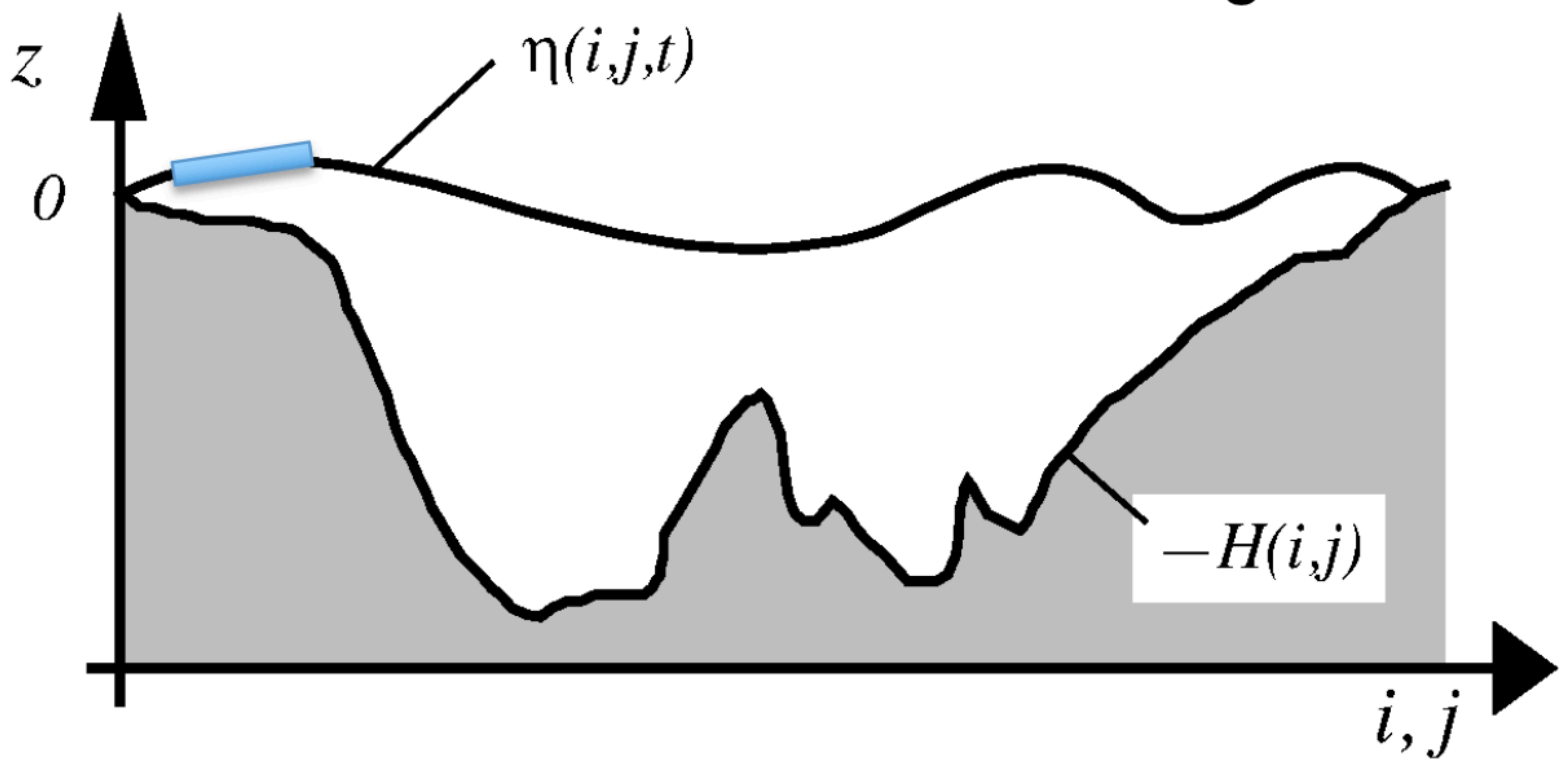
From the equations to the model



Boundary conditions

Sea ice – Ocean:
- Heat and freshwater fluxes
- Exchange of momentum

Atmosphere – Ocean:
- Freshwater (evaporation, precipitation)
- Heat fluxes
- Continuity of pressure
- Exchange of momentum (wind)

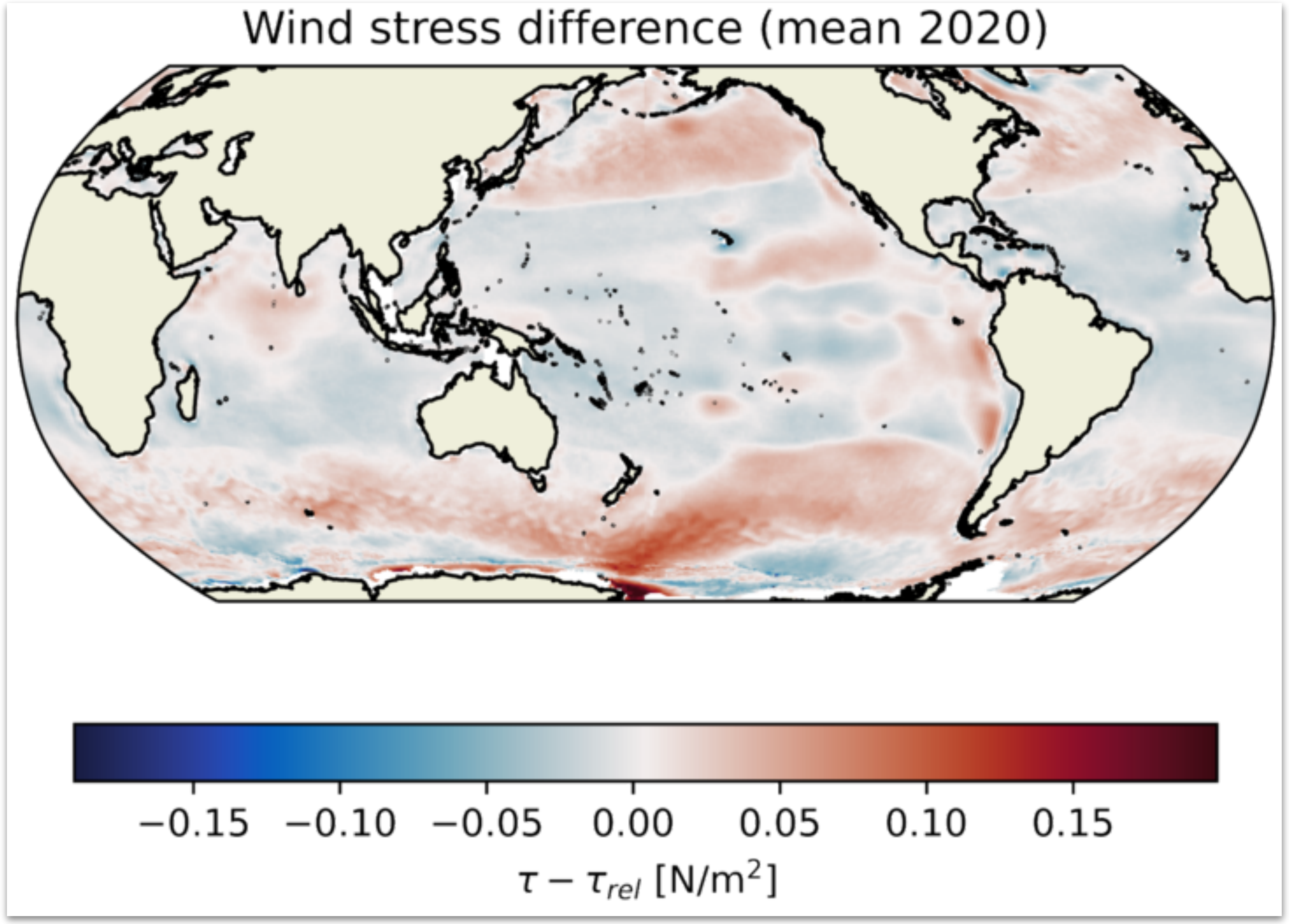


Land – Ocean:
- river runoff (fw)

Solid earth – Ocean:
- (Typically) no heat/salt fluxes
- No velocity normal to bottom/coast
- Different approaches for tangential velocity

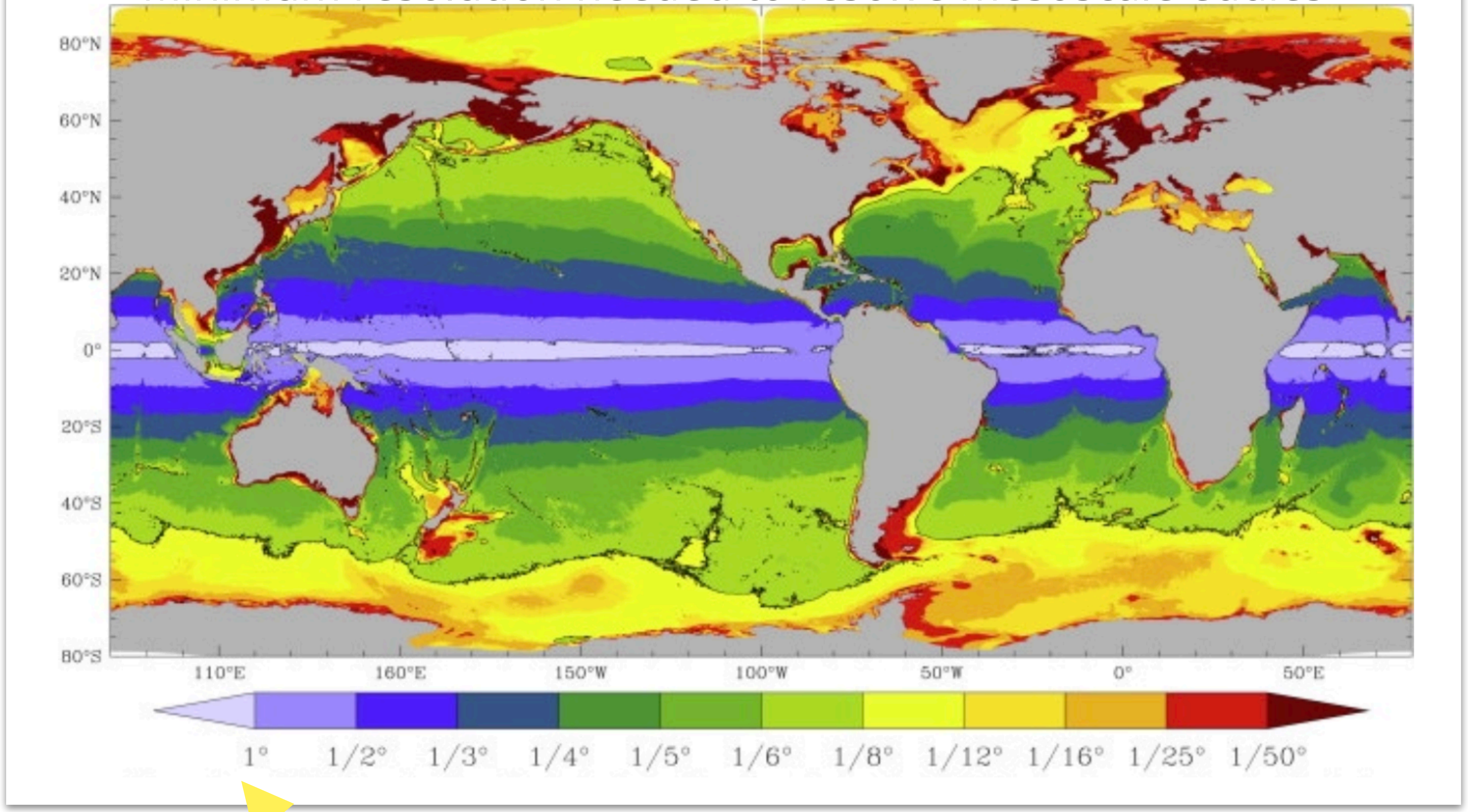
From wind speed to wind stress

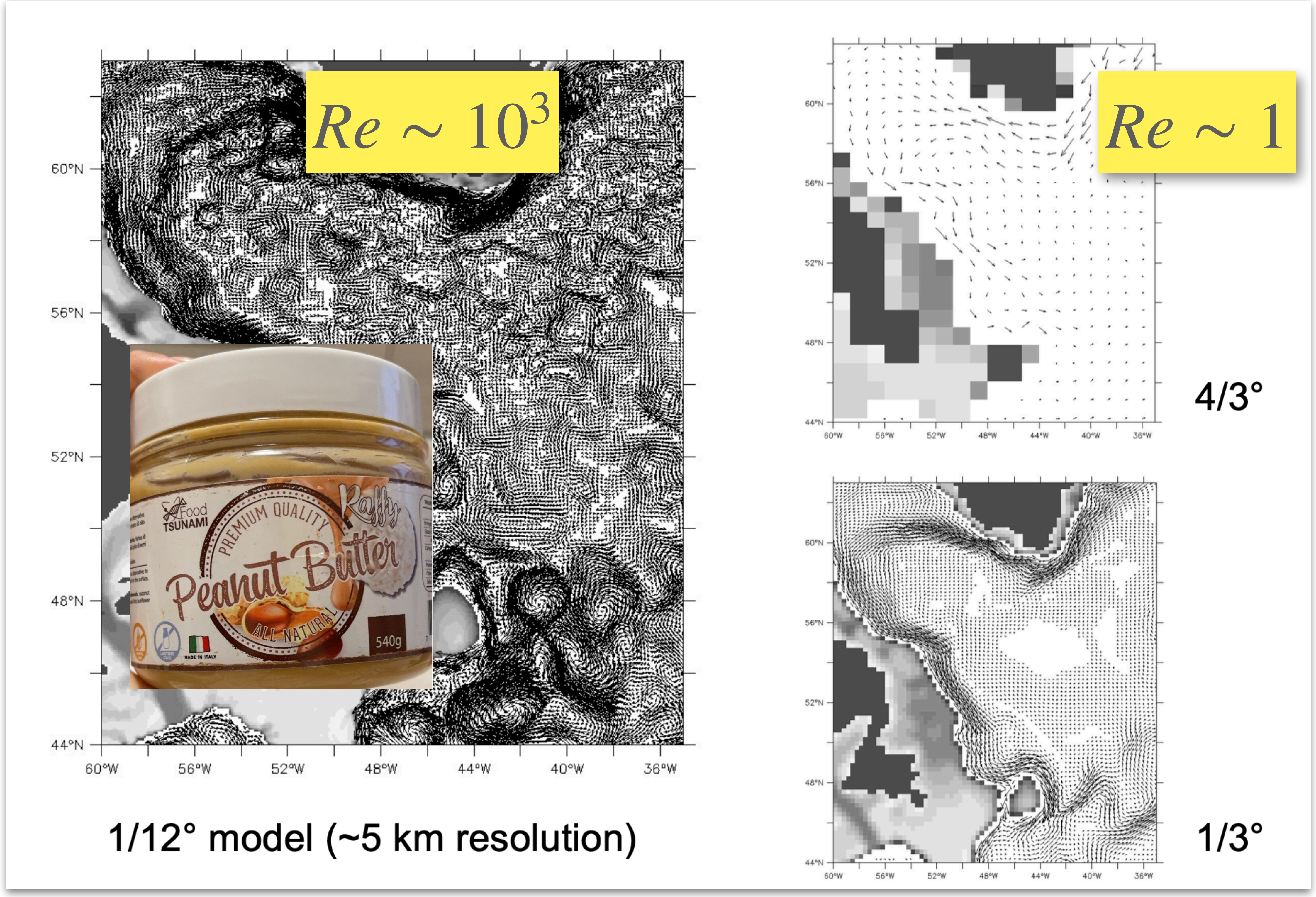
- The wind produces a stress on the surface of the ocean
  - Parameterised as $\tau_w = \rho_a C_D \left|\vec{u}_a\right| \vec{u}_a$ with $C_D = 0.0015$ drag coefficient and $\vec{u}_a$ wind at 10m.
  - Note that, even though this parameterisation is very widely used, it's inaccurate:
    - Assumes a resting ocean (so no motion)
    - This leads to 20% over-prediction of wind work
    - Better to use $\tau_w = \rho_a C_D \left|\vec{u}_a - \vec{u}_o\right| \left(\vec{u}_a - \vec{u}_o\right)$
    - But problem for forced (i.e. ocean-only) models
      - See Wikipedia article on Relative Wind Stress
        - 2022 CLPH students



Choosing a horizontal resolution

Minimum resolution needed to resolve mesoscale eddies



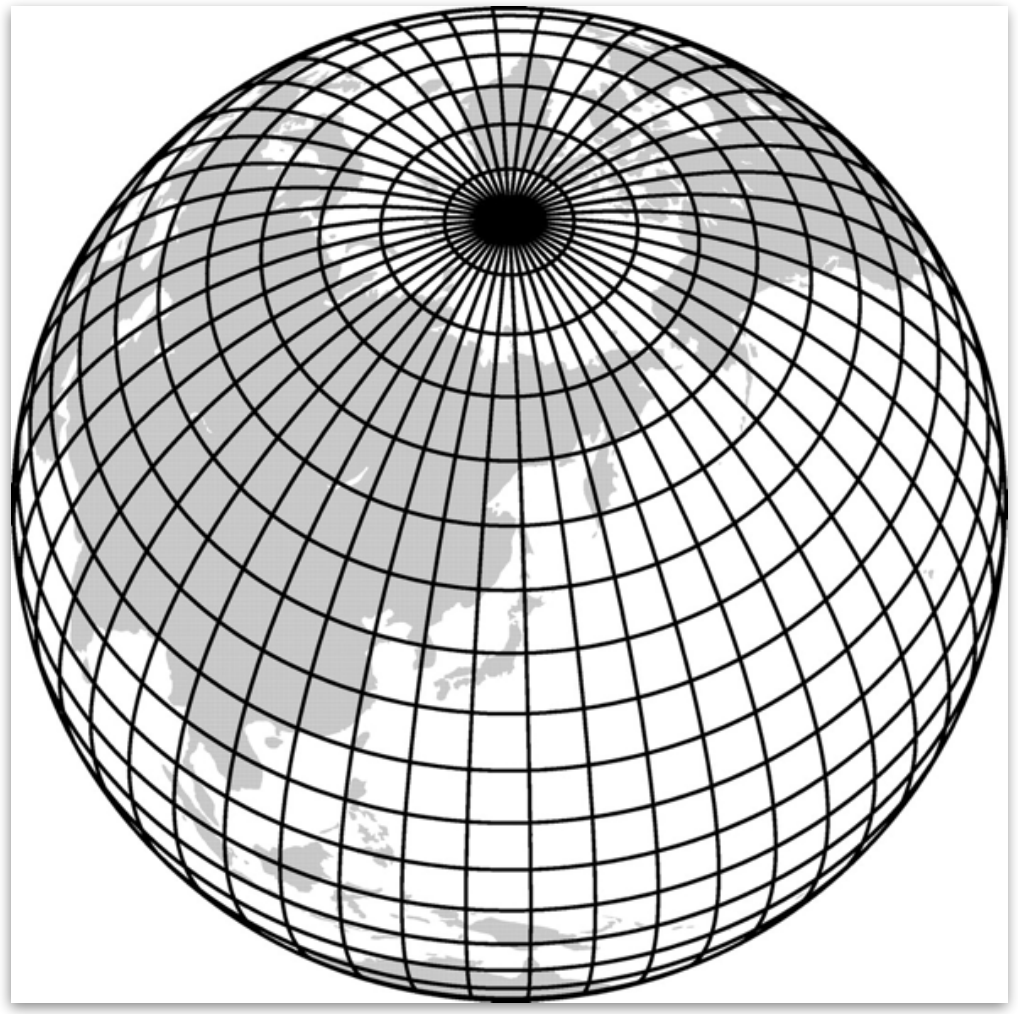


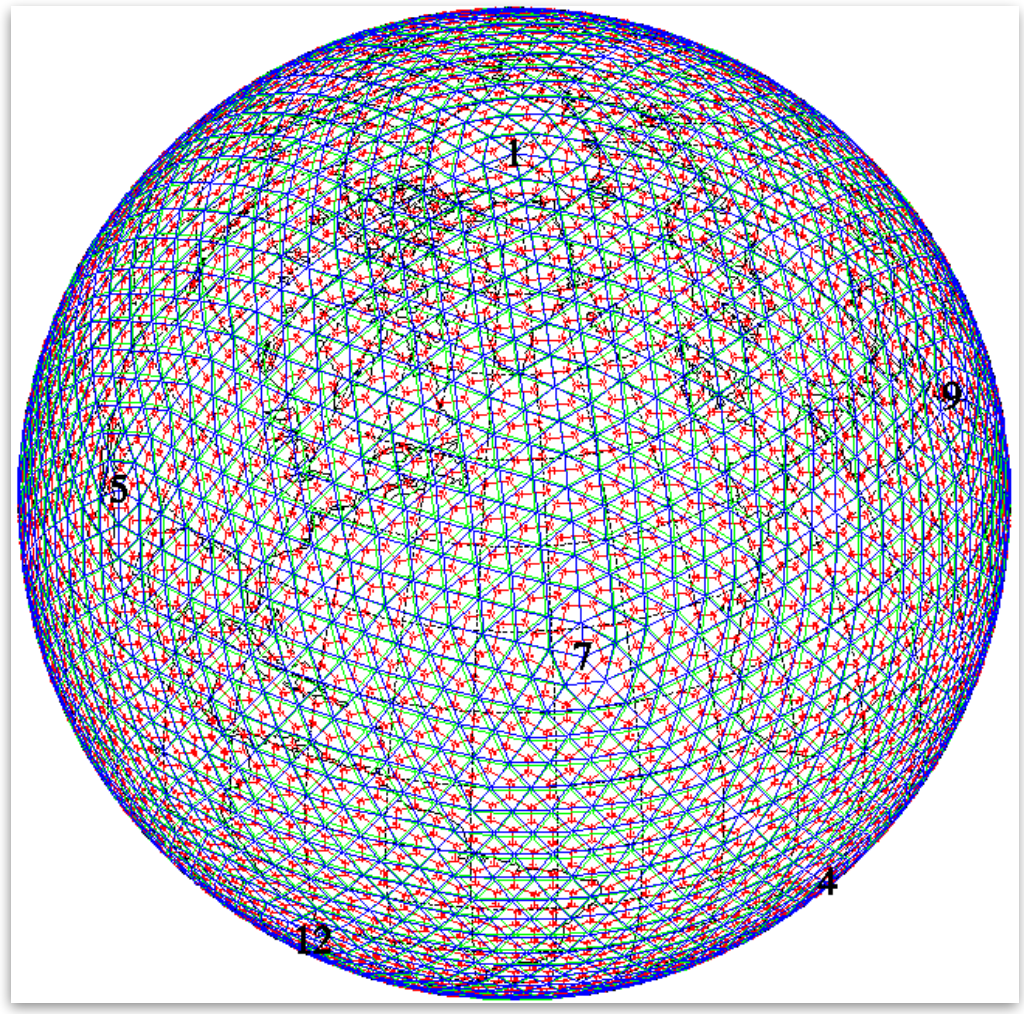
Equivalent to ~30° atmospheric model

Real Ocean: $Re = \dfrac{UL}{\nu} \sim 10^{10}$

The pole problem for ocean grids

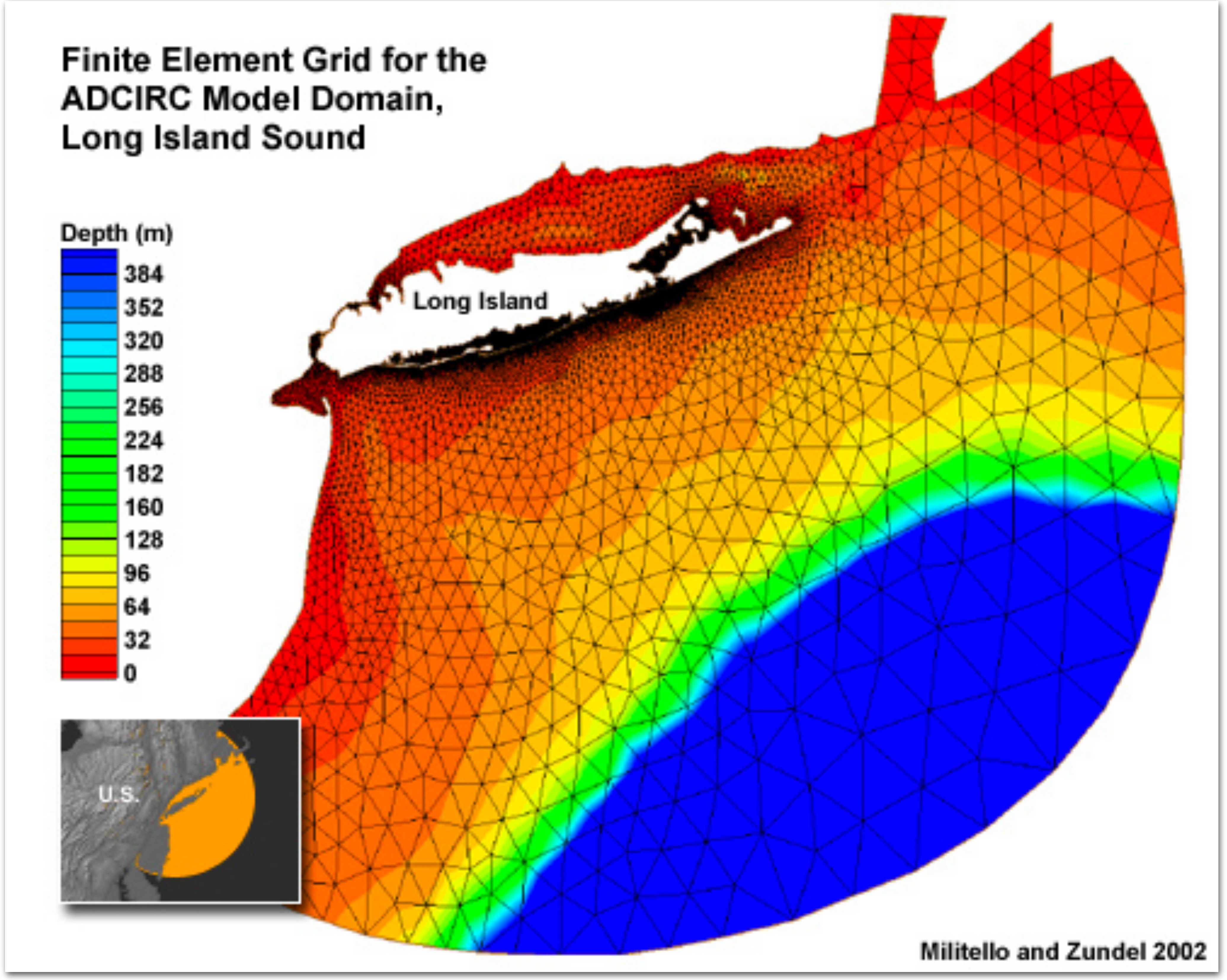
- (Global) ocean modelling has a serious problem at the poles
- Simplest possible grid is lon/lat, at fixed #degrees per gridcell (with 1/100^o state-of-the-art)
- However, near poles Δx (in m) goes to zero for a given gridspacing in degree
- And this means that Δt needs to go to zero too (because of CFL criterium)
- One solution: put poles over land (easy in South, requires tripolar grid in North)
- Other option is to use distorted/triangular meshes (but code becomes more complicated)





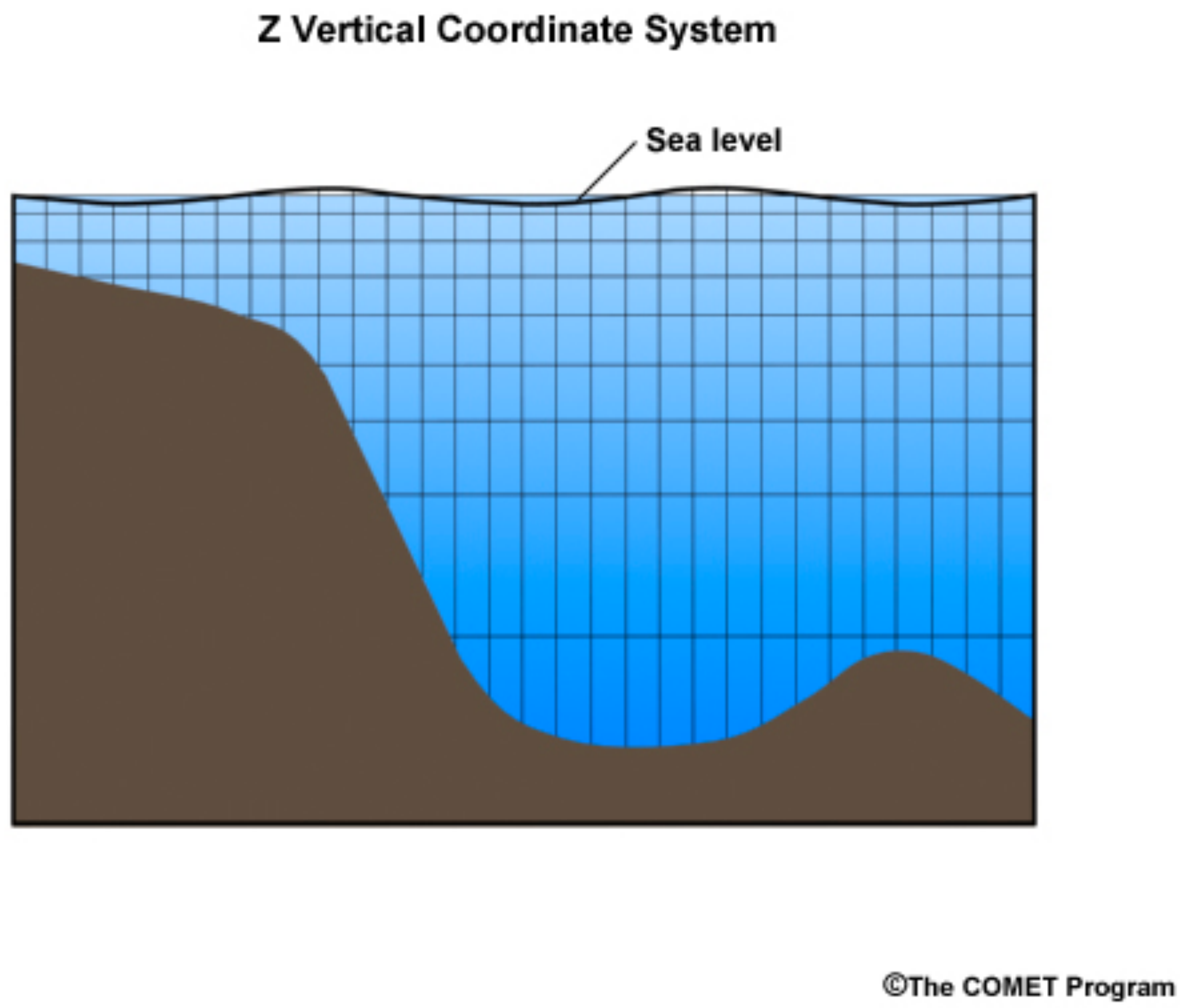
Unstructured horizontal grids

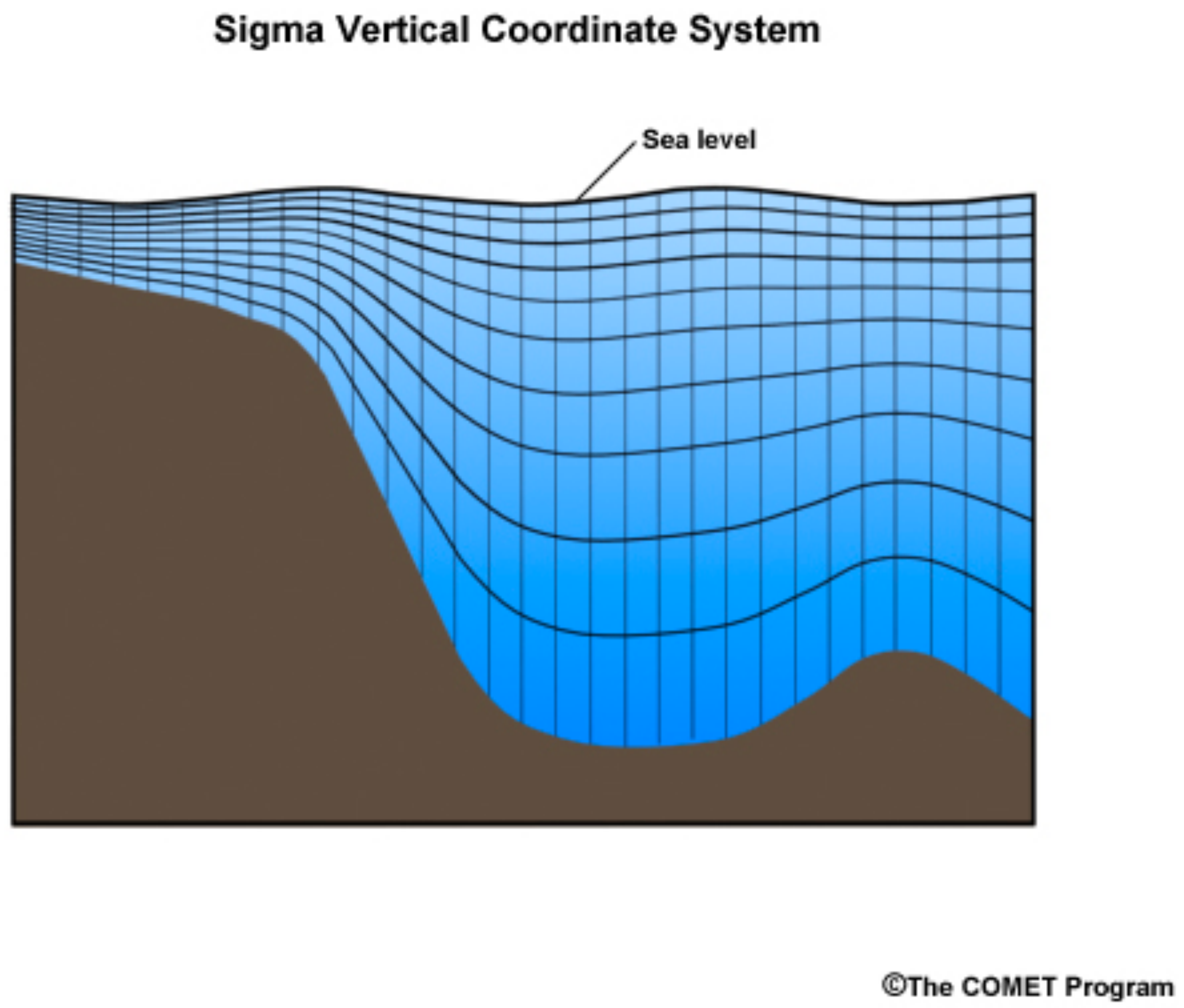
- Some (regional) models have unstructured triangular meshes, with variable resolution
- Avoids pole problem and is great to focus on specific region of interest
- But difficult to maintain conservation of mass, momentum, energy etc

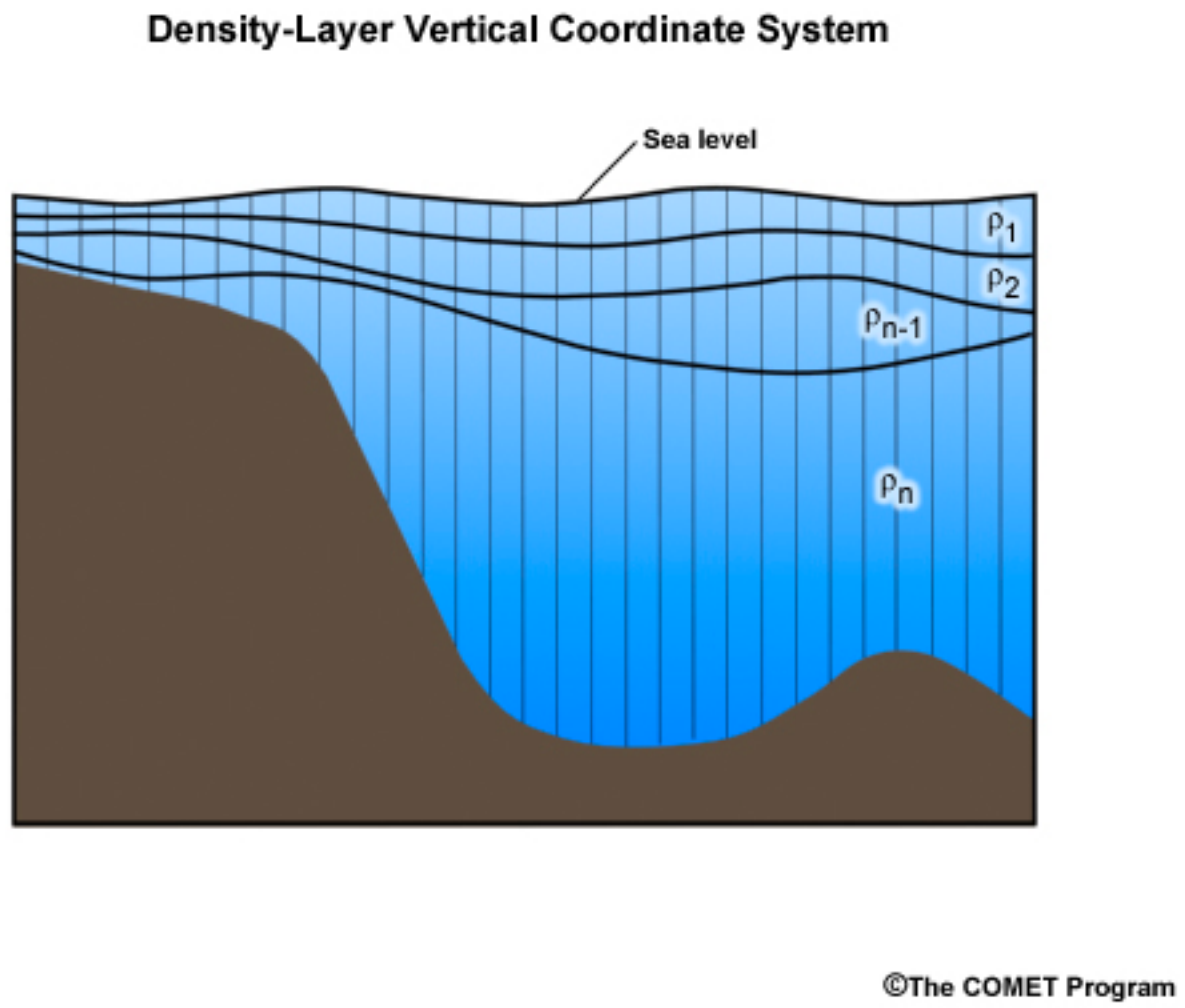


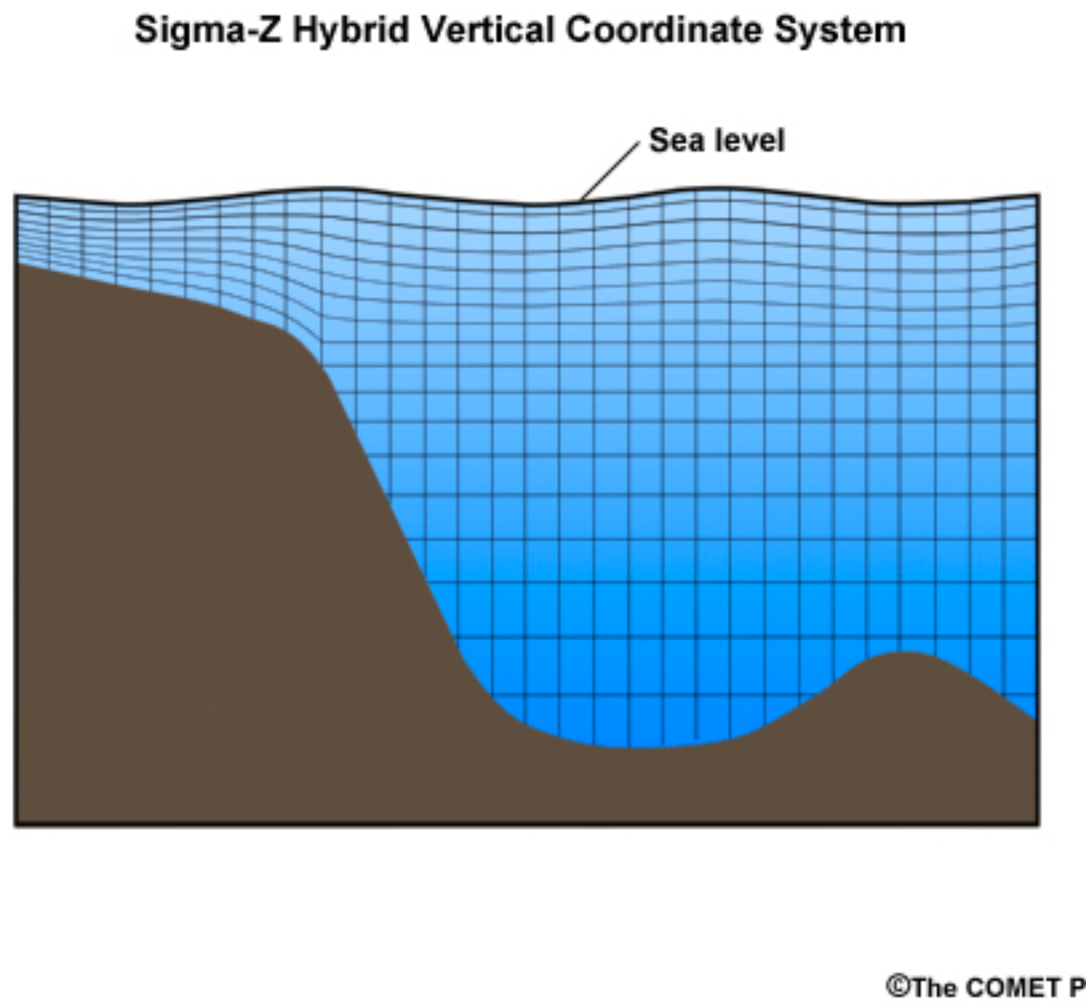
Choices for vertical grids

- In principle, three different choices for vertical grids:
  - z: Each layer has fixed depth ($z*$ if layers can be stretched a bit for sea level changes)
  - σ: Each layer has fixed fraction of local depth
  - ρ: Each layer has fixed density (does not work well in mixed layer)
- Combination of the three also possible (hybrid grid)









Bathymetry is very important

- Each grid cell can have only one value for T, S, u, v, (w) etc.
  - So by gridding, resolution is lost
- At too low resolution, ocean models can't 'see' islands
  - So they don't reproduce island processes like upwelling
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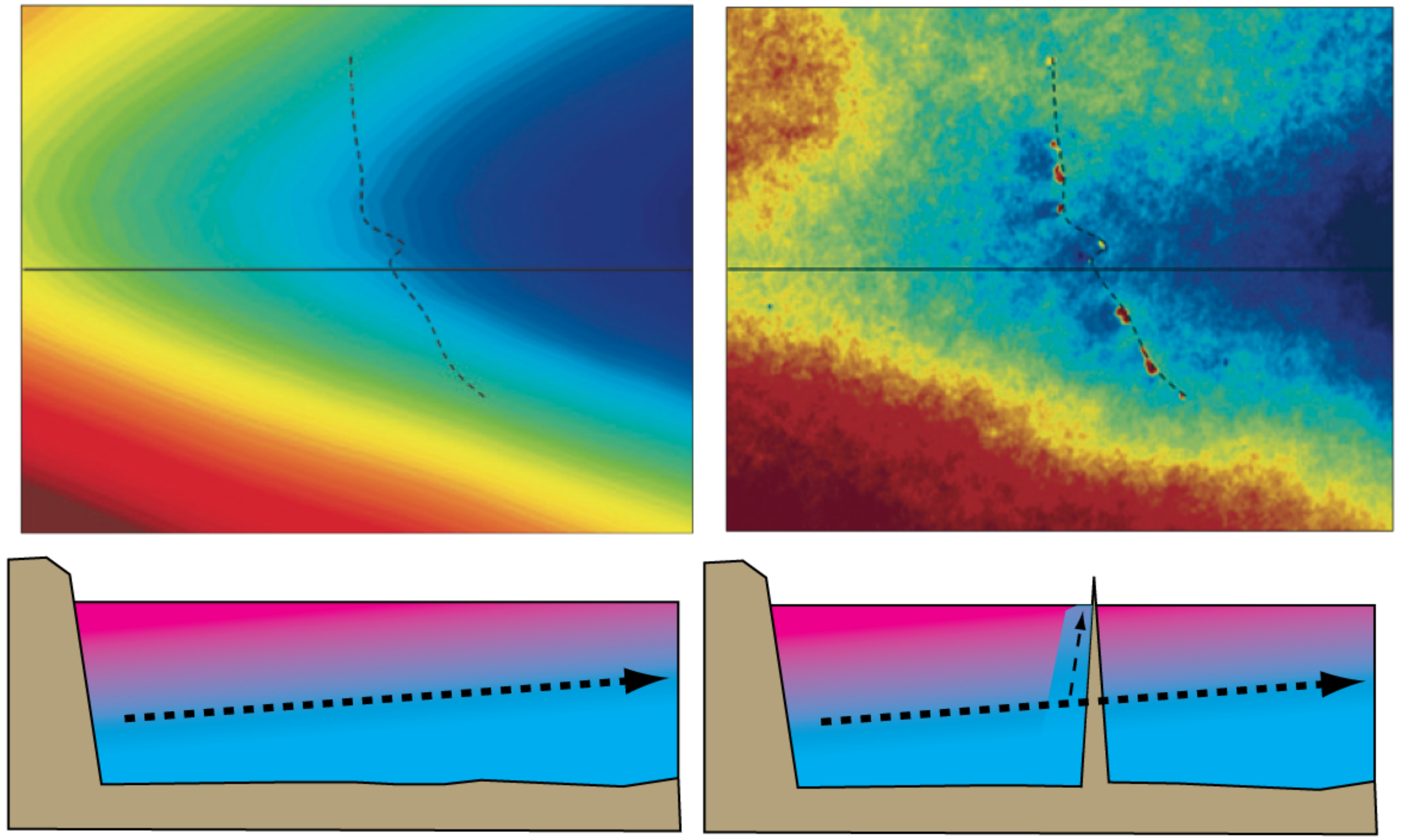
SST in climate model

SST in satellite data

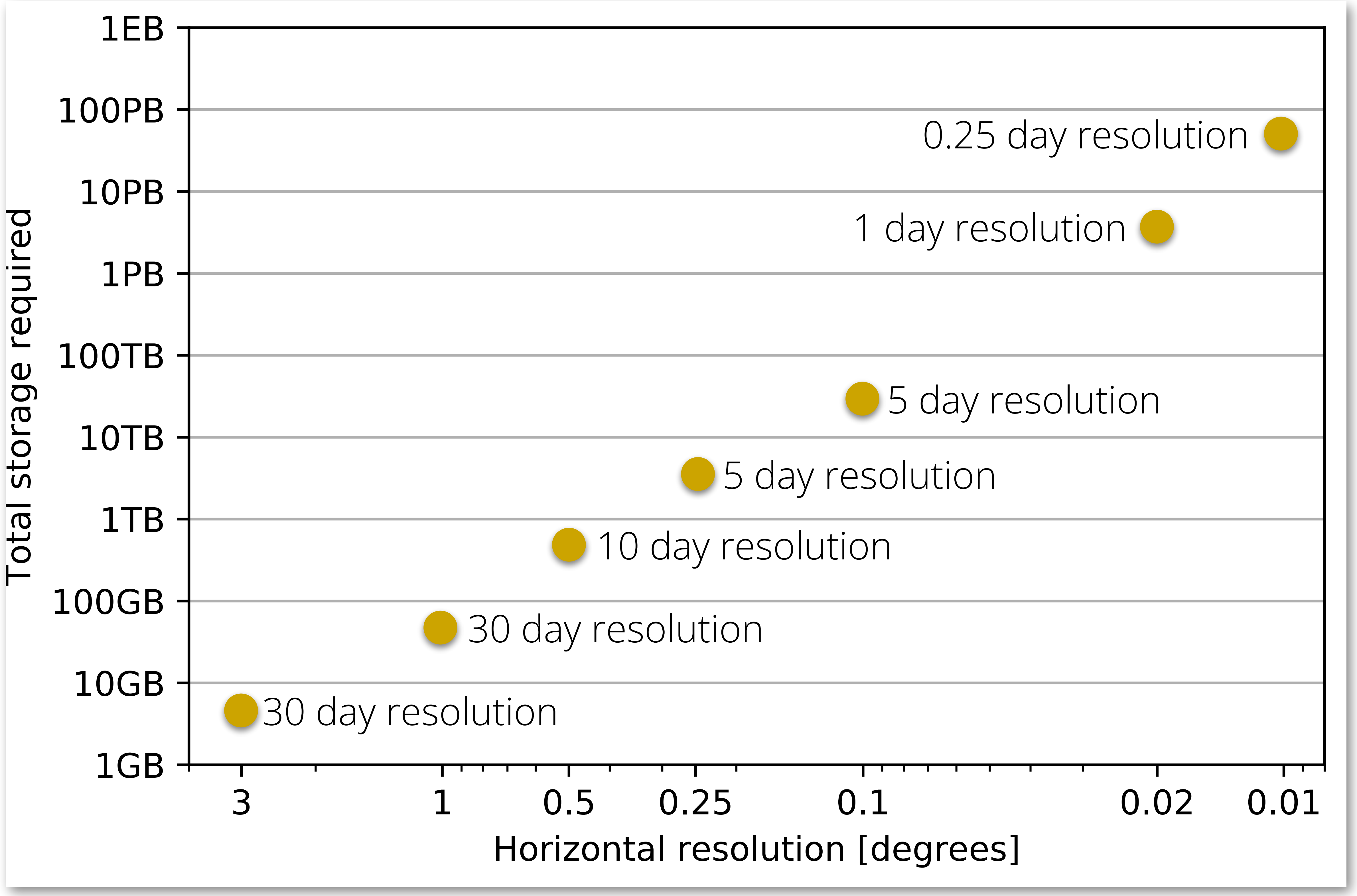


A summary of the most widely used global models

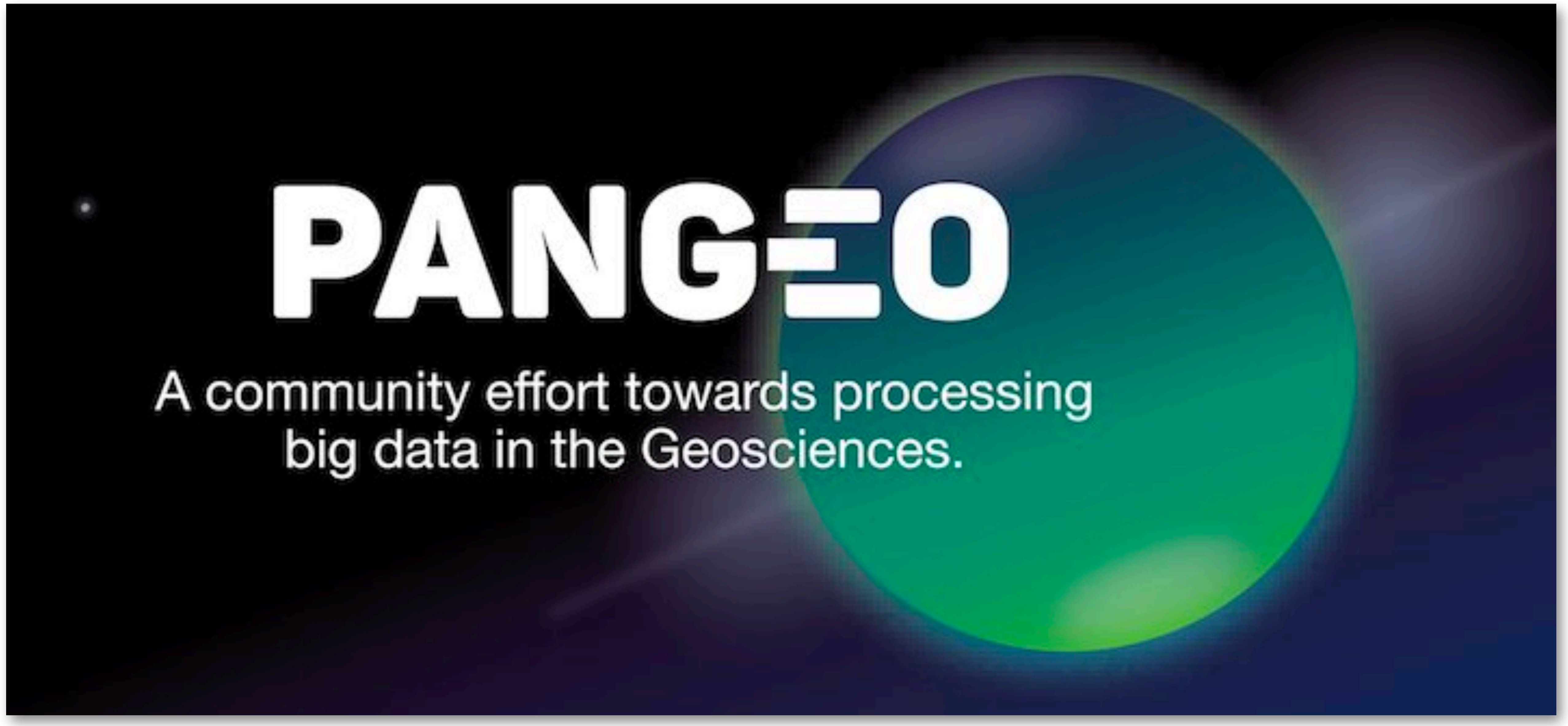
- There is no one ocean model that can simulate all from beach waves to climate change
  - Each problem requires its own ocean model

Model name	Maintainers	Vertical grid	Uses
NEMO	European consortium	z (and z*)	Global simulations
HYCOM	US Navy	hybrid (z, sigma and rho)	Global simulations
MOM	NOAA	all (generalised)	Global simulations
POP	NCAR	z	Global simulations
ROMS/CROCO	Global consortium	sigma	Coastal/regional
ICON	German consortium	z	Unstructured meshes
FVCOM	Global consortium	sigma	Unstructured meshes
MITgcm	MIT	z (and z*)	Lab to global (non-hydrostatic)

The Big Ocean Data challenge



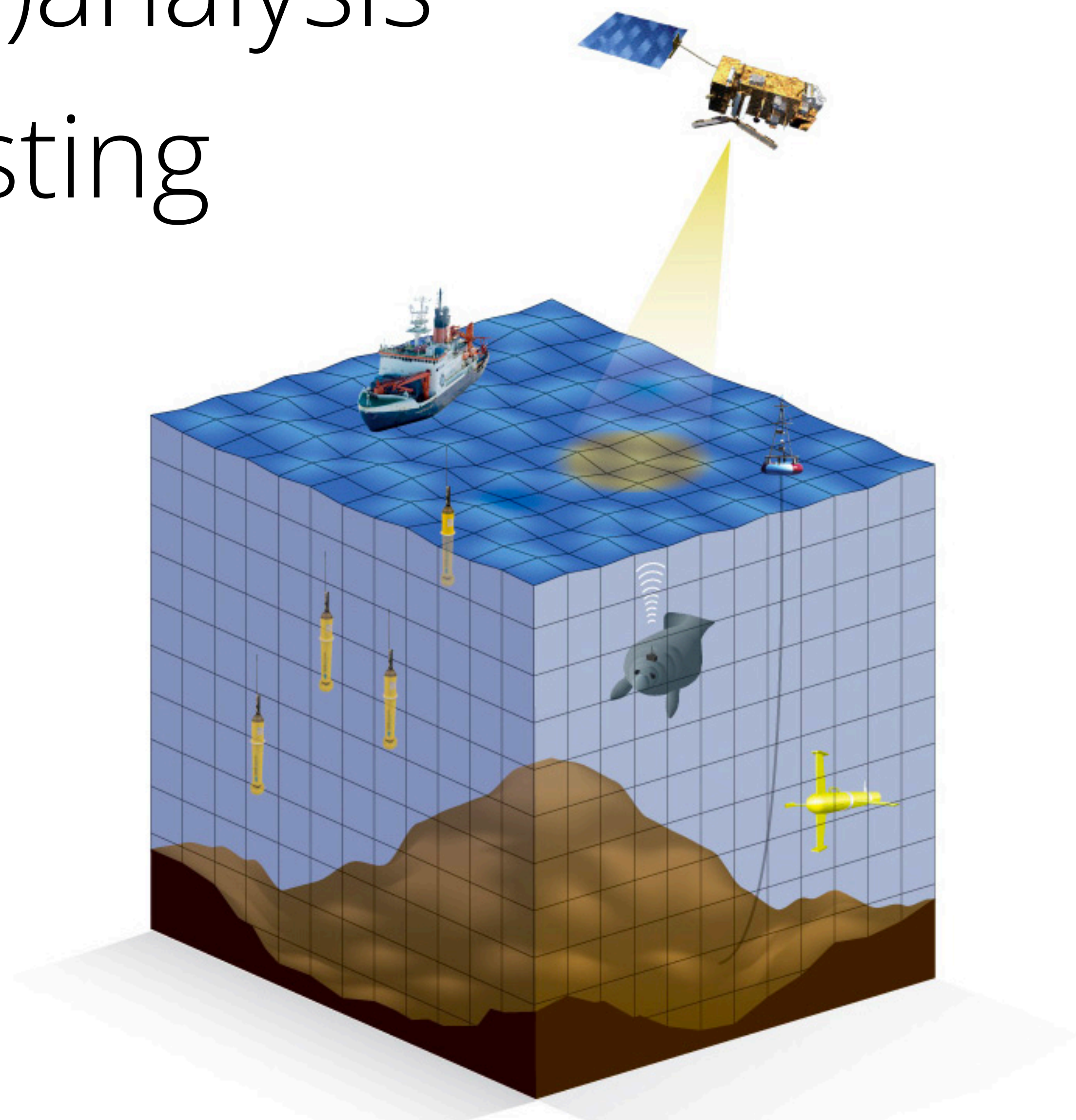
Total storage of 3D flowfield for 50-year simulation &100 vertical levels

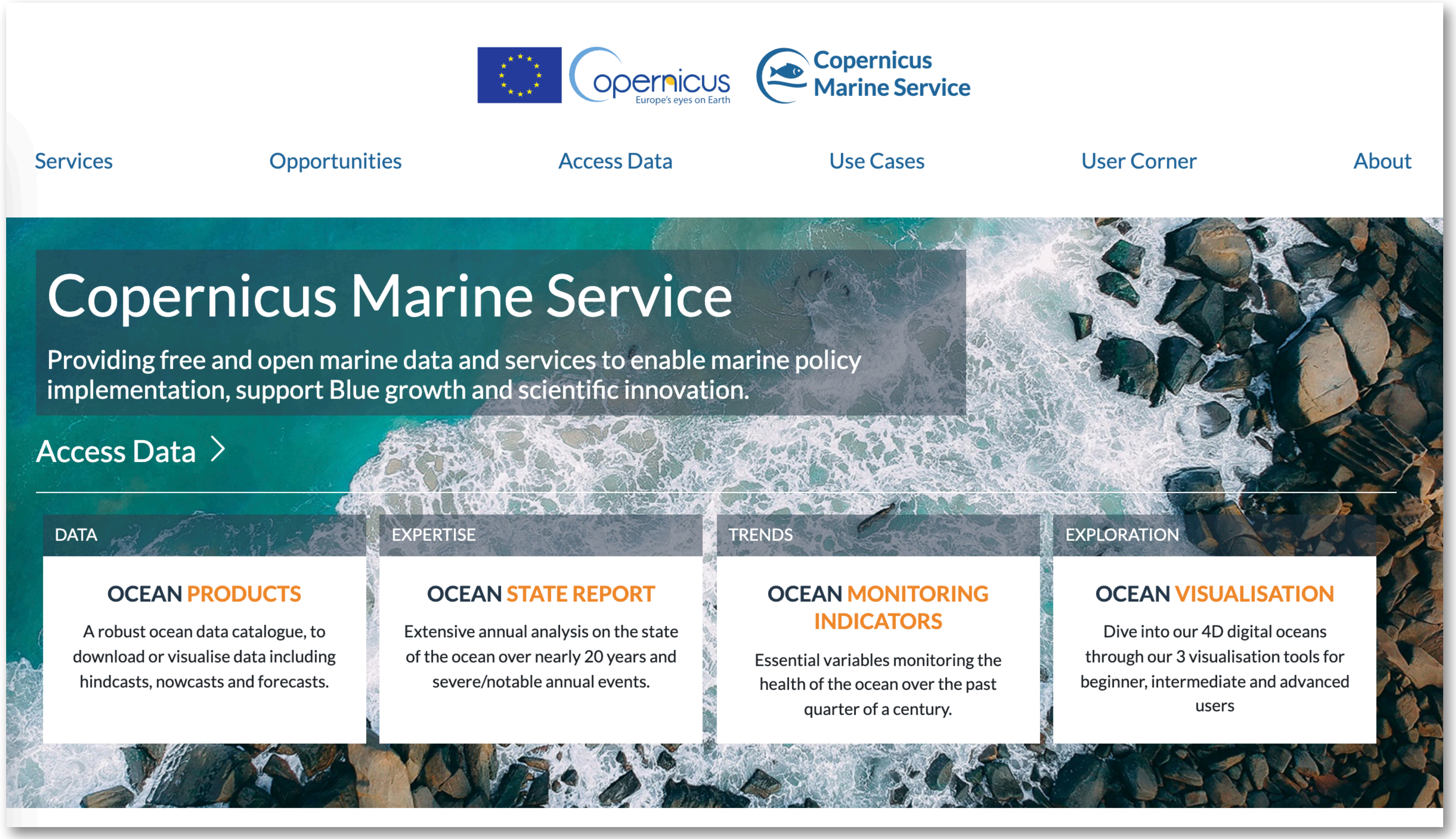


- How do we make sure our tools and infrastructure are ready for the petascale age?

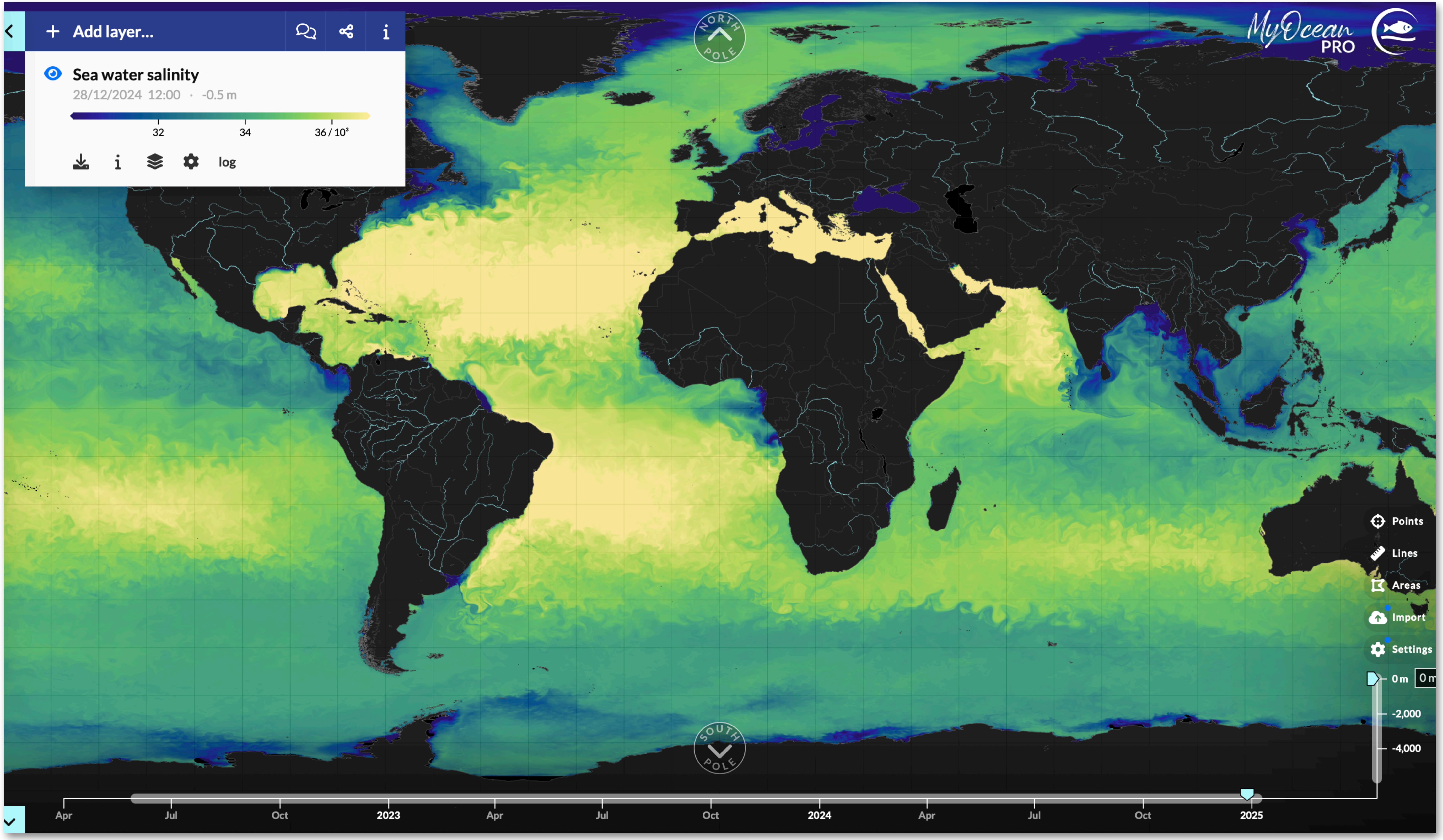
Ocean reanalysis: to assimilate or not?

- The ocean models mentioned on previous slide need forcing (winds, surface fluxes); these typically come from numerical weather/climate models
- If that is the only forcing, there is no guarantee that the ocean circulation will be 'realistic'
  - While mean flow may be representative, eddies do not need to be at certain place/time
- Hence, for applications where realism is important, data assimilation can help
  - Models 'steered' towards observations
  - Many ways to do this (4D-var, EnKF, etc)
  - Product is 'ocean (re)analysis'
  - Like weather forecasting



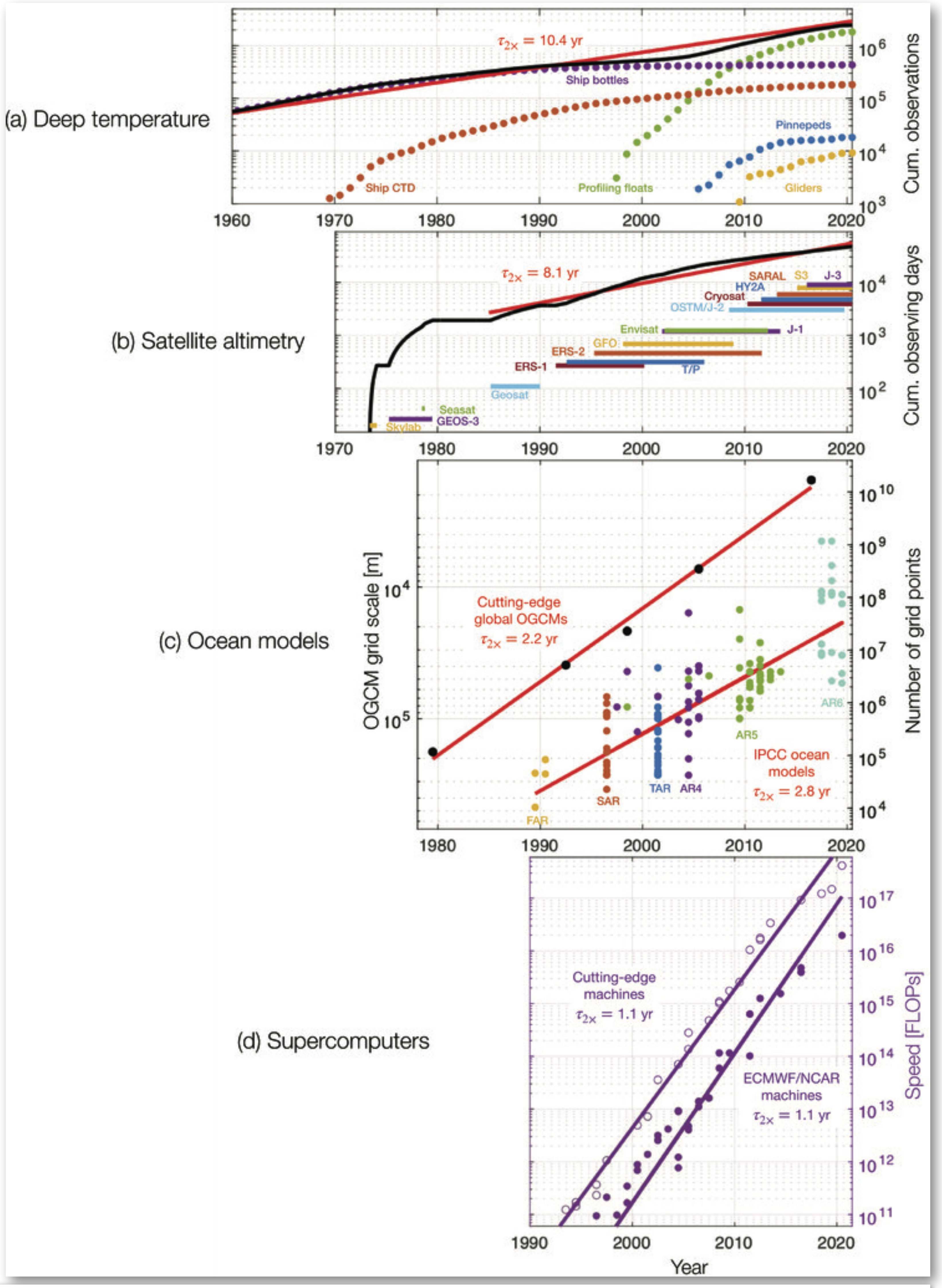


The MyOcean Pro viewer to explore ocean model data



An oceanographic Turing test?

- Models are swiftly becoming more realistic
- Thomas Haine suggested the “oceanographic Turing test”:
  - Can an oceanographer distinguish between observations and model?



Haine *et al* (2021) *Bulletin of the American Meteorological Society*