# Intrinsic Errors in Physical Ocean Climate Models

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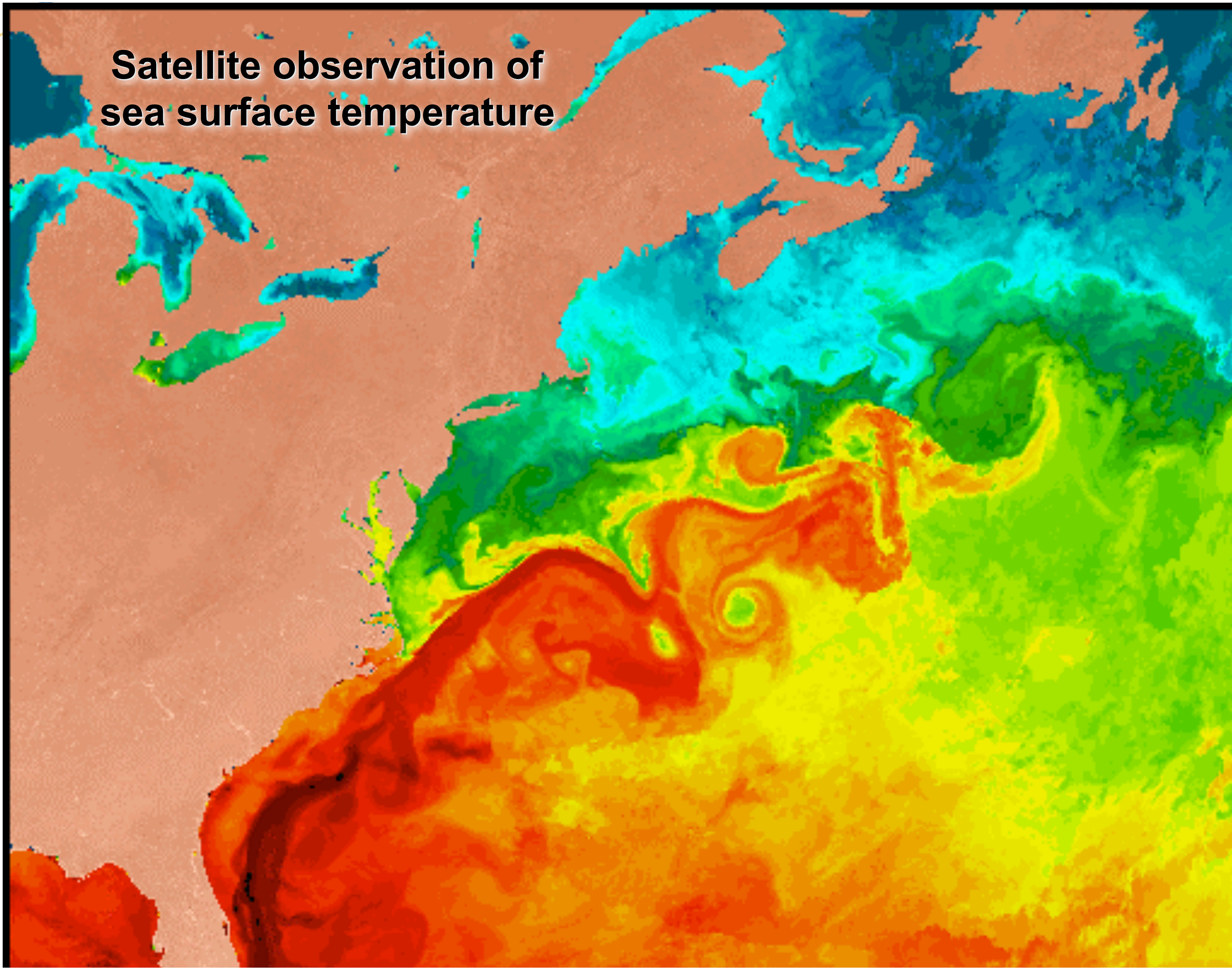
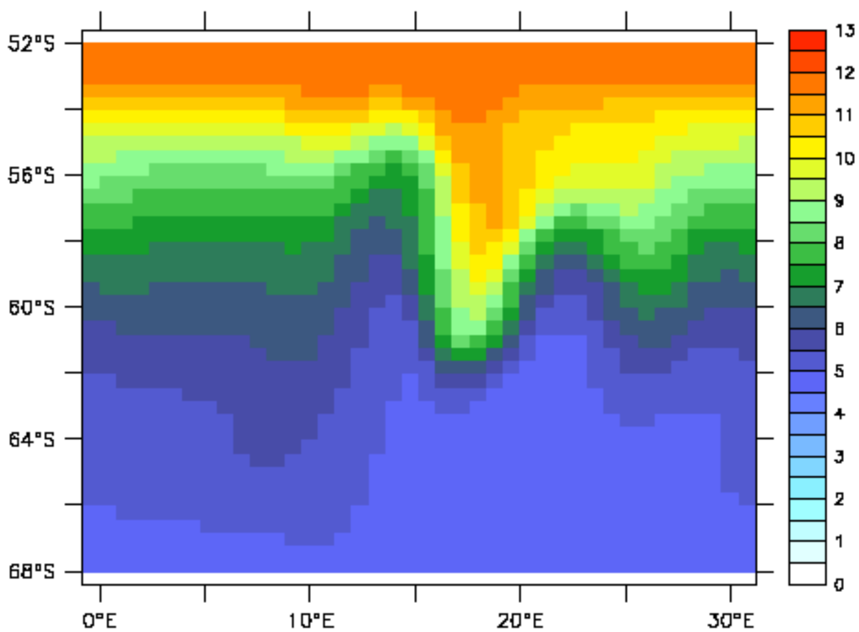

Satellite observation of
sea surface temperature

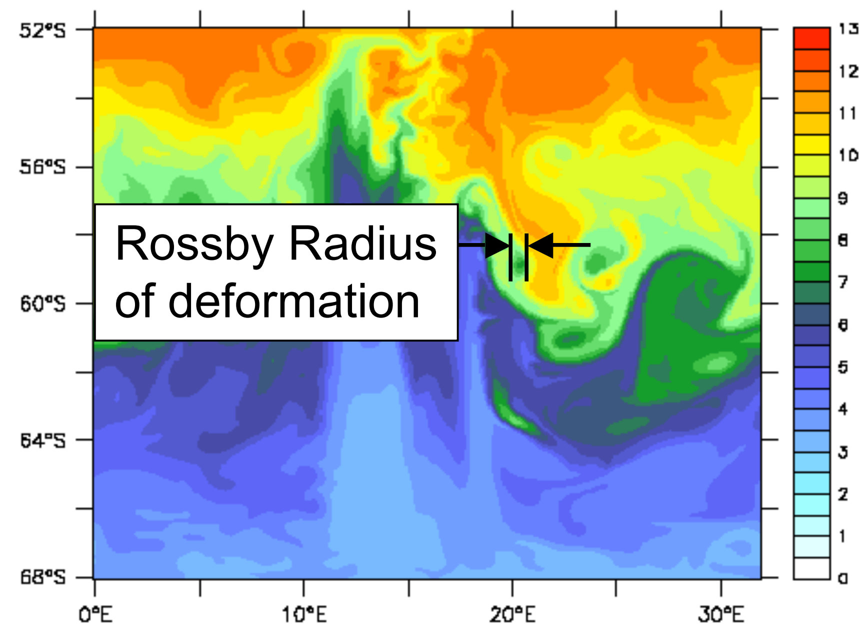
## Climate simulations

- low resolution: 1 deg (~100 km)
- long duration: 100s of years
- fully coupled to atmosphere, etc.




## Eddy-resolving sim.

- high resolution: 0.1 deg (~10 km)
- short duration: 10's of years
- ocean only



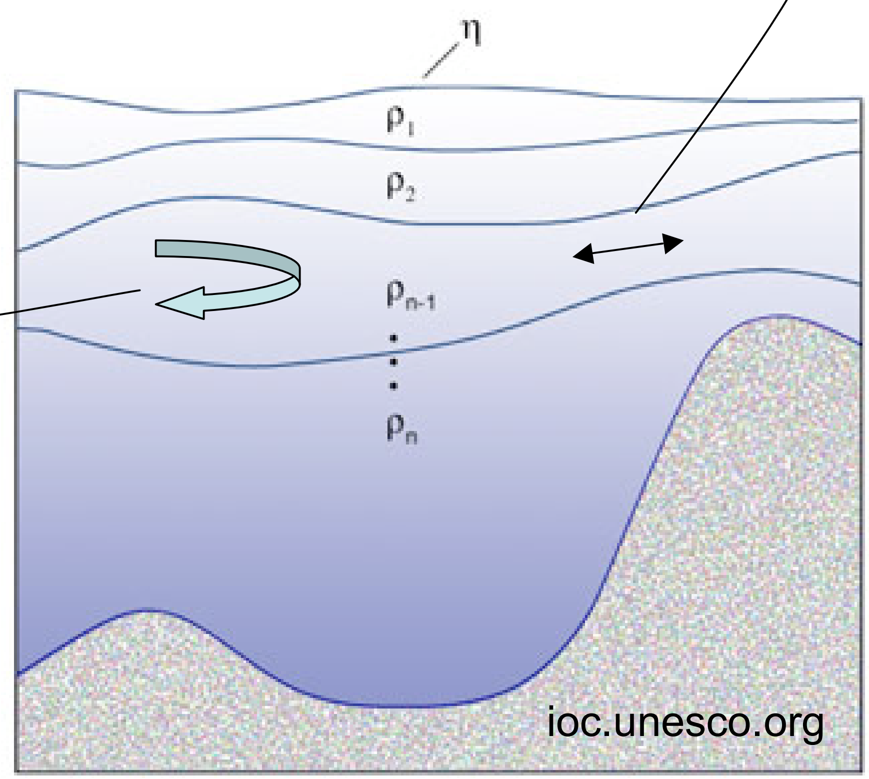

Sea surface temperatures

# Horizontal vs Vertical Mixing

- ***Observational estimates:***
  - $A_v$ order of $1 \times 10^{-4}$ $m^2/s$
  - $A_H$ order of $1 \times 10^{2}$ $m^2/s$
- ***Separation of 6 orders of magnitude***
  - These estimates for viscous mixing of momenta
  - Similar separation of scales for diffusive mixing of heat and salt

- ***But mixing of heat and salt not exactly horizontal/vertical***
  - **Large lateral mixing along local surface of constant "potential density"**

also, disturbance in layer interface translates with eddy



# Ocn Model Turbulence Param. in the tracer transport eqns

- ***GM90: Gent-McWilliams form of isopycnal tracer mixing***
  - Rotate mixing of heat, salt slightly from horizontal to "local surface of constant potential density"
  - Diffuse "layer thickness"

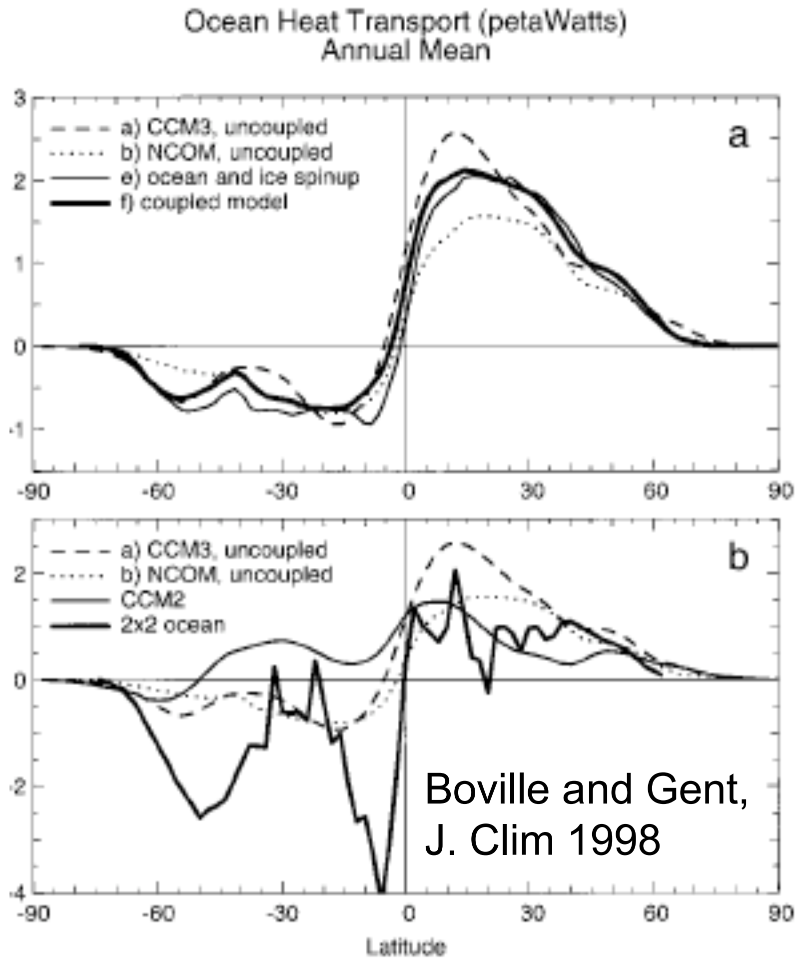
# Ocn Model Turbulence Param. in the momentum eqns

- ***Smagorinsky, sometimes***
  - **do boundary flows get dissipated too vigorously?**
- ***Anisotropic forms***
  - **High along-stream, low cross-stream**

# summarizing what we do…

- *set lateral viscosity as low as possible, consistent with minimum constraints of*
  - viscous balance with planetary vorticity in western boundary layer, where mid-latitude boundary jets live
  - noise control
- *use Gent-McWilliams form of isopycnal tracer mixing*
  - not only for direct impact of GM90 on fields of heat and salt (on the density structure), but then
  - rely on geostrophy to get much of the influence of sub-gridscale mixing on momenta

# Effectiveness of Gent-McWilliams isopycnal mixing



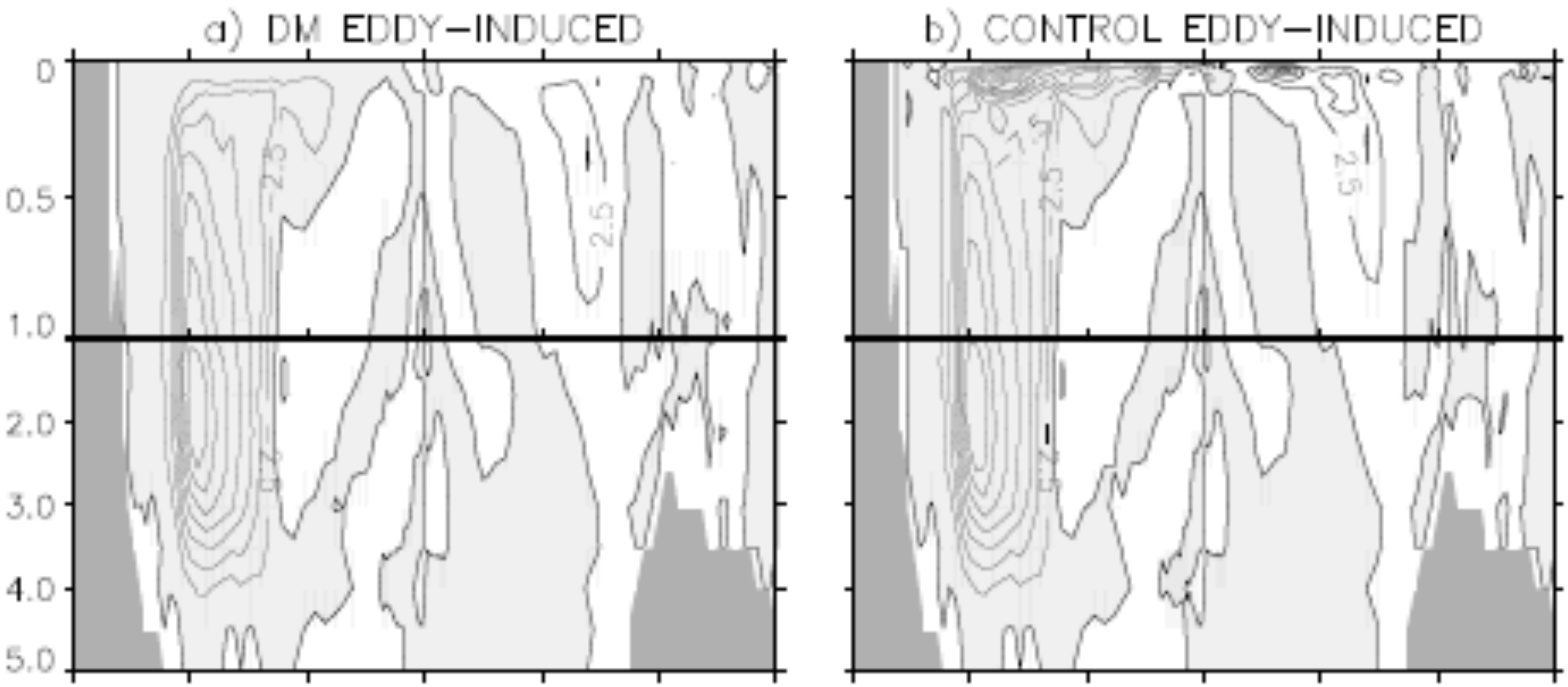

Compatible atmospheric and oceanic northward heat transports with use of GM90

Previous generation ocean model produced incompatible saw-toothed line -- required “flux corrections”

# Refinement of GM90 Isopycnal Mixing

- Isopycnal mixing is for the adiabatic interior
  - What to do in the very diabatic mixed layer?
  - How to transition between the two regimes?
- Focus of one of two NSF/NOAA funded “Climate Process Teams”

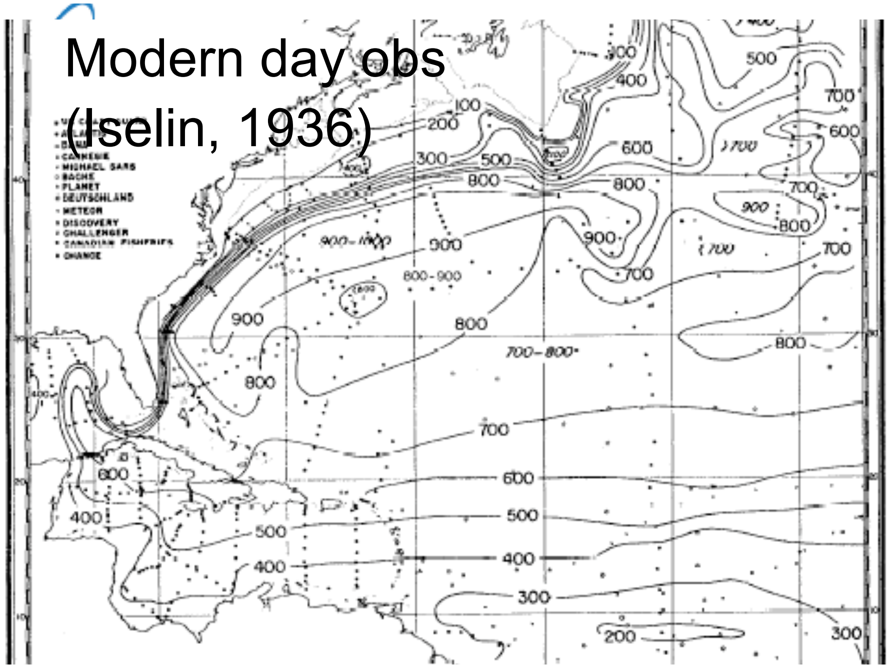
# Suspicious near-surface meridional transport cells disposed of with refinement to GM90



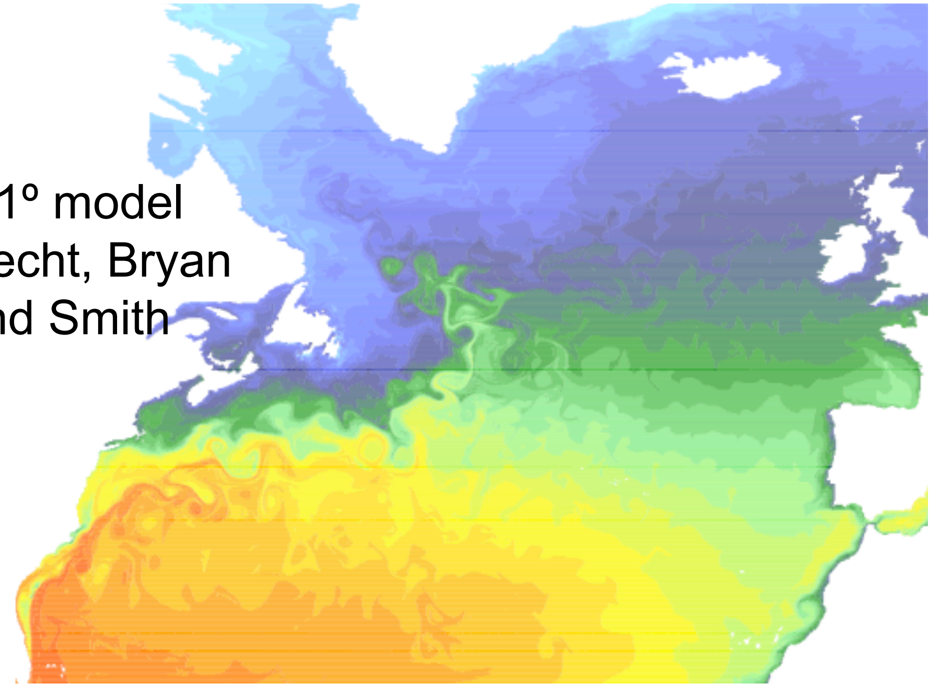

Danabasoglu, Ferrari and McWilliams, in review

# Features that resist parameterization

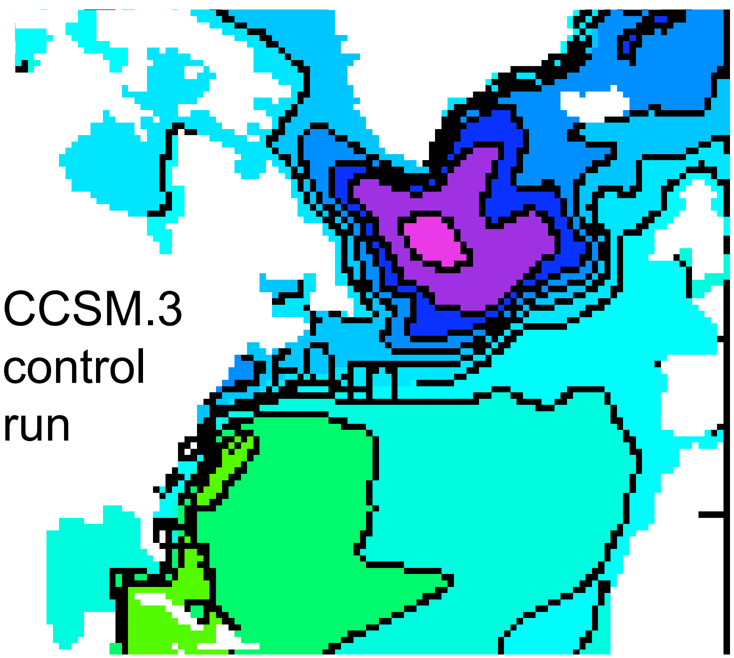
- Two examples:
  - Gulf Stream/North Atlantic Current System
  - Southern ocean response to wind stress



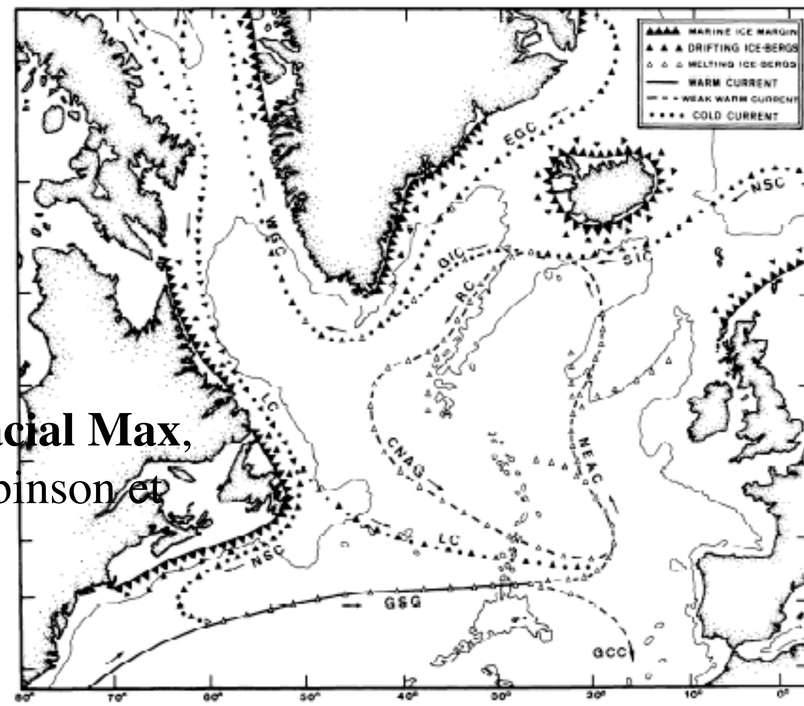
Modern day obs (Iselin, 1936)



0.1º model Hecht, Bryan and Smith



CCSM.3 control run



**Last Glacial Max**, from Robinson et al. 1995

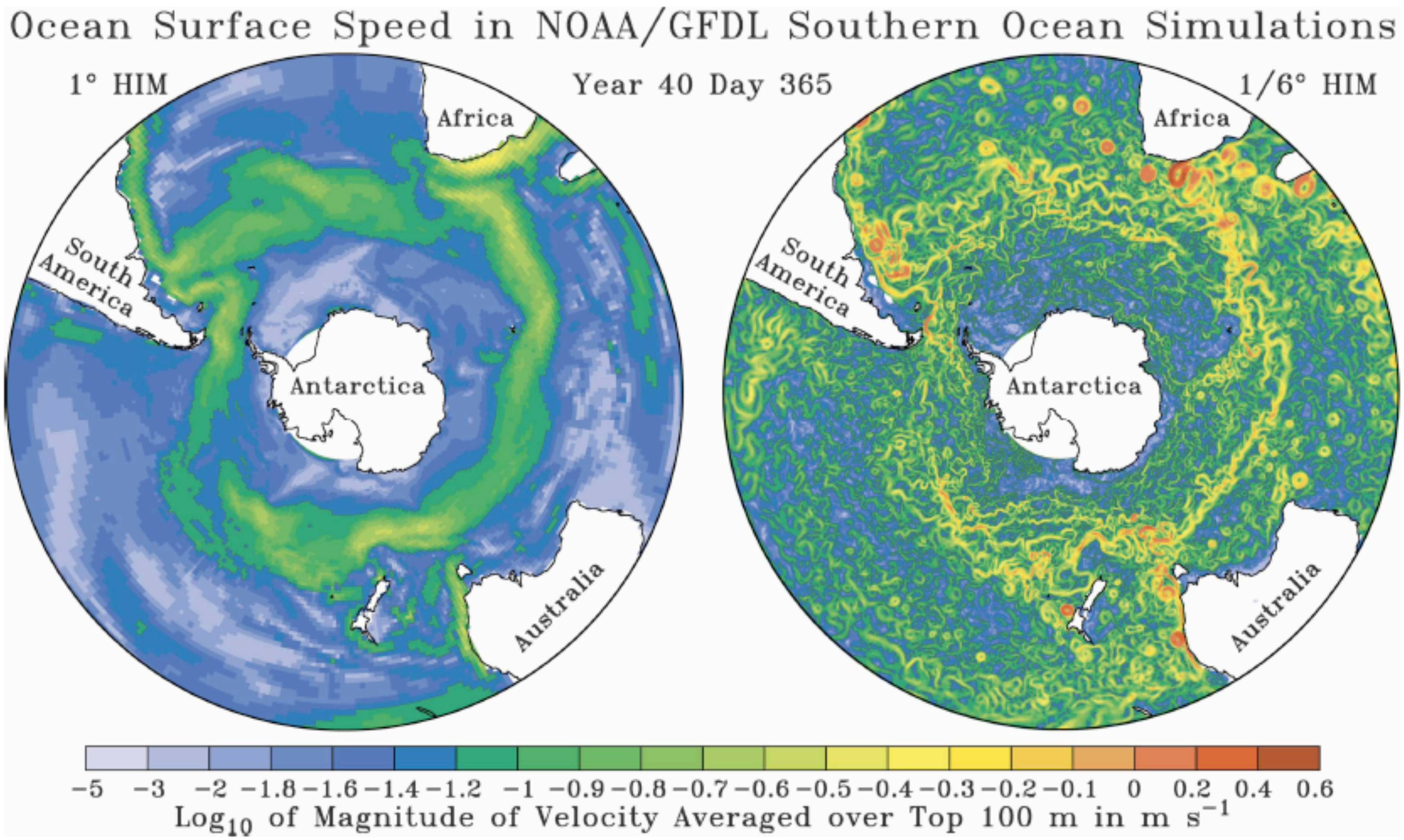



FIG. 6. Instantaneous surface speed in 1° and ⅙° models after 40 yr. Note that the large-scale structure of the 1° model is quite similar to the ⅙° model (the currents have similar locations and have similar horizontal extents). The main difference is in the presence of intense jets and eddies in the ⅙° model.

HALLBERG AND GNANADESIKAN

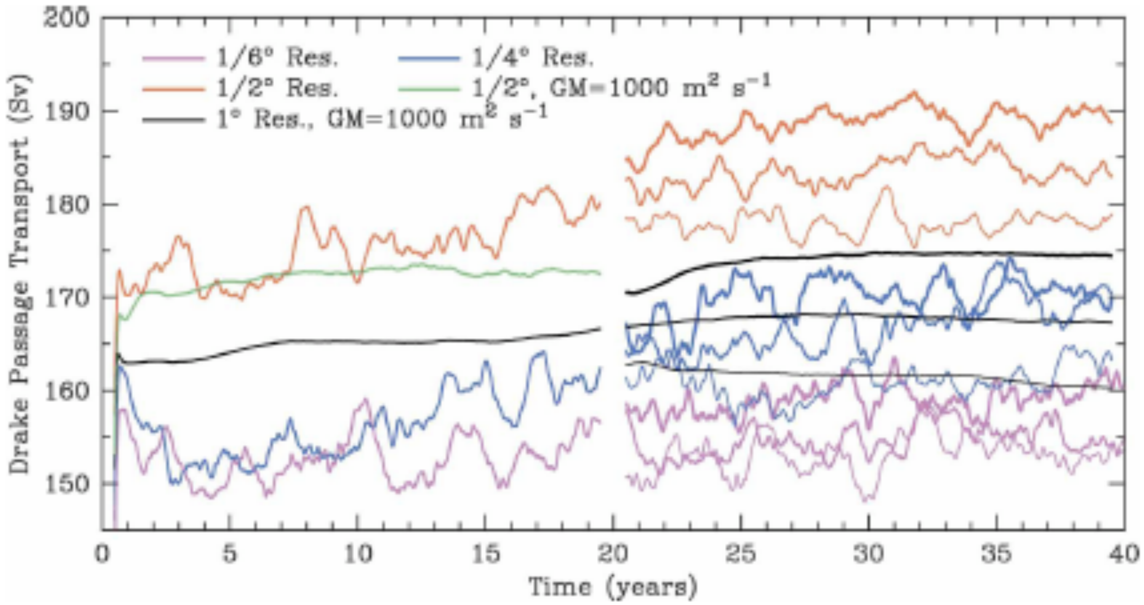


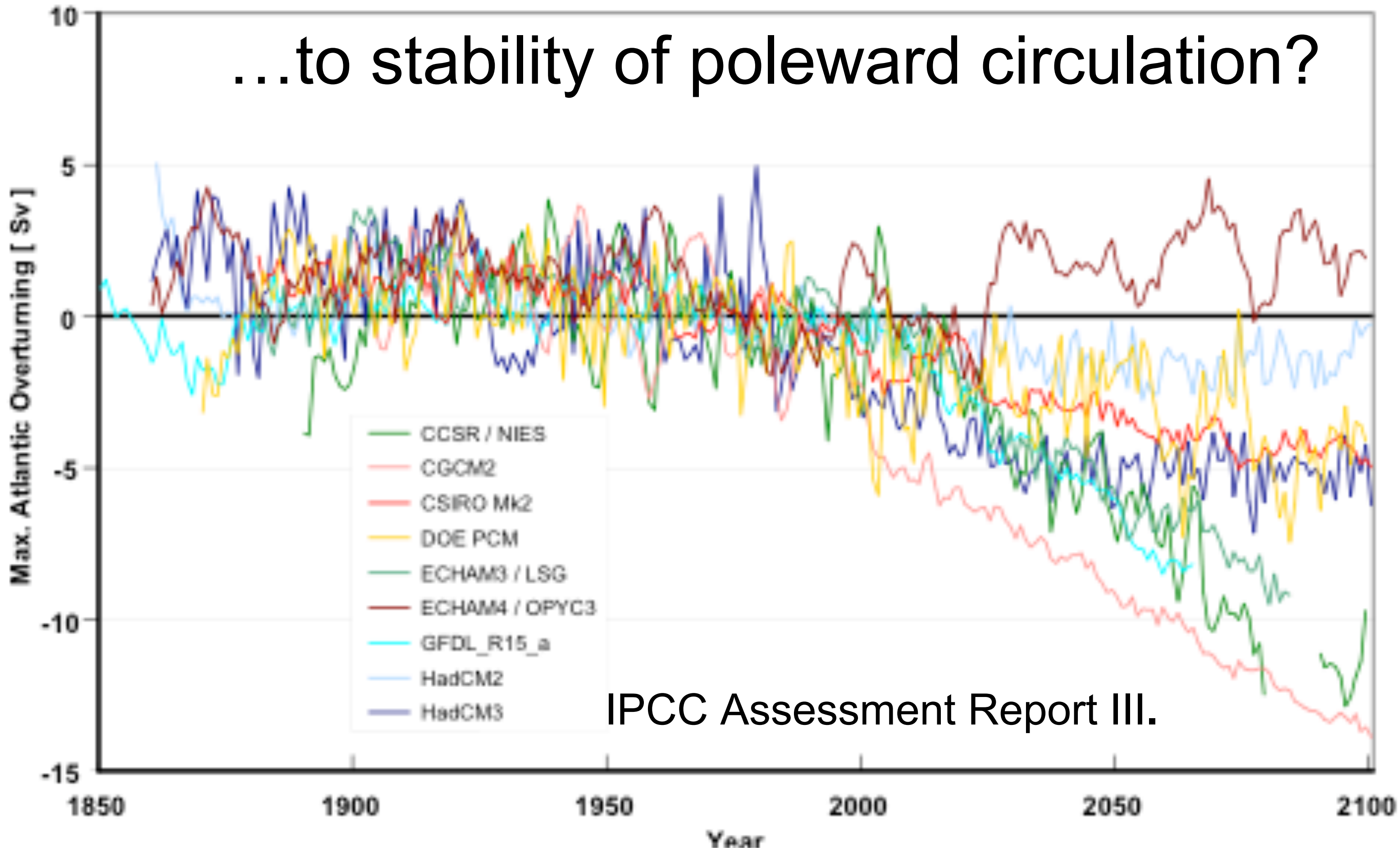

FIG. 4. One-year running mean Drake Passage transport at ⅙° (magenta), ¼° (blue), and ½° (red) resolutions with explicit eddies, and at ½° (green) and 1° (black) resolutions with eddy effects parameterized with an interface height diffusivity (akin to GM) of 1000 $m^2 s^{-1}$. After 20 yr, the heavier lines denote the cases with stronger winds and the thinner lines are with weaker winds. Adding the GM parameterization to the ½° model suppresses both the marginally resolved eddy variability and most of the Drake Passage transport variability at a range of time scales.

# Does it matter?

- Will these less adequately modeled features matter more to 21rst Century response than to 20th Century “control”?

# Does the path taken by warm, salty North Atlantic waters matter…

…to stability of poleward circulation?



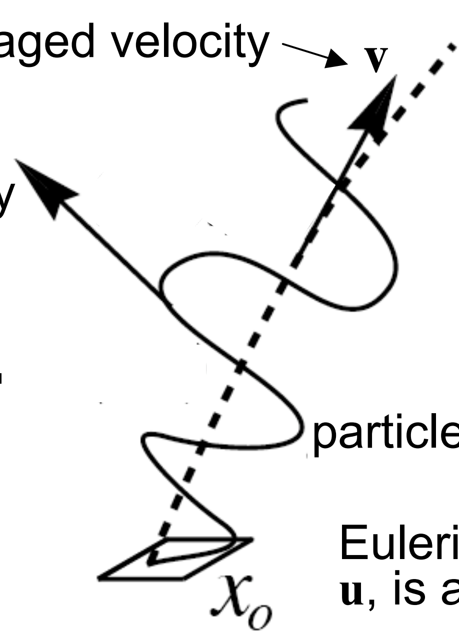

IPCC Assessment Report III.

- Efforts underway to study 21rst century climate response with more realistic eddy-resolving ocean
  – Recall that term, “grand challenge”?

- A few words on one more effort to get a more complete representation of influence of mesoscale variability on the mean circulation…

# Lagrangian-Averaged Navier-Stokes Equation (LANS-$\alpha$)

## Two ways to take averages: Lagrangian and Eulerian




$\mathbf{v}$ Lagrangian averaged velocity

$\mathbf{u}$ Eulerian averaged velocity

$$\underset{\text{smooth}}{\mathbf{u}} = \underbrace{\left(1 - \alpha^2 \nabla^2\right)^{-1}}_{\text{Helmholtz operator}} \underset{\text{rough}}{\mathbf{v}}$$

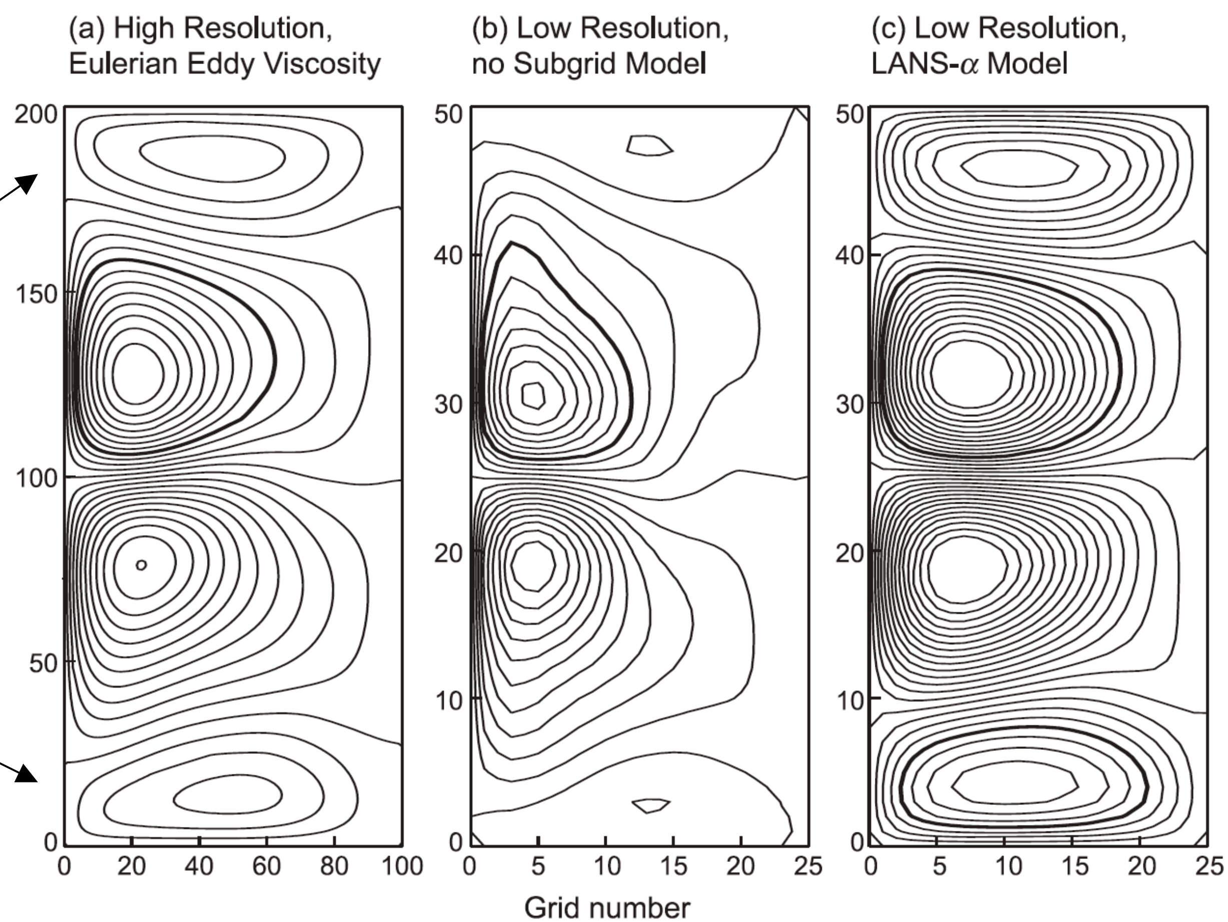
LANS-$\alpha$:

- is derived using asymptotic methods in Hamilton's principle.
- satisfies Kelvin's Circulation Thm, conserves energy and potential vorticity in the absence of dissipation.

# LANS-$\alpha$ in QG model

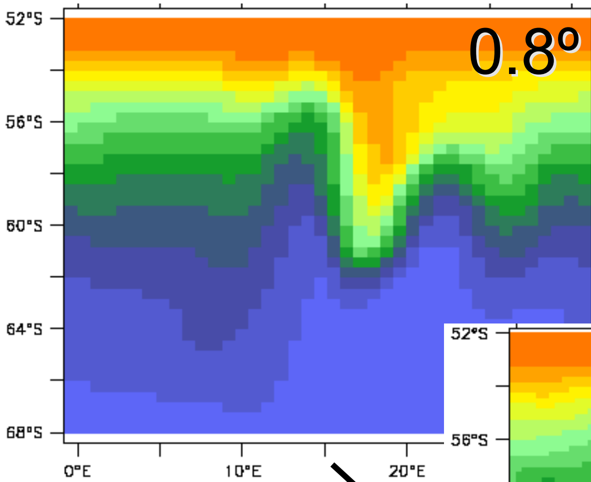
## with double gyre forcing

Secondary Fofonoff gyres appear at higher resolution -- mean features driven by mesoscale variability

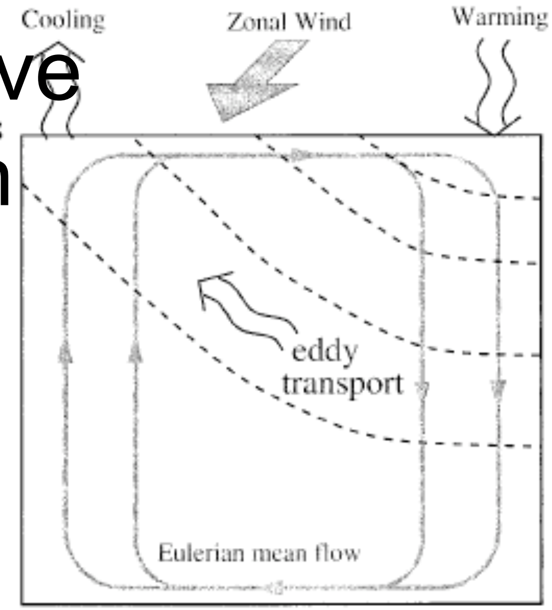



Secondary gyres captured at low resolution with LANS-$\alpha$

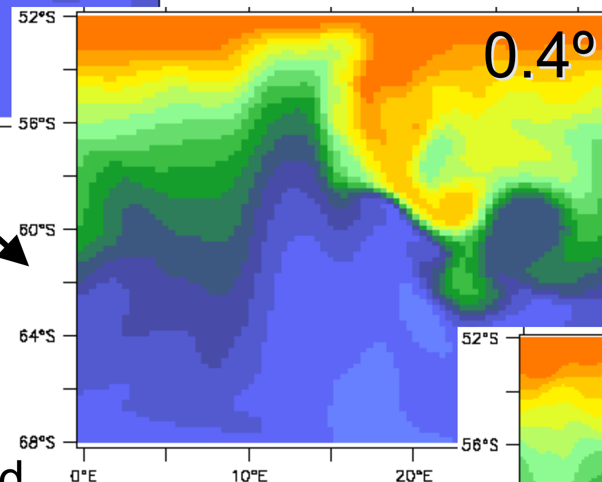
Holm and Nadiga, JPO 2003



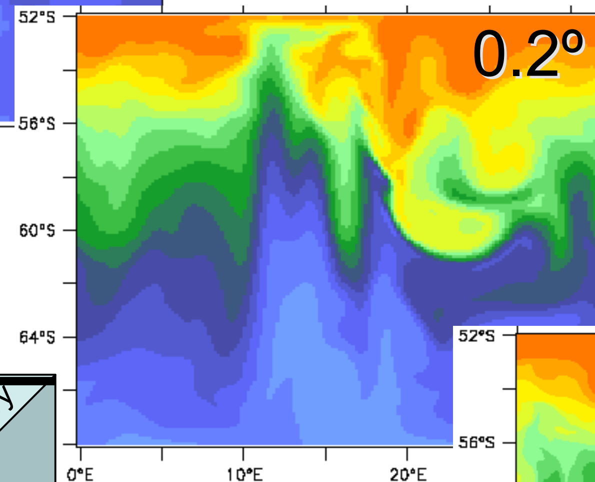

# LANS-α in Primitive Equation Ocean Model



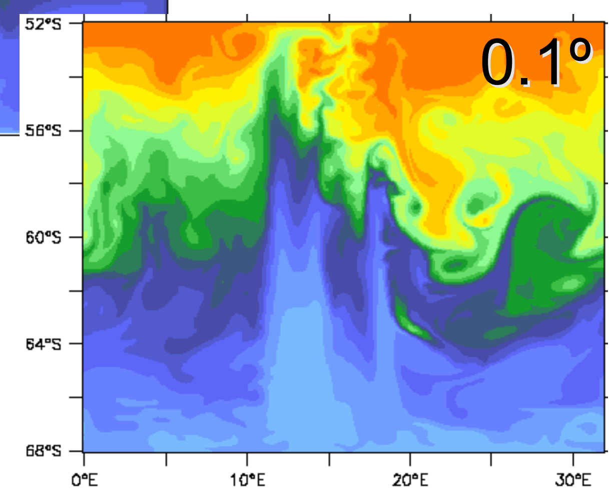

Karsten et al., JPO 2002

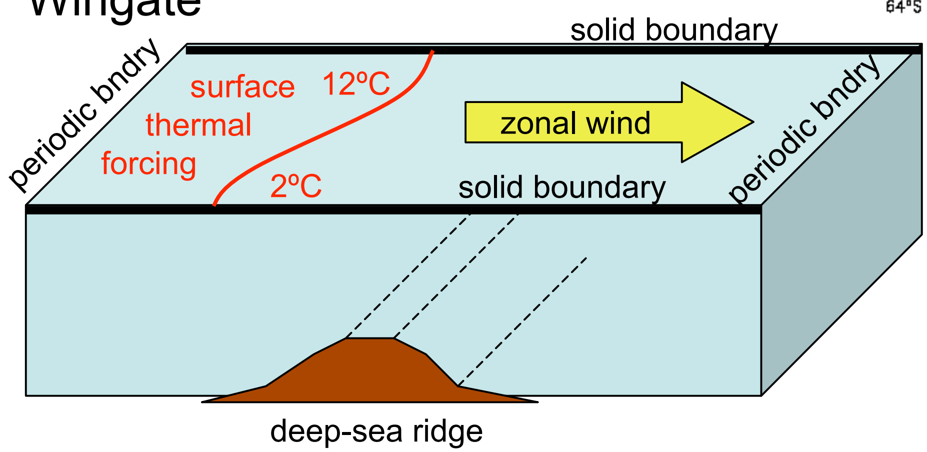



cost of doubling horizontal grid is factor of 10



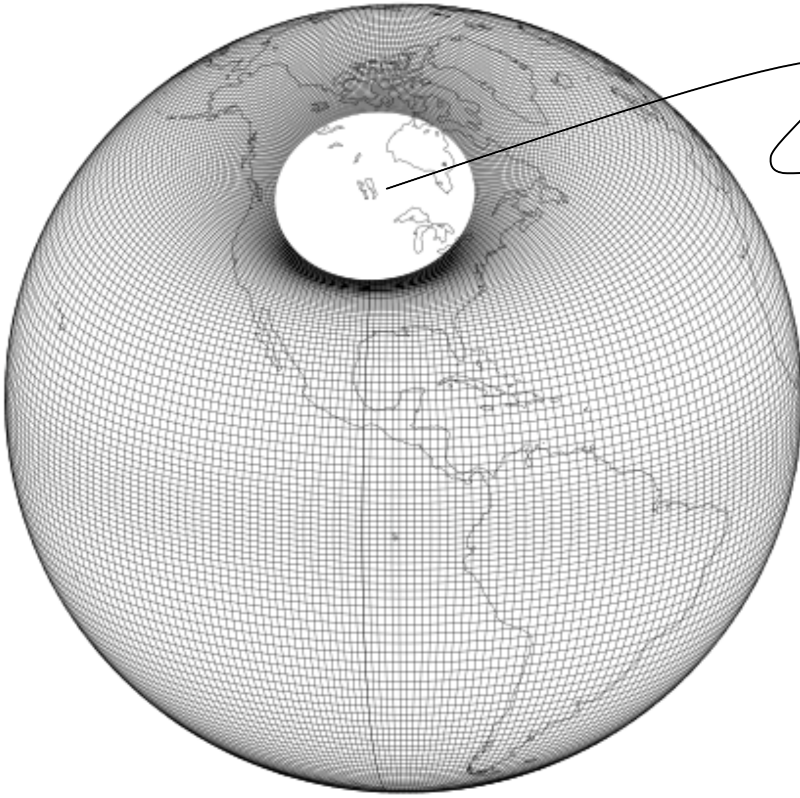

Implementation and evaluation described in Hecht, Holm, Petersen and Wingate



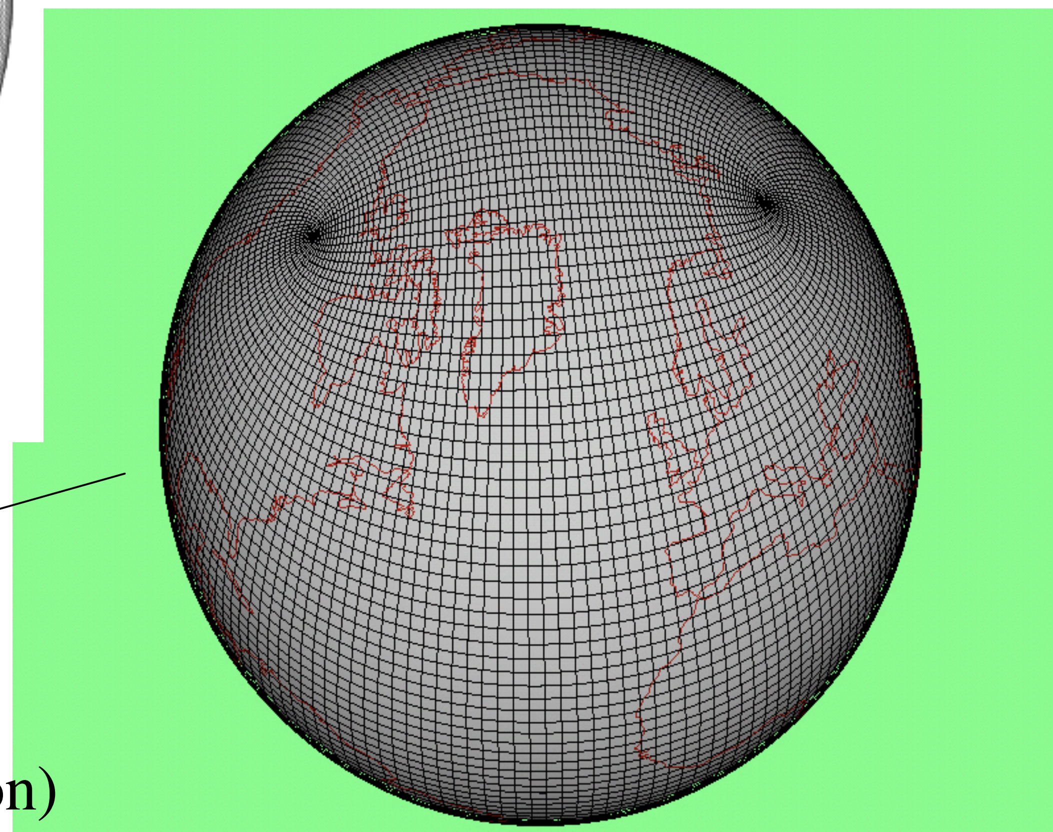



# Other considerations for climate ocean modeling

- Transport scheme
  - Do we require sign preservation, or even strict monotonicity?
  - Concern for spurious convection, 2*dx modes?
  - Griffies et al. (2000) point out:
    - spurious mixing *increases* with eddy variability
    - case for importance of transport scheme at *high* resolution.
- Horizontal grid discretization
  - Uniformity, or focused resolution?



Dipole Grid
(CCSM puts pole in Greenland,
resolution focused around Greenland)



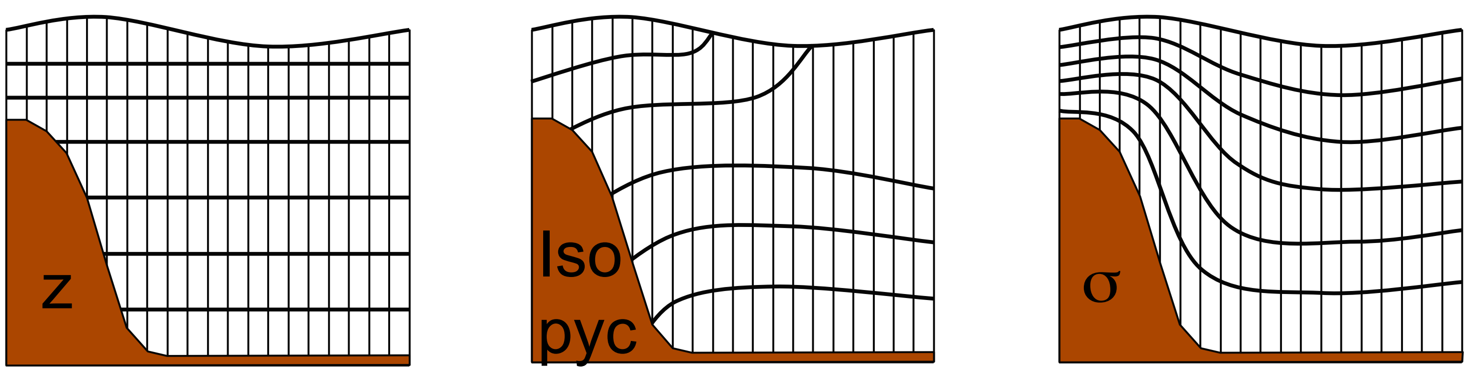
Tripole Grid
(relatively uniform resolution)

# …other considerations

- Vertical discretization of topography
  - Penduff (2002), Barnier (2006), make case for at least light smoothing
  - but still need to maintain extrema (sills, passages)
- Vertical mixing, convection
- Tides, bottom topography and mixing
- Overflows
- Can the vertical discretization of the ocean handle more than a few meters of sea ice?

# Vertical coordinates: there are choices

- We've talked about "z-coordinate" modeling
  - because this is what most of us do
- Classes of code have traditionally been set by different vertical coordinates
  - Z-models: large-scale climate
  - isopycnal-models: idealized adiabatic simulations
  - Sigma-models: coastal applications
- These barriers being eroded



# Vertical coordinates for climate

- Standard z-coordinate models to be well represented in IPCC AR5
- Hybrid isopycnal/z-coordinate model making inroads
  - HYCOM: used by GISS, studied within CCSM by FSU
- MIT has option for $z^*$
  - Variation on z-coordinate, no restriction on thickness of first level
    - Sea-ice needn't be restricted to a few meters thickness
  - GFDL MOM adopting $z^*$ as well
- LANL POP developing a different kind of hybrid
  - Hybrid isopycnal/z-coordinate for temperature, salinity
  - Z-coordinate for momenta
    - Minimization of pressure gradient errors
  - Energetically consistent interpolations between

# Take up some of these issues with an ocean modeler:

- Best options for:
  - adiabatic tracer mixing,
  - viscosity?
- Grid discretization:
  - Horizontal,
  - vertical?
- Resolution?
- Transport?
- Basic model formulation:
  - Vertical coordinate?
  - and other very fundamental issues not touched on here (but you'll know many of them)…