Coherent structures in high-resolution ocean model simulations and implications for climate prediction

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Thanks to : Enrique Curchitser, Alexey Kaplan, Chris Edwards, Nikolai Maximenko

Why high-resolution simulation of global ocean?

- **Critical for global climate prediction**

  -- IPCC projection of 21st century climate (under global warming) relies on coupled global ocean-atmosphere model simulations

- **Applications in short-term (daily-to-weekly) ocean prediction**

  -- Now routinely carried out by U.S. Navy, among others

- **Important test-ground for key parameterization schemes for large-scale fluid simulations**

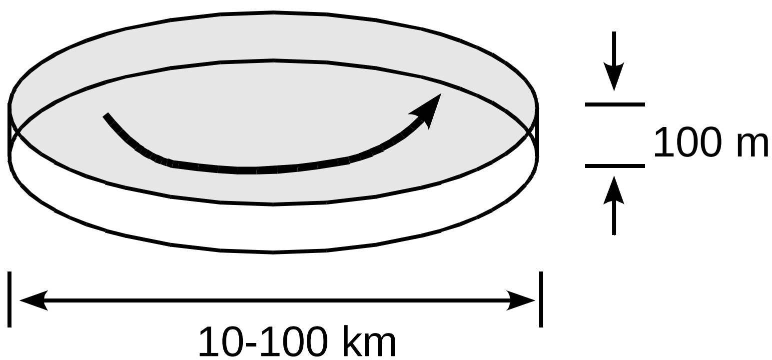
  -- Turbulent mixing, subgrid-scale form drag, etc.
  -- Model prediction can be verified by observations

- **Numerical laboratory for basic problems in geophysical fluid dynamics**

For large-scale simulation: "High resolution" means "**eddy resolving**"

"Eddies" here refers specifically to "**meso-scale eddies**"

- Quasi-two-dimensional: $L_H \sim O(10\text{-}100\ \text{km})$, $L_Z \sim O(0.1\text{-}1\ \text{km})$
- Stably stratified; Earth rotation (Coriolis force) important
- Approx. geostrophic and hydrostatic
- Approx. conservation of potential vorticity, $PV = -(\zeta+f)\partial\rho/\partial z$



Not to be confused with eddies in classical 3-D turbulence,
which still need to be parameterized in ocean models

A conventional cutoff :

$$\mathbf{L_{Eddy} \sim L_D} \quad ,$$

L_D : the 1st baroclinic Rossby radius of deformation

"Eddy resolving" simulation : Grid size < L_D

$L_D = NH/f$ N : Brunt-Väisälä frequency

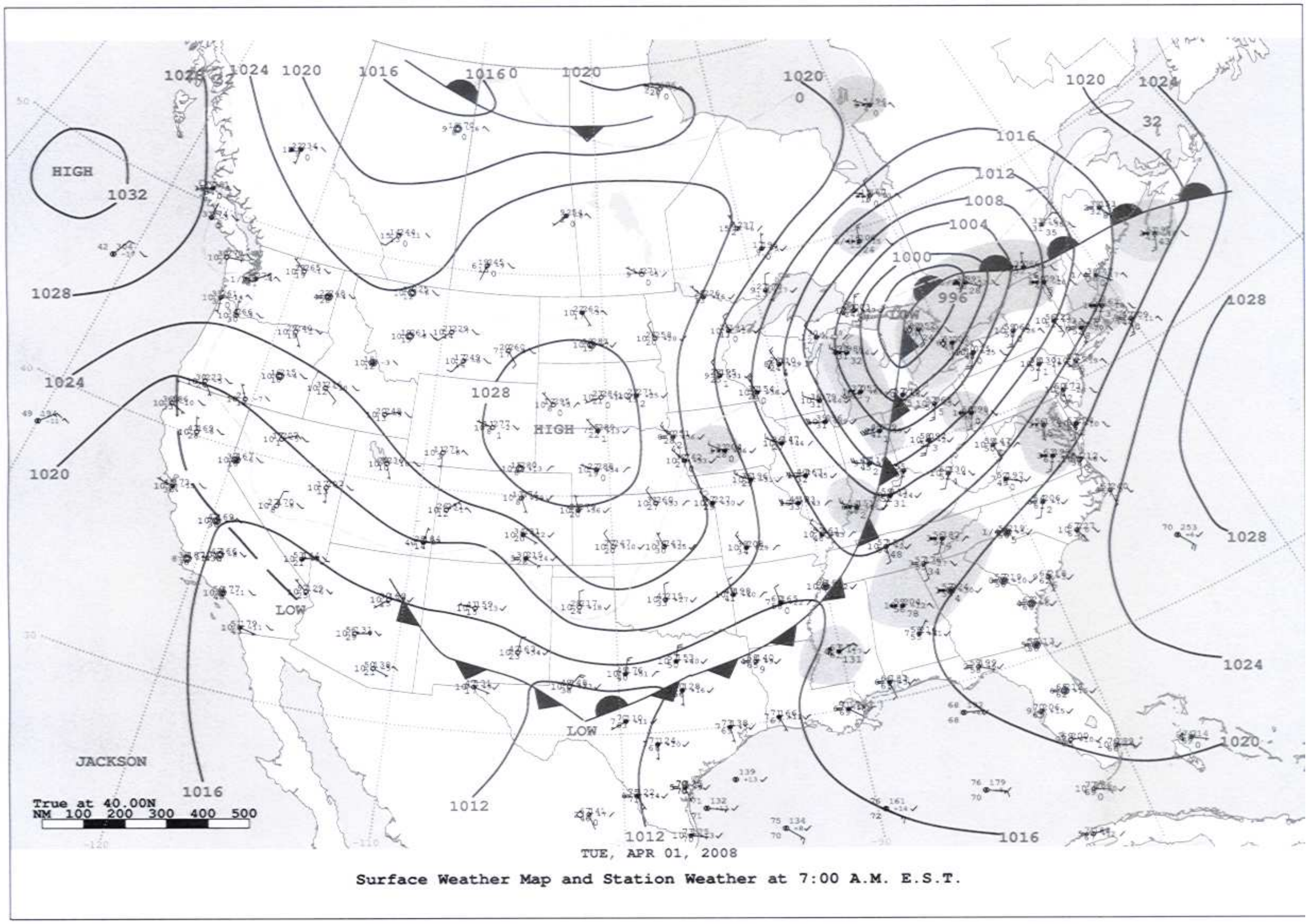
H : equivalent depth

$f = 2\Omega\sin\phi$: Coriolis parameter,

Ω : Earth rotation rate, ϕ : latitude

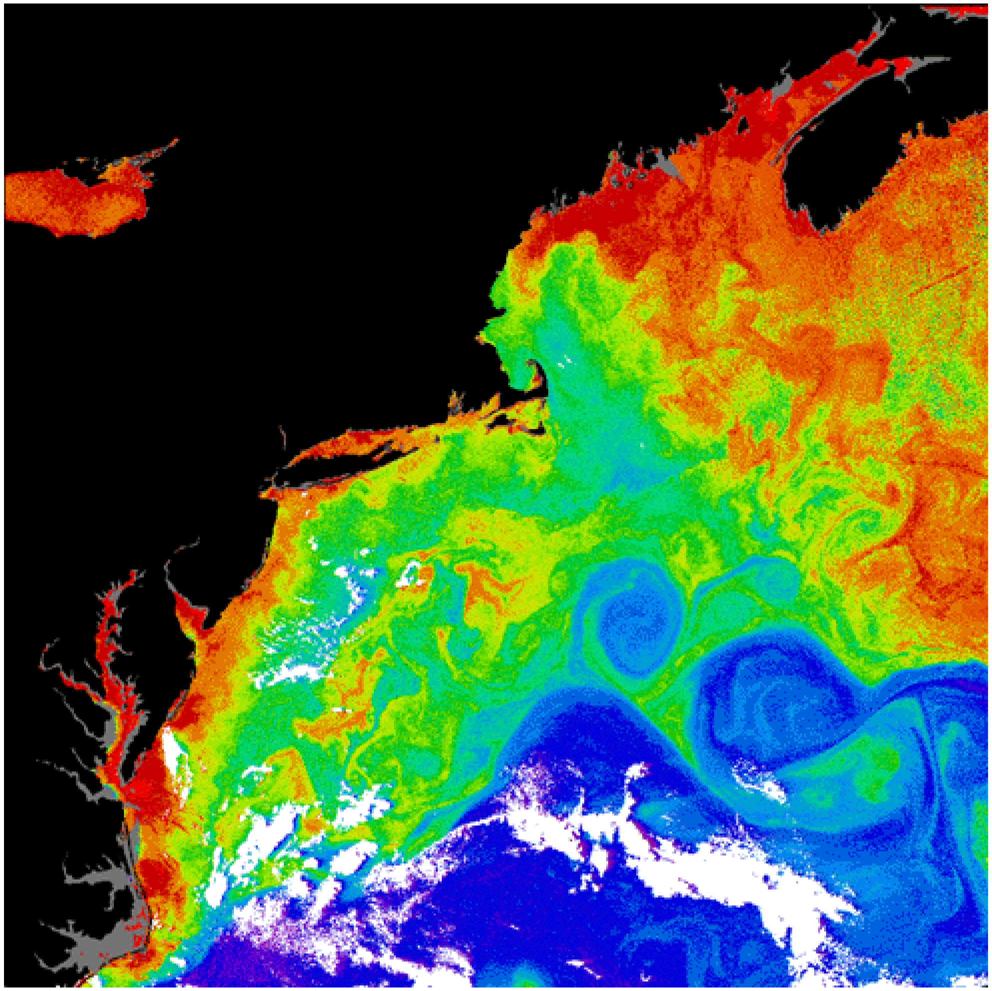
Atmosphere: $L_D \sim O(1000\ \text{km})$

Mid-latitude eddies (= weather storms) are well-observed
and relatively easy to simulate (daily weather forecast)



Weather map (sea level pressure), April 1, 2008, 00Z UTC   Source: NOAA

Ocean: L_D ~ 50 km : Eddies are small and numerous



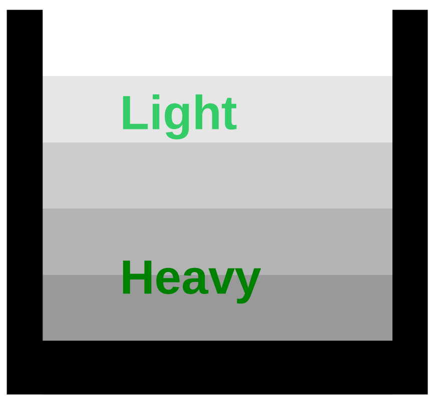
|<--->| 100 km

Satellite (Nimbus-7) observation of "**ocean color**"
(concentration of phytoplankton), NW North Atlantic
Source: NASA GSFC

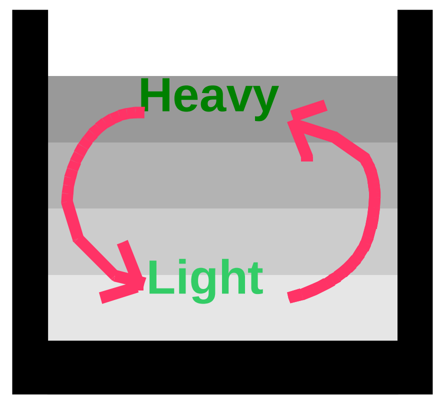
Why meso-scale eddies have a distinctive scale?

Meso-scale eddies in the ocean ("synoptic eddies" in the atmosphere) are generated by *buoyancy production* through *baroclinic instability*

Classical convection



Stable



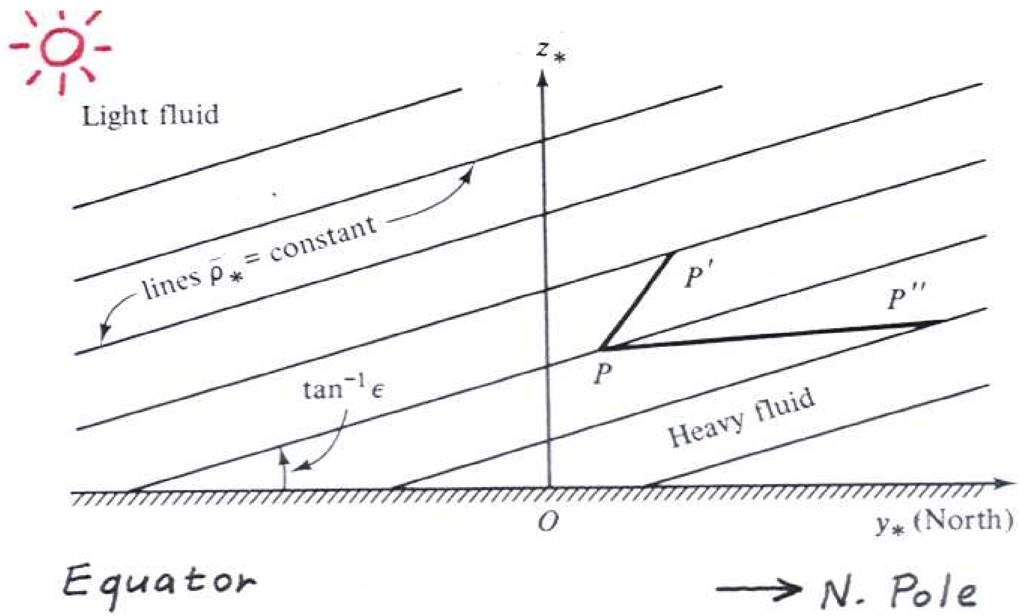
Unstable

(whichever way you perturb it)

Baroclinic instability

- Large-scale flow is stably stratified at every location
- But **density surface is tilted** due to differential solar heating
- Positive buoyancy production is possible for large eddies (path P-P'' in figure)
- Small-scale perturbations (P-P' in figure) are damped
- **Cutoff scale : L ~ L_D**

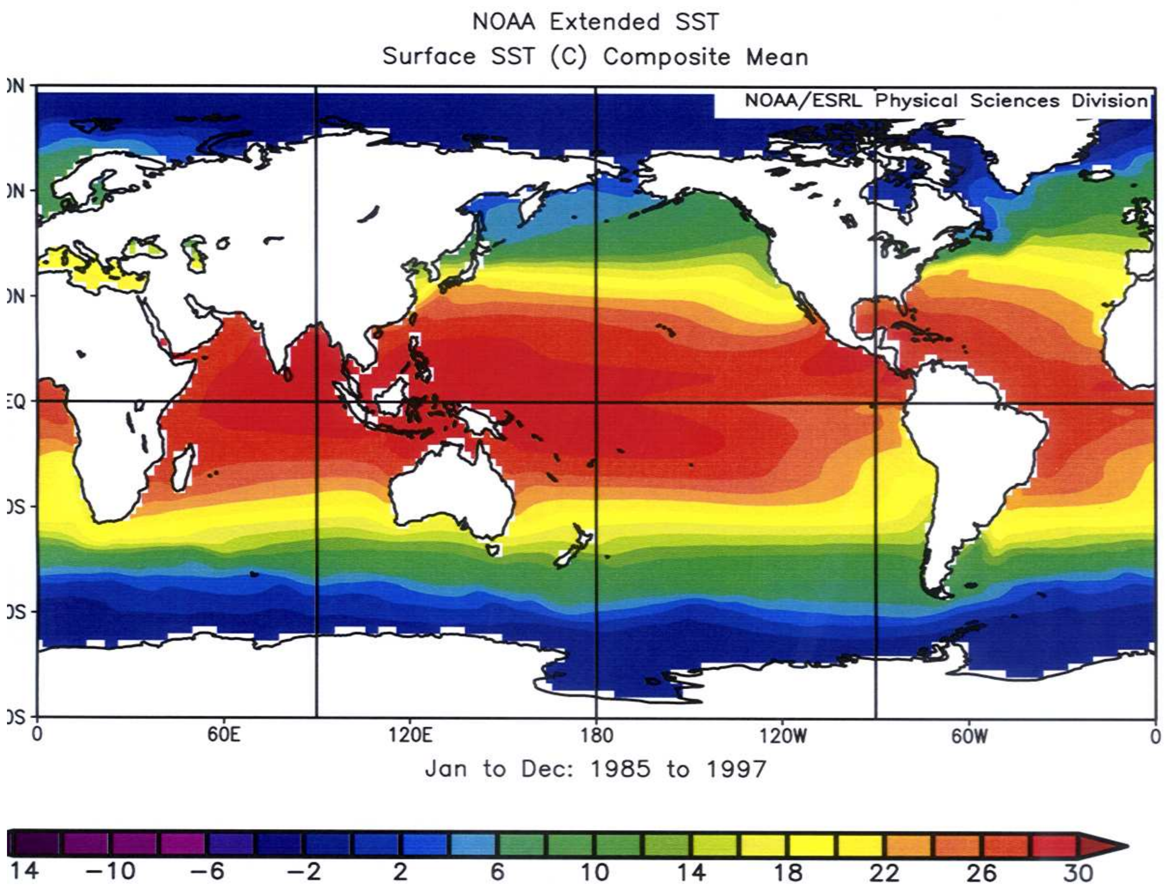
(The actual scale of a mature eddy can be somewhat larger)



(Drazin and Reid 1981)

North-south temperature gradient is important

Observed mean sea surface temperature



Observation of global ocean currents

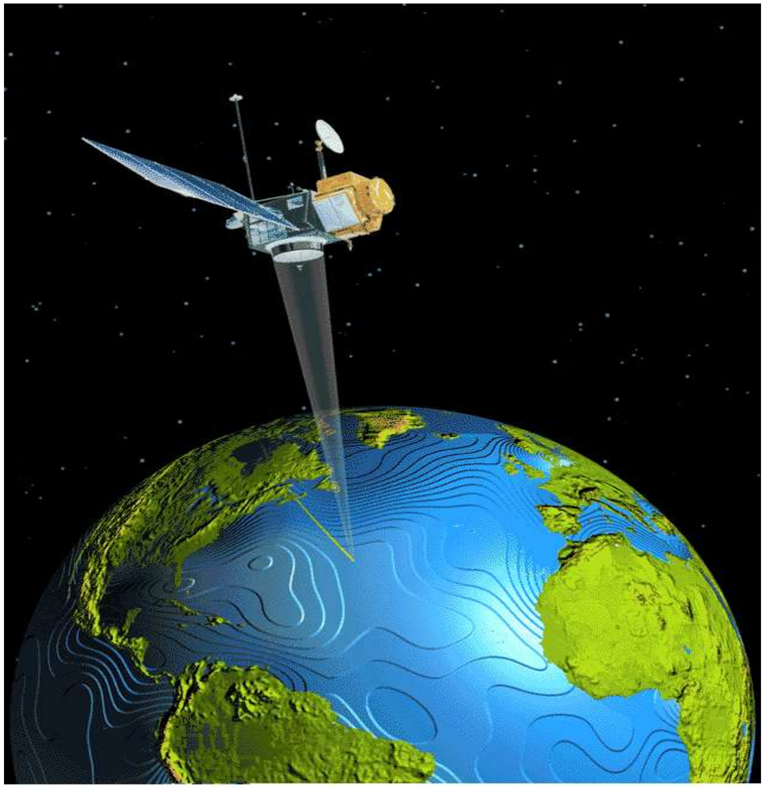
Surface:
Satellite **altimeter** measurement of sea surface height, converted to horizontal velocity by geostrophy,

$$\boldsymbol{v} \sim -\hat{\boldsymbol{z}} \times f^{-1} \nabla h$$

Resolution ~ 0.3° lon/lat, weekly, mid-1990s - present

In situ observations (buoy, float, tidal gauge) are sparse

Deep ocean:
In situ measurements only
Sparse in space & time;
Global survey a challenge



The altemeter on-board NASA's Topex Satellite is a radar. (source: NASA JPL)

Altitude of orbit = 1336 km

Required accuracy for h ~ a few cm

Numerical simulations

Long-term (T > 10 years), hydrostatic, simulations for global ocean or a full basin at $\Delta x \sim 0.1°$ lat/lon have become feasible.

The 3-D ocean model: ROMS

Regional Ocean Modeling System (Shchepetkin & McWilliams 2005, Curchitser et al. 2005)

Horizontal momentum eq.

$$\frac{\partial \boldsymbol{v}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{v}+2\boldsymbol{\Omega}\times\boldsymbol{v}=-\nabla\Phi+\boldsymbol{F}+\boldsymbol{D}\quad,\quad \boldsymbol{\Omega}\ \text{: Earth rotation}$$

Advective-diffusive eqs. for temperature & salinity

$$\frac{\partial}{\partial t}\begin{pmatrix}T\\S\end{pmatrix}+\boldsymbol{v}\cdot\nabla\begin{pmatrix}T\\S\end{pmatrix}=\begin{pmatrix}F_T\\F_S\end{pmatrix}+\begin{pmatrix}D_T\\D_S\end{pmatrix}$$

Continuity eq.: $\frac{\partial w}{\partial z}+\nabla\cdot\boldsymbol{v}=0$ Equation of state: $\rho=\rho(T,S,P)$

Hydrostatic in vertical: $\frac{\partial\Phi}{\partial z}=\frac{-\rho g}{\rho_0}$, Φ is dynamical pressure

- Flexible horizontal grid (orthogonal curvilinear, staggered Arakawa C grid)
- Flexible geometry (ocean domain, bathymetry); Terrain-following vertical grid
- Flexible boundary condition (Closed basin, prescribed, open, etc.)

- Turbulent mixing within oceanic boundary layer is parameterized (KPP, Large et al. 1994)

The large-scale ocean is primarily forced from above

Example: Precipitation over the ocean provides a negative forcing for salinity

Most important forcing for the model:

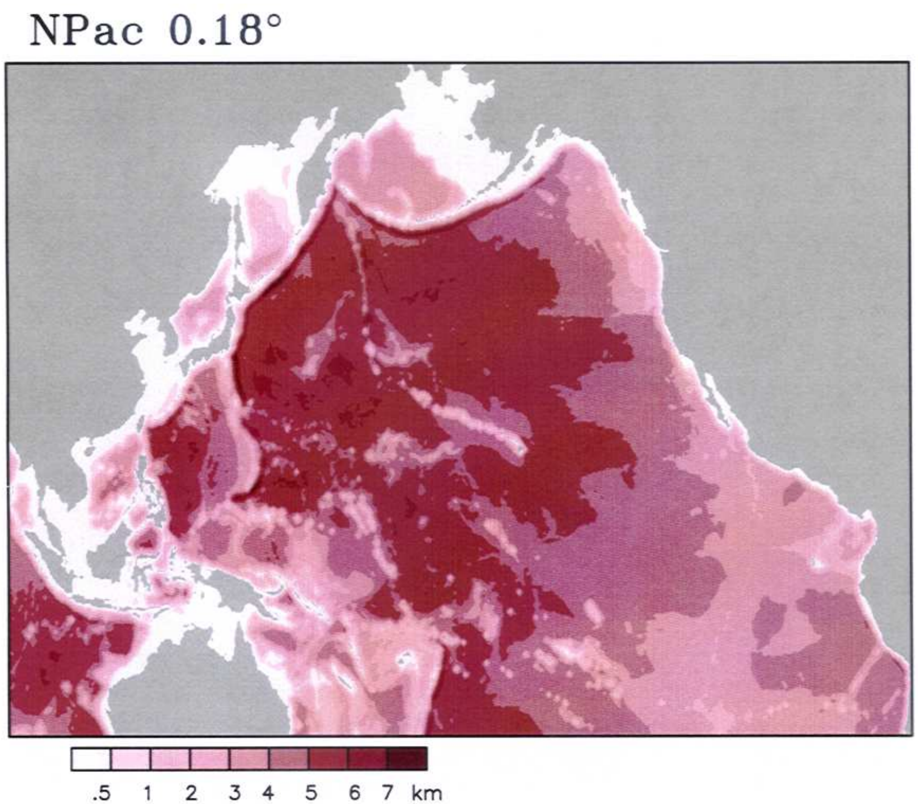
Surface wind stress, **heat flux**

Strategy for a "realistic" large-scale ocean simulation

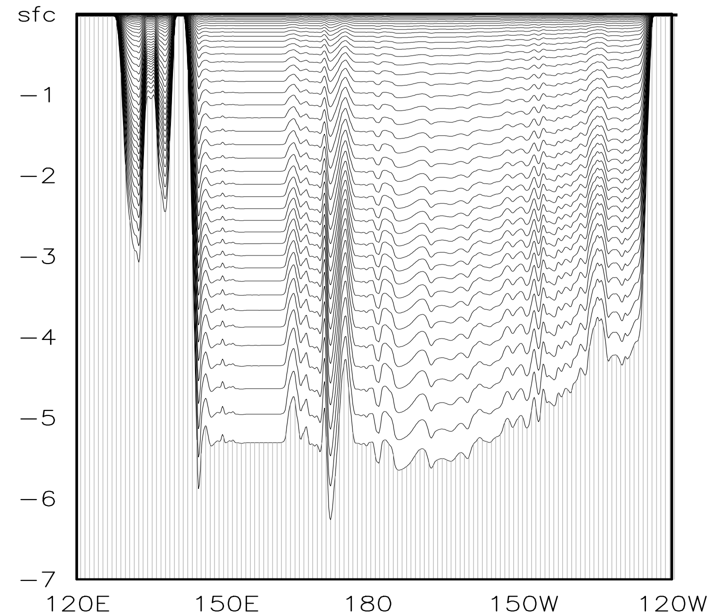
Use meteorological observations (temperature, surface wind, precipitation, etc.) interpolated onto ocean model grid as the forcing ($\boldsymbol{F}$, F_T, F_S)

Ocean feedback to the atmosphere (important for long-term climate prediction) is momentarily ignored

Simulation for the Pacific Ocean: 0.18° resolution, 42 levels



Bathymetry (bottom topography)



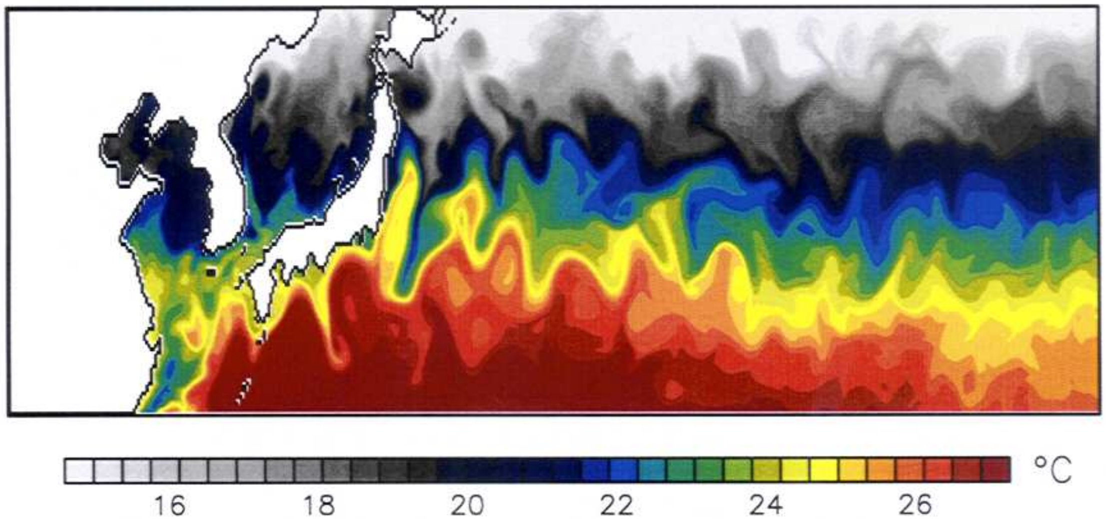
X-section of vertical levels along 40°N

- **Forcing**: Meteorological observations ("Reanalysis")
- **Lateral boundary**: This simulation is nested within a coarse resolution (1°) global ocean model simulation (NCAR CCSM)
- 20-year integration, output archived as 4-day average

Thanks to Enrique Curchitser

Sea surface temperature, snapshot

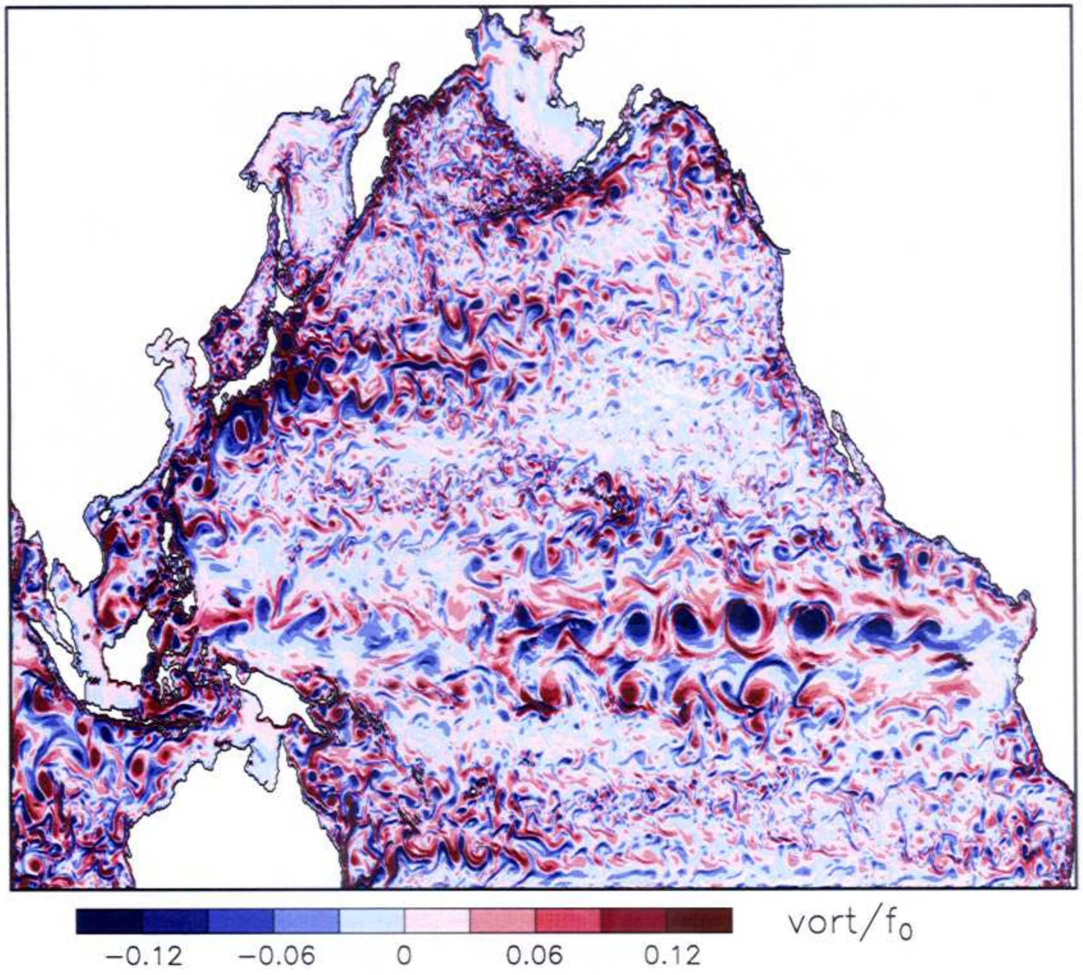
Northwest Pacific, Kuroshio region



Eddies grow along tight (N-S) temperature gradient

(recall baroclinic instability / slantwise buoyancy production)

Vorticity at surface (snapshot)



Shown is ζ/f (~ Rossby number, *Ro*), f = Coriolis parameter at 35°N

Ro ~ *O*(0.1) in midlatitude over the North Pacific

Identify the vortices

Okubo-Weiss parameter (for horizontal velocity): $Q = \|\mathbf{Z}\|^2 - \|\mathbf{S}\|^2$

Rotation dominates (coherent vortex): $Q > 0$
Shear straining/deformation dominates: $Q < 0$

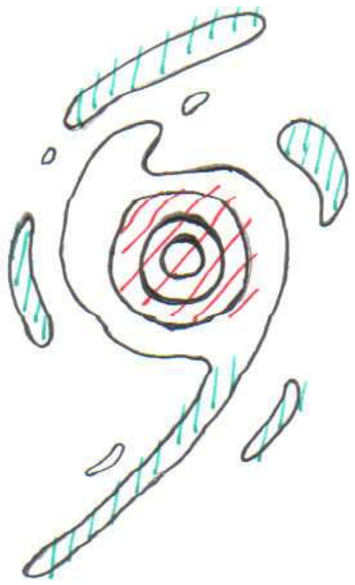
$Q \sim \zeta^2/2$ (enstrophy) at the core of a coherent vortex

Rotation tensor $\mathbf{Z} = \frac{1}{2}\left[(\nabla \mathbf{V}) - (\nabla \mathbf{V})^{\mathbf{T}}\right]$

(rate of) Strain tensor $\mathbf{S} = \frac{1}{2}\left[(\nabla \mathbf{V}) + (\nabla \mathbf{V})^{\mathbf{T}}\right]$

$\nabla\mathbf{V}$ is velocity gradient tensor

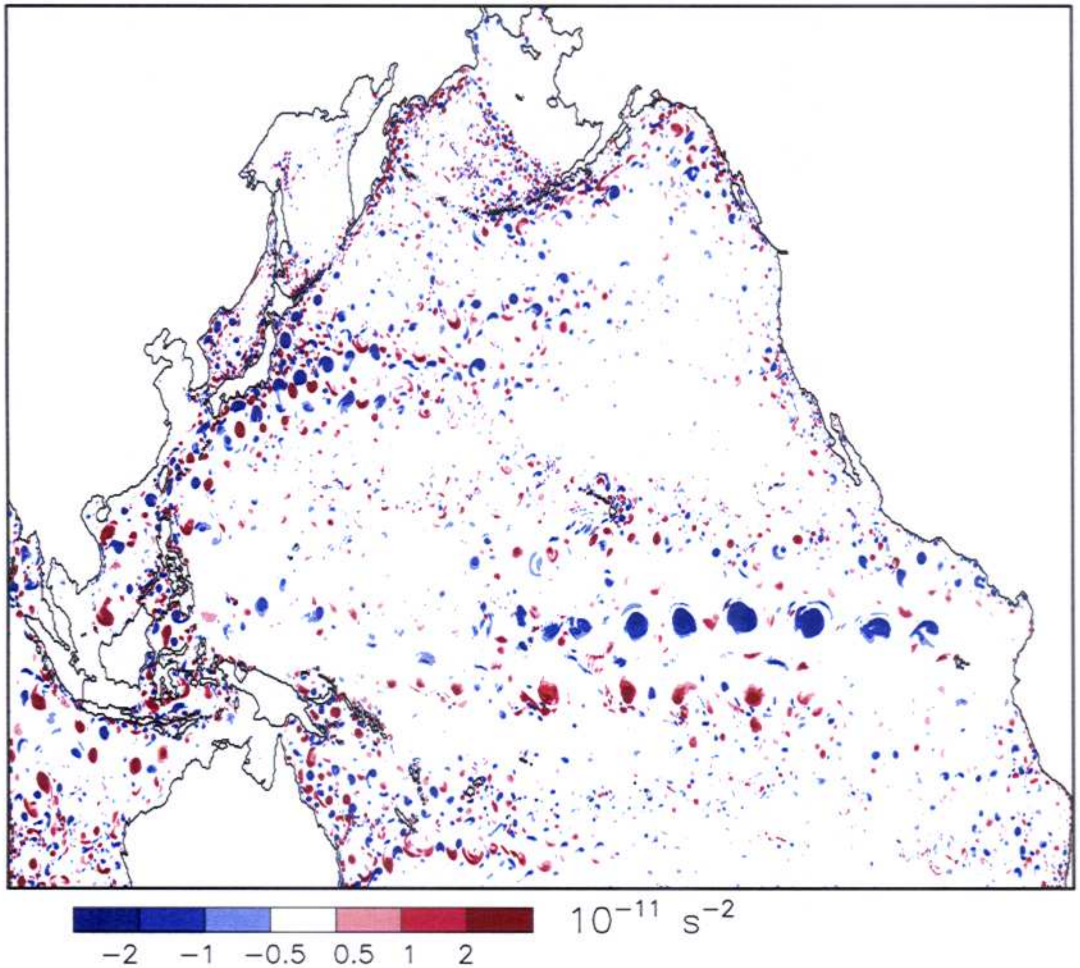
Frobenius norm: $\|\mathbf{S}\| = \left[\mathbf{tr}\left(\mathbf{S}\,\mathbf{S}^{\mathbf{T}}\right)\right]^{1/2}$, $\|\mathbf{Z}\| = \sqrt{\zeta^2/2}$



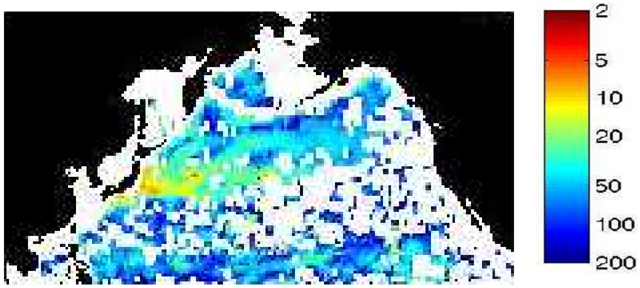
Red: Rotation dominates, $Q > 0$
Green: Straining/deformation dominates, $Q < 0$

Map of $sgn(\zeta)\ Q$ (snapshot)

Negative Q area suppressed



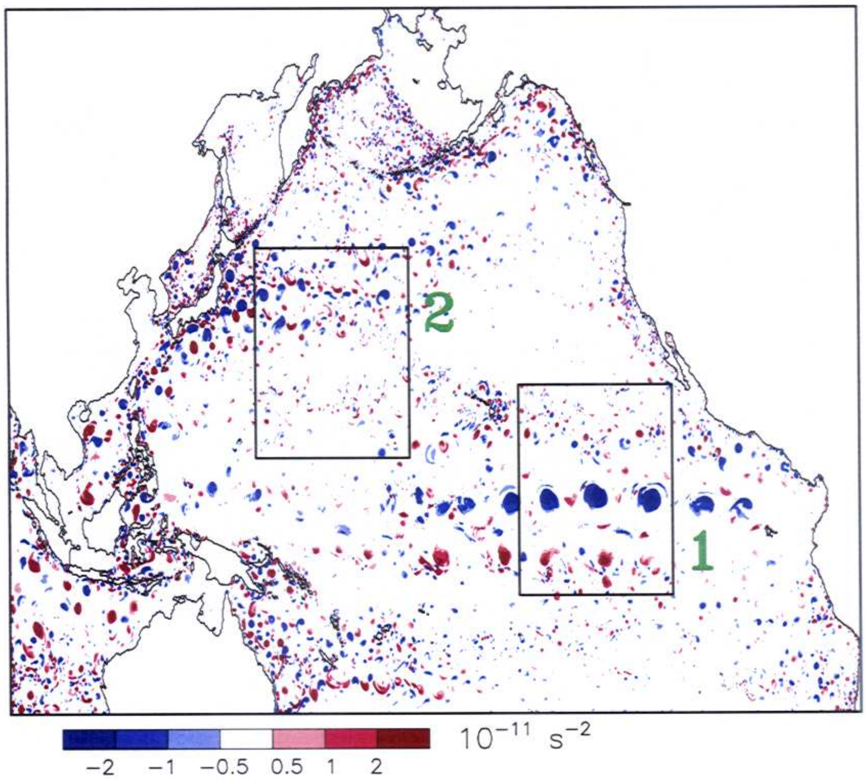
In the N.H.: Red: cyclone ($\zeta > 0$) Blue: anticyclone



Smith (2008): e-folding time, most unstable mode of baroclinic instability

Northeast Pacific has relatively fewer eddies -- consistent with observation (Chelton et al. 2007) and with local baroclinic instability calculation for observed mean flow (Smith 2008)

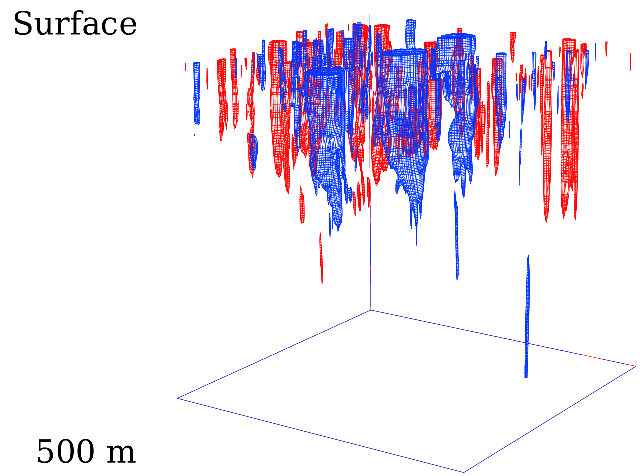
Vertical extent of the vortices



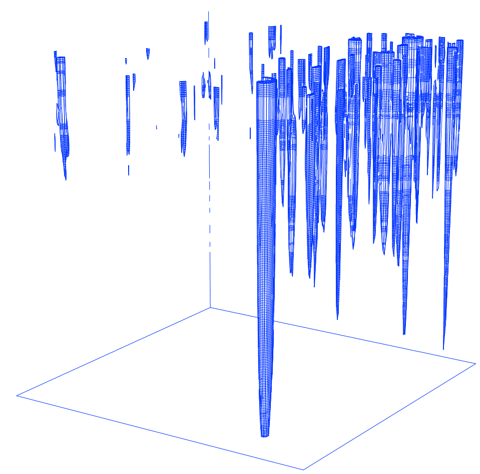
Mid-latitude eddies are deeper

Iso-surface of Okubo-Weiss parameter

$Q = \pm 1.5 \text{ x } 10^{-11} \text{ s}^{-2}$



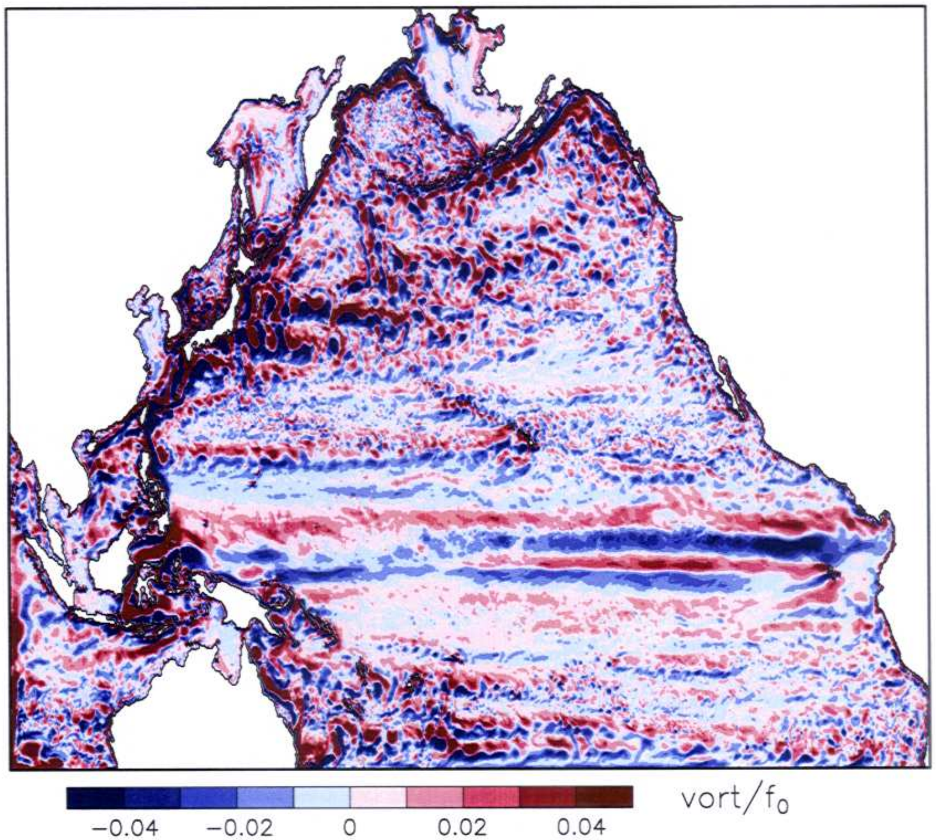
Box 1



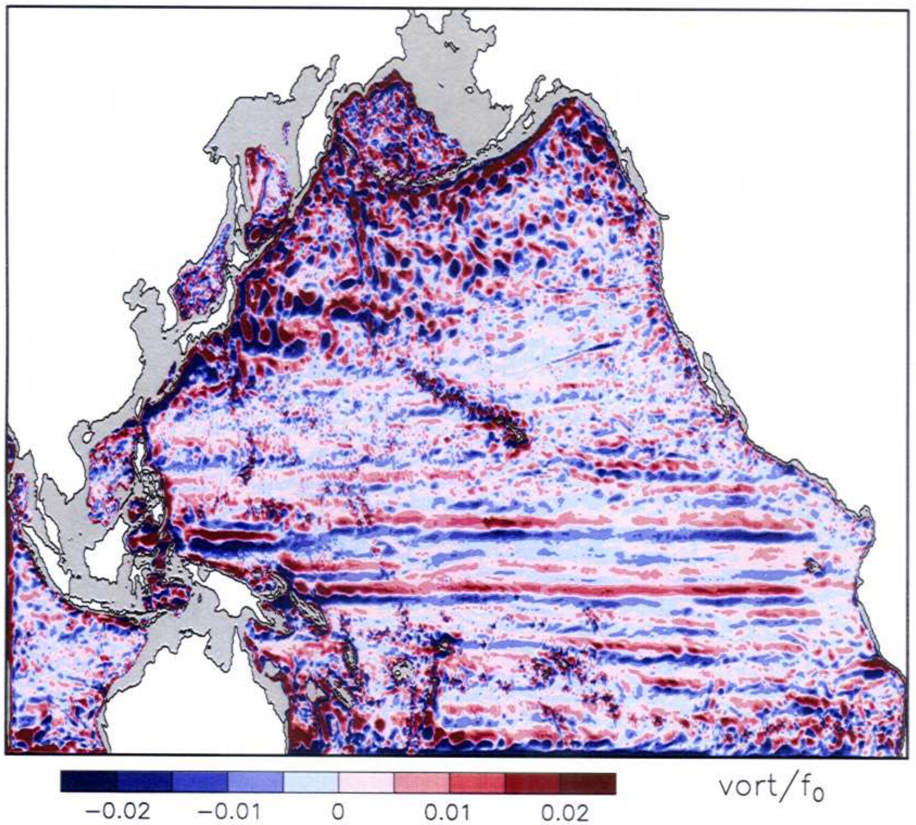
Box 2, anticyclones only
(cyclones are similar)

One-year average of vorticity field

Surface

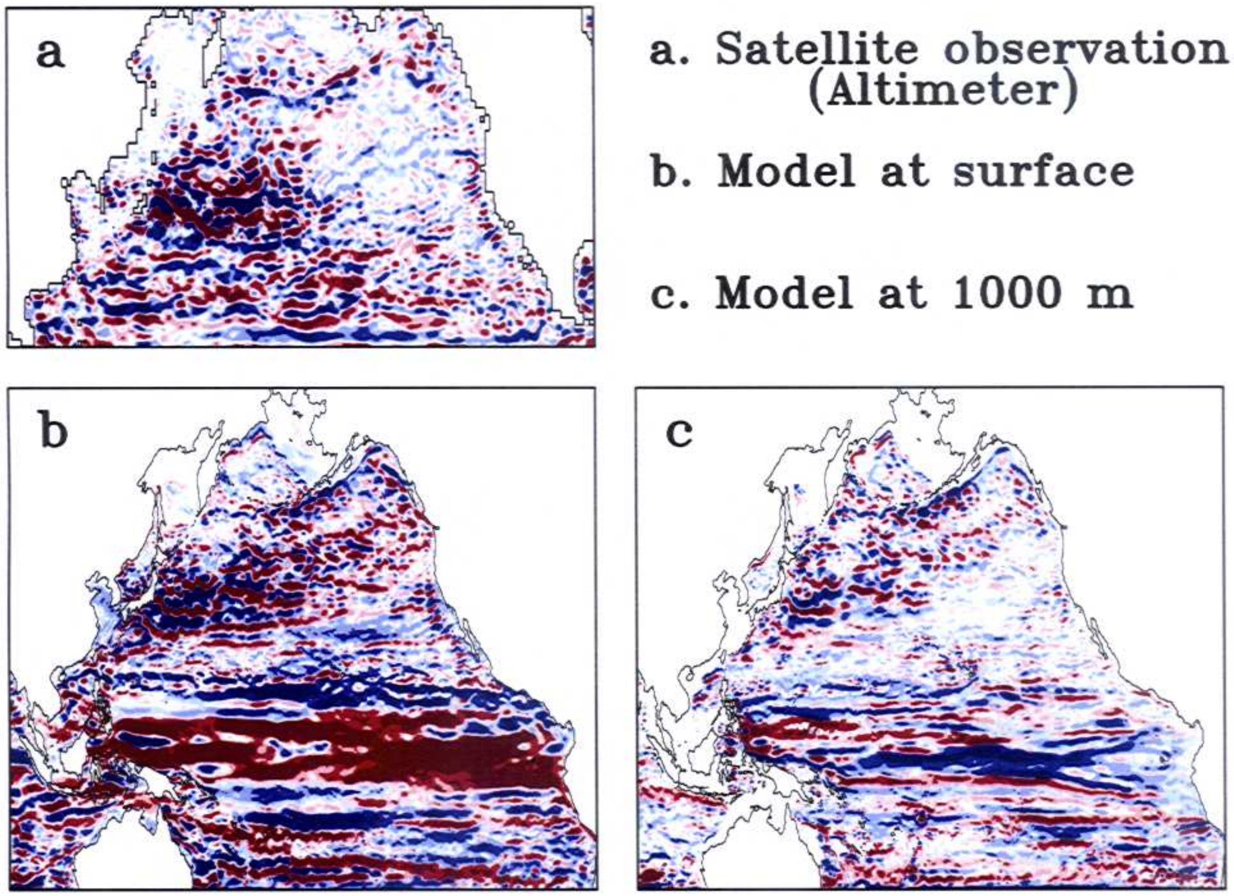


500 m



Multiple zonal-jet like structures emerge with long-term average

Zonal velocity: Model simulation vs. satellite observation (1-year average)



Color levels : ± 1, 2, 4, 8 cm/s for surface, half those for 1000 m

Red: positive (eastward) Blue: negative (After Huang et al. 2007)

Zonal stripes in model & observations have comparable strength and meridional scale (~ a few hundred km)

Instantaneous velocity field is more isotropic
Long-term averaged field becomes zonally elongated

To quantify this behavior: Use the "degree of anisotropy"

$$\alpha = \frac{\langle u^2 \rangle - \langle v^2 \rangle}{\langle u^2 \rangle + \langle v^2 \rangle}$$

<•> is domain average

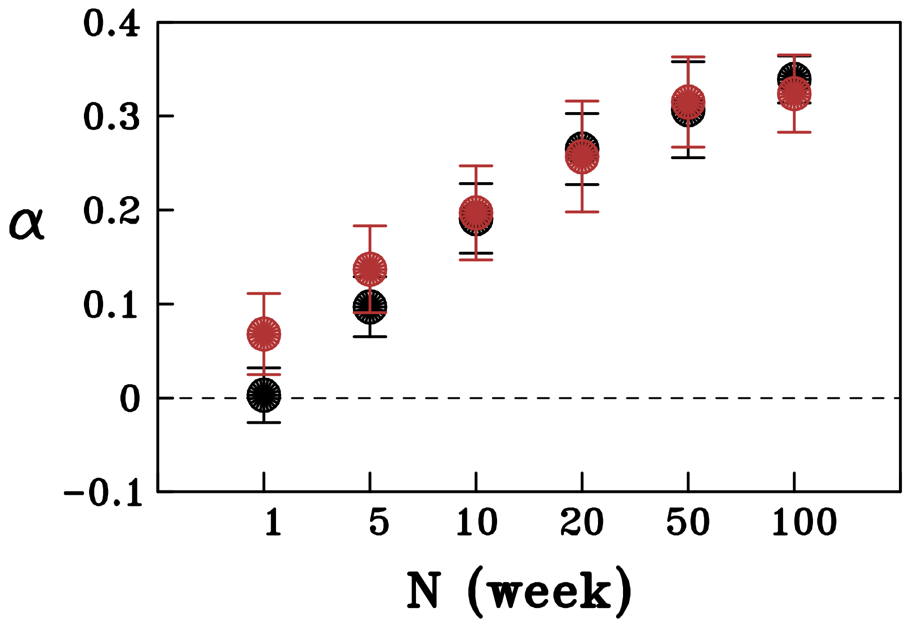
α = 0: isotropic
α = 1: purely zonal flow α = –1 : purely meridional flow

- Evaluate α using (u,v) constructed from 1-week, 5-week, ..., 100-week time average of the weekly maps

- Identical calculation for model & satellite observation

- ~ 600 weekly (u,v) fields used in both calculations

Degree of anisotropy, model vs. satellite observation
(Domain = whole North Pacific north of 12°N)



Black: Altimetry   Red: Model simulation

Agreement is also good for sub-domains of the North Pacific

Weekly velocity field is close to isotropic
Strong zonal anosotropy emerges with *T > a season*

Robust zonal stripes at *T ~ 1 yr* is consistent with other recent simulations (Treguier et al. 2004, Nakano & Hasumi 2005, Maximenko et al. 2006, Richards et al. 2006)

Processes for the formation of zonal jets

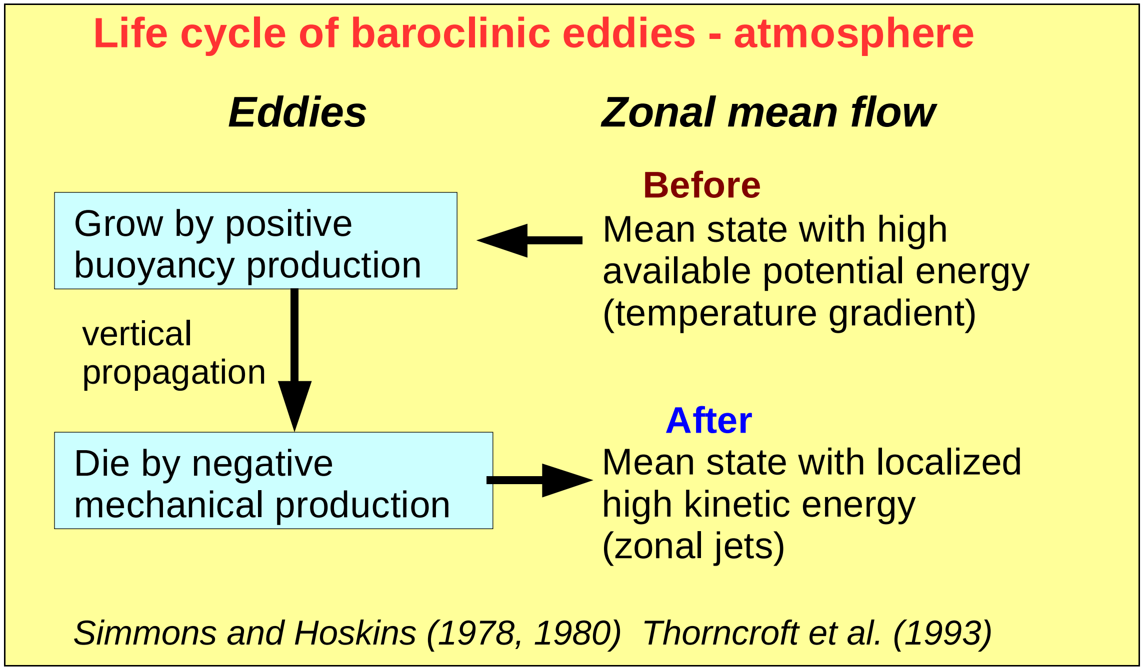
One way to look at it...   consider how the eddies die (or mature)

Mesoscale eddies grow by buoyancy production through baroclinic instability

Eddies die/mature by a secondary instability (e.g., Lorenz 1972, Pedlosky 1975, Manfroi & Young 1999, Berloff et al. 2009) that provides mechanical production (Reynolds stressing) for the mean zonal velocity --> Zonal jets

- *The process is subtle; detail of baroclinic wave "life cycle" depends on the background shear/PV (Simmons & Hoskins 1980, Thorncroft et al. 1993)*

- *The secondary instability might give rise to a specific length scale for zonal jets (Berloff et al. 2009)*



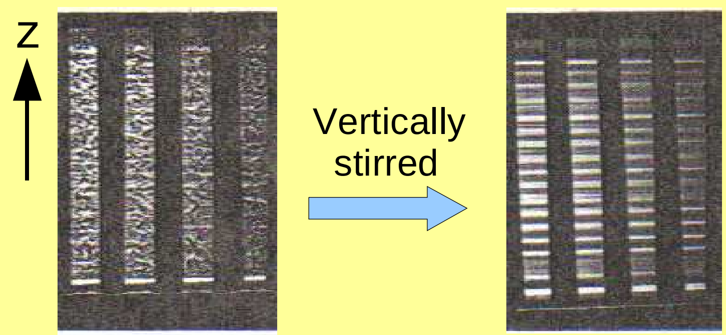
Qualitatively ...

(PV = potential vorticity)

"***PV staircase***", *Dritschel and McIntyre (2008)*

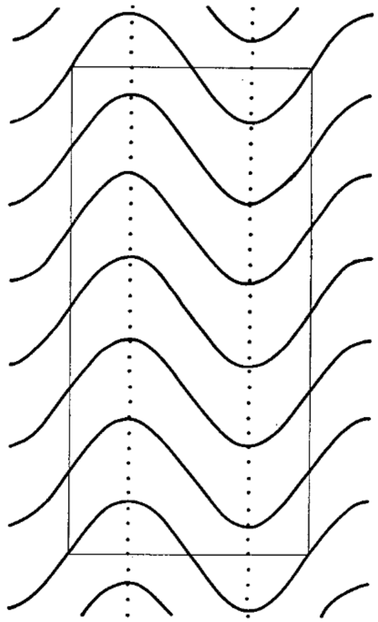
(i) Suppose that an initial stirring leads to local steepening of a stable PV gradient
→ *increased stability; resistance to further PV mixing*
(ii) Consequence: Well-mixed regions segregated by a self-steepening PV gradient
→ *a PV staircase*
(iii) PV inversion: "PV step" → eastward zonal jet

Analogy to density staircase (Phillips 1972)



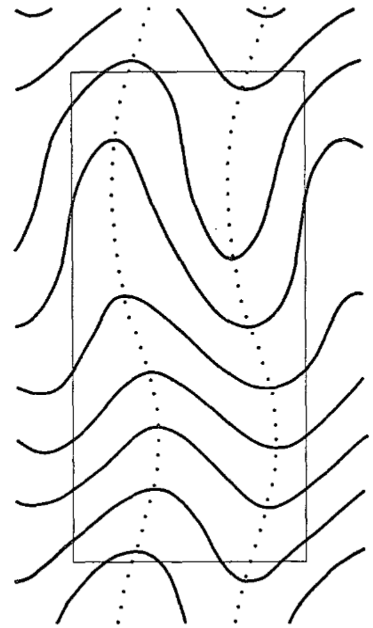
Ruddick et al. (1989)

- *The "self-steepening" process is related to the secondary instability (see previous slide) of the wavy structure maintained by the stirring force; Zonal jets are the "unstable modes" (Lorenz 1972, Manfroi & Young 1999, Berloff et al. 2009)*



Finite amplitude Rossby wave

Instability



Lorenz (1972)

The separation scale of jets reflects how far the meridional PV mixing can go: The meridional excursion would go deep if

1. Stirring is vigorous (large eddy kinetic energy, $E = \langle|\mathbf{v}'|^2\rangle$)
2. $\boldsymbol{\beta}$ is weak. ($\boldsymbol{\beta}$ = d(PV)/dy, PV gradient)

Unique length scale by (1) & (2): $L_\beta \sim \beta^{-1/2} E^{1/4}$ (A version of Rhines scale)

$L_\beta \sim$ a few hundred km for the ocean, close to L_{jet} in obs and simulations

$L_{jet} \sim L_\beta$ works over a certain parameter range but is not universal.

*It is **not** due to "upscale energy cascade" and its "arrest" by $\boldsymbol{\beta}$ effect; Hard evidences are generally against that interpretation (e.g., Thompson & Young 2007, Huang and Robinson 1998)*

- In general, the stirring does not have to be due to baroclinic eddies

  Zonal jets with $L \sim L_\beta$ form on Jupiter, where baroclinic instability is very weak (stirring is supported by internal convection)

Photo of Jupiter by Cassini
(Source: NASA)

Testing higher resolution

A hierarchy of nested simulations

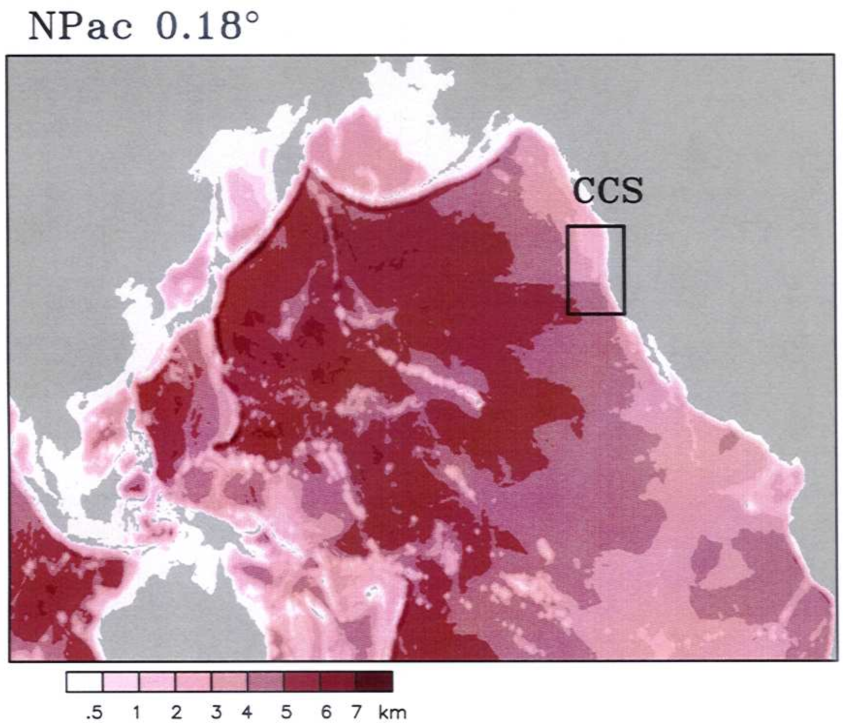
√ **NPac**	0.18°	North Pacific (20 years)	*Eddy permitting*
√ **CCS**	3 km	California Coastal Region	*Eddy resolving*
√ **MBR**	300m	Monterey Bay	*Sub-mesoscale*

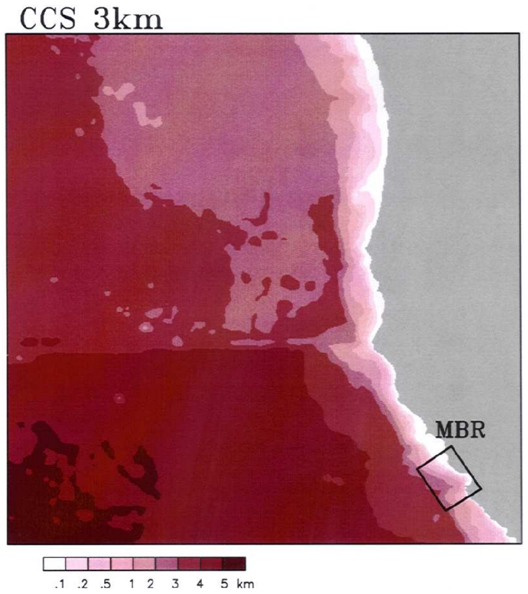
Forcing = CORE/Reanalysis for NPac, CCS
COAMPS for MBR

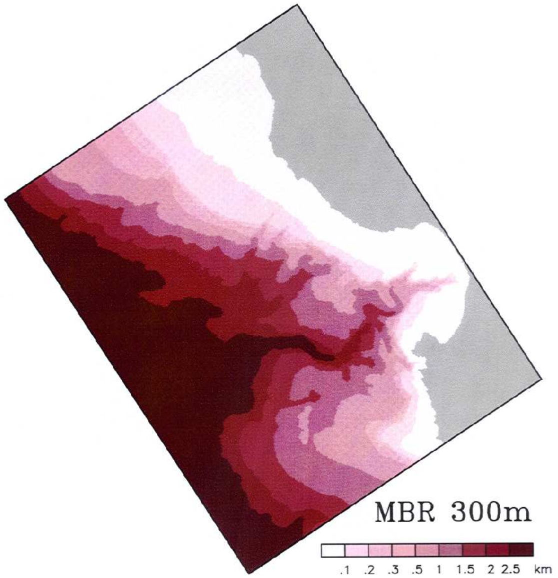
MBR Run has not only small grid size but also high-resolution forcing

Thanks to Enrique Curchitser

Model domain & bathymetry

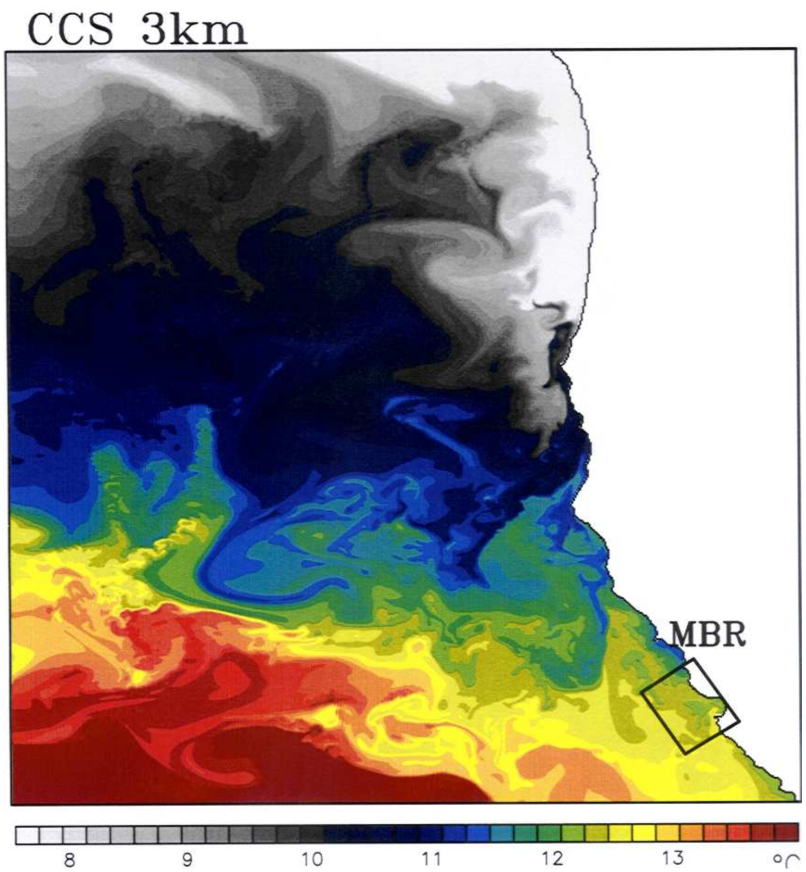


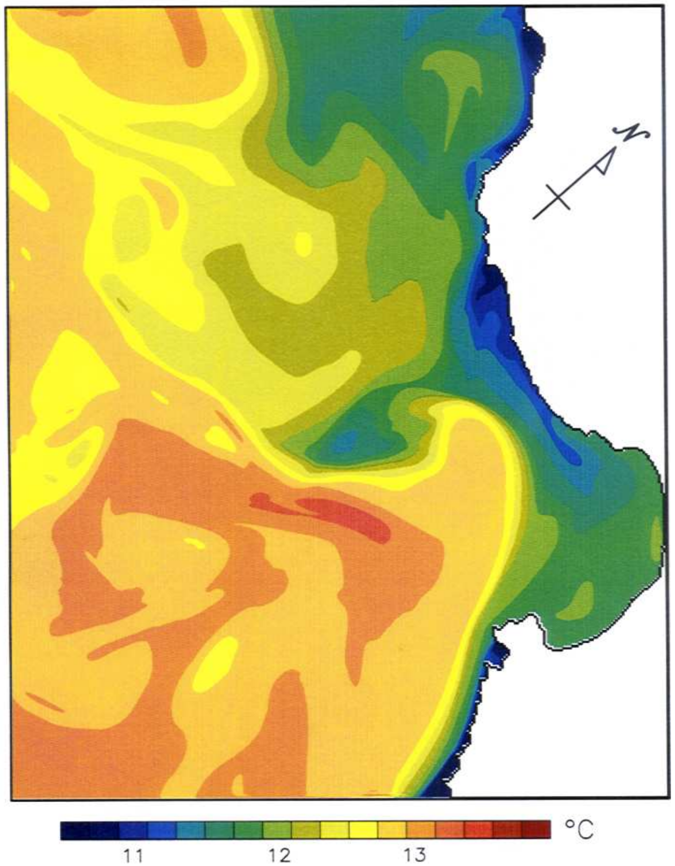




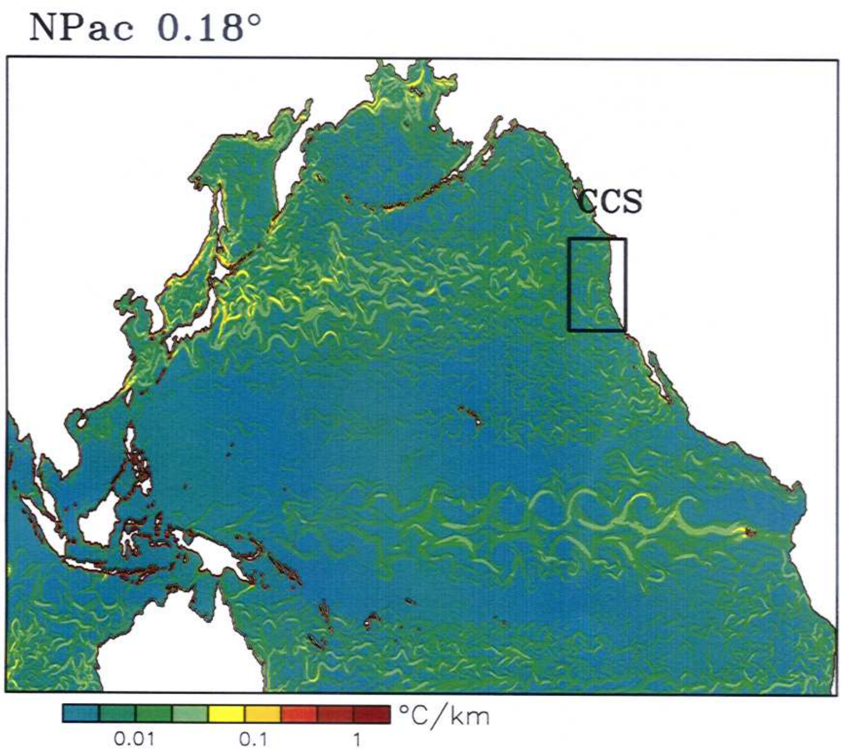
Output from low-resolution run is used as the lateral boundary condition for medium resolution run, and so on.

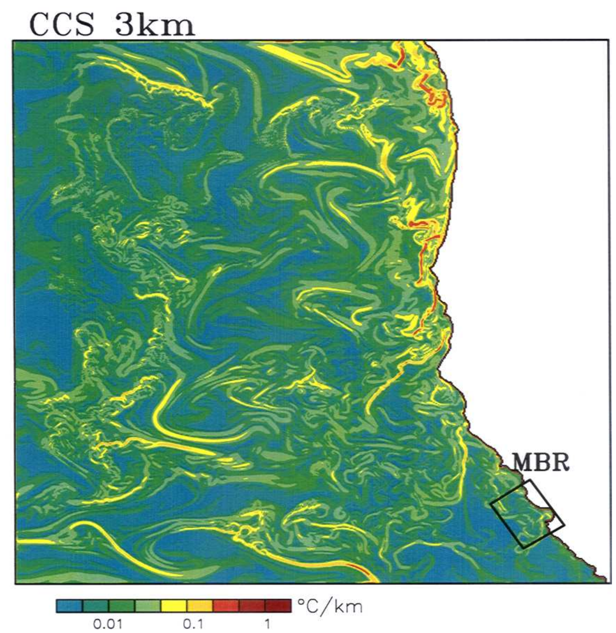
Sea surface temperature (snapshot)

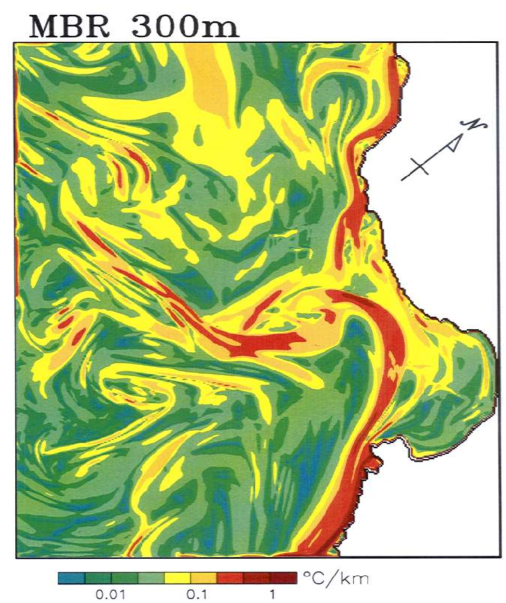




Horizontal temperature gradient $|\nabla T|$ (snapshot)

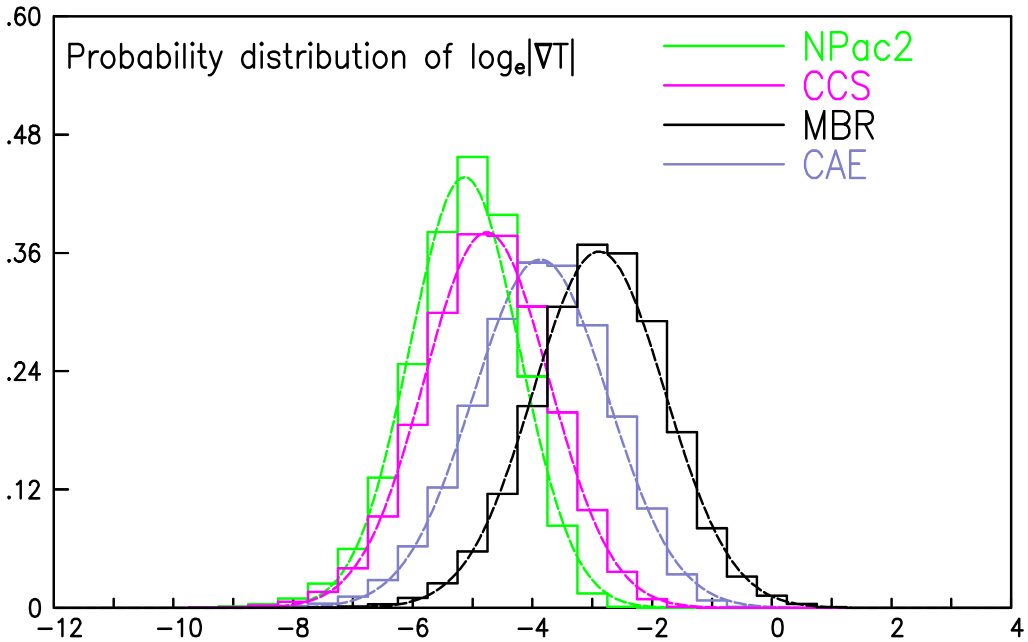






Color in log scale

Probability distribution of *log*$|\nabla T|$



CAE : Grid size ≈ **CCS** but forced by a high-resolution forcing similar to **MBR** (Thanks to Chris Edwards)

Dashed line: Gaussian fit

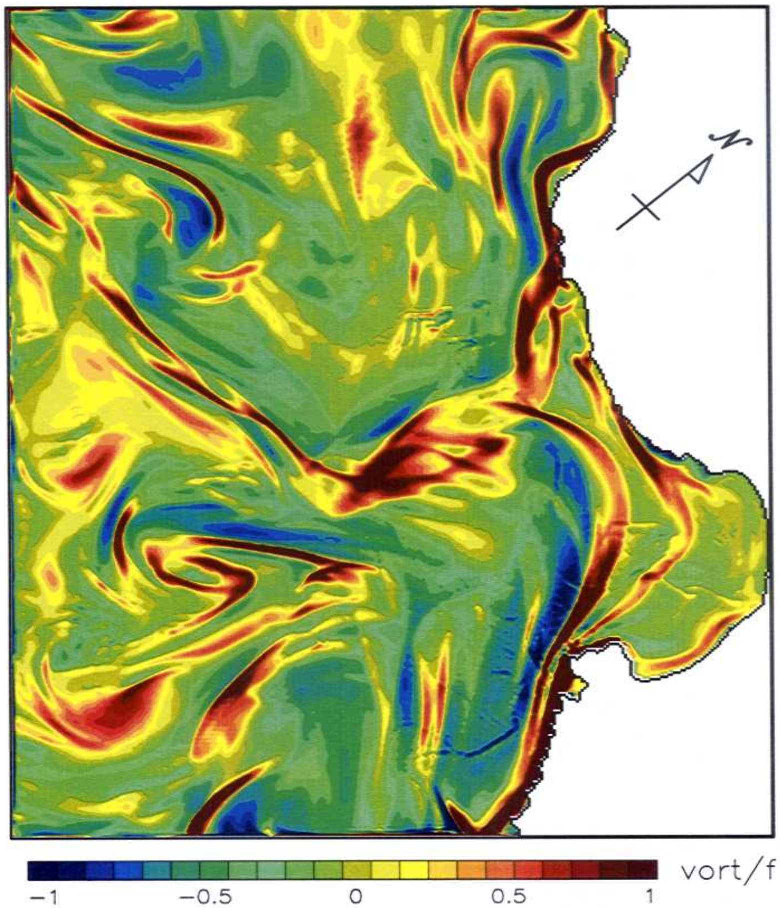
- PDF of *log*$|\nabla T|$ is approx. Gaussian → PDF of $|\nabla T|$ is log-normal
  (Note added: We don't have enough samples to detect an exponential tail, yet)

- Continued increase in horizontal temperature gradient with refinement in the grid size and atmospheric forcing

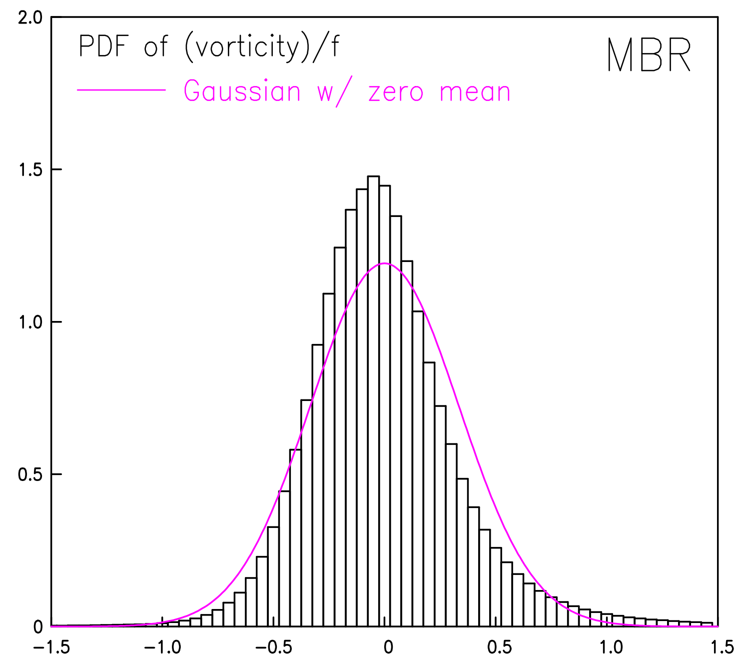
Intense coherent structures remain abundant as model marches toward smaller scales

Cyclone-anticyclone asymmetry

Vorticity/f snapshot at surface



Probability distribution of ζ/f



Skewness = 0.61 STD = 0.33

Consistent with Rudnick (2001):Obs w/ 3 km resolution

Anticyclones weak and broad

Cyclones concentrated and intense

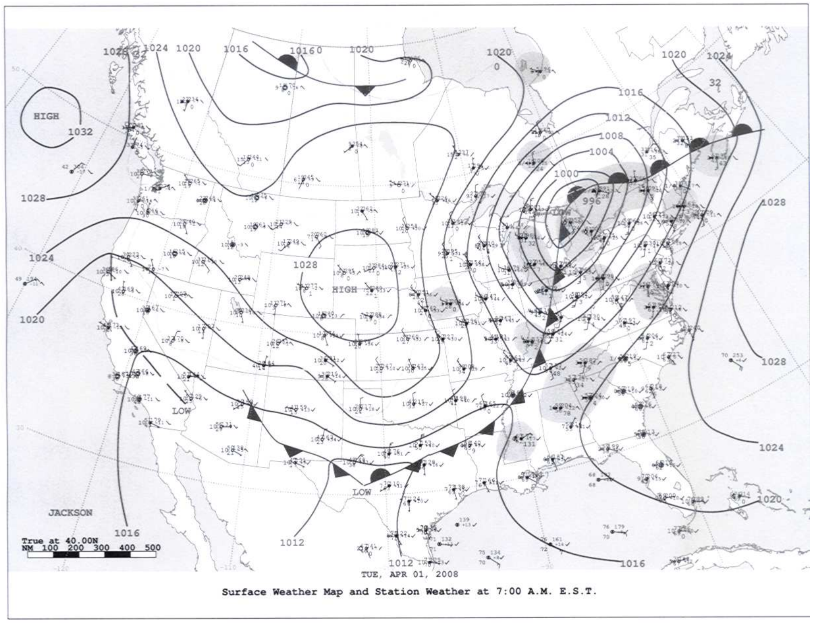
Structures with $Ro \sim O(1)$ are overwhelmingly cyclonic

Anticyclones with $\zeta + f < 0$ ($Ro < -1$) are inertially unstable

Long filaments become more prominent at this fine resolution

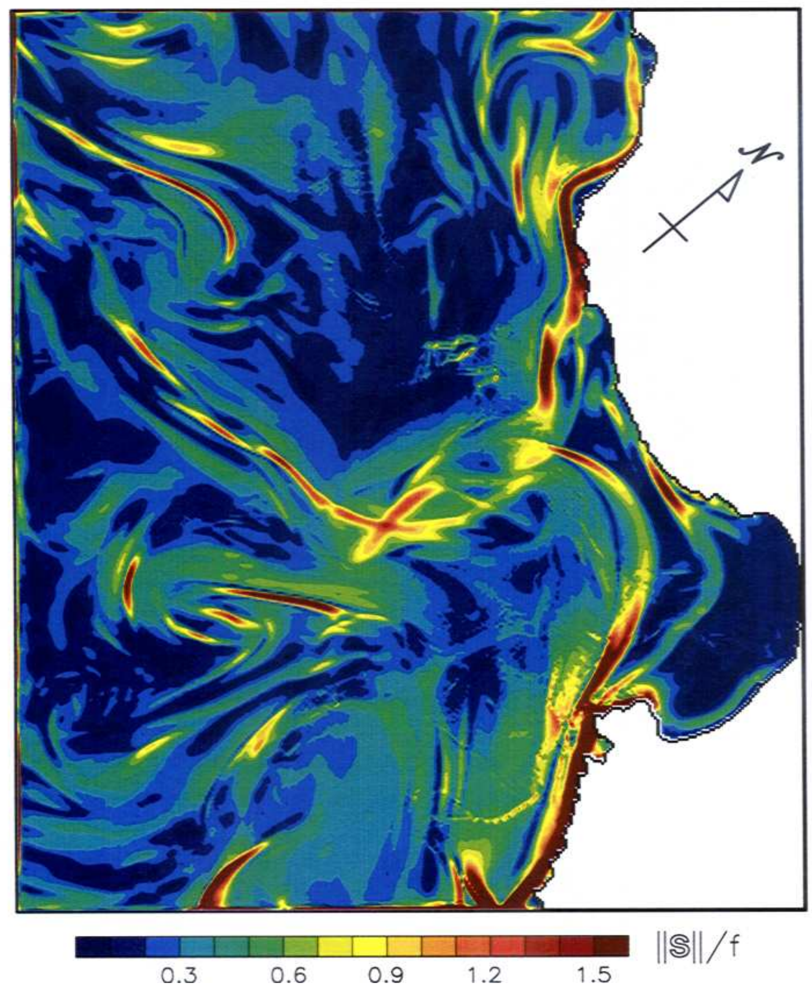
Analogy to the atmosphere

Recall the weather map

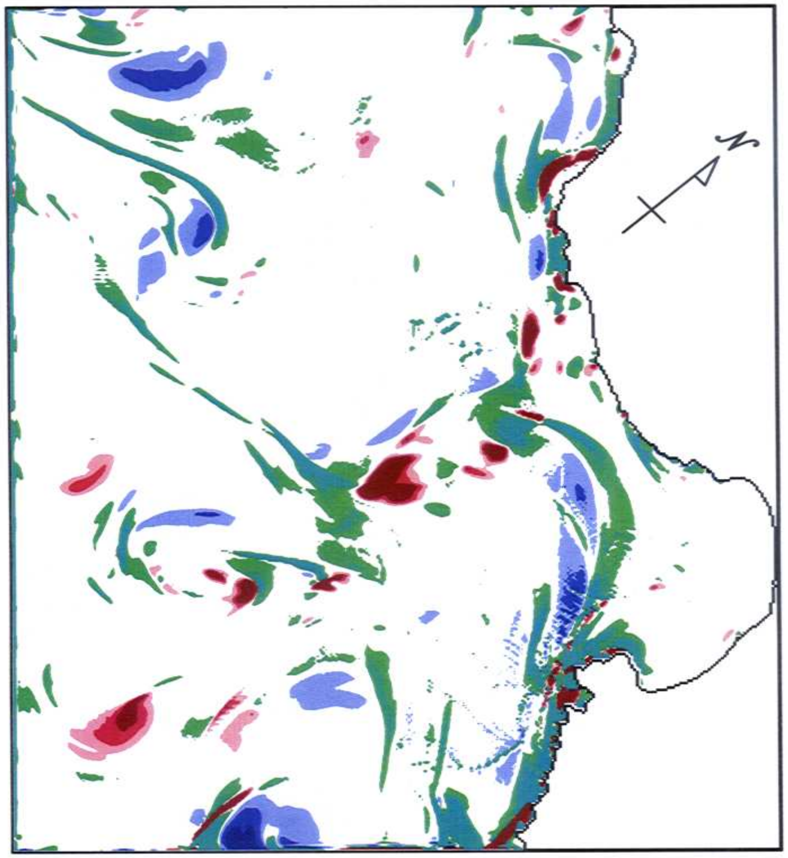


Strong concentrated cyclone / weak broad anticyclone / fronts are pervasive not only in the atmosphere - see weather maps - but also in the ocean in the mesoscale-submesoscale range

Norm of strain tensor, snapshot at surface
(Shown is $\|\mathbf{S}\|/f$)



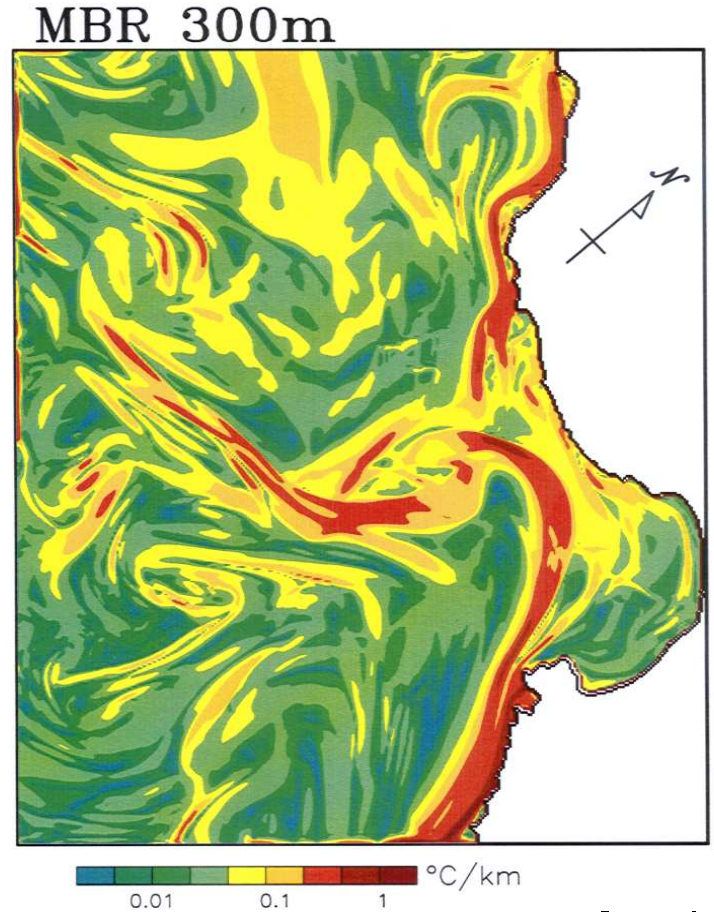
Fronts look even sharper in $\|\mathbf{S}\|$ than in vorticity or $|\nabla T|$



Okubo-Weiss parameter (in 10^{-10} s^{-2})

Red: $Q > 5$, $\zeta > 0$ Blue: $Q > 5$, $\zeta < 0$

Green: $Q < 5$



SST gradient, $|\nabla T|$

Tight temperature gradient coincides with long filnaments of large negative Okubo-weiss parameter, where straining/deformation dominates

There is evidence that the sub-mesoscale range is dominated by long filaments or fronts

A serendipitous observation

|<------------------------- ~ 100 km ------------------------->|

Photograph taken on board Space Shuttle *Challenger* over Mediterranean Sea (Source: NASA)

Highlights of results

- High-resolution ($\Delta x < L_D$) simulations of large-scale ocean produced ubiquitous coherent structures - **coherent vortices**, **zonal jets**, and **fronts** - that were absent in non-eddy permitting simulations.

- In the eddy-permitting simulation, horizontal velocity field is nearly isotropic on weekly time scale, but become strongly zonal after time averaging with *T > a season*. This behavior agrees well with satellite observation.

- **Fronts** or **stretched filaments** become more prominent as model resolution is further increased. Coherent structures are abundant even at $\Delta x = 300$ m; *The "solution" has not yet converged* at the state-of-the-art eddy-permitting resolution of $\Delta x \sim 0.1°$ for global ocean simulations.

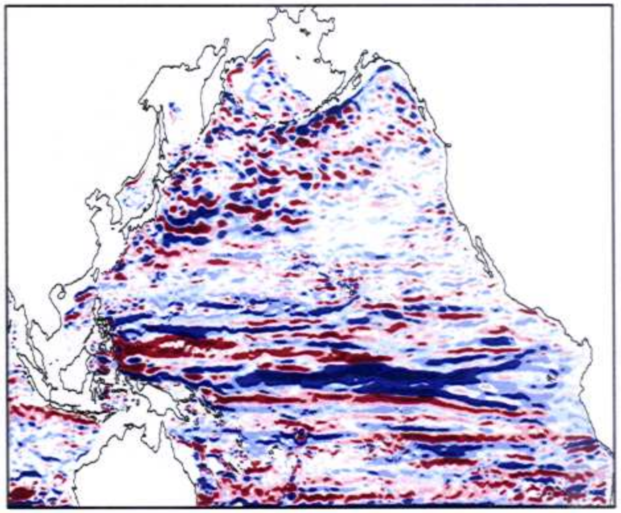
Implications

- Current generation of medium-resolution ($\Delta x \sim 1°$) ocean model used for long-term **climate prediction** (IPCC ARx) do not resolve the rich coherent structures in our eddy-permitting simulations.

- The presence of multiple zonal jets can critically affect the **transport of heat, biota, and chemical constituents** that are important for climate and life on Earth.

  Eddy diffusivities along and across zonal jets are dramatically different (e.g., Smith 2005)

- Clarification of the interaction between eddies/zonal jets and ocean gyre may lead to **revision of the classical view of ocean gyre** (eddy-free models of Stommel et al.)



Thank you