SIO 210: Eddies and mixing
L. Talley Fall, 2015

- Mesoscale eddies
- "Eddy" fluctuations in general (horizontal and vertical)
- Eddy kinetic energy
- Eddies and horizontal mixing
- Diapycnal (quasi-vertical) mixing

READING in DPO 6th:
Chapter 14.17

(Many beautiful animations out there that show mesoscale eddy field.
In class I showed one from
http://www-pord.ucsd.edu/~uriel/animations.html)

"Eddies": relationship to "eddy diffusivity"

In the lecture on non-rotating fluids, we introduced Fick's law
Molecular diffusivity and molecular viscosity

We also mentioned eddy diffusivity and eddy viscosity
Process of mixing that is enhanced by turbulence

We differentiated between horizontal and vertical eddy diffusivity
Horizontal eddy diffusivity is due to horizontal motions that stir/mix (mesoscale, submesoscale, traditional 'eddies')
Vertical eddy diffusivity is due to breaking internal waves mostly that stir/mix in the vertical

In this lecture, we look at some of the structures that are implicated in these parameterized eddy diffusivities.

What is an "eddy"?

(1) Most general, for theory:

"eddy" = "average" minus "synoptic"

That is: "eddy" = "anomaly"

In this sense, we can be looking at the "eddy" velocity (geostrophic or non-geostrophic), temperature, salinity, density, surface height, isopycnal height, in all 3 dimension (x, y, z)

(2) Confusingly,

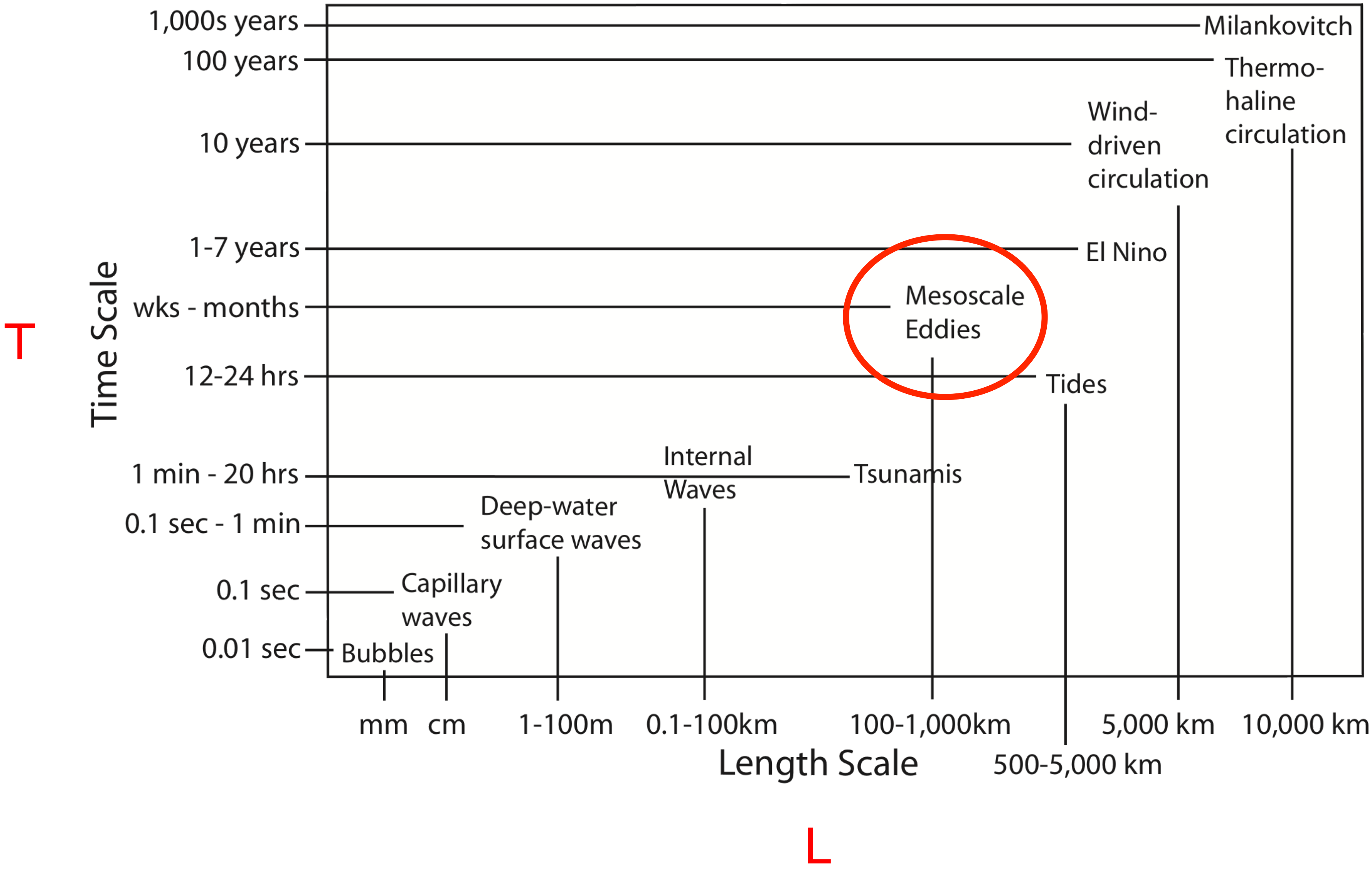
"Eddy" often refers to "mesoscale eddy", which are fluctuations in the geostrophic velocity field.

- Rossby waves
- Gulf Stream rings
- open ocean vortices
- Current meanders (California Current, Gulf Stream, etc.)
- etc.

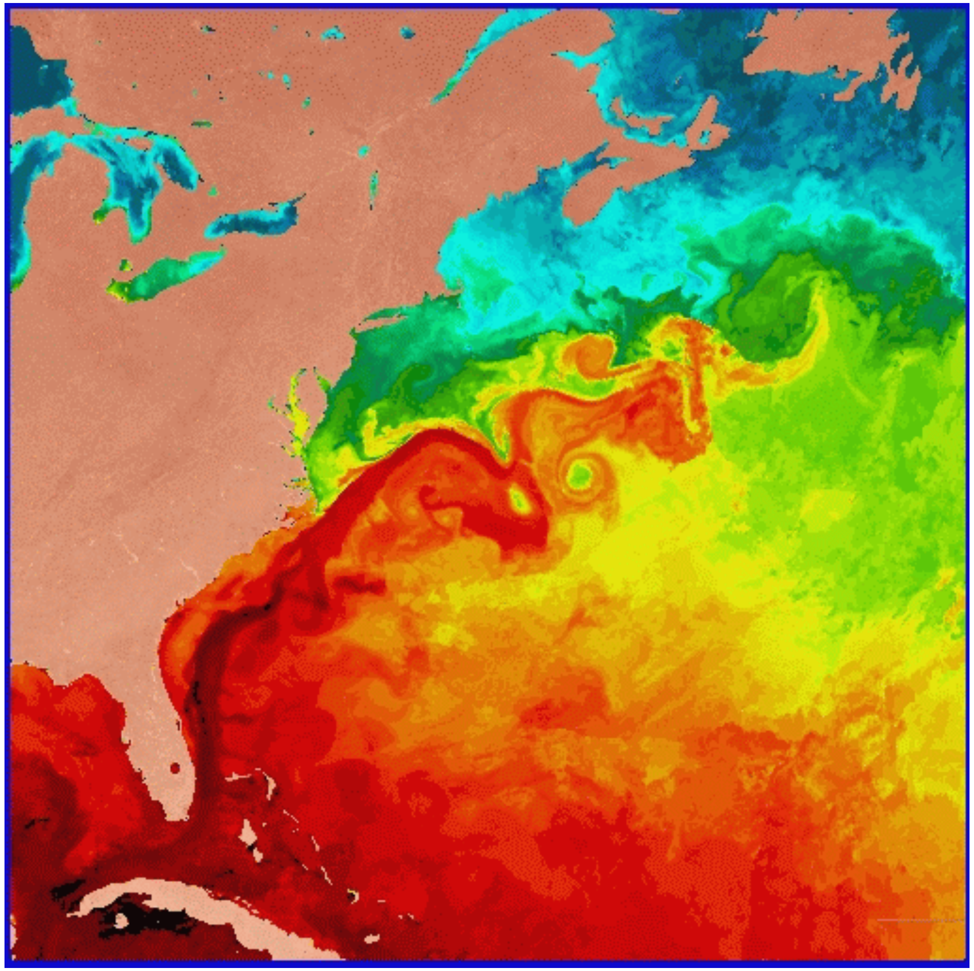
Mesoscale eddy spatial scales: order 10 km to 200 km depending on latitude and ocean stratification

Mesoscale eddy time scales: order 2 to 4 weeks.

Mesoscale eddies from Introductory lecture



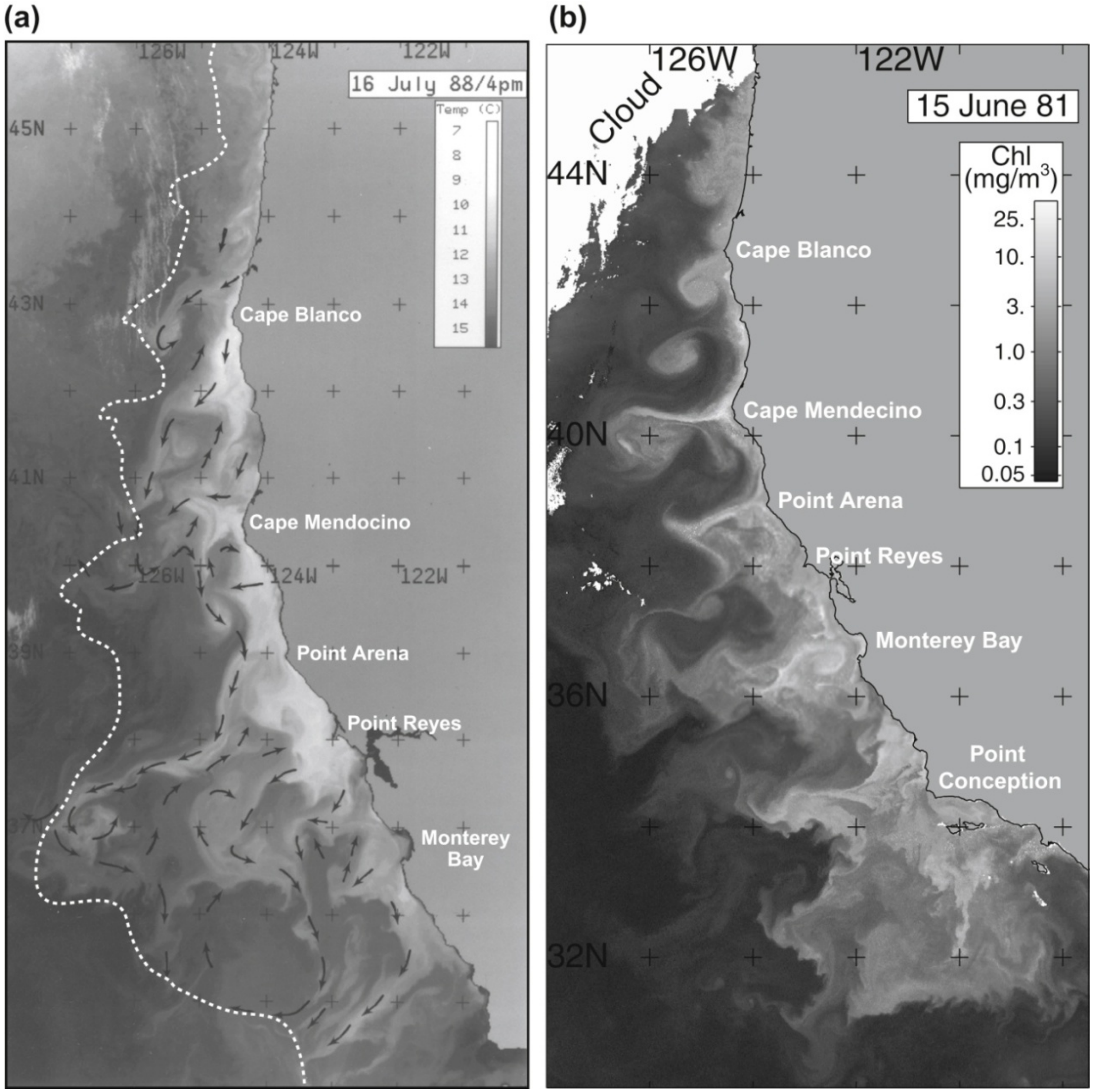
Mesoscale eddy examples



Meanders of the Gulf Stream, and Gulf Stream rings

SST satellite image, from U. Miami RSMAS

Eddies in the California Current



a) Satellite SST (July 16, 1988), with subjectively determined flow vectors based on successive images. (b) Surface pigment concentration from the CZCS satellite on June 15, 1981. *Source: From Strub et al. (1991).*

Eddies in the California Current

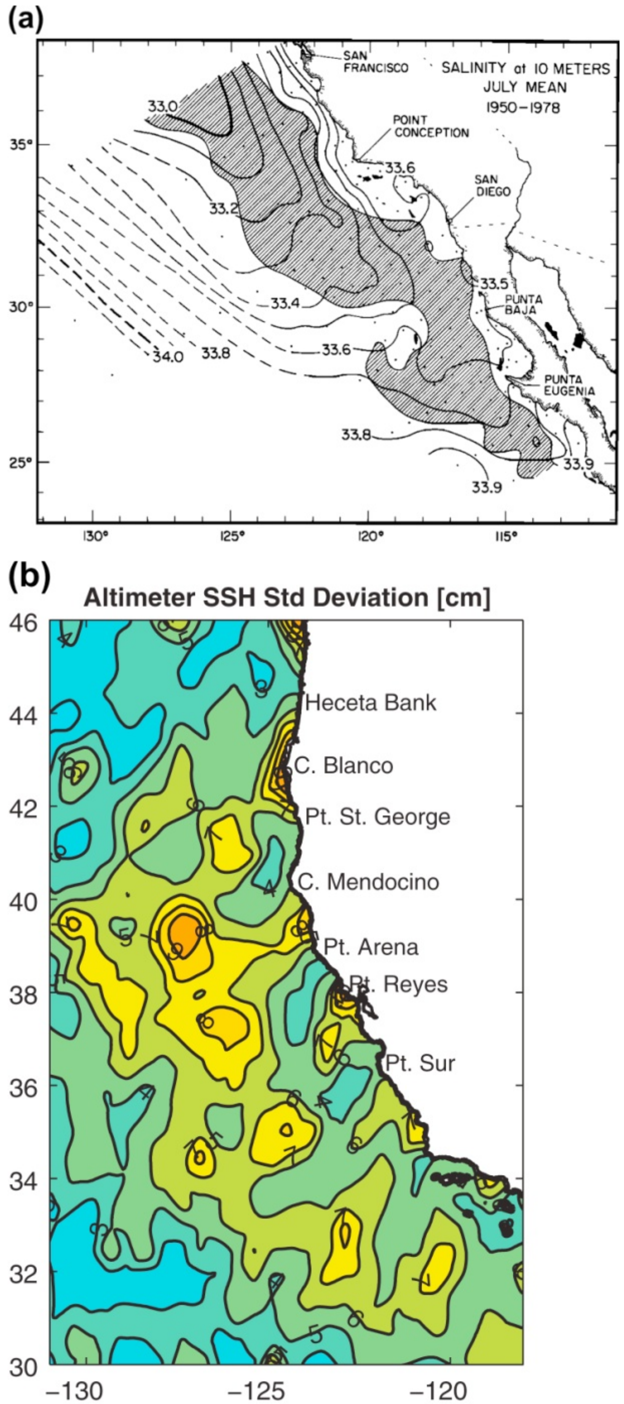


FIGURE 10.8

Gray region shows high eddy kinetic energy (see later slide for definition).

California Current as a field of eddies through which a weak current moves.

California Current eddies in altimetry – high standard deviation indicates frequent presence of eddies.

Agulhas Current eddies, meanders, rings

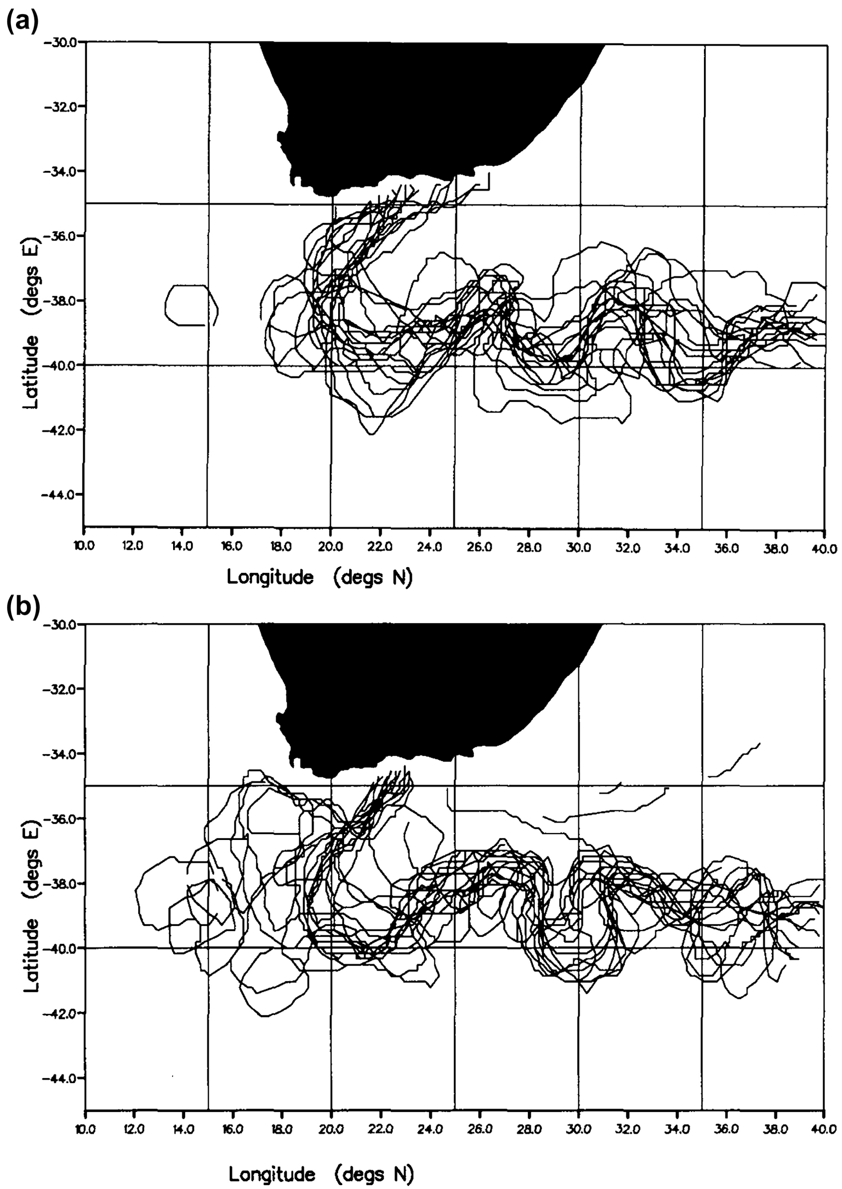


FIGURE S11.7

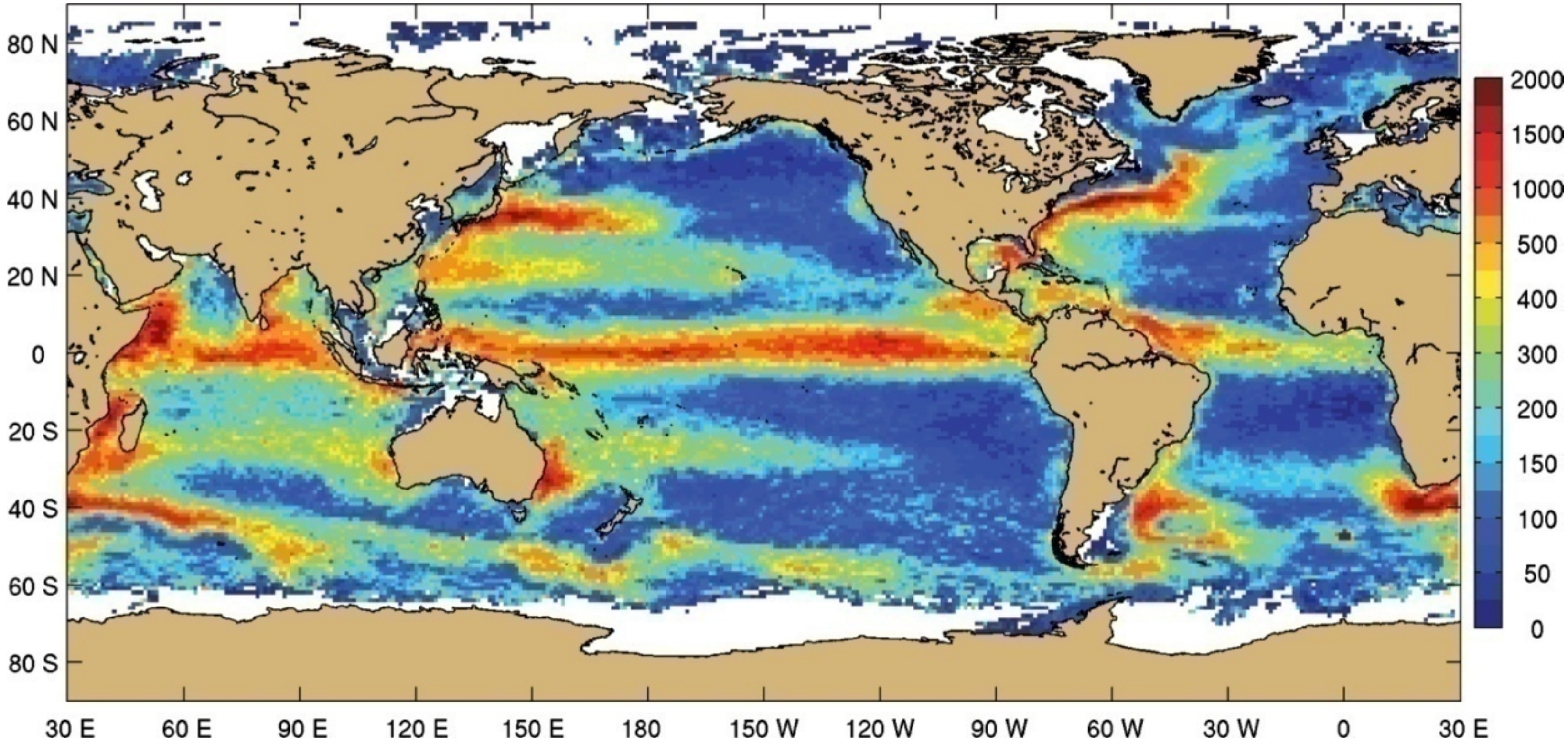
High eddy activity – time dependence, ring creation. Also standing meanders that can be called “standing eddies”

Infrared boundary of the Agulhas Current from 1985 to 1988: (a) December–February (summer) and (b) June–August (winter). ©American Meteorological Society. Reprinted with permission. *Source: From Quartly and Srokosz (1993).*

Eddy kinetic energy at the sea surface

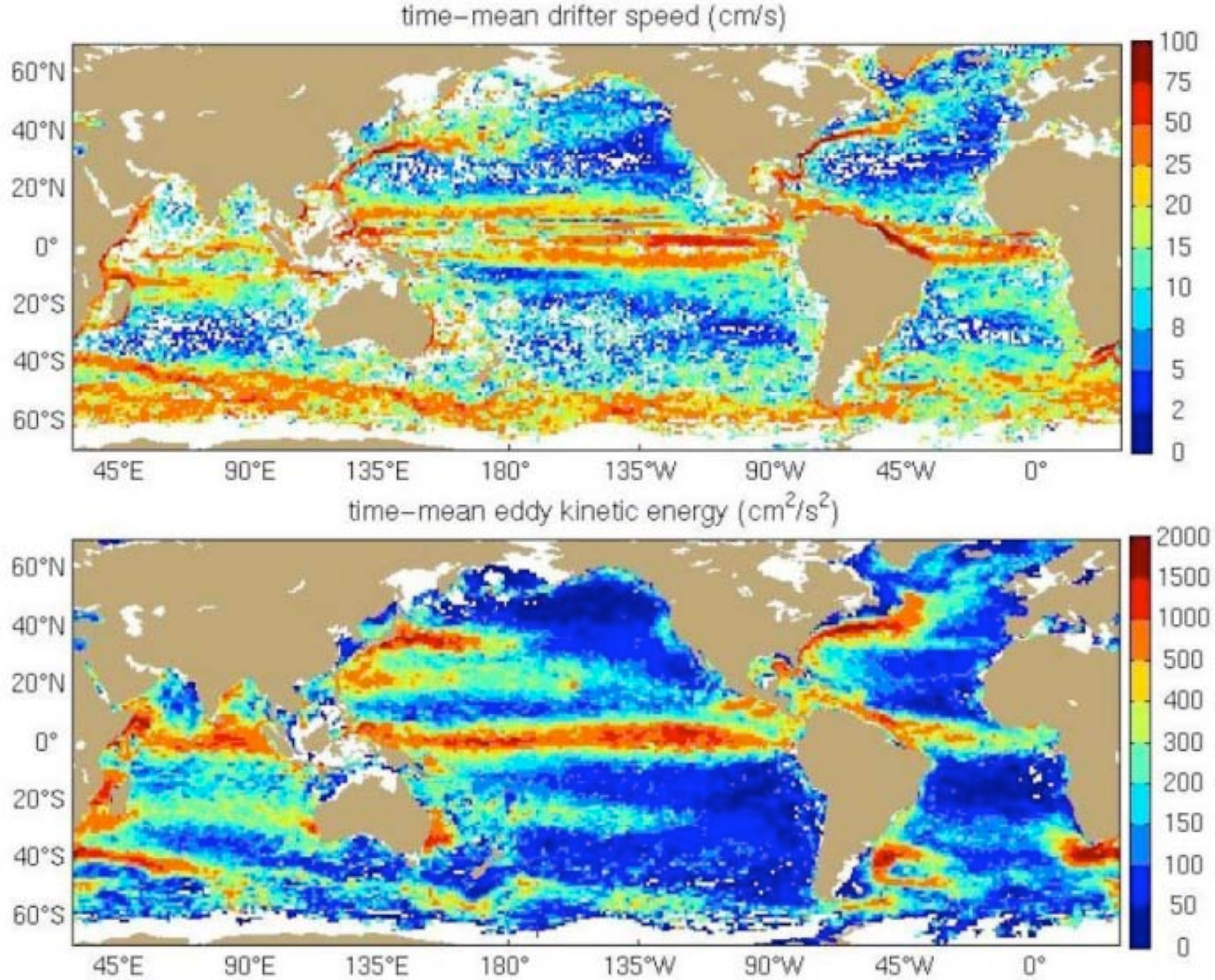
Kinetic energy in physics = ½ m$\mathbf{v}^2$ -->
for water/ocean, use ½ $\rho(u^2+v^2)$

Eddy Kinetic Energy (EKE): use $u' = u_{mean} - u_{observed}$ so
EKE = ½ $\rho(u'^2+v'^2)$ and usually plot this per unit mass (no ρ),
so EKE is usually shown in units of m^2/s^2



DPO FIGURE 14.16

Where does eddy energy come from?

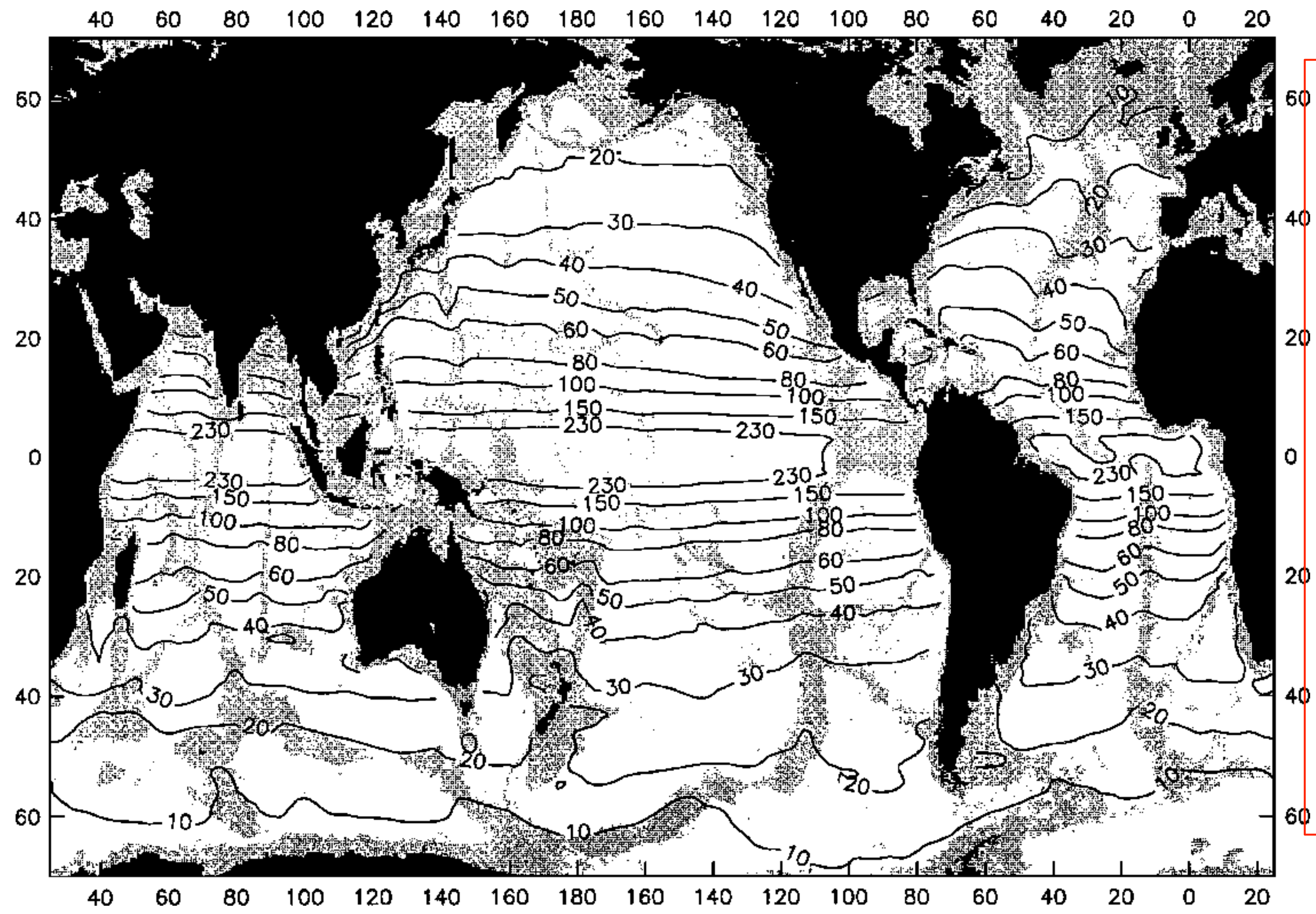


Mean speed (top) and eddy kinetic energy (bottom) calculated from drifter observations (R. Lumpkin, NOAA/AOML). Values are shown at 1 degree resolution.

Usually due to an instability of the currents.
Useful to compare the mean speeds and the eddy kinetic energy, since the mean speeds represent the mean circulation.

(Figure from NOAA/AOML)

Mesoscale eddy length scales: closely related to the "Rossby deformation radius"



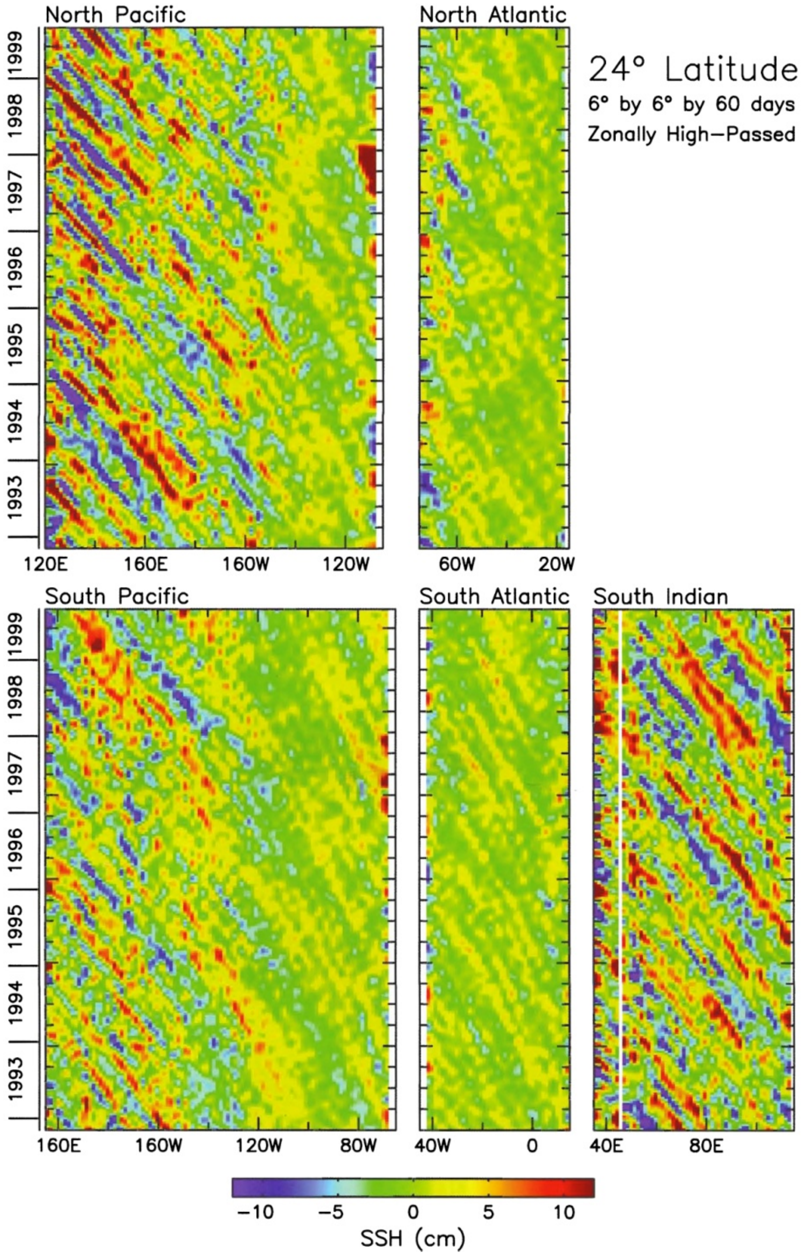
Extra for Section 2:

External deformation radius $R_{internal}=(gH)^{1/2}/f$

Internal deformation radius $R_{internal}=NH_S/f$

Fig. S7.28a Internal Rossby deformation radius (km) for the first baroclinic mode. *Source: From Chelton et al. (1998).*

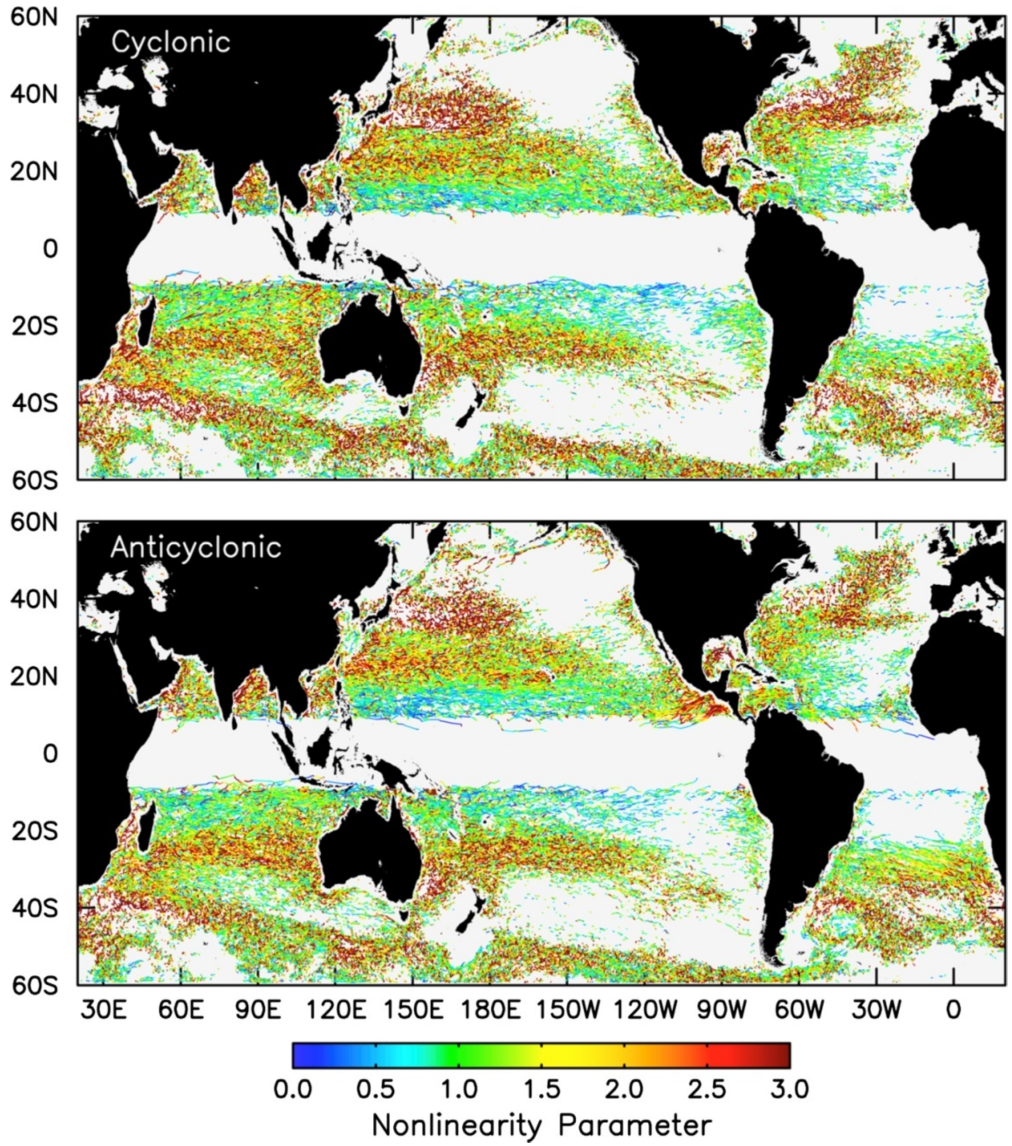
Rossby waves in observations (surface height from altimetry) westward propagating mesoscale disturbances



Surface-height anomalies at 24 degrees latitude in each ocean, from a satellite altimeter. This figure can also be found in the color insert. Source: From Fu and Chelton (2001).

Figure 14.18

Tracking anticylones and cyclones

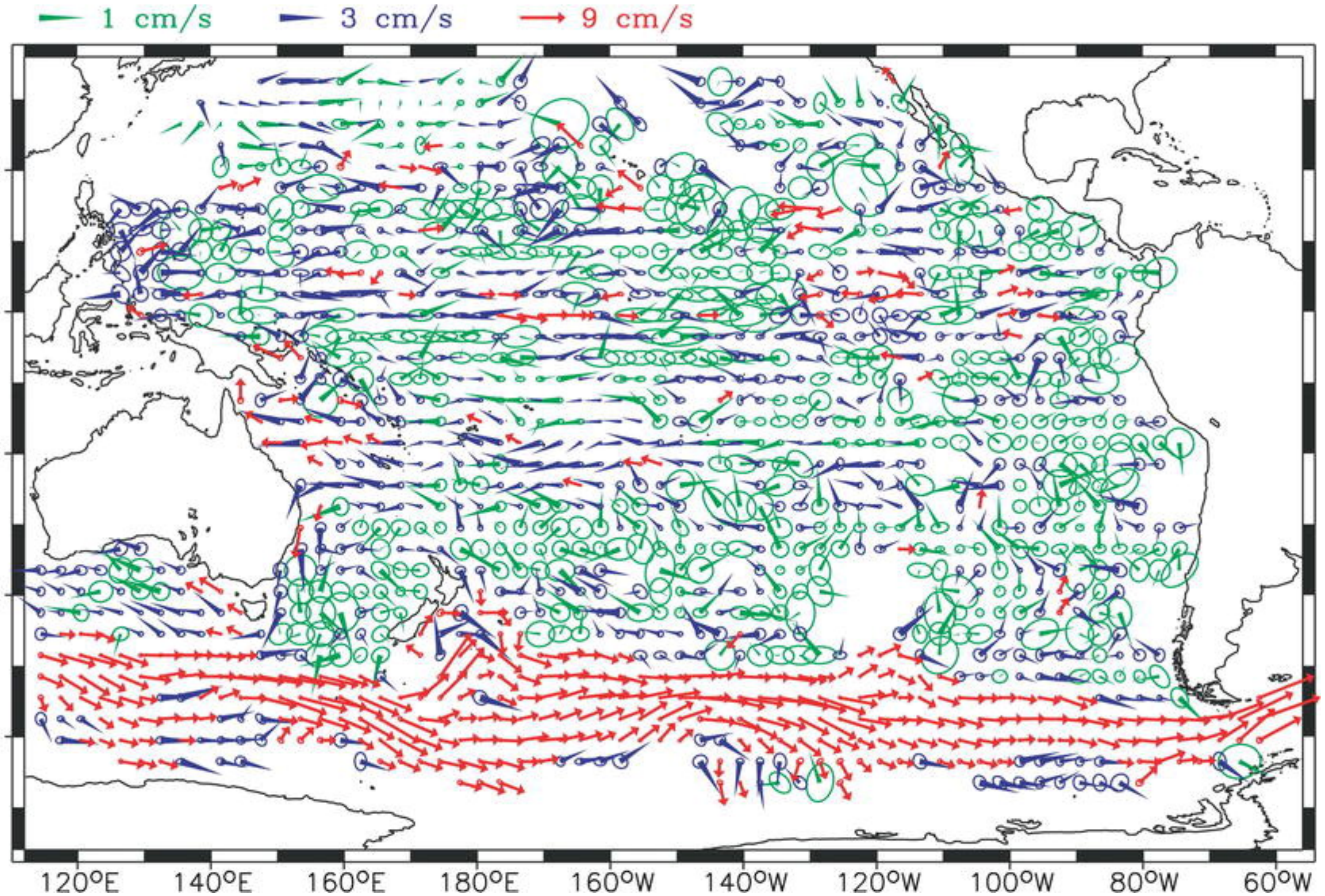


The ocean has approximately the same number of anticyclonic and cyclonic eddies. They mostly propagate westward UNLESS a major current is advecting them eastward (in which case they are still propagating westward relative to the current).

Tracks of coherent cyclonic and anticyclonic eddies with lifetimes of more than 4 weeks, based on altimetric SSH. From Chelton et al. (2007).

FIGURE 14.21

Mean flow at 1000 m depth from floats

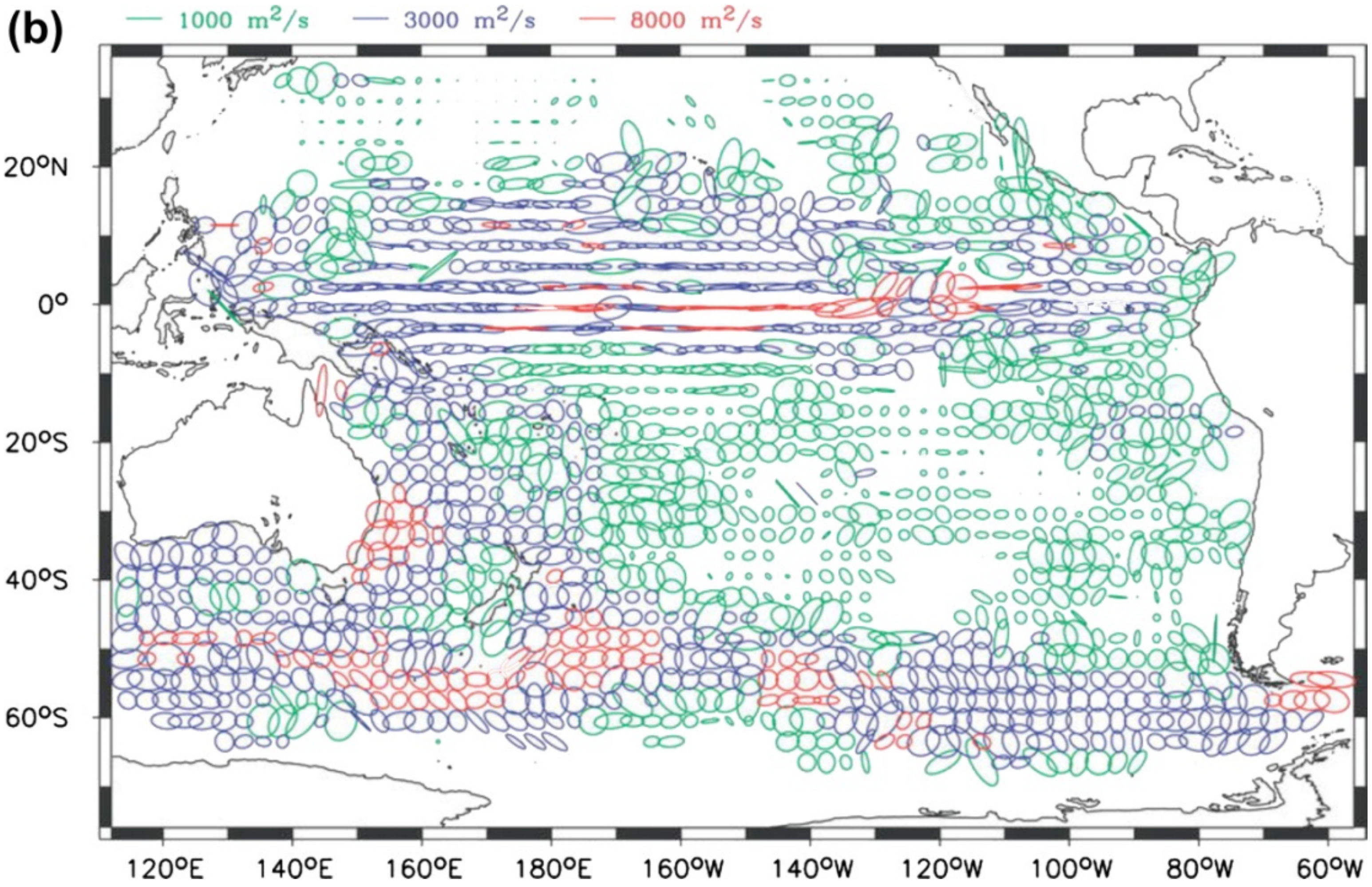


Mean flow vectors.

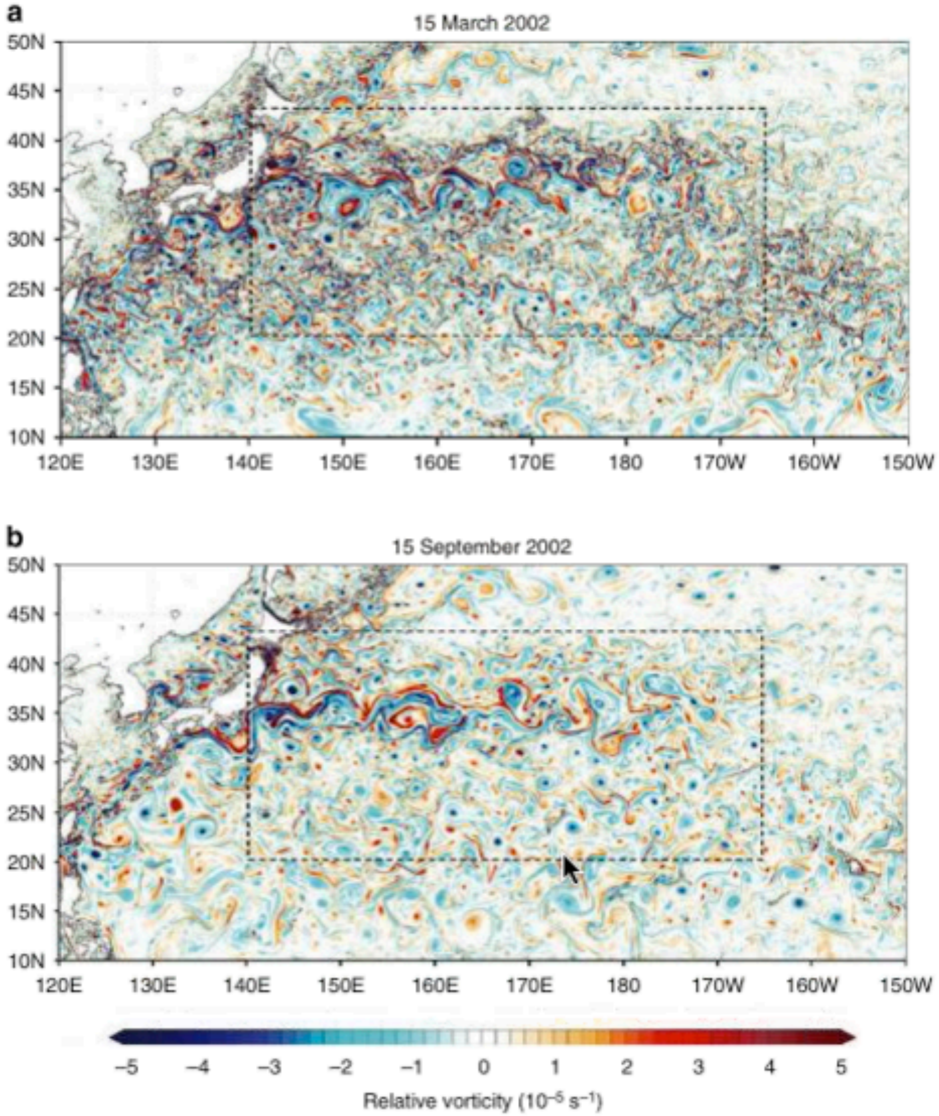
Ellipses are sampling error, not related to eddy velocities

Davis, JPO 2005

Horizontal eddy diffusivities from float velocity anomalies at 1000 m depth



Submesoscale stirring/mixing: new topic – sample from A. Thompson (CalTech) seminar Nov. 13, 2015



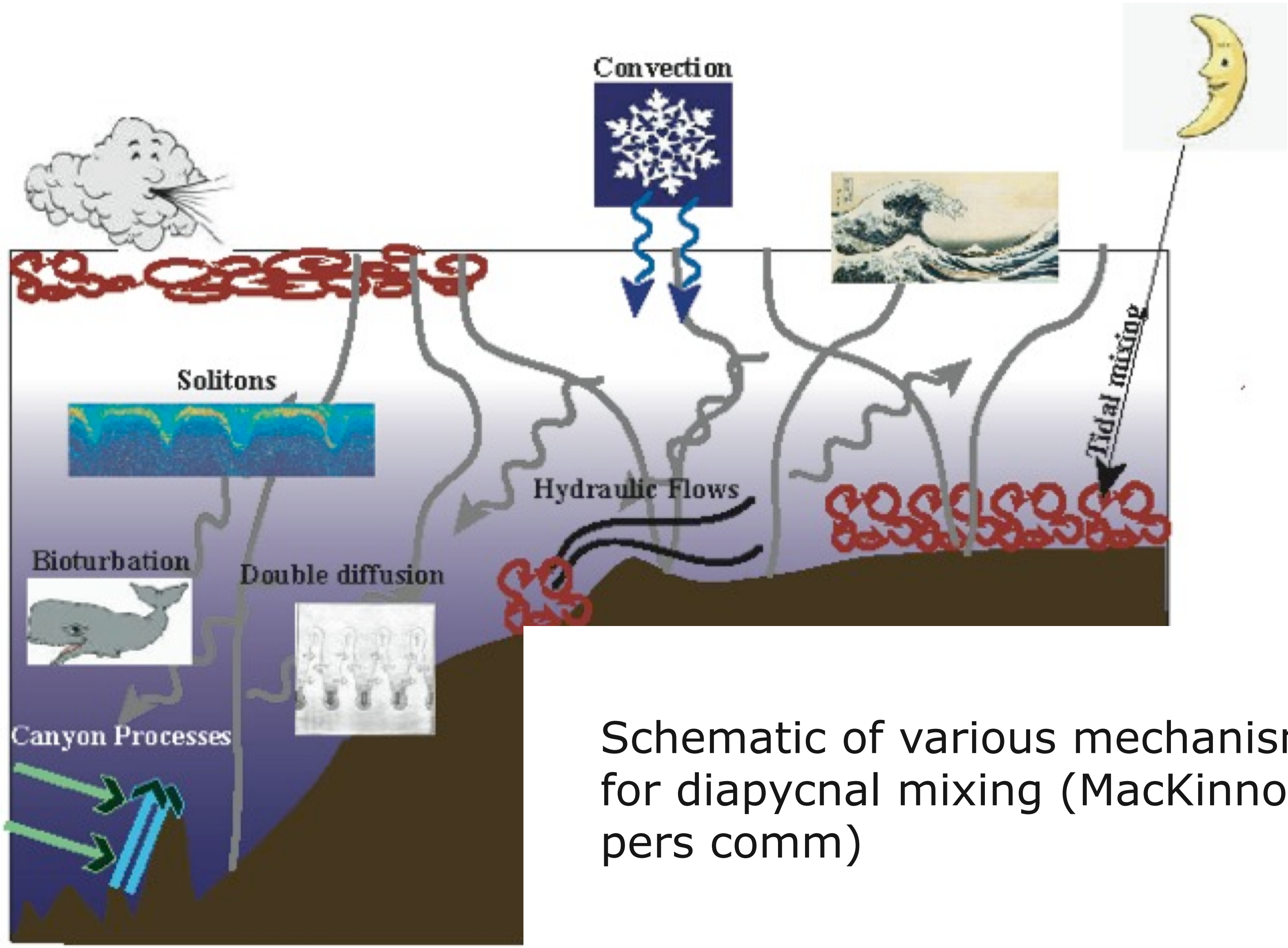
Sasaki *et al.* (2014)

Much interest in observing the scales that are shorter than mesoscale, and that are not internal waves: "submesoscale".

Filaments created and stirred around by the mesoscale.

These tend to hve Rossby number of order 1 (advection and Coriolis are both important).

Diapycnal mixing



Schematic of various mechanisms for diapycnal mixing (MacKinnon, pers comm)

Diapycnal mixing

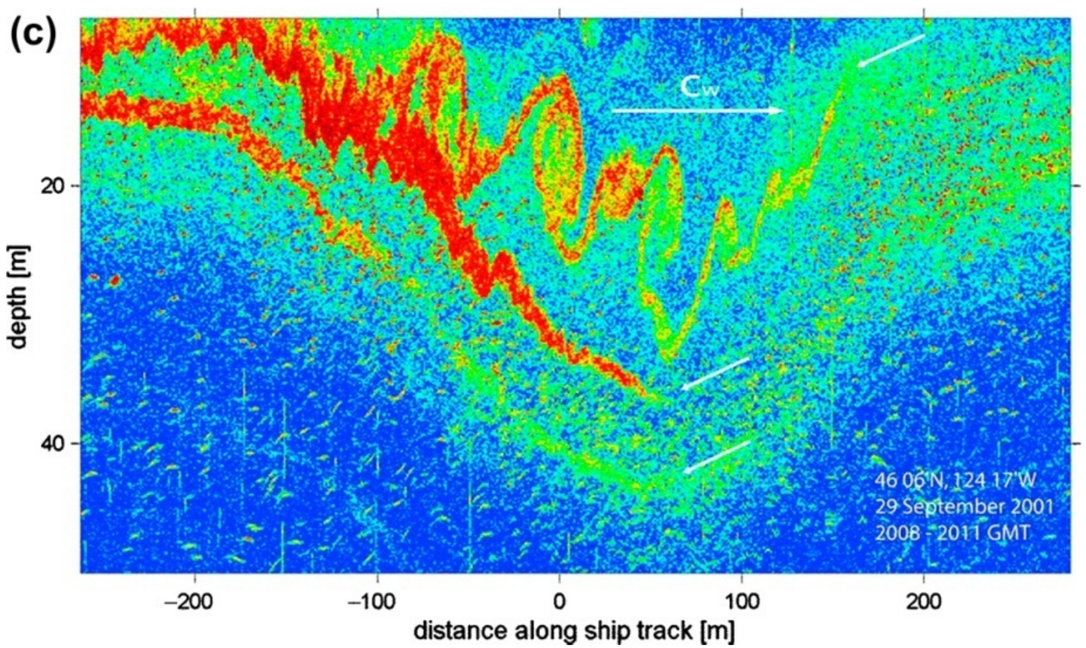


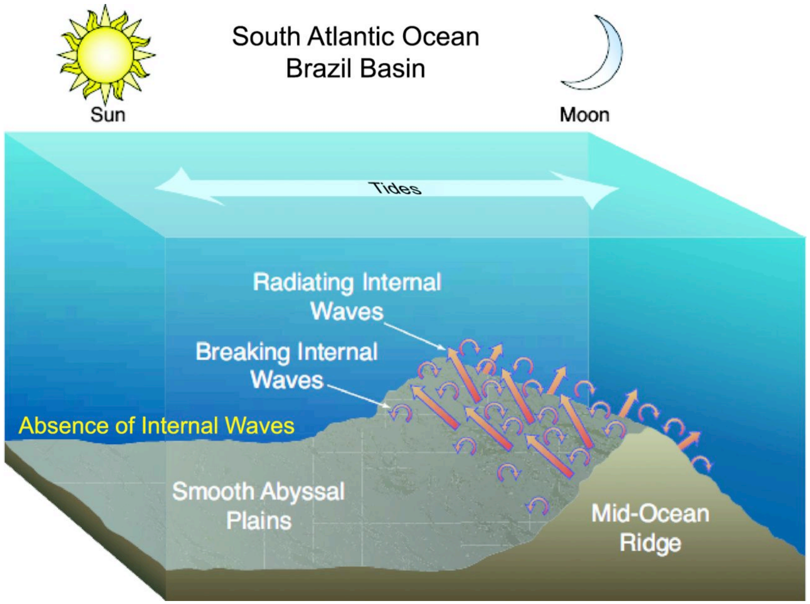
Fig. 8.11

Breaking internal solitary wave, over the continental shelf off Oregon.

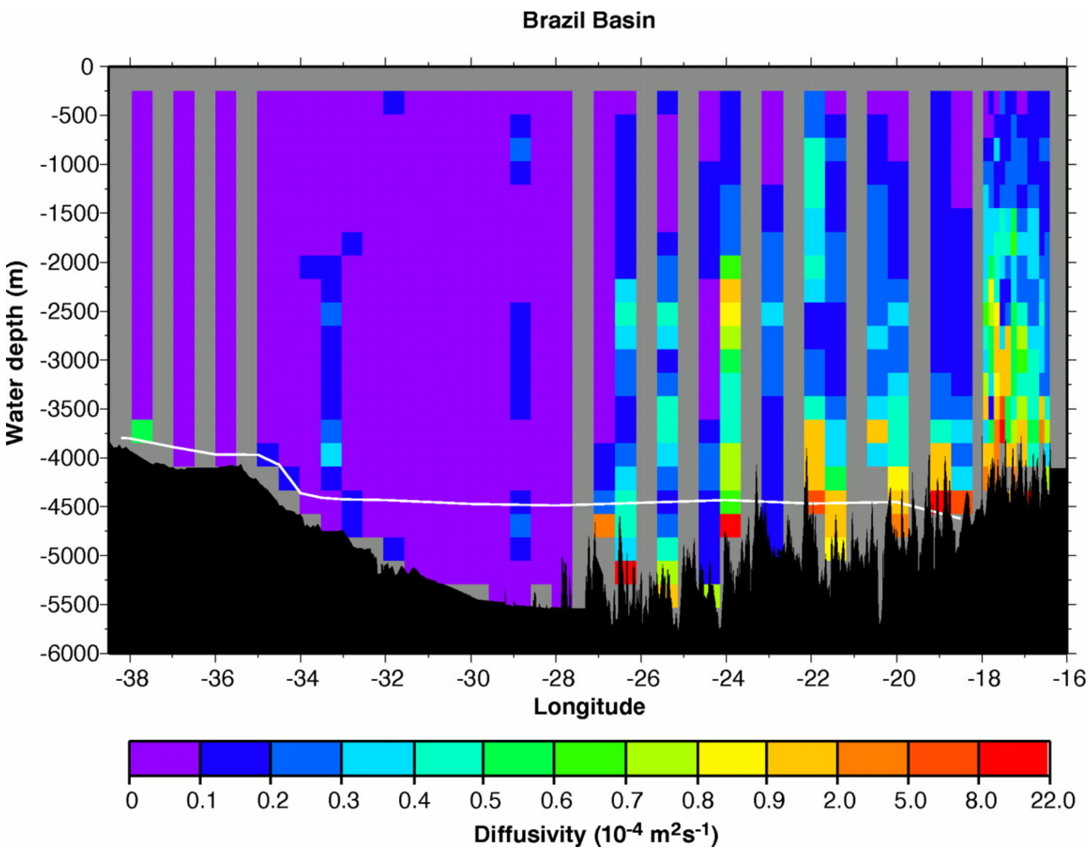
The image shows acoustic backscatter: reds indicate more scatter and are related to higher turbulence levels. ©American Meteorological Society. Reprinted with permission. *Source: From Moum et al. (2003).*

Diapycnal mixing

Enhanced mixing where internal tides are created and break over bumpy topography



Jayne et al. (Oceanography, 2004)



Polzin et al. (1997)

Relation of tides and wind to diapycnal diffusivity

Topography, Tides & Ocean stratification

⇓

Conversion of tidal energy to internal waves

⇓

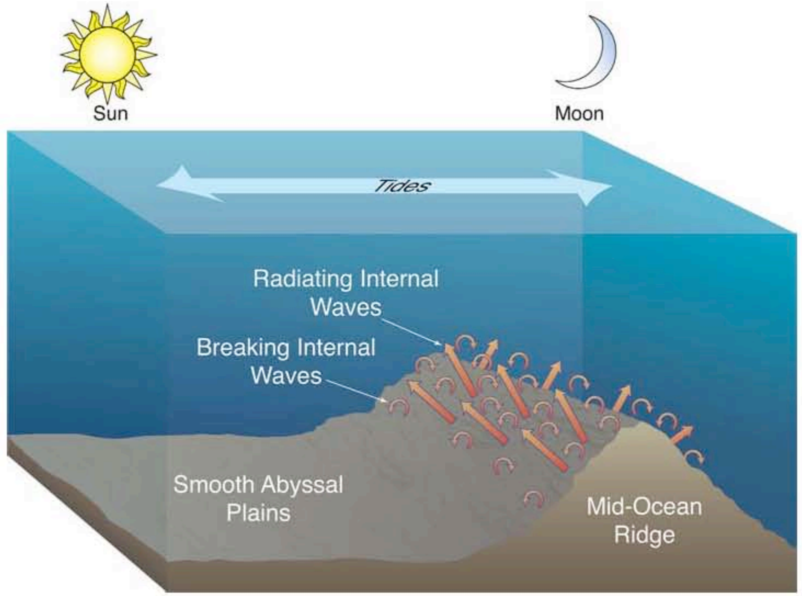
Turbulence due to breaking internal waves

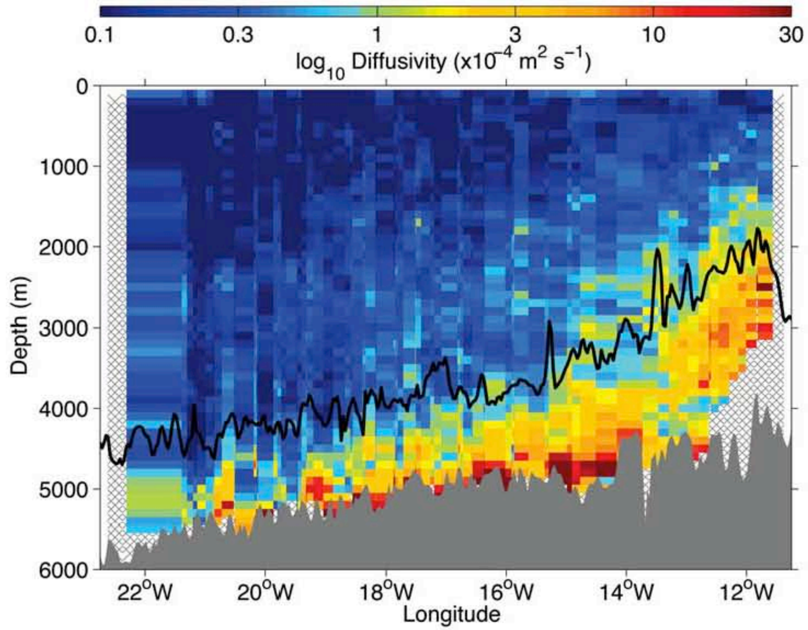
⇓

Mixing temperature, salinity & tracer fields

⇓

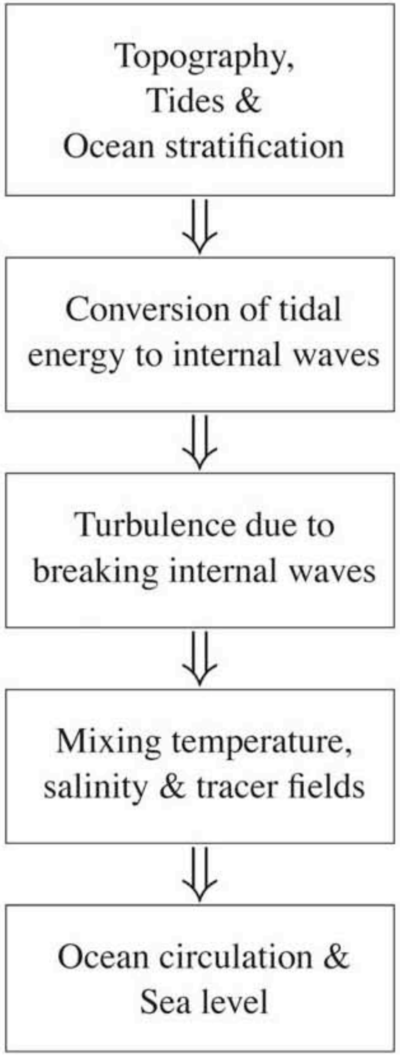
Ocean circulation & Sea level

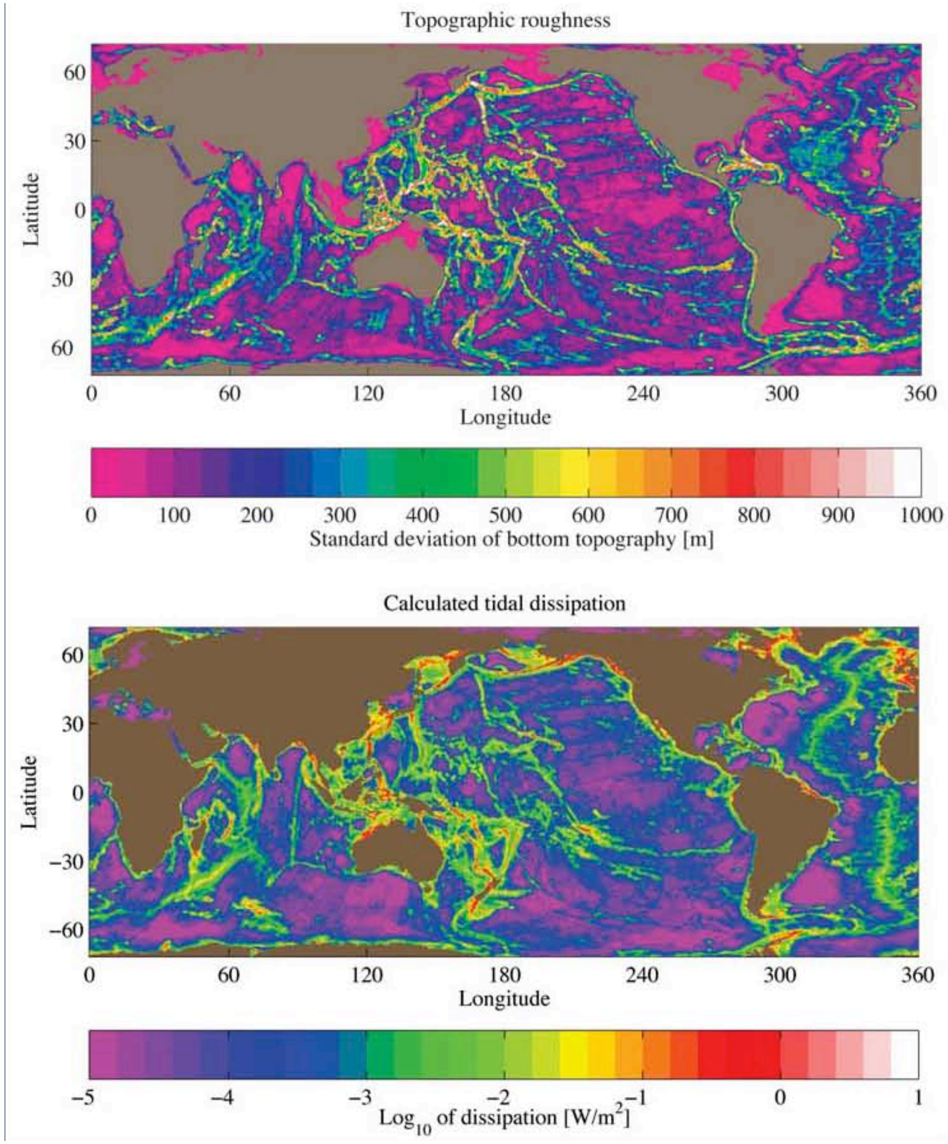




From Jayne et al (Oceanography, 2004)

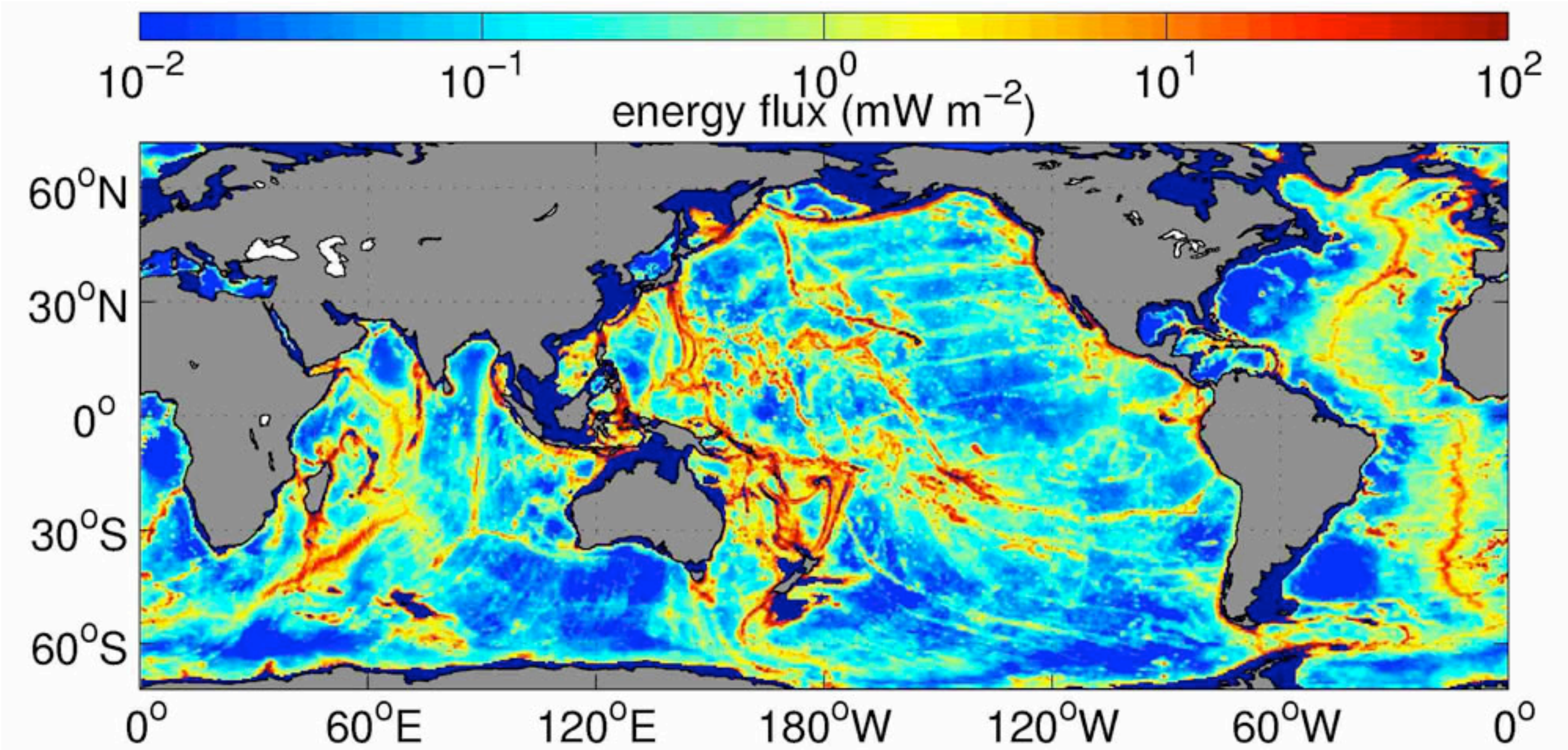
Relation of tides to diapycnal diffusivity





From Jayne et al (Oceanography, 2004)

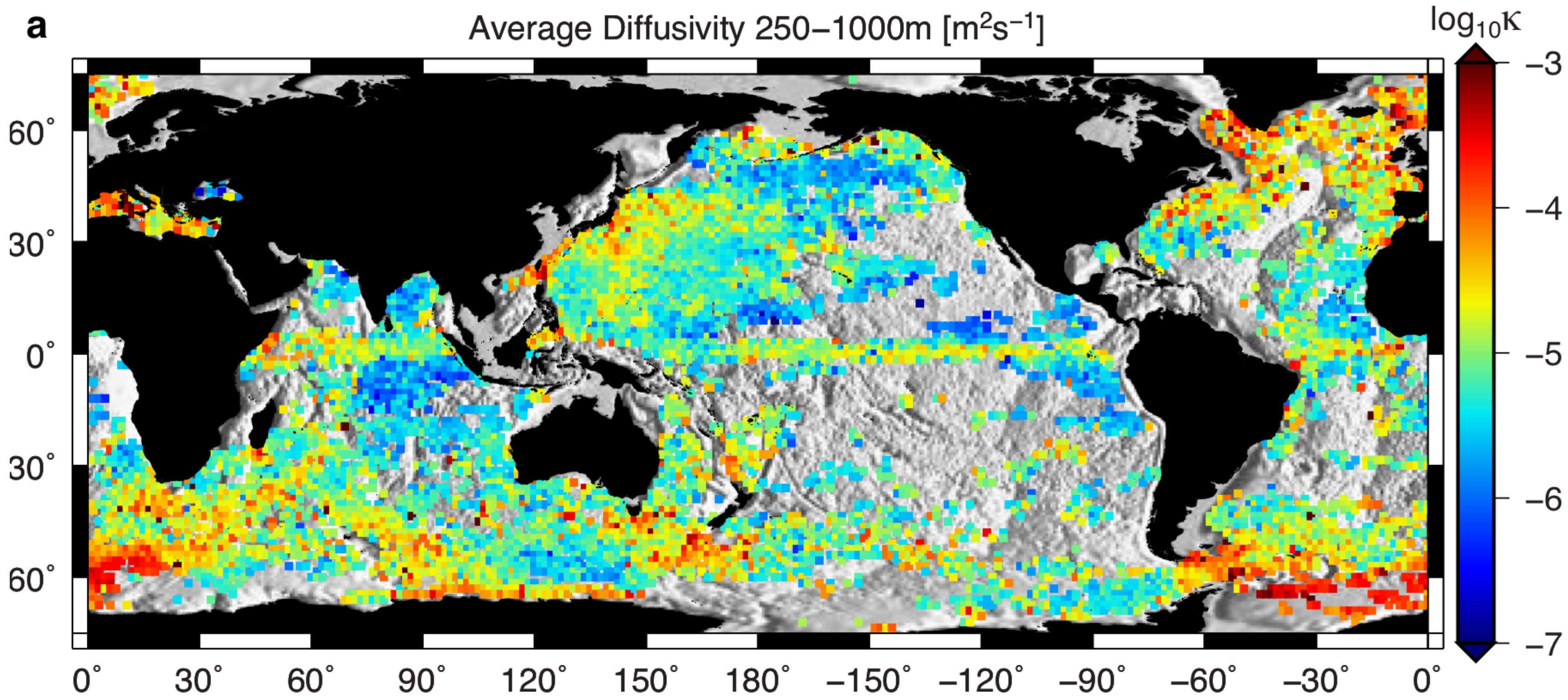
Diapycnal mixing



Energy flux from tides that can be dissipated over topography (and be available for diapycnal mixing)

Jayne and St. Laurent (GRL 2001)

Diapycnal mixing



Diapycnal diffusivity associated with internal wave breaking, estimated from Argo float data (Whalen et al., GRL 2012)