Lecture 15: The energetics of the ocean circulation

Atmosphere, Ocean, Climate Dynamics

EESS 146B/246B

The energetics of the circulation

- Sources and sinks of the kinetic energy of the large scale circulation.
- The release of available potential energy by baroclinic instability.
- The dissipation of the large scale circulation’s kinetic energy.

Sources and sinks of kinetic energy

•Equation for the total kinetic energy: $\overline{KE} = \frac{\rho_{ref}}{2} \int \mathbf{u}_h^2 dV$

$$\frac{\partial \overline{KE}}{\partial t} = \int \tau_{wind} \cdot \mathbf{u}_h \big|_{z=0} dA$$

WIND-DRIVEN SOURCE/SINK OF KE

$$- \int \tau_{bot} \cdot \mathbf{u}_h \big|_{z=-h} dA$$

SINK OF KE VIA BOTTOM FRICTION

$$+ \rho_{ref} \int wb dV$$

CONVERSION OF PE TO KE

$$- \rho_{ref} \int \epsilon dV$$

DISSIPATION

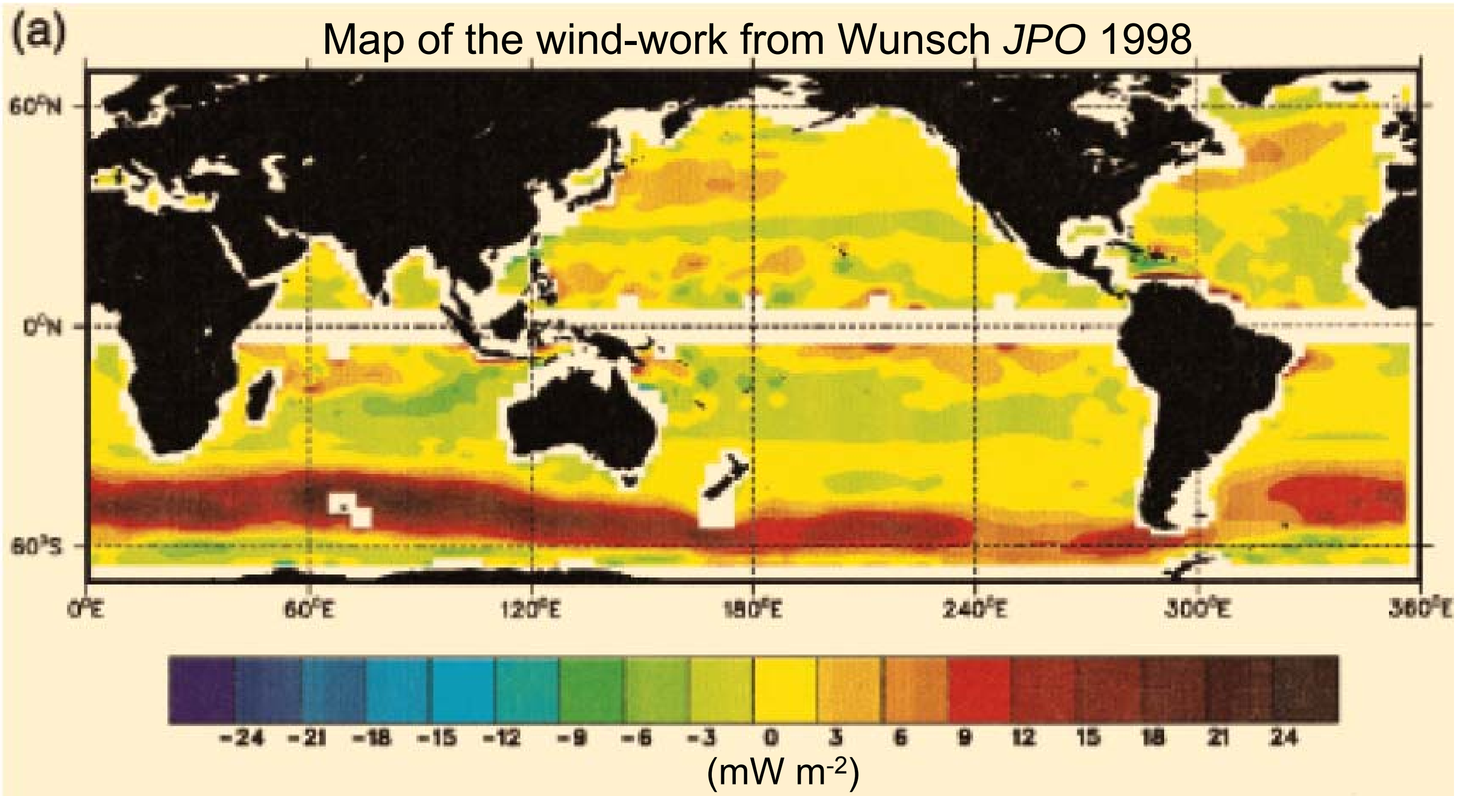
$$\epsilon = \nu \left[\left(\frac{\partial \mathbf{u}}{\partial x} \right)^2 + \left(\frac{\partial \mathbf{u}}{\partial y} \right)^2 + \left(\frac{\partial \mathbf{u}}{\partial z} \right)^2 \right]$$

Wind-work on the circulation

WIND-WORK $\boxed{\boldsymbol{\tau}^{w} \cdot \mathbf{u}_{g}^{s}}$

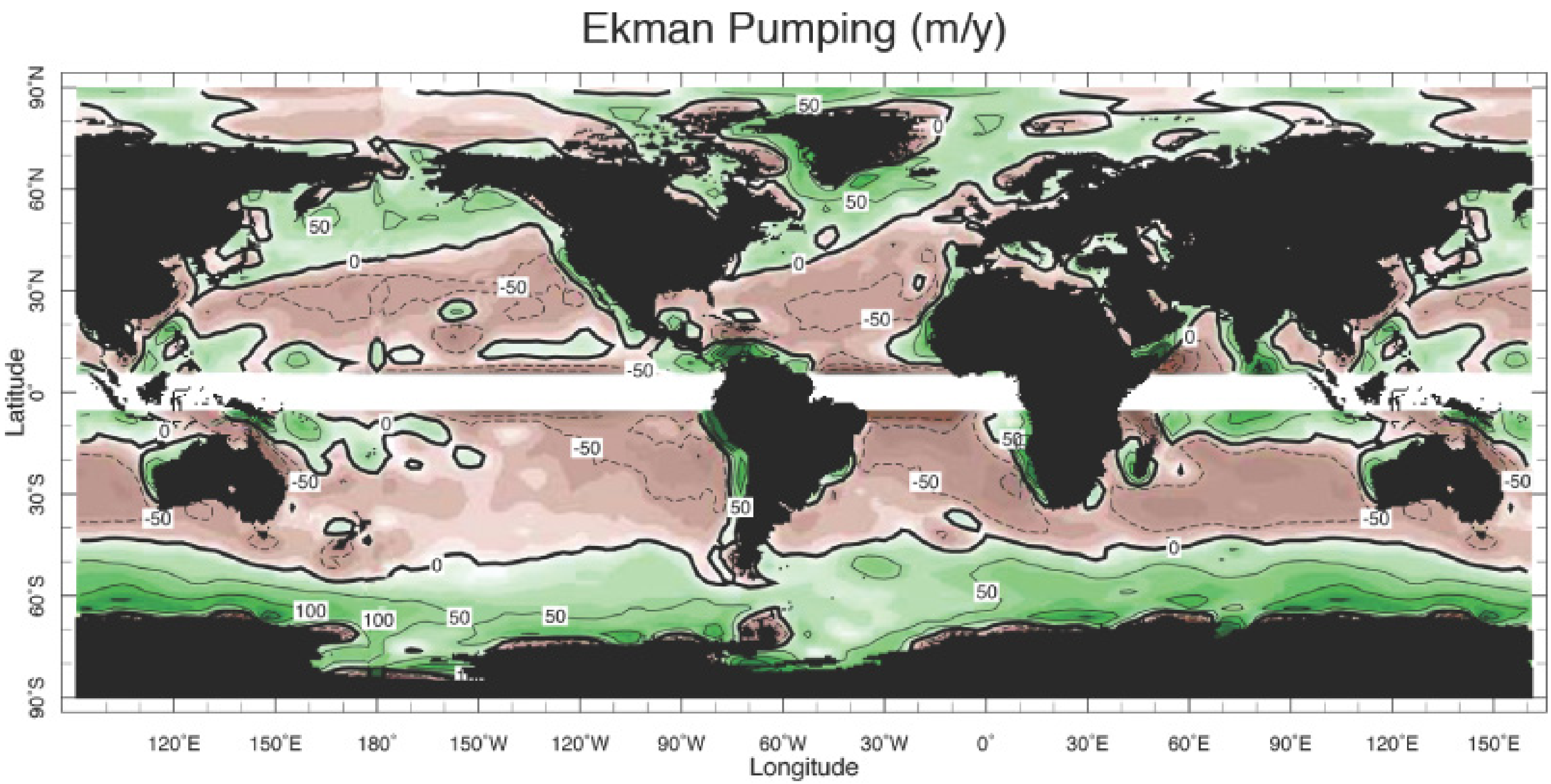
$\boldsymbol{\tau}^{w}$ wind-stress

$\mathbf{u}_{g}^{s}$ velocity of circulation at sea surface

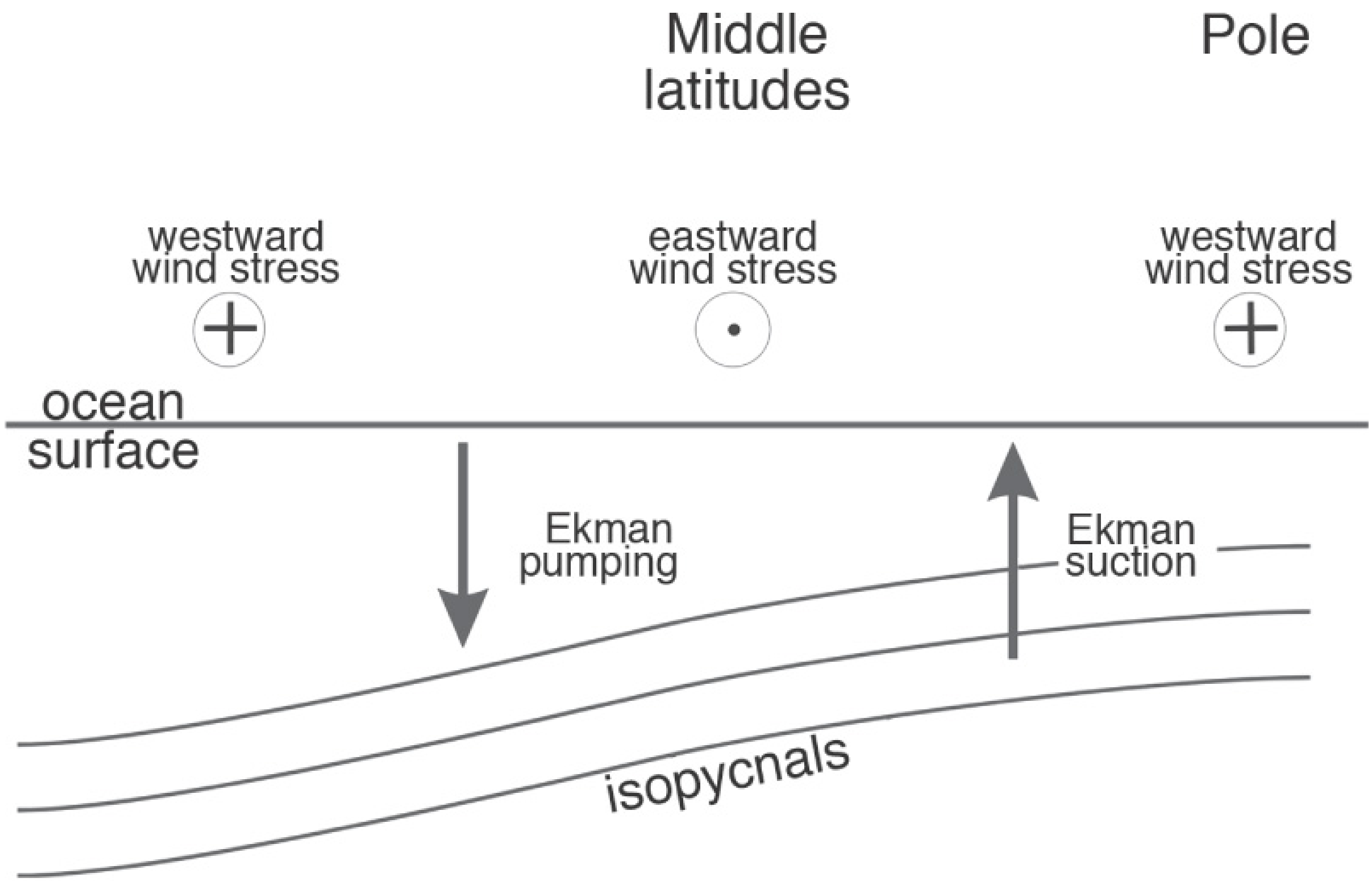


•Integrated over the area of the ocean, the winds input energy at a rate equal to **1 TW**.

How the winds input energy to the ocean circulation



How the winds input energy to the ocean circulation



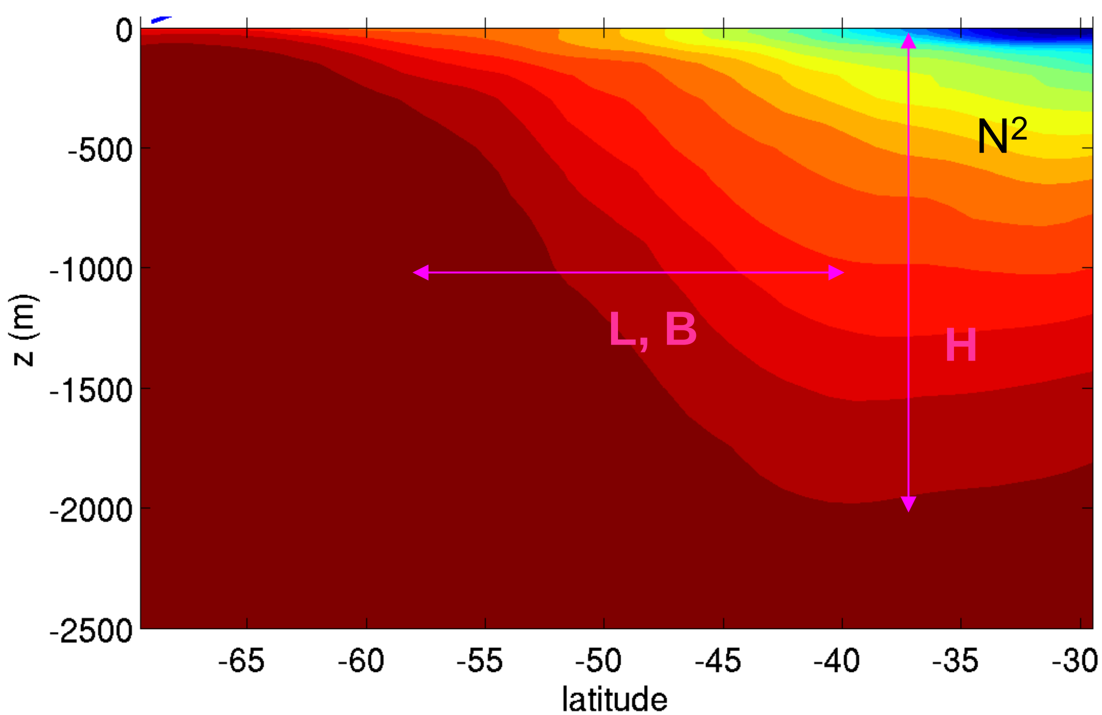
How much energy is in the form of APE versus KE?

Local APE
and KE

$$APE = -\rho_{ref} b Z$$

$$\approx \rho_{ref} b^2 / N^2$$

$$KE = \rho_{ref} u_g^2 / 2$$

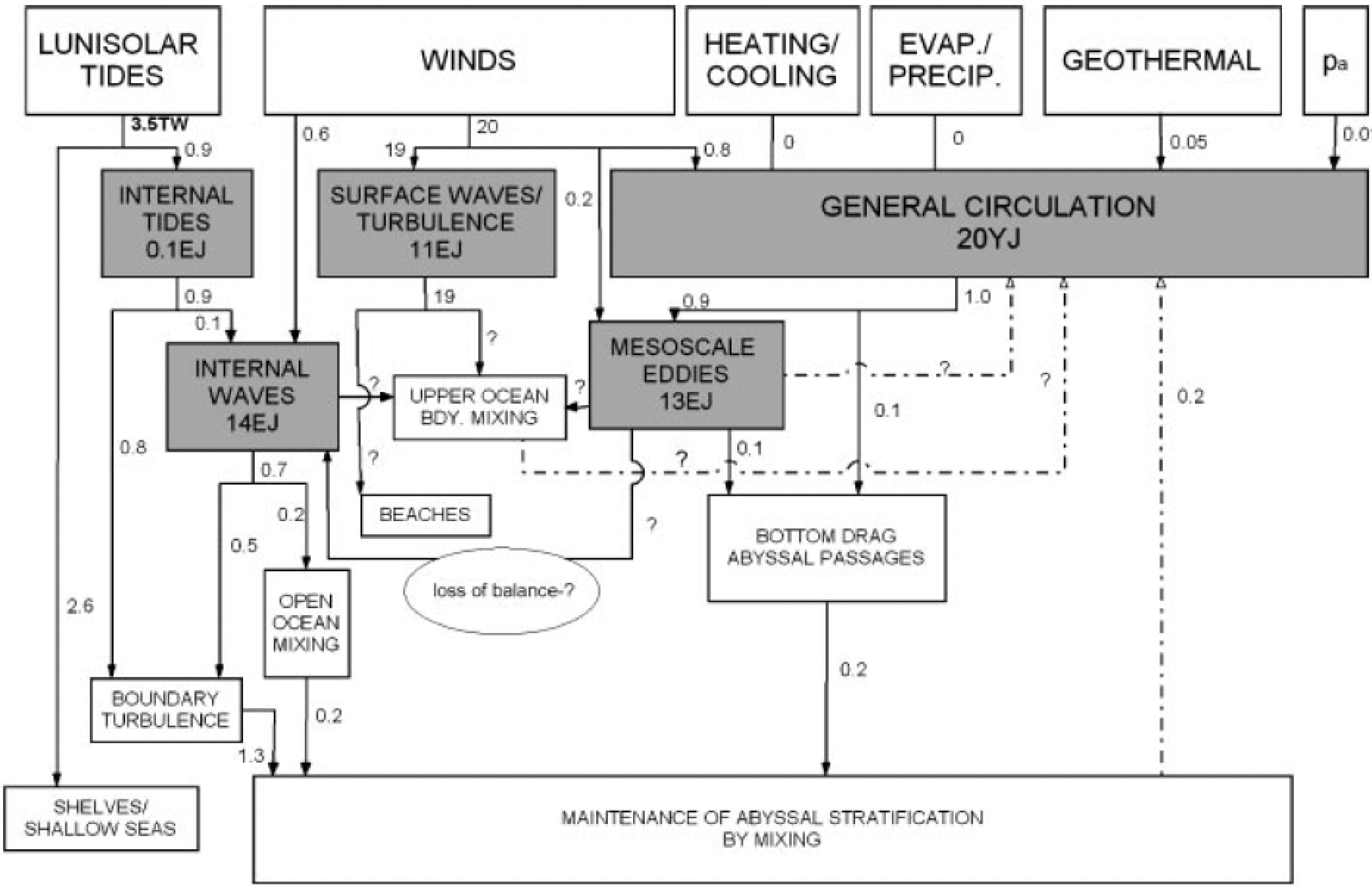


$$f \frac{\partial u_g}{\partial z} = -\frac{\partial b}{\partial y} \longrightarrow U \sim \frac{BH}{fL}$$

$$\boxed{\frac{KE}{APE} \sim \frac{N^2 H^2}{f^2 L^2} = \frac{L_r^2}{L^2}}$$

•Flows with length scales larger than the Rossby radius contain more APE than KE.

Energy budget of the ocean



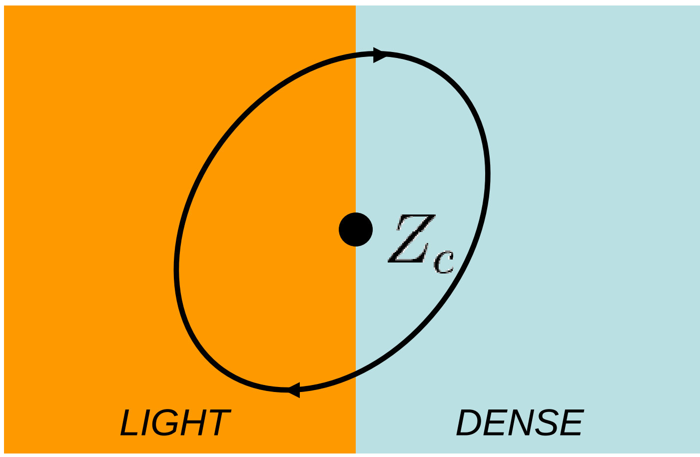
Available potential energy

$$PE = MgZ_c$$

M total mass of water

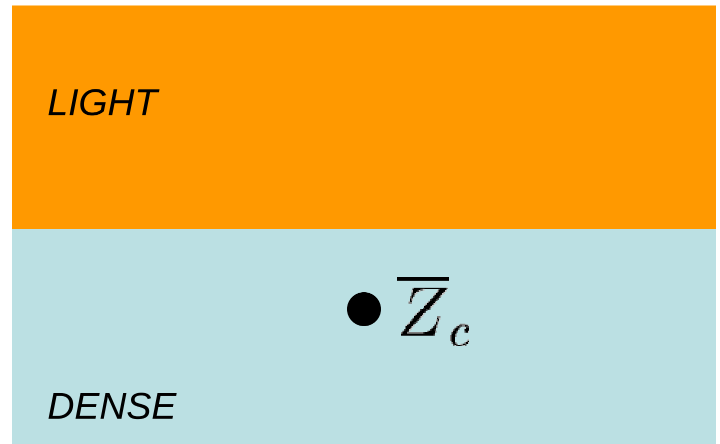
Z_c center of mass of water

FRONT



$$PE = MgZ_c$$

STATE WITH LOWEST PE



$$\overline{PE} = Mg\overline{Z}_c$$

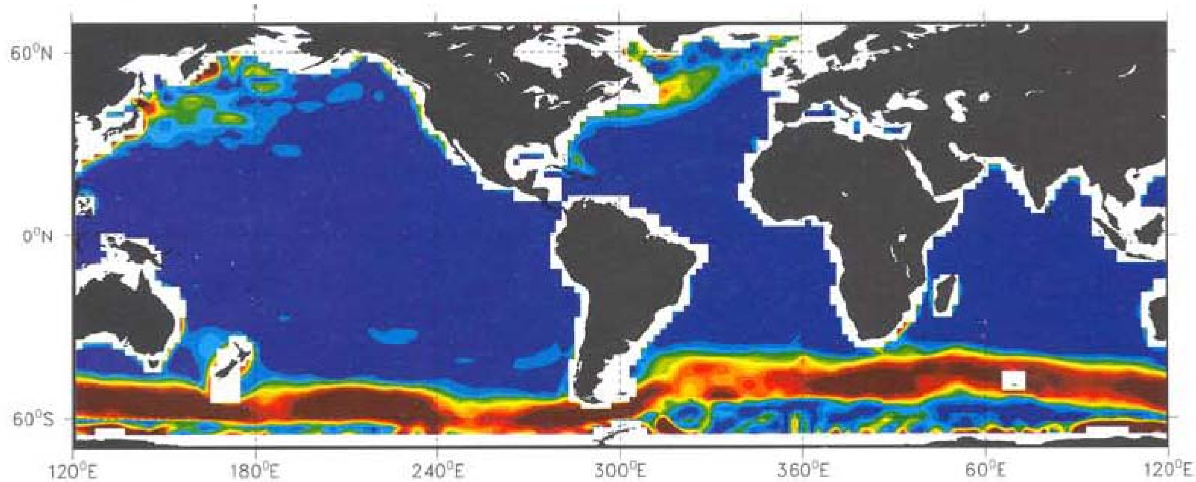
•The available potential energy is the PE that can be converted to kinetic energy

$$APE = PE - \overline{PE} = Mg(Z_c - \overline{Z}_c)$$

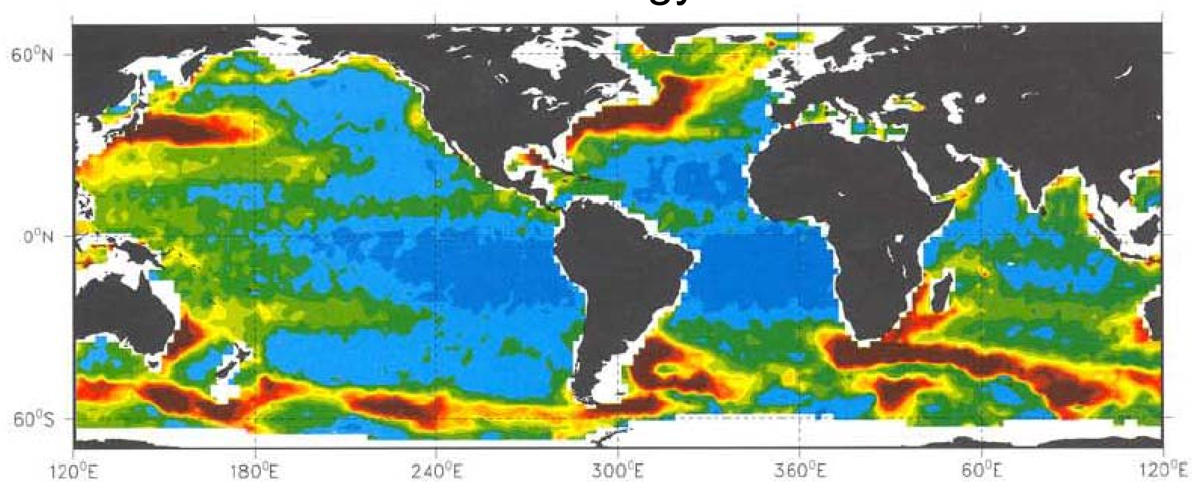
•Eddies that form at fronts draw their kinetic energy from the APE and in doing so reduce the APE by generating a net overturning motion.

Eddy versus mean kinetic energy

kinetic energy of mean circulation



kinetic energy of eddies



•One can split the circulation into a mean and eddy components:

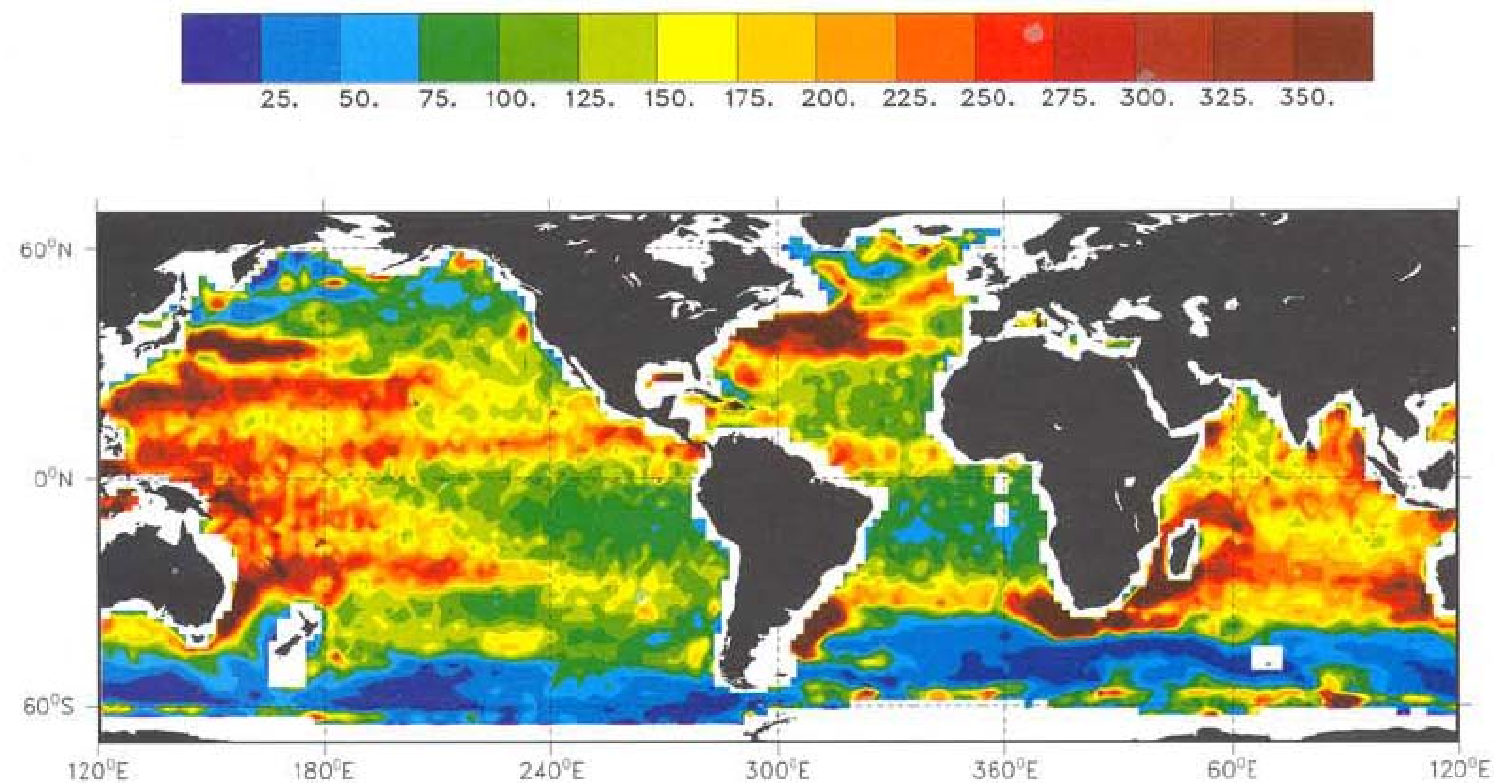
$$u = \overline{u} + u'$$

mean, time average

eddy, time-variable

•Eddy kinetic energy tends to be greatest where the mean circulation is strongest → eddies derive their energy from the mean circulation.

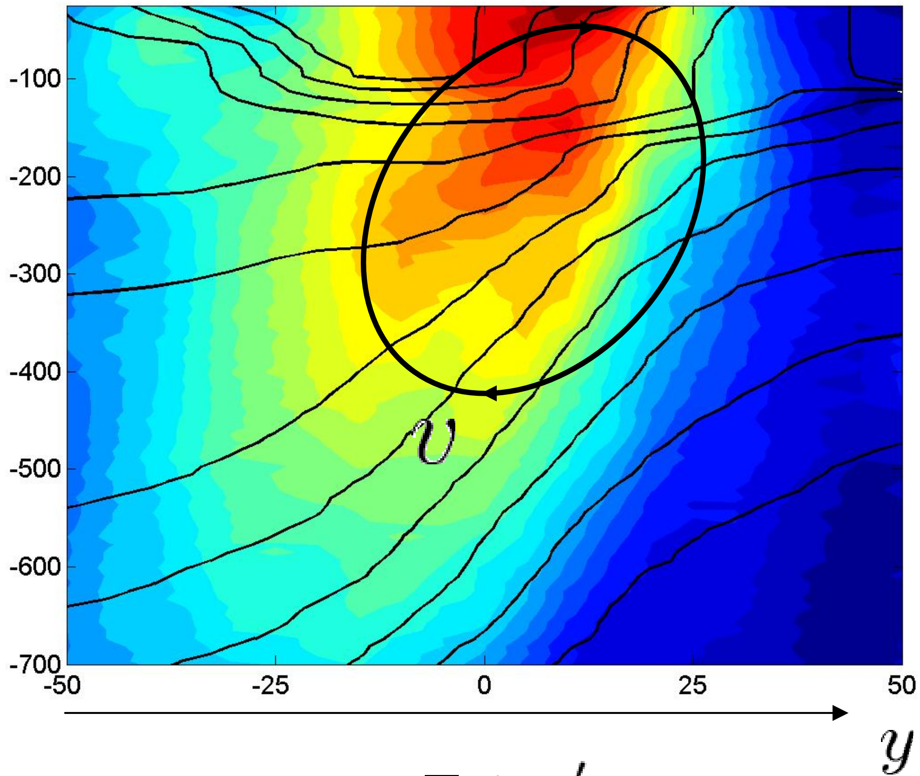
Eddy versus mean kinetic energy



From Wunsch 2002

- Oceanic kinetic energy is dominated by eddies, on average by a factor of 150.
    - The ocean circulation is to first order turbulent and dynamic.

How do eddies drive a net transport?



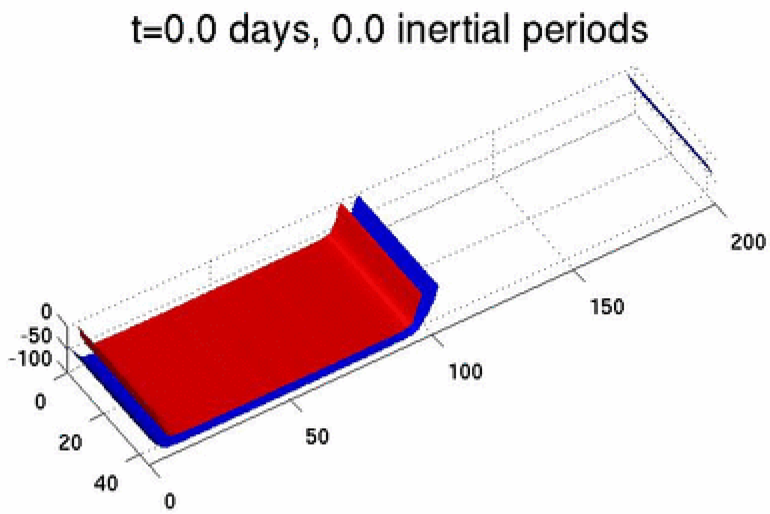
$$\underbrace{}_{}v = \overline{v} + v'$$

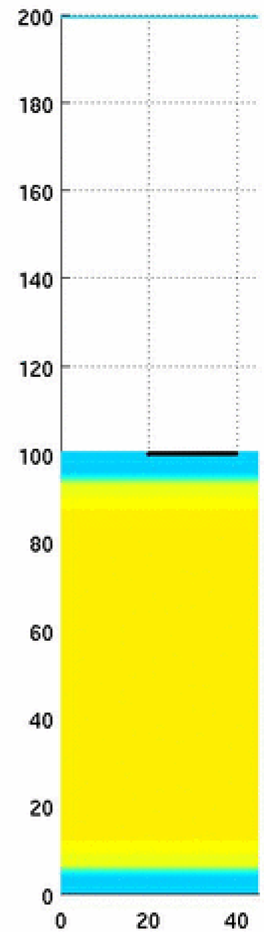
mean eddy

•If the average of an eddy quantity is zero: $\overline{v'} = 0$

how can it generate a mean overturning circulation?

How eddies generate a net transport



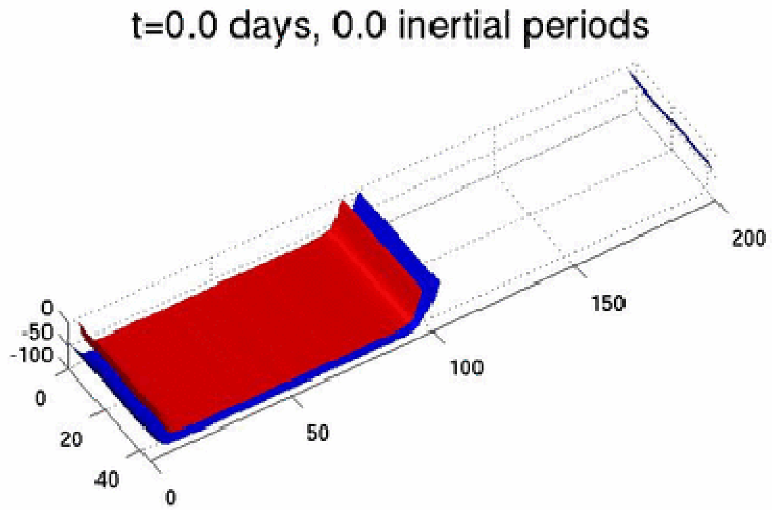


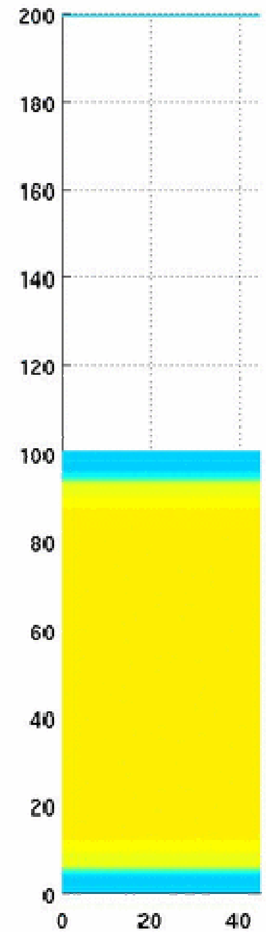
•Blue shades: thicker isopycnal layer

Quantity that measures Isopycnal layer thickness

Thomas, *Dynamics of Atm. and Ocean*, (2008)

How eddies generate a net overturning

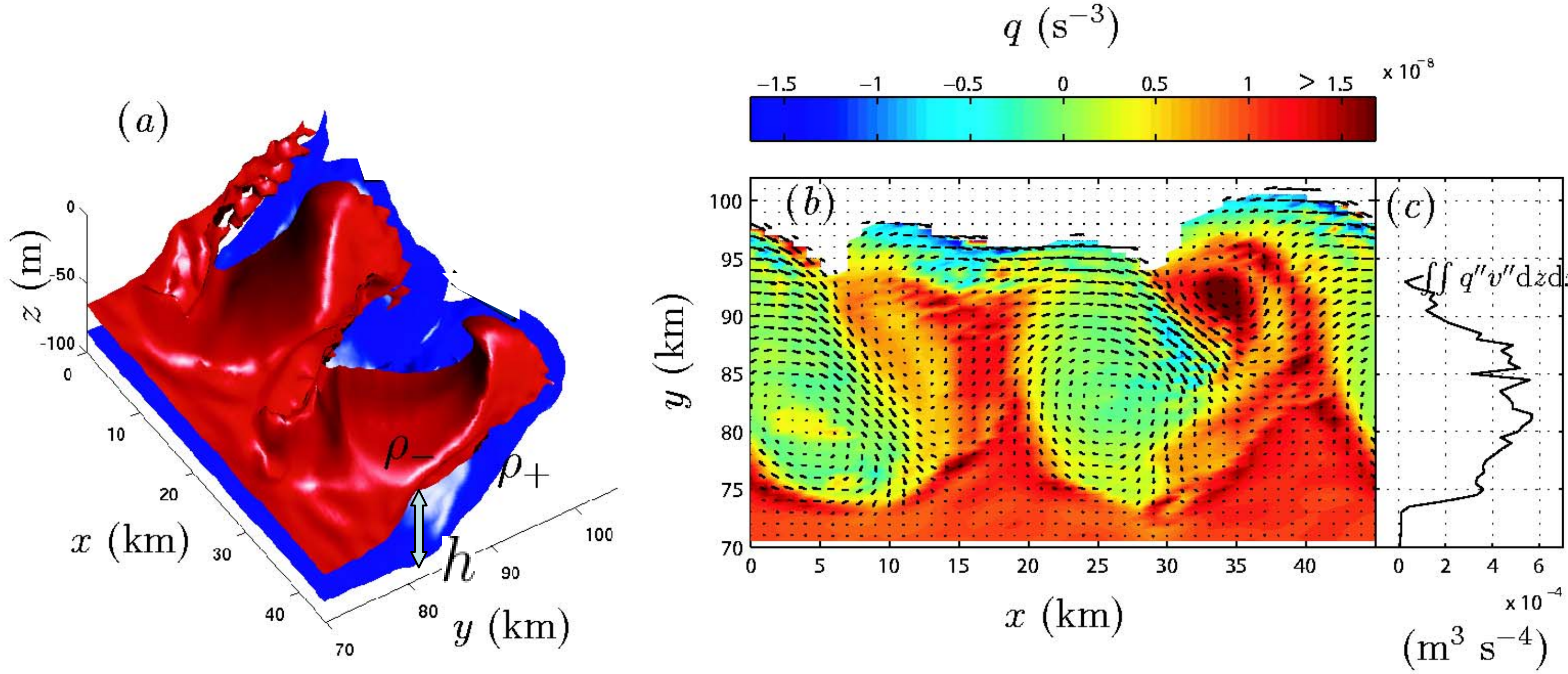




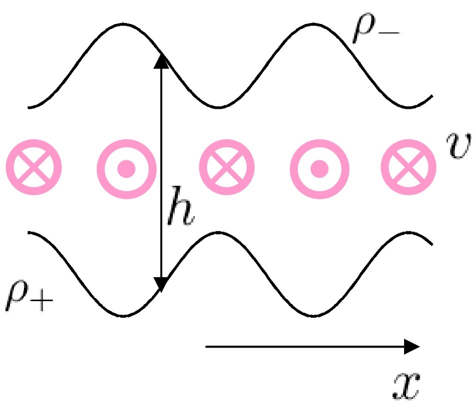
- Blue shades: thicker isopycnal layer

- Eddies subduct surface waters with greater isopycnal layer thickness while upwelling water from the interior with thinner isopycnal layer thickness.

Quantifying the eddy-induced transport



•A correlation develops between the eddy's modification of isopycnal thickness and velocity



Net transport along an isopycnal per unit length

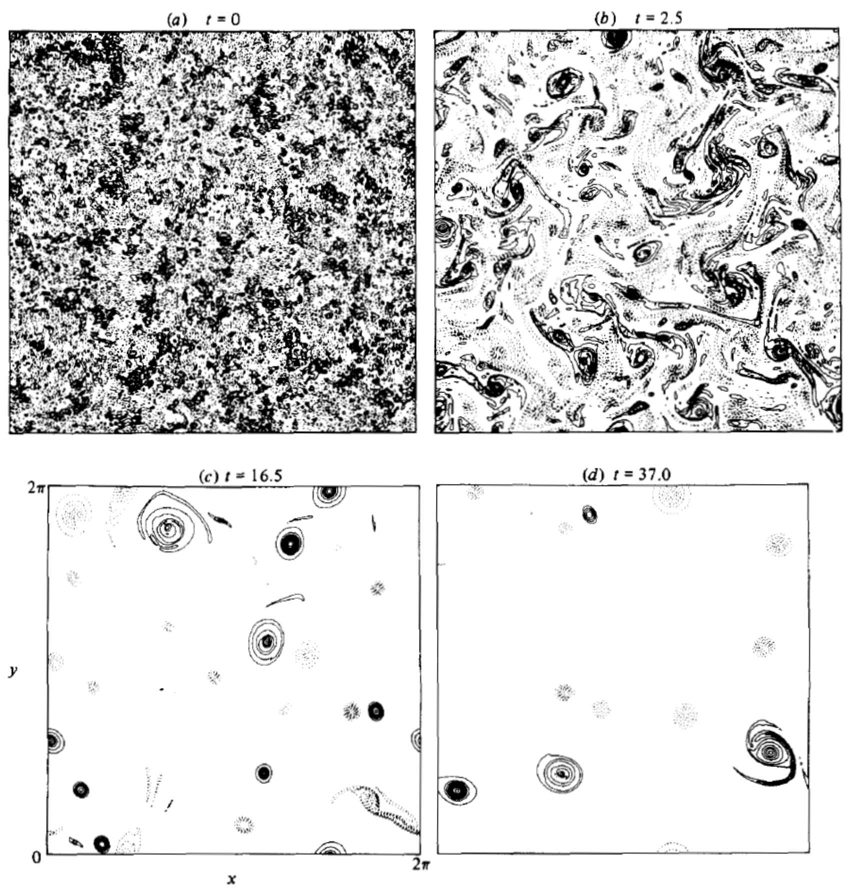
$$= \frac{1}{L_x}\int_0^{L_x} vh dx$$

$$= \overline{v'h'}$$

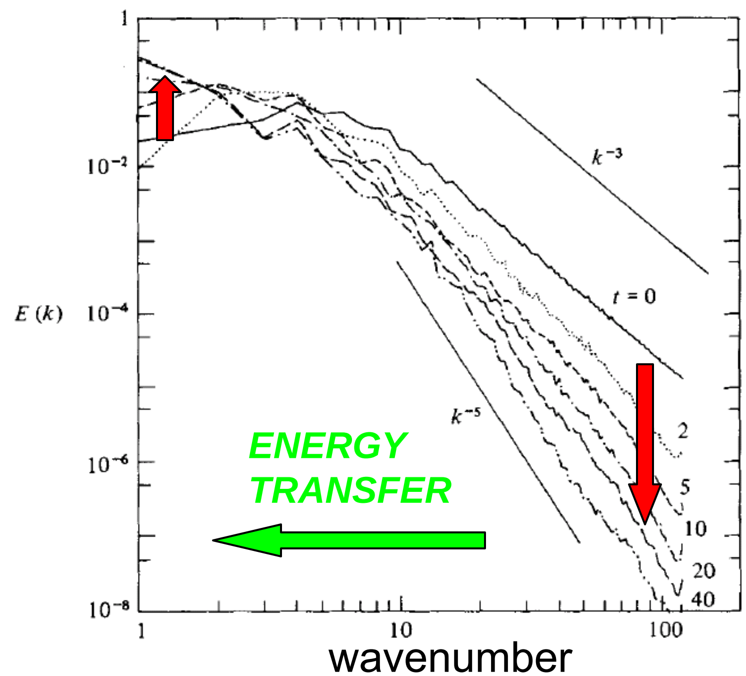
EDDY-INDUCED TRANSPORT

Two-dimensional turbulence: the inverse cascade

Evolution of the vorticity $\zeta = (\nabla \times \mathbf{u}) \cdot \hat{k}$



Kinetic Energy Spectrum

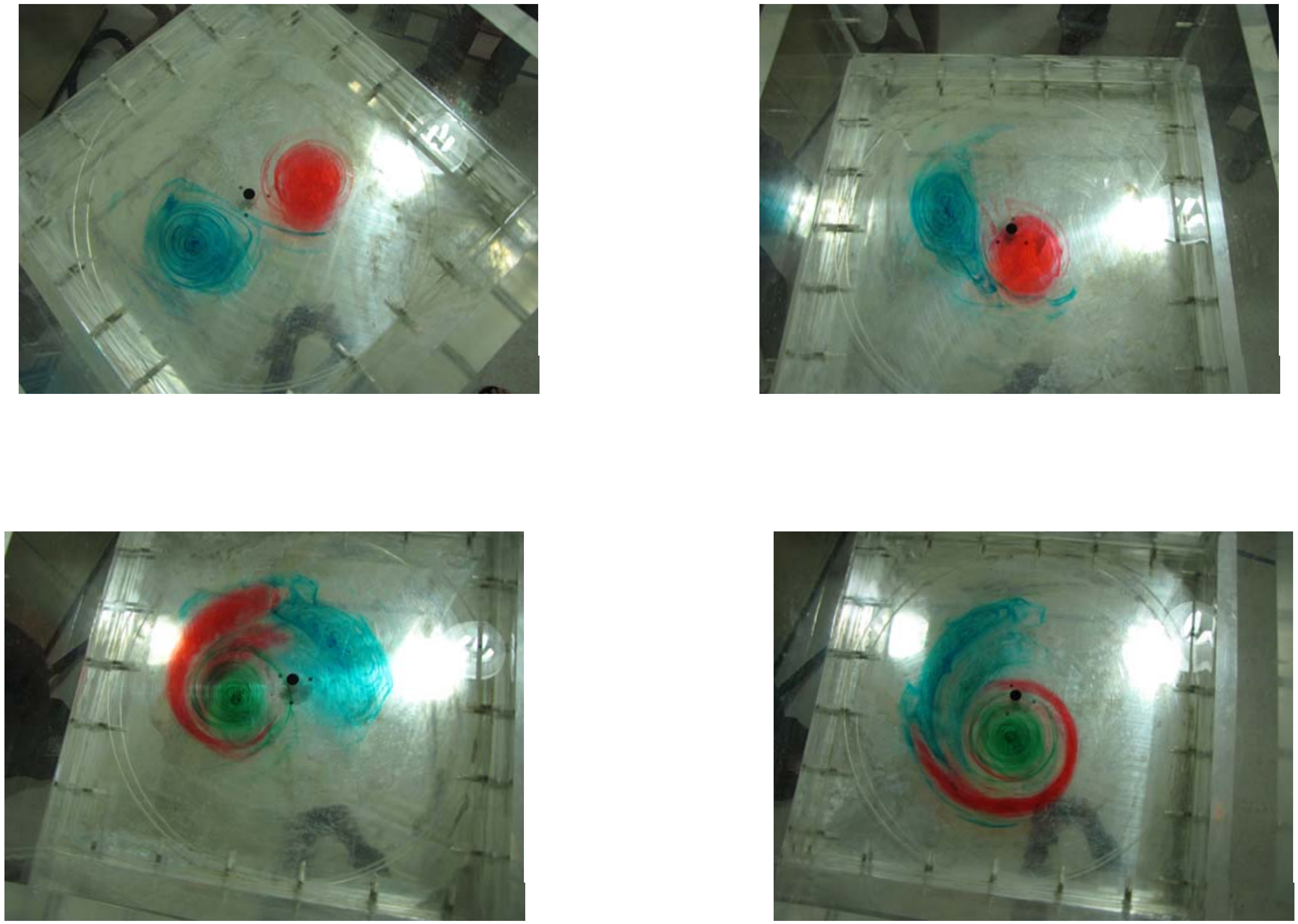


Figures from McWilliams, *JFM*, 1984.

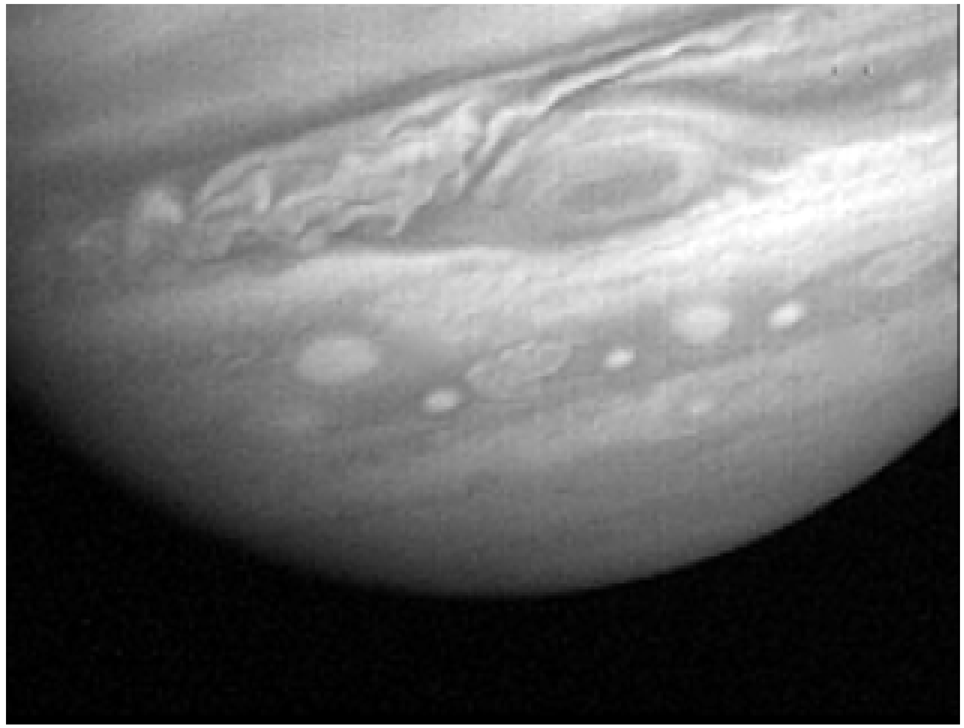
•In turbulence strongly constrained by rotation, smaller eddies are engulfed and merge with larger eddies.

•Energy is transferred from small to large scales, following an *inverse cascade* of energy.

Vortex mergers in the lab



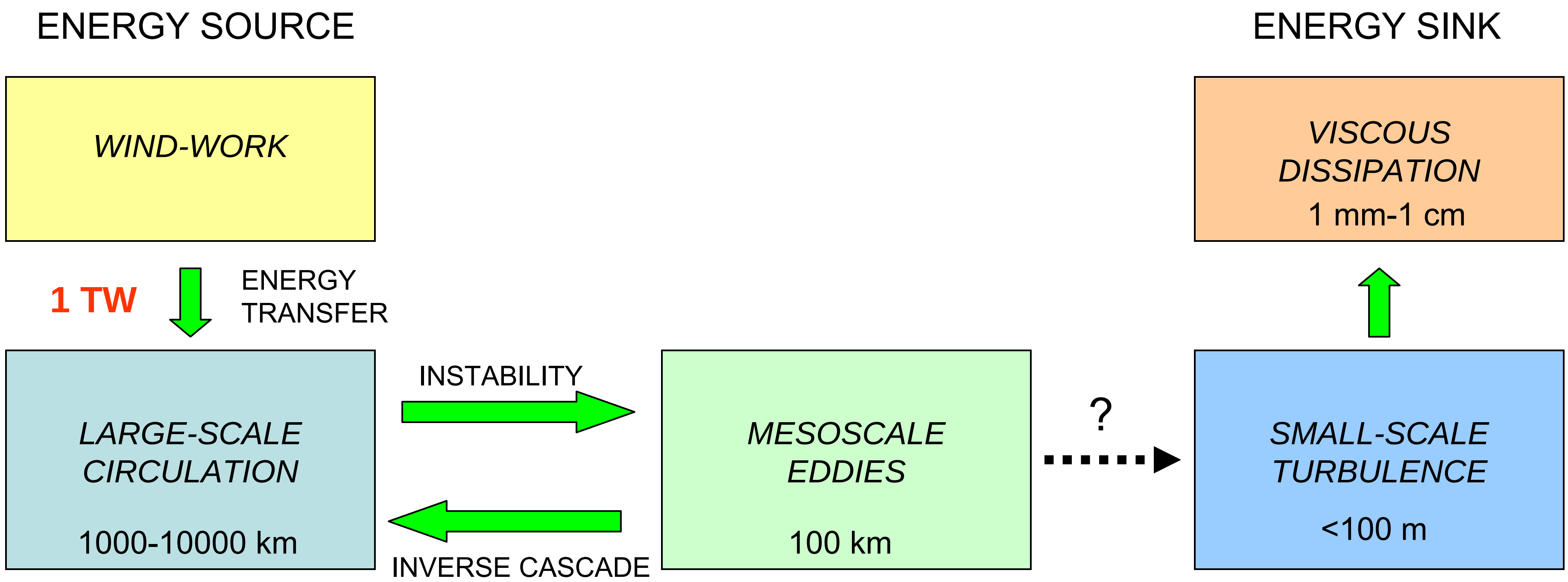
Jovian example of a vortex merger



The Great Red Spot viewed from the Voyager 1 1979. JPL/NASA

•Fluids strongly constrained by rotation such as the atmosphere of Jupiter are characterized by mesoscale turbulence that exhibits an inverse cascade.

The energy budget of the ocean



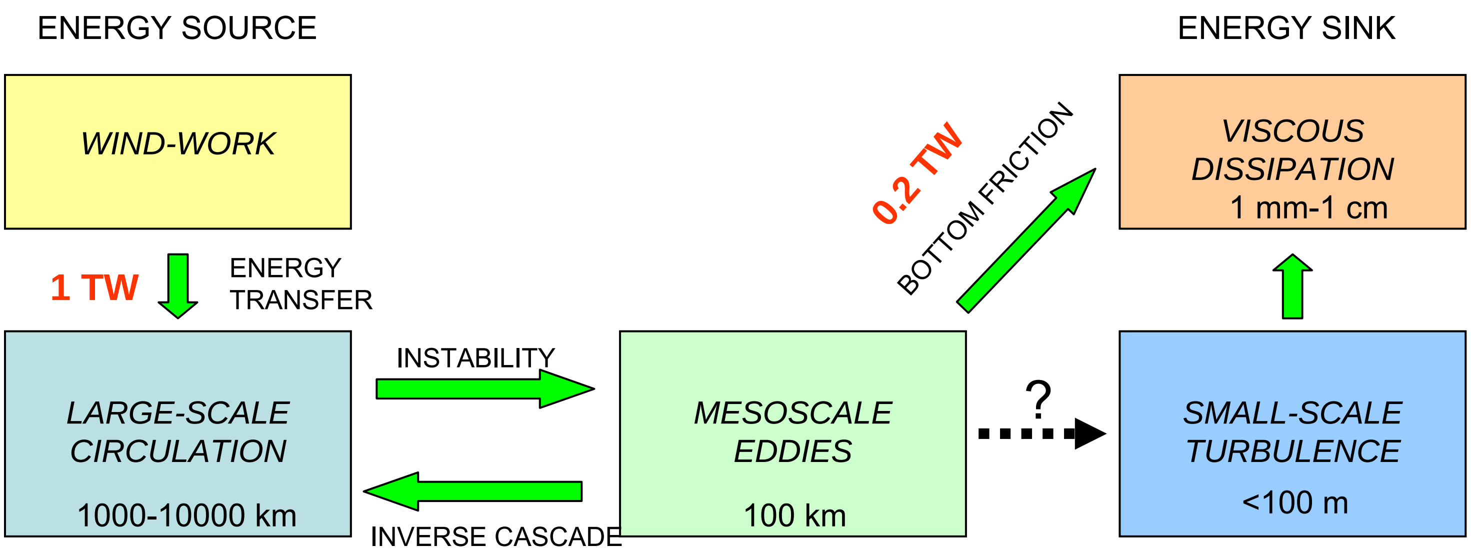
- The inverse cascade short circuits the transfer of energy from the large-scale circulation to viscous dissipation.
- How is the kinetic energy budget for the ocean circulation closed?
- How can energy be transferred from the mesoscale to small scale turbulence where viscous dissipation can act?

Removal of kinetic energy from the circulation by bottom friction.

•Bottom friction removes KE from bottom currents at a rate: $\boldsymbol{\tau}^b \cdot \mathbf{u}_g^b$

bottom stress   near bottom velocity

•Sen et al, GRL 2008 estimate using current meter observations that bottom drag removes KE from the circulation at a rate 0.2 TW.



•Bottom friction alone cannot close the energy budget, other processes are needed to transfer energy from the mesoscale to the small scales where friction can act.

Generation of internal gravity waves by mean circulation flowing over rough topography

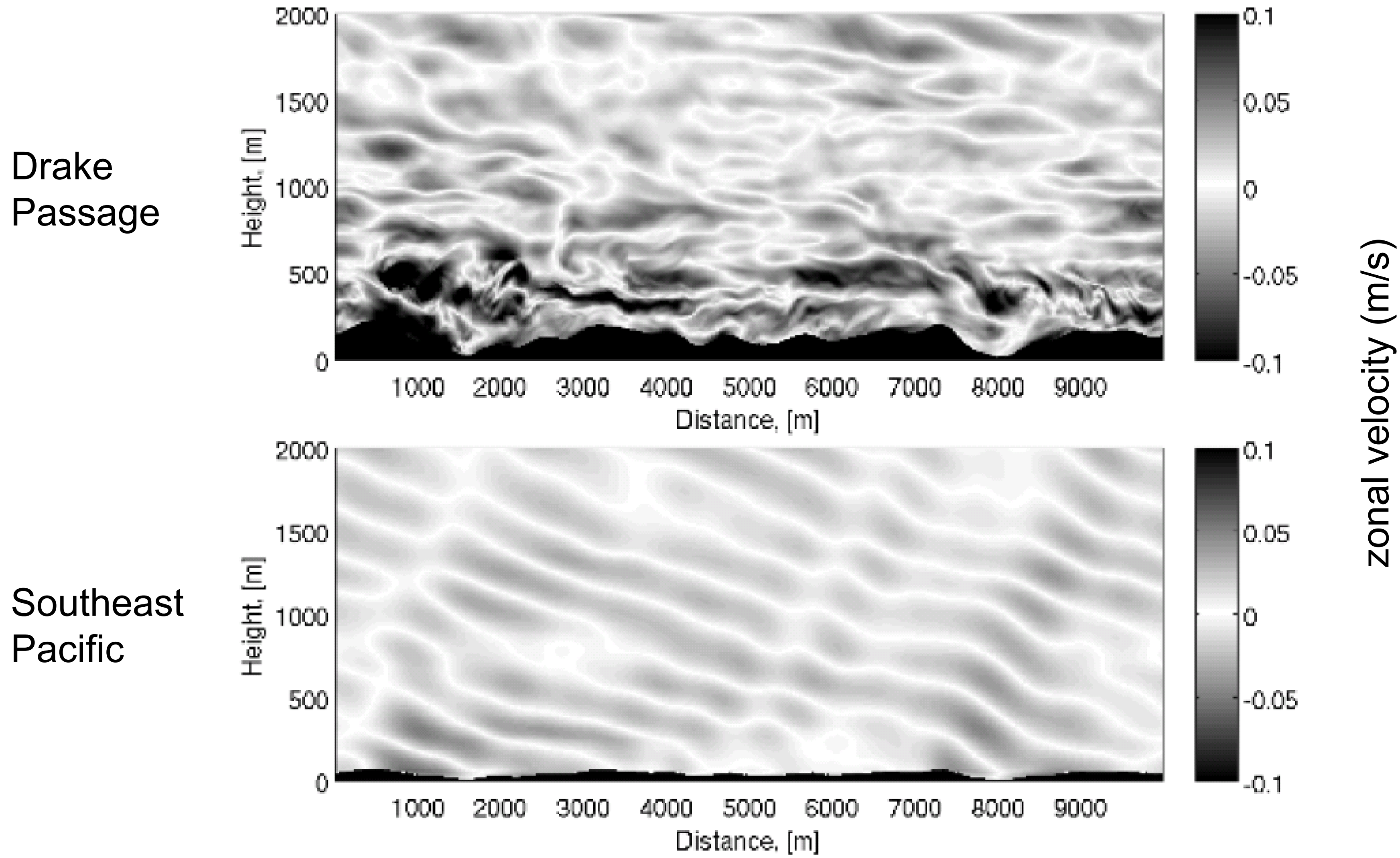
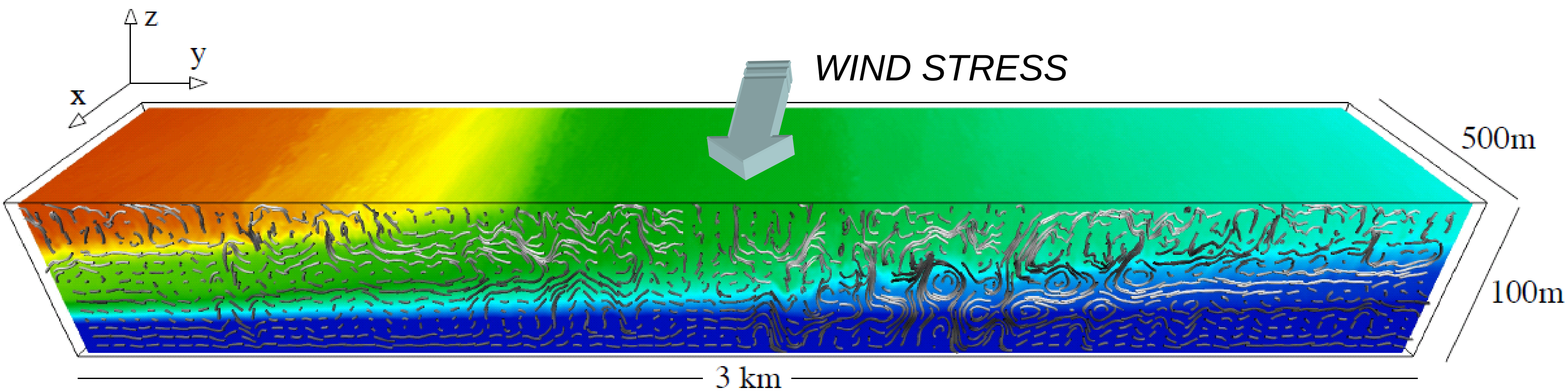
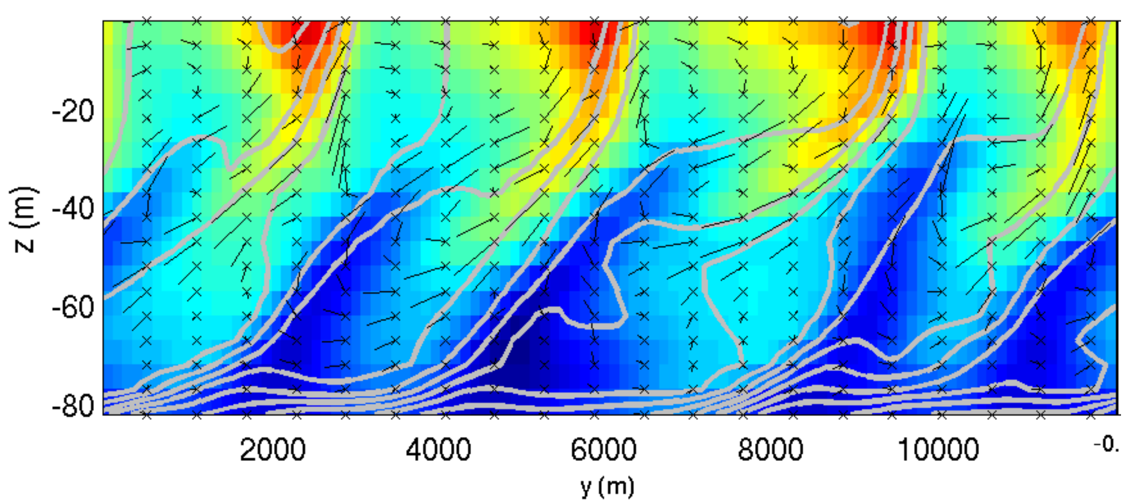


Fig. from Nikurashin and Ferrari JPO 2010

Submesoscale instabilities in the upper ocean





The correlation between the vertical and horizontal turbulent velocity shows how the submesoscale instabilities extract energy from the mean flow

$$\tau_{Reynolds_x} = -\rho_{ref}\overline{u'w'}$$