Eddy mixing in energetic ocean regions with jets: Float-based estimates and theories

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Outline

(1) Background: Eddies, climate modeling, and previous mixing theories and estimations.

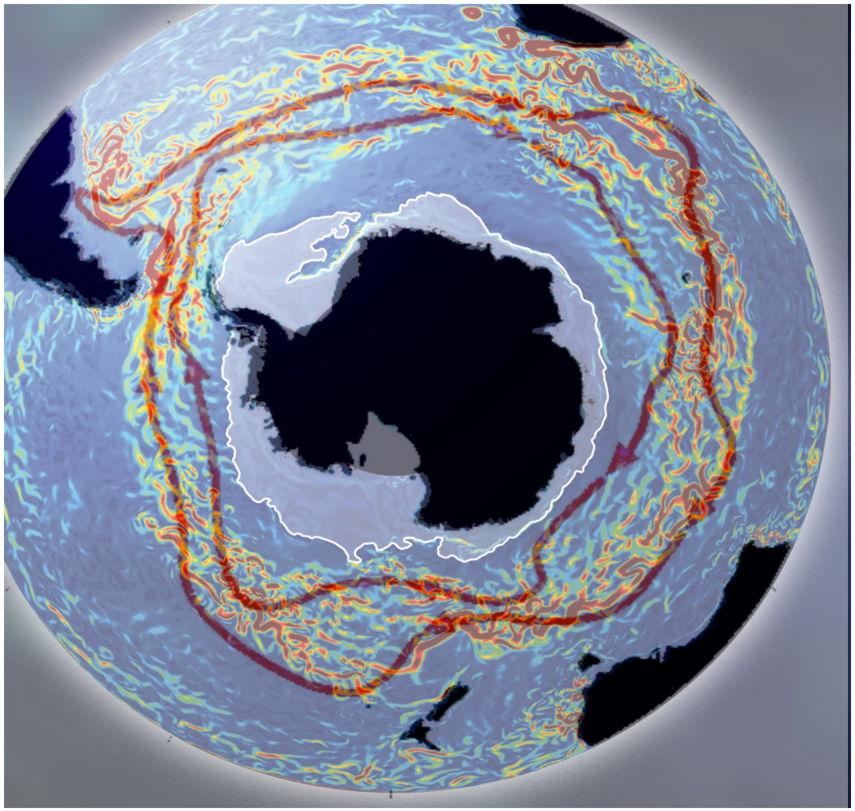
(2) Our methodology: Global eddying model with one million numerical floats.

(3) Results: Complex mixing patterns at high spatial resolution.

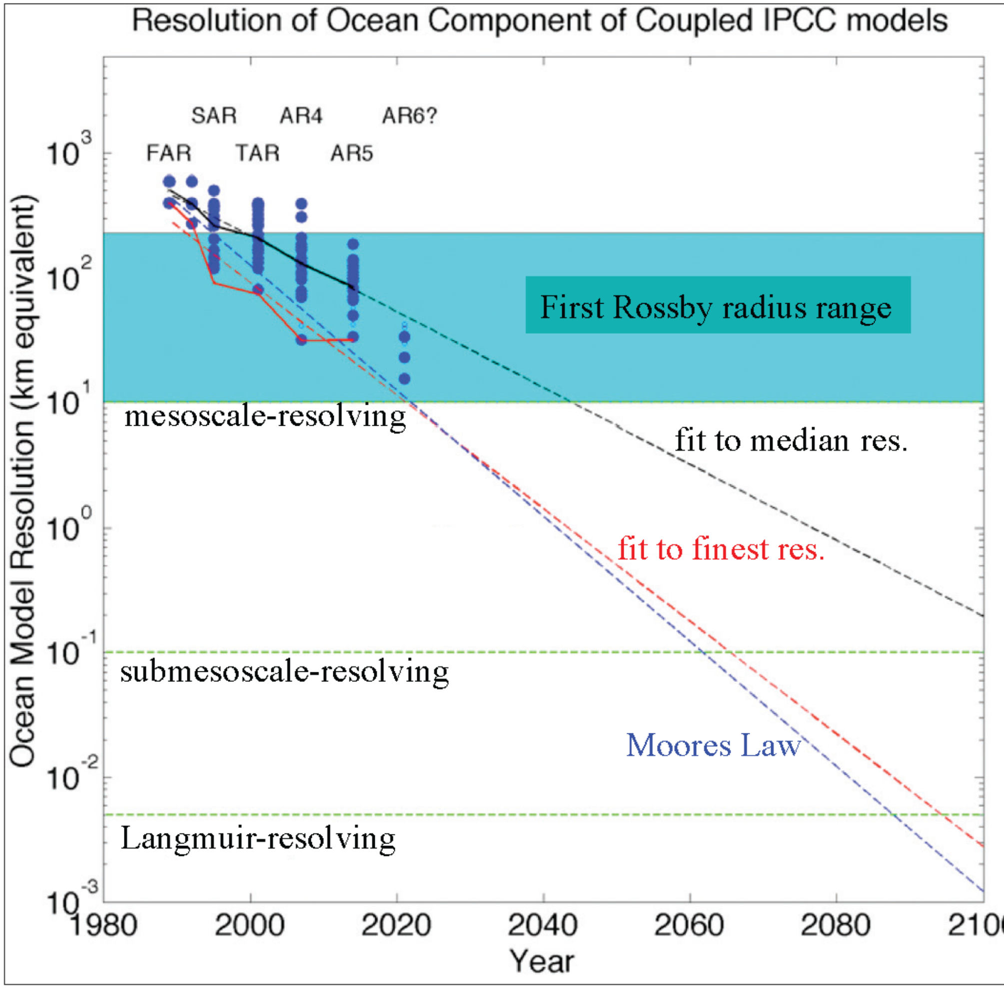
(4) Results: Comparison between new and original mixing theories.

(5) Summary

Eddy field and model resolution



Courtesy of Matt Mazloff



From Fox-Kemper et al. (2014)

Eddy parameterization in models

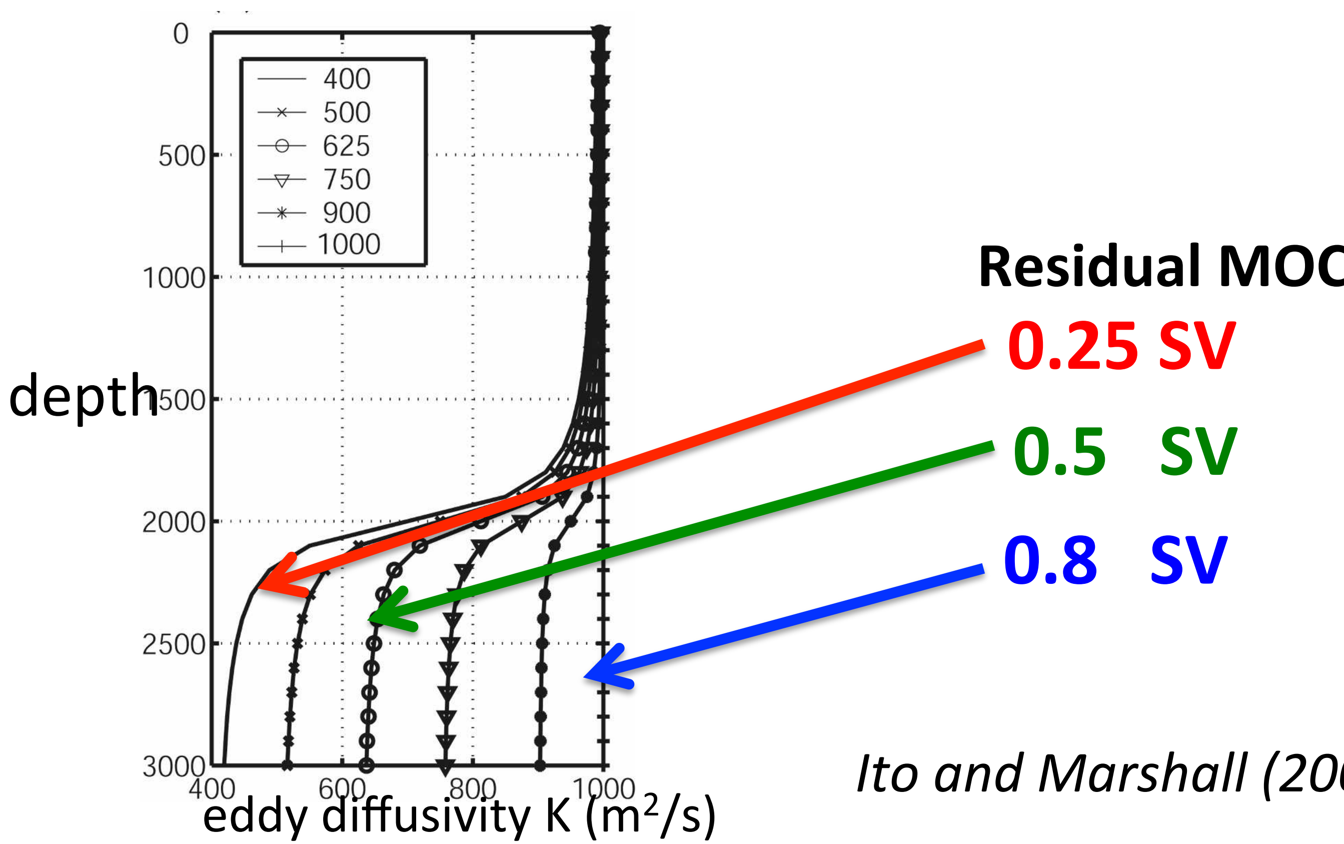
General **eddy parameterization** problem in climate models

$$\nabla \cdot \overline{\mathbf{v}'c'} = \nabla \cdot (-\mathbf{K}\nabla\overline{c})$$

K is a function of x, y, z, and t!

Eddy diffusivity

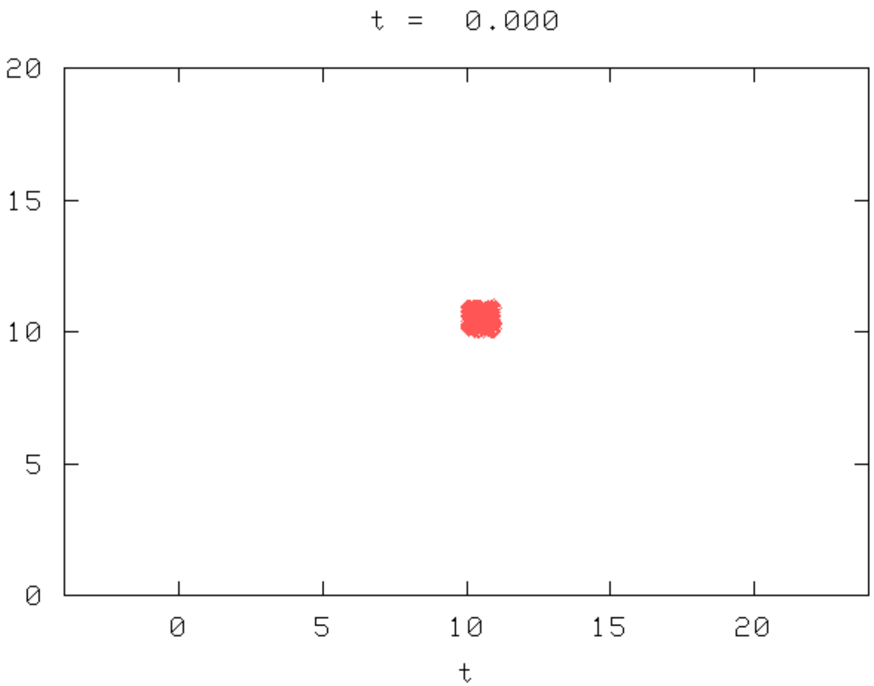
Meridional overturning circulation (MOC) is sensitive to K

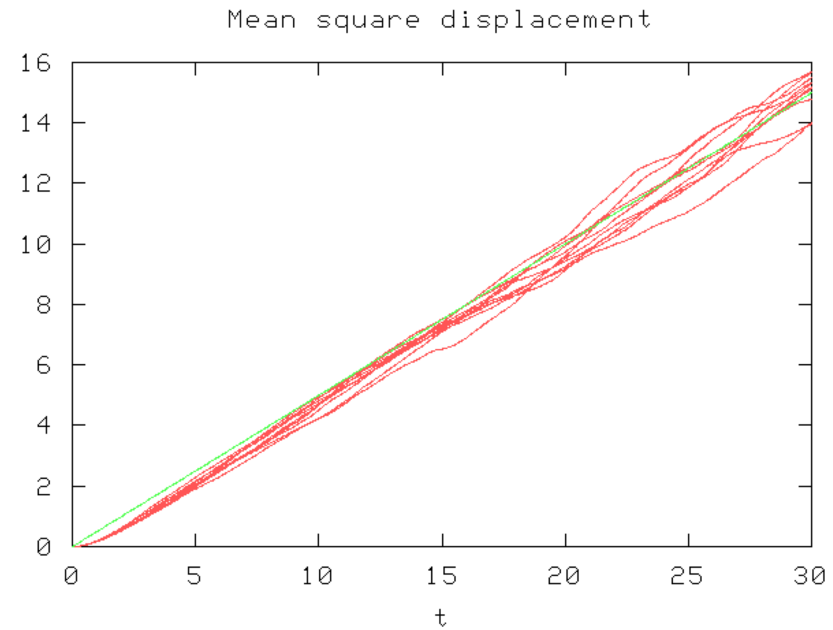


Ito and Marshall (2008)

Estimate eddy diffusivity from Lagrangian particles

Pure diffusion case: particles evolution with time through random walk (molecular diffusion).





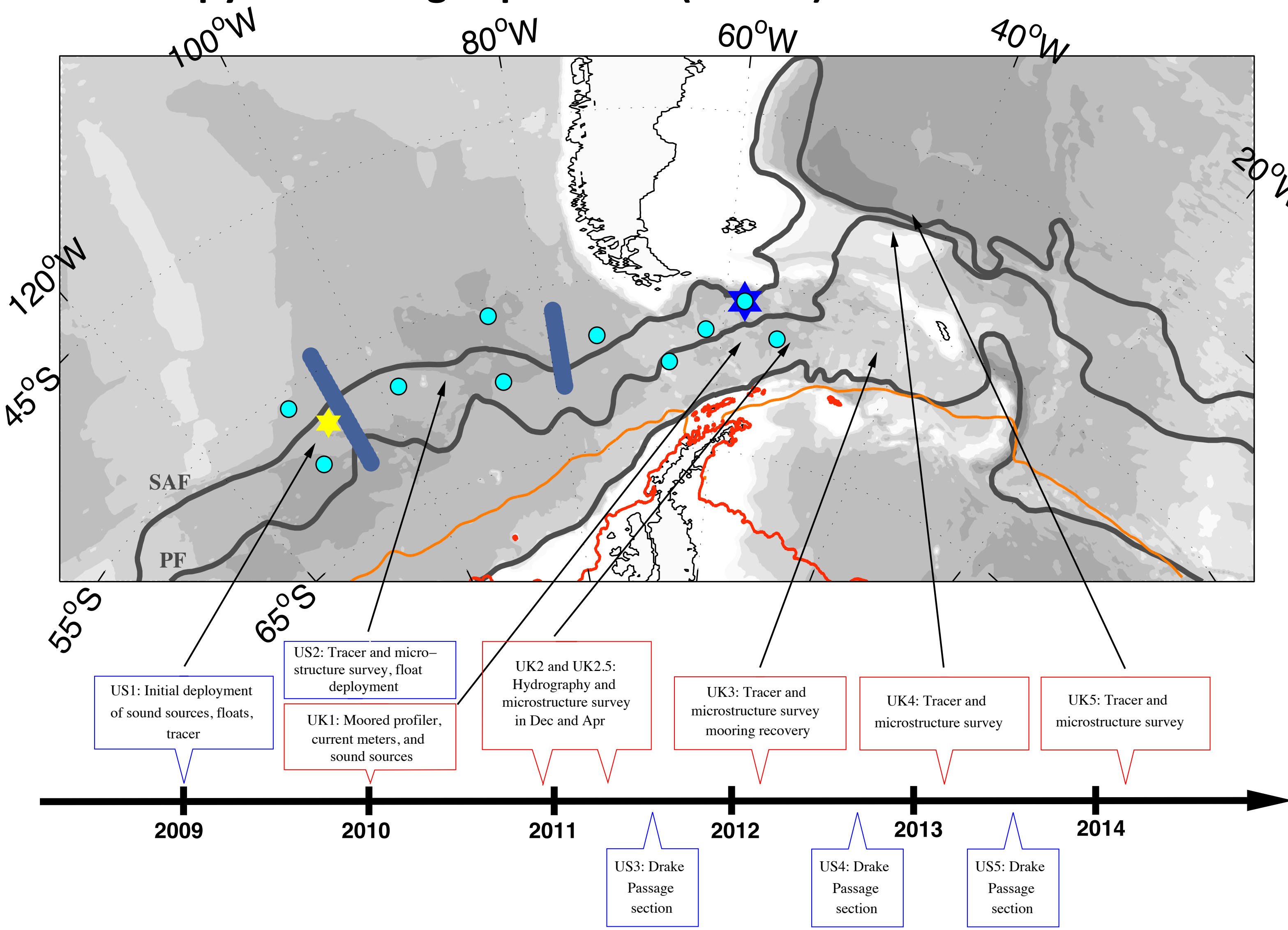
Course 12.820 at MIT

Diffusivity: half of the disperse rate

$$\kappa = \frac{1}{2} d < x^2 > / dt$$

Float-based mixing estimates: observations

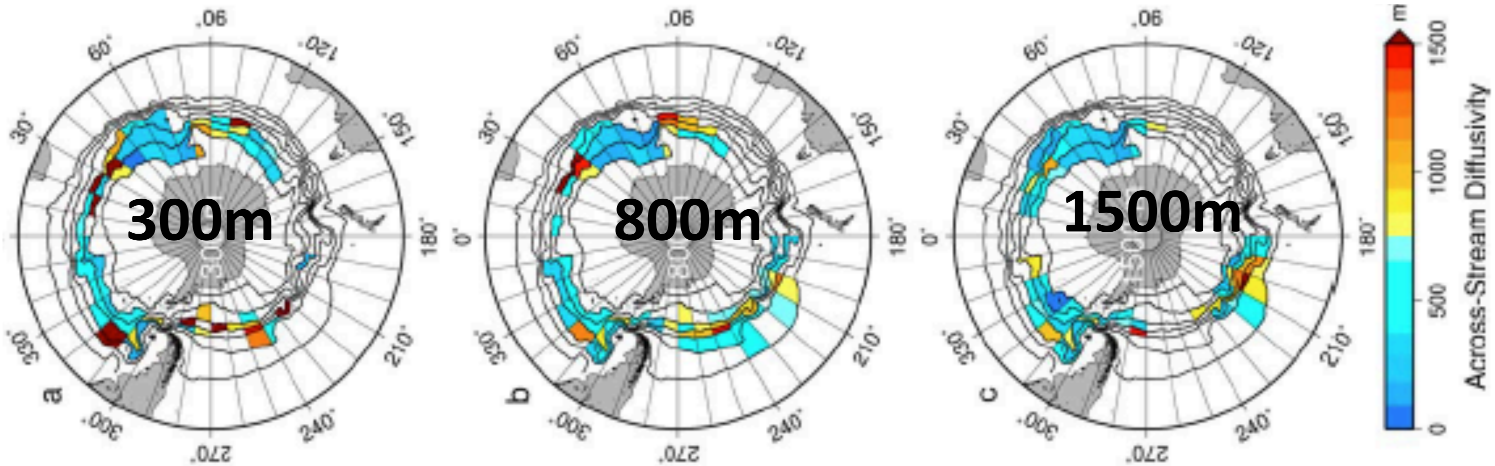
Diapycnal and isopycnal mixing experiment (DIMES)



http://dimes.ucsd.edu/

Float-based mixing estimates: numerical models

Cross-stream (mean flow) diffusivities

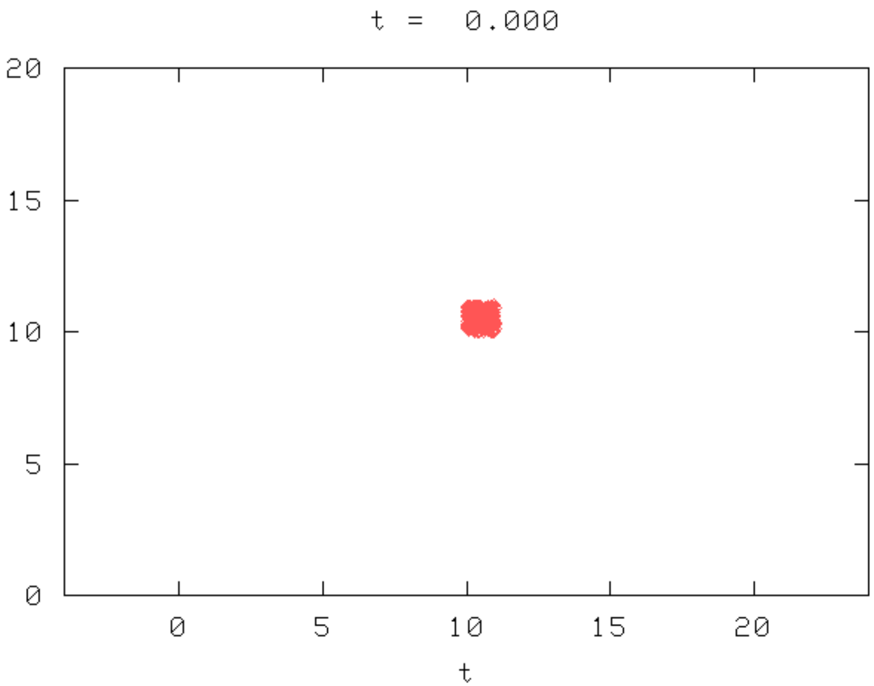


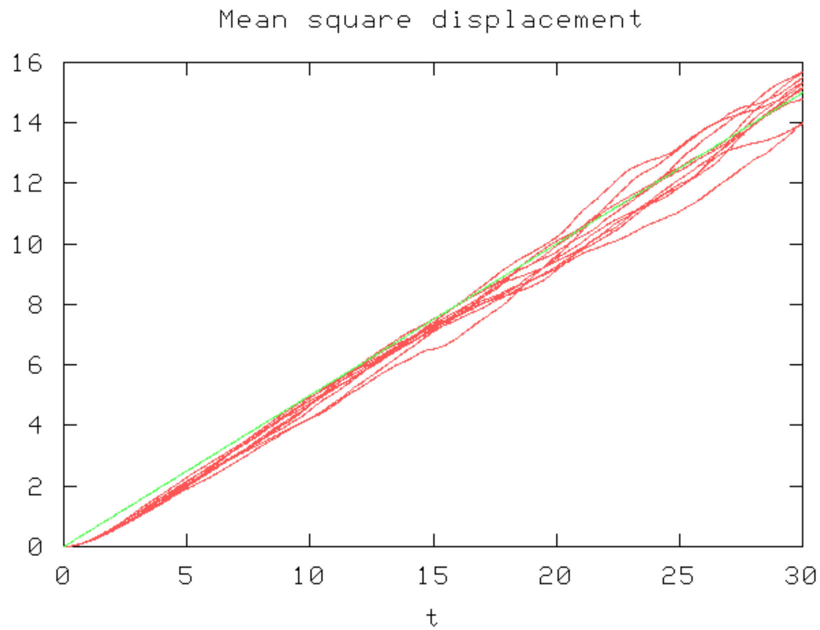
Griesel et al. (2006)

Patchy eddy mixing patterns in the Southern Ocean from a global eddying model

Estimate eddy diffusivity from Lagrangian particles

Pure diffusion case: particles evolution with time through random walk (molecular diffusion).



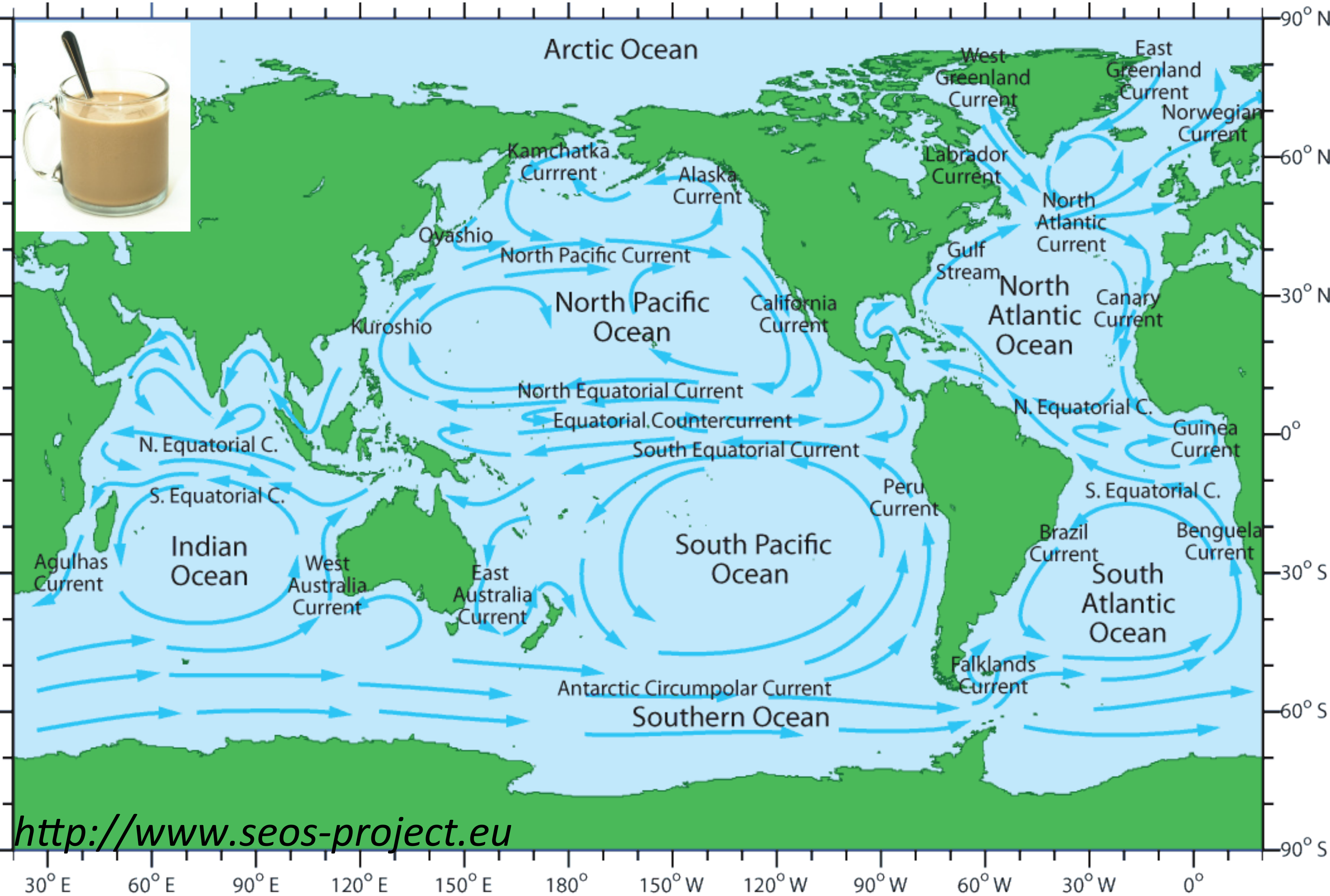


Course 12.820 at MIT

Diffusivity: half of the disperse rate

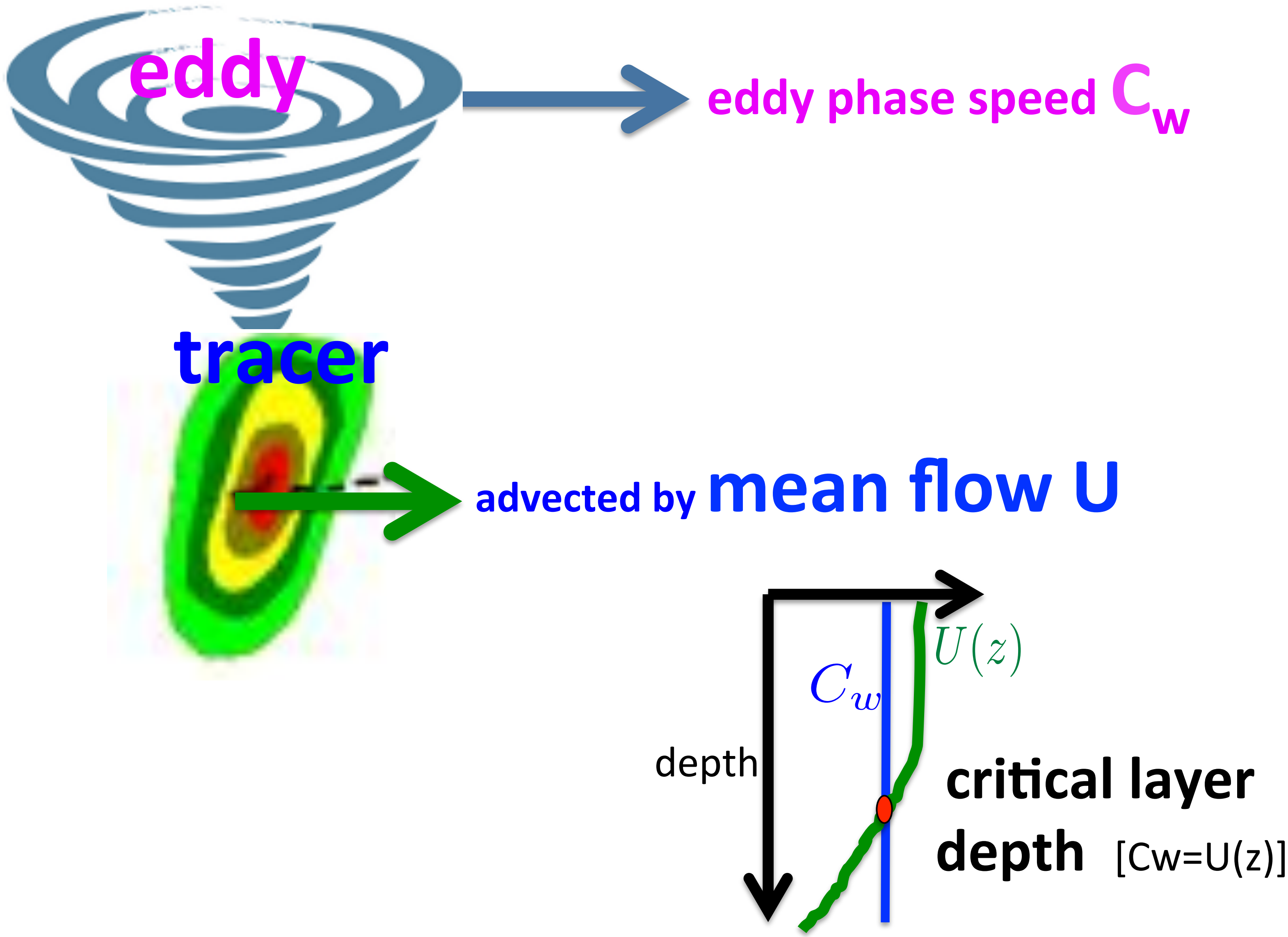
$$\kappa = \frac{1}{2} d < x^2 > /dt$$

Effect of large-scale mean flow on mixing

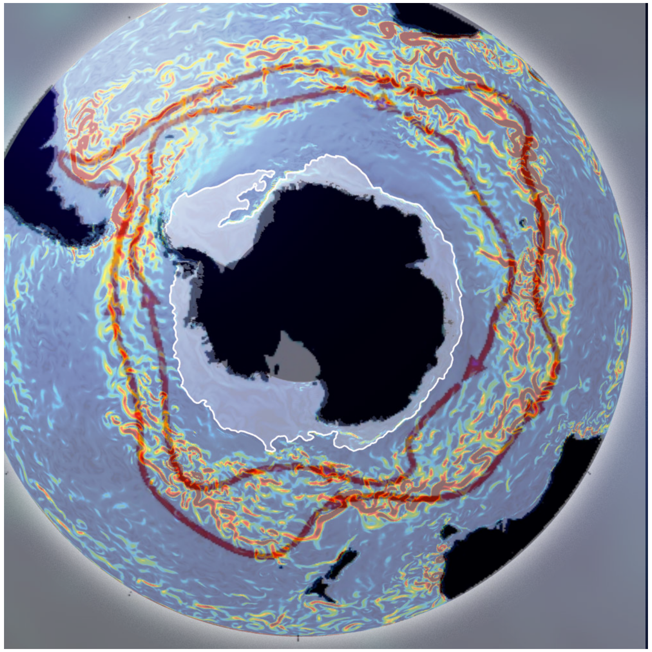


Mixing in the mean flow: Critical layer

When Cw=U, elevated mixing occurs.



Mixing in the mean flow: Theory



Courtesy of Matt Mazloff

Both eddy properties and mean flow control mixing!

cross-stream diffusivities

1/(eddy decorrelation time)

eddy kinetic energy

$$K_{\perp} = \frac{k^2}{k^2 + l^2} \frac{\gamma}{\gamma^2 + k^2[C_w - U(z)]^2} EKE$$

eddy wavenumber

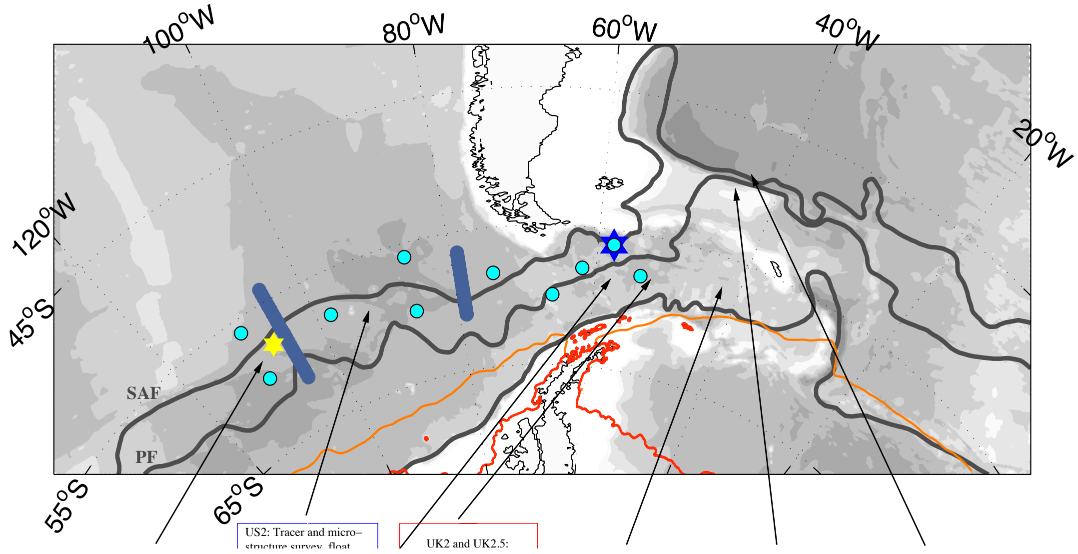
eddy phase speed

mean flow magnitude

(e.g. Green, 1970; Ferrari and Nikurashin, 2010)

Efforts testing the theory: Observations

DIMES field experiment



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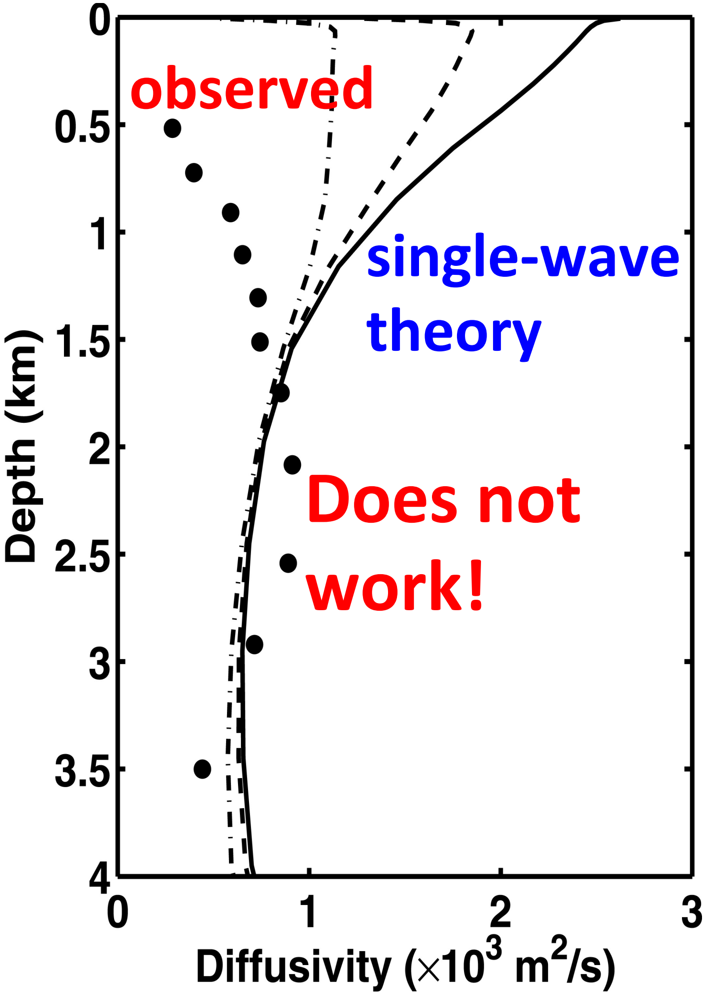
eddy diffusivities



Bates et al. (2014)

Problem of the mixing theory

cross-stream diffusivities

1/(eddy decorrelation time)

eddy kinetic energy

$$K_\perp = \frac{k^2}{k^2 + l^2} \frac{\gamma}{\gamma^2 + k^2[C_w - U(z)]^2} EKE$$

eddy wavenumber

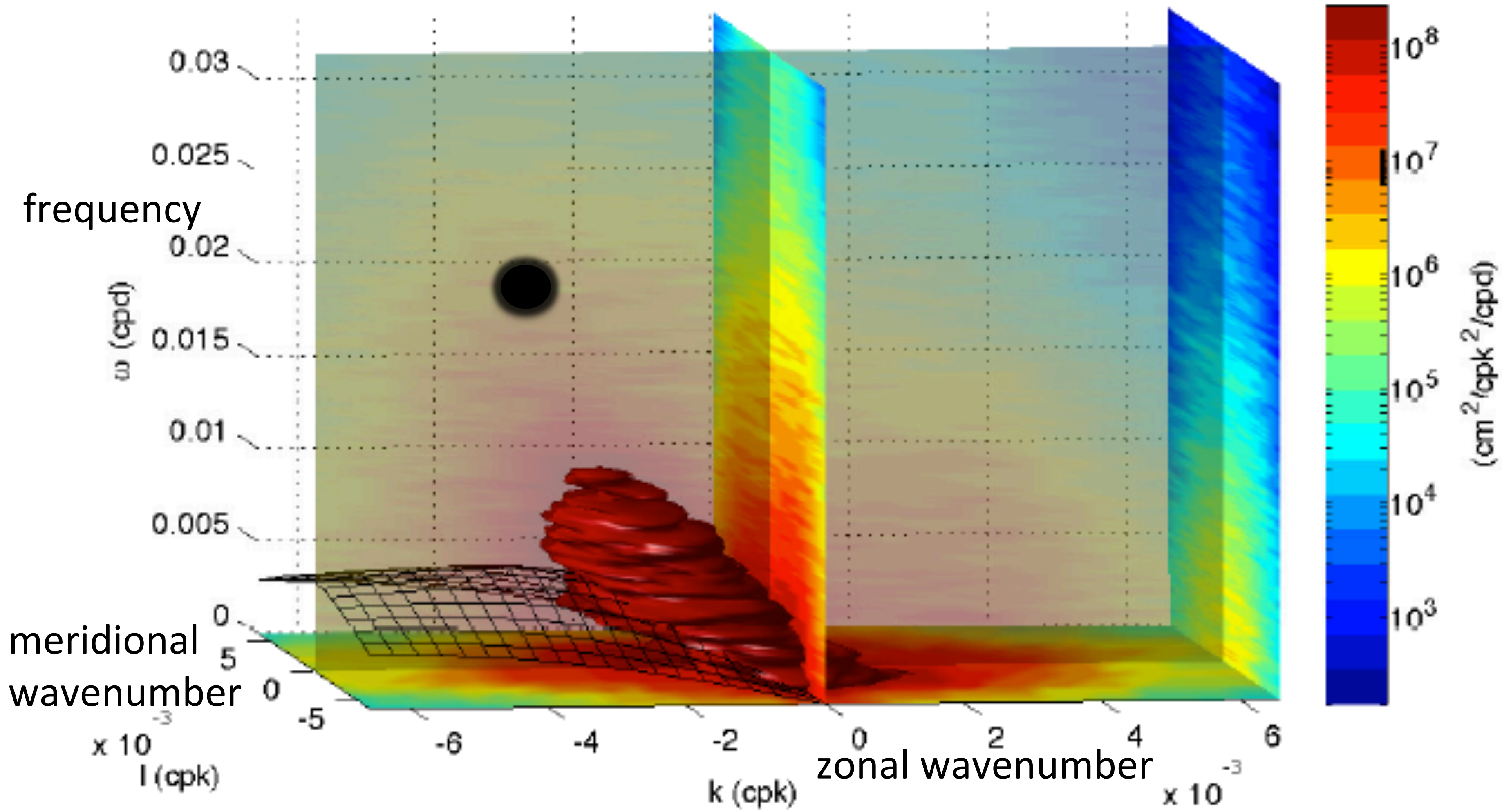
eddy phase speed

mean flow magnitude

- **(1) single wavenumber and phase speed**
- (2) constant mean flow
- (3) linear system

Our hypothesis: Multi-waves matter!

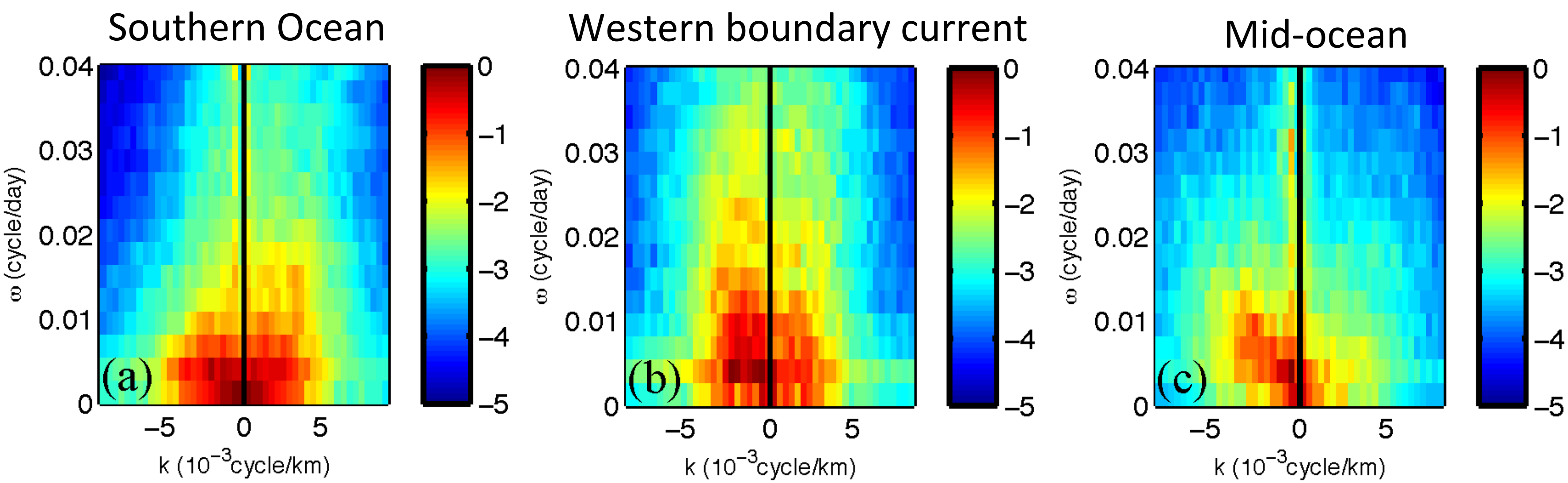
Spectrum of observed sea surface height (30ºN, 170ºW)



Wortham (2012)

Our hypothesis: Multi-waves matter!

Normalized spectrum of sea surface height



Neither single wavenumber nor single phase speed.

Our goal

Barotropic streamfunction

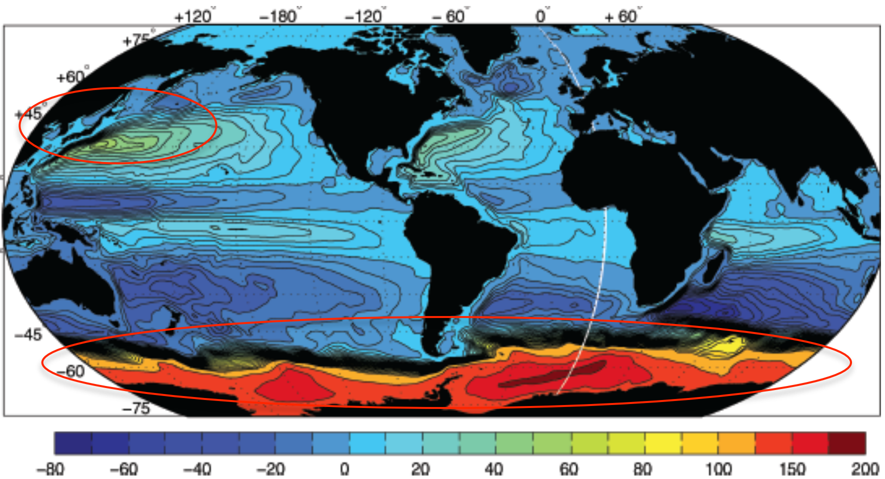


Figure 3. Transport stream function in 10^6 m^3/s from the 16-year average. Some of the contours in the high latitude Southern Ocean have been omitted. The function is set to zero on the western boundaries (from a code of B. Klinger).

Wunsch (2011)

Surface eddy kinetic energy

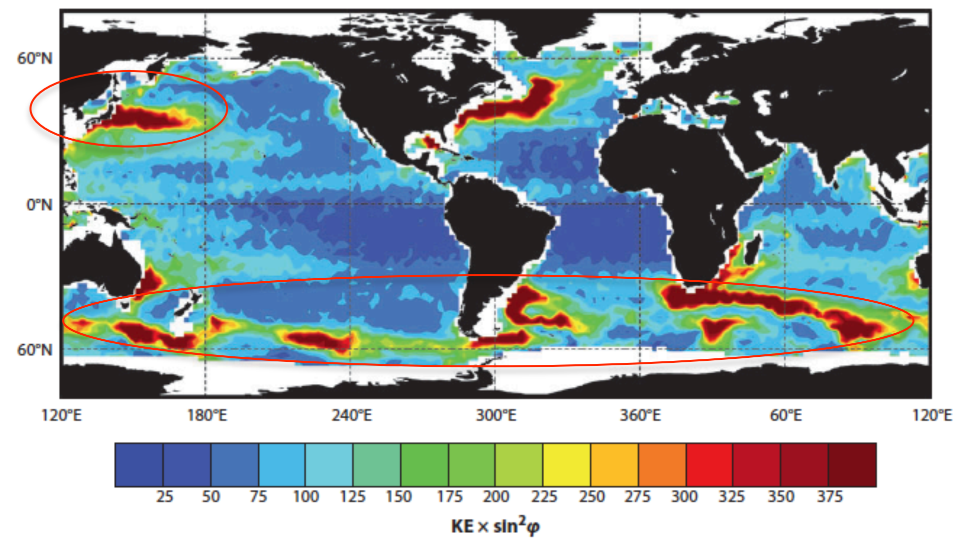


Figure 4

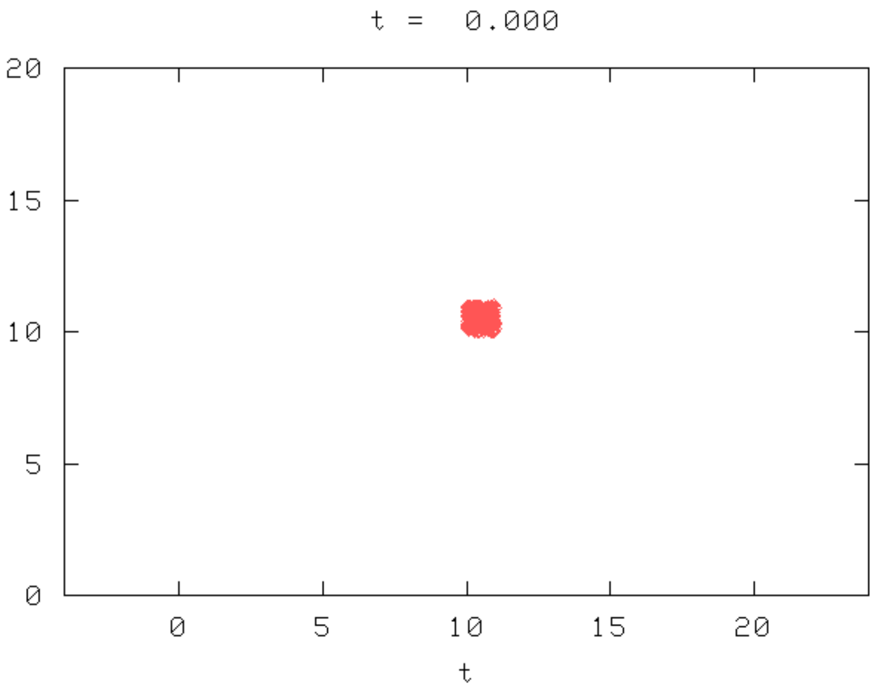
Estimate of the geostrophic kinetic energy (KE) $(cm\ s^{-1})^2$ of oceanic variability at the sea surface, here multiplied by $\sin^2 \phi$, where ϕ is the latitude, to avoid the equatorial singularity in noisy data. Note the very large spatial changes of kinetic energy. Figure taken from Wunsch & Stammer 1998.

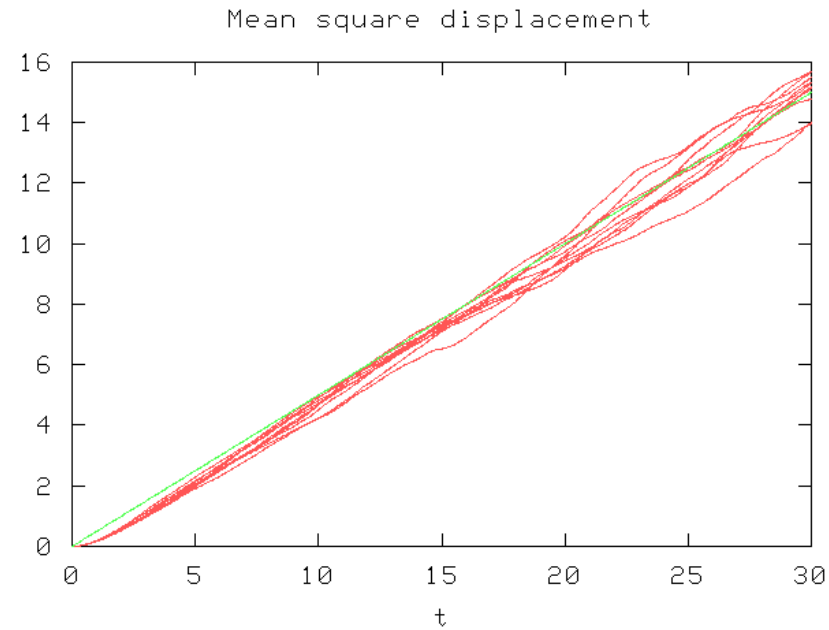
Ferrari and Wunsch (2009)

1. Provide float-based cross-jet mixing at high spatial resolution.
2. Develop a mixing theory with multi-wavenumbers and test its validity.

Tool: Lagrangian particles

Pure diffusion case: particles evolution with time through random walk (molecular diffusion).





Course 12.820 at MIT

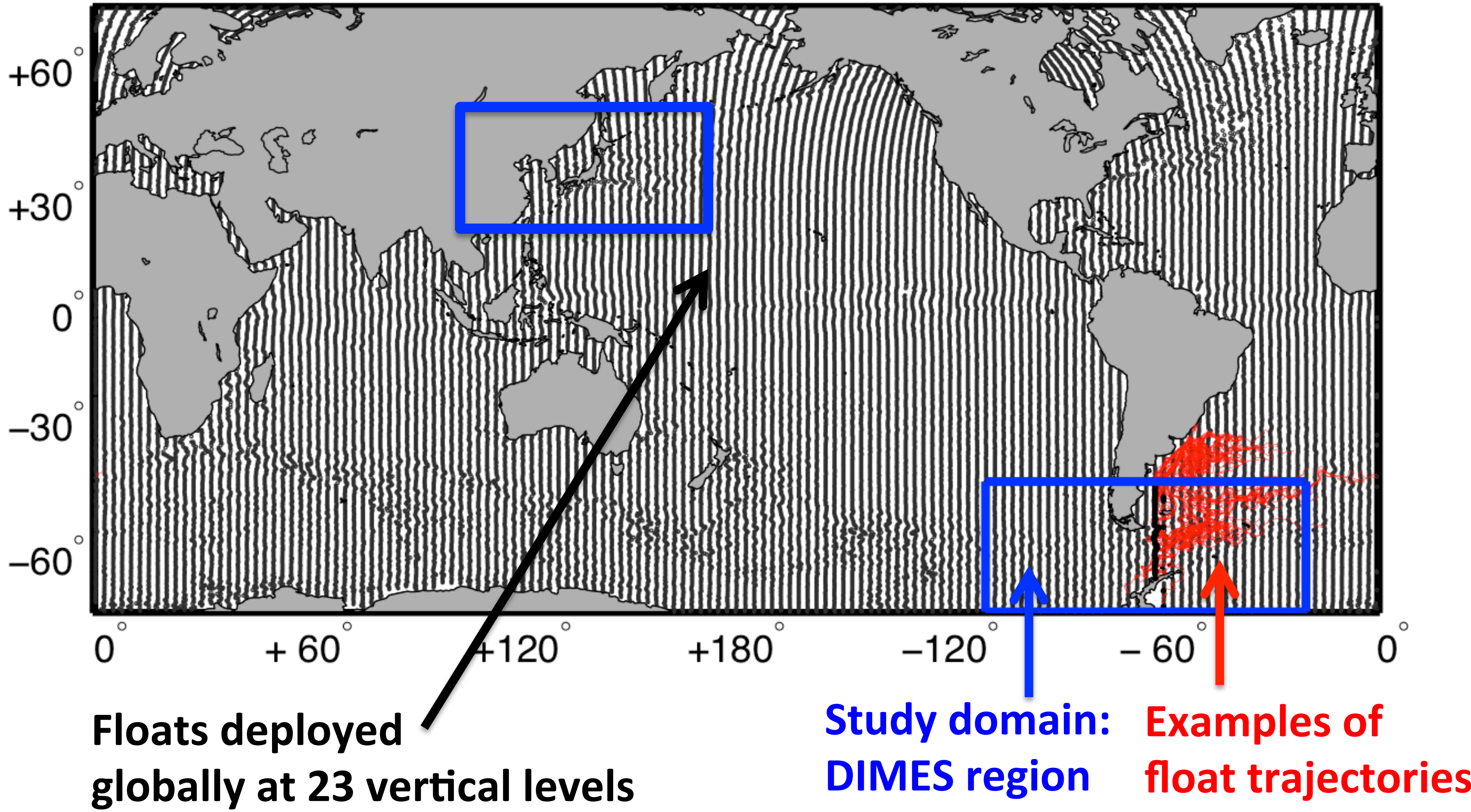
Diffusivity: half of the disperse rate

$$\kappa = \frac{1}{2} d < x^2 > /dt$$

Tool: High resolution model with floats

Parallel Ocean Program model with floats (Griesel et al. 2014)

- Global eddying (0.1deg) ocean model with 42 levels
- **One million** floats evenly deployed **globally** in 1994 and advected by velocity fields



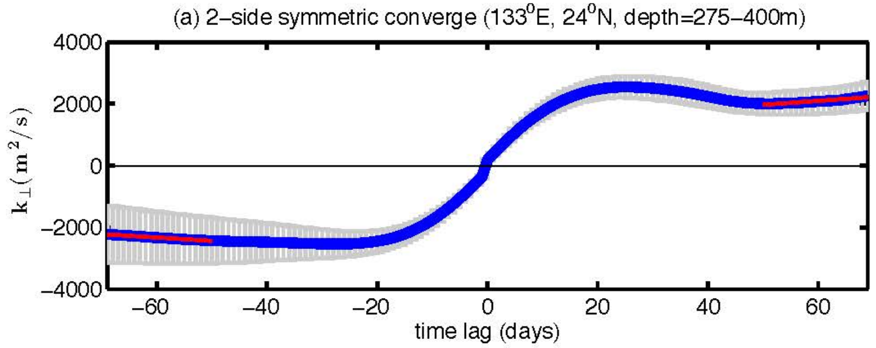
Estimating diffusivity from floats

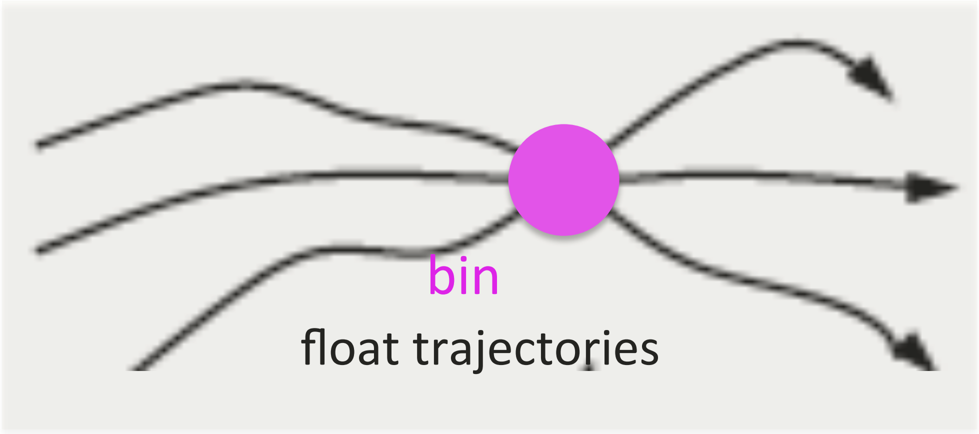
Calculation method

Average autocorrelation of residual float velocities over all tracks in the defined bin (Davis 1991).

$$\kappa_{ij}(\mathbf{x},\tau) = \int_{-\tau}^{0} d\tilde{\tau} \langle u'_i(t_0|\mathbf{x},t_0)\, u'_j(t_0+\tilde{\tau}|\mathbf{x},t_0)\rangle_L ,$$

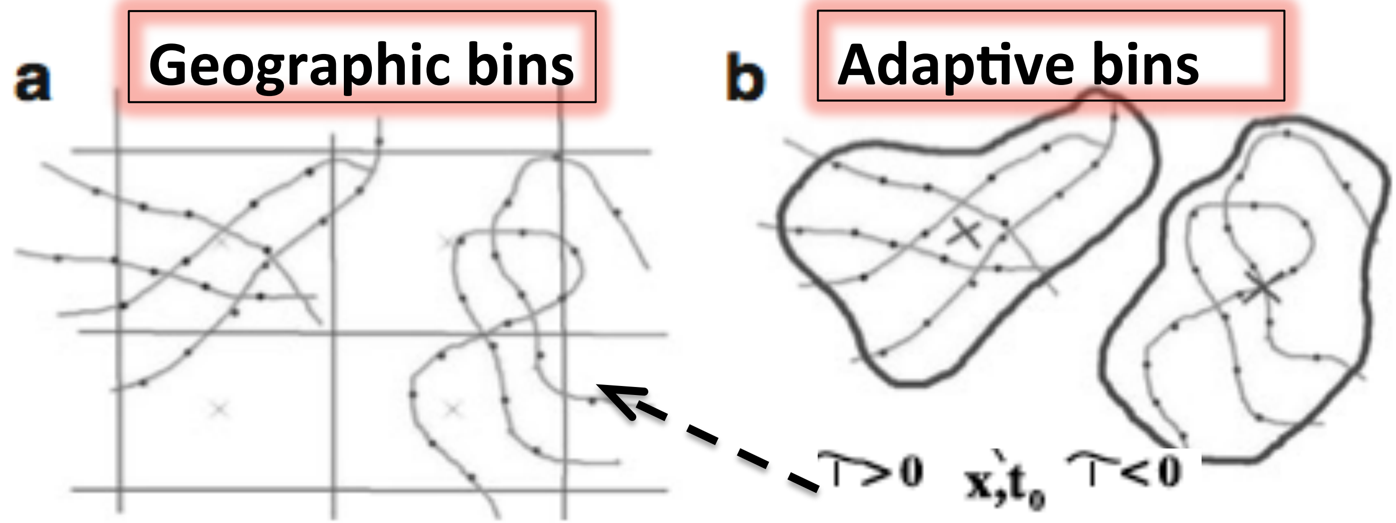
$$\kappa_{ij}^{\infty} = \lim_{\tau\to\infty} \kappa_{ij}(\mathbf{x},\tau),$$





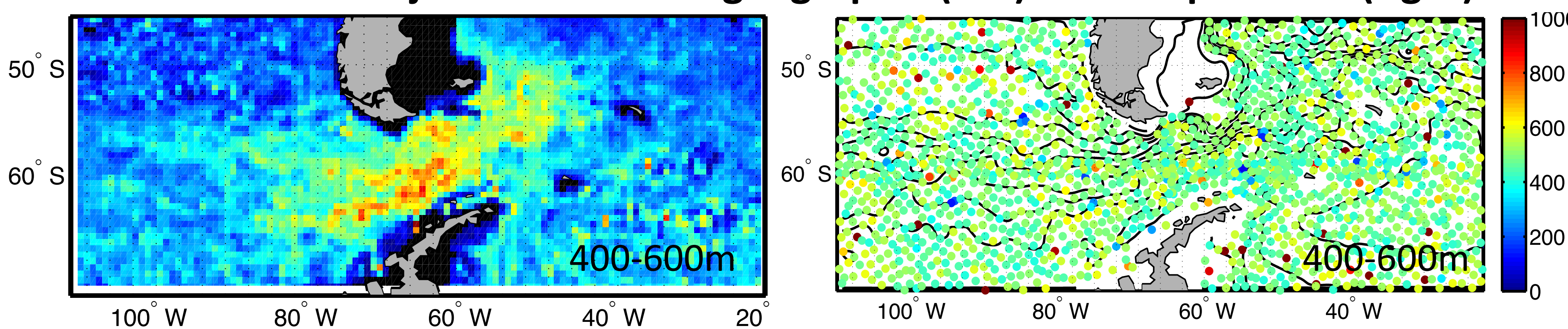
How to divide the study domain into bins?

Estimating diffusivity from floats



Koszalka and LaCasce (2010)

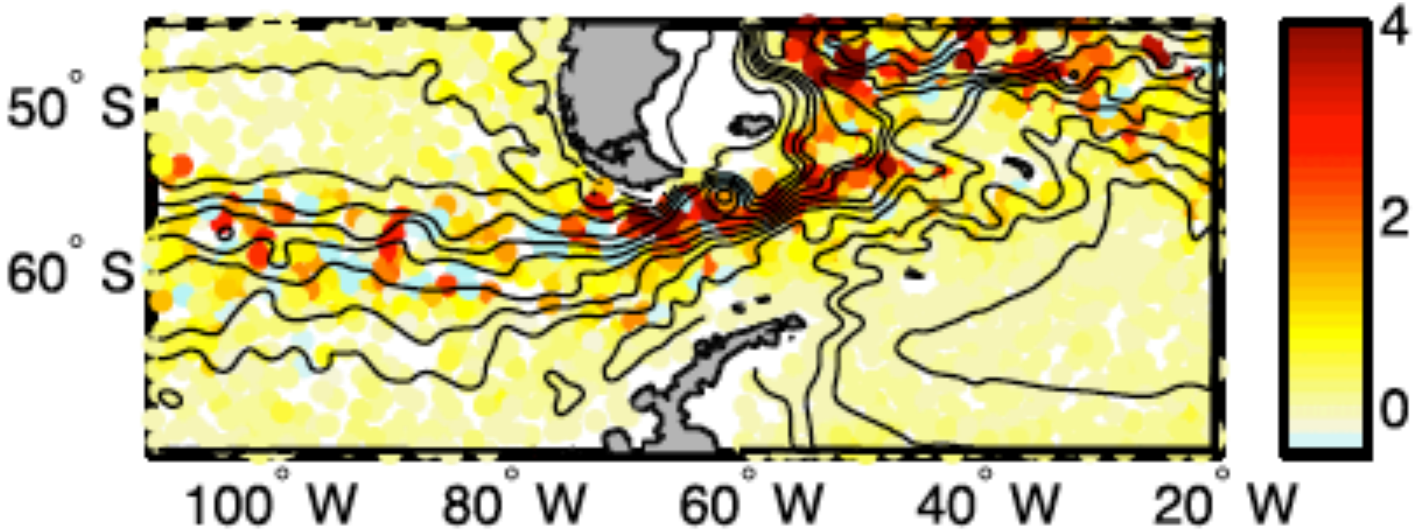
Number of trajectories in each geographic (left) and adaptive bin (right)



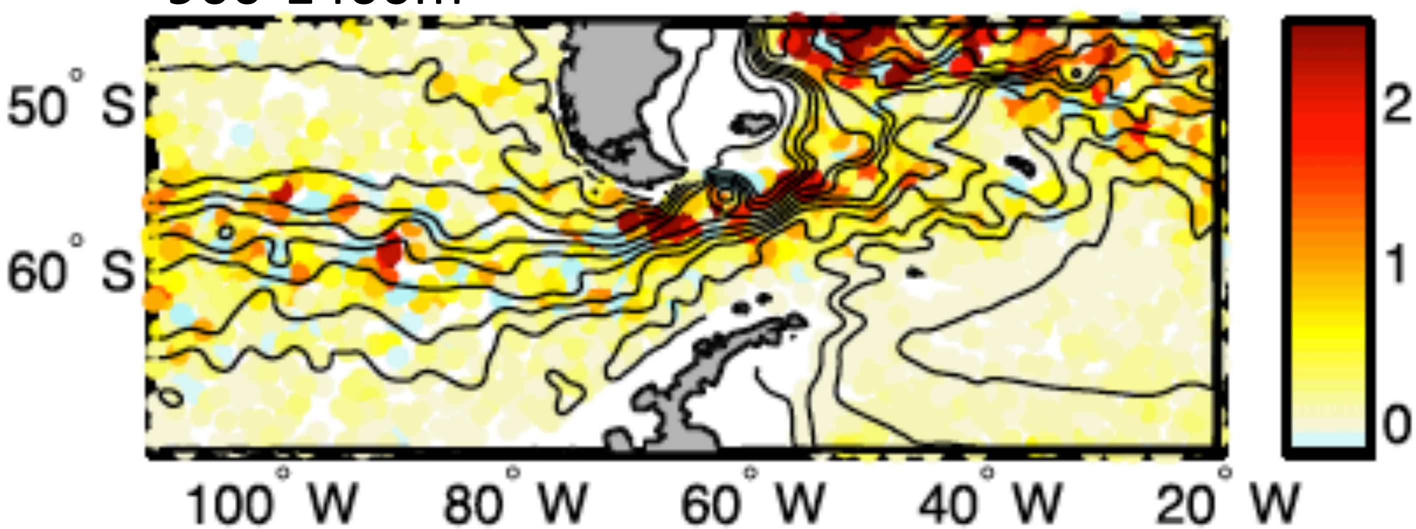
Spatial patterns of mixing: Drake Passage

400-600m

$10^3 m^2/s$



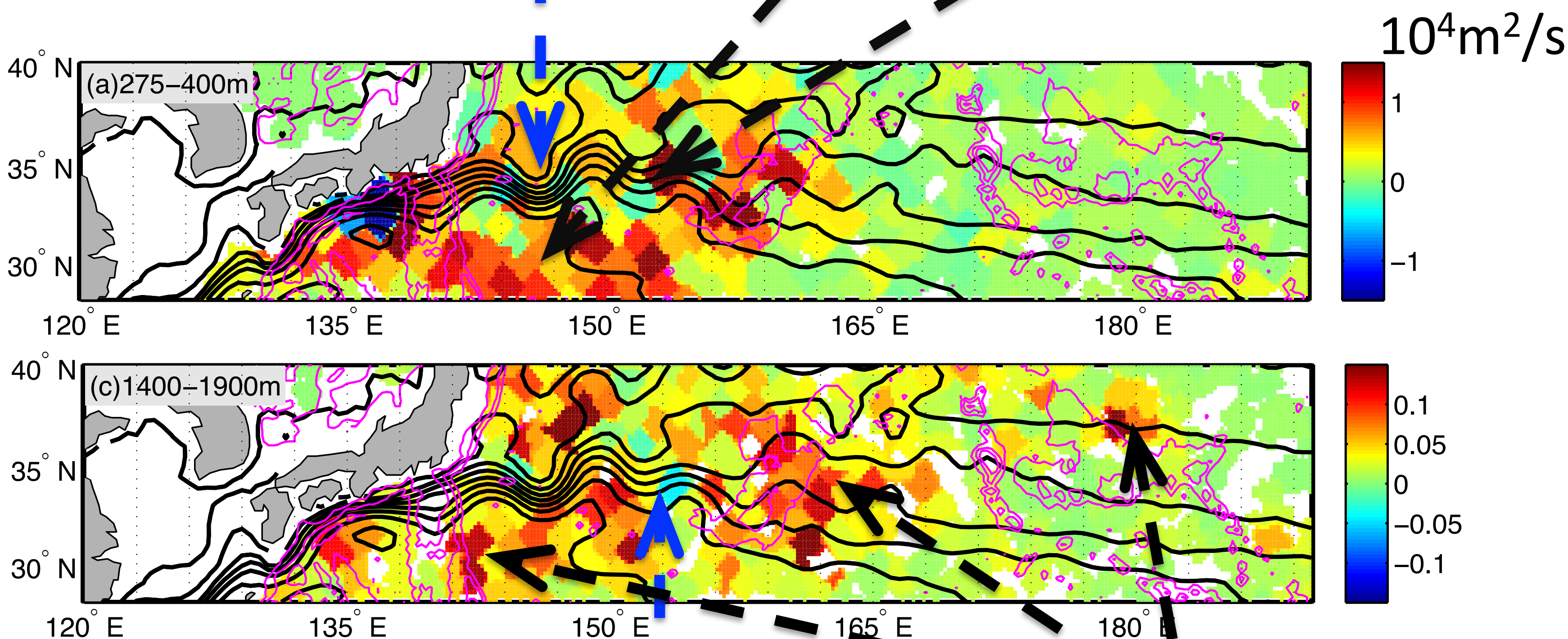
900-1400m



Spatial patterns of mixing: Kuroshio

Mixing suppression by intense jet

Enhanced mixing at downstream and recirculation gyres



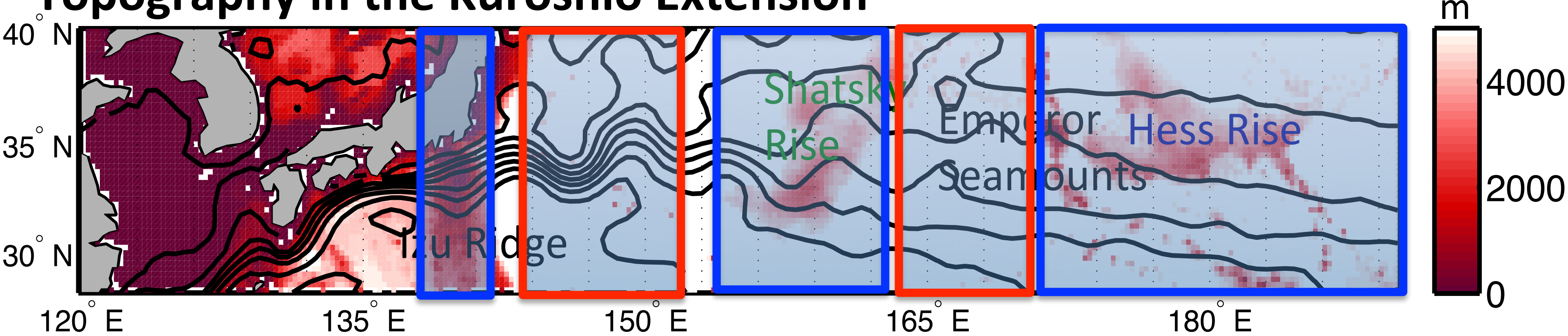
Negative diffusivity

Enhanced mixing at topography

Analogous to the Southern Ocean in many aspects

Single-wavenumber theory works poorly at topography

Topography in the Kuroshio Extension



Single-wavenumber theory

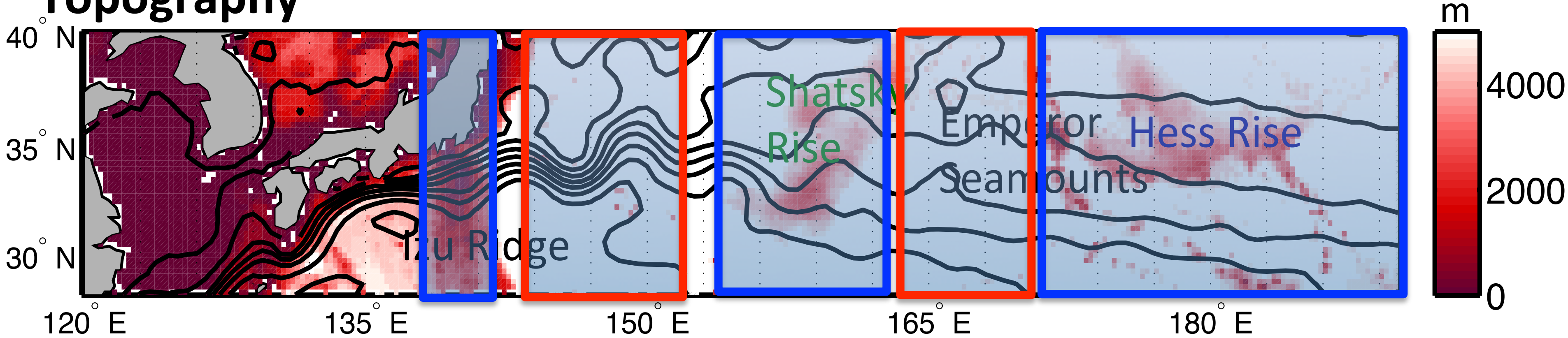
$$K_\perp = \frac{k^2}{k^2 + l^2} \frac{\gamma}{\gamma^2 + k^2[C_w - U(z)]^2} EKE$$

- cross-stream diffusivities: $K_\perp$
- 1/(eddy decorrelation time): γ
- eddy kinetic energy: EKE
- eddy wavenumber: $k^2 + l^2$
- eddy phase speed: C_w
- mean flow magnitude: $U(z)$

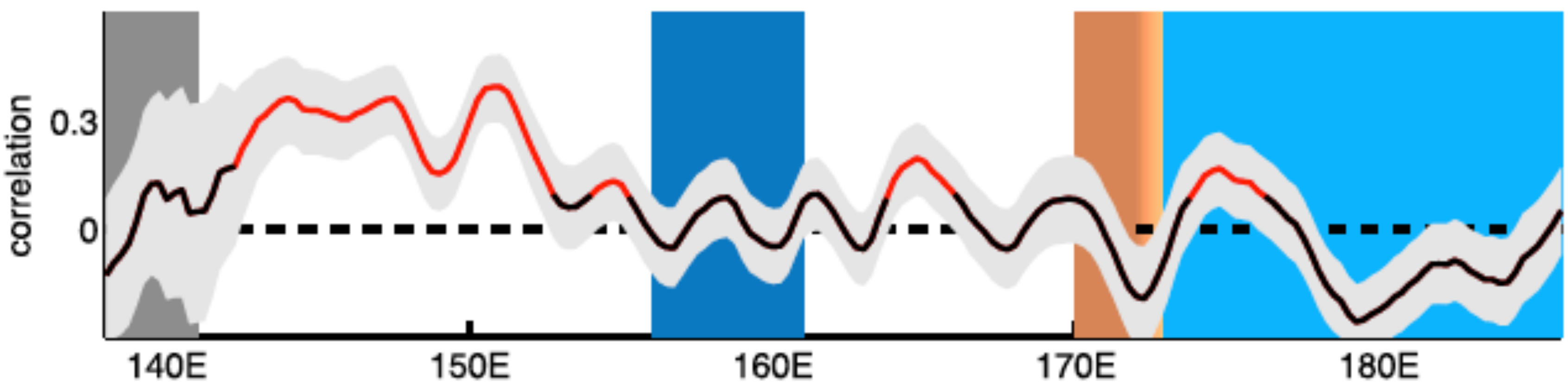
(e.g. Green, 1970; Ferrari and Nikurashin, 2010)

Single-wavenumber theory works poorly at topography

Topography



Correlation between float-based mixing lengths and single-wavenumber theory



Multi-wavenumber theory

cross-stream diffusivities

wavenumber

frequency

$$K_\perp(\mathbf{x}) = \frac{1}{2}\int_{-\infty}^{\infty} S_{u'_\perp}(k', \omega, \mathbf{x})\big|_{\omega = Uk'}\, dk'$$

mean flow magnitude

frequency-wavenumber spectrum of cross-mean flow Eulerian eddy velocities along a slice aligning with the mean flow vector

Derivation available in Chen et al. (2015).

In the single-wave limit, single-wave and multi-wave theories are equivalent!

Estimate diffusivity from multi-wavenumber theory

$$K_\perp(\mathbf{x}) = \frac{1}{2}\int_{-\infty}^{\infty} S_{u'_\perp}(k', \omega, \mathbf{x})|_{\omega=Uk'}\, dk'$$

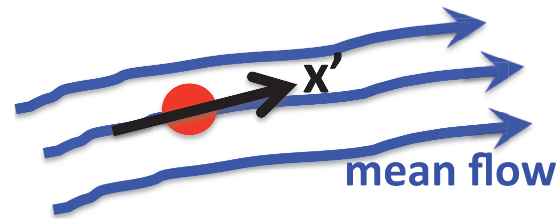
cross-stream diffusivities

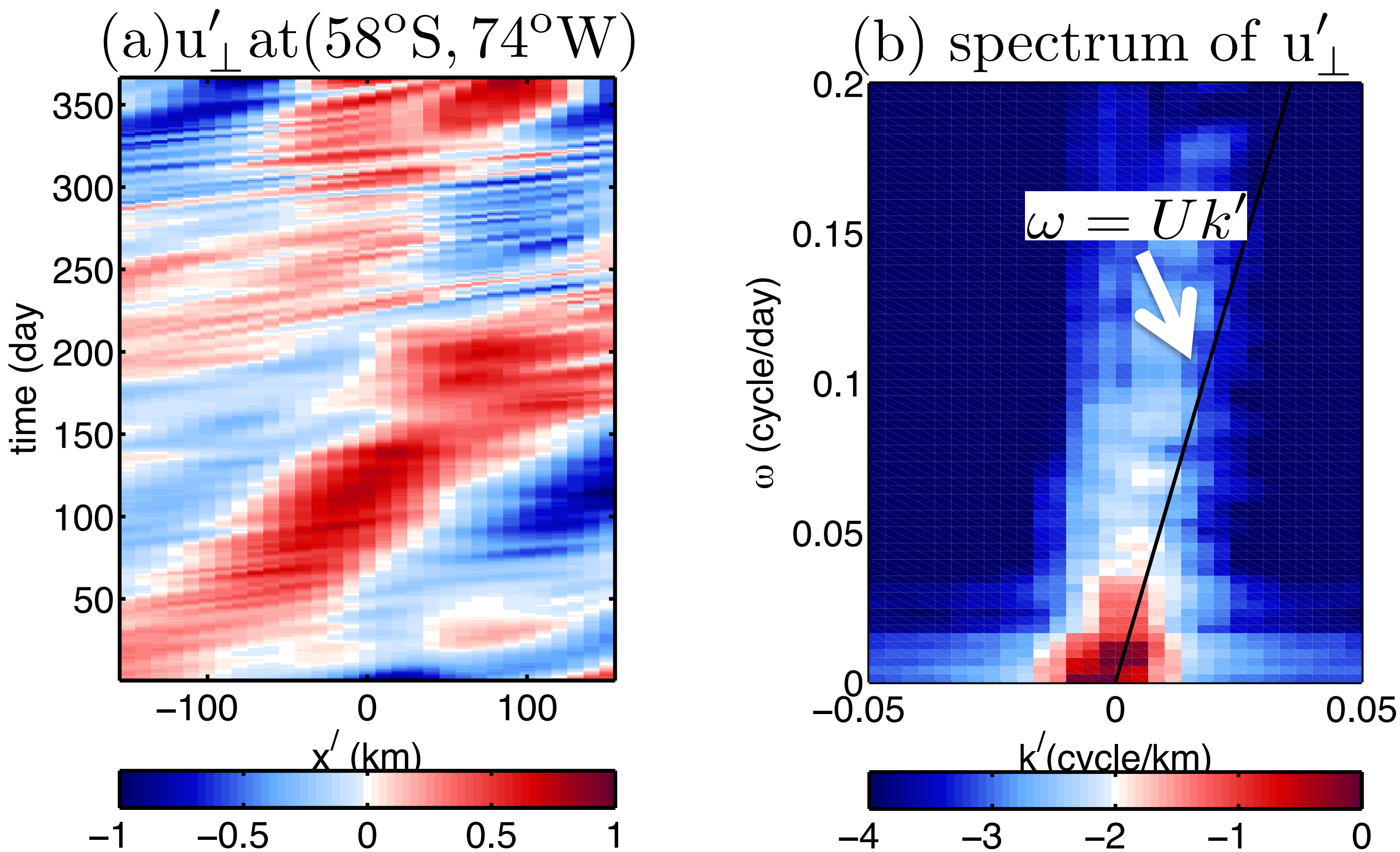
wavenumber

frequency

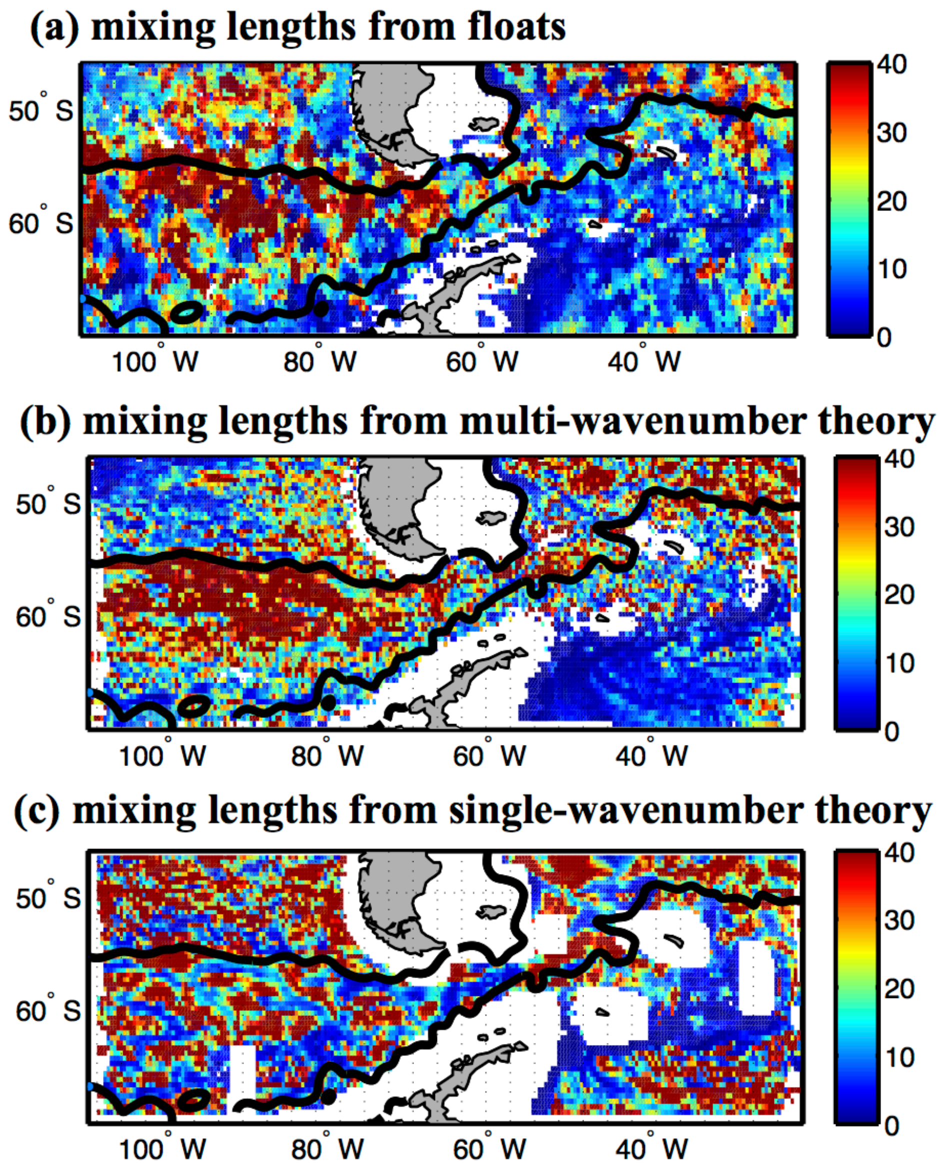
mean flow magnitude

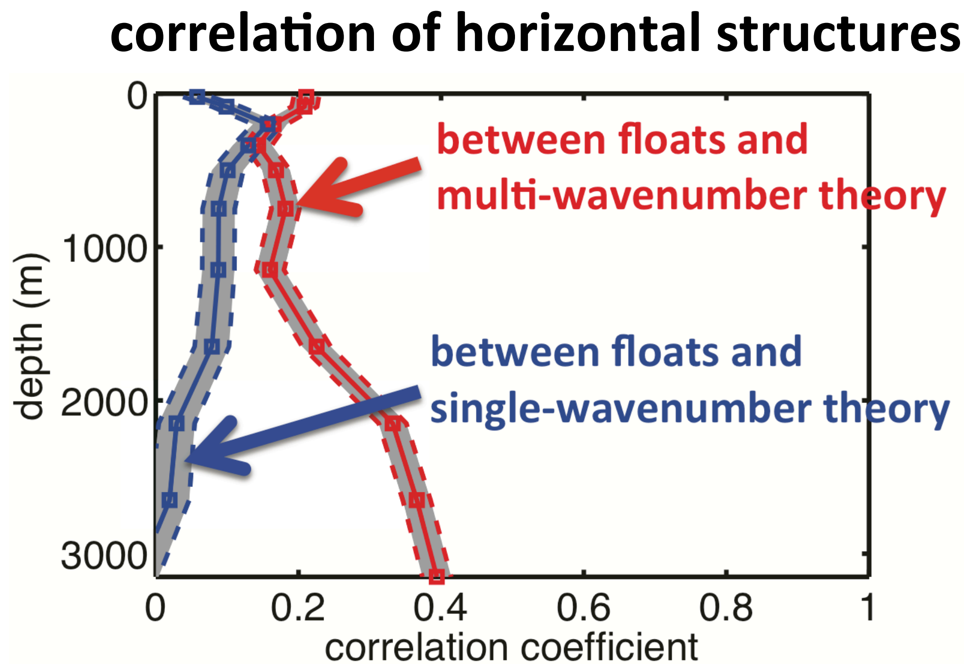
frequency-wavenumber spectrum of cross-mean flow Eulerian eddy velocities along a slice aligning with the mean flow vector





Testing the theory: Mixing lengths





0.4

0

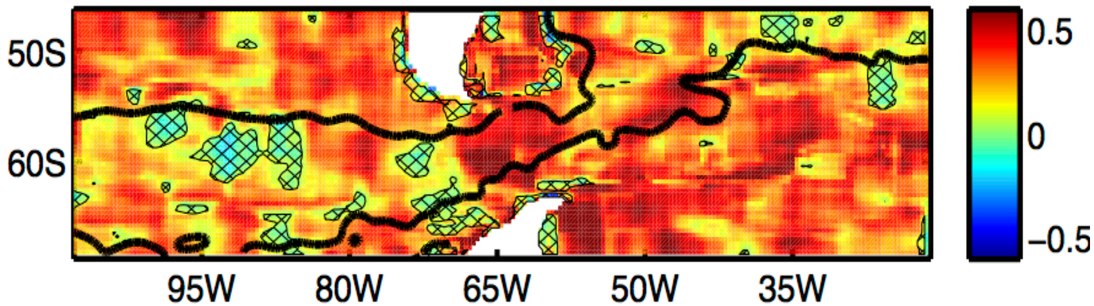
1900-2400m

Testing the theory: Diffusivities

correlation of vertical structures

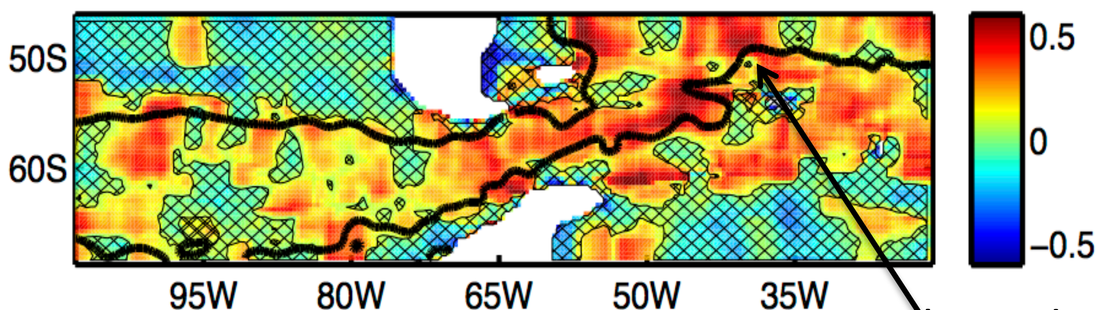
K varies with z!

(a) floats vs. multi-wavenumber theory



91%

(b) floats vs. single-wavenumber theory



55%

Hatched: negative correlation.
Non-hatched: positive correlation.

mean flow vs. eddies

Summary

(1) To include the contribution of the entire eddy spectrum to mixing, **we formulated and tested a multi-wavenumber theory.**

equivalent in the single-wavenumber limit

Single-wavenumber theory → **Multi-wavenumber theory**

Single-wavenumber theory:

Breaks down in topographic regions In the Kuroshio Extension and at the spot of the DIMES experiment

Multi-wavenumber theory:

DIMES region from the Southern Ocean

a. Better represents both horizontal and vertical structures of mixing lengths.

b. Better represents the vertical structures of eddy diffusivities.

c. Both theories capture large-scale horizontal structure of eddy diffusivities.

(2) **Details are available at**

a. Chen et al., 2014: "Isopycnal eddy diffusivities and critical layers in the Kuroshio Extension from an eddying ocean model." *JPO*.

b. Chen et al., 2015 "A multi-wavenumber theory for eddy diffusivities and its application to the southeast Pacific (DIMES) region." *JPO*.

Thanks to …

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