The global ocean circulation

from Kuhlbrodt, Griesel, Montoya, Levermann, Hofmann, Rahmstorf, Rev. Geophys. 2007
Antarctic Circumpolar Current system "2D"

after Speer et al. (2000)

- Balance between wind driven *Ekman* contribution (isopycnal steepening) and opposing *eddy* advection (isopycnal flattening)
- No perfect cancellation $\rightarrow$ residual circulation
- Details of the form of this recirculation: under debate.
Eddies and climate models

Ocean Surface Speed in NOAA/GFDL Southern Ocean Simulations

Hallberg, Gnanadesikan JPO 2006
Fyfe et al. JC (2006): Changes in Southern Ocean circulation in response to increased GHG concentrations in an ensemble of 12 climate models:

- strengthening and poleward shifting of the zonal wind stress throughout the 20th and 21st centuries

- strengthening and poleward shift of ACC
Decreased sensitivity to surface forcing changes the more eddies are resolved

Southern Ocean residual circulation change due to increased/decreased winds: 1° 1/4° 1/6°

Hallberg, Gnanadesikan JPO 2006
Differences between eddy parameterized and eddy resolving models

ACC strength with increased SO wind stress Farneti et al. JPO 2010

consistent with observations of isopycnal slopes not changing in spite of increased wind stress over last decade (Böning et al. 2008), also Spence et al. (2010)
**Eddy Parameterization**

\[
\partial_t \langle q \rangle + \mathbf{\nabla} \cdot \left( \langle \mathbf{u} \rangle \langle q \rangle \right) = - \mathbf{\nabla} \cdot \langle \mathbf{u}' q' \rangle
\]

\(\langle \rangle\) temporal and/or spatial Eulerian average, \(\mathbf{'}\) deviation

Parameterize: flux-gradient relationship:

\[
\langle \mathbf{u}' q' \rangle = -K \mathbf{\nabla} \langle q \rangle
\]

- Eddy diffusivities constant in time and space in climate models (often), or tuned
Some fundamental questions for Southern Ocean eddies still are

- Is the eddy-diffusivity model appropriate?  
  (on a local basis and not only for zonal/streamline averaged properties)

- What are the horizontal and vertical distributions of diffusivities?  
  (different methods may give different answers)

Outline

- Hypotheses for eddy diffusivity distributions and methods of computation

- Eddy diffusivities from Lagrangian floats in 1/10°POP
Methods for eddy diffusivity calculation

\[ \langle \vec{u}'q' \rangle = -K \vec{\nabla} \langle q \rangle \]

A Flux/gradient estimates
B Tracer based estimates
C Lagrangian particle dispersion
Methods for eddy diffusivity calculation

A Flux/gradient estimates: relate $\langle \vec{u}' q' \rangle$ and $\vec{\nabla} \langle q \rangle$

- Main problem: bias from large rotational parts
A Flux/gradient estimates: relate $\langle \vec{u}' q' \rangle$ and $\vec{\nabla} \langle q \rangle$

- Main problem: bias from large rotational parts

Only the divergence of the eddy flux matters for net eddy tracer transport

Marshall, Shutts (1981); Eden (2006); Griesel et al. (2009)
Methods for eddy diffusivity calculation

B Tracer based estimates

- \( \partial_t q + \nu \nabla q = k \nabla^2 q \)

- stretching and folding of tracer contours

\[ \kappa_{eff} = \partial_A \int |\nabla q|^2 / (\partial_A q)^2 = \frac{L_e^2}{L_{min}^2} \]


- Main problem: non-local estimate
Methods for eddy diffusivity calculation

A relate $\langle \vec{u}' q' \rangle$ and $\vec{\nabla} \langle q \rangle$

B Tracer based estimates

C Lagrangian particle dispersion

Different methods may lead to different diffusivity distributions
Near-surface eddy diffusivities in the SO

Along-streamline average as a function of latitude:

Marshall et al. (2002) $\kappa_{eff}$
Near-surface eddy diffusivities in the SO

Along-streamline average as a function of latitude:

Marshall et al. (2002) $\kappa_{eff}$

Sallee et al. (2008) $\kappa_L$
Near-surface eddy diffusivities in the SO

Along-streamline average as a function of latitude:

Marshall et al. (2002) $\kappa_{\text{eff}}$

Sallee et al. (2008) $\kappa_L$

Horizontal distributions $\kappa_{\perp} \propto EKE$ Sallee et al. (2008)
Depth dependence

Maximum at ~1500 m

Baroclinically unstable jet
Treguier (1999)

Effective diffusivity in SOSE
Abernathy et al. (2009)
Depth dependence

Maximum at ~1500 m

Baroclinically unstable jet
Treguier (1999)

flux/gradient

Effective diffusivity in SOSE
Abernathy et al. (2009)

Decrease with depth?

Johnson, Bryden (1989)

k(z) = eke(z)?

Eden (2006) flux/gradient
Hypotheses for eddy diffusivity distributions

\[ \kappa \propto U_e L_e \]


- Strong (PV) gradients, strong mean flow inhibit mixing, leading to small eddy length scales (except at critical layers)

- Mixing is strong where EKE, eddy fluxes, SSH variability are enhanced

What dominates?
\( \kappa = \alpha L_e^2 T_{bc}^{-1} \)

Left: \( L_e = 100 \text{ km} \)

Right: \( L_e = \text{Rossby Radius} \)
Eddy diffusivities in coarse resolution model

\[ \kappa = \alpha L_e^2 T_{bc}^{-1} \]

ACC and AMOC maximum as a function of time with increased SO winds

\[ \kappa \text{ ACC enhanced} \quad \text{ACC mixing barrier} \]

Griesel, Montoya in prep.
Motivation - DIMES project

US1: Initial deployment of sound sources, floats, tracer

US2: Tracer and microstructure survey, float deployment

UK1: Moored profiler, current meters, and sound sources

UK2: Hydrographic and microstructure survey

UK3: Tracer and microstructure survey mooring recovery

2008 2009 2010 2011

Drake Passage section  Drake Passage section  Drake Passage section
What are typical Lagrangian diffusivities in the model ACC region? Does diffusivity exist?

What are horizontal and vertical distributions and do these distributions reconcile with existing hypotheses?

Dispersion of floats along isopycnal surfaces across the ACC
Horizontal trajectories from all deployments

- POP: 1/10° horizontal, 40 levels
- spin-up 14 years
- run w' realistic forcing 1994-2003
- release in 4 patches
- 300 m, 800 m and 1500 m
- initial deployment grid: 1/4° spacing
- deployed 1-1-1999
- floats are advected by model flow
Lagrangian Diffusivity

Variance of particle displacements $\rightarrow$ integral of velocity autocovariance

$$\kappa(\tau) = \frac{1}{2} \langle (y'(\tau) - y'(0))^2 \rangle = \int_0^t \langle v'(t + \tau) v'(t) \rangle dt$$

$$\kappa^\infty = \lim_{\tau \to \infty} \kappa(\tau)$$

Taylor (1921), Davis (1987,1991)
P3, 300 m:

2-year Eulerian mean velocity

\[ u' = u_f - u_e \]
\[ v' = v_f - v_e \]

- Subtract local Eulerian mean (reduces shear dispersion in along-stream direction)
- Project along/across Eulerian mean (cross-stream dispersion by mean is zero)
Long-time diffusivities P3

\[ \kappa(\tau) = \int_0^{1045 \text{days}} \langle v'(t + \tau)v'(t) \rangle \, dt \]
Long-time diffusivities

Diffusivities as a function of time lag from 2-year long trajectories

$\kappa_\perp (m^2/s)$

$\kappa_\parallel (m^2/s)$

$\kappa_{\text{max}} \neq \kappa_\infty$
meandering and circling trajectories

Diffusivities

\[ \kappa \text{m}^2 \text{s}^{-1} \]
meandering and circling trajectories

Diffusivities

see also Berloff et al. (2002), Veneziani et al. (2004, 2005)
Horizontal distributions 800 m DD

Bin trajectories in $10^\circ$ longitude X barotropic streamline, time lag of 75 days
Eddy velocities and eddy length scales

\[ \kappa = \sqrt{\langle u'^2 \rangle} L_e \]
What determines the horizontal distribution of $\kappa_\perp = u'L_e$?

$L_e$ dominates horizontal distribution
What determines the horizontal distribution of $\kappa_\perp = u'L_e$?

- $\kappa^\infty$:
  - $L_e$ dominates the horizontal distribution

- $\kappa^{\max}$:
  - $u'$ dominates the horizontal distribution
Depth Dependence PFZ: Cross-stream

Cross-stream: \( \kappa = u'L_e \)

- Diffusivity depth invariant around Polar Frontal Zone
- Eddy velocity decreasing with depth
- Eddy length scale increasing with depth
Depth Dependence: Cross-stream $\kappa^\infty - \kappa_{\text{max}}$

\[ \kappa^\infty : \quad \kappa = u'L_e \]

\[ \kappa_{\text{max}} \]

\[ \begin{align*}
\kappa^\infty : & \quad \kappa = u'L_e \\
\kappa_{\text{max}} : & \quad \kappa_{\text{max}}
\end{align*} \]
Small values of $\kappa_\perp$ tend to be towards higher $U_m$

compare to Shuckburgh et al. (2008)
Conclusions

- method of computation (mean, projection, time lag) matters

- with long enough time lags and projection across $u_E(x, y, z)$:
  - cross-stream diffusive limit reached
  - reduction of rotational parts $\rightarrow$ reduced dominance of correlation with EKE
  - $\kappa_L$ cannot be determined from EKE alone

- identify mixing barriers, but $\kappa_L, L_e$ are not consistently reduced where mean flow is strong (importance of interaction mean flow - eddies - topography)

- $\kappa$ should not be a constant parameter in climate models