Deep flow and mixing in the Indian Ocean

MacKinnon      Pinkel      Johnston
Deep Mixing: Southwest Indian Ocean

Evidence of elevated turbulence above the Southwest Indian Ridge

Kunze et al 06 (+ correction Dec 06)

Estimates from Lowered ADCP measurements during WOCE
Possible sources of mixing above the SW Indian Ridge

**Tidal Generation**

Internal waves with 12.4 hour period

**Near-inertial Generation**

Internal waves with 15 hour period (inertial period in souther ocean)

Egbert and Ray

M. Alford
Deep Mixing: Southwest Indian Ocean

Net overturning rate poorly constrained
(3-30 Sv)

Donohue et al 03, van Aken et al 03, Toole and Warren 93, Reid 93, Bryden and Beal 01

- Dec 07 - Jan 08
- R/V Revelle
- NSF / UC Ship Funds

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Deep Mixing: Southwest Indian Ocean

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Southwest Indian Ocean: Instruments

4-day time series

Wave-powered wire-walker
- Freely drifting
- Profile to 500 meters
- C, T, P, U, V, Fluorescence

Pinkel “Fast CTD”
- 1000 meters in 5 minutes
- C, T, P, microconductivity
Southwest Indian Ocean: Instruments

50-day mooring deployments

McLane Moored Profilers
(WHOI mooring pool)

Full depth (2 profilers each) C,T,P,U,V
Southwest Indian Ocean: Instruments

Atlantis II Fracture Zone

Lowered ADCP
(Kunze et al 06, Polzin)

2 cross-trench sections
36 hour time series

- 300 kHz RDI broadband
- Full depth (6000 meters)
- Velocity, density => shear, strain
- 8-m nominal resolution
- ~40 meter actual resolution

Generous loan by Kevin Speer (FSU)
Strong northward transport of deep+bottom water

Water mass transport

- **deep water**
  \[ \gamma \geq 27.96 \text{ kg m}^{-3} \]
- **bottom water**
  \[ \gamma \geq 28.11 \text{ kg m}^{-3} \]

[Jackett & McDougall 97, Donohue & Toole 03]
Net deep and bottom transport of $3 \pm 2$ Sv

Compare to 10-15 Sv basin-wide MOC

(consistent with Johnson et al 98
Drijfhout and Naveira Garabato 08,)
Strong northward transport of deep+bottom water

Depth-integrated transport ($\gamma > 27.96$)

Net deep and bottom transport of $3 \pm 2$ Sv

Compare to 10-15 Sv basin-wide MOC

(consistent with Johnson et al 98 Drijfhout and Naveira Garabato 08,)

Flow is below bounding topography
Time variability of Deep Jet

Variability of northward velocity

Harmonic fits of V(z)

Internal tide beams in upper water column

Deep jet oscillates at 15 hours

Jan 12-15, 2008
Dec 3, 2007
Estimating turbulence - overturns

Static instabilities in density

Thorpe Scale mixing estimate
(Dillon 82)

\[ K_\rho = 0.32 \, N \, L_T^2 \]

\[ L_t = 33 \, m \]
Estimate turbulent diffusivity ($\kappa$) by comparing shear/strain spectral levels to canonical Garrett-Munk internal-wave spectrum, based on wave-wave interaction theory (Gregg et al 03, Polzin, McComas and Muller)

$$\kappa = 2 \times 10^{-5} \text{ m}^2/\text{s}$$
Turbulence profiles

Velocity

Dissipation

Diffusivity

Thorpe scale method
Shear/strain method

what produces mixing?
Mean jet shear not unstable
Fine-structure shear elevated

**Velocity**
- $S^2_{jet}$
- $S^2_{GM}$

**Shear**
- $N^2$
- $S^2_{60}$

**Dissipation**
- $\varepsilon / W kg^{-1}$

**Diffusivity**
- $\kappa / m^2 s^{-1}$
Mixing away the deep salinity maximum

Steady change in water properties as water flows north through fracture zone.
What mixes away the salinity maximum?

1) Vertical/diapycnal turbulent mixing

\[ \frac{\Delta S(z)}{\Delta t} = \kappa \frac{\partial^2 S}{\partial z^2} \]

- \( \Delta S(z) \): observed change between southern and northern profiles
- \( \Delta t \): transit time through fracture zone \( \sim 15-20 \) days
What mixes away the salinity maximum?

1) Vertical/diapycnal turbulent mixing

\[
\frac{\Delta S(z)}{\Delta t} = \kappa \frac{\partial^2 S}{\partial z^2}
\]

\(\Delta S(z)\): observed change between southern and northern profiles

\(\Delta t\): transit time through fracture zone ~ 15-20 days

Explanation for discrepancy:
- longer transit time due to recirculation
- stronger mixing elsewhere in FZ than what we observed
What mixes the salinity maximum?

2) Lateral (isopycnal) stirring

\[ \frac{\Delta S}{\Delta t} = \kappa H \frac{\partial^2 S}{\partial y^2} \]

possible leakage of fresher Madagascar Basin water through gaps in the ridge

variability in T-S time series
Tidal beams in upper ocean

- $U(z)$
- cw/ccw energy
- diffusivity

Downward propagating
Tidal beams: model results

Princeton Ocean Model (G. Carter)

- Modeled tidal beams fill the domain
- Ridge corrugation close to tidal wavelength
- Enhanced upper ocean shear and turbulence along entire length of SW Indian Ridge?
Model reproduces vertical structure and phase of tidal beam. Next step is use model to extrapolate observed mixing along the 1000 km long ridge.
Aside: what happened to the inertial waves??

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Aside: what happened to the inertial waves??

Actual average wind input during cruise period = 6 mW/m² (42-52 S) => ~5 kW/m
Aside: what happened to the inertial waves??

Mooring spectra

Low modes must dissipate in ~10 deg latitude. Surface/bottom bounces? ACC fronts?

Actual average wind input during cruise period = 6 mW/m² (42-52 S) => ~5 kW/m
Conclusions - another example of patchy mixing

- Dissipation in upper 2500 m only (above ridge crests) is about 15 mW/m², similar to Egbert and Ray
- Extrapolating along entire SW Indian Ridge gives a rough total dissipation rate of 12 GW
- Deep mixing in series of fracture zones much larger
- Indian Ocean mixing concentrated in western half of basin, Drijfhout and Naveira Garabato 07 argue that this zonal mixing asymmetry significantly impacts basin-wide circulation patterns.
Consequences of patchy mixing

Strong mixing may continue as bottom water flows north in concentrated boundary current (Donohue et al 03)

Palmer et al 07: Modeled Indian Ocean overturning streamfunction

Constant $k = 1.2 \times 10^{-4}$

Bottom enhanced diffusivity