Climate and Dynamics in the Southern Ocean: A Lagrangian Perspective

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Southern Ocean Dynamic Topography (900 m)
Potential Temperature & Isopycnals

Outline

Climate: Is this system changing?
Dynamics: How do eddies influence North-South heat transport?
Large uncertainties in Southern Hemisphere
Levitus et al., Science, 1998
Autonomous Floats (1990- )

Autonomous Lagrangian Circulation Explorers (ALACE)
Profiling ALACE (PALACE)
ALACE measurements from the 1990s
1990s Float vs 50+ years of ship sampling

Depth Range: 700 to 1100 m

12,437 ALACE observations

20,659 Hydrographic observations
Temperature at 900 m: objectively mapped fields

Atlas (1930s-1990s)
Gouretski and Jancke, 1998
Hydrography: SODB (Olbers et al., 1992); WODB (Levitus et al., 1998)

Floats (1990s only)
Gille, JPO, 2003
Floats: ALACE and PALACE (courtesy of R. Davis)
Temperature Difference at 900 m
Nearest neighbor comparisons

- Ship observation within 110 km radius
- Ship observation within 220 km radius
- Float within 110 km radius
Temperature Trends (700 to 1100 m depth)

[Graph showing temperature trends with data points from 1940 to 2000, indicating decadal variations.]

Gille, Science, 2002
Temperature Trends (700 to 1100 m depth)

Gille, Science, 2002
Trends along streamlines of the flow

Gille, Science, 2002
Stratification changes (Hydrography minus PALACE)
Temperature trend in vertical structure
Cooling near the surface is seasonal bias

All data October to April only
Heat content changes

D. OCEAN HEAT CONTENT (10^{22} J)
0-1000 m LAYER, 5-YR RUNNING COMPOSITES

- SOUTHERN HEMISPHERE
- NORTHERN HEMISPHERE
- WORLD OCEAN

YEAR

VOLUME MEAN TEMPERATURE ANOMALY (°C)

HEAT CONTENT (10^{22} J)

YEAR

0-10
0
-5
-10
-15

-20
-15
-10
-5
0
5
10

All Data
Summer Data Only
Open Question: Is this anthropogenic?

Possible Mechanisms

\[ \frac{\partial T}{\partial t} + \nabla \cdot (\overline{uT}) + \nabla \cdot (\overline{u'T'}) = \text{forcing} \]

- heat input from atmosphere
- southward displacement of ACC
- oceanic heat transport
Has the ACC heated or migrated?

Average SAF maximum gradient in 10 WOCE sections spanning ACC:

0.15 $\pm$ 0.30°C warmer than atlas

0.36 $\pm$ 0.25° latitude further south
A closer look at eddy heat flux

\[
\frac{\partial \overline{T}}{\partial t} + \nabla \cdot (\overline{uT}) + \nabla \cdot (\overline{u'T'}) = \text{forcing}
\]

- Meridional heat transport: ACC as barrier to mixing?
- Parameterization:
  \( \nabla \cdot (\overline{u'T'}) \propto -\nabla^2 \overline{T} \) or something else?
Eddy heat flux

Estimate: $\overline{u'T'}$ from float data
Floats measure $\overline{v'}_{10 \text{ days}}$ and $\overline{T'}_{10 \text{ days}}$. We want $\overline{v'T'}_{10 \text{ days}}$. What have we lost?
Geographic distributions: Meridional heat flux

Gille, JPO, 2003
Along-stream averages: Net meridional heat flux

Total heat flux at 900 m: 4.7 to 7.5 kW/m$^2$. Implies 0.3 PW heat loss to atmosphere south of ACC. Temperature change at 900 m in 50 years: $>2^\circ$ C.

Gille, JPO, 2003
Parameterizing heat fluxes: \( \overline{u'T'} = -\kappa \nabla \overline{T} \)

\[ \kappa = 422 \pm 130 \text{ m}^2 \text{ s}^{-1} \]
EKE-weighted parameterization

$$u'T' = -C(u'^2 + v'^2)\nabla \overline{T}$$

$$C = 6.3 \pm 1.4 \times 10^4$$
Argo: Continuing these Inquiries
Summary

- Mid-depth warming of about 0.17°C from 1950s to 1990s.
- Water column has heated at all depths.
- Warming concentrated within Antarctic Circumpolar Current.
- Eddy heat flux elevated along path of Antarctic Circumpolar Current.
- Less than half of eddy heat flux captured as diffusive process.
Open Questions: Reduced CO$_2$ uptake?

CO$_2$ is more soluble in cold water than in warm water.

Caldeira and Duffy, Science, 2003

Warming of 0.3$^\circ$C (e.g. skin vs bulk temperature) implies 0.6 Gt C/yr reduction in uptake
Comparing temperatures: objective mapping

Gridding irregularly spaced data (Bretherton et al., 1976)

\[
T_{grid} = P_{gd}(P_{dd} + \epsilon I)^{-1}T_{obs}
\]

\[
P_{grid} = P_{gg} - P_{gd}(P_{dd} + \epsilon I)^{-1}P_{dg}
\]

\(P\): covariance matrix

\(\epsilon\): measurement noise

Minimizes formal mapping error.
Temperature change suggests geostrophic transport change

1950s

hot
low density

gradient

cold
high density

1990s

warm

gradient

cool
Temperature change implies transport reduction

net reduction between 40 and 63°S: 9 Sv

total geostrophic transport above 900 m: 30 Sv
SAF appears to have moved north—may be seasonal bias.

Future work may help decipher changes.
Continuing these Inquiries in the Future
Profiling Floats: Changes in the top 1000 m

- **Hydrography**: World Ocean Database 2001 data quality flags—reject questionable values. CTD, BT, XBT, Bottle Data: up to 150,000 obs.
- **Floats**: PALACE (1990s) up to 9600 observations
- Analysis on WOD01 standard levels: 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000, (1100)
- As many as 3.5 million data pairs at each depth
Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES)

- tracer release
- microstructure measurements
- acoustically-tracked floats

300 m

1500 m