Observed Eddy Heat Fluxes across the ACC in northern Drake Passage

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PRELIMINARY OVERVIEW

• For ocean mesoscale eddy heat fluxes, the dynamically important component is the divergent field, because it modifies its environment, whereas the rotational component just recirculates.

• Helmholtz showed that vector fields are uniquely separable -- if they vanish at infinity -- into irrotational and non-divergent parts.

• Divergent eddy heat fluxes (DEHFs) are driven by nearly depth-independent geostrophic eddy currents that can cross the temperature front.

• This presentation will characterize DEHFs using cDrake observations.
“cDrake”
Dynamics and Transport of the ACC in Drake Passage

Quantify ACC transport and dynamics for 4 years, 12/2007 - 12/2011
• Transport line determines horizontal and vertical structure of the time-varying transport.
• Local dynamics array at EKE max: maps the daily \((u,v)\) T, \(\rho\) field with mesoscale resolution.
• Local dynamics array observes eddy heat flux, vorticity and buoyancy flux in order to quantify their lateral and vertical transfers in the ACC.

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CPIES: current and pressure recording inverted echo sounder

Measures bottom current.
(50 m off bottom)

Emits 12kHz sound pulses.
Measures round trip travel times of acoustic pulses to sea surface and back.

Measures bottom pressure.
A CPIES array yields daily maps of upper and deep stream function.

Look-up tables interpret acoustic travel times as geopotential height (0 referenced to 4000 dbar).

2-D arrays of CPIES estimate horizontal gradients of geopotential to calculate geostrophic velocities.

Velocity profiles are referenced by measured near-bottom currents.

Bottom pressures are leveled using time-mean near-bottom currents.
EXAMPLE -- ONE DAY’s MAP in LDA

Upper and deep flow fields.
- On this day a SAF meander crest and trough passed through the LDA, as shown by the meandering baroclinic stream function, $\varphi_{0,4000}$, and SSH.
- The meanders were accompanied by deep barotropic HI and LO pressure anomalies,
  - which were offset $\sim \lambda/4$ downstream from the upper HI and LO this day.

Black contours: $\varphi$ baroclinic stream function
Gray contours: SSH from satellite altimetry
Colorbar: $P'$ at 4000 dbar (bt streamfunction)
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• The meanders were accompanied by deep barotropic HI and LO pressure anomalies,
  - which were offset \( \sim \lambda/4 \) downstream from the upper HI and LO this day.

In circled region currents turned with depth as \( \mathbf{u}_{bt} \) crossed the baroclinic front – as sketched on following slide.

Black contours: \( \varphi \) baroclinic stream function
Gray contours: SSH from satellite altimetry
Colorbar: \( P' \) at 4000 dbar (bt streamfunction)
Absolute geostrophic currents $\mathbf{u}$ turn with depth as the vector sum $\mathbf{u}_{bc} + \mathbf{u}_{bt}$.

$\mathbf{u}_{bc}$ is the vertically-aligned baroclinic current, that is zero at the bottom; $\mathbf{u}_{bt}$ is a nearly depth-independent reference current (labeled barotropic) measured at the bottom.

Note labeling convention:
* $\varphi$ is baroclinic stream function
* bc is thermal wind shear re zero at bottom
* bt is the bottom reference
$(u,v)$ and $T$ are estimated well in LDA, top to bottom

e.g., comparison with French mooring (thanks to C.Provost)

Fig. 6. Daily zonal and meridional currents and temperature from M4 mooring (red) and cDrake interpolated to mooring $p(t)$ (blue), nominally at (top to bottom) 520 dbar, 930 dbar, and 2540 dbar. Squared correlation coefficients ($r^2$), rms differences (rmsd) and standard deviations of each record (indicated by color) are given on each panel.

Y. Firing et al., 2013 in prep for JTech.
Using \((u,v), T\) observations, we estimate and map eddy heat fluxes

Start with \(<u'T'>\) fields in the cDrake LDA,
--- mid-thermocline at 400 dbar
--- superimposed with surface EKE

\[
<u'T'>
\]

Four-year average field of mapped vector eddy heat fluxes (EHF)
\[
u'T' = u'_bcT' + u'_btT'
\]
- where multiplication by \((\rho_o C_p)\) is implied

Total EHF\s tend to be large (~0.05 °C m s\(^{-1}\))
where EKE is large, and the angle may be any direction, equatorward and poleward, depending upon location.
Using \((u,v), T\) observations, we estimate and map eddy heat fluxes

Marshall and Shutts (JPO, 1981) discussed the importance of separating non-divergent and divergent eddy fluxes. They presented a method to separate them if the mean flow is nearly along temperature contours, satisfying approximately, 
\[ \psi \approx \psi(T). \]
They showed the non-divergent part of EHF recirculates around \(<T'^2> = \text{EPE extrema.}\)

In the EPE equation (neglecting triple correlations)
\[
U \cdot \nabla \left( \frac{<T'^2>}{2} \right) + <u'T'> \cdot \nabla <T> + <w'T'> \theta_z = 0,
\]
when the eddy heat flux is separated into non-divergent and divergent parts,
\[
U \cdot \nabla \left( \frac{<T'^2>}{2} \right) + <u'T'>^{\text{nondiv}} \cdot \nabla <T> = 0,
\]
and
\[
<u'T'>^{\text{div}} \cdot \nabla <T> + <w'T'> \theta_z = 0.
\]
\(i.e.,\) the non-divergent EHF term balances lateral advection of EPE by the mean flow, and the divergent EHF term balances \(<w'T'> \theta_z\), which produces EPE and EKE.
• The divergent flux fields are observed in vector sum with typically more energetic rotational fluxes, masking their important dynamics.
• Separation is particularly difficult using sparse observations with noise. -- it helps to first remove a large non-divergent part, as follows...

* Mapped vector eddy heat fluxes (EHF)
  \[ \mathbf{u}'T' = \mathbf{u}'_{bc}T' + \mathbf{u}'_{bt}T' \]
  - where multiplication by \((\rho_oC_p)\) is implied

* baroclinic part is entirely non-divergent, \(\nabla \cdot \langle \mathbf{u}_{bc}'T' \rangle = 0\)
  • because \(\mathbf{u}_{bc}\) thermal wind parallels isotherms,
    \(\phi = \phi(T)\) at each pressure level (like MS81)

* barotropic part, \(\langle \mathbf{u}'_{bt}T' \rangle\) contains all dynamically important EHF
  • a part of it may still be non-divergent
    and we deal with this issue in a moment, to estimate DEHF
Four-year mapped mean EHF fields

Display the separate bc and bt contributions

The bt EHF is large (~0.025 °C m s\(^{-1}\)) immediately downstream of SFZ ridge and mainly poleward
Superpose $<T'^2>$ field, supporting the MS result that this bc flow along isotherms produces recirculating non-divergent EHF around $<T'^2>$ extrema.

Next examine what part of this bt EHF field is divergent.
Method builds upon several studies of divergent eddy heat fluxes...

- Marshall and Shutts (JPO, 1981) separation method was just discussed, for flow approximately along isotherms, with $\psi \approx \psi(T)$.
- Cronin and Watts (JPO, 1996) applied the MS method in the Gulf Stream in SYNOP.
- Jayne and Marotske (JPO, 2002) studied global ocean eddy heat transport in a general circulation model and separated the divergent and rotational fluxes. They noted difficulties in applying this method to observations.
- Daley (MWR, 1985) noted the difficulty of analysis of divergent wind components even in atmospheric ECMWF data sets, $\partial v/\partial y$ and $\partial u/\partial x$ are nearly equal and opposite, and the direct estimate is overwhelmed by observational error. He proposed an OI method to fit coupled rotational and divergent fields, and applied it to a tropical flow field.
- Fox-Kemper et al. (JPO, 2003) noted the indeterminacy of the rotational and divergent fluxes in a bounded domain, interior field estimates depend upon separation of fluxes through the boundary; a harmonic term (i.e., irrotational and nondivergent) appears in a bounded domain.
**Method:** estimate divergent and rotational flux fields via OI

-- 1st for insignificant fluxes through domain boundary

Start with $<u'_b T'>$ “full” fields, $F$

(1) Apply non-divergent OI to full input vector field $F$.
When the correlation functions for vector variables are non-divergent, the output vectors are the best fitted estimates of the non-divergent field, $\mathbf{ND}$.

-- Bretherton *et al.* (1976)
Method: estimate divergent and rotational flux fields via OI

-- 1st for insignificant fluxes through domain boundary

Start with

\(<u'_b T'>\)

“full” fields, \(F\)

\[ F - \text{ND} = D1 \]

Divergent part \(D1\) estimated as residual of non-div \(ND\)

\[ IR = D2 \]

Divergent part \(D2\) is all in mapped irrot field \(IR\).

(2) Apply irrotational OI to full input vector field \(F\).

-- When the correlation functions for vector variables are irrotational, the output vectors are the best estimates of the irrotational field, \(IR\).

In the Kuroshio Extension study, KESS, the \(D1\) and \(D2\) estimates are nearly identical.
In a limited domain with boundary fluxes

Method: estimate divergent and rotational flux fields via OI

Start with {
\begin{align*}
\langle u'_b T' \rangle
\end{align*}
}
“full” fields, \( F \)

\[ \text{ND} = \mathbf{R} + \mathbf{H}_1 = \mathbf{R}^+ \]
\[ \mathbf{F} - \text{ND} = \mathbf{D}^- \]
\( \mathbf{R} \): true rotational part
\( \mathbf{H}_1 \): apparent harmonic part

\[ \text{IR} = \mathbf{D} + \mathbf{H}_2 = \mathbf{D}^+ \]
\[ \mathbf{F} - \text{IR} = \mathbf{R}^- \]
\( \mathbf{D} \): true divergent part
\( \mathbf{H}_2 \): apparent harmonic part

\( \Rightarrow \) The two OI analyses produce (\( \mathbf{D}^+, \mathbf{D}^- \)) and (\( \mathbf{R}^+, \mathbf{R}^- \)), which respectively over- and under-estimate \( \mathbf{D} \) and \( \mathbf{R} \).

If a domain’s boundary cuts across normal fluxes, the OI\text{non-div} and OI\text{irrot} will each attempt to include them, i.e., because boundary vector gradients are well-specified in only one dimension, it may be difficult to distinguish whether they are non-divergent or irrotational.

\( \Rightarrow \) Effectively they “appear” to contribute a harmonic part, \( \mathbf{H} \).
Parts of “apparent \( \mathbf{H} \)” contribute to \( \text{ND} \) and \( \text{IR} \).
**Method:** Estimate divergent and rotational flux fields via OI

Start with $\langle u'_b T' \rangle$ “full” fields, $\mathbf{F}$

- **Divergent part** $D$ estimated as residual of non-div
  
  \[ ND = \mathbf{R} + H1 = \mathbf{R}^+ \]
  \[ \mathbf{F} - ND = D^- \]

- **Rotational part** $R$ estimated as residual of irrot
  
  \[ IR = D + H2 = D^+ \]
  \[ \mathbf{F} - IR = R^- \]

**Best combined estimate is the average** based on simulations and sub-regions of KESS data. (Discuss afterwards.)

\[ D = (D^+ + D^-)/2 \]
\[ R = (R^+ + R^-)/2 \]

In cDrake we used this, because the LDA domain size was small & fluxes crossed its boundaries
CONTINUE, we had arrived at this slide

Superpose $<T'^2>$ field, supporting the MS result that this bc flow along isotherms produces recirculating non-divergent EHF around $<T'^2>$ extrema.

Purely non-divergent bc-EHF, & bt-EHF may have mixed div and non-div parts

White contours: SSH variance colors: bathymetry
Four-year mapped mean EHF & DEHF fields

Separate $\langle u'_{bt} T' \rangle$ into rotational and divergent EHF components
Four-year mapped mean EHF & DEHF fields

The rotational part associated with barotropic EHF recirculates, but not around $<T'^2>$ extrema. (Discuss afterwards)

Contours: mean $\varphi$, bc front

DEHFs are downgradient in purple shaded region
**Vertical structure of DEHF**

(4-yr mean field)

- Downgradient flux all along PF and SAF
- Important contrib’n top-to-bottom
  - with 50% of flux below 800m
- Peak in thermocline near 400 m,
  - yet still ~20% as large between 1500-3500m

- Median sites 2,4,5 :
  - peak .008 °C m s\(^{-1}\) = 32 kW m\(^{-2}\)
  - vertical integral ~ 50 MW m\(^{-1}\)

Six locations in the 400m mean DEHF field, chosen to examine vertical structure of \(\langle u'T'\rangle^{\text{div}}\)
Time series of DEHF, and a case-study (1)

Meridional DEHF at site 1 typifies all sites. The mean accumulates from many short-lived events. The short integral time scale ~4 days accounts for why 1-yr means are similar.

Poleward DEHFs arise when southward crests develop and grow on the warmer SAF. Additional poleward peaks arise when northward troughs of the colder PF develop.

Case: Daily snapshots at 6-d interval, during poleward peak DEHF.

Rapid growth of a SAF meander crest (A) jointly steepens with deep anticyclone. (B) signature BC instability, upper crest and trough led (~λ/4) by deep high and low; note strong poleward DEHFs. (C) grows more vertically aligned. (D) separated ring, mature vertically-aligned current structure and thereafter little divergent heat flux.

bc geopotential \( \varphi_{0, re 4000} \) (solid contours) bt ref-pressure anomaly, \( P'_{4000} \) (colorbar) daily DEHF \( u'T'^{\text{div}} \) (green arrows, six sites)
Time series of DEHF, and a case-study (2)

Meridional DEHF at site 1 typifies all sites. The mean accumulates from many short-lived events. The short integral time scale ~4 days accounts for why 1-yr means are similar.

Poleward DEHFs arise when southward crests develop and grow on the warmer SAF. Additional poleward peaks arise when northward troughs of the colder PF develop.

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cDrake findings recap...

• Observed 4-yr mean divergent eddy heat fluxes (DEHF) in the northern Drake Passage are mainly down-gradient and are stable estimates.
  – arising from several poleward-DEHF events per year.

• Strongest DEHFs occur immediately downstream of Shackleton Fracture Zone (SFZ, topographic ridge) between the Subantarctic Front (SAF) and Polar Front (PF), where
  – meanders develop jointly with deep-reference barotropic eddies,
  – rings pinch off, and
  – SSH variability is highest.

• Baroclinic current component parallels isotherms and produces only non-divergent EHFs

• Deep-reference barotropic eddy currents can cross the baroclinic front, and do produce divergent eddy heat flux
  – their phase-offset in growing baroclinic instability events favors downgradient flux
Context – other EHF estimates in Southern Ocean

- Mean downgradient DEHF at 400m is 0.008 °Cm/s (median sites 2,4,5)
  \( \approx 32 \text{ kW/m}^2 \)
  - contrast \( \langle –_b'T' \rangle \) are ~2X larger, poleward but partly non-divergent
  - contrast \( \langle u'T' \rangle \) have ~5x larger magnitude, but in recirculating directions

- Vertically-integrated downgradient DEHF is 50 MW/m

- Compare Phillips & Rintoul (2000) AUSSAF vertical average EHF in shear coordinates 11.3kW/m² (vertical integral ~40 MW/m).
  - shear coordinates attempt to remove non-divergent bc EHF

- Compare Bryden (1979) Drake P average EHF at 2700m
  \( = 0.16 \text{cal/cm}^2\text{s} \approx 6.5 \text{ kW/m}^2 \).
  - resembles \( \langle –_b'T' \rangle \) at 2700m because \( \mathbf{u}_{2700}' \) resemble the deep barotropic reference, without the confusion of \( \langle –_b'T' \rangle \) that affects upper layers

- Compare Lenn, et al. (2011) Drake P XBT +SADCP transects, poleward EHF in upper 300m up to 290±80 kW/m² calculated relative to mean stream coordinates.
Compare DEHF with simple barotropic EHF time series

Coherence ~ 0.8
• END