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Wave-turbulence-mean flow interaction in the Antarctic Circumpolar Current

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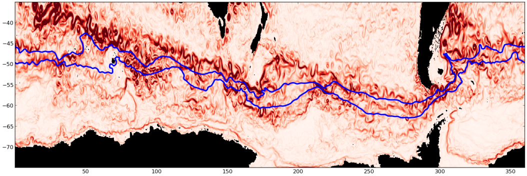
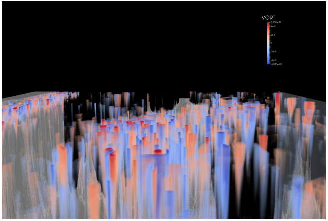


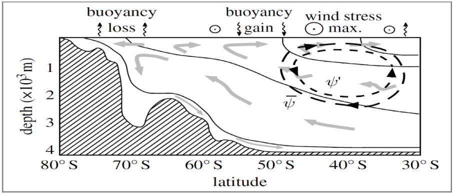
in collaboration with J. R. Maddison, D. P. Marshall and A. C. Naveira Garabato

Outline

- Background
- Data
- Local vs. non-local dynamics
- Wave-turbulence-mean flow interaction
- Application to the ACC
- Conclusions

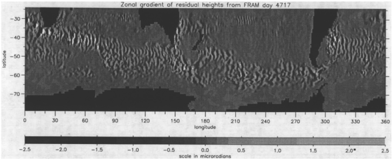


Baroclinic mesoscale eddies / turbulence



- The wind tilts isopycnals due to a northward Ekman transport.
- The steep isopycnals become baroclinically unstable, leading to the generation of baroclinic mesoscale eddies.
- Baroclinic mesoscale eddies then act to flatten isopycnals.
- The stratification in the ACC is therefore a residual between the effects of the wind and the eddies.

Barotropic Rossby waves



- Both satellite-based observations and an ocean model reveal standing Rossby waves with wavelengths of order 300-500 km, i.e. Rossby waves with a westward phase speed which opposes the ACC's eastward mean flow (Hughes, 1996,2005).
- Using scaling arguments Hughes (2005) reached the conclusion that these Rossby waves are likely to be short barotropic Rossby waves.

Radiation stresses

- These observations suggest that the ACC is unstable with respect to its baroclinic component and stable with respect to its barotropic component.
- In such a situation Rossby waves tend to organise the fluctuating fields associated with mesoscale eddies, inducing systematic correlation amongst the components of those fields and giving rise to **systematic, long-range momentum transport**.
- This wave-induced long-range momentum transport is commonly referred to as **radiation stresses**.

Goals of this talk

In this talk I will explain radiation stresses and their role in the formation of **storm tracks** in the Antarctic Circumpolar Current.

I will do this by analysing three interrelated phenomena, in particular

- the spatial inhomogeneity of PV mixing
- the 'antifrictional' or upgradient eddy momentum fluxes $\overline{u'v'}$, and
- the spontaneous creation and self-sharpening, or narrowing, of jets.

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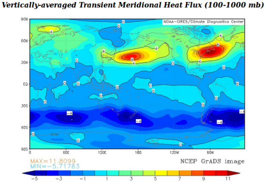
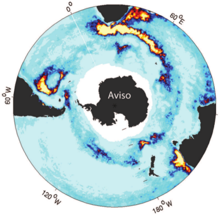
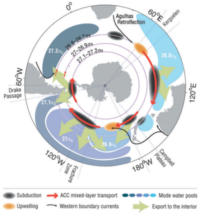
Storm tracks

- Storm tracks are regions of enhanced eddy kinetic energy and eddy mixing:







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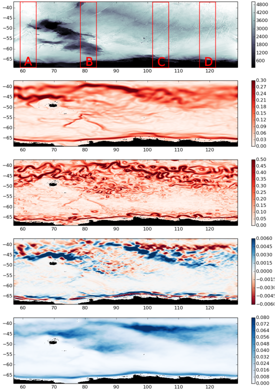
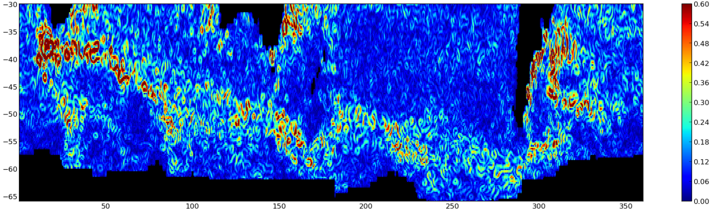
KERG20 model configuration



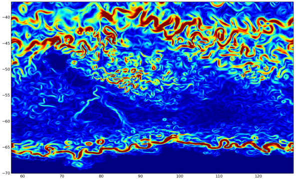
- Sector model of the ACC using MITgcm
- 1/20 degree horizontal resolution
- 150 vertical layers
- Realistic topography made periodic at east/west boundaries
- Steady, zonally symmetric surface forcing and restoring at northern boundary
- Variables are 30yr means after equilibration
- All non-zonal behaviour is due to topography

Satellite-derived geostrophic velocity fields



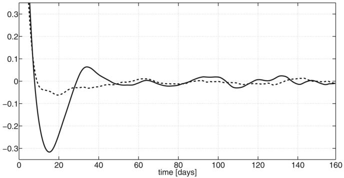
- Geostrophic velocities derived from TOPEX/ERS satellite data
- 1/4 degree horizontal resolution
- 10 days temporal resolution
- Sea-level anomalies calculated with respect to a three-year mean

Local vs. non-local dynamics



- The ACC is a region of strong eastward jets which lack zonality and tend to merge, split and meander close to topographic features.
- These strong eastward jets are a consequence of the interaction of fast mean flows with slowly propagating mesoscale eddies.

The Lagrangian perspective



- The most intuitive way to understand these strong eastward jets is from a Lagrangian perspective by looking at Lagrangian particles and their decorrelation behaviour.
- Using a simple kinematic model, the Lagrangian velocity autocorrelation of these particles can be written as

$$R_L = e^{-\gamma_L t} cos[k(c - \overline{U})t]$$

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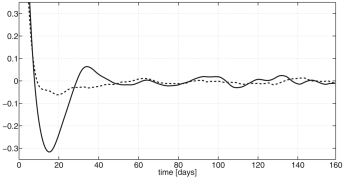
The Lagrangian perspective - eddy diffusivities



- In the ACC the decorrelation time of particles is order 60 *days*, which, assuming a surface velocity of 10 cms^{-1}, leads to a spatial scale of order 500 *km*.
- These temporal scales are important for the estimation of eddy diffusivities which can be written as

$$K = EKE \int_0^t R_L$$

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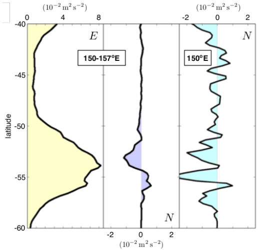
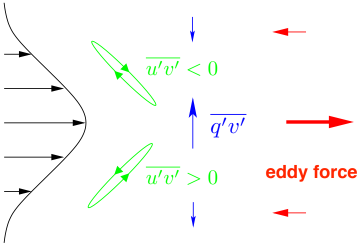
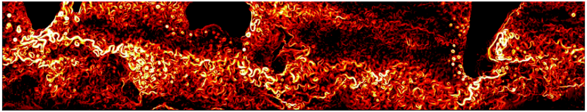
Local and non-local eddy momentum fluxes





- Lateral eddy momentum fluxes are written as $N = \overline{u'v'}$.
- **Locally** N is related to velocity filaments, as shown by the Lagrangian velocity autocorrelation R_L.
- **Non-locally** N is related to one large jet, the ACC.

Local vs. non-local dynamics



- It is crucial to distinguish **local** observations, where eddy diffusivities are ill-defined and eddy momentum fluxes are related to velocity filaments, and **non-local**, **large-scale** observations, where eddy diffusivities are well-defined and eddy momentum fluxes are related to the large-scale dynamics.
- In the remaining talk I will focus on the **non-local, large-scale dynamics**.

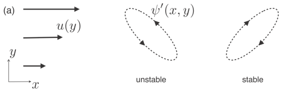
Wave-turbulence-mean flow interaction

The close interaction between waves, turbulence and mean flow is best summarized by the **Taylor-Bretherton identity**:

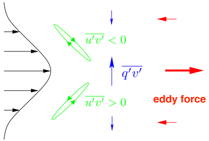
$$\overline{v'q'} = -\frac{\partial N}{\partial y} + \frac{\partial S}{\partial z}$$

- LHS is the eddy PV flux due to for instance PV mixing by mesoscale eddies.
- $\frac{\partial N}{\partial y}$ is the meridional convergence of eddy momentum fluxes due to Rossby waves and mean flow shear; related to barotropic stability/instability.
- $\frac{\partial S}{\partial z}$ is the vertical convergence of eddy buoyancy fluxes; related to baroclinic stability/instability;

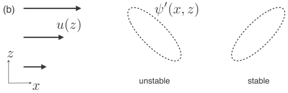
- Barotropic stability/instability ($EKE \leftrightarrow MKE$).



- A barotropically stable jet.



- Baroclinic stability/instability ($EKE \leftrightarrow MPE$).



PV mixing by mesoscale eddies

$$\overline{v'q'} = -\frac{\partial N}{\partial y} + \frac{\partial S}{\partial z}$$

- PV mixing is often described using eddy diffusivities

$$\overline{v'q'} = -K\frac{\partial \overline{q}}{\partial y}$$

- Eddy diffusivities are proportional to the eddy kinetic energy (EKE) and suppressed by a PV gradient:

$$\beta_{effective} = \beta - \overline{U^z_{yy}}$$

Barotropic instability

$$\overline{v'q'} = -\frac{\partial N}{\partial y} + \frac{\partial S}{\partial z}$$

- A barotropic Rossby wave goes unstable when
$$\beta_{effective} = \beta - \overline{U^z_{yy}} = 0.$$
- This is intuitive since Rossby waves rely on a PV gradient.
- In regions of barotropic instability $MKE \rightarrow EKE$.
- $EKE \uparrow$ and no suppression of eddy mixing due to $\beta_{effective} = 0$ $\Rightarrow$ enhanced eddy mixing ($K \uparrow$).
- Localised regions of enhanced EKE and eddy mixing are what defines **storm tacks**.

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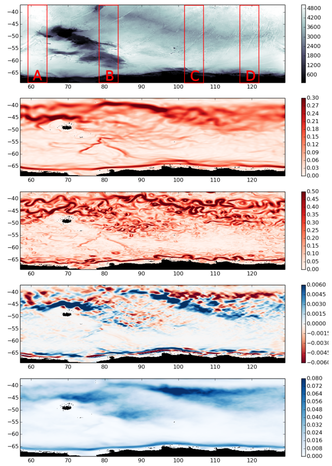
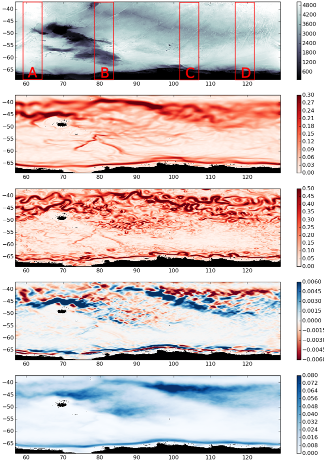
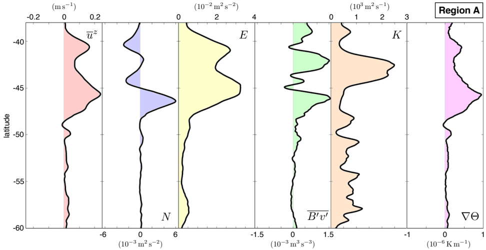
Storm tracks in the ACC

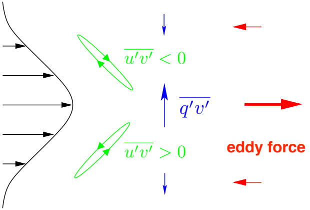


- Bathymetry $[m]$
- Magnitude of mean flow $[ms^{-1}]$
- Snapshot of magnitude of mean flow $[ms^{-1}]$
- Eddy momentum flux $[m^2 s^{-2}]$
- Eddy kinetic energy $[m^2 s^{-2}]$

Storm tracks in the ACC - region A







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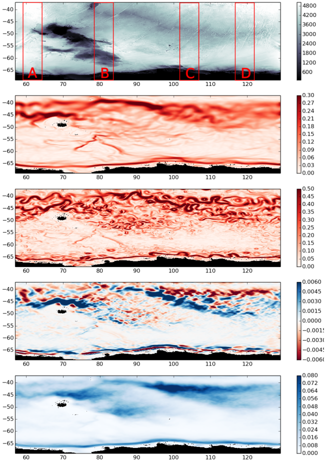
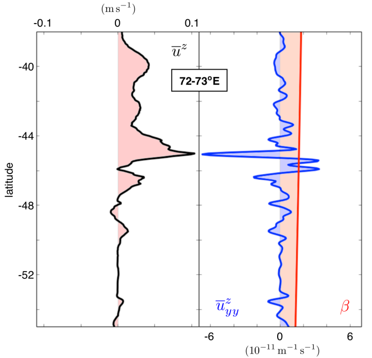
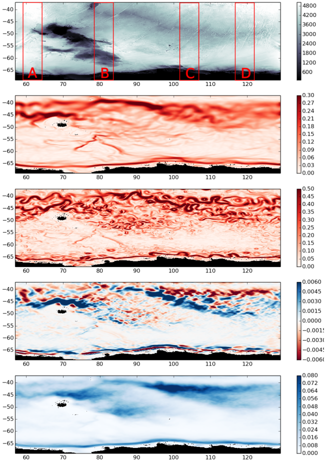
Storm tracks in the ACC - barotropic instability

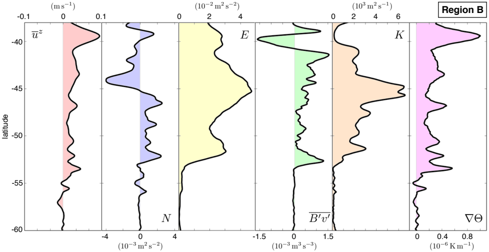


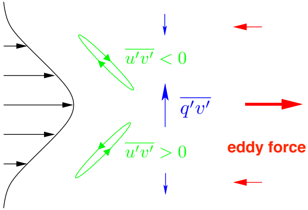


- $\beta_{effective} = \beta - \overline{U^z_{yy}} = 0$

Storm tracks in the ACC - region B







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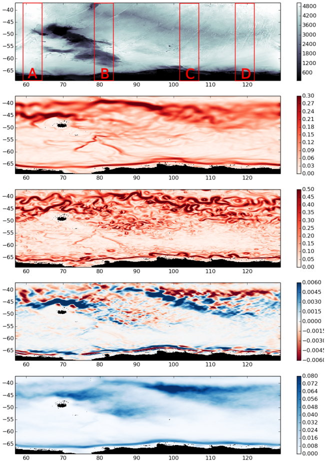
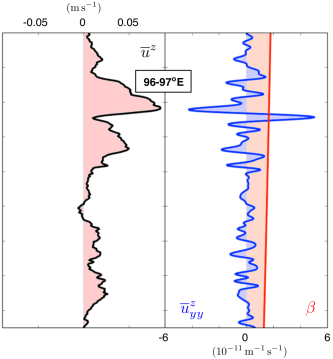
Storm tracks in the ACC - barotropic instability





- $\beta_{effective} = \beta - \overline{U^z_{yy}} = 0$

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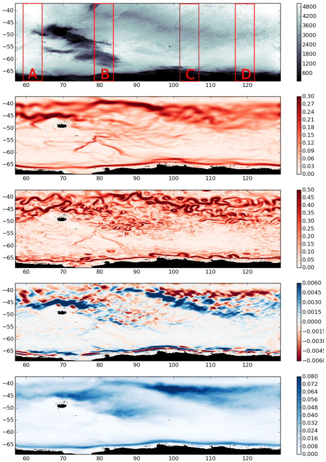
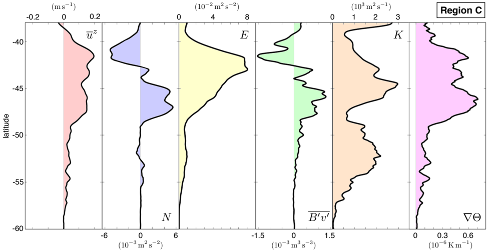
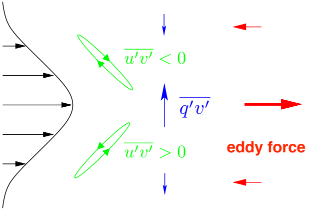
Storm tracks in the ACC - region C







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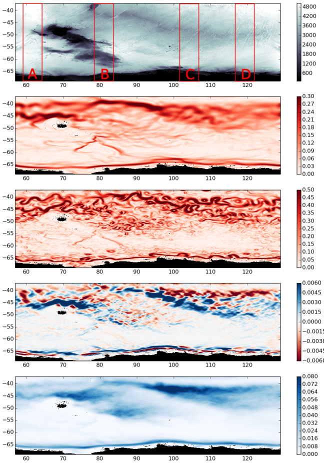
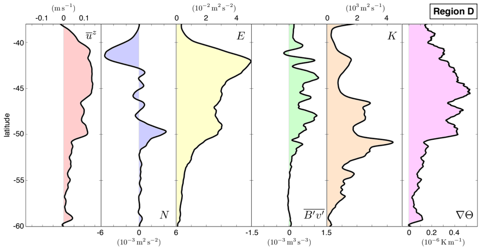
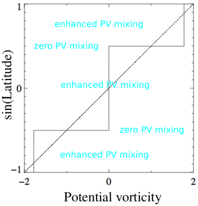
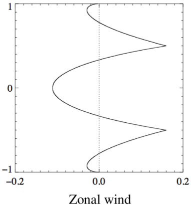
Storm tracks in the ACC - region D

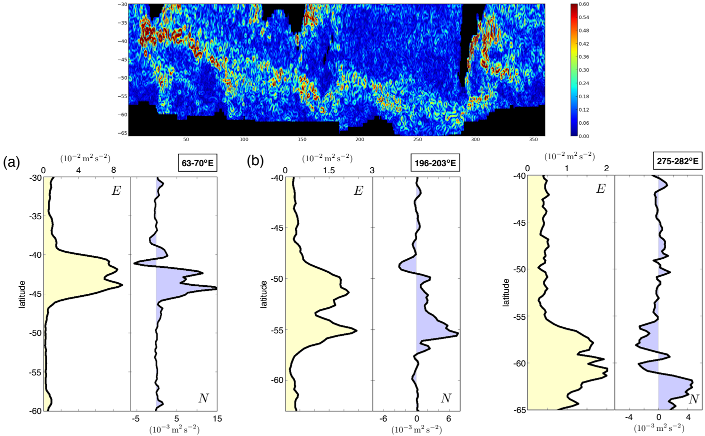








Satellite observations of eddy momentum fluxes



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Summary of ACC dynamics

1. The wind tilts isopycnals due to a northward Ekman transport, increasing the available potential energy ($APE \uparrow$).
2. The steep isopycnals become baroclinically unstable, leading to the generation of baroclinic mesoscale eddies ($APE \rightarrow EKE$).
3. Due to the interaction of baroclinic mesoscale eddies with barotropic Rossby waves and mean flow, the mean flow becomes concentrated in multiple jets ($EKE \rightarrow MKE$).
4. These jets accelerate past topography to a point where the PV gradient becomes zero, leading to barotropic instability ($MKE \rightarrow EKE$) and consequently ocean storm tracks.

Conclusions

1. To understand ACC dynamics one has to take into account baroclinic eddies, barotropic waves and the mean flow.
2. When analysing wave-turbulence-mean flow interaction it is essential to distinguish local and non-local dynamics.
3. Rossby waves organise baroclinic turbulence, leading to long-range momentum transport due to radiation stresses.
4. Storm tracks are regions of enhanced eddy kinetic energy and eddy mixing, which are the consequence of breaking barotropic Rossby waves.
5. Hydrographic fronts are associated with standing barotropic Rossby waves.

QUESTIONS??

- Thanks to Marshall Ward for excellent computational support.
- Model simulations run on Raijin at the National Computational Infrastructure (NCI).

NCI

The redistribution of EKE

- The full EKE budget (for a zonal barotropic ocean) can be written as

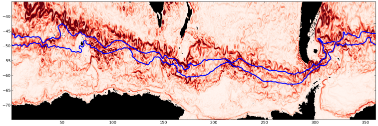
$$\frac{\partial EKE}{\partial t} - \overline{U}\frac{\partial N}{\partial y} + \frac{\partial \overline{B'v'}}{\partial y} = -D,$$

where where B' is the pertubation Bernoulli potential

$$B' = u'\overline{U} + EKE + \frac{p'}{\rho},$$

and D is the dissipation of EKE.

Hydrographic fronts



- Two disparate views which exist on hydrographic fronts in the ACC - continuous ACC fronts vs. multiple filaments.
- This was previously explained by describing the filaments as different branches of the main fronts.
- Differences between filaments and continuous fronts are due to local vs. non-local, large-scale observations.
- Enhanced mixing across fronts downstream of topographic obstacle is due to breaking of barotropic Rossby waves.