PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2008) **366**, 4529–4541
doi:10.1098/rsta.2008.0196
Published online 25 September 2008

The atmospheric ocean: eddies and jets in the Antarctic Circumpolar Current

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Although the Antarctic Circumpolar Current (ACC) is the longest and the strongest oceanic current on the Earth and is the primary means of inter-basin exchange, it remains one of the most poorly represented components of global climate models. Accurately describing the circulation of the ACC is made difficult owing to the prominent role that mesoscale eddies and jets, oceanic equivalents of atmospheric storms and storm tracks, have in setting the density structure and transport properties of the current. The successes and limitations of different representations of eddy processes in models of the ACC are considered, with particular attention given to how the circulation responds to changes in wind forcing. The dynamics of energetic eddies and topographically steered jets may both temper and enhance the sensitivity of different aspects of the ACC's circulation to changes in climate.

Keywords: Antarctic Circumpolar Current; mesoscale eddies; zonal jets

1. Introduction

Within the ocean's circulation system, the Antarctic Circumpolar Current (ACC) stakes its claim to a number of superlatives. The ACC is both the longest and the strongest current in the ocean carrying a volume transport of 130 Sv (1 Sverdrup = 1 Sv = $1\times10^6\ \mathrm{m^3\ s^{-1}}$) along a 24 000 km path encircling Antarctica (figure 1*a*; Rintoul *et al.* 2001). The ACC is also unique because no continental barriers exist in the latitudes spanning Drake Passage (the gap between South America and the Antarctic Peninsula), which allows the current to close upon itself in a circumpolar loop. This trait makes the ACC the most important oceanic current in the Earth's climate system because it links the Atlantic, Pacific and Indian Oceans and is the primary means of inter-basin exchange of heat, carbon dioxide, chemicals, biology and other tracers. Despite its essential role in the climate system, though, the ACC remains one of the most poorly understood currents in the ocean.

The difficulty in obtaining observations from the remote Southern Ocean has, in part, hindered progress in describing the circulation of the ACC, but a more fundamental complication is that the ACC is dynamically distinct from ocean

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One contribution of 10 to a Triennial Issue 'Earth science'.

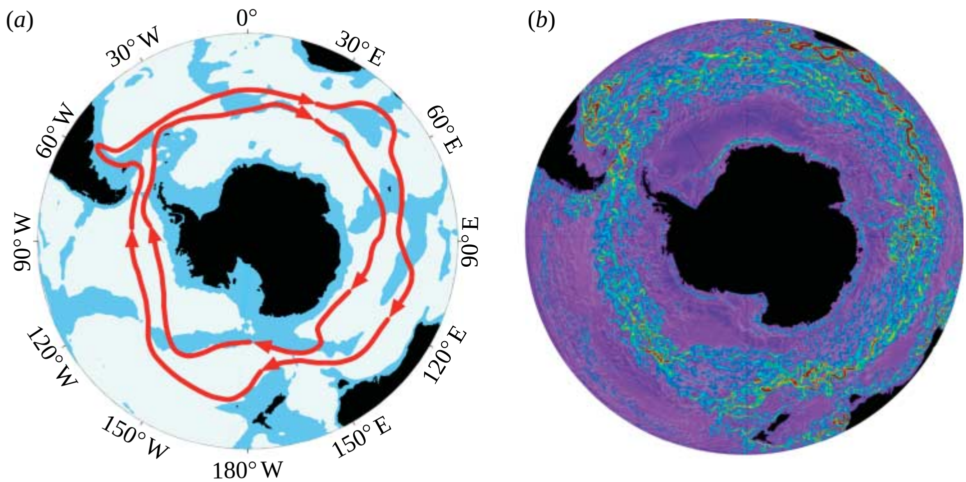

Figure 1. (*a*) Schematic path of the ACC. Regions shaded blue have depths shallower than 3500 m. (*b*) Snapshot of the surface current speed from the OCCAM 1/12° ocean model (Lee & Coward 2003), where the filamentary structure of the ACC's jets is clear (courtesy of Andrew Coward).

basin currents. As winds blow over the ocean surface, they drive a flow in a thin frictional layer at the top of the ocean. This Ekman transport is perpendicular to the wind motion due to the Earth's rotation. Latitudinal variations in easterly and westerly wind velocities then create areas of convergence and divergence at the surface that are balanced by vertical motions that 'pump down' or 'suck up' on the water column, respectively. In ocean basins, this surface forcing gives rise to a meridional (north–south) flow in the interior that is balanced by a zonal (east–west) pressure gradient—a balance known as geostrophy. The pressure gradient in this case is related to a slope in sea surface height across the basin. Similar regions of surface pumping and suction occur in the ACC, however, here, there are no meridional boundaries, above the highest topographic feature or sill depth, to support a sustained zonal pressure gradient. Thus, unlike ocean basins, a mean geostrophic meridional flow may only occur below the sill depth (approx. 2500 m) in the ACC; a more complete description of this 'Drake Passage effect' is given in §2.

The magnitude of the ACC's circumpolar, or zonal, flow component greatly exceeds its meridional component. Yet the export of dense water formed around Antarctica to lower latitudes and the transport of heat poleward are essential elements of a steady global circulation. Mesoscale eddies—coherent, vortex-like structures with a roughly 20 km diameter in the ACC—are a key mechanism for generating meridional transport, particularly above the sill depth. Ocean eddies are similar to atmospheric storms in many ways, and like storms, they tend to align or concentrate along zonal bands referred to as jets. These jets also strongly influence transport properties. Because ocean eddies and jets have a much smaller length scale than their atmospheric counterparts, the ACC has a rich and complicated structure, as shown in figure 1*b*.

With present computing capabilities, large-scale ocean and climate models cannot explicitly resolve eddies and jets. Instead, their effects are incorporated through parametrizations with varying degrees of success. Recently, more work has focused on the response of jets and eddies to observed changes in climate, such as increasing atmospheric wind forcing, in order to provide more realistic model parametrizations and to improve predictions of the ACC's behaviour in a changing climate. In §2, the sensitivity of the ACC's circulation to different representations of eddy processes is considered. The distinctive structure of ACC jets and their ability to localize meridional exchange are discussed in §3. Finally, §4 speculates on how eddy processes in the ACC are modulated by and feedback on changes in climate.

2. The ACC meridional circulation

(*a*) *Mesoscale eddies: the ocean's weather systems*

The transport of a water mass $h\boldsymbol{u}$ within a constant density layer of thickness h and velocity $\boldsymbol{u}$ is accomplished through a combination of a time-mean Eulerian circulation and transient eddies. The standard convention is to decompose h and $\boldsymbol{u}$ into time-mean (an average over many eddy life cycles and indicated by an overbar) and eddy contributions, such that the total time-mean transport becomes

$$\overline{h\boldsymbol{u}} = \overline{(\bar{h}+h')(\bar{\boldsymbol{u}}+\boldsymbol{u}')} = \bar{h}\bar{\boldsymbol{u}} + \overline{h'\boldsymbol{u}'} = \bar{h}(\bar{\boldsymbol{u}}+\boldsymbol{u}^*). \tag{2.1}$$

Here, $\boldsymbol{u}^* = \overline{h'\boldsymbol{u}'}/\bar{h}$ is the eddy-induced velocity, or 'bolus' velocity, and $\bar{h}\boldsymbol{u}^*$ is the eddy or bolus transport.[1] A consideration of the ACC's steady state momentum balance indicates the importance of eddy transport in determining the circulation.

Wind stress imparted by strong westerlies at the ocean surface is the primary source of momentum into the ACC, which must be transferred to solid boundaries. Bottom friction alone is too small to accomplish this without generating unrealistically large zonal flows, and the pressure gradient term integrates to zero over a circumpolar path above the sill depth (i.e. the Drake Passage effect). Thus, bottom form stress arising from pressure gradients across major topographical features is the only mechanism that can balance the wind stress (Munk & Palmén 1951). Importantly, though, mesoscale eddies are required to transfer the momentum vertically from the ocean surface to topography at the bottom. To illustrate this, consider a simple, two-layer model of the ACC, where wind effects are only felt in the upper layer and topography does not extend above the bottom layer (figure 2*a*). The steady-state, zonally averaged momentum equations, after neglecting small terms, become

$$-\rho_0 f\overline{V_1} = -\overline{h'p'_x} + \overline{\tau^x} \quad \text{(upper layer)} \tag{2.2}$$

and

$$-\rho_0 f\overline{V_2} = \overline{h'p'_x} + \overline{Hp'_x} \quad \text{(lower layer)}. \tag{2.3}$$

Here, ρ_0 is a reference density; f is the Coriolis frequency or planetary vorticity; V_i is the meridional transport in layer i; h is the depth of the interface between upper and lower layers (equivalently, thickness of the upper layer); H is the ocean

[1] In practice, eddies influence the mean mass transport through eddy fluxes, according to the bolus transport, as well as through Reynolds stresses that alter the mean flow. This distinction, along with a number of subtle relations between eddy transport, vertical momentum transfer and potential vorticity fluxes, are beyond the scope of this paper; the interested reader is referred to Greatbatch (1998) for more details.

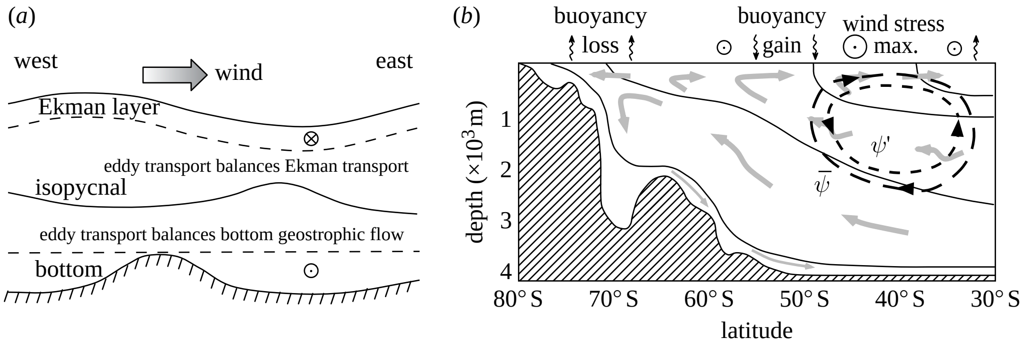

Figure 2. (*a*) Schematic of a zonal (east–west) section along the ACC (adapted from Olbers *et al.* 2004). Mesoscale eddies generate isopycnal displacements that transport momentum vertically and balance the meridional (north–south) transport. (*b*) Schematic of a meridional section of the ACC (adapted from Speer *et al.* 2000). The grey arrows indicate transport and the solid lines are levels of constant density. The circular curves represent the sense of the Eulerian $\bar{\psi}$ and eddy ψ' overturning cells in residual-mean theories. Patterns of wind and buoyancy forcing at the surface are also shown.

depth; p_x is the zonal pressure gradient; and $\boldsymbol{\tau}^x$ is the zonal component of the wind stress. Overbars now indicate zonal averages and primes represent deviations from this average, i.e. the eddy contribution.

If we assume that there is no mixing between layers, then the transport of each layer must disappear by mass conservation or $\overline{V_1} = \overline{V_2} = 0$. In the upper layer, westerly winds drive a northward Ekman transport that must be balanced by a southward flow above topography. Equation (2.1) reveals that this flow arises from zonal pressure gradients related to transient displacements of the interface between the two layers ($-\overline{h'p'_x}$). Mesoscale eddies are the primary mechanism for generating these interface displacements. Furthermore, geostrophy implies $p'_x \approx \rho_0 f v'$ such that $\overline{h'p'_x} \approx \rho_0 f \bar{h} v^*$, i.e. it is the eddy induced transport in the upper layer that balances the Ekman transport. The appearance of the interface displacement term ($\overline{h'p'_x}$) in both the upper and lower layer equations indicates that mesoscale eddies also enable the vertical transport of momentum to a layer where it can be balanced by bottom form stress ($\overline{Hp'_x}$). This model can be extended to include more layers or to allow mixing between layers (Olbers *et al.* 2004), but the behaviour remains qualitatively similar. This example shows how eddies alleviate some of the restriction on meridional flow imposed by the Drake Passage effect.

A schematic of the ACC's meridional structure illustrates how these eddies arise (figure 2*b*). The curvature of the wind stress south of the wind stress maximum produces a divergence in the Ekman transport. In order for water to rise and replace this surface flow without undergoing large density modifications, as is consistent with a largely adiabatic ocean interior, isopycnals or levels of constant density, tilt upwards across the ACC towards its poleward edge. Buoyancy forcing at the surface (heating/cooling and evaporation/precipitation) also helps to maintain this tilt, which is related to the strength of the ACC's zonal flow through geostrophy. The potential energy stored in the isopycnal tilt is then released through a process known as baroclinic instability that converts the potential energy into kinetic energy in the form of coherent mesoscale eddies. The motion of these eddies acts to relax the isopycnal tilt and permits the southward return flow that maintains a steady meridional overturning circulation.[2] In addition, there is a deeper overturning cell driven by the equatorward export of Antarctic bottom water, but we will focus on the upper cell where eddy processes are thought to be most important (figure 2*b*).

(*b*) *Meridional overturning*

Proper representation of eddy processes has guided the development of numerical and theoretical models of the ACC's meridional circulation. In particular, residual-mean theories, developed in the context of atmospheric flows and reviewed in Andrews *et al.* (1987), have achieved some success in reproducing the density structure and magnitude of overturning of the ACC's meridional circulation (Marshall & Radko 2003; Olbers & Visbeck 2005). Residual-mean theories determine a steady-state, circumpolar-mean residual overturning ψ from the summation of an Eulerian mean overturning $\bar{\psi}$, driven by wind forcing, and an eddy-induced overturning ψ'. Overturning of the Eulerian cell, with its associated northward Ekman transport, acts to tilt isopycnals, while overturning of the eddy cell has the opposite sense, and relaxes isopycnal tilt through baroclinic instability (figure 2*b*). The residual overturning, then, is typically much smaller than its components due to cancellation. The density structure of the ACC responds to the residual overturning that is responsible for the transport of heat, salt and other tracers.

A key element of residual-mean theories is that buoyancy B is not modified in the ocean interior—it is carried passively by the residual circulation. This implies that ψ and B have a functional dependence that can be established from the buoyancy distribution and the buoyancy forcing near the ocean surface, or more specifically at the base of the mixed layer. Residual-mean theories also require a relationship between eddy-induced velocities and the mean flow. A common approach is to relate ψ' to the slope s of isopycnals. For example, following Visbeck *et al.* (1997), $\psi' = k|s|s$, where k is a constant of proportionality. This relationship produces enhanced eddy overturning with increasing isopycnal tilt, as expected from baroclinic instability theory. This is an example of a parametrization used to represent eddy processes that are not resolved explicitly. This relationship also closes the residual-mean equations, such that, in this model at least, the entire horizontal and vertical structure of ψ can be determined from observations made at the sea surface alone (Speer *et al.* 2000).

The density structure of the residual circulation can be modified through eddy motions that change the thickness of a constant-density layer, however, the model assumes diabatic processes are absent in the ocean interior so that the density of a given layer is fixed. This may limit the reliability of residual circulation predictions in regions where flow over rough topography generates turbulent mixing events that produce diapycnal fluxes that transfer buoyancy and mass between layers (Naveira Garabato *et al.* 2004). In fact, because residual-mean theories necessarily take an averaged view of the circulation, any

[2] Oceanographers use meridional overturning circulation, or MOC, to refer to the vertical and meridional structure of the zonally averaged flow or transport of heat. The term MOC does not imply that isopycnals tilt to such a degree that they become convectively unstable.

spatial variations in topography or surface buoyancy forcing may cause individual meridional sections of the ACC to deviate substantially from the circumpolar-averaged structure.

The rising, or upwelling, of dense water along isopycnals, a characteristic of the ACC's meridional circulation (figure 2*b*), plays an important role in the global overturning circulation. Toggweiler & Samuels (1995) suggested that strong ACC upwelling could allow the global circulation to short-circuit vertical mixing at low- and mid-latitudes, the traditionally proposed mechanism for returning dense water to the surface. While a steady global circulation likely requires both ACC upwelling and vertical mixing, a consequence of significant upwelling in the ACC is that the global circulation is sensitive to the ACC's response to wind forcing. Thus a key prediction and a possible means of validating the residual-mean theory is that, in the limit that ψ is small compared with $\bar{\psi}$ and ψ', the zonal transport of the ACC increases linearly with increasing wind stress (Marshall & Radko 2003).

Understanding the response of the ACC to changes in wind stress has become a priority in climate research due to evidence that westerly wind speed in the Southern Hemisphere has increased during the past 30 years, largely in response to greenhouse gas increases and ozone depletion (Thompson & Solomon 2002). Fyfe & Saenko (2006) have shown that most global coupled climate models, which must parametrize eddy processes, experience a linear increase in the zonal transport of the ACC in response to increasing wind stress. However, the possibility of an 'eddy saturated' regime, where zonal transport is independent of wind stress, has been considered in a number of eddy-resolving numerical studies (e.g. Hallberg & Gnanadesikan 2001; Hogg *et al.* 2008).

Following arguments of the eddy-saturation model, an increase in wind speed over the ACC leads to larger wind stress forcing, which, in turn, increases northward Ekman transport. This creates a steeper isopycnal tilt across the ACC—essentially increasing the Eulerian overturning in the residual-mean framework. While this may lead to a transient change in zonal transport, over time the baroclinic instability acting on the steeper isopycnal tilt drives a more energetic and vigorous mesoscale eddy field. The eddies have a stronger tendency to relax the isopycnal tilt, which results in a minimal change in the mean zonal transport of the ACC. Hallberg & Gnanadesikan's (2001) numerical exploration of the response of an ACC-like channel to variable wind forcing indicated that eddy parametrizations based only on local mean flow properties, like that of Visbeck *et al.* (1997) above, are unable to capture certain eddy effects, such as the asymmetry of eddy transport around a topographical feature. Hallberg & Gnanadesikan (2006) argued that any parametrization based on mean properties may be unreliable, since eddy dynamics also influence the climate response to changes in forcing.

The response of the ACC's zonal transport to changes in wind stress forcing appears to depend crucially on whether eddies are parametrized or resolved explicitly. General climate models are essentially confined to using parametrizations owing to the computational burden of resolving the eddies explicitly. However, eddy-resolving models alluded to above are not perfect either, since they typically use a framework that does not permit modifications to the density structure. A step towards resolving this issue is the recent work of Hallberg & Gnandesikan (2006), which shows, using an eddy-resolving model that incorporates diabatic processes, that the response of the zonal transport to wind stress forcing is diminished by the action of the vigorous eddy field.

3. Jets in the ACC

(*a*) *Jets in atmospheres and oceans*

Atmospheric and oceanic flows have both turbulent and wave-like properties that cause large-scale motions to organize into persistent, narrow zonal jets (Rhines 1994). In the absence of friction, these flows conserve potential vorticity (PV) Q, which is a measure of the total vertical vorticity—local vorticity ζ plus planetary vorticity f—of a fluid parcel divided by its depth h,

$$Q = \frac{\zeta + f}{h}. \tag{3.1}$$

The restoring force responsible for wave-like motions is the apparent change in f with latitude ($f = 2\Omega \sin\theta$, where Ω is the Earth's rotation rate and θ is latitude). Changes in fluid depth due to topography also cause fluid parcels to either migrate meridionally or change their local vorticity in order to conserve Q; the former case is known as topographical steering and plays an important role in the ACC. The importance of (3.1) is that the velocity field can be obtained at any instant by inverting the PV distribution—a time history of Q is not required.

The formation of zonal jets is a robust feature in observations and numerical models, and these jets have a number of consistent characteristics. Jets exhibit an east–west asymmetry with narrow, energetic eastward flow and broader, weaker westward flow. Baroclinic instability and eddy formation is concentrated in the eastward jet cores. These eddies become sheared along the flanks of the jets, a process which produces an upgradient momentum flux that sharpens the eastward jets and contributes to their persistence and asymmetry. Eastward jets coincide with strong meridional gradients of PV, while PV gradients are weaker across westward jets. Strong and weak PV gradients are associated with regions of weak and strong horizontal mixing, respectively. This relationship, in addition to the 'invertibility principle' that links PV and velocity, underlies the theory that patterns of eastward and westward flow arise from local PV mixing processes, which produce a meridional 'PV staircase' of alternating weak and strong gradients (Dritschel & McIntyre 2008).

Figure 3 shows examples of jet structures in snapshots of (*a*) PV in an idealized two-layer rotating fluid, (*b*) Jupiter's atmosphere and (*c*) surface velocities inferred from satellite data from a section of the ACC (D. Stevens & S. Thorpe 2008, unpublished work). All three images show that both eddy and jet structures coexist, however, jets in the ACC depart from the other examples in their lack of zonality. This behaviour occurs because eddies communicate topographical features through the water column, as described in §2*a*, which allows topography to steer the flow (Hughes & Ash 2001). ACC jets also have a greater tendency to meander in the wake of topographical features. The spacing between jets is related to the Rhines scale $\ell_R \sim \sqrt{U/\beta}$, where β is the large-scale PV gradient and U is a velocity scale—typically a measure of the eddy velocity and therefore difficult to predict *a priori*. Jet spacing can be modified if topography produces a PV restoring force that changes β or if topographical steering drives a non-zonal mean flow, which is known to generate more vigorous baroclinic instability that can alter U.

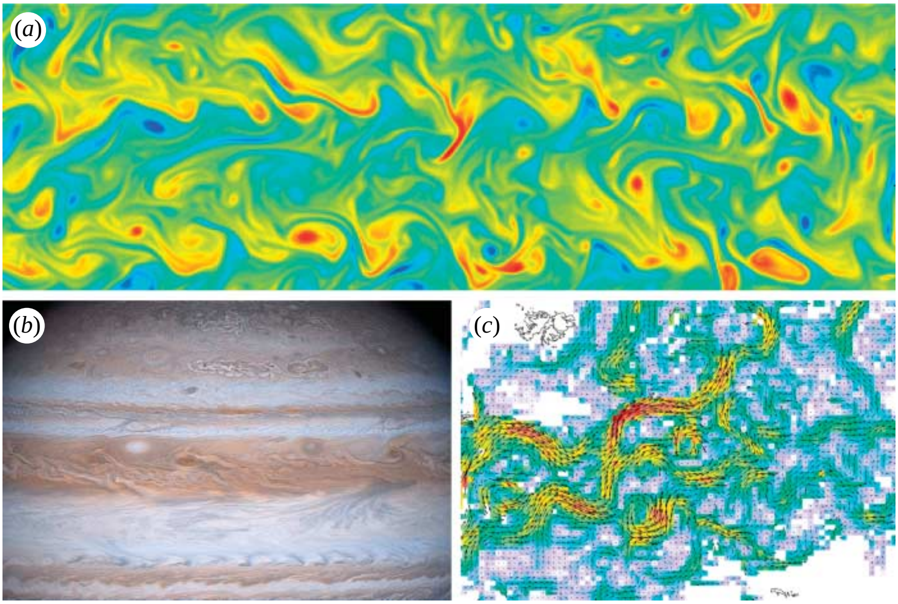

Figure 3. Examples of jets: (*a*) snapshot of a PV field from a numerical simulation of an idealized geophysical fluid (details in Thompson & Young 2007), (*b*) Jupiter's atmosphere and (*c*) surface current speed near Drake Passage in the ACC inferred from satellite altimetry (courtesy of David Stevens and Sally Thorpe).

Traditionally, ACC jets have been viewed as circumpolar features related to regions of strong horizontal gradients in water mass properties (Orsi *et al.* 1995). The position of the jets, or fronts, is identified by specific water mass properties, such as the location of a particular temperature contour at a given depth. The ACC is most commonly partitioned by three fronts that are thought to extend from the surface to the ocean bottom. However, with the advent of satellite data and better resolved numerical models, a very different picture of Southern Ocean jets has taken precedence. The narrow, filamentary structures shown in figure 1*b* seem to bear little similarity to a fixed number of smooth circumpolar jets. Sokolov & Rintoul (2007) have tried to resolve these two views by suggesting that the narrow jets are branches of the major ACC fronts. Still, there is little evidence that any particular jet maintains a circumpolar presence. Over time, ACC jets are observed to merge and split, strengthen and weaken, yet they exhibit a remarkable persistence. The following section considers the physical processes that maintain this complicated structure and influence transport in the ACC.

(*b*) *Jets and transport in the ACC*

As suggested earlier, a proper description of eddy processes in the ACC's meridional circulation is still an area of active research. The further complexity of understanding how the focusing of eddies into narrow jets modifies the local circulation is a topic that has received much less attention.

Some of the most insightful work related to ACC jets has used satellite data to consider how eddies and jets interact. In planetary atmospheres, jets are maintained primarily by eddy forcing on the jet flanks, which acts to accelerate jets to the east. Hughes & Ash (2001) looked for similar behaviour in the ACC, identifying jet positions using gradients in sea surface temperature, but found that eastward acceleration of jets by eddies was less robust. Instead, eddies were found to both accelerate and decelerate jets in localized regions along the path of the ACC. A related study by Williams *et al.* (2007) attempted to document similarities between atmospheric storms and bands of high eddy activity in the ocean. The authors concluded that the ocean, and especially the ACC, does indeed exhibit storm track characteristics. In particular, where these jets, or storm tracks, form, eddies accelerate the jets eastward. As eddies weaken and decay, though, the eddy forcing may reverse sign and decelerate an individual jet. This mechanism likely contributes to the fragmented structure of ACC jets.

The process of jet formation and decay also suggests that eddy fluxes will have important spatial variations along the path of the ACC, which marks a departure from circumpolar-averaged models of the ACC's meridional circulation. It remains to be determined whether spatially varying eddy transport makes a significant difference in modelling the climate system. However, it is not inconceivable that local regions may either dominate the total meridional exchange across the ACC, or in some way influence eddy processes further downstream. What is perhaps clearer is that spatial variability of this type will almost certainly result from topographical effects. An example suggested by Williams *et al.* (2007) is that local variability in eddy kinetic energy may provide the necessary forcing that allows jets to accelerate and manoeuvre around or through topographical features. In turn, the structure of these jets sustains the eddy field. The coupling between topography and *local* eddy fluxes will be an important issue to resolve in attaining a complete description of ACC dynamics.

Observational insight into jet and eddy behaviour in the ACC has been almost exclusively obtained from satellite-derived data of sea surface properties. Thus, the vertical structure of eddy processes in the ACC is largely unknown. In general, jets can exhibit both 'barrier' (weak cross-jet exchange) and 'blender' (enhanced cross-jet exchange) characteristics, with a transition between the two occurring abruptly in the vertical (Greenslade & Haynes 2008). A similar transition in the ACC at a depth of roughly 1000 m (in a spatially and temporally averaged sense) has been proposed by Smith & Marshall (in press) based on numerical simulations. This depth is thought to be set by the position of the steering level, where the current velocity exactly opposes the Rossby wave velocity, and would likely exhibit considerable spatial and temporal variability.

4. The ACC and the global climate

Two features in particular contribute to the ACC's crucial role in the climate system. First, circumpolar flow links the major ocean basins and permits a global overturning circulation that dominates the transport of heat, carbon dioxide and other properties. Second, the ACC's meridional density structure, with its strongly tilted and outcropping isopycnals, influences surface buoyancy fluxes and carbon dioxide uptake while also allowing rapid exchange between surface and mid-depth waters. This second feature is especially sensitive to eddy processes. Climate change is occurring in the Southern Ocean; warming of the upper ocean (Gille 2008) and a weakening of carbon dioxide uptake (Le Quéré *et al.* 2007) are two examples. It is less clear how the complicated balance between wind forcing, baroclinic instability, eddy transport and topographically steered jets determines the sensitivity of different aspects of the ACC to climate variability.

An example of this potentially complex dependence is the ACC's response to changes in wind forcing. As described in §2*b*, eddy saturation theories predict that the strength of the wind stress is positively correlated with eddy kinetic energy. Hogg *et al.* (2008) have shown that increasing wind speed over the ACC leads to warming as the enhanced poleward eddy heat transport dominates the equatorward Ekman transport of cool surface waters. They suggest that observed changes in atmospheric wind forcing during the past 30 years are sufficient to alter the temperature structure in a manner that is equivalent to a 0.5°C warming. This value is comparable with estimates of Southern Ocean warming over the same period as determined from ocean float data (Gille 2002). Thus, further changes in atmospheric forcing may leave the zonal transport of the ACC largely the same, but have important consequences for heat content. An alternative explanation for the observed warming is that the core of the ACC is shifting poleward (Gille 2008), in which case related changes to the ACC's jet structure would need to be explored.

Resolution of a number of outstanding questions will ultimately be necessary to improve the ACC's representation in climate models. A key present complication is that different observational measures of eddy transport or diffusivity produce decidedly different results. Lagrangian data statistics indicate that eddy diffusivity is correlated with eddy kinetic energy, while tracers advected with satellite-derived surface velocities imply a dependence on both eddy kinetic energy and the mean flow. This results in the core of the ACC being, respectively, a maximum or minimum of eddy diffusivity. Variability of eddy transport with depth also remains poorly resolved. Both of these issues would benefit from new observations arising from projects such as the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES), a joint UK/US field programme starting in 2009. The project will use float data, tracer release and microstructure (centimetre scale or smaller) measurements to directly quantify mixing along and across isopycnals. The hope is that these observations will provide well-needed guidance and verification for future theoretical models of the ACC circulation. Finally, a complete survey of the conditions under which the ACC conforms to an eddy saturation regime would be useful. If studies indicate that eddy saturation holds over a wide range of conditions, it will be a priority to develop parametrizations consistent with this regime. While observations will surely provide important insight into this development, improvements in parametrizing local jet and eddy effects will likely remain in the domain of numerical studies for the near future.

I am grateful to Andrew Coward, David Stevens and Sally Thorpe for permission to use their stunning images of Southern Ocean jets. Comments on a preliminary draft from Sarah Gille, Peter Haynes, Alberto Naveira Garabato and two anonymous reviewers are gratefully acknowledged. This work was supported by a NERC Postdoctoral Fellowship.

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AUTHOR PROFILE

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Andrew F. Thompson was born in 1978 and grew up in Rhode Island, USA. He earned a BA in engineering sciences at Dartmouth College in New Hampshire in 2000, after which he spent two years at Trinity College, Cambridge as a Keasbey Memorial Fellow. He completed Part III of the Mathematical Tripos and earned an MPhil in fluid flow, working with Herbert Huppert and Grae Worster in the Department of Applied Mathematics and Theoretical Physics (DAMTP) on an experimental study of solidification and convection. He returned to the USA to take up a National Defence Science and Engineering Graduate fellowship at Scripps Institution of Oceanography at the University of California, San Diego. He was also a Fellow of the Woods Hole Geophysical Fluid Dynamics Summer Program in 2003. Andrew completed his PhD thesis on baroclinic eddy fluxes under the supervision of William Young in 2006. He then returned to the UK to work with Karen Heywood at the University of East Anglia on an observational study of the surface circulation near the Antarctic Peninsula. Andrew began a NERC Postdoctoral Fellowship in DAMTP, Cambridge in 2007; his research focuses on mixing and transport processes in the Southern ocean. He is also a College Research Associate at St. John's College. Outside of work, Andrew enjoys helping his football team prop up the bottom of the Cambridge & District Friendly League and reading books and singing songs with his daughter.