Modelling the Antarctic Circumpolar Current: Eddy-dynamics and their parameterization

Jörg-Olaf Wolff, Antarctic CRC, Hobart, Australia

Abstract The Antarctic Circumpolar Current (ACC) is an important and integral part of the global ocean conveyor belt that connects the major ocean basins. Coarse resolution global climate models therefore need a realistic simulation of the ACC in order to correctly transport anomalies of heat and freshwater or geochemical tracers throughout the world ocean. The intrinsic dynamics of the ACC are dominated by the action and effects of the mesoscale eddy field, which cannot be resolved explicitly in climate models. It is therefore necessary to include the eddy field via parameterization of the subgrid scale effects. In this note we will discuss the sources and sinks of momentum that are involved in the dynamical balance of the ACC, the dominant role the eddy field plays in the momentum and heat balance of the Southern Ocean and give an account of recent attempts to parameterize the effect of the eddy field on the large scale circulation for use in coarse resolution climate models.

1 Introduction

The strongest and mightiest ocean current in the world is the Antarctic Circumpolar Current (ACC), carrying about 130 million cubicmeters per second through its tightest spot, the Drake Passage. The ACC is the longest continuos current with a length of about 20,000 km (half the earth's circumference) and is located in one of the world ocean's most hostile environments, the Southern Ocean. Gale force winds, 8-10 meter waves, sub-zero temperatures and the relative unimportance for commercial shipping lanes or fisheries are responsible for our lack of observations in this area of the world. The interactions of atmosphere, ocean and sea ice in the Southern Ocean (SO) are thought to be extremely important in shaping the world's climate and the World Climate Research Program established the most intensive ocean observing program in mankind's history to collect more information about the global ocean and in particular the Southern Ocean. WOCE, the World Ocean Circulation Experiment, had one of its three components concentrated on the Southern Ocean. The 40 - 50 % of the water masses that constitute the volume of the global ocean are formed here, providing a window to the deep ocean for sequestering carbon dioxide and other greenhouse gases, as well as storing heat and ventilating the ocean with oxygen. The ACC is linked with the other ocean basins to the north through a global conveyor belt and basically is the common agent of interchange between those ocean basins. Any change or disruption in this capacity could hold potentially dramatic changes for the global climate system.

In order to be able to predict any potential changes, be they brought upon by anthropogenic influences, or by the variability of the climate system itself, we need to understand the basic underlying dynamics of the system SO/ACC. For many years the dynamical balance of the ACC has been a mystery to oceanographers and some still argue that it is. The basic, but not simply answered, question is, what are the major forces that control the momentum balance of this mighty current. A starting point for the discussion is, that we believe the system to be in a quasi-steady balance, which means that under undisturbed conditions the current does not accelerate to speeds over the legal limit in this area of the world and on the other hand, does not come to a halt either. So we are looking for a balance between the mechanisms that provide momentum and those that take it away, leaving a balanced mean state behind. This short note is organized as follows. We will first discuss the driving (or momentum) sources and then focus on the potential momentum sinks for the ACC. After having established ("beyond reasonable doubt") that the mesoscale perturbations (or eddies) are responsible for the currently observed balance we will present clues to their overall impact on the system and present a new parameterization, that might be useful in climate models which currently cannot afford to resolve the eddy scales due to computational restrictions.

2 The forcing of the ACC

Two forces are driving the ACC, the exchange of heat and freshwater with the atmosphere, and the stress of the wind on the sea surface.

2.1 Heat and Freshwater Forcing

The thermohaline or buoyancy forcing, as it is sometimes called, is an indirect source of momentum. Through differential changes of the density structure (heating/cooling, evaporation/precipitation and mixing) pressure gradients are created that subsequently change the momentum of water particles in the system. Over 90 % of the ocean's larger scale momentum is trapped in a balance of two major forces, the pressure gradient force and the apparent Coriolis force. For the more or less zonal ACC this means that the meridional density gradient has to be maintained by either buoyancy forcing or wind forcing, or a combination of both. The relative role of these two processes in the momentum balance of the ACC is still much debated. Recent estimates of the relative importance of the wind stress over the buoyancy forcing (Oort et al. 1994, Ivchenko et al. 1997a) point to the dominance of the wind forcing, although Ivchenko et al. (1997a) argue that more precise estimates of air-sea fluxes in the Southern Ocean are necessary to confirm this view.

2.2 Wind Stress

The time mean zonal wind, the strongest on the globe, provides the ACC with a continuous source of eastward momentum through surface exchange of momentum. The exact mechanism and the magnitude of the net vertical momentum transfer are still not well understood. Especially the role of surface gravity waves in the vertical transfer of momentum from air to ocean, which is traditionally ignored in numerical models of the global coupled climate system (with very few exceptions), has received renewed attention in recent years (see e.g. Janssen and Viterbo, 1996 and references therein). A major result of these studies has been that the interaction of atmosphere and ocean in terms of the momentum they exchange is not a one-way-street, but has to be considered as a mutually interacting system. This has led to a novel theoretical surface stress formulation that takes implicit account of the surface wave field in the ocean (Bye, 1995,1996, Bye and Wolff, 1997, Wolff and Bye, 1996, 1997). Even though the exact details of air-sea momentum exchange are still not fully understood, basically because of observational difficulties, it is clear that the wind is a continual source of eastward momentum to the ACC. This continual source, however, does not lead to an ever increasing momentum (or speed) of the current, i.e. there have to be one or more braking mechanisms (or sinks) in the system. Having established the sources of momentum for the ACC we now turn to the sinks.

3 The momentum sinks of the ACC

In the latitude band of the Drake Passage (56° S to 62° S) the ACC flows from west to east around Antarctica uninterrupted by continental land masses. This means that it is impossible to built up net zonal pressure gradients that could balance the wind stress, a mechanism that is mainly responsible for the momentum balance of the currents in the northern hemisphere oceans. A lack of net zonal pressure gradients further implies that there can be no mean north-south geostrophic flow in the upper layers of the ACC and hence no mean north-south transport of heat. This creates an important constraint on the heat balance of the Southern Ocean, which we will discuss in more detail further down. The only possible sinks for eastward momentum are friction (lateral and/or vertical) and pressure gradients in deep layers where the path of the ACC is blocked by submarine ridges. We will now consider these potential sinks in turn.

3.1 Lateral Friction

For lateral friction to be an effective sink of eastward momentum, the momentum has to be transported meridionally away from the core of the ACC by the action of turbulent Reynolds stresses due to the meso- scale eddy field. Momentum that is transported to the south could then be balanced by friction against the Antarctic Continent, or if it is transported to the north it could be balanced by the above mentioned net zonal pressure gradients against the northern continental land masses. Coarse resolution ocean models rely on this type of balance and therefore typically produce a 1000 km wide ACC to accomplish the balance through lateral friction (see Fig. 1).

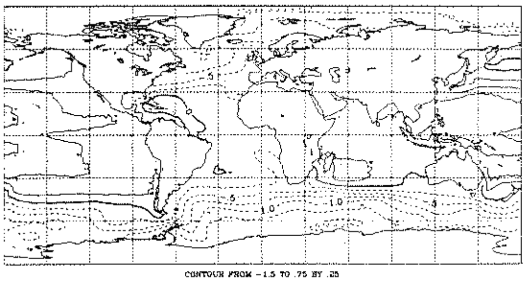

Figure 1: Sea surface elevation of a global coarse resolution model after 10000 years of integration. Contour interval (CI) is 0.25 m.

Models that explicitly resolve the meso-scale eddies on the other hand have demonstrated that the ACC is strengthened by up-gradient momentum transport into the jet center, i.e. momentum is transported into the jet instead of away from it. To include this effect in coarse resolution models, a negative eddy-viscosity would be required, which constitutes a mathematically ill-posed problem and is unconditionally unstable. Furthermore satellite altimetry observations have shown that the divergence of the Reynolds stresses either has the wrong sign, i.e. accelerates the ACC as in the eddy-resolving models, or is much too weak to balance the ACC (Morrow et al. 1994).

3.2 Vertical Friction

For friction at the ocean bottom to be an effective momentum sink, time mean zonal bottom velocities would have to be much larger than observed. These velocities of O(0.5 ms^{-1}) can only be produced by a current with transport values of the order of 1000 Sv (1 Sv=10^6 m^3s^{-1}). Early coarse resolution models over flat topography in the Southern Ocean have indeed had the problem of too high transports (e.g. Hidaka and Tsuchiya 1953). Of course, this is not a problem of the coarse resolution, eddy-resolving models over flat bottom topography show the same behaviour (Wolff et al. 1991).

3.3 Pressure gradients across topography

The last possible momentum sink for the ACC is therefore the capacity of the flow field to adjust into a deep ocean pressure pattern that supports net zonal pressure gradients across the submarine ridges or other prominent topographic features, an idea originally put forward by Munk and Palmén (1951). While this issue remains a topic of active debate (Warren et al. 1996, Hughes 1997, Olbers 1997) recent observational and theoretical work supports this hypothesis. Eddy-resolving models indicate that momentum is transferred downward in the water column to depths where it can be balanced by topographic pressure gradients (McWilliams et al. 1978, Wolff et al. 1991, Killworth and Nanneh 1994, Stevens and Ivchenko 1997). This downward transport of momentum is accomplished by a mechanism very similar to the idea of pressure gradients across topography. The mechanism, called interfacial form stress, describes the work done by horizontal pressure gradients on isopycnal surfaces in the ocean's interior, which effectively accelerates deeper layers of the ocean (Fig. 2). A source off eastward momentum is realized when a higher pressure is located west of an isopycnal bulge, thus vertically transferring eastward momentum. Because this mechanism can act in both ways, to accelerate or decelerate the deeper flow it is more accurately described as a stress instead of a drag. Although at first sight it seems to be a more or less random phenomenon, it is not entirely free to choose its actions. The pressure force against bottom topography, essentially the same mechanism, is therefore called topographic form stress (see Fig. 2). The only difference is that the topography does not react dynamically to the flow, it is constant. So the flow has to arrange a deep ocean pressure pattern of high and low pressure systems, that is out-of-phase with the topography and with the right distribution to be an effective sink for eastward momentum. Fig. 3 shows the zonal mean momentum balance in an eddy-resolving quasi-geostrophic model over realistic topography, indicating the importance of the form stresses and the relative unimportance of the frictional processes.

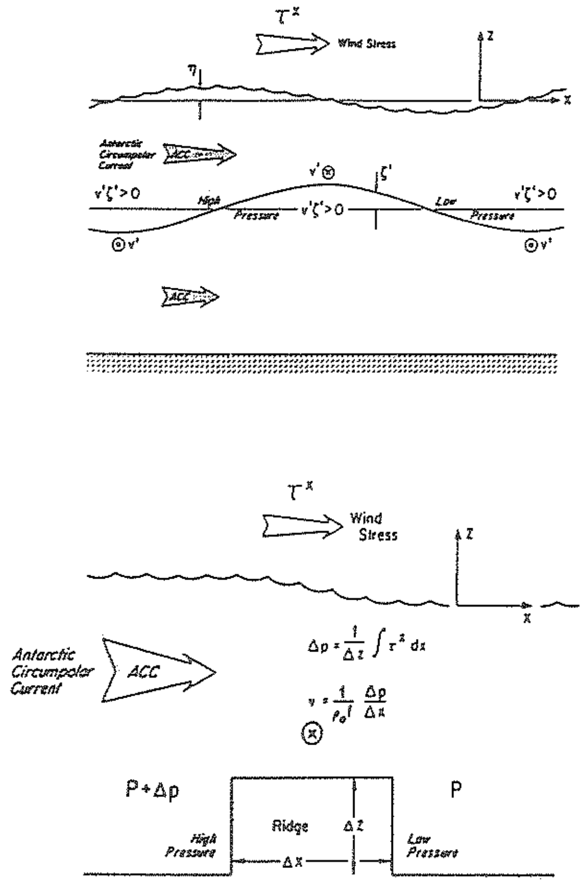

Figure 2: Schematic representation of (top panel) interfacial form stress and (bottom panel) topographic form stress (after Johnson and Bryden, 1989). Eastward momentum imparted by the wind stress can be transported vertically by pressure differences along isopycnal surfaces and be removed from the system by pressure differences across a submarine ridge.

High-resolution models show that the eddies have a peculiar shape, that allows them to concentrate momentum into an eastward flowing jet (not for a westward flowing jet) and that they structure the deep flow so that both form stresses are responsible for balancing over 95 % of the momentum input by the wind stress (Wolff 1990, Wolff et al. 1991, Ivchenko et al. 1997). All this is achieved while producing a mean transport that is close to observations. Unfortunately, these form stress mechanisms are beyond modern measurement technologies (see e.g. Rintoul et al. (1997) for a recent account of observations in the system SO/ACC). Observations can so far only provide circumstantial evidence and the thermal balance of the SO gives a further hint at the dynamical balance at work. The SO loses heat to the atmosphere south of the ACC and as has been stated before there does not exist a meridional poleward mean flow that could provide the necessary heat to keep the SO in a thermal equilibrium. Again the eddies provide the only other mechanism for the needed poleward heat flux. It can be easily shown that under quasi-geostrophic assumptions a vertical momentum flux (as required in the momentum balance of Munk and Palmén) is dynamically equivalent to a poleward heat flux (see e.g. Johnson and Bryden 1989, Wolff 1990). As a result, theoretical arguments and modelling studies indicate that the eddies play an important role in both the heat and momentum balance of the SO/ACC and observational studies, from satellite altimetry and moored instruments show that all along the axis of the ACC we find high variability on mesoscale space and time scales. Given the importance of the eddies in the SO, what can be done to include their effects in the necessarily coarse resolution modern climate models?

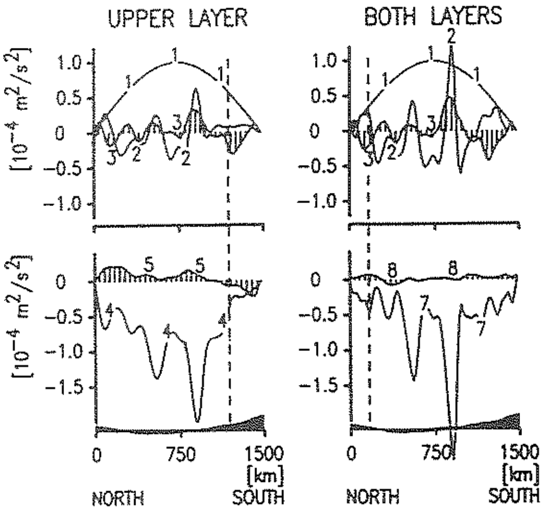

Figure 3: Zonal momentum balance of a two-layer quasigeostrophic model of the ACC over realistic topography. The upper layer balance is shown in the left panel and the vertically integrated (or barotropic) balance is shown in the right panel. The lines indicate: wind stress (1), Reynolds stress divergence from standing (2) and transient (3) eddies, interfacial form stress due to standing (4) and transient (5) eddies, topographic form stress (7) and bottom friction (8). Horizontal explicit momentum diffusion (6) is much smaller than all other terms and has been omitted. (after Wolff et al. 1991).

4 Parameterization of eddy-fluxes in coarse resolution ocean models

Parameterization attempts have a long history with their earliest roots in atmospheric models used for numerical weather forecasting. While the necessity to parameterize eddy-induced transports of active and passive tracers in atmospheric models is no longer required because of increased computer power - even coarse resolution climate models resolve to a large proportion the synoptic weather pattern - this cannot be said for ocean models. In the atmosphere the scale ratio between the global and the synoptic scale is of O(20) over the SO/ACC, whereas in the ocean it is of O(2000). The scales are linked to the Rossby Radius of Deformation and the first internal Rossby Radius is close to 10 km at 60 S in the ocean. Most of the concepts in ocean eddy parameterizations are borrowed from the atmospheric counterpart of eddy-mean flow interaction in mid-latitudes where eddies are generated by baroclinic instability and feed back on the mean zonal circulation (Green 1970, Stone 1972). Based on these earlier theoretical attempts, new concepts are rapidly evolving in oceanographic applications (Gent and McWilliams 1990, Gent et al. 1995, McDougall and McIntosh 1996). These parameterizations are mostly guided by considerations of the transformed Eulerian mean circulation (see e.g. Andrews et al. 1987), where the eddy effects are separated into an eddy-induced mean advection and conservation of properties during eddy-induced mixing, rather than by dealing directly with the processes of eddy generation and eddy-mean flow adjustment (Olbers et al. 1997). Global ocean simulations performed with the parameterizations based on the eddy-induced mean advection and mixing properties have shown substantial improvements in a number of features of the Southern Ocean, e.g. a closer to observed deep ocean density distribution, improved seasonal cycle and depth of the mixed layer and better representation of the penetration depth of chemical tracers originating in the atmosphere (Hirst and McDougall 1996). A systematic comparison of coarse resolution models incorporating these closure schemes with truly eddy-resolving models is needed to assure that these beneficial effects are not due to compensating errors in the models, but due to a correct representation of the eddy effect on the larger scale circulation. In this note we will concentrate on a discussion of parameterization efforts that are based on dynamical considerations, i.e. directly incorporate the processes of eddy generation (flow instabilities) and the dynamics of eddy-mean flow interaction. We focus here on a simpler class of eddy-driven circulations - quasigeostrophic flow in a two-layer channel - where closure schemes have been derived and tested by analysis of the relations between the eddy-induced transports and the mean circulation, using 'data' from eddy-resolving numerical simulations. The work described here is discussed in much greater detail in Ivchenko et al. (1997b), Olbers et al. (1997) and to some degree in an earlier account in Wolff (1990). Here we will just outline the procedures and concepts involved and give some examples. For the mathematical derivation and more detailed aspects the reader is kindly referred to the above mentioned papers. The class of flow we are concerned with here - the quasigeostrophic flow in a two-layer channel - has been intensively studied in atmospheric and oceanographic conditions, both for the investigation of the dynamics of zonal flows (McWilliams et al. 1978, McWilliams and Chow 1980, Treguier and McWilliams 1990, Wolff and Olbers 1989, Wolff et al. 1991) as well as for the investigation of closure schemes (or parameterizations) (Marshall 1981, Ivchenko 1984, Vallis 1988, Larichev and Held 1995, Pavan and Held 1996). The atmospheric applications are mainly studied in a regime of homogeneous turbulence where lateral gradients do not exist, i.e. the lateral Reynolds stresses and the mean flow are uniform. But also the specific forcing implemented in these models – the flow is driven by relaxation to a prescribed homogeneous baroclinic shear flow – prevents a direct transfer of the results to oceanic conditions. In the oceanic experiments the flow is forced by a prescribed stress in the surface layer and a narrow eddy-intensified jet develops in both layers. In contrast to the homogeneous turbulence regime, where the use of diffusive parameterizations of the eddy-induced transport of quasigeostrophic potential vorticity along the concept of Green and Stone works successfully, the wind-driven regime defies such a simple approach. Ivchenko et al. (1997b) studied the quasi-geostrophic dynamics in an eddy-resolving zonal channel for two dynamically distinct situations, east- and westward wind forcing (based on earlier work by Wolff 1990) in order to find a parameterization for the eddy-flux of potential vorticity,

$$\overline{v'q'} = k\frac{\partial \overline{q}}{\partial y} \tag{1}$$

where $\overline{q}$ is the potential vorticity of the mean (or large scale) flow, q' is the eddy potential vorticity, v' the eddy meridional velocity and k is a diffusion coefficient. In the eastward forcing experiment, transient eddies strongly intensified the flow in the channel center into a jet (see Fig. 4), a feature totally absent in the westward forcing case.

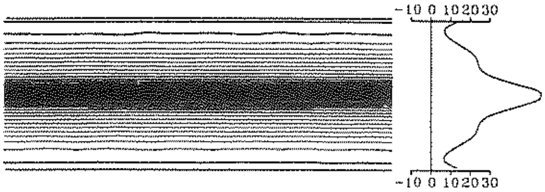

Figure 4: Time mean streamfunction of the westward forcing experiment. Notice the strong jet in the channel center (after Wolff, 1990).

It was recognized that earlier parameterization attempts by Marshall (1981), who related the diffusion coefficients to the vertical shear of the zonal velocity $U = \partial u/\partial z$,

$$k \sim |U|/|U|_{\max} \tag{2}$$

reproduced the structure of the westward forcing case (no jet), but failed to produce the jet in the eastward forcing case. This apparent failure has been interpreted by Ivchenko (1985) as being due to the effect that Marshall's parameterization could only work for weak baroclinic flows, but not for the strong baroclinic flow in the eastward forcing experiment. Ivchenko (1985) using the eddy-potential-enstrophy balance and replacing the eddy transport of potential vorticity with a diffusion ansatz,

$$k \sim U/\left(\frac{\partial \overline{q}}{\partial y}\right)^2 \tag{3}$$

demonstrated that the resulting equation for the diffusion coefficients indeed reflected the necessary meridional distribution needed to concentrate momentum into a jet. Fig. 5 shows the diagnosed diffusion (or transfer) coefficients k_i for both layers ($i = 1, 2$) of the eddy-resolving numerical experiments with east and westward wind forcing. The interesting feature in the eastward flow is the local minimum of the coefficients in the jet center.

This distribution is reflected in Ivchenko's formula (3), through the relative maximum of the gradient in potential vorticity which appears in the denominator. The parameterizations of Marshall and Ivchenko have been generalized into a single formula by Ivchenko (1985)

$$k = \kappa|U|/\left[\epsilon\left(\frac{\partial \overline{q}}{\partial y}\right)^2 + U^2_{\max}\right] \tag{4}$$

with two free parameters κ and ϵ. Wolff (1990), Sinha (1994) and Ivchenko et al. (1997b) have tested this parameterization and found for various situations, that with a suitable choice of parameters it is possible to reproduce the structure of the diffusion coefficients that have been diagnosed from eddy- resolving experiments as those shown in Fig 5. In these attempts the contribution of the relative vorticity has been neglected with the result, that

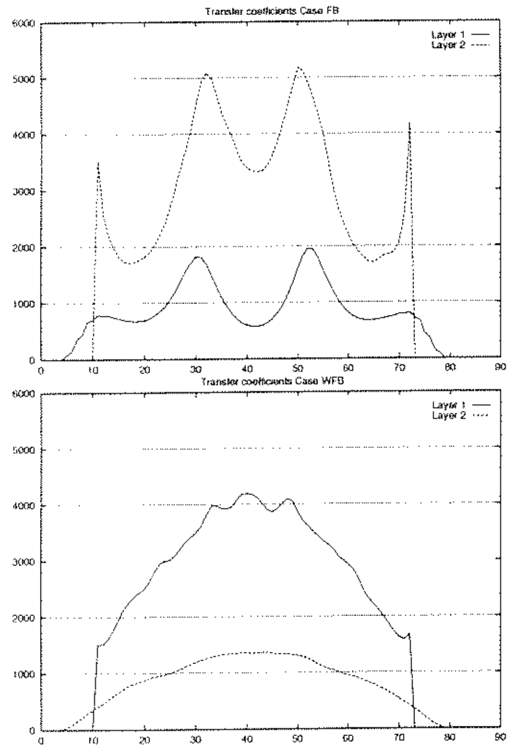

Figure 5: Diffusion coefficients for both layers of the eddy-resolving channel experiments. Units are m^2s^{-2}. Eastward (top panel) and westward (bottom panel) wind stress forcing. The abscissa shows the meridional grid point number from the northern (4) to the southern (79) boundary.

the coarse resolution flow (including the parameterization) exhibited a more or less concentrated jet, but the velocity profile at the jet flanks was not successfully reproduced.

4.1 Second order closure parameteriztion based on the eddy enstrophy balance

As shown in Olbers et al. (1997) these diffusive parameterizations have some merits, but also some severe limitations. On the positive side, the eddy fluxes of QPV are down gradient in these experiments, so that the diffusion coefficients are positive, as diagnosed from the eddy resolving experiments, and they have the desired effect to concentrate momentum into an eastward flowing jet. The limitations are seen in the non-uniqueness of the functional dependence on the vertical shear of the horizontal velocities. So, the vertical shear, as an indication of baroclinic instability, is probably not the only mechanism that needs to be taken into account or is not inclusive enough to be used in a parameterization. Second order quantities of the flow are obviously important. Olbers at al. (1997) used the balance of eddy potential enstrophy (EPE) directly to investigate its usefulness in deriving a parameterization of the eddy flux of potential vorticity. This approach was only made possible through the capability to diagnose the EPE balance from the eddy-resolving experiments. As has been shown by Wolff et al. (1993) a fourth-order numerical representation of the advection operator of potential vorticity is necessary to compute the EPE correctly. The EPE balance consists of three terms, the production of EPE, a redistribution term or triple moment that describes the eddy-induced transport of EPE, and a dissipation of EPE. A parameterization of the eddy-induced transport and dissipation of EPE of the flow has been given by Olbers et al. (1997). The parameterized form of the balance of EPE (in terms of lower order moments of the flow) can then be converted to a constraint which in combination with the requirement of the overall momentum balance of the mean flow is used to find a new closure scheme.

$$\overline{v'q'} = -\Lambda \left[\frac{\partial \overline{q}}{\partial y} - \gamma H \frac{\partial^2 \overline{u}}{\partial y^2} \right] \tag{5}$$

with a diffusivity

$$\Lambda = \delta^* |u| \left[\left(\frac{\partial \overline{q}}{\partial y} \right)^2 + \left(\gamma H \frac{\partial^2 \overline{u}}{\partial y^2} \right)^2 \right]^{-1} \tag{6}$$

where H is a layer depth and δ^* and γ are free parameters. According to this new closure, the eddy flux of potential vorticity possesses in addition to a diffusive transport a non-gradient correction. This latter contribution is a flux which is upgradient with respect to the mean relative vorticity, it appears to be essential in determining the correct meridional shape of the jet. Fig. 6 shows the results of the coarse resolution model for an optimal set of the parameters δ^* and γ.

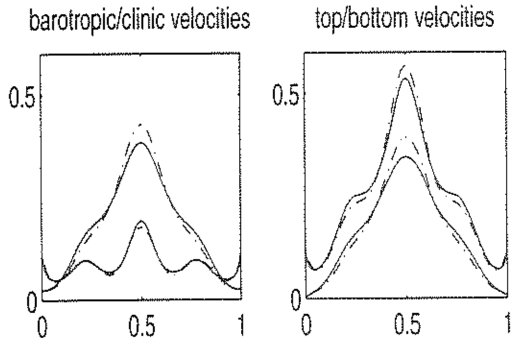

Figure 6: Profiles of velocities in ms^{-1} as simulated by the coarse resolution model with the parameterization (5) for the eastward wind stress experiment. The results of the coarse model (solid lines) are compared with the results of the eddy-resolving simulation (dashed lines). In the left panel the two top curves show the barotropic velocity and the lower two curves the baroclinic velocity. In the right panel the same grouping shows the velocities in the upper and lower layer, respectively.

These correlations of eddy quantities (in particular the dissipation of eddy enstrophy) and mean fields have been substantiated by a new scaling model which relates the shear, the transports and dissipation of the eddy kinetic energy and enstrophy to the basic scale parameters. Here the most important are the scale of the barotropic velocity and the integral time scale of the correlation function of the eddy velocity (Olbers et al., 1997).

5 Summary

The Antarctic Circumpolar Current is the longest ocean current in the world, but its dynamics are controlled to a high degree by small scale perturbations of the mean flow, the mesoscale eddies. Produced by flow instabilities, most noteably the baroclinic or shear flow instability mechanism, the eddies structure the internal pressure field in the Southern Ocean in a way that allows a unique momentum balance not found in the northern hemisphere ocean basins and for that matter in coarse resolution ocean/climate models. Given the need for more accurate climate predictions and the importance of the Southern Ocean in the climate system, the need for a more comprehensive inclusion of the effects of the oceanic eddies in climate models is obvious. New sub-grid-scale parameterizations of the eddy field in the ocean are rapidly evolving but need to be thoroughly tested before better simulations of the Southern Ocean can be confidently used for climate change assessments. A promising new parameterization is discussed in this short note, that has shown dramatic improvements in simple (more theoretical) flow situations, but needs considerably more work before it can be implemented into standard coarse resolution ocean/climate models.

6 References

Andrews, D. G., J. R. Holton and C. B. Leovy, *Middle atmosphere dynamics*, Academic Press, 1987.

Bye, J. A. T., Inertial coupling of fluids with large density contrast, *Phys. Lett. A*, 202, 222-224, 1995.

Bye, J. A. T., Coupling ocean-atmosphere models. *Earth-Science Rev.*, 40, 149-162, 1996.

Bye, J. A. T., and J.-O. Wolff, On atmosphere-ocean momentum exchange in general circulation models, submitted, 1997.

Gent, P. R., and J. C. McWilliams, Isopycnal mixing in ocean circulation models, *J. Phys. Oceanogr.*, 20, 150-155, 1990.

Gent, P. R., J. Willebrand, T. J. McDougall and J. C. McWilliams, Parameterizing eddy-induced tracer transports in ocean circulation models, *J. Phys. Oceanogr.*, 25, 463-474, 1995.

Green, J. S. A., Transfer properties of the large-scale eddies and the general circulation of the atmosphere, *Quart. J. Roy. Met. Soc.*, 96, 157- 185, 1970.

Hidaka, K., and M. Tsuchiya, On the Antarctic Circumpolar Current, *J. Mar. Res.*, 12, 214-222, 1953.

Hirst, A. C., and T. J. McDougall, Deep water properties and surface buoyancy flux as simulated by a z-coordinate model including eddy-induced advection, *J. Phys. Oceanogr.*, 26, 1320-1343, 1996.

Hughes, C. W., Comments on "On the obscurantist physics of 'form drag' in theorizing about the circumpolar current", *J. Phys. Oceanogr.*, 27, 209-210, 1997.

Ivchenko, V. O., On the parameterization of the eddy fluxes of quasigeostrophic potential vorticity in zonal currents, *Dokl. Acad. Sci. SSSR*, 277(4), 972-976, 1984.

Ivchenko, V. O., Parameterization of eddy momentum exchange in zonal flows, *Morskoi Gidrofizicheskii Zhurnal*, 5, 47-52, 1985.

Ivchenko, V. O., A. M. Treguier and S. E. Best, A kinetic energy budget and internal instabilities in the Fine Resolution Antarctic Model, *J. Phys. Oceanogr.*, 27, 5-22, 1997a.

Ivchenko, V. O., K. J. Richards, B. Sinha and J.-O. Wolff, Parameterization of eddy fluxes in zonal flow of the ocean, *J. Mar. Res.*, accepted, 1997b.

Janssen, P. A. E. M. and P. Viterbo, Ocean waves and the atmospheric climate, *J. Climate*, 9, 1269-1287, 1996.

Johnson, G. C. and H. L. Bryden, On the size of the Antarctic Circumpolar Current, *Deep-Sea Res.*, 36, 39-53, 1989.

Killworth, P. D. and M. M. Nanneh, Isopycnal momentum budget of the Antarctic Circumpolar Current in the Fine Resolution Antarctic Model, *J. Phys. Oceanogr.*, 24, 1201-1223, 1994.

Larichev, V. D. and I. M. Held, Eddy amplitudes and fluxes in a homogeneous model of fully developed baroclinic instability, *J. Phys. Oceanogr.*, 25, 2285-2297, 1995.

Marshall, J. C., On the parameterization of geostrophic eddies in the ocean, *J. Phys. Oceanogr.*, 11, 257-271, 1981

McDougall, T. J. and P. C. McIntosh, The temporal-residual-mean velocity. Part I: Derivation and the scalar conservation equations, *J. Phys. Oceanogr.*, 26, 2653-2665, 1996.

McWilliams, J. C. and J. H. S. Chow, Equilibrium geostrophic turbulence. I. A reference solution in a beta-plane channel, *J. Phys. Oceanogr.*, 11, 921-949, 1981.

McWilliams, J. C., W. R. Holland and J. H. S. Chow, A description of numerical Ant-arctic Circumpolar Currents, *Dyn. Atmos. Oceans*, 2, 213-291, 1978.

Morrow, R., R. Coleman, J. Church and D. Chelton, Surface eddy momentum flux and velocity variances in the Southern Ocean from Geosat altimetry, *J. Phys. Oceanogr.*, 24, 2050-2071, 1994.

Munk, W. H. and E. Palmén, Note on the dynamics of the Antarctic Circumpolar Current, *Tellus*, 3, 53-55, 1951.

Olbers, D. J., Comments on "On the obscurantist physics of 'form drag' in theorizing about the circumpolar current", submitted, 1997.

Olbers, D. J., J.-O. Wolff, V. O. Ivchenko and C. Völker, Eddy-flux parameterizations of wind-driven quasigeostrophic zonal flows, submitted, 1997.

Oort, A. H., L. A. Anderson and J. P. Peixoto, Estimates of the energy cycle of the oceans, *J. Geophys. Res.*, 94, 3187-3200.

Pavan, V. and I. M. Held, The diffusive approximation of eddy fluxes in baroclinically unstable jets, *J. Atmos. Sci.*, 53, 1262-1272, 1996.

Sinha, B., The influence of meso-scale eddies and topography on Southern Ocean flow, Ph.D. thesis, University of Southampton, UK, 1994.

Stevens, D.P., and V.O. Ivchenko, The zonal momentum balance in an eddy-resolving general-circulation model of the Southern Ocean, *Quart. J. Roy. Meteor. Soc.*, 123, 929-951, 1997.

Stone, P. H., A simplified radiative-dynamical model for the static stability of rotating atmospheres, *J. Atmos. Sci.*, 29, 405-418, 1972.

Treguier, A. M. and J. C. McWilliams, Topographic influences on wind-driven, stratified flow in a $\beta-$plane channel: an idealized model for the Antarctic Circumpolar Current, *J. Phys. Oceanogr.*, 20, 321-343, 1990.

Vallis, G. K., Numerical studies of eddy transport properties in eddy-resolving and parameterized models, *J. R. Meteorol. Soc.*, 114, 183-204, 1988.

Warren, B. A., J. H. LaCase and P. E. Robbins, On the obscurantist physics of 'form drag' in theorizing about the circumpolar current. *J. Phys. Oceanogr.*, 26, 2297-2301, 1996.

Wolff, J.-O., Zur Dynamik des Antarktischen Zirkumpolarstromes. Ph.D. thesis, Max-Planck-Institut für Meteorologie, 137 pp., Hamburg, Germany, 1990.

Wolff, J.-O., and J. A. T. Bye, Inertial surface stress coupling in a two-layer quasi-geostrophic channel model. *Ocean Modelling*, 112, 6-8, 1996.

Wolff, J.-O., and J. A. T. Bye, Drift patterns in an Antarctic channel from a quasi-geostrophic model with surface friction, *Annals of Glaciology*, in press, 1997.

Wolff, J.-O., A. V. Klepikov and D. J. Olbers, On the eddy-enstrophy balance in a two-layer quasi-geostrophic channel model, *Ocean Modelling*, 101, 12pp., 1993.

Wolff, J.-O., E. Maier-Reimer and D. J. Olbers, Wind-driven flow over topography in a zonal $\beta-$plane channel: A quasigeostrophic model of the Antarctic Circumpolar Current, *J. Phys. Oceanogr.*, 21, 236-264, 1991.

Wolff, J.-O., and D. J. Olbers, The dynamical balance of the Antarctic Circumpolar Current studied with an eddy-resolving quasi-geostrophic model, in *Mesoscale/Synoptic Coherent Structures in Geophysical Turbulence*, Elsevier Science Publ., 435-458, 1989.