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Gill's model of the Antarctic Circumpolar Current, revisited: The role of latitudinal variations in wind stress

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A B S T R A C T

Gill's (1968) model of the Antarctic Circumpolar Current (ACC) is reinterpreted for a stratified, reduced-gravity ocean, where the barotropic streamfunction is replaced by the pycnocline depth, and the bottom drag coefficient by the Gent and McWilliams eddy diffusivity. The resultant model gives a simple description of the lateral structure of the ACC that is consistent with contemporary descriptions of ACC dynamics. The model is used to investigate and interpret the sensitivity of the ACC to the latitudinal profile of the surface wind stress. A substantial ACC remains when the wind jet is shifted north of the model Drake Passage, even by several thousand kilometers. The integral of the wind stress over the circumpolar streamlines is found to be a useful predictor of the magnitude of the volume transport through the model Drake Passage, although it is necessary to correct for basin-wide zonal pressure gradients in order to obtain good quantitative agreement.

1. Introduction

The Antarctic Circumpolar Current (ACC) is the only current to circumnavigate the globe, with a thermal wind volume transport through Drake Passage of 137 ± 7 Sv ($1\,\mathrm{Sv} \equiv 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$), relative to the sea floor (Meredith et al., 2011). The ACC plays a pivotal role in setting the global ocean stratification, heat content and overturning circulation (e.g., Gnanadesikan and Hallberg, 2000; Vallis, 2000), and may also set the time scale on which the ocean equilibrates to changes in forcing (Allison et al., 2011; Jones et al., 2011; Samelson, 2011). Moreover, it has been proposed that changes in the strength and latitude of the Southern hemisphere wind jet, due to its impact on the circulation along and across the ACC, may have a profound influence both on past climate variations (e.g., Toggweiler et al., 2006) and anthropogenic climate change in the future (e.g., Fyfe et al., 2007; Le Quéré et al., 2007)

Despite its global climatic importance, there is no consensus on the dynamical processes that set the volume transport of the ACC and its lateral structure, i.e., its meridional excursions with longitude, even in simple models. The traditional, textbook view is that the ACC is driven locally by wind and buoyancy forcing, with geostrophic eddies playing a central role in the equilibrated state (for excellent reviews, see Rintoul et al., 2001; Olbers et al., 2012), although more recent developments have challenged this purely local perspective (e.g., Gnanadesikan and Hallberg, 2000; Fučkar and Vallis, 2007; Munday et al., 2011). Diagnostic studies with climate models find no clear relation between the volume transport of the ACC and the strength and latitude of the Southern Ocean wind jet (e.g., Russell et al., 2006).

Gill (1968) published a seminal paper in which he solved analytically and numerically for the barotropic circulation in an idealized basin with circumpolar connection over a restricted latitude band. One of his key objectives was to reconcile zonally-symmetric models of the ACC, in which the volume transport is excessively large, with basin models of the ACC in which the flow consists of a Sverdrup interior and a frictional western boundary current (Stommel, 1957). Key findings were that the volume transport is controlled by the bottom friction and the width of the narrowest constriction in Drake Passage, although the current spreads out to several times this width at other longitudes. However, Gill's model has limited applicability due to its assumption of barotropic dynamics, its excessively large volume transport, and the dependence of the latter on the coefficient of bottom friction.

A key ingredient of contemporary models of the ACC is the intense geostrophic eddy field. In the simplest, zonally-symmetric models, as first developed by Johnson and Bryden (1989), the ACC volume

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transport is determined through the zonal momentum budget under so called "non-acceleration conditions". Due to the absence of continental barriers at the latitude of Drake Passage, the surface wind stress is mostly balanced by a bottom form stress (Munk and Palmén, 1951). Thus, momentum must be fluxed vertically from the surface to the abyss, which Johnson and Bryden assume is achieved by the eddy form stress. An alternative, but equivalent, physical interpretation is that the equilibrium ACC arises through the competition between the wind-driven Ekman cell (the "Deacon cell") acting to steepen, and the eddy-induced cell generated through baroclinic instability acting to flatten, the isopcynals (e.g., see Danabasoglu et al., 1994). Finally a prediction of the ACC volume transport follows on adopting a closure for the eddy buoyancy fluxes following Green (1970) and Stone (1972), and assuming thermal wind balance and vanishing flow at depth.

However, the ACC is not zonal, but undergoes significant meridional excursions, which are of dynamical importance because the majority of the wind work on the Southern Ocean occurs north of Drake Passage (e.g., see Fig. 14 of Mazloff et al., 2010). Understanding the cause of these meridional excursions is important as several studies have suggested that the integral of the wind stress over the circumpolar streamlines of the ACC may serve as a useful predictor of its volume transport (e.g., Ishida, 1994; Allison et al., 2010; LaCasce and Isachsen, 2010). The traditional explanation for these northward excursions is Sverdrup balance (Sverdrup, 1947; Stommel, 1957; LaCasce and Isachsen, 2010). However, if the Ekman driven upwelling is compensated by eddy-induced downwelling, then, at least for that part of the fluid column with circumpolar connection, Sverdrup balance should be modified to include the effect of the eddy-induced downwelling. Intricate interplays between the Sverdrup-like excursions and eddy dynamics are documented in the series of papers by Nadeau and Straub (2009; 2012) and Nadeau and Ferrari (2015).

Recent developments have included the recognition that the ACC cannot be considered independent of the depth of the global pycnocline and the meridional overturning circulation (Gnanadesikan, 1999; Gnanadesikan and Hallberg, 2000). The implication is that the ACC volume transport is influenced not only by Southern Ocean wind forcing and eddies, but also the rate of North Atlantic Deep Water formation (Fučkar and Vallis, 2007), buoyancy forcing (Hogg, 2010) and global diapycnal mixing (Munday et al., 2011).

Finally, it is important to emphasize that the ACC volume transport exhibits far less sensitivity to the surface wind stress in models with explicit, rather than parameterized, eddies, both in equilibrium (Hallberg and Gnanadesikan, 2001; Tansley and Marshall, 2001b; Munday et al., 2013) and during its adjustment (Hallberg and Gnanadesikan, 2006; Hogg and Blundell, 2006; Meredith and Hogg, 2006; Farneti et al., 2010; Farneti and Delworth, 2010). This behavior was first predicted by Straub (1993) on theoretical grounds and has become known as "eddy saturation". Notwithstanding the importance of explicitly resolving eddies, it is important to understand the dynamics of the ACC in models with parameterized eddies, not least because such parameterizations will continue to be used in many climate models for the foreseeable future. Moreover, we have little chance of understanding the dynamics of the ACC with explicit, turbulent eddies if we cannot first understand the dynamics of a quasi-laminar ACC in a model with parameterized eddies.

The goal of this contribution is to develop a simple reduced-gravity model of the ACC that can be used to address three complementary questions:

- How does the volume transport of the ACC vary as the latitude of wind stress forcing is varied?
- Which dynamical processes control the equatorward and poleward excursions of the ACC?
- Can the volume transport of the ACC be predicted from the surface wind stress and model parameters?

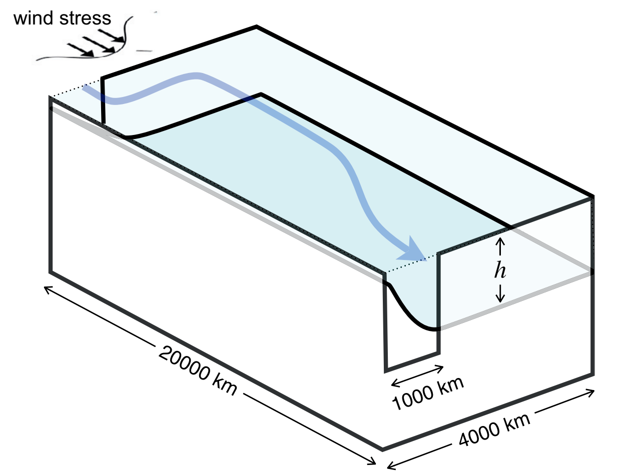

Fig. 1. Schematic diagram illustrating the model formulation and domain. Flow is confined to a reduced-gravity layer (shaded) overlaying a motionless abyss. The two layers are separated by a "pycnocline" of depth *h*, across which the density increases abruptly. The upper layer is forced by a prescribed surface wind stress. A re-entrant channel occupies the most southerly quarter of the domain. The model dimensions are indicated on the figure.

The advantage of using a reduced-gravity model is that it is the simplest model that can represent each of the most important elements one might wish to include in a simple theory of the ACC: (i) wind forcing; (ii) basin geometry with partial circumpolar connection; (iii) stratification; (iv) (parameterized) geostrophic eddy fluxes; (v) surface cooling (through imposed layer outcropping). Inevitably, a simple model cannot capture every important process and perhaps the most important processes missing from the present model are explicit geostrophic eddies, variable bottom topography and a realistic representation of buoyancy forcing; some likely impacts of these neglected processes are outlined in the concluding discussion.

The model developed here turns out to bear many similarities to the linear barotropic model derived by Gill (1968), with differences arising through nonlinearity in our equations, boundary conditions, and physical interpretations of model parameters. Thus, a parallel goal of this contribution is to cast Gill (1968) in the language of contemporary descriptions of the ACC dynamics and thereby restore it to the center-stage of theoretical understanding of the ACC.

The manuscript is structured as follows. In Section 2 we describe the formulation of our model and its relation to Gill (1968). In Section 3, the suites of model calculations are summarized. In Section 4, we describe the lateral structure of a typical model solution and its physical interpretation. In Section 5 we investigate how the structure of the solution varies as the wind jet is moved northward. In Section 6 we investigate the extent to which the volume transport through the model Drake Passage can be predicted by integrating the wind stress over the circumpolar streamlines following the suggestion of Allison et al. (2010). Finally, a concluding discussion is given in Section 7.

2. Model formulation

2.1. Equations of motion

We consider a reduced-gravity model of the Antarctic Circumpolar Current, forced by surface wind stress. For analytical convenience, we work with a Cartesian coordinate system (x, y) on the β plane where x and y are the zonal and meridional coordinates. The domain extends from $(0, 0)$ to (x_0, y_0), with a re-entrant "Drake Passage" between $y = 0$ and $y = y_0/4$. We set $x_0 = 20\,000$ km and $y_0 = 4\,000$ km, giving a model Drake Passage of width 1 000 km, as sketched in Fig. 1. The lower, abyssal layer is considered at rest, but plays an important