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A numerical study of cross-equatorial abyssal ocean currents with a complete representation of the Coriolis force

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Ocean currents that flow close to and across the equator present a challenging dynamical problem. These currents form an important part of the circulation in the world ocean, yet our understanding of them remains limited. For example, the Antarctic Bottom Water (AABW) crosses the equator northward in the western Atlantic off the coast of Brazil. The AABW thus forms part of the Atlantic Meridional Overturning Circulation (AMOC), predictions for which vary substantially even in the most recent report of the Intergovernmental Panel on Climate Change (IPCC). We investigate the behaviour of currents flowing through cross-equatorial abyssal channels using a set of shallow water equations that include a complete representation of the Coriolis force. These equations thus account for the locally horizontal component of the Earth's rotation vector, which is commonly neglected in models of the ocean under the so-called "traditional approximation". However, weak stratification and almost-horizontal alignment of the rotation vector combine to maximise non-traditional effects in the abyssal equatorial ocean.

The movement of fluid across the equator is strongly constrained by the conservation of potential vorticity (PV) following fluid parcels. A parcel that crosses between hemispheres experiences a change in sign of the Coriolis parameter f. To conserve its PV, the parcel must therefore acquire a large relative vorticity to compensate for the change in f. Cross-equatorial currents therefore tend to generate eddies, and to retroflect back across the equator. In reality, the PV may be modified by dissipative processes, thereby permitting some form of cross-equatorial flow.

The conserved potential vorticity acquires a further contribution from the non-traditional component of the Coriolis force, proportional to the meridional gradient of the bottom topography. This partially balances the change in f for a current, such as the AABW, that crosses the equator through an almost zonal channel. The fracture zone off the coast of Brazil provides a suitable channel for the AABW. Non-traditional effects should thus enhance cross-equatorial flow, since the fluid need not acquire as much relative vorticity as it otherwise would need. More intuitively, fluid crossing a zonal equatorial channel undergoes a smaller change in its distance from the axis of rotation, and is therefore subject to a smaller change in planetary angular momentum as it crosses the equator.

We analyse the cross-equatorial flow problem using numerical integration of our shallow water equations with complete Coriolis force in an idealised steep-sided channel, and in realistic equatorial bathymetry based on ETOPO1 data. Our scheme is a generalisation of the Arakawa–Lamb (1981) scheme that exactly conserves total mass, energy, and potential enstrophy in the absence of explicit dissipation. However, we include an explicit second-order dissipation to represent the effect of sub-gridscale eddies.

A substantial portion of a northward-flowing current retroflects as it crosses the equator, and exits back into the southern hemisphere. Including the complete Coriolis force increases the cross-equatorial transport, particularly in the case of weak dissipation, when the portion of the current that enters the northern hemisphere does so as a series of eddies. Fourier analysis of the time series for the channel exit flux shows that qualitative features of the behaviour, such as the eddy timescale and the peak outflow, are also substantially modified. Numerical integrations in the realistic equatorial bathymetry yield qualitatively similar results to the idealised channels, but the paths of the currents entering and exiting the actual channel are strongly steered by the bathymetric contours.