

Results from FRAM

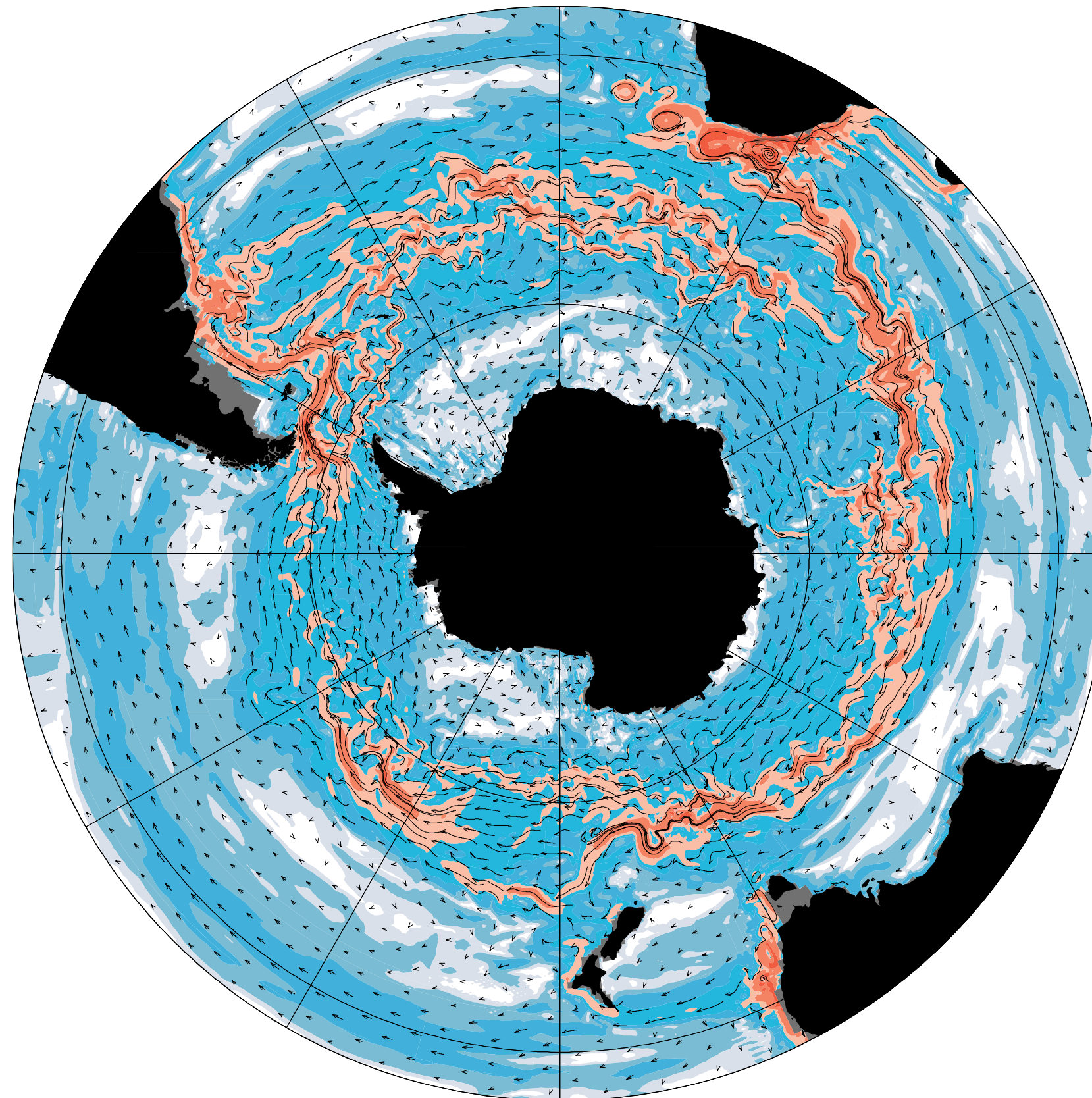
The Fine Resolution Antarctic Model

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The FRAM Model

The Fine Resolution Antarctic Model was developed as part of a UK Natural Environment Research Council Community Research Programme and was the first high resolution model covering the Southern Ocean.

The ocean model is based on the Cox code and uses a rigid lid. It has a resolution of 1/4 degree in the north-south direction and 1/2 degree in the east-west direction. There are 32 levels in the vertical ranging in thickness from 20 m at the surface to 250 m at a depth of 5500 m. Topography was taken from the US Navy DBDB5 data set. The model was spun up using the Levitus mean annual climatology and ran for 20 model years driven by seasonal Hellerman and Rosenstein winds with seasonal relaxation of the surface layer to monthly Levitus (1972) climatology to represent the surface heat and fresh water fluxes. (The FRAM Group (Webb, D.J. et al). 1991: EOS, Trans. Am. Geophys. Union, 72, 15, 169-174).



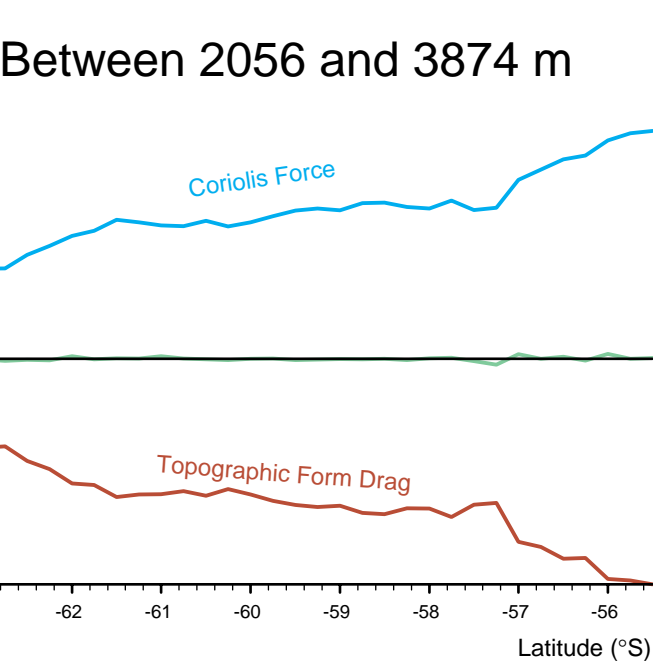
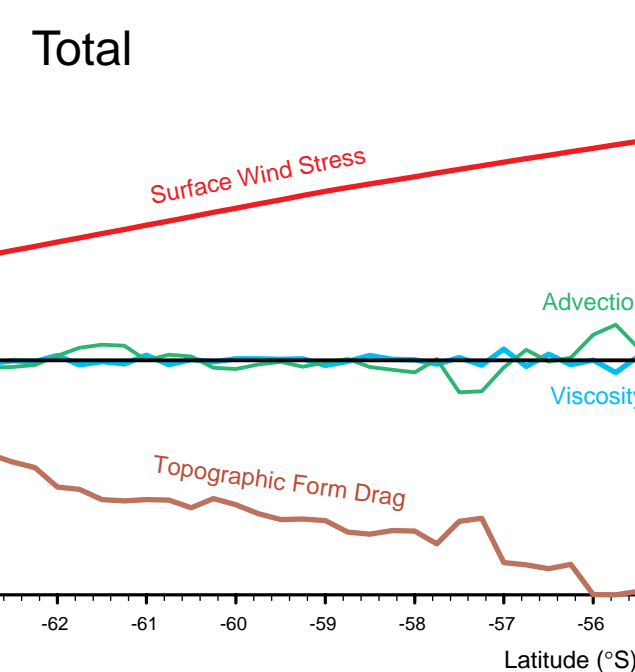
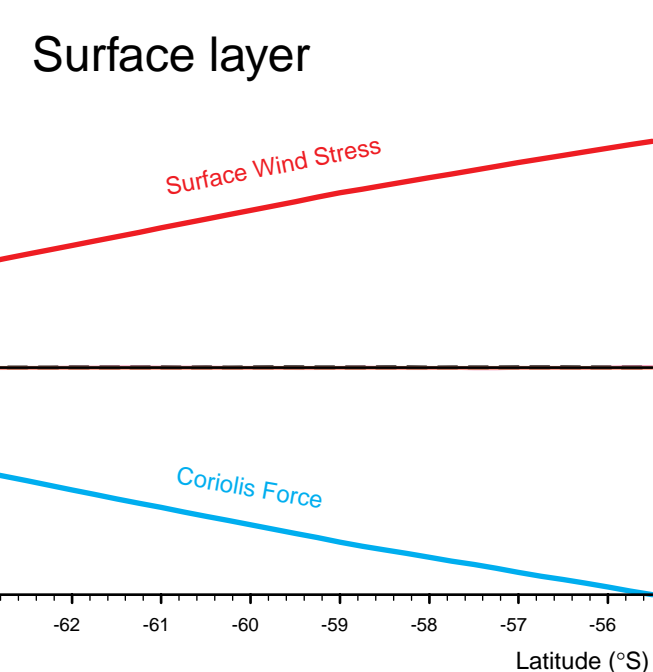
The Large Scale Circulation

The figure, taken from the FRAM Atlas, shows simulated particle paths over a 50 day period at a depth of 125m and after six years of the model run. Colour coding denotes speed with colour changes at 0.5, 1.0 (blue), 2.0, 5.0, 10.0, 20.0 (orange) and 50.0 cm/s.

The FRAM model showed that the Antarctic Circumpolar Current (ACC) had a braided structure with many boundary currents and jets controlled the bottom topography. Note particularly the strongly barotropic boundary currents along the north of Drake Passage, feeding the Falkland Current; to the north and east of the Kerguelen Plateau and to the south and west of the Campbell Plateau off New Zealand. Note also the narrow jets through the mid-ocean ridge fracture zones in the South Pacific and the northward displacement of the current as it crosses the mid-ocean ridge in the Atlantic.

Further north the model shows the Agulhas Current spawning eddies which carry warm salty water northeastwards into the Atlantic. Eddies are also generated by the East Australian Current which is seen to turn eastwards to round the North Island of New Zealand. (Webb et al., 1991: The FRAM Atlas of the Southern Ocean, Natural Environment Research Council, Swindon, UK, 67 pp).

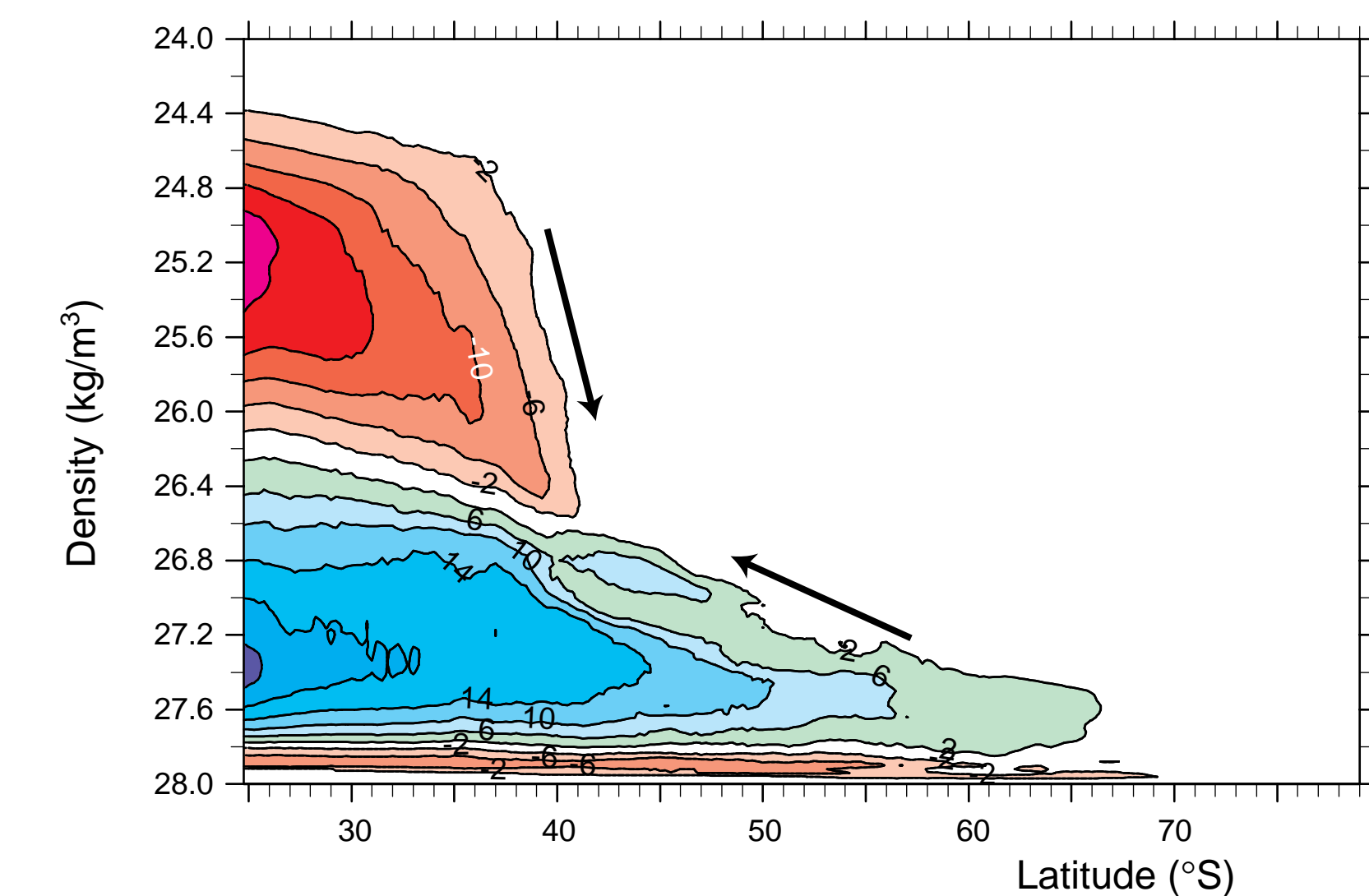
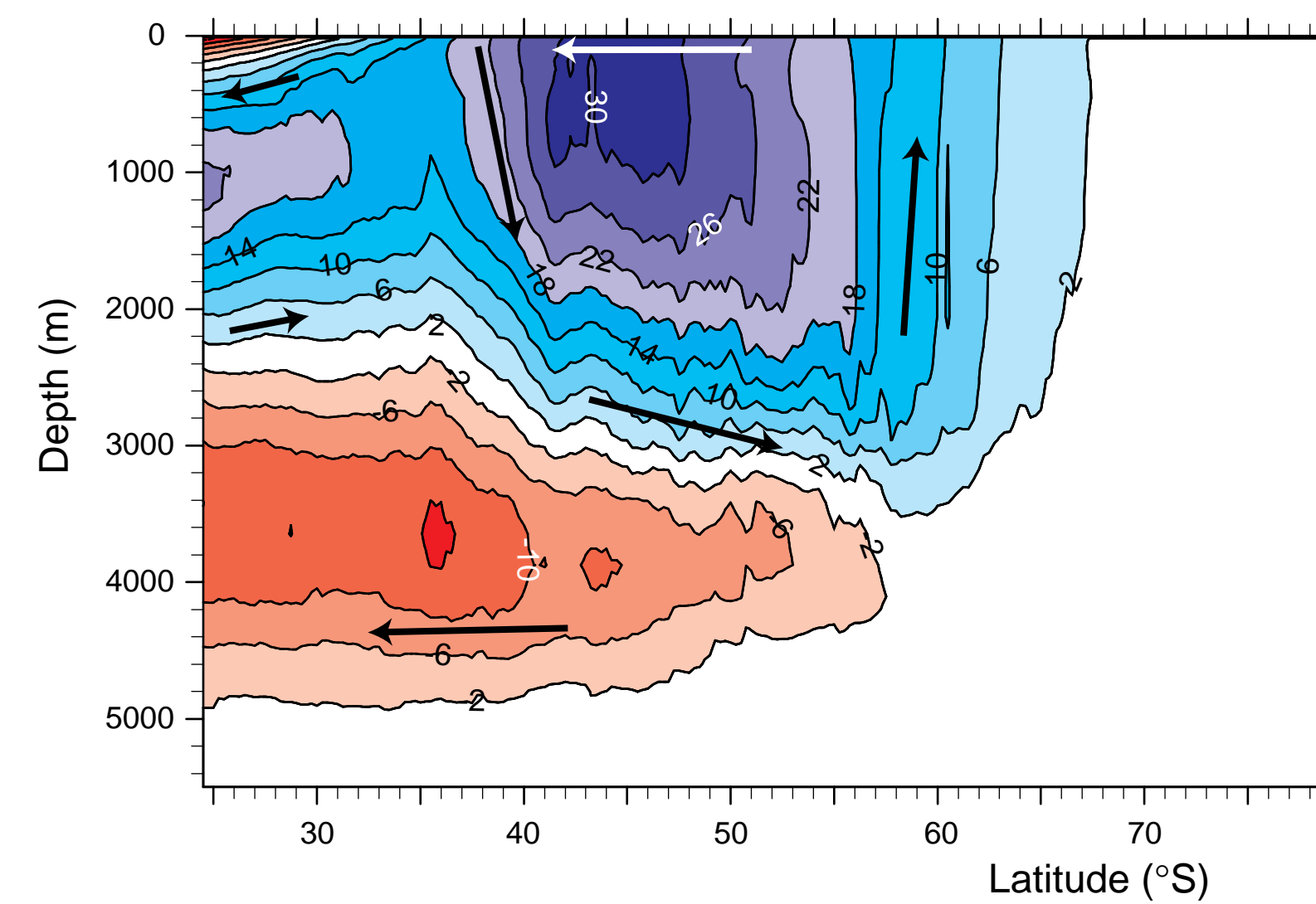
Momentum and Angular Momentum



Between 56°S and 63°S the Southern Ocean has no zonal barriers so the torque due to the east-west wind stress cannot be balanced by a net surface pressure gradient as occurs at other latitudes. FRAM confirmed the earlier suggestion of Munk and Palmén that the torque is balanced by the northwards flow in the surface Ekman layer. There is a net return flow at depth, (see the Deacon Cell figures), the associated Coriolis force being balanced by east-west pressure differences acting across the abyssal topography.

Non-linearities, viscosity and meso-scale eddies have a small effect but in practical terms their effect on the downward flux of angular momentum is negligible. (Stevens et al. 1997: Q.J.R. Meteorological Soc., 123, 929-951)

The Deacon Cell



The left figure shows the overturning stream function when plotted on depth levels. At the surface it shows the Ekman layer with a northward transport of over 30 Sv near 45°S. Below this, at depths near 2000 m, North Atlantic Deep Water flows south, eventually upwelling south of the ACC. Lower still, near 4500 m, Antarctic Bottom Water flows northwards. The Deacon Cell is the 12 Sv which appears to sink from the surface to 1600 m near 40°S and return to the surface near 55°S. Because of the large change in density that it requires, such a flow is physically unrealistic.

The right figure shows the stream function when plotted relative to potential density (σ_θ). This shows no Deacon Cell. Further study confirmed that the Deacon Cell is an artifact of averaging on depth levels. As the ACC meanders around the Southern Ocean, passing to the south of Cape Horn and to the north of Kerguelen, water between the surface and 200m flows southwards at a depth which is about 50 m greater than when it flows northwards. This vertical motion helps to transfer the wind's torque down to depths where it can be balanced by pressure differences across topography. (Döös & Webb, 1994: JPO, 24, 429-442)

Note also the North Atlantic Deep Water entering with a density of 27.8. On reaching the surface near 60°S, it flows northwards becoming less dense due to the surface input of fresh water and heat. It eventually sinks near 40°S as intermediate water with a density of 26.4. In the OCCAM model this is shown to be a major part of the global thermohaline circulation.

The ACC Vorticity Budget

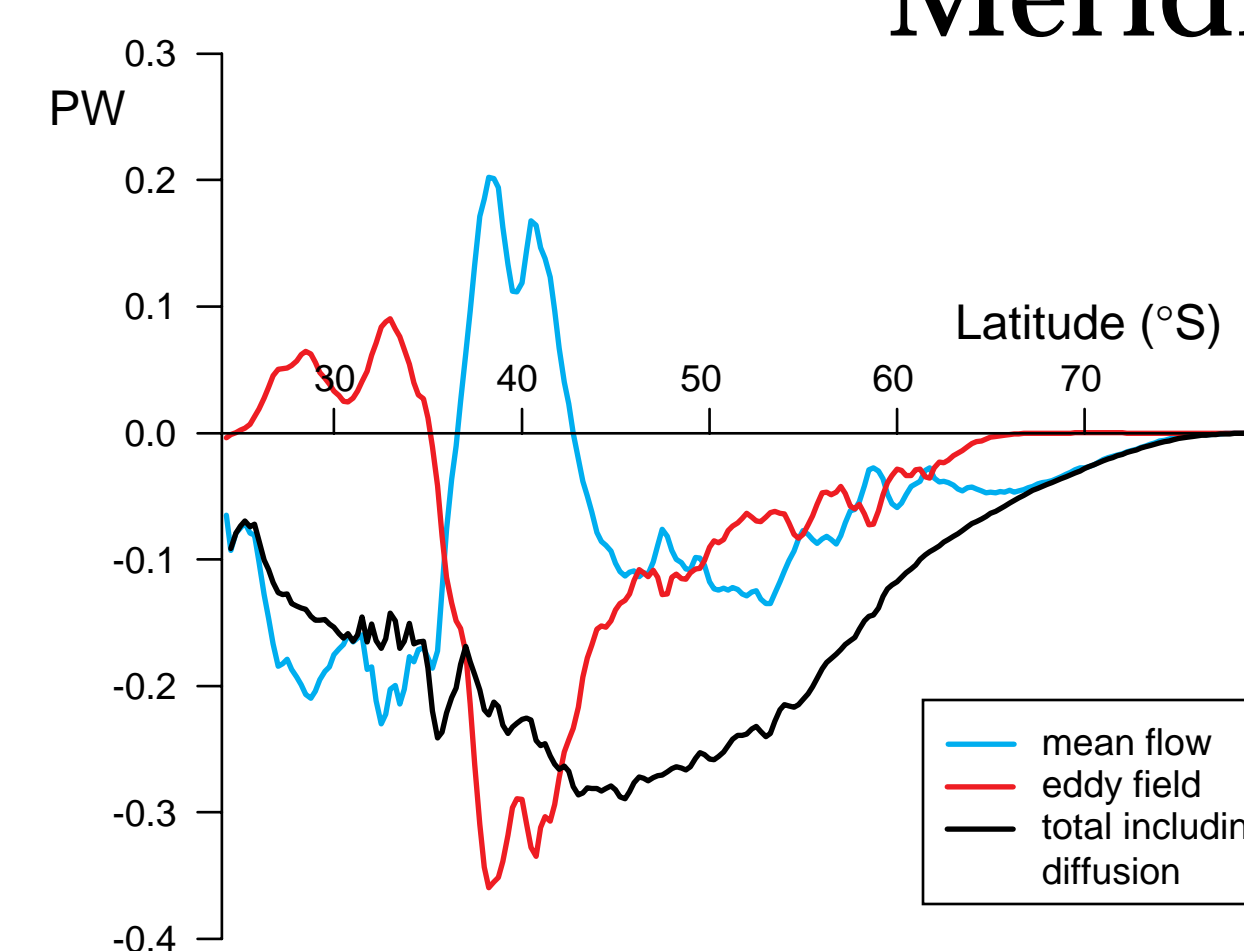
Term in the Vorticity Eqn.	ACC Average ($\times 10^{-12} \text{ ms}^{-2}$)
Wind Curl	-66.85
Bottom Pressure Torque	75.78
Beta	0.80
Advection	-8.19
Lateral Viscosity	-3.78
Bottom Friction	1.67

The table shows the contributions to the depth integrated and time averaged vorticity budget for the different terms in the vorticity equation averaged over the path of the ACC. The primary balance is between the curl of the wind stress and the bottom pressure torque. Eddies contribute about 25% of the advection term.

A regional analysis shows that the main contribution to the pressure torque comes from the Drake Passage, Scotia Sea, Argentine Basin and the region south of Tasmania and New Zealand. At these longitudes the main balance is between the beta (Coriolis) term and the bottom pressure torque. At other longitudes the main balance is between the curl of the wind stress and the beta term. (Wells & de Cuevas, 1995: Journal of Physical Oceanography, 25, 2569-2582).

The total transport through Drake Passage in the model is 180 Sv. Of this 157 Sv is due to density differences across the ACC. The remaining 23 Sv is a direct response to the wind, the change occurring on a timescale of less than 10 days.

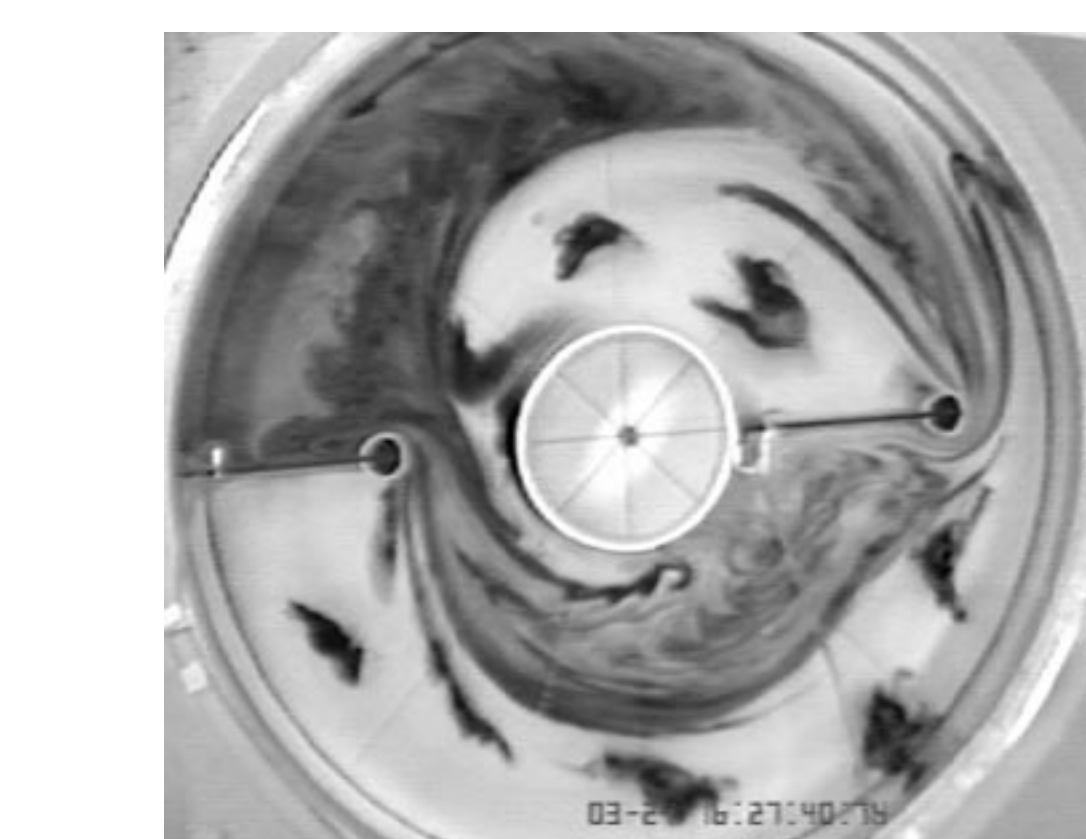
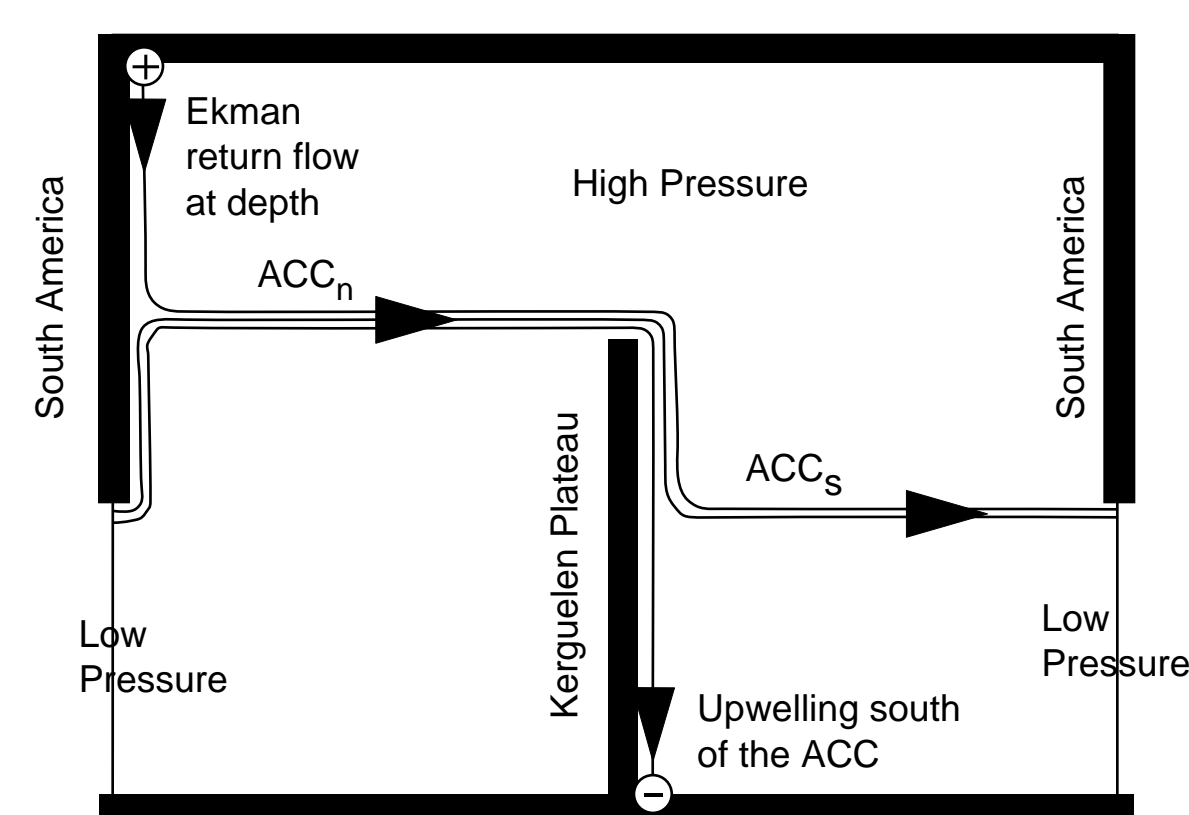
Meridional Heat Transport



The figure shows the total meridional heat transport in the FRAM model together with the contribution of the mean flow and the fluctuating eddy field. The mean flow includes the sub-tropical and polar gyres, which transport heat southward, and the strong surface Ekman layer. Between the two gyres, at 40°S, the Ekman contribution dominates, producing a net northward transport.

Compared with these terms the eddy contribution is generally small. However at 40°S the eddy contribution becomes very large and results in a net southward heat transport at all latitudes. The Southern Ocean appears to be the only region where the heat transport due to meso-scale eddies is dominant. (Thompson et al., 1997: J. Geophys. Res. 102(C2), 3303-3315)

A Simple Model of the ACC



The FRAM results suggested a rather simple model for the generation of the ACC. The model showed that in the weakly stratified Southern Ocean bottom topography controls the path of the ACC. Hughes has suggested that this is because the speed of the baroclinic Rossby waves is small compared with the advective velocity of the current. As a result topographic features, like the Kerguelen Plateau, act as though they reached the surface of the ocean.

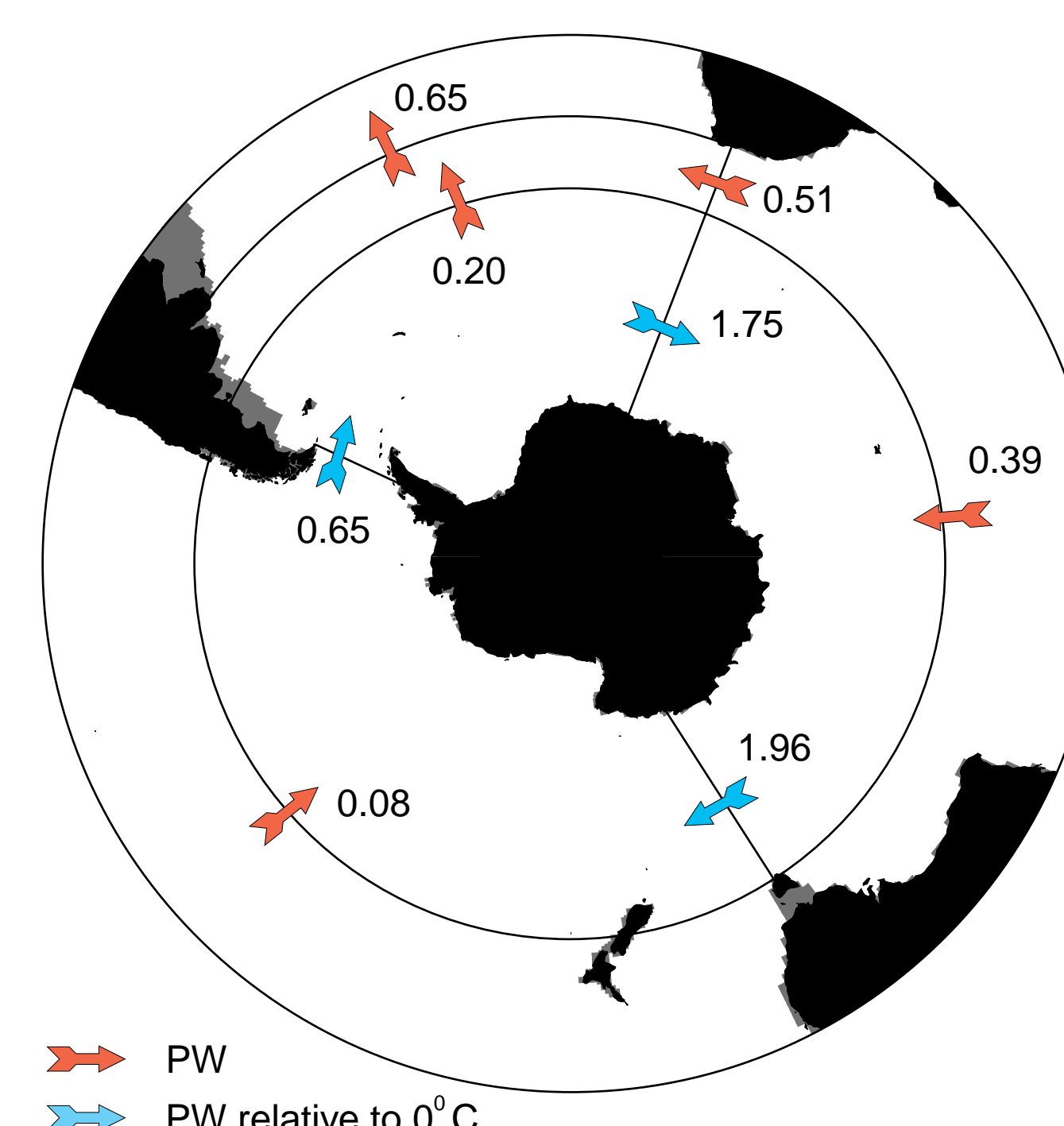
The ACC thus acts as a current in a meandering channel driven by the Ekman return flow. The top figure shows what happens if it is treated as a one layer ocean. Water can move north and south in western boundary currents but otherwise flows in a series of zonal jets. If only the Ekman return flow is present then there is an unphysical pressure drop across Drake Passage. If the ACC is added then a realistic solution is possible. This is because with a constant pressure drop across the current, the change in the Coriolis term means that the transport in the S Atlantic sector, between S. America and Kerguelen (ACC_N), is greater than that in the S. Pacific sector (ACC_S). If E is the Ekman transport and f_N and f_S the northern and southern values of the Coriolis term, then:

$$ACC_N \cdot f_N = ACC_S \cdot f_S \text{ or } ACC_N = E \cdot f_S / (f_S - f_N)$$

For the latitudes of Drake Passage and Kerguelen, the amplification factor is seven. Thus for an Ekman transport of 25 Sv, the strength of the ACC is predicted to be 175 Sv. This is a little high compared to observations. (Webb, D.J. 1993: Geophysical and Astrophysical Fluid Dynamics, 70, 57-84).

Such a flow can also be modelled in a rotating tank, using a sloping bottom to represent the changes in the Coriolis term. The image is taken from such an experiment where the flow is driven by a source and sink at the appropriate points on the inner and outer boundaries.

The Warm Water Path



Analysis of the FRAM results shows that most of the northward heat transport in the South Atlantic is associated with warm Agulhas Eddies which bring heat from the Indian Ocean. A low resolution version of the model did not produce eddies and the heat flow from the Indian Ocean dropped from 0.51 PW to 0.02 PW.

The results were also used to investigate whether the return path of the thermohaline circulation is via the warm water path from the Indian Ocean or via the cold path through Drake Passage. The results give support to the warm water path but are not conclusive because of uncertainties in the air-sea heat flux in the S. Atlantic sector. (Thompson et al., 1997: J. Geophys. Res. 102(C2), 3303-3315)

Further reading

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