

## Variability of the Southern Ocean in annual to decadal time scales

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I review physical oceanographic changes observed in the Southern Ocean since ca. 1980 i.e. modern instrumental records started.

The Southern Ocean is surrounded by the atmosphere, solid Earth, sea ice, and ice sheets. Eastward momentum flux from the atmosphere shows a significant increasing trend with southward shift. Heat and fresh water flux from the atmosphere are not well constrained. Freshwater flux from the ice sheet is generally increasing with regional contrasts.

Despite increasing wind stress, the Antarctic Circumpolar Current transport has not shown a trend. Geostrophic surface currents estimated from satellite altimeters suggest that the increased wind enhanced mesoscale eddies generated via baroclinic instability. The eddy enhancement is spatially localised. The role of these "standing eddies" is a recent hot topic.

In some numerical simulations, the meridional overturning circulation shows a strengthening trend in the upper cell (Circumpolar Deep Water upwelling and surface northward transport) and a weakening trend in the lower cell (CDW upwelling and Antarctic Bottom Water sinking). Estimated transport from a box inverse model does not contradict these results.

The most conspicuous hydrographic change is the decreasing AABW, which has a strong link with recent warming and freshening of the water mass. In the Indian-to-Pacific sector, dissolved oxygen decreased (appears as an increase in the density coordinate), which might have resulted from an ice calving event in the Ross Sea in the 1990s.

I emphasise that these changes, which have been discussed as though they are independent, interact with each other. Feed back mechanisms likely exist. Comprehensive understanding of the "Antarctic climate system" requires a comprehensive observing system that covers atmosphere, solid Earth and ice components of the system as well as the ocean.

Keywords: SAM intensification, eddy saturation hypothesis, Antarctic Bottom Water decrease, freshening