WATER MASS VARIABILITY AND CHANGE IN THE
SOUTHERN OCEAN

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INTRODUCTION

THE GOAL of this paper is to examine the magnitude and dynamics of natural variability in the Southern Ocean and the overlying atmosphere. This included an analysis of how each of the major Southern Ocean water-masses varied in both space and time. We also wanted to discover what physical mechanisms were at play: such as the relative importance of air-sea heat and freshwater fluxes, ocean circulation, and sea-ice exchange. Of particular interest was the nature of variability of sea surface temperature, interior oceanic water masses, and variability associated with the Southern Annular Mode (SAM), a climatic fluctuation in the wind field over the Southern Ocean. Extended integrations of global climate models were analysed to determine the nature of seasonal, interannual, decadal and centennial variability in upper-ocean circulation, water-mass properties, Antarctic sea-ice, and atmospheric circulation. Wherever possible, observational data were analysed and compared to the model-simulated variability.

Detection and attribution of climate change depends on a sound knowledge of natural modes of variability in the ocean-atmosphere system. This is because any signal of change needs to be compared, in both magnitude and time-scale, to that due to internally generated climate oscillations. The goal of this paper is to improve our ability to detect Southern Hemisphere climate change by better characterising natural ocean-atmosphere variability in the region. Our knowledge of natural climate oscillations in the tropics and in the Northern Hemisphere is more advanced than for the Southern Oceans, due to better data coverage and a greater effort in these geographic areas. One of the goals of this study was to quantify modes of climate variability in the Southern Hemisphere and to estimate how these modes impact on water properties in the Southern Ocean.

METHODOLOGY

The model experiments assessed comprised multi-millennia natural variability simulations run with constant atmospheric CO₂, either provided by the CSIRO or involving runs of the NCAR CCSM3. The duration of the model runs provides a longer timescale estimate of natural climate variability than that available from observations alone. Systematic dynamical processes and feedback loops were explored using statistical analyses, including empirical orthogonal functions and wavelets, to extract relationships between the different climate parameters. In addition, momentum and property budgets were employed to elucidate the dominant processes controlling the frequency and magnitude of ocean-atmosphere variations. Variables analysed included atmospheric conditions such as air temperature, cloud cover, precipitation, winds, and sea-level pressure, sea-ice extent, air-sea property fluxes, ocean circulation and hydrography.

WATER-MASS VARIABILITY

The main results from this work relate to a comprehensive assessment of the natural variability of water masses in the Southern Ocean (Rintoul & England 2002; Santoso & England 2004; Santoso, England & Hirst 2006; Santoso & England 2008). The water masses analysed include Antarctic Bottom Water (Fig. 1), which forms under sea ice off the Antarctic coast, sinks to the ocean’s abyss, and then flows
northward into each of the major ocean basins. Another focus was Antarctic Intermediate Water and Subantarctic Mode Water (see also Fig. 1), both of which contribute to a substantial component of the ocean’s uptake of carbon dioxide. Quantifying the natural variability of Southern Ocean water masses, including their properties and overturning rates, is vital for detecting anthropogenic climate change.

Antarctic Bottom Water variations were found to be controlled by Antarctic sea-ice fluctuations, with a dominantly decadal to multi-decadal time-scale (Fig. 2). The variability mechanism for Subantarctic Mode Water, in contrast, was discovered to be linked to wind-driven northward flow of cool Subantarctic Water, with the rate of mode water formation controlled by interannual variability in the circumpolar westerly winds (Rintoul & England 2002; Fig. 3). Previously, SAMW variability was thought to be controlled mainly by air-sea heat fluxes. Instead, we found that wind-driven northward Ekman flow of colder Subantarctic Water competes with southward flowing warmer saltier water from western boundary current extensions, with variability resulting in upper ocean water-mass characteristics and mixed layer depth. Under this mechanism, interannual variability in the circumpolar westerly winds drives variability in Ekman fluxes, and therefore variability in the rate of mode water formation near 40°S.
These analyses were extended to include an assessment of Antarctic Intermediate Water and Circumpolar Deep Water variability. Antarctic Intermediate Water variations were found to be mainly linked to fluctuations in air-sea and ice-sea fluxes, whereas Circumpolar Deep Water variability was found to be sourced primarily in North Atlantic Deep Water (NADW) variations. For full details of these analyses and results, refer to the series of papers appearing in the *Journal of Physical Oceanography* during 2002-2006 (see References).

THE IMPACT OF THE SOUTHERN ANNULAR MODE

Another focal point of this project has been documenting the impact of the Southern Annular Mode on natural oceanic variability (Sen Gupta & England 2006). The Southern Annular Mode is the leading mode of climate variability over the Southern Ocean, manifesting as a circumpolar pressure oscillation between Antarctica and southern midlatitudes. The Southern Annular Mode thus controls the latitude and strength of the Southern Hemisphere subpolar westerly winds. These winds, often termed the ‘Roaring Forties’, play a pivotal role in controlling ocean circulation and water-mass formation (Oke & England 2004). In this project we analysed a natural variability model experiment run over 200 years as well as measurements dating back to the 1950s to elucidate the way the Southern Annular Mode impacts upon the Southern Ocean and regional climate. Variations in the position and strength of the circumpolar winds result in a dynamic and thermodynamic forcing of the ocean, summarized below in Figure 4.

![Schematic representation of the climate system response to a positive phase of the Southern Annular Mode (SAM). Warm and cold anomalies are denoted by cross and dash hatching respectively. Arrow heads / tails denote flow out of / into the page. The corresponding diagram of circulation, properties and fluxes for the negative phase of the SAM exhibits the same patterns as displayed here, only with reversed directions of circulation and the opposite sign for property anomalies (from Sen Gupta & England 2006).](image-url)
Both meridional and zonal components of ocean circulation are modified through Ekman transport which in turn leads to anomalous surface convergences and divergences that strongly affect the meridional overturning circulation, and potentially the pathways of intermediate water ventilation.

**SUMMARY**

The major conclusions can be summarised as follows:

1. Subantarctic Mode Water (SAMW) variability was found to be controlled by interannual variations in wind-driven northward Ekman transport.
2. Antarctic Intermediate Water (AAIW) variations were found to be driven by air-sea heat fluxes and ice-ocean salt fluxes on a 3-5 year time-scale.
3. Circumpolar Deep Water (CDW) variations in T-S were discovered to be sourced from changes in transport/properties of NADW, dominated by time-scales centennial and beyond.
4. Antarctic Bottom Water (AABW) variability of the order of 3-5 Sv was found to be dominantly multi-decadal and linked to Antarctic sea-ice formation rates.
5. The Southern Annular Mode forces an organized circumpolar response in ocean circulation, SST, mixed layer depth and sea-ice.
6. The sea surface temperature response is significant due to a conspiring of ocean circulation effects and air-sea heat fluxes.
7. The atmosphere responds to Southern Ocean SST and sea-ice variations by prolonging phases of the Southern Annular Mode.

**REFERENCES**


