Intermediate Water Mass Production Controlled by Southern Hemisphere Winds

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Abstract

It is demonstrated that the production of intermediate water in a coarse resolution ocean general circulation model is controlled by Southern Hemisphere winds. Results from four equilibrium experiments using simplified topography and surface forcing are presented. The first experiment was carried out with no wind forcing, subsequent experiments employed annual mean surface stresses, which were amplified using factors of 0.5, 1, and 2.0 south of 30^o S. In all experiments, the salinity minimum characteristic for intermediate water is reproduced. Volume transports are directly proportional to the applied Southern Hemisphere surface stresses. These force an increased export of intermediate water and heat into the South Pacific Ocean northward across 30^o S and through Drake Passage into the South Atlantic Ocean. It results in a warming of the South Pacific Ocean, which is at a maximum in the intermediate water density range.

Introduction

The formation of intermediate water in the Southern Hemisphere was recently studied by employing primitive equation z-coordinate ocean general circulation models (OGCM) [Cox, 1989; England et al., 1993; Ribbe, 1999]. The traditional view is that surface buoyancy fluxes in the mid-latitudes of the South Pacific Ocean are the primary force which drive an intermediate water mass formation process as a combination of open ocean mid-latitude convection and subduction [Tomczak, 1999]. Intermediate water is subducted into the permanent thermocline of the South Pacific Ocean gyre or it is advected with the Antarctic Circumpolar Current (ACC) through Drake Passage into the South Atlantic Ocean. A subsurface salinity minimum within a depths range of about 800 – 1000 m is characteristic for intermediate water. It is the freshest of the global scale water masses.

Here an attempt is made to quantify the contribution made by Southern Hemisphere winds upon the intermediate water mass formation process. Intermediate water formed in the South Pacific Ocean ventilates upper ocean on interannual to decadal time scales. To explain its exact formation process may help to understand better, for example, recent Pacific basin wide observed changes to intermediate water mass characteristics [Wong et al., 1999]. In a series of computational experiments, it is shown that in addition to accelerating the gyre scale circulation, the Southern Hemisphere surface wind stresses exert control over mid-latitude open ocean convection and the amount of intermediate water formed. By assimilating an ideal tracer into the OGCM, the simulated warming of the intermediate water level is traced back to the intermediate water formation process in the South Pacific Ocean basin.

Model Design and Experiment

The model applied in this study is that recently employed by [Goodman, 1998] and [Ribbe, 1999]. [Goodman, 1998] investigated changes to the global circulation with North Atlantic Deep Water (NADW) formation switched on and off by imposing a surface salinity anomaly in the Northern Hemisphere. [Ribbe, 1999] studied a wind-driven convection process. The model is of coarse resolution with 3.75^o and 4.5^o in zonal and meridional direction and with 20 vertical levels with a total water depth of 5000 m (see Fig. 1 inset for model layout). Simulated surface temperature and salinity are forced toward zonal and annually averaged data from the [Levitus, 1994] climatology using a 50 day restoring time scale. In the high-latitudes of the Southern Ocean, sea surface salinity values are increased to 35 psu at 70^o S. This increase accounts for a bias of the observed salinity data to what are primarily summer conditions. It is a reasonably simple correction to a lack in observations, which in turn results in a much improved presentation of the intermediate water and the global salinity profile [England et al., 1993; Goodman, 1998]. The wind driven part of the oceanic circulation results from forcing the model with zonal and annually averaged surface wind stress [Hellerman and Rosenstein, 1983].

The results from four computational experiments are presented. The experiments are referred to as the no-wind, the weakened wind, the control or normal wind, and the enhanced wind experiment. South of 30^{o} S, surface wind stresses are amplified by factors of 0, 0.5, 1, and 2 respectively. These factors are similar to those used in recent studies reporting a link between Southern Hemisphere winds and the formation of NADW [e.g. Rahmstorf and England, 1997; Hasumi and Suginohara, 1999], or which were used to study a wind-driven mid-latitude convection mechanism [Ribbe, 1999]. Each model configuration was integrated for a period of 6000 years after which a steady state was achieved. Results are only shown for the South Pacific Ocean basin where intermediate water is being formed.

Results

In all experiments, a subsurface salinity minimum is reproduced (Fig. 1), which is located within the depth range of about 500-1000 m. It is less pronounced in the no-wind case and most noticeable in the enhanced wind experiment. The correlation with sea surface wind stresses indicates that the production of intermediate water in the South Pacific basin strongly depends upon wind forcing. The production of intermediate water and its correlation with surface stresses was quantified by computing the volume budgets for the Pacific Ocean basin only. The budget was calculated for the entire water column using potential density ranges of less than 26.5, 26.5 to 27.5, and greater than 27.5 kg m^{-3} for surface, intermediate and deep water respectively. [Goodman, 1998] applied identical density ranges for surface and intermediate water, but for potential densities larger than 27.5 kg m^{-3} distinguished between deep and bottom water, which is not done here.

There are changes to the large-scale hydrography due to alterations in wind stress (Fig. 1). The basin averaged salinity (or potential density) decreases with an increased Southern Hemisphere wind stress and anomalies are largest in the intermediate water density range (depth range of about 500-1000 m). Despite these large-scale changes and based upon the salinity profile, it is possible to distinguish in all experiments between three water mass ranges (Fig. 1). To compute the volume budgets in the different density classes some fixed boundary was chosen. A variation of these boundaries is possible, but does not result in significant changes to the analysis and the interpretation of the model experiments. Using these three fixed potential density ranges, the net transports across 30^o S, through Drake Passage and south of Australia, and between the three potential density layers were calculated.

The correlation between wind stress, net zonal and meridional transports is evident (Fig. 2). No water within the surface density ranges is leaving the Pacific Ocean basin through Drake Passage (Fig.2, top). Both the zonal and meridional transports for the normal wind experiment (control experiment) in this density class are similar to those reported in a previous study using a similar model configuration [Goodman, 1998]. In all experiments, the zonal flow is eastward. This is the case even in the no wind experiment, indicating that an eastward flow of the ACC is maintained through surface buoyancy fluxes alone. Meridional net transports in the surface density range are always northward across 30^o S, with the exemption being the no-wind case characterized by weak southward flow of $3.4 \cdot 10^6$ m^3s^{-1} [$1 \cdot 10^6$ m^3s^{-1}, referred to as 1 Sv]. It is not surprising that the net meridional flow in the surface layer is correlated with wind stress. The latter forces a strong northward flow in the Ekman layer. In combination with the equatorial trade winds, it drives the gyre scale circulation of the South Pacific Ocean and down-welling in the interior of the subtropical gyre.

A distinct correlation of the net meridional transport with surface wind stress is also evident in the intermediate water density range (Fig. 2, middle). Water in this density range is formed by mid-latitude convection in the Southern Hemisphere ocean [England et al., 1993; Ribbe, 1999]. The northward export across 30^o S increases from about 1.5 Sv in the no wind to about 8.9 Sv in the enhanced wind case. This correlation is also evident for the zonal transport south of Australia and through Drake Passage. It is larger than that observed in the real ocean, which is a feature in most OGCM simulations.

The net meridional transport of deep water varies only within a range of less than 1 Sv (Fig. 2, bottom) and no significant correlation of the meridional transport with wind stress is evident. The changes in the zonal transport of deep water to increased wind stress is found to be not as linear as the changes to flows within the surface and intermediate water density class. This non-linear response within the deep water density class reflects changes in deep water up-welling regions within other ocean basins not studied further in this paper. For example, by integrating the zonal deep water flow from the South Atlantic into the South Indian Ocean basin, it is found that the amount of deep water that joins the ACC in the South Atlantic Ocean basin is reduced in the enhanced wind stress experiment. This indicates that more deep water is directly converted to surface water in the South Atlantic basin and returns into the Northern Hemisphere.

The South Pacific basin is a source region for intermediate water. Both surface layer and deep layer water is being converted into intermediate water with a net conversion rate of about 9.7, 16.8, 35.0, and 29.7 Sv in no, weak, normal, and enhanced wind experiments respectively. The total volume of intermediate water within the South Pacific Ocean basin increases from 17, 27, 34, to 50 %. The larger fraction of this converted water remains with the ACC and is transported eastward through Drake Passage as intermediate water.

The increased conversion of deep to intermediate water with a larger surface wind stress is consistent with the proposal of a link between wind driven enhanced up-welling of deep water in the Southern Ocean and the production of NADW [Hasumi and Suginohara, 1999]. The enhanced conversion of deep water into intermediate water drives a net northward flow and meridional circulation in the North Atlantic. It increases the production (or maximum overturning) of NADW in the simple model applied in this study from about 9 Sv in the no-wind case to about 16 Sv in the case of enhanced surface stresses**.**

[Hasumi and Suginohara, 1999] reported increased deep ocean temperatures due to enhanced deep water production in the Northern Hemisphere. The same result is obtained for intermediate water in this study. Both its production in the Southern Hemisphere, and its flow is correlated with wind stress, and with enhanced surface stress, also the conversion of deep water to intermediate water increases (Fig. 2). This increases the temperature flux from the deep water into the intermediate water density class south of 30^{o} S and results in a warming of water within the latter density class north of the up-welling region. Furthermore, an enhanced surface heat flux north of 40^{o} S in the South Pacific Ocean basin is another source for enlarged heat transports into the intermediate level. This intensified heat flux is a result of the increased Ekman layer transport of cold surface layer water northward, which in turn forces a large oceanic heat gain under restoring boundary conditions north of the maximum wind stress zone [Ribbe, 1999].

The latter process is elucidated through a passive tracer study. The tracer is introduced into the model as an independent diagnostic tool to analyze the simulated circulation and to trace origin and pathway of intermediate water formed in the South Pacific Ocean. In each of the four equilibrium experiments, Pacific Ocean surface water is labeled north of about 40^{o} S. The technique was used previously by, for example [Cox, 1989]. At the surface, the tracer is equal to '1' only in the Pacific Ocean, while outside of the region it is zero, therefore, being a tracer of Pacific Ocean surface water.

There are two possible pathways for Pacific Ocean surface water to be converted into intermediate water by mid-latitude convection. Firstly, Pacific Ocean surface water is advected through the Indonesian passage into the Indian Ocean. This transport increases from 4.2, 12.4, 15.5 to 17.5 Sv in no, weak, normal, and enhanced wind experiments respectively. Indonesian throughflow water is advected with the South Indian Ocean gyre scale circulation southward into the higher latitudes of the Southern Ocean and joins the ACC. In all experiments, the net volume and heat transports across 30^{o} S in the Indian Ocean is southward within the surface and intermediate water density classes (not shown here). As shown by [Hasumi and Suginohara, 1999], the oceanic heat gain increases with enhanced winds north of the latitude of maximum wind stress. In consequence, the surface ocean warms, the heat transport in the throughflow domain increases and more heat re-enters the South Pacific basin south of Australia. The on-set of mid-latitude convection driven by heat and buoyancy losses in the southeast Indian Ocean starts the conversion process of this surface water into mode water and subsequently into intermediate water in the southeast Pacific [Schmitz, 1995; Ribbe 1999]. This is the main pathway for heat at the surface into the South Pacific basin.

A second pathway for Pacific Ocean surface water into the intermediate water density range is via convection in the southeast Pacific Ocean basin, its advection with the ACC through Drake Passage into the South Atlantic, and subsequent re-entry into the South Pacific south of Australia. However, this zonal pathway is located south of the zone of oceanic heat gain and water advected with the ACC makes no contribution to a meridional heat transport.

The Pacific Ocean surface tracer anomalies are computed as the difference between the no-wind case and all subsequent experiments. Pacific Ocean surface water is increasingly converted into intermediate water and ventilates into the upper ocean thermocline. The results show that the conversion of South Pacific Ocean surface water, its advection and subduction into intermediate water is largest in the enhanced wind experiment with anomalies of the basin average being larger than 35 % (Fig. 3, right side). Associated with this increased ventilation is the subduction of heat into the upper ocean. Basin wide temperature anomalies are computed with a maximum of more the 4^{o} C in the intermediate water level (Fig. 3, left side) of the enhanced wind experiment.

Conclusion

The four computational experiments demonstrate that the formation of intermediate water in the South Pacific Ocean is forced by Southern Hemisphere winds in this particular OCGM. The Pacific Ocean basin is a source region for intermediate water. With buoyancy forcing only, the salinity minimum is virtually absent. With an intensification of the surface wind stresses, the meridional volume transport and that of heat increases across 30^{o} S into the South Pacific Ocean basin. It leads to a subsurface warming, which is at a maximum in the intermediate water range and a rapid ventilation of the upper ocean. The mechanisms identified in this study help to advance knowledge of water mass formation processes that operate upon interannual to decadal time scales. In the South Pacific Ocean, changes to the climatological mean state have already been observed upon these temporal and spatial scales.

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Figure Captions:

Figure 1: Simulated salinity profiles for no (1), weak (2), normal (3) and strong (4) wind equilibrium experiments averaged for the South Pacific Ocean basin. The model domain and for comparison the corresponding profile of the [Levitus, 1994] climatology (5) are indicated.

Figure 2: Volume transport ($\cdot 10^6$ m^3s^{-1} = 1 Sv) integrated for sections south of Australia, at Drake Passage and at 30^o S. Conversion between density classes on the left. Thinnest arrow no wind and thickest arrow strong wind experiment.

Figure 3: Mean Pacific Ocean basin surface tracer anomaly ([%], right) and and temperature anomaly ([^{o}C], left). Anomalies are the difference between no-wind and weak (top), normal (middle), and enhanced (bottom) wind experiment.