Evaluation of Interior Circulation in a High-Resolution Global Ocean Model. Part II: Southern Hemisphere Intermediate, Mode, and Thermocline Waters

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ABSTRACT

A high-resolution, offline ocean general circulation model, incorporating a realistic parameterization of mixed layer convection, is used to diagnose pathways and time scales of Southern Hemisphere intermediate, mode, and lower thermocline water ventilation. The use of such an offline methodology represents the only feasible way of simulating the long time scales required to validate the internal pathways of a high-resolution ocean model. Simulated and observed chlorofluorocarbon-11 (CFC-11) are in reasonably good agreement, demonstrating the model’s skill in representing realistic ventilation. Regional passive dye and age tracer experiments aid in the identification of pathways originating from different Southern Hemisphere locations. Northern Hemisphere penetration of intermediate, mode, and thermocline waters is most extensive and rapid into the North Atlantic Ocean because these waters are involved in closing the Atlantic meridional overturning cell. However, less than 8% of this ventilation is derived from subduction within the South Atlantic in the simulation. Instead, this water enters the Atlantic just to the south of South Africa, having originally subducted primarily in the east Indian Ocean, but also in the west Indian Ocean and the west Pacific region where a pathway advects water westward to the south of Australia. This pathway also plays a large part, together with water overturned in the east Indian Ocean, in ventilating the northern reaches of the Indian basin. Northward propagation in the Pacific Ocean is limited to the low latitudes of the Northern Hemisphere and is almost exclusively accomplished by water subducted in the South Pacific. A small contribution is made from the other basins from water that spreads northward, fed by a circumpolar pathway associated with the Antarctic Circumpolar Current that forms a conduit for intermediate and mode water exchange between all three basins. Intermediate water is injected into and branches off this pathway in all basins, but most vigorously in the southeastern Pacific.

1. Introduction

This paper extends the work of Sen Gupta and England (2004, hereinafter Part I), which identified the ventilation pathways and time scales of deep-water and bottom-water masses in an offline eddy-permitting ocean general circulation model (OGCM). Here we investigate the interior propagation pathways, time scales, and composition of intermediate-depth waters derived from the Southern Ocean. In particular, we consider ventilation between the depths of the $\sigma_0 = 26.6$ and $\sigma_0 = 27.6$ isopycnals, which span intermediate, mode, and some thermocline waters. The offline nature of our model means that the computational cost of running integrations at high resolution is much smaller than fully prognostic models, permitting multiple long integrations. This method complements the more quantitative Lagrangian techniques (see, e.g., Speich et al. 2002; Donners and Drijfhout 2004; Drijfhout et al. 2005), providing a continuous tracer field that can be affected by ocean mixing and convection processes. It also allows for the inclusion of a variety of different tracer types, which can provide additional diagnostics (e.g., ideal age) and may be directly compared with observations [e.g., chlorofluorocarbons (CFCs)].

In the Southern Ocean the formation and subsequent northward spreading of intermediate, mode, and thermocline water masses play a vital role in closing the global meridional overturning circulation. This thermohaline circulation (THC) is often visualized as starting with the southward export of deep water away from the North Atlantic Ocean in a deep western boundary current (WBC) to the Southern Ocean. The circumpolar
nature of the Southern Ocean and the overlying zonal wind field cause, via Ekman pumping, the upwelling of this deep circumpolar water to shallower depths. At the surface, air–sea fluxes of heat and freshwater modify buoyancy characteristics of the upwelled water, eventually resulting in the formation of new water masses: bottom water along sections of the Antarctic margin and mode and intermediate waters at midlatitudes. Subantarctic Mode Water (SAMW) is generally associated with a thick thermostad with high oxygen concentrations formed through deep winter convection just to the north of the Antarctic Circumpolar Current (ACC). Mode water formation is considered to occur most strongly in the southeast Indian (Ribbe and Tomczak 1997) and mid to southeast Pacific Oceans (McCartney 1977, 1982) coincident with regions of strongest convection. SAMW can be tracked northward as it ventilates water in the lower thermocline of the subtropical gyres (McCartney 1982). Antarctic Intermediate Water (AAIW) is associated with a distinct circumpolar salinity minimum that originates to the south of the SAMW near the Subantarctic Front. The question of AAIW formation is still a matter of debate. McCartney (1977) and Talley (1996), for example, suggest that new AAIW is sourced by the coldest and freshest varieties of SAMW occurring in the southeast Pacific, which subsequently feeds into the southwest Atlantic via the Drake Passage, while Molinelli (1981) puts greater emphasis on isopycnal mixing across the Polar Front, particularly in the central Indian and southeast Pacific basins. Piola and Gordon (1989) also acknowledge the importance of southeast Pacific formation but demonstrate the need for additional mixing with Antarctic water masses from the south in order to explain changes in water mass properties. This is also demonstrated by Gordon et al. (1977), who find contamination of SAMW by Antarctic water in the southeast Atlantic, and more recently by Sloyan and Rintoul (2001) using an inverse model of the Southern Ocean. The eastward advection of AAIW and SAMW in the ACC across the Southern Ocean disguises zonal asymmetries in the formation of these water masses. Tropical thermocline central water, found at low latitudes in all ocean basins, is subducted to a large extent in the Southern Hemisphere subtropical convergence region where SAMW formation occurs during autumn and spring conditions (Sprintall and Tomczak 1993). Young water enters the permanent thermocline and northward advection occurs along isopycnals mediated by the circulation of the subtropical gyres.

Intermediate, mode and thermocline waters have a particular importance in the Atlantic sector where they play a major role in the renewal of the upper branch of the THC. In recent years two primary sources for water entering the South Atlantic basin have been identified: (i) eastward transport of cold, fresh, water from the northern Drake Passage (NDP) and (ii) westward transport of warmer water from south of South Africa (SSA) as part of the intermittent leakage of Agulhas rings. These constitute the so-called cold (Rintoul 1991) and warm NADW return routes (Gordon 1986), respectively. The warm route has often been associated with water derived from the tropical Pacific that entered the Indian Ocean via the Indonesian Throughflow and flowed westward into the subtropical gyre before reaching the Atlantic. Distinction between the warm and cold routes is complicated, however, by the fact that a proportion of NDP water may cross the South Atlantic—subject to significant transformation as a result of air–sea fluxes and lateral mixing—and loop into the southwestern Indian Ocean before finally reentraining into the Benguela Current. More recent studies have also suggested a component of the SSA input derived from intermediate and mode waters that have entered the Indian Ocean south of Australia (Speich et al. 2001, 2002). The sparsity of Southern Hemisphere observations, however, means that the relative importance of these renewal pathways is still a matter of debate. You (2002), for example, uses optimum multiparameter water mass analysis to investigate the contribution of water masses entering via NDP and SSA as it spreads northward. He finds that the contribution of NDP water to intermediate water entering the subtropics is approximately 2 times as great as waters from the Indian Ocean. In addition, the SSA component is predominantly formed by water that has passed through the Drake Passage, advected across the South Atlantic, and recirculated in the Indian Ocean before reentering the South Atlantic. Sloyan and Rintoul (2001) use an inverse model constrained by Southern Ocean hydrographic sections together with independent estimates of diapycnal and air–sea fluxes to constrain intermediate and mode water circulation. They also suggest that closure of the thermohaline circulation in the Atlantic sector is predominantly due to NDP-derived water. They find that water leaving the Drake Passage is significantly modified by both internal diapycnal and air–sea fluxes at the Brazil–Malvinas Confluence, along the eastward traverse of the South Atlantic and during any recirculation that extends into the southwestern Indian Ocean (although they suggest that the majority of upper northward transport is directly linked to Drake Passage with only a small proportion of water looping through the Indian Ocean). Their flow pathways are consistent with those proposed by Gordon et al. (1992), Stramma and England (1999),
and Reid (1989), although Gordon et al. attribute a greater importance to Indian Ocean–sourced water in the Atlantic Intermediate Water budget. Gordon et al. (1992) finds that over 50% of Benguela Current water is made up of South Atlantic water that has transited eastward south of the Agulhas retroreflection to the Indian Ocean and looped back to the west within the Indian Ocean recirculation gyre.

Recent modeling studies are suggestive of a far greater role for SSA pathways. Drijfhout et al. (2005) and Donners and Drijfhout (2004) find that most of the upper branch North Atlantic THC is originally subducted in the eastern Indian Ocean and enters the Atlantic south of South Africa. In a complementary study, Speich et al. (2002) find that both model and observational results are consistent with an important contribution by SSA water coming from south of Australia via the Tasman “Outflow.”

Although much of the focus of intermediate, mode, and thermocline water pathways revolves around the renewal of deep water in the Atlantic, these water masses play an important role in the ventilation of the southern subtropical and, to a lesser extent, Northern Hemisphere waters in the other ocean basins. For example, in both the Indian and Pacific Oceans there is evidence of signatures of Southern Hemisphere intermediate and thermocline waters in the Northern Hemisphere WBCs (You 1998; Qu and Lindstrom 2004). Finally it is important to note that Southern Hemisphere mode and intermediate waters play a major role in the oceanic uptake of anthropogenic carbon dioxide (CO$_2$) (e.g., Sabine et al. 2004; McNeil et al. 2003), as well as likely affecting meridional transports of heat in the Southern Ocean.

The remainder of this paper is divided into four sections. Section 2 gives a brief summary of the offline tracer model. A variety of tracer types and surface source regions are used to identify the ventilation pathways, time scales, and the relative importance of various formation zones. In section 3a we compare simulated and observed CFC sections to assess the model’s ability to capture interior ventilation. Section 3b describes the use of an age tracer to constrain ventilation time scales. Sections 3c and 3d present passive tracer experiments from discrete regional surface source zones. Section 4 provides a discussion of simulated and observed Atlantic, Indian, and Pacific Ocean pathways together with some final conclusions.

2. Method

Our offline tracer model is an adaptation of the tracer component of the original Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOMI) (Bryan 1969; Cox 1984; Pacanowski et al. 1991). It is forced with monthly advection, temperature, and salinity fields from the Parallel Ocean Climate Model (POCM 4C; Semtner and Chervin 1992; Stammer et al. 1996). The POCM simulates ocean circulation between 68°N and 75°S, with a resolution of 0.4°east-latitude × 0.4°longitude × 20 variable depth levels, resulting in an average grid size of 0.25° in latitude. Forcing data consists of 20 years of observed daily varying momentum, heat, and freshwater surface fluxes. To avoid model drift a relaxation to observed monthly temperature and salinity is made at the surface and a further relaxation is made at high latitudes to account for the exchange of water properties with areas beyond the model domain. Horizontal mixing of tracers is parameterized using a biharmonic scheme [with $B_h = 5 \times 10^{19} \cos^2(\text{lat});$ McClean et al. 1997], while vertical mixing uses the scheme of Pacanowski and Philander (1981). The 12 monthly mean fields of advection, temperature, and salinity used in the offline model were calculated by averaging fields from years 1992–98 of the POCM 4C integration.

The offline model is run at the same spatial resolution as the POCM. Horizontal mixing uses the same biharmonic scheme; however, a simplified vertical mixing based upon the Bryan and Lewis (1979) depth profile is used because of difficulties applying the Pacanowski and Philander (1981) method to the model averaged density fields. Neither the prognostic nor the offline models attempt to include enhanced along-isopycnal or eddy-induced mixing [e.g., the mixing parameterization of Gent and McWilliams (1990)] consistent with the approach used in Part I of this study. This should not greatly affect our results as we are not concerned with the representation of eddy-induced mixing per se, and isopycnals become more horizontal at lower latitudes along intermediate water pathways.

To simulate the convective mixing that would normally be absent in the offline model, a scheme was implemented whereby a mixed layer depth (MLD) is calculated whose density $\sigma_t$, relative to a near-surface value, changes by $\Delta \sigma_t = \sigma_t(T + \Delta T, S, p) - \sigma_t(T, S, p)$, where $T$ is the reference temperature, $S$ is salinity, and the pressure $p = 0$ (Kara et al. 2000). A comparison between observed and simulated maximum monthly mixed layer depths showed that the best agreement is obtained adopting $\Delta T = 0.2^\circ$C (see Part I). We use this value throughout the present study. A comparison with the observations (Fig. 1) demonstrates that, while the simulated lateral pattern of MLDS is more homogeneous in the model than the sparse observations sug-
gest, zonally averaged MLDs across the ocean basins are generally in good agreement.

Three different tracers are implemented within our offline model. First, a CFC-11 tracer is included using the method of England et al. (1994). Twentieth-century model integrations forced by observed atmospheric concentrations allow direct comparison with oceanographic CFC-11 sections and provide a method of model evaluation. Second, a passive “dye” tracer is released from a variety of discrete regions at the ocean surface (Fig. 2). Within a given region, surface tracer levels are continuously held at unity while everywhere outside the region surface values are reset to zero. Internal concentrations evolve through advection and

![Fig. 1. (top) Simulated mixed layer depths (m) for July, August, and September. White contours mark the boundaries of the release regions defined in Fig. 2. (bottom) Corresponding modeled (thick black) and observed (blue) zonally averaged mixed layer depths for the east and west sides of the three ocean basins. Observations are based on the Naval Research Laboratory Mixed Layer Depth Climatology (Kara et al. 2000).](image)
mixing processes. This method allows additive results from multiple source regions to give a census of source water contributions in a particular region (Cox 1989). The temporal evolution of this tracer provides a clear indication of spreading pathways into the ocean interior. Last, to obtain a more quantitative global estimate of ventilation time scales, an “age” tracer, run out to near steady state, is included. In such experiments the age of all interior grid points is incremented at each time step, while the age is held at zero at the model’s surface level. In this way, a steady-state tracer age for an interior water parcel—made up of the mixing of water elements that have followed numerous pathways from the surface—represents a volume-weighted average of the times that each of the constituent water elements has been away from the sea surface (England 1995; Hall et al. 2002).

3. Results

a. Model–observation comparison

To assess the skill of the offline model in representing interior circulation we present a comparison of observed and simulated salinity and CFC-11 along two World Ocean Circulation Experiment (WOCE) sections (Figs. 3–6). Also shown along these sections are the observed oxygen concentration and simulated (year 80) passive tracer concentrations for tracer released from the surface Subtropical and Subantarctic regions (as defined in Fig. 2; release regions are loosely termed Northern, Subtropical, Subantarctic, Antarctic, and Polar, and italics and a leading uppercase letter are used to distinguish these regions from generic usage). We demonstrate in section 3c that source waters outside the Subtropical and Subantarctic regions play no significant role in the northward export of intermediate-depth tracer in the offline simulation. As oxygen solubility is temperature dependent and so broadly varies with latitude and oxygen is a nonconservative tracer, being consumed in biological activity, it is not directly comparable to the passive dye tracer. However, both oxygen and passive tracer are indicators of rapid ventilation and so have been included in the analysis.

Along the Pacific WOCE P15 section (Fig. 3a) at ~170°W a distinct observed salinity minimum penetrates north to ~10°N. The core of the minimum lies between the \( \sigma_0 = 27.0 \) and \( \sigma_0 = 27.2 \) isopycnals. These surfaces initially deepen, flatten out between 750–1000 m, and then gradually shoal while moving northward. There is not, however, an uninterrupted northward flowing pathway of freshwater into the interior; a region of relatively saline water sits at ~40°S at intermediate depths to the south of a local salinity minimum between ~20° and 35°S. As the POCM has been integrated starting from observed initial conditions for only a few decades, salinities will not have fully equilibrated. Nevertheless it is still useful to compare the transient model values with the observed sections. The gross features of the simulated fresh tongue (Fig. 3b) match well with observations. Again, the salinity minimum is disconnected from the region of surface ventilation along the section although it tends to lie at a slightly greater depth between \( \sigma_0 = 27.2 \) and \( \sigma_0 = 27.4 \). Both surface and subsurface local minima are less fresh than observed. This is a possible indication of erroneously weak AAIW formation in the prognostic model. It does
Fig. 3. Meridional PFS section along 170°W from the Ross Sea (January–February 1996): (a) Observed annual mean salinity; (b) simulated salinity; (c) observed CFC-11; (d) simulated CFC-11. Superimposed in the salinity panels are contours showing the
isopycnals.

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not, however, necessarily follow that the formation rate in the offline model is also underestimated, as formation is driven by the parameterized convection that has been tuned to give realistic CFC inventories via the MLD parameterization (Part I). The distributions of simulated and observed CFC-11 (Figs. 3c,d) are also broadly consistent, with the deepest penetration occurring in regions of deep convection, a shoaling of tracer depths extending north to ~10°S followed by a flattening in penetration depths, and shallow subsurface tracer maxima associated with ventilation under the subtropical gyres. Although well placed at ~60°S, there is excessive upwelling of Circumpolar Deep Water (CDW) in the simulation (Part I). Although not directly comparable, both oxygen and passive tracer should show some common features, as both are indicators of rapid ventilation. The depth of the observed subsurface oxygen maximum—centered on the $\sigma_0 = 27.0$ isopycnal—sits above the corresponding salinity minimum. As with the salinity, a local oxygen maximum exists that is separated from the area of strong surface ventilation farther south. These are suggestive of remote sources of low salinity and high oxygen water that has been advected zonally to the P15 longitude. The oxygen maximum must be interpreted with some caution, however, as biological activity is also playing a role in its distribution and, as a result, it is not an unambiguous proxy of the physical circulation. A distinct maximum is also evident in the simulated passive tracer at a similar location to the observed oxygen maximum and at a shallower depth than the simulated salinity minimum core. The breakdown of the tracer into components originating from the different release regions (Figs. 4c,d) indicates that the tracer that constitutes the maximum is derived from the Subantarctic release zone (Fig. 2). In contrast, the Subtropical release zone transports tracer at much shallower depths at this longitude.

Along the Indian Ocean section at ~90°E (Fig. 5), the observed salinity minimum is slightly deeper than in the Pacific section, with the core following the $\sigma_0 = 27.2$ isopycnal. This is also true of the simulated salinity distribution although, as in the Pacific, the minimum is deeper—situated nearer the $\sigma_0 = 27.4$ isopycnal. Like the Pacific section, the Indian Ocean POCM salinity minimum is weaker than observed, indicating understrength model subduction. The observed and simulated Indian Ocean CFC signals show similar distributions with a much broader penetration than in the Pacific. Again, an enhanced upwelling of CDW at high latitudes results in shallow penetration of CFC in this region in the model. While the observed salinity minimum is deeper in the Indian than the Pacific sections, the observed oxygen signal (Fig. 6) is significantly shallower, spreading northward between $\sigma_0 = 26.6$ and $\sigma_0 = 26.8$. Like the observed salinity, there is no indication of an isolated subsurface maximum. The passive tracer experiment also shows greatest northward spreading at these shallow depths. This time, however, the northward spreading is due to tracer derived from the Subtropical release zone. This is partially explained by the more equatorward position of deep winter convection in the Indian Ocean compared to the Pacific.

A number of other CFC sections were also analyzed in Part I of this study, including the AJAX section in the South Atlantic. Here broad agreement was evident between observed and simulated distributions and column inventories. As with the corresponding Indian and Pacific salinity sections, described above, the salinity minimum along the AJAX section (not shown) is, however, overly saline.

### b. Tracer age

Experiments whereby a global age tracer is evolved out to near steady state provides useful information on ventilation time scales. Figure 7 shows tracer age on $\sigma_0 = 27.2$ after 1500 years of integration. At intermediate depths, this is sufficient time for most areas to reach a near steady state. The main exception to this is in the equatorial regions of the Indian and Pacific Oceans where there is upwelling and subsequent westward advection of deep tracer-depleted waters. In the Atlantic upwelled water is relatively well ventilated by NADW and, as a result, there is no corresponding age maximum at the equator.

The youngest waters associated with AAIW are bound to the north (near 20°–30°S) by strong fronts where age quickly increases from around 150 to 250 yr (100 to 250 yr in the Atlantic). This denotes the northern limits of the subtropical gyres at these depths. Consequently most of the spreading of AAIW in the southern basins is ultimately driven by the overlying wind-driven circulation. In the Pacific the ventilation pathway is particularly clear: young water follows the Chilean coast, turning west north of ~40°S and following the northern limb of the deep subtropical gyre to the western basin where part of it recirculates southward. In the Indian Ocean the band of young water stretching from south of the Tasman Sea northwestward toward South Africa is coincident with a region of parameterized deep mixed layers (Fig. 1). Interpretation of the AAIW age distribution is complicated by the contamination of the $\sigma_0 = 27.2$ isopycnal by waters not associated with AAIW. In the Atlantic region passive tracer experiments, where water is tagged in the high-latitude North Atlantic (described in Part I), show a contamination at these intermediate depths by NADW.
Meridional P15S (a) observed oxygen concentration; (b) sum of simulated passive tracer originating from the Subtropical and Subantarctic regions; (c) simulated passive tracer—Subtropical region only; (d) simulated passive tracer—Subantarctic region only (after 80 yr). Superimposed are contours showing the $\theta = 26.6$, $\theta = 27.0$, $\theta = 27.2$, $\theta = 27.4$, and $\theta = 27.6$ kg m$^{-3}$ isopycnals.
Fig. 5. Meridional 108°S to 108°N sections along 80°–95°E (January 1994–February 1995): (a) Observed climatological salinity; (b) simulated salinity; (c) observed CFC-11; (d) simulated CFC-11. Superimposed are contours showing the \( \rho_0 = 26.6 \), \( \rho_0 = 27.0 \), \( \rho_0 = 27.2 \), \( \rho_0 = 27.4 \), and \( \rho_0 = 27.6 \) kg m\(^{-3}\) isopycnals.
Fig. 6. As in Fig. 4 but for meridional 108S – 108N sections P15S.
spreading away from the WBC, equatorial, and eastward branching ventilation pathways. To isolate ages associated with the southern sources only, a further integration was performed where age is held at zero in the Subtropical and Subantarctic surface regions only (Fig. 8). In the area of the subtropical gyres the age distribution remains essentially unchanged, indicating that ventilation here is primarily from these two regions. North of the subtropical gyres the water mass ages show the same overall structure as the global surface age experiment but with increased ages. In the North Pacific and north of the Indian Ocean subtropical gyre, tracer ages are much older than for the full surface release experiment (\(>800\) and \(>600\) yr, respectively). This suggests that northward AAIW penetration is somewhat limited in the Pacific and Indian sectors. In contrast, the North Atlantic still shows relatively young ages (\(\sim350\) yr), indicating much more extensive and rapid northward propagation of AAIW into the Atlantic sector. This is presumably mostly due to the North Atlantic meridional overturning cell drawing intermediate waters to close the global ocean conveyor.

c. Passive tracers by region

To identify in greater detail the flow pathways together with the importance of various source regions, further experiments were carried out in which a passive tracer was released from a number of surface regions (Fig. 2) over a period of 500 yr. These regions exhibit very different behavior in terms of the resulting flow pathways. The Subtropical and Subantarctic regions (Fig. 9), which encompass most of the area over which deep convection occurs in the Southern Hemisphere, are the dominant source regions for intermediate water pathways extending to the north. Both regions show subsurface tracer intensification and spreading away from their respective source regions into the Northern Hemisphere. The Subtropical release shows significantly shallower and more extensive ventilation pathways with the tracer maxima generally centered near \(\alpha = 26.6\) at a depth of around 500 m. The Subantarctic zone, where many of the AAIW surfaces outcrop, has northward pathways that are generally centered at greater depths, between \(\alpha = 26.8\) and \(\alpha = 27.2\) (750–1000 m). Along the advection pathways the maximum tracer concentrations occur in the vicinity of areas of deep convection. It is evident, therefore, that for the case of the offline model, at least, with its parameterization of wintertime convection, intermediate water formation is intimately connected to mode water formation. This is borne out by the fact that the Antarctic region (figure not shown) to the south, which also contains outcropping intermediate water isopycnals, shows little evidence of along-isopycnal spreading either northward or to depths exceeding a few hundred meters. As mentioned, however, neither the POCM nor the offline model incorporate any explicit along-isopycnal mixing. As expected, the Polar region release (figure not shown) also lacks intermediate depth spreading. However, significant tracer penetrates to great depths at locations close to the Antarctic margin.
and throughout the Ross and Weddell polar gyres. This Antarctic Bottom Water ventilation and its subsequent spreading is detailed in Part I.

d. Passive tracers by subregion

To isolate flow pathways associated with more localized portions of the Subtropical and Subantarctic regions, 80-yr integrations were performed where these domains were divided into subregions representing the east and west portions of each ocean basin [denoted west Atlantic (WA), east Atlantic (EA), west Pacific (WP), east Pacific (EP), west Indian (WI), and east Indian (EI); see Fig. 2 for locations]. To visualize ventilation from the subregions we present the evolution of the 1% tracer concentration contour in Figs. 10 and 11 (i.e., the time taken for concentrations to reach 1% of the release zone concentration). Note that the dye tracers used in this calculation are reset to zero at each time step outside each subregion so that each tracer exclusively tracks surface waters overturned from within that subregion. Distinct pathways are shown superimposed on these figures. The tracer field for the Subtropical region release is shown on the $\sigma_0 = 26.8$ isopycnal, while the Subantarctic region field is shown on the $\sigma_0 = 27.2$ isopycnal, as the more poleward region is associated with deeper northward spreading. To aid our analysis, tracer depth sections together with animations of tracer concentrations on multiple isopycnals were used to differentiate pathways where identification was ambiguous or where there were significant vertical variations in the pathways (these are available at www.maths.unsw.edu.au/~alexg/). The remainder of this section focuses on the model simulated pathways; a comparison with observations is left for section 4.

1) Southwestern Atlantic Ocean: ST\textsubscript{WA} (Fig. 10a) and SA\textsubscript{WA} (Fig. 11a)

Tracer subducted in the western Atlantic primarily ventilates the South Atlantic subtropical gyre. Some tracer does, however, escape into the other basins via South Africa, mainly from the Subantarctic source region (SA\textsubscript{WA}), strongly constrained to a region south of 40°S (north of which the mean flow is westward) stretching from the surface to below 1000 m. While advecting eastward, the near-surface signal is eroded leaving only a subsurface maximum that increases in depth and moves poleward, reaching a maximum depth in the eastern Pacific. This high-latitude pathway, which represents the intermediate-depth portion of the ACC, is fed by many of the source regions and acts as a subsurface circumpolar conduit between all of the basins. In the Indian Ocean some of the eastward-moving tracer branches northward—most strongly in the central to eastern basin, centered at $\sigma_0 = 27.4$, and recirculates westward. A small portion of this tracer reenters the eastern Atlantic close to South Africa, resulting in a weak tracer signal just above the northern limit of the well-ventilated gyre region (Fig. 11a). Tracer entering the Pacific region does so as a narrow jet south of the Macquarie Ridge/Cambell Plateau to the south of New Zealand. On reaching the Chilean coastline some tracer continues through the northern Drake Passage with the rest moving northward and then westward.
across the Pacific, centered between $\sigma_0 = 27.2$ and $\sigma_0 = 27.4$ at $\sim 1100$ m.

2) SOUTHEASTERN ATLANTIC OCEAN: $\text{ST}_{\text{EA}}$ (Fig. 10b) AND $\text{SA}_{\text{EA}}$ (Fig. 11b)

Tracer released from the eastern Atlantic, where convection is relatively shallow, stays almost exclusively in the Atlantic at shallow depth. Two pathways feed the $\sigma_0 = 26.8$ isopycnal from the Subtropical release region ($\text{ST}_{\text{EA}}$; Fig. 10b). The first is on the eastern side of the subtropical gyre from where tracer circulates northward along the northern limb of the gyre (centered between 200 and 300 m) and then southward in a shallow WBC. The second is near the southwest coast of South Africa from where there is northwestward spreading, stretching across to South America north of $\sim 20^\circ$S (Fig. 11b), centered at $\sim 200$ m.

3) SOUTHWESTERN INDIAN OCEAN: $\text{ST}_{\text{WI}}$ (Fig. 10c) AND $\text{SA}_{\text{WI}}$ (Fig. 11c)

In the western Indian Ocean most deep convection occurs in the subtropical $\text{ST}_{\text{WI}}$ region. There is little

Fig. 9. Passive tracer (%) released from (left) Subtropical and (right) Subantarctic surface regions on potential density surfaces shown. White contours show position of release regions.
spreading of tracer sourced from the Subantarctic region away from shallow depths (Fig. 11c). For the more northern release zone, eastward spreading occurs as a subsurface maximum in the ACC pathway described for the western Atlantic release. Significant quantities of tracer move westward into the Atlantic Ocean, sandwiched between South Africa and 40°S as a subsurface maximum. In the Atlantic, this westward transport can be resolved into two distinct pathways. The more southerly portion ventilates the South Atlantic gyre at intermediate depths. The more northern pathway spreads northwestward to the South American coast, reaching Brazil as a broad jet south of ~15°S, centered near $\sigma_0 = 26.6$ between 400 and 500 m. Tracer is sub-

Fig. 10. AAIW pathways from Subtropical (a) WA, (b) EA, (c) WI, (d) EI, (e) WP, and (f) EP subregions. Contouring represents the evolution of the 1% passive on $\sigma_0 = 26.8$ surface (i.e., number of years to reach a 1% concentration); black contours show position of fronts at 20, 40, 60, and 80 yr. Superimposed pathways were constructed with the help of animated sequences of passive tracer on various density surfaces spanning AAIW densities. The superimposed yellow line shows the position of $\sigma_0 = 26.8$ isopycnal 100-m depth contour. Release subregions are also shown in red.
sequently transported northward in a fast moving WBC until finally breaking northeastward at the Grand Banks in a broad jet along the northern limb of the subtropical gyre. For $\sigma_0 > 27.0$ the 1% tracer contour reaches as far as $\sim 60^\circ N$ in the northeastern Atlantic within 60 yr, while at shallower depths tracer does not extend beyond $\sim 45^\circ N$ but reaches this latitude in as little as 20–25 yr. Branching from the WBC a shallow pathway extends eastward along the equator, centered just below $\sigma_0 = 26.6$ ($\sim 300$ m). Two slightly deeper branches spread southeastward and northeastward at low latitudes in the Southern and Northern Hemispheres, respectively. In the northern midlatitudes running northeastward at $\sim 20^\circ N$, a sharp front in tracer concentration marks a boundary between the well-ventilated water coming from the western boundary and tracer-free waters entering from the northeast basin as part of the subtropical gyre.

4) SOUTHEASTERN INDIAN OCEAN: ST\textsubscript{EI} (FIG. 10D) AND SA\textsubscript{EI} (FIG. 11D)

Eastward transport of the eastern Indian Ocean sourced tracer is along the ACC pathway. The westward pathways entering the South Atlantic south of South Africa are generally coincident with those of the western Indian Ocean source regions with both subregions contributing to the northward ventilation and some ventilation of the deeper South Atlantic subtropical gyre. Unlike its western counterpart, eastern release Indian Ocean water plays a significant role in ventilating the northern Indian Ocean. From the Subtropical release zone (ST\textsubscript{EI}) the main pathway traversing the
basin moves northward up the coast of southwestern Australia and curves westward in a broad swathe toward Madagascar, centered near \( \sigma_0 = 26.6 \) between 400 and 500 m (Fig. 10d). On reaching the Mascarene Plateau east of Madagascar the pathway splits with branches going southward, extending into the South Atlantic, and northward around the northern tip of Madagascar and to the African margin and a WBC that extends through to the Gulf of Aden (13°N). Three eastward branches ventilate the tracer-depleted eastern basin. The first, just north of \( \sim 15^\circ S \) fed by tracer that recirculates from the dominant northwestward pathway, a second that branches from the WBC near \( \sim 5^\circ S \), and a third that extends northeastward in a broad swathe from the WBC north of the equator, to ventilate the northern reaches of the basin. The Subantarctic tracer release zone (SA\(_{EP}\)) pathways closely match those of ST\(_{EP}\), although the dominant northwestward pathway across the basin is deeper and farther to the south, resulting in relatively more water moving south of Madagascar than to the north and subsequently weaker Northern Hemisphere ventilation.

5) **SOUTHWESTERN PACIFIC OCEAN: ST\(_{WP}\) (Fig. 10e) and SA\(_{WP}\) (Fig. 11e)**

From the western Pacific release zones—most strongly from the southern (SA\(_{WP}\)) region—there is significant subsurface transport westward along the margin of South Australia and into the Indian Ocean, from where it follows pathways similar to, albeit slightly deeper than, those described for the east Indian Ocean release (ST\(_{EP}\)). These source regions also play a significant role in ventilating the northern Pacific basin. From the Subtropical source region (ST\(_{WP}\)) the greatest ventilation occurs as water recirculates within the western portions of the subtropical gyre, centered along \( \sigma_0 = 26.6 \). Significant eastward transport only occurs at shallow depths above \( \sigma_0 = 26.6 \) (figure not shown) and in the subsurface ACC pathway. This latter pathway is much enhanced for the southern source region (SA\(_{WP}\)). A portion of this flow enters the Atlantic and continues eastward, forming a deep circumpolar band; the remainder turns northward at the South American margin turning to the northwest at \( \sim 40^\circ S \). At shallower depths there is also strong ventilation of the northern and eastern parts of the gyre from the Subantarctic release zone. Tracer from both subregions reaches the western basin in recirculated flows south of \( \sim 15^\circ S \) with some tracer returning southward in a WBC and the remainder moving northward along the east coast of Australia and extending as far north as the Philippines. Three pathways extend eastward from the western basin, one at \( \sim 7^\circ N \) and one at \( \sim 7^\circ S \), both centered between \( \sigma_0 = 26.8 \) and \( \sigma_0 = 27.0 \), and a third at the equator, centered above \( \sigma_0 = 26.6 \).

6) **SOUTHEASTERN PACIFIC OCEAN: ST\(_{EP}\) (Fig. 10f) and SA\(_{EP}\) (Fig. 11f)**

From the Subtropical source zone (ST\(_{EP}\)) tracer is almost exclusively confined to the Southern Hemisphere Pacific—with a small amount of tracer ventilating the low-latitude northern Pacific via the eastward transpacific pathways at \( \sim 7^\circ N \), coincident with the ST\(_{WP}\) release. In comparison with the ST\(_{WP}\) release, however, little tracer ventilates the interior of the subtropical gyre. The dominant pathway moving northward and westward away from the source region has a more northerly position between 10° and 20°S. Unlike the Subtropical sourced tracer, the Subantarctic tracer extends beyond the Pacific basin eastward along the ACC pathway, part of which recirculates within the South Atlantic gyre region and westward to the south of Australia. The dominant transpacific pathway is situated deeper and to the south of the ST\(_{EP}\) pathway, consistent with the deep SA\(_{WP}\) pathway. The three eastward pathways are weaker than those for the ST\(_{EP}\), as a greater proportion of the deeper westward advected tracer heads south on reaching Australia. This southward WBC again branches with part moving east around the northern tip of New Zealand and then south to eventually merge with the circumpolar ACC pathway and part feeding the south of Australia pathway and into the Indian and ultimately Atlantic basins.

e. **Water mass census**

More quantitative estimates of the proportion of water subducted in the various subregions and advected northward along pathways described in section 3d are given across two sections at 20°S and the equator (Figs. 12 and 13, respectively). Figure 12f shows the tracer concentration (from the combined Subtropical and Subantarctic regions) across 20°S after 200 model years. In the Indian and Pacific basins this section cuts across the northwestern subtropical gyres. In the Atlantic basin, it lies to the north of the more poleward subtropical gyre and cuts the transbasin pathway that eventually feeds the WBC. Only areas where concentrations exceed 70% are considered, as these areas are relatively rapidly ventilated by SAMW/AAIW and thermocline waters. Figure 13 shows the same features as Fig. 12, only along the equator where the sections cut the WBCs and the eastward spreading pathways. As concentrations are weaker at the equator a >50% cutoff is used to define the census regions in Fig. 13. This analysis shows little sensitivity to changes in the volumetric
region selected (via the cutoff criteria). The only significant difference occurs in the Atlantic where the use of a more extensive analysis area (using a 50%/30% cutoff for the 20°S/equatorial section, respectively) shows an increased fraction of Subtropical east Atlantic source water. This is due to the inclusion of a contribution from the shallow pathway (200-m subsurface maximum seen in Fig. 13f) that originates close to the South African margin (Fig. 10b). Also shown are estimates of the annually averaged net northward transport associated with these areas.

Along both Indian Ocean sections most of the volumetric analysis focuses on the lower thermocline waters at 400–600 m (Figs. 12a, 13a), which originate from the subtropical east Indian subregion (~57%). However, a significant contribution is made by tracer that advects westward from the western Pacific (~22%/25% at 20°S/equator). Relatively little of the Indian Ocean ther-
Mocline and intermediate waters originate outside these two regions. In the Pacific area at 20°S, water is sourced almost exclusively from within the Pacific basin. The deep gyre (Fig. 12d) is ventilated by a greater proportion of Subantarctic region water while the shallow pathway (Fig. 12e) contains primarily Subtropical (mostly eastern) Pacific water. The relative contributions remain very similar in the WBC at the equator. In the Atlantic areas AAIW is dominated by Indian- and Pacific-derived water, with <8% of this water actually being subducted in the east or west Atlantic. Of the extra-Atlantic contributions, the majority of water comes from the Indian basin. In the deeper equatorial area a greater proportion of the water is derived from the Subantarctic region than at 20°S, to be expected as this region includes more direct intermediate water ventilation.

By integrating tracer concentrations globally or over individual ocean basins, for a combination of release subregions, it is possible to estimate basin storage capacities and the importance of basin-scale ventilation to global inventories (see Table 1). In the simulation over 50% of the globally distributed water subducted in the Subtropical and Subantarctic regions originates from the Pacific basin; whereas just over a third originates in the Indian sector and only about 15% is subducted within the Atlantic. By scaling these results by the surface area of the subduction zones in each basin, we see that the rate of overturning must be twice as large in the Indian and Pacific regions as compared to the Atlantic (Table 1, second row). In addition, almost one-half of the water subducted across the entire Subtropical and Subantarctic region ends up being stored in the Pacific (Table 1, third row). This compares to almost one-third being stored in the Indian Ocean, with the remaining 20% in the Atlantic. While this is in apparent contradiction to the more extensive penetration in the Atlantic sector to close the NADW overturning cell, zonally averaged tracer for individual basins (figure not shown) demonstrates that the majority of storage occurs within the Southern Hemisphere subtropical gyres, particularly in the Pacific sector. The estimate of Subtropical
Table 1. Ocean basin contributions to the formation and storage of water subducted in the combined Subtropical and Subantarctic (SAS) region. Row 1 is estimated from the globally integrated tracer concentration from tracer subducted in the SAS portion of each basin. Row 2 is estimated as row 1 divided by the respective surface area of the SAS portion of each basin. Row 3 is estimated by integrating the tracer subducted in the total SAS region over each basin. Row 4 is estimated as row 3 divided by the width of the respective basin. Rows 2 and 4 are shown relative to the Atlantic value.

<table>
<thead>
<tr>
<th></th>
<th>Atlantic</th>
<th>Indian</th>
<th>Pacific</th>
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</thead>
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<td>Relative percentage of global waters that originated from the SAS portion of each basin</td>
<td>14.5</td>
<td>33.7</td>
<td>51.9</td>
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<tr>
<td>Relative overturning strength of each basin (per unit area)</td>
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<td>2.0</td>
<td>1.9</td>
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<td>Relative percentage of SAS water that ends up residing in each ocean basin</td>
<td>20.2</td>
<td>32.3</td>
<td>47.5</td>
</tr>
<tr>
<td>Relative tracer storage per unit longitude per basin</td>
<td>1</td>
<td>1.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

and Subantarctic water transport in the Atlantic of 5.6 Sv ($Sv = 10^6$ m$^3$ s$^{-1}$) at 20°S (Fig. 12; 4.8 Sv at the equator, Fig. 13) is consistent with observations by Schmid et al. (2000), who find 5 Sv moving northward in the western boundary to the north of the subtropical gyre. The transport estimates across the equator are considerably larger for the Atlantic sector than for the other basins, consistent with the greater ventilation found in the Northern Hemisphere of this basin.

4. Discussion and conclusions

Figure 14 shows a schematic of the major pathways identified for the various regional releases. Numbers within braces in the text below refer to the labeled pathways marked on this schematic diagram. Much of this section analyzes these simulated flow pathways in comparison to available observed estimates and other modeling studies.

a. Ventilation of the Atlantic basin

The regional tracer release experiments demonstrate that the offline model ventilation for the Atlantic interior to the north of the Southern Hemisphere subtropical gyre is dominated by pathways that originate or pass through the Pacific and Indian Oceans. The only exception occurs at relatively shallow depths (primarily above $\sigma_0 = 26.6$) sourced near the south Chilean margin (pathway 1) (see also Fig. 10b). The water mass census across the equator suggests that only 5% of water in the WBC is subducted within the Atlantic south of 30°S (percentages are derived from Fig. 13, assuming the small residual is apportioned in the given ratios between all source regions). In contrast, $\sim 51\%$ and $\sim 22\%$ of the water is derived from the Indian and Pacific regions, respectively. The “cold route” pathway via the northern Drake Passage has long been thought to contribute a large volume of water to the THC return flow (e.g., Reid 1989; Stramma and England 1999; Sloyan and Rintoul 2001; You 2002). Here we find that this route is part of the circumpolar pathway 2 at $\sigma_0 = 27.2$ and below, fed predominantly from the eastern Pacific, the western Atlantic, and to a lesser extent the western Pacific and eastern Indian Oceans. While significant tracer enters the Atlantic basin, most of it continues eastward into the Indian Ocean. A portion of tracer does recirculate back into the Atlantic (pathway 13), but no tracer is found to directly ventilate north of the Atlantic subtropical gyre without an Indian Ocean sojourn. This is at odds with the above observational studies, which generally suggest a dominant role from direct Drake Passage ventilation of the upper THC limb, although it is in better agreement with studies such as Gordon et al. (1992).

Other model studies using Lagrangian techniques are, however, suggestive of a greater role for a “warm route” pathway in the THC upper branch. Drijfhout et al. (2005) find that most of the THC return flow is originally subducted in the eastern Indian Ocean. Moreover, less than $\sim 20\%$ of this water originates directly from water entering via Drake Passage. Speich et al. (2002) find that intermediate and mode water passing through the Tasman outflow constitutes a major source of water entering the Atlantic south of South Africa. Their study finds this pathway to be significant in three different OGCMs, having a contribution between 20% and 35% to the Atlantic upper branch flow. Donners and Drijfhout (2004) track Lagrangian particles crossing the equatorial Atlantic in the eddy-permitting OCCAM OGCM. Their results have $\sim 90\%$ of transport bound for the North Atlantic moving westward to the south of Africa. In an apparent contradiction to their direct Lagrangian analysis, these authors also find that section-averaged water mass transports calculated for their model are consistent with a predominant Drake Passage source. The discrepancy is explained by large, near-compensating, east and west flows south of South Africa removing Drake Passage water from, and adding Indian Ocean water to, the Atlantic. This spuriously diminishes the importance of water entering via the Indian Ocean in an analysis that uses integrated mass fluxes across ocean sections (which is the basis for many of the observational analyses; Donners and Drijfhout 2004). Our regional tracer experiments also demonstrate the importance of these
extra-Atlantic sources, with both eastern Indian Ocean release experiments (ST_{EI}, SA_{EI}) demonstrating major westward pathways and water subducted in both the southeast and southwest Pacific zones directly feeding the flow passing to the south of Tasmania.

The simulated pathways entering the Atlantic region south of Africa traverse the Atlantic basin along the northern limb (pathway 8) and to the north (pathway 9) of the subtropical gyre as part of the deep Benguela Current. The shallower levels play a greater part in northward water transport, while deeper levels play a greater role in ventilating the gyre's interior. The southward flowing WBC along the Argentinean margin only recirculates eastward and ventilates the gyre interior at these greater depths. While Drake Passage pathways contribute to the subtropical gyre ventilation, there is no direct flow north of this region. The property maps of Suga and Talley (1995) demonstrate that most AAIW entering the Tropics comes via the northern limb of the subtropical gyre; however, they also find evidence for a possible weak continuous WBC pathway along the Brazilian coastline to the west of the gyre. Both of the simulated westward trans-Atlantic pathways (1 and 9) merge as part of a WBC that extends into the Northern Hemisphere. South of the equator a pathway extends southeastward to again cross the Atlantic. You (1999) presents South Atlantic flow pathways based on the WOCE observations (see their summary Fig. 16). These are in good qualitative agreement with the simulation presented here. The main discrepancy is in the assignment of the relative importance of Drake Passage and Indian Ocean water entering the Atlantic, with You (1999) finding a majority of cross-equatorial intermediate water being sourced directly from Drake Passage. The simulated eastward transatlantic pathway 10 is coincident with the observed northern limb of the You (1999) tropical gyre, although in the simulation this pathway does not appear to recircu-

**Fig. 14.** Schematic diagram showing major ventilation pathways for the Subtropical region (thin lines, black text) and Subantarctic (thick lines, gray text). White circles indicate AAIW formation in (a) the west Atlantic, (b) the east Atlantic, (c) the west Indian, (d) the east Indian, (e) the west Pacific, and (f) the east Pacific regions. Numbers in black circles are referenced in the text.
late westward again, but instead extends to the African margin and moves southward. In a mirror image of the Southern Hemisphere flow, a northeastward pathway extends across the basin just north of the equator (pathway 11). A shallow simulated eastward pathway also exists across the equator (pathway 12). Gouriou et al. (2001) find a series of vertically stacked equatorial jets that extend along the equator in both directions in a set of hydrographic sections spanning the tropical Atlantic. While these jets appear to connect the east and west basins, there is evidence that their direction may reverse on seasonal time scales.

Although the observed low salinity signature of AAIW is only evident as far as the subtropics in the North Atlantic (Suga and Talley 1995), the simulation shows that traces of AAIW extend to high latitudes. The WBC breaks away from the continental margin just south of 40°N and runs along the northern boundary of the subtropical gyre toward northern Europe.

Tracer age experiments demonstrate that the Atlantic shows significantly more rapid Northern Hemisphere penetration than the other basins—closing the strong North Atlantic overturning cell. This is despite the relatively small proportion of the total southern origin water (ST + SA) that is stored in the Atlantic basin (Table 1). This is possible as the overriding majority of subducted water remains with Southern Hemisphere subtropical gyres. Global budget calculations also suggest that the rate of Atlantic overturning is considerably weaker than in the Indian and Pacific Oceans (Table 1). Although not directly comparable, this appears to be at odds with observed CO₂ inventories, which are suggestive of larger reservoirs of CO₂ in both the North and South Atlantic relative to the other basins (Sabine et al. 2004). Difficulties in partitioning these reservoirs into components ventilated by NADW or AAIW/SAMW do not permit a direct comparison however.

b. Ventilation of the Indian Basin

The simulated pathways ventilating the Indian Ocean region originate from south of Australia (paths 3 and 4), to the south of Africa (pathway 2), and from the central/southern Indian Basin. The latter two routes only directly ventilate the subtropical gyre region, although part of the south of Africa pathway eventually ventilates the northern Indian basin via pathways encompassing the south Pacific subtropical gyre. These pathways are evident in the circulation fields of Davis (2005, their Figs. 11 and 13) based on averaged intermediate-depth autonomous Lagrangian floats. To the south, a broad observed advection pathway is associated with the deep ACC. Northward branches take water from this circumpolar pathway in the central and eastern basins consistent with the simulated pathways (13 and 4, respectively). The POCM shows no significant ventilation via the Indonesian Throughflow in these density classes. Water entering the Indian basin via south of Africa does so to the south of ~40°S. Water from this ACC pathway is entrained into the subtropical gyre primarily in the central basin, recirculating westward south of 30°S (pathway 13). Direct ventilation from the water subducted in the central Indian Ocean also enters the subtropical gyre in the central basin (pathway 7). Our water mass analysis suggests that ~61% (~54%) of water moving northward at 20°S (the equator) is subducted in the eastern Indian Ocean. The remainder is mostly derived from the Pacific basin—21% (22%) or to the north of 30°S.

The pathway entering the Indian Ocean south of Australia is fed by water formed primarily in the eastern Indian basin but also across the Pacific region. A part of this water can be traced from the Pacific moving westward as a narrow boundary current south of Tasmania and continuing close to the Australian margin to its southwest tip. This pathway, which ultimately connects to the North Atlantic, has been identified in a number of other OGCMs (e.g., Speich et al. 2002) where it represents an important source of intermediate water in the North Atlantic (see section 4a). Near the southwest tip of Australia the flow splits with the shallower flow traveling north along western Australia before curving northeastward across the basin (pathway 3) while the deeper portion moves westward to the central basin before curving northwestward to reach Madagascar just to the south of the shallower flow (pathway 4). The observed Lagrangian float pathways (Davis 2005) also show strong westward flow south of Australia and the subsequent splitting into the two transindian routes. Along the eastern margin of Madagascar the flow bifurcates to the north and south. A greater proportion of the flow moves southward from the more southerly deep transindian pathway than the more northern shallow pathway. The stronger southern branch moves south and then westward to the south of Madagascar where it again splits north and south on reaching the African margin, with the southward flow connecting to the Atlantic via the Agulhas system and the northward flow moving north as a WBC. The float observations (Davis 2005) also show this bifurcation around Madagascar; however, observations suggest a mean southward flow to the west of Madagascar. Simulated flow fields (not shown) show both northward and southward flows sandwiched in this channel. The discrepancy with the float flow fields may stem from the significantly higher tracer concentrations on the south-
ern side of Madagascar, giving the impression of a purely northward flow. Optimum multiparameter property maps presented by You (1998) are also suggestive of this north–south bifurcation, particularly at deeper intermediate levels.

The pathway moving northward along western Madagascar has an offshoot near the north of the island that extends eastward across much of the basin (pathway 14). The main flow however moves westward around the northern tip of Madagascar and continues northward as a WBC along the African continent. Just south of the equator a further pathway branches south–eastward across the basin. Unlike the Atlantic and Pacific Oceans, however, there is no eastward branch along the equator at intermediate depths. North of the equator most of the flow moves northeastward away from the coastline (although a weak boundary current persists as far as the Gulf of Aden). This pathway heads toward the southern tip of India from where a cyclonic circulation takes part of the water into the Arabian Sea. A weak signal also persists across the basin and anticyclonically around the Bay of Bengal. The Lagrangian float pathways (Davis 2005) show a WBC extending to the equator with eastward flow in the equatorial region. Coherent float circulation pathways into the Northern Hemisphere are, however, indistinct.

Our Indian Ocean circulation compares well with many of the observed features of the optimum multiparameter and velocity potential analysis of You (1998, his Figs. 9–11a and 18)—including increased northward ventilation in the central basin, western intensification along eastern Madagascar and Africa, strong ventilation derived from south of Australia, and flow pathways extending to the south of India. We do, however, find discrepancies with the resulting flow pathways postulated by You (his Fig. 19). Part of this discrepancy lies in our focus on AAIW while You includes other intermediate water masses. In addition, the modeling approach allows us to resolve smaller-scale features and hence separate pathways that would be indistinguishable from the much sparser observations. You (1998) postulates a pathway from the Southern Ocean to the Tropics in the central basin, whereas our analysis suggests that this is not in fact a continuous pathway. Instead we find a pathway from the ACC region that initially moves northward but quickly recirculates westward within the subtropical gyre. A second pathway moves west from the southwest tip of Australia into the central basin before curving north–westward. You (1998) finds AAIW ventilation north of Madagascar primarily due to a recirculating gyre in the central/western basin that extends into the Northern Hemisphere and a southward flow at the far western boundary (north of Madagascar), while our simulation has a WBC extending to the north of the equator with eastward pathways ventilating much of the western basin. This would explain the elevated AAIW water mass contribution of You (1998) extending east from the western margin. The simulation is also in good agreement with the steric height maps of Reid (2003) at 800 db in the Southern Hemisphere. Notably the maps show pathways from the south of Tasmania westward to Madagascar from where the flow bifurcates, as in the simulation. A distinct pathway can also be traced from south of Western Australia sitting to the north of the aforementioned route, similar to pathway 3. Recirculations within the subtropical gyre also exist that move northward in the central basin and return westward well to the south of Madagascar. Like Davis (2005) but in contradiction to the simulation, Reid (2003) finds southward flow west of Madagascar. While Reid (2003) shows a northward WBC in the Arabian Sea between 10° and 20°N, it is not connected to the Southern Hemisphere WBC, as seen in the simulation.

c. Ventilation of the Pacific basin

The simulated ventilation of the Pacific region by Indian and Atlantic source waters only takes place via the circumpolar ACC pathway. Northward penetration primarily occurs in the far southeastern basin where a bifurcation takes the remainder of the flow eastward through the northern Drake Passage. This circumpolar pathway is fed to some extent by all of the surface subregions, although the southeastern Pacific (where the simulated convection reaches to depths of almost 1000 m) is the dominant source. Water flowing on this pathway is entrained into the eastern extent of the deep subtropical gyre and travels northward to ~40°S, making an “S”-shaped detour from the Chilean margin under the influence of the bathymetry of the Chile Rise. North of 40°S the pathway turns westward across the basin toward Australia.

Water subducted in the western Pacific to the north of the annually averaged \( \alpha_0 = 27.2 \) isopycnal only ventilates the western portion of the subtropical gyre primarily at shallower depths. Water subducted farther to the south does not ventilate the western interior of the gyre but moves eastward. Centered between \( \alpha_0 = 26.8 \) and \( \alpha_0 = 27.0 \) a strong ventilation pathway (pathway 5) takes water northward in the central/western basin to the northern limb of the gyre where it again moves westward to the Australian margin near ~20°S. Water subducted in the eastern basin is injected into the northern limb of the subtropical gyre. The more northerly subducted water stays at shallower depths and crosses the Pacific at lower latitudes (pathway 16),
reaching the western basin near the northern tip of Australia. The more southerly subducted water moves along the northern limb of the deep gyre (pathway 6) along the same route as water feeding from the circum-polar ACC pathway 2. As the anticyclonic circulation reaches the western basin, the flow bifurcates into northward and southward flowing boundary currents, although the lower latitude pathway that reaches the western boundary to the north of Australia only continues northward. The southward branch including the deep East Australian Current extends to below Tasmania at intermediate depths greater than \( \sigma_0 = 27.0 \). From here the flow turns westward and pathways extend into the Indian Ocean. At shallower depths the flow recirculates eastward, just south of \( \sim 30^\circ \text{S} \), passing to the north of New Zealand. The northward WBC can be traced to \( \sim 15^\circ \text{N} \) along the east Philippine margin via a boundary flow east of Papua New Guinea and Irian Jaya. This matches well with observations based on historical and repeat hydrographic sections that suggest that the WBC extends only as far as \( \sim 15^\circ \text{N} \) (Qu and Lindstrom 2004). Furthermore, AAIW concentrations remain high across the basin with the most northerly observed signal occurring in the eastern Pacific. Intermediate water also spreads into the Celebes/Banda Seas, but little tracer is evident entering the Indian basin via the Indonesian Throughflow (ITF) in the model. This is at odds with observations that suggest that the ITF is partly composed of water coming from the South Pacific (Gordon and Fine 1996) with both AAIW/SAMW (Schmitz 1995) and thermocline/surface water (Sloyan and Rintoul 2001) playing a role. While the POCM possesses a realistic throughflow (8.5 Sv), transport is constrained above 500 m and is strongest near the surface. The core of the northward-flowing boundary current is, on the other hand, centered at greater depths. In addition, the source of the ITF is, to a large extent, north of the point where the boundary current breaks east and crosses the Pacific basin, in a region of low tracer concentration. This results in only a weak AAIW/SAMW tracer pathway via the ITF that is swamped by the pathway to the south of Australia. In the equatorial region an eastward pathway is evident at and above the \( \sigma_0 = 27.0 \) isopycnal. Below this the equatorial circulation is reversed, transporting poorly ventilated water from the west. In the northern Tropics a further pathway extends eastward from the western boundary at \( \sim 10^\circ \text{N} \). The steric height maps derived by Reid (1997) also show eastward equatorial flow but suggest that flow extends from the surface to depths of 4500 m. He also finds that the cross-equatorial flow turns eastward around \( 10^\circ-12^\circ \text{N} \); however, the observed pathway appears to recirculate westward unlike the simulated pathway.

The Lagrangian float circulation field of Davis (2005) again shows a dominant pathway in the deep ACC that is strongly steered by the underlying bathymetry. Davis (2005) notes the main departures from this pathway occur near \( 135^\circ \text{E} \), as a retroflection into westward flow south of Australia and a northward flow into the subtropical gyre over the East Pacific Rise. Along the western limb of the gyre some flow continues south around Tasmania, while the remainder moves eastward around the northern tip of New Zealand where it flows southward to ultimately rejoin the ACC pathway. These pathways are well captured in the simulation. Agreement is poor, however, at the eastern boundary of the subtropical gyre. Davis (2005) finds the eastern limb of the gyre to be well removed from the South American margin, located just east of the East Pacific Rise, while the simulation shows the strongest flow adjacent to the continental margin. The simulation does however show northward flow away from the ACC pathway 15 in the East Pacific Rise region, and Davis (2005) notes a lack of float data east of this region. The steric height maps of Reid (1997) at 800 and 1000 dbar demonstrate the more poleward center to the subtropical gyre found at these depths compared to the surface, in agreement with the simulation. Like Davis (2005), and in contrast to the simulation, he also finds that this gyre turns northward in the central/western basin. Part of the flow moves as part of the gyre to reach the western basin near \( 20^\circ \text{S} \), while the remainder turns cyclonically near \( 30^\circ \text{S} \) and poleward again along the Chilean margin.

The water mass analysis (see Figs. 12, 13) shows that the northern limb of the subtropical gyre and water within the northward WBC comprises an almost even split between waters subducted from the western and eastern sides of the Pacific. No significant contribution is made to the budget from water originating outside the basin in the offline model.

d. Conclusions

We have used an offline high-resolution OGCM in conjunction with a variety of simulated tracers to validate the model performance in capturing intermediate and thermocline depth ventilation. We have also diagnosed the pathways of AAIW, mode, and thermocline water away from their regions of formation. At present, an offline methodology is the only feasible means of integrating high-resolution ocean models for the extended periods—up to thousands of years—required to investigate circulation for intermediate, deep, and abyssal waters.

The use of a monthly climatology to force the model
has the drawback of averaging out much of the important eddy activity, and as such the focus of this study was the mean advective pathways and time scales of intermediate and mode waters. Future work might include nonaveraged fields taken from a number of years of online model integration, or an explicit parameterization of the effect of eddies on the mean ocean flow. The lack of convective activity associated with the offline methodology is overcome by the addition of a mixed layer parameterization. Favorable comparisons between model and observed CFC indicate that the mixed layer scheme results in reasonably realistic pathways and rates of ventilation in the offline simulation.

The use of an age tracer provides a characteristic time scale for ventilation by southern source waters. The age within the subtropical gyres ranges from 50 to 150 yr, with the most rapid ventilation occurring within the Atlantic gyre. There is a clear indication of western intensification north of the subtropical gyres, although only in the North Atlantic do we find substantial interhemispheric transport of AAIW. The use of discrete surface source regions (Fig. 2) facilitates the identification of intermediate and thermocline pathways originating at different locations in the Southern Hemisphere. In the Atlantic, contrary to some of the observational studies but in agreement with other modeling results, the offline model shows that the majority of water forming the THC return route is sourced from the Indian and to a lesser extent the Pacific basins via a pathway to the south of South Africa. In contrast, water ventilating areas north of the Pacific subtropical gyre are almost exclusively derived from water subducted within the Pacific basin. Northward ventilation in the Indian Ocean originates from both the eastern Indian and the Pacific basins. Atlantic sourced water helps to ventilate the Indian Ocean subtropical gyre but does not make a direct contribution to pathways north of this.

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