The Age of Water and Ventilation Timescales in a Global Ocean Model

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ABSTRACT

The age of water in the World Ocean is studied using a passive age tracer introduced into a global ocean model. Additional information is derived from a transient "dye" tracer that tracks the time-dependent spreading of surface waters into the model ocean interior. Of particular interest is the nature of ocean ventilation over the 10–100-yr timescale, as well as the simulated age of deep and bottom water masses. In the upper model levels young water is found to correspond with regions of convergence (and downwelling) in the surface Ekman layer. Upwelling and convection are both shown to age the upper ocean by entraining older waters into the surface mixed layer. In the deep model levels, water age varies greatly between oceans, with young water found in convectively active regions (in the North Atlantic and in the Ross and Weddell Seas), and old water found in the deep North Pacific. The oldest water mass mixture (located at 2228-m depth in the western Pacific Ocean) is dated at 1494 years, made up of a combination of sources of water whose age varies between 500 and 5000 years. In the bottom layers of the model, Antarctic Bottom Water ventilates the extreme Southern Ocean over a 50–100-yr timescale, whereas the age approaches 1000 years in the northern limit of the Pacific basin. An analysis of age on the $\sigma_t = 27.4$ kg m^{-3} isopycnal surface shows North Atlantic Deep Water (NADW) leaving the Atlantic Ocean with an average age of 300 years, although part of this water mass mixture is as young as 60 years. The young signal of NADW penetrates the Indian Ocean and the South Pacific via the circumpolar current over a timescale as short as 15 years, although water penetrating the far deep North Pacific is not detected in significant quantities (using a 10% concentration criterion) until about 500 years after the NADW formation time. A volumetric census of age in the World Ocean model shows relative maxima at 2°–3°C, 1200 years (corresponding to water in the deep North Pacific), and at 3°C, 300–500 years (corresponding to water in the deep Atlantic Ocean). The parameterization of mixing in the ocean model partly determines age, with an isopycnal mixing scheme reducing the deep and bottom water ventilation timescale by about 30%. By monitoring the gradual penetration of surface dye into the most remote ocean grid boxes, the time taken to ventilate the entire World Ocean model can be estimated to be around 5000 years.

1. Introduction

Oceanographers refer to the "age" of seawater as the time elapsed since a given water parcel was last exposed to the atmosphere. The atmosphere imprints a temperature–salinity (T–S) and dissolved gas signature on the upper ocean via surface exchanges of heat, freshwater, and natural and anthropogenic gases (e.g., O_2, CO_2, CFC-11). Subsequent to the subduction or convective overturn of a given water parcel, it is only the surrounding environment (and for dissolved gases, the natural decay of chemical isotopes) that modifies the original atmospheric imprint. The clear analogy with biological processes renders the term age quite appropriate in the oceanographic context.

The World Ocean circulation at its largest scale can be thought of as a gradual renewal or ventilation of the deep ocean by water that was once at the sea surface. While many researchers have developed notions of exactly how this renewal takes place, there remains much uncertainty in the timescales involved in the ocean renewal process. Some insight can be gained from the concentration of certain chemicals in the ocean [e.g., Carbon-14 (^{14}C), Stuiver et al. 1983; ^{14}C, O_2, Broecker et al. 1991; CFC-11, CFC-12, Smethie 1993], although the mixing of waters of different chemical concentrations typically biases the age estimate toward younger values (Smethie 1993; Hirst 1995). In addition, short atmospheric histories (bomb-produced ^{14}C, CFCs, tritium) and the influence of biological processes (^{14}C, O_2, CO_2) render the age estimate either approximate or inadequate for the global ocean.

An understanding of the age of water and the ventilation timescale in ocean models is important for a variety of reasons. First, the estimates obtained complement the approximate values suggested from observed geochemical tracers. Second, the ventilation timescale sheds insight into the role of the oceans in moderating climate change in the world's environment. In particular, the response of a climate model to atmospheric change will be determined in part by the way

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the ocean model redistributes heat vertically and meridionally, and therefore by the nature and timing of ocean ventilation. For example, a model with "young" water at depth indicates rapid overturning of the local surface water, which typically translates to a regional moderation of climate change (e.g., Manabe and Stouffer 1994). In this paper we present the results of some numerical simulations of the age and ventilation timescales of water in a global ocean model. The age tracer represents the weighted average time for the source water components of any ocean grid box to arrive from the surface to that grid box. An additional tracer of surface water concentration tracks the transient penetration of surface waters into the ocean interior.

There have been several studies that have considered the use of passive tracers for determining the ventilation pathways and timescales of flow in ocean general circulation models (GCMs). Certain studies adopt *realistic* geochemical tracers that can be compared directly with observed ocean patterns (e.g., tritium, Sarmiento 1983; ^{14}C, Maier-Reimer and Hasselmann 1987; Toggweiler et al. 1989a,b; CFC-11 and CFC-12, England et al. 1994), while other studies adopt *idealized* tracers that selectively measure certain aspects of ocean model ventilation (e.g., Cox 1989; Stocker et al. 1992; Hirst 1995). The usefulness of the realistic tracers relates to the critical assessment of the reliability of ocean models in representing the real ocean system (e.g., for use in coupled climate models), whereas the idealized tracers give a clear diagnosis of certain aspects of model behavior. For example, Cox's (1989) numerical experiments isolate the relative contribution of certain source regions to the composition of water in the ocean interior. His study, however, does not address the question of ventilation timescales and the age of the water mixture obtained. To address this additional question, a separate set of age tracers would be required to determine exactly how long each source water type had taken to ventilate the ocean interior, effectively doubling the computational load of the passive tracer component of the model. Hirst (1995), on the other hand, tracks both the relative concentration and the volume-weighted age of North Atlantic Deep Water (NADW) by configuring two passive tracers of water leaving a subsurface zone of the far North Atlantic. His study could easily be generalized to an arbitrary number of source waters, although the computational load can become heavy with too many additional tracers. In principle, the ocean modeler requires $2n$ passive tracers to study both the ventilation timescale and the relative concentration of n source water types.

Until now, no study has been made of the overall age and interior water ventilation timescales operating in a global ocean model. If the interest of the diagnosis remains on the rate of ocean ventilation from water that was once at the sea surface (i.e., the location of the original water mass formation is of secondary importance), then only two passive tracers are required to solve the problem. In this study we diagnose the results of including an age tracer and a transient surface water dye tracer in a global ocean model. Of particular interest is the nature of ocean ventilation over the 10–100-yr timescale, as well as the simulated age and renewal timescales of deep and bottom waters.

The rest of this paper is divided into four sections. We describe the ocean model and the age and dye tracers in section 2. The general circulation of the model is detailed in section 3, with particular focus on the vertical convection, near-surface vertical motion, and meridional overturning, since these represent the main renewal processes operating in the model ocean. In section 4 we discuss the resulting simulations of age as well as the ventilation timescales operating in the World Ocean model. Finally, section 5 covers the discussion and conclusions.

2. Model description

a. The World Ocean model

The ocean model used in this study is the Bryan–Cox ocean GCM developed at the Geophysical Fluid Dynamics Laboratory (Bryan 1969; Cox 1984; Pacanowski et al. 1991). The specific configuration of the model is identical to that used by England et al. (1994), and so only a brief overview is presented here. The model domain has a global coverage of the World Ocean extending from the Antarctic continent to the North Pole, with a realistic representation of the ocean bottom bathymetry. The model grid spacing is 3.75° longitude by approximately 4.5° latitude with 12 unequally spaced vertical levels. The effects of mesoscale eddies are taken into account implicitly by simple parameterizations of the subgrid-scale mixing of momentum and tracers. The horizontal (A_{MH}) and vertical (A_{MV}) viscosity coefficients are taken to be constants independent of depth (A_{MH} = 2.5 × 10^9 cm^2 s^{-1}; A_{MV} = 50 cm^2 s^{-1}). Vertical diffusion (A_{HV}) is lowest in the surface layer (0.3 cm^2 sec^{-1}), increasing below the thermocline toward a maximum of 1.3 cm^2 s^{-1} in the deeper model levels. The horizontal diffusivity (A_{HH}) reflects the ocean's tendency to mix more rapidly at the surface than at depth (A_{HH} = 1 × 10^7 cm^2 s^{-1} in the surface level decreasing gradually toward 0.5 × 10^7 cm^2 sec^{-1} at depth). Convection is treated implicitly by the model; whenever vertical instabilities are detected the diffusion rates are increased to simulate complete mixing over the unstable portions of the water column. This vertical mixing homogenizes T–S and passive tracers (for example, CFC-11, ^{14}C, model age) over the model levels originally detected to be dynamically unstable. No deep accelerated time stepping is incorporated into the model; the tracer time step remains constant at 30 hours throughout the model domain.

The ocean is forced at the sea surface by seasonally varying climatological boundary conditions of temperature, salinity, and wind stress. The atmosphere to ocean momentum flux is determined from the wind stress climatology of Hellerman and Rosenstein (1983) interpolated spatially onto the model grid and temporally at each time step. The effective surface fluxes of heat and freshwater are implied by restoring the model's surface layer temperature and salinity toward the Levitus (1984, 1986) seasonal climatology [using a Newtonian timescale of (30 days)$^{-1}$ for T and (50 days)$^{-1}$ for S]. Apart from including a seasonal cycle in the sea surface conditions, the control ocean model carries none of the boundary condition embellishments available for improved T–S representation (see, e.g., England 1993).

In order to study the sensitivity of the water mass age and ventilation timescales to the choice of mixing parameterization, an experiment with increased tracer diffusion is also considered. It is simply the control ocean model with an enhanced along-isopycnal mixing [following the formalism of Redi (1982)] using isopycnal diffusion coefficients identical to the model of England (1993). The background Cartesian mixing is unchanged from the control case, leaving the experiment with an unrealistically strong blending of water mass properties (such as age). This case then provides an upper bound on how strongly the parameterized diffusion processes might determine the rate of ventilation of deep and bottom waters in the model. In the future we plan to undertake a more systematic study of the sensitivity of simulated age to a range of mixing coefficients and parameterizations. For the present, one simple case is considered to enable an estimate of how strongly the diffusion processes might determine the model water age.

b. The age and dye tracers

Generalizing the definition of Haidvogel and Bryan (1992), the model ocean age of water (A) originating from a given region (V_s) can be defined according to the equation

$$dA/dt = \mathcal{L}(A) + 1, \qquad (1)$$

where $\mathcal{L}(A)$ refers to the standard tracer diffusion (and implicitly, convection) terms in the model and where A obeys the boundary condition

$$A(x, y, z) = 0 \qquad (2)$$

over the considered source water volume $(x, y, z) \in V_s$, and the initial condition $A(x, y, z) = 0$ over the entire model domain. In our study, V_s is defined as the surface model level over the global ocean. In Hirst's (1995) study, V_s corresponds with the North Atlantic north of 30°N and below 1250-m depth. In effect, A is incremented by the model time step during each time step, with the only processes limiting the indefinite growth of A associated with the ventilation of the ocean interior by water originating from the sea surface (or in the general case, the volume of water defined by V_s). By definition, water in direct contact with the sea surface (i.e., the upper model level) retains an age of zero throughout the model integration. Regions of persistent surface convective overturn acquire near-zero ages during wintertime months, since the surface age signal is overturned on short timescales (the model time step is just over one day) during the convection process.

In an equilibrated state, the age tracer (A) measures the *volume-weighted* timescale at which any point in the ocean interior communicates with the sea surface. In a primitive equation ocean model, the source water of any given grid box will be some finite combination of waters that originate from the surface model level. With the gradual mixing and advective processes that operate in both the real and modeled ocean, any part of the ocean interior is likely to derive its water mass properties from a wide range of locations (see, e.g., Cox 1989). However, certain regions of the ocean are overturned or ventilated somewhat more rapidly than elsewhere (e.g., the North Atlantic and Southern Oceans), so some dominant signal will appear. In addition, the relative contribution of the source waters determines the properties of water at the given grid box. It is not the purpose of this study to decipher exactly where each interior grid box derived its source waters; in the limit such a study requires one extra tracer for any given surface region of interest (and two if the timescale for ventilation is required). Rather, we are concerned with the question of how rapidly surface waters communicate with the ocean interior and how quickly a complete grid box is renewed by water that was once at the sea surface.

The final equilibrated age of any interior grid box will be derived from a combination of a finite (though potentially very large) number of sources having a variety of ventilation timescales. For example, water in the deep Pacific Ocean might have an age mixture of 1500 years; though this could be a complex combination of waters as young as several hundred years, with additional components of varying ages up to many thousands of years, and perhaps older. Very old water can exist when a specific water parcel undergoes many recirculations within a given basin or around the circumpolar ocean, without being upwelled or convected into the surface mixed layer. Such water might age significantly before entering a slow pathway into a quiescent part of the World Ocean, where it is destined (through the lack of any strong ambient circulation) to reside in the deep ocean for a very long time. It is of some interest, therefore, to track the extremes in water mass age that might exist in any given equilibrated mixture. To study this a transient dye experiment is performed with the concentration of dye (D) governed by the standard tracer conservation equation; namely,

$$dD/dt = \mathcal{L}(D) \qquad (3)$$

and where D obeys the boundary condition

$$D(x, y, z) = 1 \text{ unit m}^{-3} \quad (4)$$

over the considered source water volume $(x, y, z) \in V_s$, and the initial condition

$$D(x, y, z) = 0 \quad \text{unit m}^{-3} \text{ for all } \quad (x, y, z) \notin V_s. \quad (5)$$

As such, water in direct contact with the surface (i.e., the uppermost model level), has a dye concentration D of 1 unit m^{-3} throughout the integration, whereas the interior grid boxes are gradually filled with the surface dye at a rate proportional to the ventilation timescales of the model. Water in convectively active regions will be rapidly flushed by the idealized surface dye, whereas water in the deep North Pacific might wait hundreds of years until the first significant levels of surface dye contaminates the region. The transient response of the model to the injection of dye will track the gradual renewal or flushing of the ocean system by water originating from the sea surface.

While the dye experiment provides useful information during the course of the model integration, the age tracer is of little value until the entire age field is completely equilibrated. For example, a 1000-yr integration of the model might not give the true age of water whose mixture is as young as 50 years, because a component of that water mass might include upwelled deep water whose true age (say 1500 years) is not attained until several thousand years of model integration. To ensure that A represents the true age of the model water mass mixtures, the age experiments are run until little change in age is detected throughout the model domain (a criterion of less than 6-months aging per 100-yr integration is required over all model grid points). The control age experiment takes 4650 years to meet this criterion, with the oldest water mass mixture reaching an age of just under 1500 years in the deep Pacific Ocean.

A measure of the time taken to ventilate a given region of the ocean can be obtained from the transient surface dye experiment (using a criterion of, say, 99% renewal in the region of interest). To study the nature of ocean ventilation over very long timescales, the dye experiment is integrated until this renewal criterion is met in even the most remote locations. Typically this requires similar integration times as the equilibration of the passive age tracer.

3. Model ocean circulation and vertical convection

The location and timescale of ocean ventilation will be determined largely by the vertical velocity and vertical convection in regions of water mass formation, and in addition the horizontal circulation in regions not directly ventilated during the vertical formation process. Along with the parameterized vertical and horizontal diffusion, these processes define the transfer of tracers from the sea surface into the ocean interior in the model.

Two caveats should be mentioned concerning vertical tracer communication in the model. First, the model parameterization of convection does not strictly involve a circulation; tracers are mixed vertically outside any calculation of vertical motion. In fact, certain instances of vertical convection can actually induce an upward motion in the velocity field (Rahmstorf 1995). Second, the vertical motion itself is not a prognostic variable of the model; it is simply determined diagnostically through the continuity equation.

a. Vertical convection

In the context of the age simulations, the convective activity of the model is somewhat more important than the meridional overturning. This is because the timescale for convective adjustment in the ocean (hours to days) is much more rapid than the timescale for vertical motion. For example, the vertical motion (or meridional overturning) would require just over 30 years to communicate *some* surface level information to 1000-m depth, based on a generous scale vertical velocity of 10^{-6} m s^{-1}. Convection in the model efficiently homogenizes entire unstable water columns during just one time step (i.e., just over 1 day). The meridional overturning maps are more relevant, in the ventilation context, for revealing renewal rates *from* regions of convective activity (e.g., the outflow rate of NADW).

The overall maximum depth of water convectively overturned from the sea surface is shown in Fig. 1a. The map is derived from a ten-year integration of the equilibrated ocean state, when the major variations in convective activity occur from one season to the next, and little interannual variability is detected. Convection is intense during the wintertime months, and nearly absent during summer because of the stabilization of the surface mixed layer by summer heating (see England et al. 1994). Convection during the Northern Hemisphere winter occurs virtually exclusively in the North Atlantic and North Pacific Oceans, with much deeper convective events (up to 1200-m depth) in the North Atlantic. The Southern Hemisphere winter sets off deep convection in a broad region of the Southern Ocean. Deep convective layers of up to 2500-m depth are found in the Ross and Weddell Seas during July–October. A band of convective overturn in the South Pacific Ocean progressively deepens from east of Australia toward Cape Horn, with mixed layers 750-m thick being convected in the southeast Pacific Ocean. This band of convection is important for the formation of Subantarctic Mode Waters and subsequently the renewal of Antarctic Intermediate Water (AAIW) in the model ocean (England et al. 1993).

Recent simulations of CFC uptake in the ocean model by England et al. (1994) suggest that the intensity of convective overturn is too strong and pervasive in the Southern Ocean. There appears to be not enough recirculation of older Circumpolar Deep

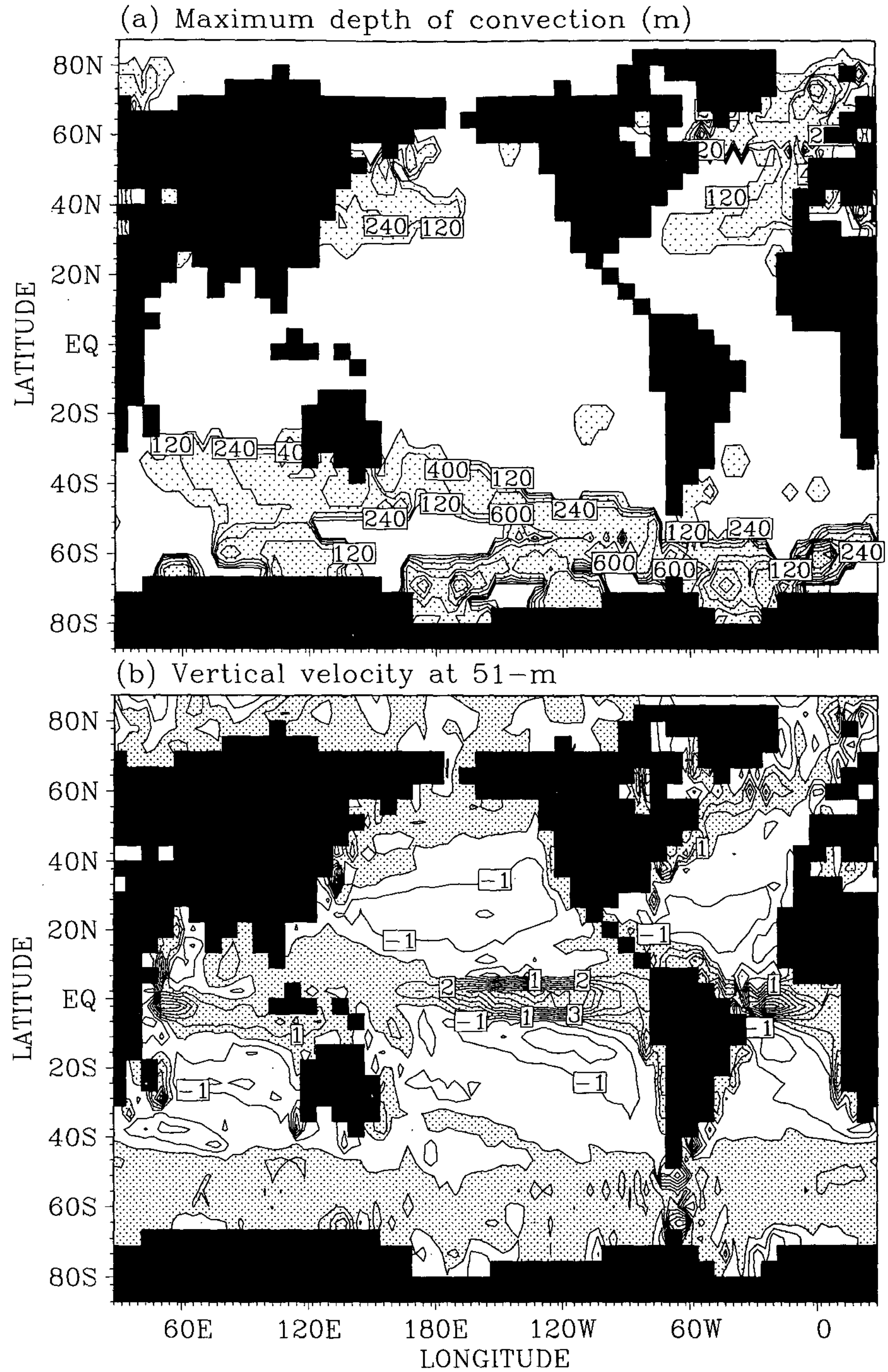

FIG. 1. (a) Maximum depth of surface level convective overturn (m) during a complete annual cycle of the equilibrated ocean model. (b) Vertical velocity (10^{-6} m s^{-1}) at 51-m depth. In (a) contours are chosen that coincide with successive model level depths. Regions of convective overturn greater than 120 m (i.e., the upper three model levels) are shaded. In (b) shaded regions denote surface level upwelling. Contours in (b) are drawn at uniform intervals of 10^{-6} m s^{-1}.

Water (CDW) in the latitude band 55°–70°S. The lack of an old variety of CDW enables local surface waters to have an exaggerated contribution to the properties of the ocean interior, with modeled CFC concentrations greatly exceeding observations in the region. The implications are that the model ventilation timescale is too rapid in the subpolar Southern Ocean, so we can expect the corresponding age of water to be somewhat too young at depth in the region.

b. Vertical advection

The near-surface annual mean vertical motion diagnosed in the global ocean model is shown in Fig. 1b. Vertical motion between the first and second model levels is largely determined by the curl of the surface wind stress (i.e., the divergence in the surface Ekman transport), with water being upwelled along the tropical oceans and under the subpolar westerlies. In addition, water tends to upwell in the western boundary currents because of a deficiency in the parameterization of horizontal mixing across density fronts in the Bryan–Cox Ocean GCM (McDougall and Church 1986). In regions of near-surface upwelling, older water will be entrained into the upper model levels, yielding a mixture of thermocline water that is somewhat older than that directly ventilated by the wind-driven circulation. In regions of surface downwelling (largely in the subtropical convergence zone), direct ventilation of the thermocline occurs via the vertical advective fields. This crudely corresponds to the model equivalent of the ventilated thermocline of Luyten et al. (1983).

c. Meridional overturning

The annual mean meridional overturning in the control ocean model is mapped in Fig. 2. The corresponding overturning map in the enhanced isopycnal mixing case is very similar (England 1993; England 1995b), and so is not drawn here. The production rate of NADW is realistic at 20.1 Sv (Sv ≡ 10^6 m^3 s^{-1}), although only 8.5 Sv flows out into the Southern Ocean. This is due to a substantial component of upwelling in the Gulf Stream, an artifact of the model's parameterization of subgrid-scale mixing (see, e.g., Gent and McWilliams 1990; Danabasoglu et al. 1994). In the Atlantic basin, a further 5.3 Sv of recirculated bottom water originating from the Weddell Sea outflows under the NADW (Fig. 2b). A total of 26.0 Sv of Antarctic Bottom Water (AABW) is overturned off Antarctica, the majority upwelling south of 60°S. Seasonal changes in the thermohaline overturning rates remain curiously small (~1 Sv variation in NADW production and ~0.5 Sv variation in AABW; England et al. 1994). This contrasts to the rapid response of the model overturning to the shifting wind stress field. Evidently the deep overturning responds to changes in convective intensity more slowly than the seasonal timescale (3–6 months), whereas surface Ekman transports and divergences in flow respond rapidly to the wind stress cycling.

4. Water mass age and ventilation timescales in the model

a. Basin-averaged latitude–depth sections of age

Because of interseasonal variations in convective overturn and vertical motions (and therefore also in the simulated age), the age data presented in this paper correspond with the annually averaged age obtained at the end of the model integration. The simulated age of water in the World Ocean model is summarized in Fig. 3, which shows the basin-averaged latitude–depth sections of age in the Atlantic, Indian, and Pacific Oceans. Broadly speaking, much of the water in the deep Atlantic Ocean is 50–500 years old, indicating somewhat more recent ventilation than water in the deep Indian (200–800 years old), and Pacific (100–1350 years old) Oceans. The ventilation of the Atlantic Ocean is due in part to the convective overturn and outflow of NADW (particularly at depths of 1500–2500 m), and in part to the inflow and recirculation of AABW (from 2500 m to the bottom, see Fig. 2b). The oldest water in the Atlantic basin is found in the bottom model levels near the Greenland–Scotland Ridge (540 years old), although a distinct signal of relatively old upper CDW (originating from the Pacific Ocean) contaminates the Atlantic at 1600-m depth near 50°S (Fig. 3a). This older Pacific water enters the Atlantic Ocean directly via the Drake Passage (see also Fig. 4c).

The influence of the inflowing AABW into the northern ocean basins is particularly evident in the Atlantic and Pacific sectors (Fig. 3). The oldest water in the far North Pacific Ocean is located at 2228-m depth in the Gulf of Alaska (near 140°W, 58°N), comprising a mixture of age 1366 years. In contrast, Pacific Ocean bottom water age is at most 965 years, because of the influence of inflowing AABW along the bottom model levels. The Indian Ocean age maximum also appears at mid-depth levels (2228-m depth, Fig. 3b). In short, only the Atlantic Ocean is ventilated over centennial timescales at all model levels; it has the interleaving influence of AABW, NADW, AAIW, and thermocline ventilation to ensure relatively short residence times throughout the water column. In contrast, both the Indian and Pacific Oceans lack a direct source of deep water ventilation. Water in the 1500-m to 3500-m layer is only gradually ventilated by upwelled AABW and recirculated NADW. This amounts to ventilation over the timescale of millenia.

b. Age on model depth levels

The overall maximum and minimum age mixtures found at each of the 12 model levels are presented in Table 1. The youngest waters are found either in the North Atlantic or Southern Ocean, whereas the oldest water is consistently located in the Pacific Ocean (most often near the equatorial region or in the far north of the basin). The oldest water mass mixture in the global

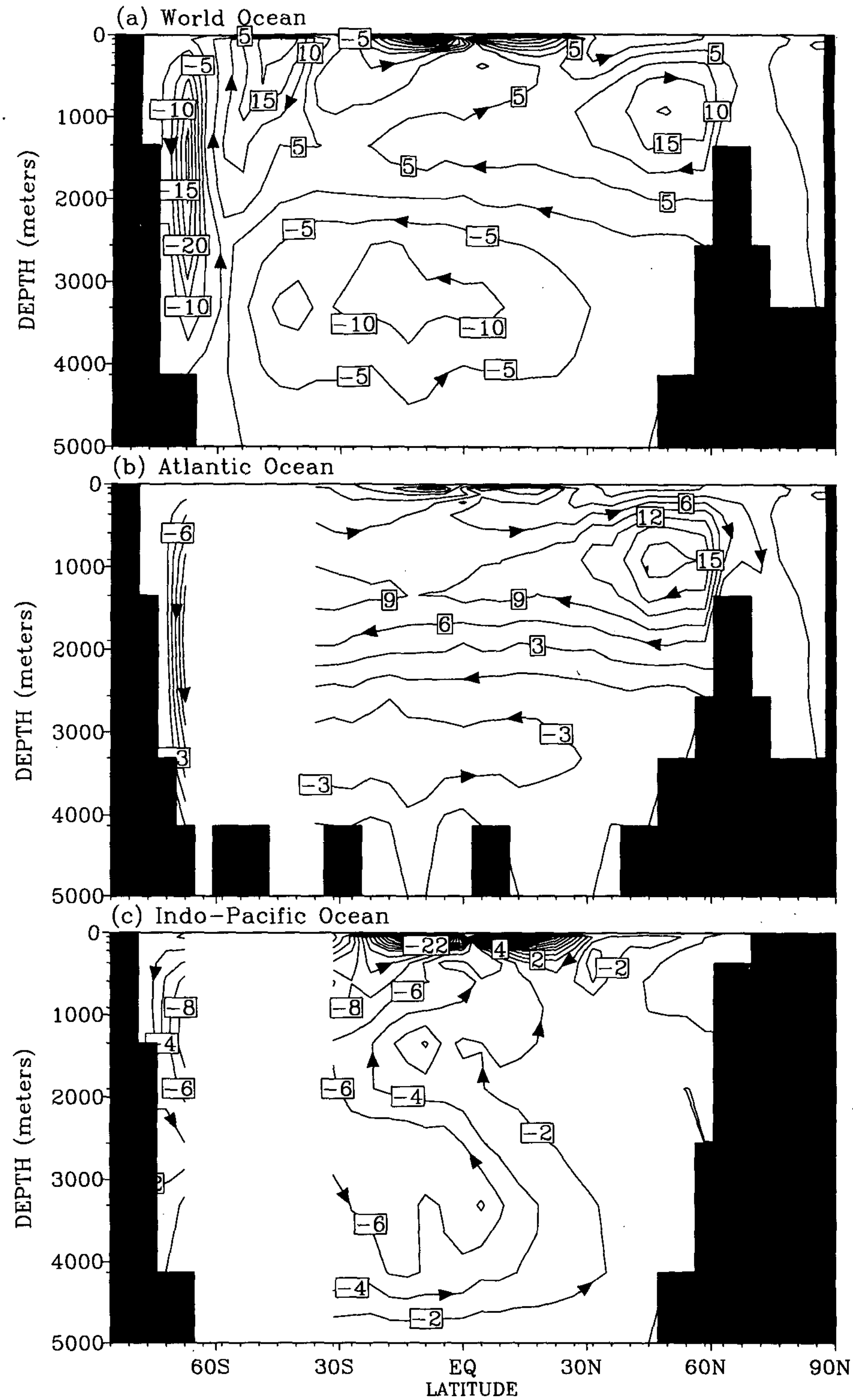

FIG. 2. Annually averaged meridional overturning (Sv) in the model simulation for the (a) global, (b) Atlantic, and (c) Indo–Pacific Oceans. No contours are drawn where the model ocean is free to exchange mass zonally. Contour intervals are 5 Sv, 3 Sv, and 2 Sv respectively.

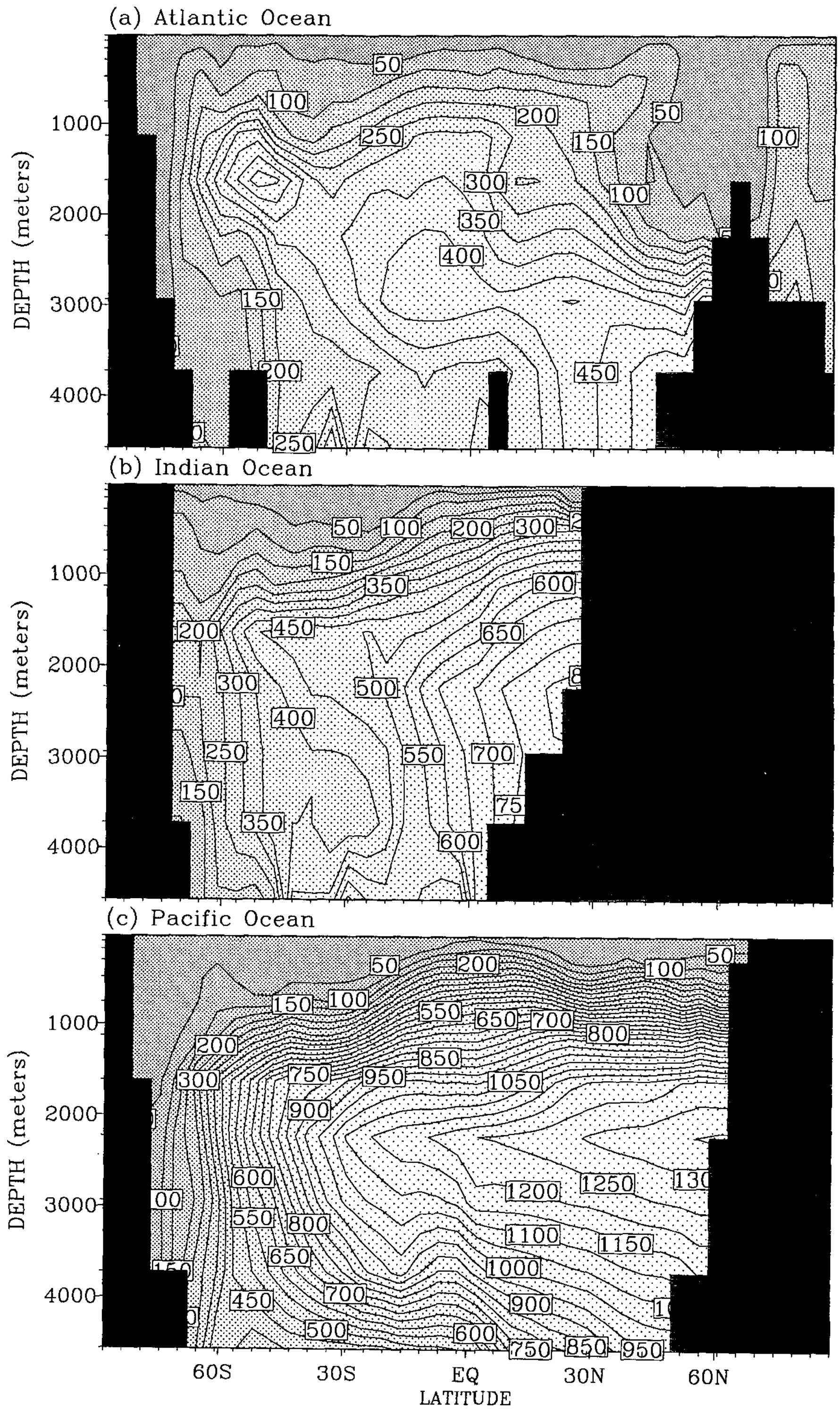

FIG. 3. Basin-averaged age (years) in the (a) Atlantic, (b) Indian, and (c) Pacific Oceans of the control experiment. The contour interval is 50 years. Stippling density decreases with age in each panel.

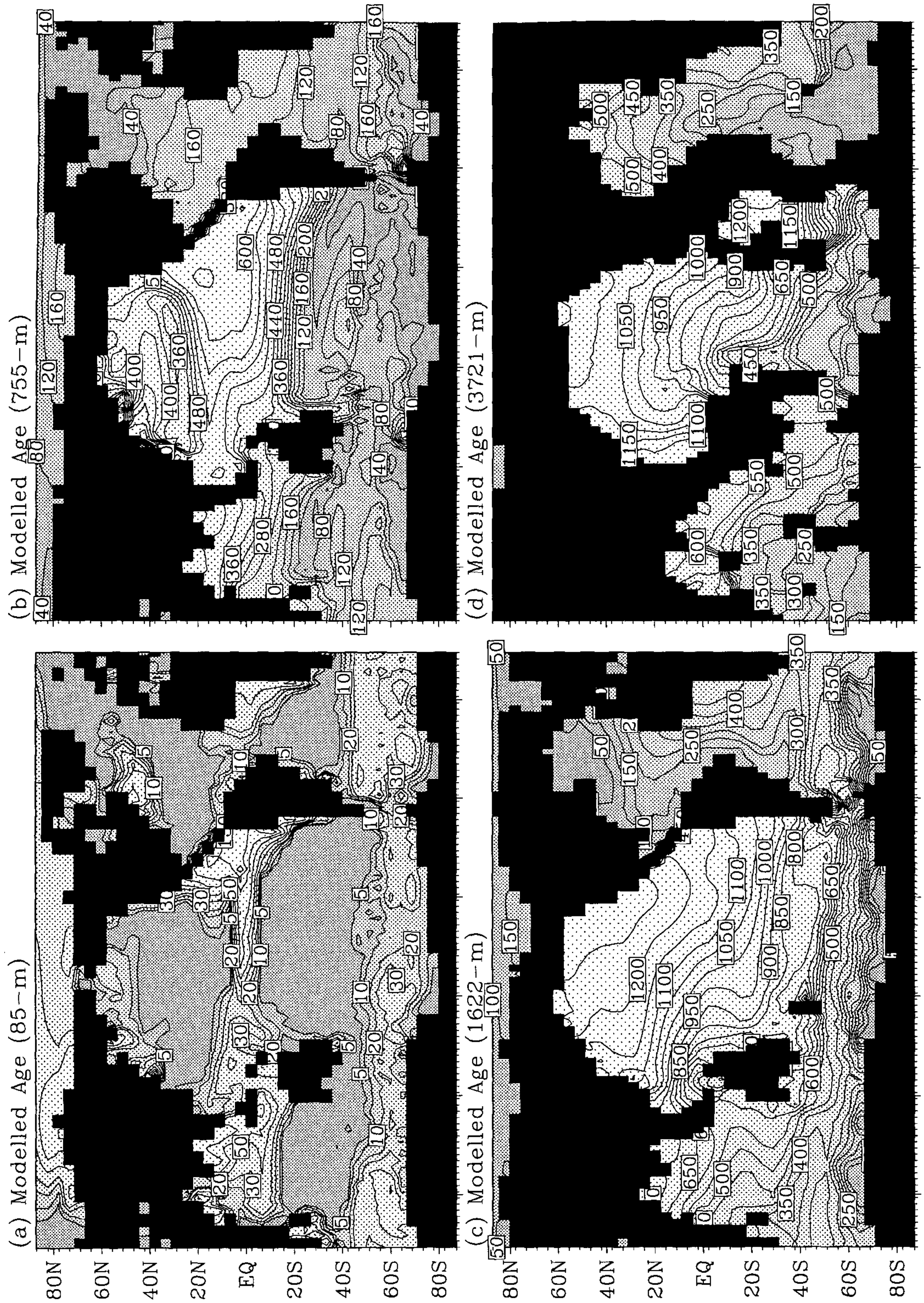

FIG. 4. Model water age (years) at depths (a) 85 m, (b) 755 m, (c) 1622 m, and (d) 3721 m. In (a) the contour interval is irregular; in (b)–(d) contours are drawn every 40 or 50 years. In each panel, stippling density decreases with age.

TABLE 1. Age (years) of the oldest water mass obtained at each model level in the control experiment (A_{MAX}). All maxima are located in the Pacific Ocean (see also Fig. 4): either in the tropical region (e.g., levels 2, 6), in the northern extreme of the basin (e.g., level 8), or in the Peru Basin (level 11). Also shown are the youngest water mass mixtures obtained in the North Atlantic north of 40°N ($A_{NA,MIN}$) and the Southern Ocean south of 60°S ($A_{Weddell,MIN}$, $A_{Ross,MIN}$). The Southern Ocean minimum appears in the Ross Sea for the upper 2500 m and the Weddell Sea for the lowest three levels. Age at the surface level is, by definition, zero at all times.

Model level	A_{MAX}	$A_{NA,MIN}$	$A_{Weddell,MIN}$	$A_{Ross,MIN}$
2 (85 m)	232	0.4	1.4	0.3
3 (170 m)	334	0.7	1.4	0.4
4 (295 m)	366	0.8	1.3	0.4
5 (483 m)	709	1.2	1.3	0.4
6 (755 m)	650	1.1	2.1	0.4
7 (1131 m)	1027	3.6	3.0	2.6
8 (1622 m)	1289	4.2	6.6	5.3
9 (2228 m)	1494	6.9	15	14
10 (2935 m)	1413	277	18	39
11 (3721 m)	1287	519	37	75
12 (4566 m)	1256	467	43	171

ocean is dated at 1494 years, located at 2228-m depth in the western Pacific Ocean. The transient dye experiment confirms that this very old water mass is made up of a combination of sources of water whose age varies between 500 and 5000 years. Water masses in the bottom model level can be as young as 43 years in the Weddell Sea (45% of this water mixture being less than 10 years old), while upper thermocline water (at 85-m depth) can be as old as 232 years in the eastern equatorial Pacific. Clearly, the age of water in the ocean model is a complicated function of geographical location.

Near-uniform minimum age in the upper ocean results from consistent wintertime convection in a particular region. Rapid aging from one level to the next (e.g., from level 9 to 10 in the North Atlantic Ocean) indicates the limit of direct ventilation by vertical convection of near-surface waters. Particularly old water under convectively active regions indicates contamination by waters of remote origin (e.g., the North Atlantic and Ross Sea Bottom Water both age significantly at depth, Table 1).

Age mixtures on selected model levels are drawn in Fig. 4, corresponding roughly to the age of water in the upper thermocline (85 m), intermediate water (755 m), upper NADW (1622 m), and bottom water (3721 m). In the upper thermocline, young water mixtures are found in regions of surface Ekman convergence and downwelling (see Fig. 1b), whereas older waters are found in regions of deep convective overturn or strong surface upwelling. The process of vertical convection effectively entrains older deep water into the surface mixed layer. The oldest water mixtures in the upper thermocline appear in the eastern equatorial Pacific, linked with strong upwelling in the region (e.g., Fig. 1b). In addition, these upwelled waters have a component of recirculated North Pacific Deep Water, which can be more than 1300 years old.

At intermediate model levels, the contrast in water age between the three ocean basins becomes more apparent, with the volume-weighted age largely increasing from 20 to 200 years for the Atlantic Ocean, 40–500 years in the Indian Ocean, and up to 644 years in the eastern Pacific. Well ventilated waters are found throughout the Southern Ocean, a direct consequence of the convective activity in the region during the austral winter (e.g., Fig. 1a). The relative youth of waters in the southeast Pacific Ocean at 755-m depth is due to the renewal of the model equivalent of Subantarctic Mode Water just west of Cape Horn (see, e.g., England et al. 1993). The results from the transient surface dye experiment confirm that the water here is completely renewed over a 10–20-yr timescale.

At the level of NADW outflow (Fig. 4c) a clear signal of young water appears in the Atlantic Ocean, with the water mass age increasing from 5 years in the convectively active formation region through to around 300 years where the NADW enters the Southern Ocean. Older water is found in the Gulf of Guinea (up to 485 years old), since the model path of NADW outflow remains on the western boundary of the Atlantic. In the Southern Ocean very young water appears adjacent to the Antarctic continent, with the water mass age increasing rapidly with latitude away from the Ross and Weddell Seas. Evidently, the convective activity in the region is limited to the surface 1000 m in subantarctic waters, whereas the extreme polar waters are overturned to substantial depths. The relatively youthful water in the deep overturning regions gradually recirculates into the other ocean basins, so that age generally increases with distance from the water mass formation zones. The oldest water at 1622-m depth is located in the far North Pacific Ocean, having a volume-weighted age of 1289 years. The transient dye experiment shows that water in this region is only 10% flushed by surface water over a 500-year integration (see, e.g., Fig. 6d).

In the very deep and bottom model levels, the youngest waters are found in the far Southern Ocean (Fig. 4d). Water in the North Atlantic remains somewhat younger than water in the North Pacific, partly because of the influence of the overturned NADW, but also because the Weddell Sea variety of AABW spreads more rapidly into the Atlantic Ocean than the corresponding Ross Sea water in the Pacific Ocean. The surface dye experiment confirms that the bottom northernmost regions of each basin (both at around 50°N) are flushed by 10% of surface water at different times during the model integration: 200 years in the Atlantic Ocean and 400 years in the Pacific Ocean. The transient dye signal can be tracked directly to a Southern Ocean source at this depth. The reason for the different ventilation timescales of the bottom water is related to the convective intensity in the Ross and Weddell Seas, as well as the speed of currents leaving the formation regions. England et al. (1994) have shown in a model simulation of CFC-11 uptake that the bottom water ventilation from the Weddell Sea is somewhat too strong in the model.

c. *Age on selected isopycnal surfaces*

The distribution of age on three surfaces of constant potential density is shown in Fig. 5. The chosen surfaces correspond with ventilation of the lower thermocline ($\sigma_t = 26.0$ kg m^{-3}), ventilation of intermediate water ($\sigma_t = 26.6$ kg m^{-3}), and the outflow and recirculation of upper NADW ($\sigma_t = 27.4$ kg m^{-3}). It is important to remember that the model density field varies somewhat from observations: in general the model water is insufficiently dense because deep waters are too fresh and the thermocline too diffuse. For easy reference, the depth distributions of the three isopycnal surfaces are also shown. These maps are useful for determining the aging of certain water types; in particular, thermocline water, intermediate water, and deep water. Maps on purely geopotential surfaces (Fig. 4) cut through surfaces of constant potential density, and are therefore less useful in the context of tracing specific water mass ventilation.

The model equivalent of thermocline water ages in agreement with the simple theory of thermocline ventilation proposed by Luyten et al. (1983). In particular, the equatorial shadow zone appears in each basin, with the oldest thermocline water residing along the equatorial waveguide. In addition, from the region of subduction of thermocline water in the subtropical ocean, the most rapid ventilation follows the major gyre flows in each basin. In short, youngest thermocline waters are subducted poleward of the subtropical gyre, recirculating equatorward with the wind-driven circulation. As a result of this ventilation, subtropical pools of older thermocline water are found near the western boundaries along the axis of the major subtropical gyres (particularly in the North Pacific Ocean).

Intermediate water ages rapidly in the southeast Pacific Ocean (Fig. 5d), partly because upwelled bottom water contaminates the region (see Fig. 2c). In contrast, only gradual northward aging is noted in the Atlantic and Indian Ocean varieties of AAIW. In the North Pacific, intermediate water resides on slightly shallower density surfaces than the $\sigma_t = 26.6$ kg m^{-3} surface shown, and it is less rapidly ventilated than the intermediate waters to the south. Like waters to the south, the North Pacific variety of intermediate water becomes contaminated with older recirculated bottom water, yielding old water mass mixtures near 1000-m depth.

The $\sigma_t = 27.4$ kg m^{-3} surface more or less coincides with the core of NADW formed in the model. Over much of the ocean this isopycnal surface is at about 2000-m depth, although it outcrops during wintertime in the North Atlantic and in the far Southern Ocean (Fig. 5e). The water mass age is naturally youngest where the density surface outcrops. The age of water on the σ_t surface generally increases as a function of distance from the NADW formation zone, although there is some contamination in the Southern Ocean from waters locally overturned in that region. The average age of water leaving the Atlantic Ocean on the chosen density surface is around 300 years, although the transient dye experiment shows that some of this water mixture (about 15%) is less than 60 years old (see Fig. 6b). The $\sigma_t = 27.4$ kg m^{-3} water ages an additional 300–400 years before ventilating the Indian and South Pacific Oceans, and then a further 650 years before reaching the northern part of the Pacific basin. Results from the dye experiment show that the youngest signal of outflowed NADW penetrates the Indian Ocean and the South Pacific via the circumpolar current over a timescale as short as 15 years. On the other hand, water penetrating the far deep North Pacific is not detected in significant quantities (using a 10% concentration criterion) until about 500 years after the NADW formation time (see Fig. 6d).

d. *Transient surface water ventilation of the model deep ocean*

The gradual ventilation of the deep ocean by surface water can be studied by monitoring the concentration of the dye tracer on an appropriate isopycnal surface. In Fig. 6 we show the percentage concentration of surface water on the $\sigma_t = 27.4$ kg m^{-3} isopycnal surface during several stages of the model integration. Much of the chosen density surface resides at 2000–2400-m depth, except in the Southern Ocean and in the far North Atlantic (Fig. 5e). Almost complete ventilation is achieved near the density surface outcrop regions within 10 years (Fig. 6a). Only 50 years later (Fig. 6b), NADW outflow is exporting some of the surface dye tracer into the Southern Ocean. Additional surface water of Antarctic origin is mixing with the NADW signal near 50°S. Even after 200 years of model integration, negligible traces of surface water have appeared in the far North Pacific in the deep model levels (Fig. 6c). In contrast, much of the North Atlantic and extreme Southern Oceans have been well ventilated by this time. After 500 years, surface waters have renewed more than 90% of the North Atlantic, yet less than 10% of the North Pacific. This indicates that in coupled ocean–atmosphere models, a change in the climate at a given time would only be very weakly detectable in the deep North Pacific some 500 years later (assuming that the model ocean circulation remains mostly unchanged). In contrast, a climate change signal in the deep North Atlantic and Southern Oceans should be detectable within decades.

Over much longer timescales, the deep Pacific and Indian Oceans are gradually ventilated by the surface

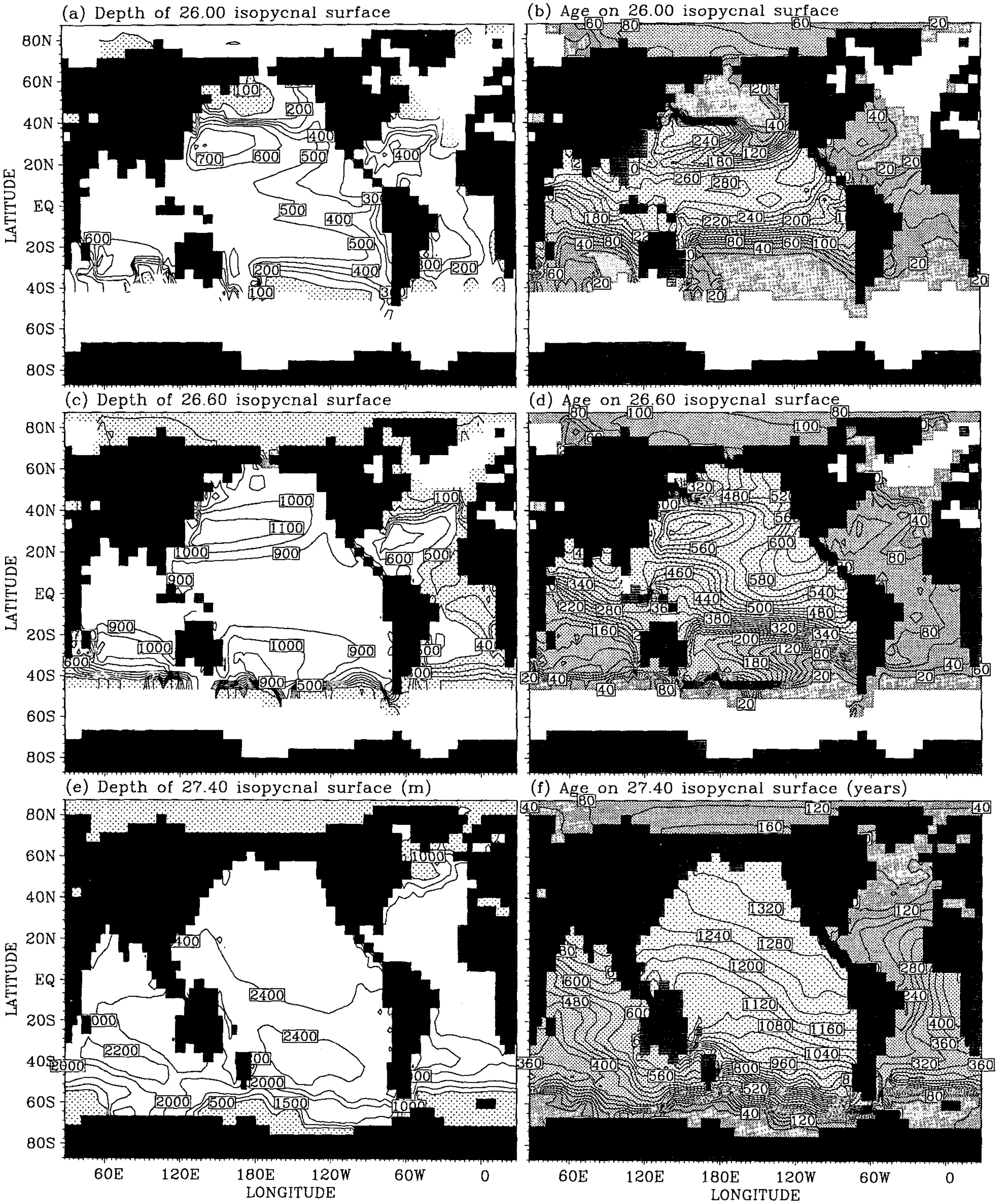

FIG. 5. The depth (m) and age (years) of water on several isopycnal surfaces (σ_t = 26.0 kg m^{-3}, σ_t = 26.6 kg m^{-3}, and σ_t = 27.4 kg m^{-3}) in the World Ocean model. Contour interval is 100 m in (a) and (c), and 500 m in (e), with additional contours drawn at 200-m intervals for depths greater than 2000 m. Age contours are drawn every 20 years in (b) and (d), and every 40 years in (f). In the depth of isopycnal maps, stippling indicates regions where the σ_t surface is in the upper 100 or 500 m. Stippling density decreases with age in (b), (d), and (f).

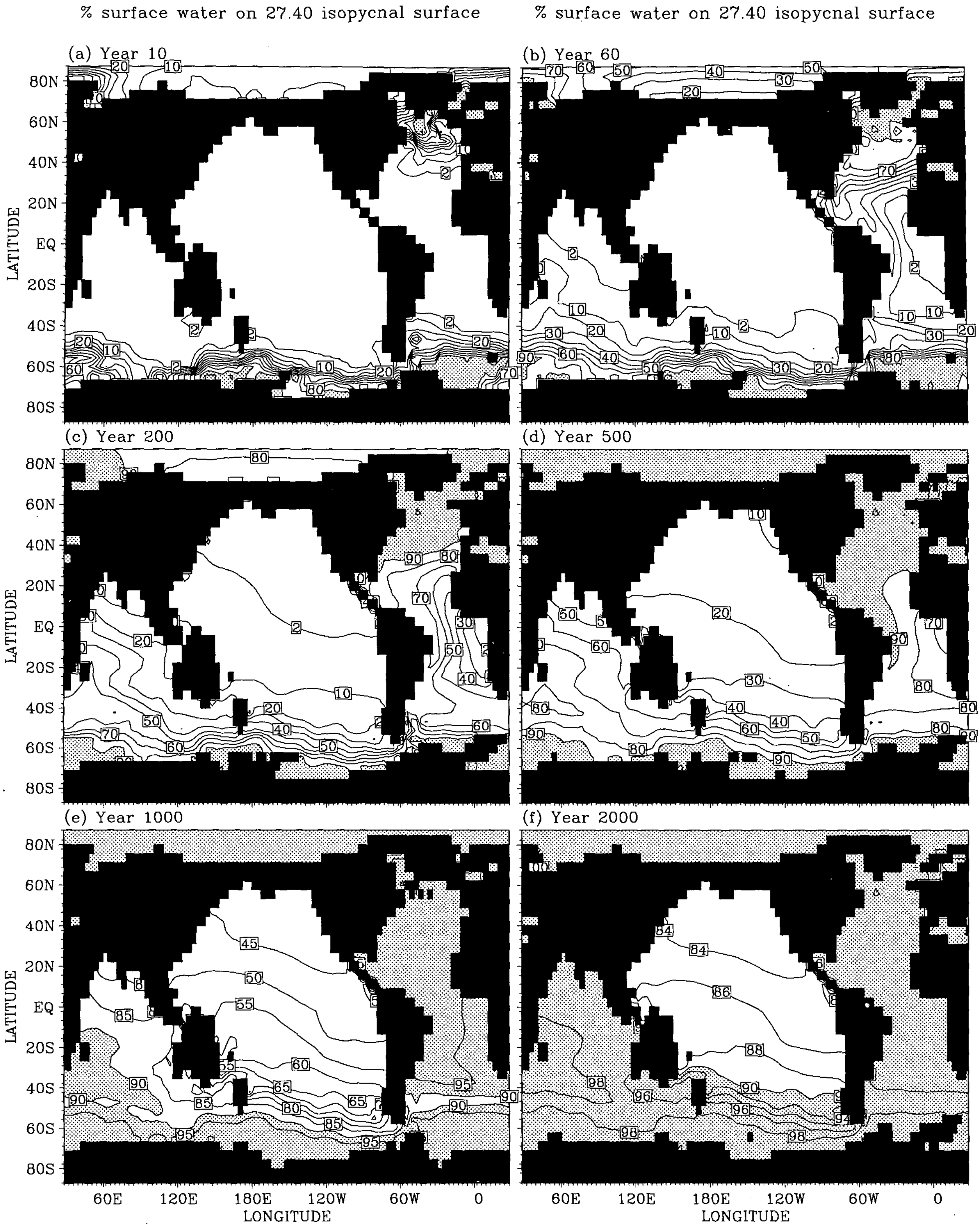

FIG. 6. Percentage concentration of surface water on the $\sigma_t = 27.4$ kg m^{-3} isopycnal surface after (a) 10 years, (b) 60 years, (c) 200 years, (d) 500 years, (e) 1000 years, and (f) 2000 years. Regions that are at least 90% renewed by surface water are stippled. Contour interval is 10% in (a)–(d), 5% in (e), and 2% in (f). An extra contour level is drawn at 2% renewal in (a)–(c).

dyed waters (Figs. 6e,f). After 1000 years, the Indian Ocean deep waters have been at least 80% renewed, whereas the far North Pacific remains as much as 60% unventilated. The entire Atlantic sector has been almost completely flushed out by this time. After another 1000 years of ocean model ventilation (Fig. 6f), only the North Pacific has detectable levels of new surface waters contributing to the local water mass mixtures. As much as 17% of North Pacific Deep Water is older than 2000 years on the $\sigma_t = 27.4$ kg m^{-3} surface. This contributes to the final age mixture of around 1350 years in the region (Fig. 5f).

e. Sensitivity of age to the model's mixing parameters

An enhanced mixing experiment was run to determine the relative sensitivity of the idealized age tracer to the choice of mixing parameterization in the ocean model. This involved maintaining exactly the same level of horizontal diffusion as the control experiment and enhancing mixing along surfaces of constant potential density. The ocean model was at first run out to an equilibrated state under the new mixing scheme carrying only *T* and *S* as tracers. The age tracer *A* was then initialized to zero and carried as an additional passive tracer obeying Eqs. (1) and (2), until there was negligible long-term drift in *A* throughout the model domain.

The response of the model circulation and water mass formation to the inclusion of isopycnal mixing has been documented elsewhere (e.g., England 1993, 1995b; Hirst and Cai 1994), so here we focus primarily on the sensitivity of age to the effective change in mixing parameterization. The isopycnal diffusion coefficients chosen are rather strong, and therefore this experiment provides an approximate upper bound on the sensitivity of age to the model mixing parameters. Furthermore, even though isopycnal mixing can improve the model representation of certain water masses (e.g., England 1993), it can also lead to unrealistically strong mixing if the ocean model stratification is too weak, or if the model ocean density structure is erroneous (England 1995a,b). Unless the background Cartesian diffusion is set to zero or very small values (which is now possible using the mixing parameterization of Gent and McWilliams 1990), the isopycnal mixing scheme acts mainly to increase the diffusion of water properties in an already overdiffusive model. For example, recent simulations of CFC-11 uptake over the global ocean suggest that the isopycnal diffusion term can lead to unrealistically strong blending of water masses in the subpolar Southern Ocean (England 1995a). In short, the age simulations in the isopycnal mixing experiment are likely to be less realistic than those of the control run. The isopycnal mixing case is studied moreover as a test of sensitivity of modeled age to the chosen mixing terms.

Figure 7 shows the distribution of age zonally averaged in the Atlantic, Indian, and Pacific Oceans in the isopycnal mixing experiment. The oldest water masses obtained in both the control and isopycnal mixing cases are shown for each model level in Table 2. With the increased mixing of tracers along surfaces of constant potential density, the overall ventilation rate of the World Ocean increases significantly. Deep and bottom waters are on the whole 20%–40% younger. For example, the oldest water parcel obtained in the isopycnal run is 1126 years (as in the control experiment this water is found in the deep western Pacific Ocean at 2228 m), compared with 1494 years in the control experiment. The age of Upper NADW leaving the Atlantic Ocean near 40°S becomes about 220 years (Fig. 7a), compared with 300 years in the control run. Deep waters in the north Indian Ocean are as much as 50% younger (Fig. 7b). In the Pacific Ocean, deep waters are ventilated about 30% more rapidly (Fig. 7c), with little trace of old Pacific Deep Water entering the Atlantic Ocean via the Drake Passage (compare Figs. 3a and 7a). The oldest variety of intermediate water (at 755-m depth) is only 354 years in the isopycnal mixing experiment, compared with over 600 years in the control case (Table 2).

The overall renewal timescale of the global ocean model (measured as the time taken to ventilate at least 99% of all model grid boxes) is 4930 years for the control experiment and only 3620 years in the isopycnal run. These timescales for ocean ventilation are derived from very long integrations of the transient dye experiment. Because the slowest ventilated ocean regions in the deep North Pacific witness only very weak advection, the overall renewal timescales are necessarily set by the model lateral diffusion rates. Increased horizontal and vertical diffusion accelerate the ventilation processes by mixing water masses more rapidly.

In view of the sensitivity of the modeled age and interior water ventilation to the choice of mixing scheme, the analyses presented in this paper should be viewed foremost as a quantitative diagnosis of model behavior rather than a set of ventilation timescales that can be extrapolated to the real ocean system. On the other hand, the simulated age has about the same order of error (20%–40%) as estimates derived from radiocarbon dating of seawater. In this context, the model age simulations provide useful information that complements the ^{14}C estimates.

5. Discussion and conclusions

The age of water in a global ocean model has been studied using an idealized tracer that represents the volume weighted time taken for waters at the sea surface to arrive at a given point in the ocean interior. The tracer ages naturally during the model integration, with water that is directly exposed to the sea surface having zero age, and water in the ocean interior aging by the model time step over any given

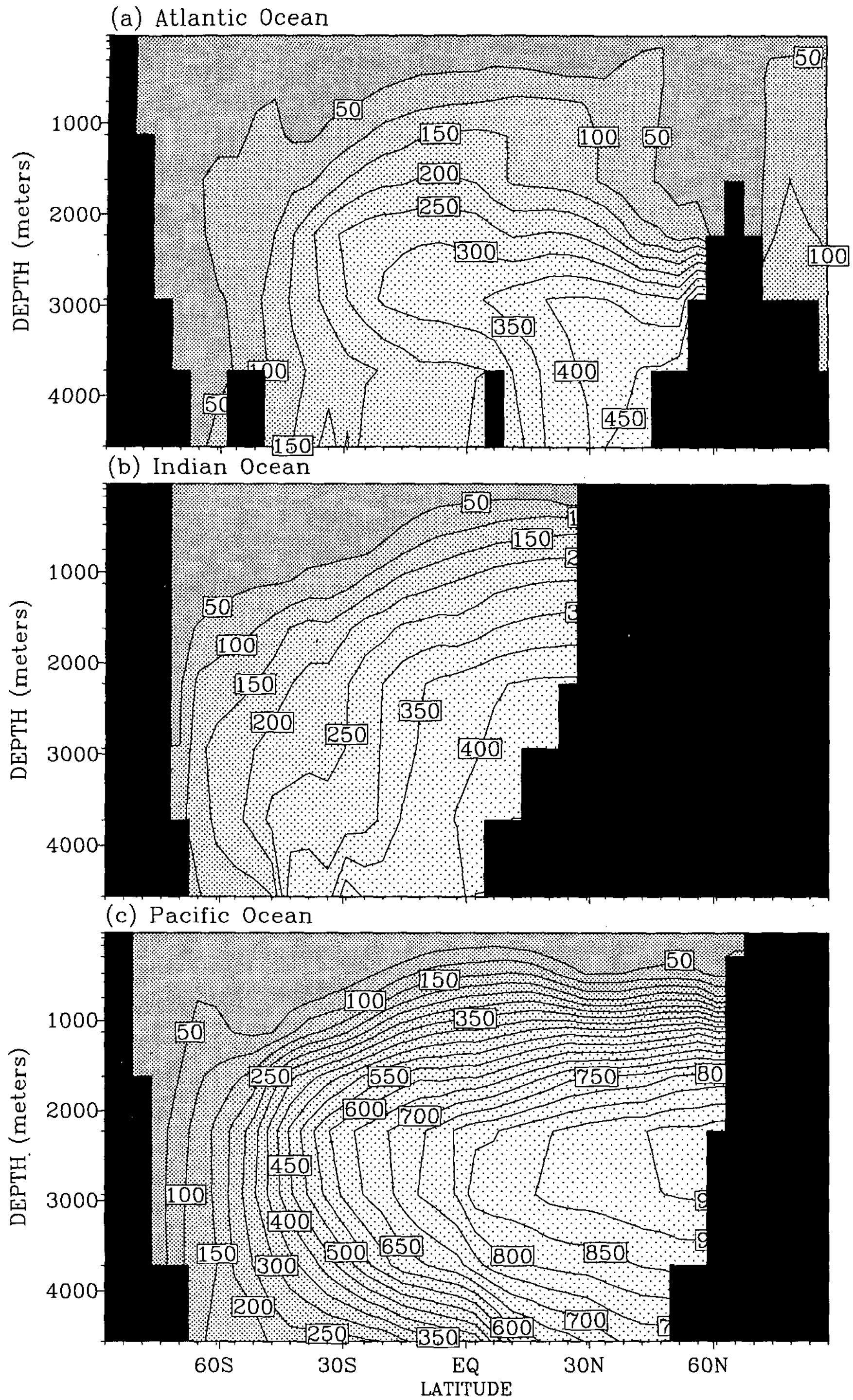

FIG. 7. Basin-averaged age (years) in the (a) Atlantic, (b) Indian, and (c) Pacific Oceans of the isopycnal mixing experiment. The contour interval is 50 years.

time step. The processes of advection, diffusion, and vertical convection communicate the zero age signal at the sea surface into the ocean interior, limiting the indefinite growth of the age tracer by mixing young waters into the ocean. An additional dye experiment was used to monitor the transient ventilation of the ocean by water originating from the uppermost model level. The dye experiment can be used to de-

TABLE 2. Age (years) of the oldest water mass mixture obtained at each model level in the control and isopycnal experiments. All maxima are located in the Pacific Ocean (see also Fig. 4): either in the equatorial region (e.g., level 2) or in the northern extreme of the basin (e.g., level 8). Age at the surface level is, by definition, zero at all times.

Model level	A_{MAX} (control expt.) (years)	A_{MAX} (isopycnal expt.) (years)
2 (85 m)	232	94
3 (170 m)	334	130
4 (295 m)	366	156
5 (483 m)	709	265
6 (755 m)	650	354
7 (1131 m)	1027	573
8 (1622 m)	1289	825
9 (2228 m)	1494	1126
10 (2935 m)	1413	1066
11 (3721 m)	1287	968
12 (4566 m)	1256	961

termine when the youngest waters first ventilate a given region of the ocean, adding useful information to the time-independent age tracer that is only meaningful in a fully equilibrated system.

It is of some interest to compare the simulations of ocean model age with observed estimates, even though age (like most model diagnostics) is sensitive to the choice of model mixing parameters. The observed distribution of radiocarbon (or ^{14}C) provides the best estimate of deep ocean ventilation rates over long timescales (say, century timescales and beyond). Modern anthropogenic tracers (e.g., CFCs, bomb-produced tritium) only resolve the decadal to interdecadal timescale. Because the ^{14}C isotope is created in the atmosphere (both naturally and through human activities) and subsequently dissolved in the surface mixed layer, its natural radioactive decay can be monitored to give an estimate of seawater age (Stuiver et al. 1983). The more remote a given water sample is from communication with the atmosphere, the more depleted the ^{14}C content becomes (in proportion to the concentration of ^{12}C). The half-life of Carbon-14 is 5730 years, making it suitable for estimating ocean ventilation rates over very long timescales.

It should be stressed that there are certain sources of possible error in the radiocarbon age estimate. For example, oceanic ^{14}C and ^{12}C are influenced by biological processes and therefore their concentrations are complicated functions of the water mass history. In addition, the $^{14}C/^{12}C$ ratio for waters descending in the North Atlantic is different to that for waters descending in the Southern Ocean (Broecker and Peng 1982), meaning that radiocarbon age estimates require some knowledge of the relative contribution of southern and northern source waters (e.g., Broecker et al. 1991). Related to this, the nonlinear decay of radiocarbon yields an age bias when different water masses are mixed, although the age error resulting from this mixing process has not yet been quantified. Finally, atmospheric ^{14}C concentrations exhibit millennial variability, so that some knowledge of the water mass formation time is required when reconstructing past ventilation rates (Andree et al. 1986).

The ^{14}C content of the ocean is normally expressed as the deviation of the $^{14}C/^{12}C$ ratio (in parts per thousand) from a standard atmospheric ratio. The notation used for this difference is $\Delta^{14}C$, which is normally negative since the ^{14}C isotope decays in the ocean. The more negative the value of $\Delta^{14}C$, the more time has elapsed since the water mass was last in contact with the atmosphere. Figure 8 shows sections of $\Delta^{14}C$ measured along the western Atlantic and Pacific Oceans during the Geochemical Ocean Sections Study (GEOSECS, Ostlund et al. 1987). No contours are drawn in regions where the radiocarbon data are contaminated by bomb-produced ^{14}C. For direct comparison, we include sections of simulated age at the corresponding geographical location of the control model. In general, there is broad agreement between the model age and that suggested by the GEOSECS $\Delta^{14}C$ data, particularly in the Pacific Ocean. In both model and observations, oldest waters are located near 2000-m depth in the far North Pacific. The suggested timescale for the aging of AABW along the GEOSECS Pacific section (a $\Delta^{14}C$ decay from -160 ppt to -220 ppt) is 600 years, which is exactly the model age difference between Southern Ocean bottom water and AABW in the far North Pacific. The $\Delta^{14}C = -240$ ppt water at middepth is about 800 years old relative to Southern Ocean bottom water ($\Delta^{14}C = -160$ ppt), slightly younger than the 1000-year age difference in the model. In the Atlantic sector north of 30°N, young waters occupy much of the water column in the observations, whereas water ages substantially with depth in the model. Much of the $\Delta^{14}C$ data in the Atlantic suggests ventilation of deep water from the north of the basin, whereas the model simulates a substantial contribution of bottom water from the south.

A map of the radiocarbon estimated age of water at 3000-m depth is shown in Fig. 9a (redrafted from Broecker et al. 1988). The map was derived by considering the difference between the $^{14}C/^{12}C$ ratio for water at 3000-m depth with that of the overlying surface water, taking into account the natural radioactive decay of ^{14}C isotopes. The reference $^{14}C/^{12}C$ ratio is therefore somewhat arbitrary, and considering that deep water is formed predominantly in the North Atlantic and Southern Oceans, somewhat inappropriate in certain locations (e.g., the North Pacific). Because of the sensitivity of estimated age to this choice of reference $^{14}C/^{12}C$, the error margin on the observed radiocarbon age is rather large. Even though exact deep water age is not well known, there is general agreement as to the qualitative trend in age shown in the Broecker et al. (1988) figure. For direct comparison with the control model simula-

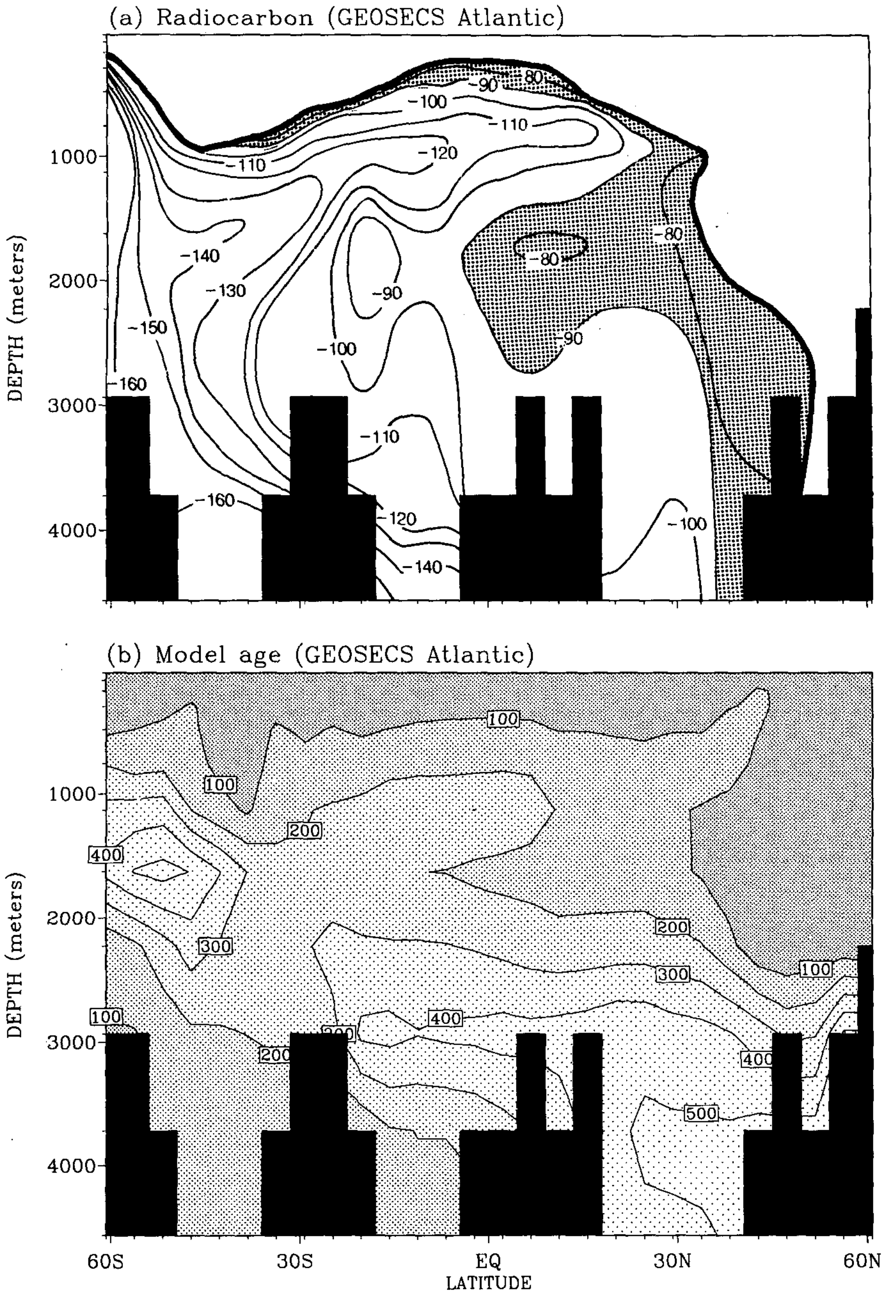

FIG. 8. Western Atlantic GEOSECS section of (a) radiocarbon ($\Delta^{14}C$) and (b) model age. Contour interval is −10 ppt for $\Delta^{14}C$ and 100 years for age. The bold line indicates the limit to which waters contaminated with bomb-produced ^{14}C penetrated the sea at the time of the GEOSECS Survey (1972–1974). (c)–(d) As in (a)–(b), only for the western Pacific GEOSECS section. In the model age plots, stippling density decreases with age. In the radiocarbon sections, Atlantic water with $\Delta^{14}C$ greater than −90 ppt is stippled, as is old Pacific deep water where $\Delta^{14}C$ levels are depleted to below −240 ppt.

tion, age at 2935-m depth (model level 9) is shown in Fig. 9b.

Overall, the model age is in good qualitative agreement with the findings of Broecker et al. (1988), although the simulated age of deep North Pacific water is 200–400 years younger than the radiocarbon estimate. In the far Southern Ocean, water younger than 250 years is seen at similar locations in both the model and $\Delta^{14}C$ age, except notably in the South Atlantic where particularly young water extends northward in

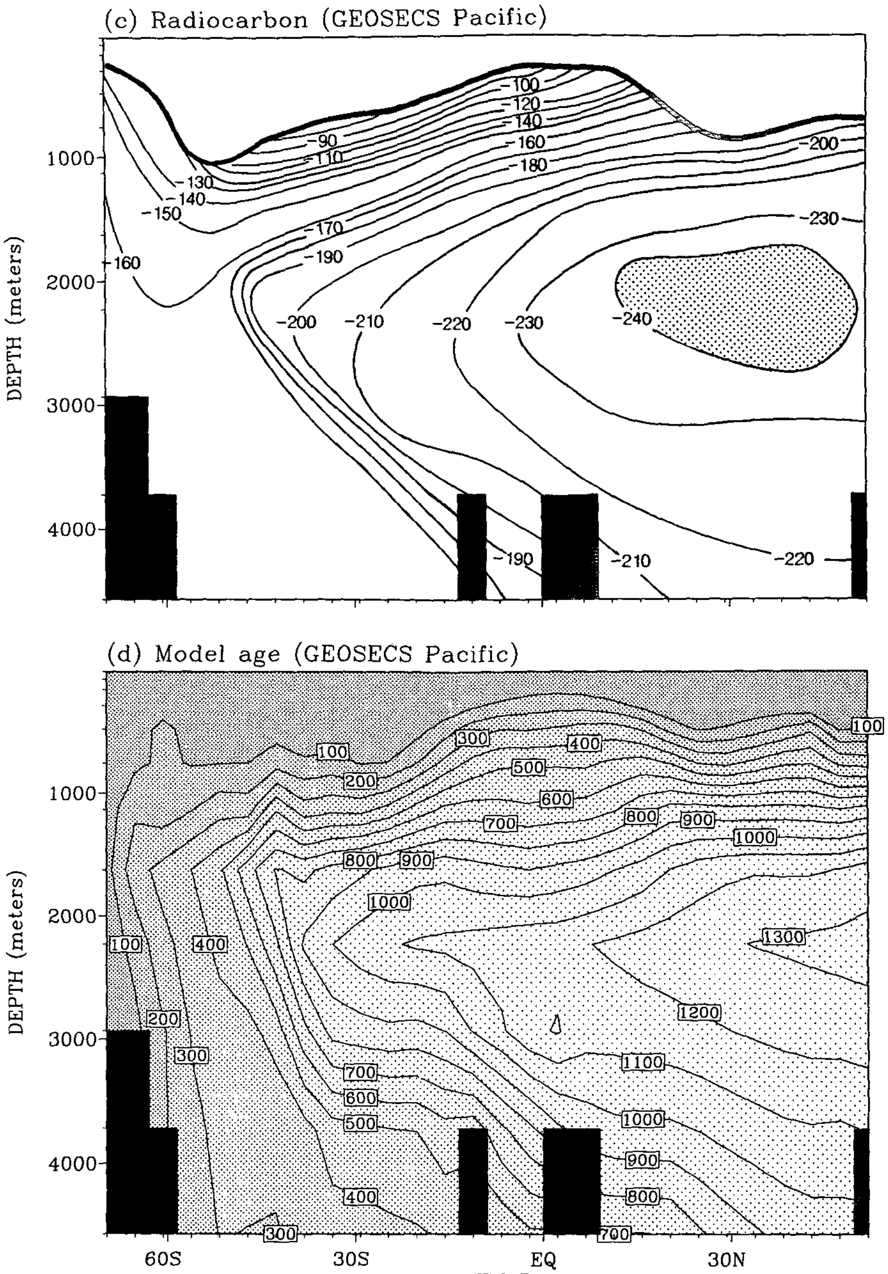

FIG. 8. (*Continued*)

the model. The rapid aging of deep water in the South Pacific Ocean (from 500 to 1000 years) is obtained in both the simulation and the $\Delta^{14}C$ estimate. Deep Indian Ocean water is younger in the model and its age varies more strongly with latitude than the radiocarbon data suggest (Broecker et al. estimate near-uniform Indian Ocean deep water age of 1200–1300 years). Good agreement is found between model and $\Delta^{14}C$ age in outflowing lower NADW (300-yr old water is found at the equator in both the model and observed estimates). However, some discrepancy is noted in the outflowing NADW near 40°S: model age is around 350 years compared with the $\Delta^{14}C$ estimate of 500 years, although in the model there is likely to be some contamination of the outflowing NADW by water of Southern Ocean origin at this latitude.

The age distributions simulated in the global ocean model can be analysed in terms of the total volume of ocean occupied by water of a given age. It is useful to map this as a function of potential temperature as well,

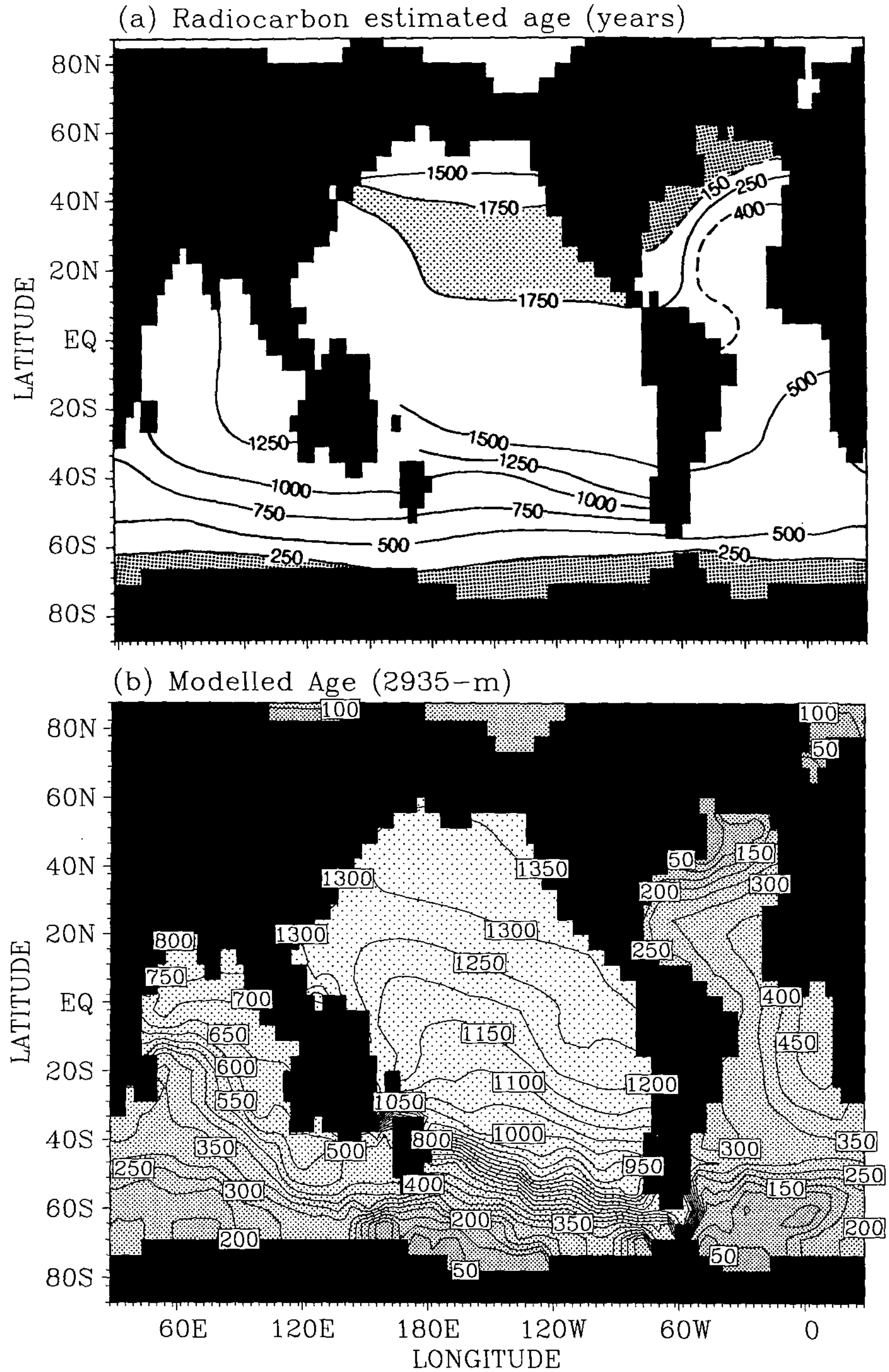

FIG. 9. (a) Radiocarbon-derived estimates of water age (years) at 3000-m depth in the global ocean, as estimated by Broecker et al. (1988) referencing $^{14}C/^{12}C$ ratios at 3-km depth relative to those of the overlying surface water. (b) Model age (years) at 2935-m depth (level 9). Contour interval is 250 years in (a) (with additional contours in the North Atlantic) and 50 years in (b). The oldest water in (b) is located in the western Pacific Ocean just north of Australia (1494 years).

to further distinguish water masses according to location in the ocean. Figure 10 shows a volumetric census of water in the World Ocean model as a function of age and potential temperature for both the control and isopycnal mixing cases. A great majority of the water in the model ocean (like the real ocean) has temperature

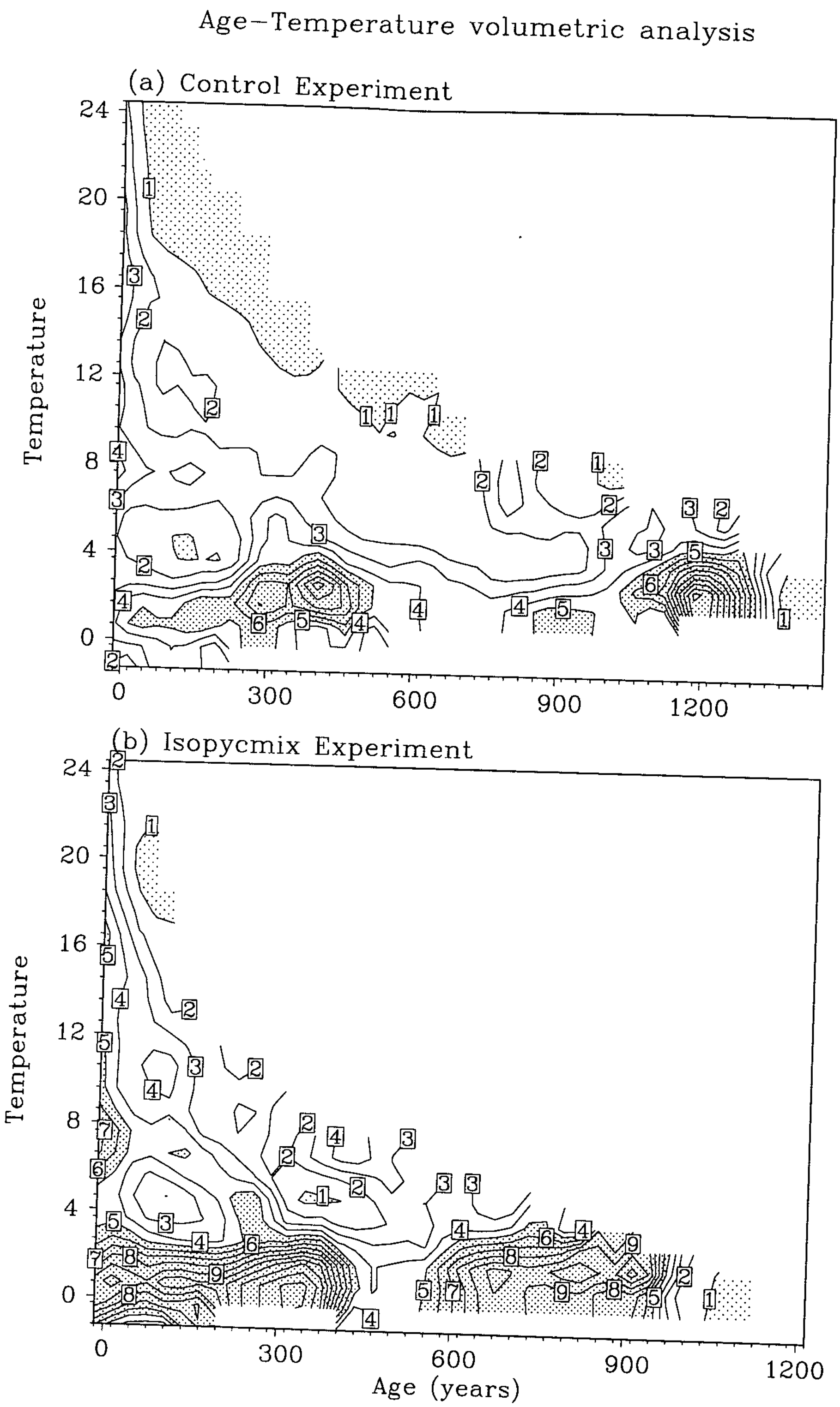

FIG. 10. Volumetric age potential temperature analysis of the ocean model: (a) Control experiment and (b) isopycnal mixing experiment. The volumetric census is performed by binning water masses over a uniform mesh with 1°C and 30-yr incrementation. Contours are drawn every 10^6 km^3. Light stippling indicates a total volume of less than 10^6 km^3, whereas dense stippling indicates an integrated volume in excess of 5×10^6 km^3. Note the slight difference in scaling along the age axis of each panel.

in the range 1°–6°C, and so most of the age–temperature census falls into this domain. Water masses drawn along the y axis represent water in the upper model level (having zero age), whereas water to the right of the diagram denotes the oldest variety of water of any given temperature. For example, 20°C water is at most 240 years old in the control experiment (appearing in the tropical eastern Pacific), although the great majority of water at this temperature is younger than 50 years.

In the control experiment, there are two relative maxima in the volumetric analysis performed; one at 2°–3°C and 1200 years (corresponding to water in the deep North Pacific) and another at 3°C and 300–500 years (corresponding to water in the deep Atlantic Ocean). A relatively large volume of water connects these two maxima, reflecting the large spatial scales over which the outflowing NADW eventually ages and blends with other water masses to contribute to the deep North Pacific water. The contribution of AABW to the volumetric map can be thought of as occupying the colder end of the diagram, with young cold water (near the origin of the diagram) slowly aging and warming as it makes its way northward into the three ocean basins. The warming comes from the blending of the originally cold water mass with surrounding warmer waters; whereas the aging is a result of both this mixing process and the natural accumulation of age as the water mass gradually penetrates the northern parts of the Atlantic and Pacific Oceans.

In the isopycnal mixing experiment the global-scale variations in age become somewhat weaker (Fig. 10b), reflecting the tendency for stronger mixing to more rapidly blend water mass properties (such as age). The two volumetric maxima discussed above now appear at younger ages; the deep Atlantic water has an age of 200–400 years, with deep Pacific water becoming 800–900 years old. As has been emphasized, the isopycnal diffusion was chosen to be rather strong so that the experiment provided an approximate upper bound on the sensitivity of age to the choice of model mixing rates. Further studies of the dependence of the model water age on the parameterized subgrid-scale mixing are presently being undertaken.

The age and ventilation timescales of water masses are important parameters that help determine the ocean's role in climate and climate change. In particular, the location of young water indicates those areas of the ocean that are being overturned or renewed rapidly, and would therefore tend to moderate climate change in a coupled ocean–atmosphere model. Realistic passive tracers such as CFCs certainly provide better model constraints than age (England 1995a) because a whole set of accurate subsurface measurements are currently becoming available to the ocean modeler. However, the CFC signature only tracks ocean ventilation over relatively short (interdecadal) timescales. In contrast, idealized passive tracers can be carefully chosen to explore a particular aspect of ocean model behavior. Age and dye tracers are particularly useful in the context of climate and climate change, as well as studies of ocean ventilation, water mass formation, and deep water recirculation.

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