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On models of bomb ^{14}C in the North Atlantic

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Abstract. Coarse resolution general circulation ocean models show a tendency to accumulate an excess of bomb ^{14}C on the eastern margin of the subtropical gyres, while observations suggest an excess is found in the west. Here simulations of the bomb ^{14}C transient in the North Atlantic Ocean are made using coarse resolution ($1.0^o \times 1.2^o$) and "eddy–permitting" ($1/3^o \times 2/5^o$) tracer transport models. The former employs large horizontal diffusivities to parameterize eddy transfer. Both models employ the same air–sea exchange parameterization, with a specified tropospheric history of $\Delta^{14}C$. The coarse resolution model accumulates ^{14}C evenly over the whole subtropical gyre, while the eddy–permitting model has a pronounced maximum column inventory in the western part, consisent with the observed patterns. The prescence of explicit eddies enhances the ventilation of density surfaces in the recirculation zone on the western margin of the gyre, suggesting that the zonal gradient hinted at in the observations is intimately tied to properties of geostrophic eddy dynamics which are not captured parametrically in the coarse resolution model.

1. Introduction

High–altitude testing of nuclear weapons in the 1950s and 1960s introduced a significant perturbation to the natural stratospheric ratio of ^{14}C and ^{12}C, which is naturally dependent on the cosmogenic production of ^{14}C. The transient signal in $\Delta^{14}C$ due to bomb fallout (see Figure 1) has been transported through the troposphere and into the oceans. Observations of $\Delta^{14}C$ in the ocean can provide insight into the ventilation rates and pathways between the surface and deeper ocean (see, for example, *Broecker et al.* [1985]).

Using the Geophysical Fluid Dynamics Laboratory (GFDL) ocean model, configured globally at coarse resolution, *Toggweiler et al.* [1989] modeled the oceanic distribution of the transient, bomb–produced perturbation in $\Delta^{14}C$. The study compared the modeled and observed Geochemical Ocean Section Study (GEOSECS) column inventories of ^{14}C (i.e., the distribution of vertically integrated ^{14}C loading) for the year 1972. The authors found that in the subtropical gyres of both the Atlantic and Pacific Oceans, the modeled longitudinal gradients of the column inventory are the reverse of those suggested by the observations, as depicted in Figure 2. (It should be emphasized, however, that the observed map is based on few observations and the column inventories are subject to errors of up to 20% [*Broecker et al.*, 1985]). They suggest that this discrepancy may be a consequence of unrealistically strong upwelling on the inner flank of the western boundary currents in such models. *Veronis* [1975] showed that such upwelling can be forced by a strong horizontal diffusion of buoyancy that results from the parameterization of eddies as horizontal mixers of temperature and salinity. As a result, the modeled ^{14}C distribution may be influenced by older, low $\Delta^{14}C$ waters upwelling to the surface in the western basin and displacing the high $\Delta^{14}C$ waters eastward.

Duffy et al. [1995] present results from two global simulations of bomb $\Delta^{14}C$, using a perturbation approach. One simulation is based on the National Center for Atmospheric Research Modular Ocean Model, of similar formulation to the GFDL general circulation model (GCM) employed by *Toggweiler et al.* [1989]. The second uses an isopycnic coordinate model [*Oberhuber*, 1993], which has the advantage of isopycnally aligned fluxes of temperature and salinity, ameliorating the spurious upwelling associated with the Veronis effect. If this upwelling is indeed the cause of the aforementioned discrepancy in bomb radiocarbon column inventory, one should expect a better agreement with the GEOSECS observations in the isopycnic model. However, *Duffy et al.* [1995] report that this is not so, obtaining distributions in both models very similar to those of *Toggweiler et al.* [1989] in this respect. It must be surmised that the Veronis effect is not the source of the discrepancies in the modeled column inventories.

Here we investigate the possibility that vigorous eddy transfer of bomb $\Delta^{14}C$, which is poorly represented in coarse resolution GCMs, may play a significant role in ventilating the western part of the subtropical gyre. This

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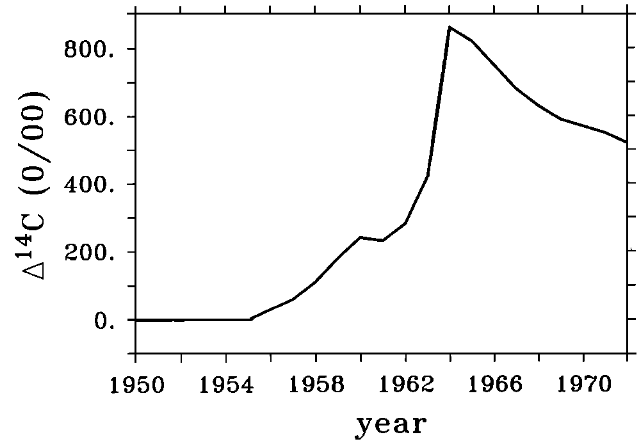

Figure 1. Transient of $\Delta^{14}C$ in northern hemisphere troposphere (data from *Tans*, [1981]). The signal is mostly attributable to bomb-produced ^{14}C, but is slightly modified by the carbon isotope ratios released during fossil fuel burning.

has been shown to be the case for potential vorticity and an age tracer in model experiments by *Cox* [1985]. *Williams et al.* [1995] found an idealized "date" tracer to be ventilated more readily into the western subtropical gyre in an eddy-permitting model of the North Atlantic, when compared to ventilation in a coarser resolution model. We expect, and find, that eddies play a similar role in setting the distribution of bomb $\Delta^{14}C$.

Two model experiments are performed in the North Atlantic basin, one with parameterized eddies and the other with resolved eddies. Both transport models employ the same mixed-layer boundary conditions, appropriate to the bomb-produced transient in $\Delta^{14}C$, and both are integrated for 23 years: 1950 to 1972 (i.e., prebomb to GEOSECS). We find that the model which explicitly resolves geostrophic eddies can indeed reproduce the longitudinal gradient in column inventories suggested by the observations. In contrast, a coarser model, with a simple diffusive representation of eddy transfers, fails to capture the broad distribution.

2. Model Experiments

2.1. The North Atlantic Tracer Models

2.1.1. General circulation model. The tracer transport models used here are based on velocity, temperature, and salinity fields from integrations of the Community Modeling Effort (CME) North Atlantic general circulation model [*Holland and Bryan*, 1994a, b]. The CME model is a primitive equation ocean GCM based on the GFDL ocean model. It is formulated with realistic North Atlantic topography and forced with seasonal wind stresses. In the integrations from which we have fields the surface layer was relaxed toward seasonal Levitus salinity and "atmospheric" temperature, the former on a 25-day timescale, the latter with a parameterized heat flux. Open boundaries were relaxed toward Levitus climatology for both salinity and temperature. Turbulent mixing of temperature and salinity was represented by an isopycnally aligned diffusion [*Solomon*, 1971; *Redi*, 1982; *Cox*, 1987] with a uniform value of 1000 m^{-2} s^{-1} at coarse resolution. In fine resolution integrations, turbulent mixing was achieved by explicitly resolved eddies and a biharmonic horizontal dissipation. For detailed discussion of the CME model, see *Holland and Bryan* [1994a, b] and references therein.

2.1.2. Off-line tracer model. In the experiments presented here, following *Williams et al.* [1995], we run the tracer models off line, using velocity and density fields specified from two integrations of the CME model; one which has resolution of $1.0^o \times 1.2^o$ and the other $1/3^o \times 2/5^o$. The latter model has sufficient resolution (tens of kilometers) to explicitly represent the larger scales of mesoscale eddies ("eddy permitting").

A subdomain of the model is used in order to reduce computation time. The off-line tracer model domain spans the uppermost 15 levels (surface to 1600 m) of the CME model, with the northern boundary at 60°N and the southern boundary at 10°N. Fields of velocity, temperature, and salinity, sampled regularly from a single model year, are repeatedly cycled. For the coarse resolution model, dynamical fields change every 3 days, and for the finer resolution, fields change every 6 days, a choice dictated by the considerably greater data handling demands of the high-resolution calculation.

The tracer model adopts the B grid of the CME model. Upstream differencing is used for tracer advection. While somewhat diffusive, it is positive definite, avoiding negative tracer values and instabilities at fronts and in the vicinity of near-zero tracer mixing ratios, which may occur with centered differencing schemes. (The general circulation model was integrated using centered differencing; temperature and salinity have large background values and are not subject to such problems.) The diffusivity due to finite differencing is typically smaller than the imposed horizontal diffusivity in the coarse resolution case. For the off-line tracer experiments presented here, diffusivities are uniform in the horizontal and vertical planes. A horizontal diffusivity K_h of 1000 m^2 s^{-1} is used in the coarser resolution experiment, parameterizing the effects of eddy transfer. For the fine resolution experiment, where eddy transfer is resolved, we choose a much smaller horizontal diffusivity, $K_h = 10$ m^2 s^{-1}. Vertical diffusivities of $K_z = 10^{-5}$ m^2 s^{-1} are used in both experiments, consistent with field observations of a deliberately released tracer in the subtropical gyre [*Ledwell et al.*, 1993].

Fluxes of tracer through the open boundaries and bottom most level (at 1600 m) are determined by assuming that tracer mixing ratios at the boundary are equal to those in the adjacent interior box. Zero normal gradient ensures that the diffusive fluxes across the boundaries are zero but allows advective fluxes across the boundary using the upstream differencing scheme.

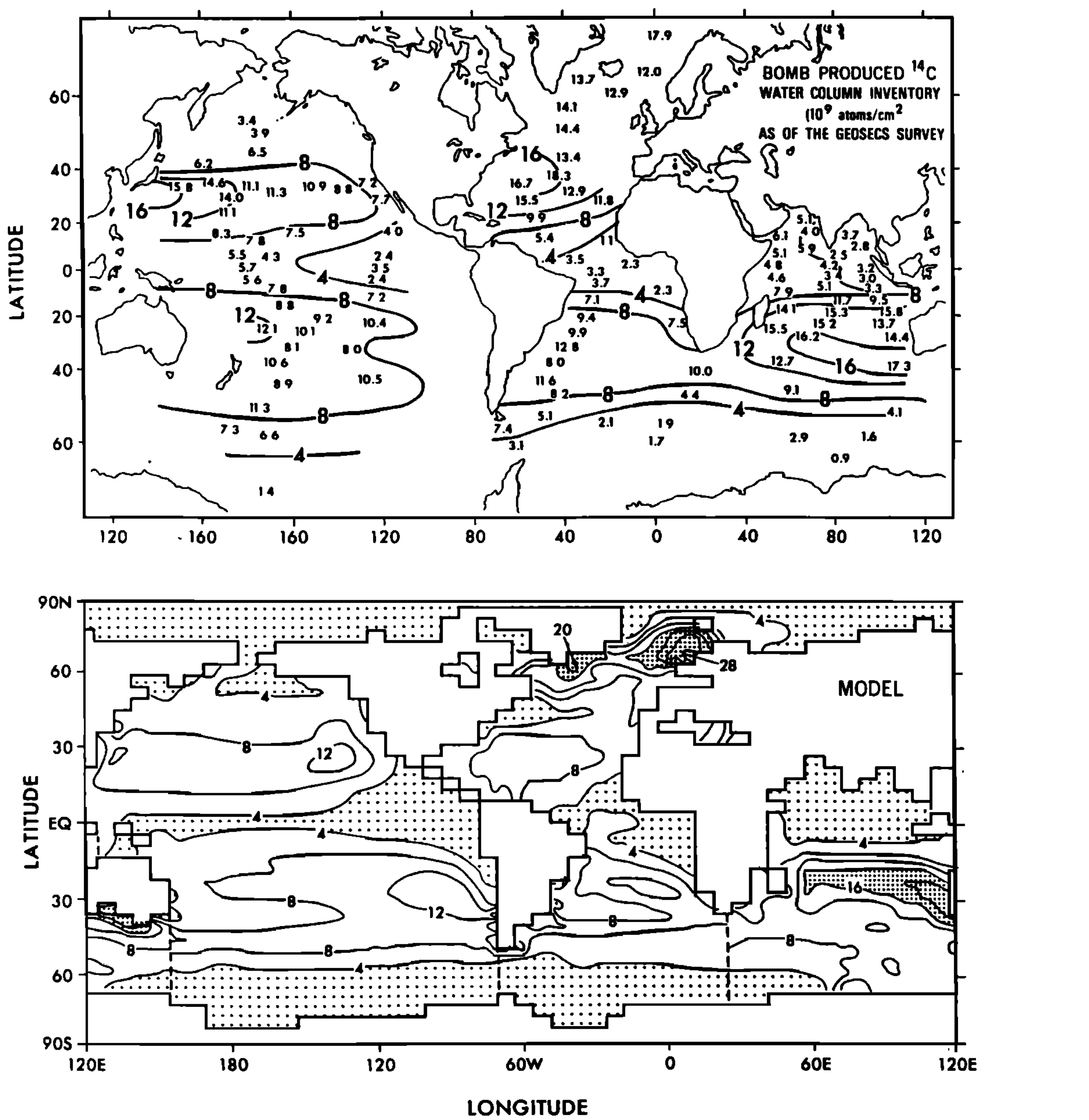

Figure 2. Column inventories of bomb ^{14}C as revealed from the Geochemical Ocean Sections Study data [*Broecker et al.*, 1985] and the model of *Toggweiler et al.* [1989], for the year 1972. Reproduced from *Toggweiler et al.* [1989].

We diagnose the seasonally varying mixed–layer depth h from the model density field, using a density change criterion of 0.05 kg m^{-3} from the surface. This layer is assumed well mixed and in contact with the atmosphere at all times.

2.2. Boundary Conditions and Approximations for ^{14}C

The ratio of carbon 14 and carbon 12 isotopes in a sample $^{14}C/^{12}C = \gamma$ is normalized to a standard ratio γ_s,

$$\delta^{14}C = \left(\frac{\gamma}{\gamma_s} - 1\right) 1000. \qquad (1)$$

The standard ratio is defined as that found in certain environmental samples prior to the atmospheric bomb tests: $\gamma_s = 1.18 \times 10^{-12}$ [*Stuiver et al.*, 1981].

Observations of $\delta^{14}C$ are corrected for fractionation during biological processes and air–sea exchange so defining a quantity $\Delta^{14}C$ (see, for example, *Broecker and Peng* [1982]). In the experiments presented here, where these fractionation processes are not represented, model $\delta^{14}C$ results can be compared to observed $\Delta^{14}C$, and we will use the notation $\Delta^{14}C$. Assumptions have also been made concerning the influence of mixing and fractionation during air–sea exchange on $\Delta^{14}C$. *Fiadeiro* [1982] showed that, due to the comparatively small gradients in oceanic ΣC (dissolved inorganic carbon 12), $\Delta^{14}C$ can be treated as a simple tracer for advection and diffusively parameterized mixing. This also holds for mixing of $\Delta^{14}C$ during entrainment into the mixed layer, to an accuracy of a few percent. Since the timescale of the model experiments, about 20 years, is very short compared to the half-life of ^{14}C, 5730 years, we omit radiodecay from the model.

We make three further assumptions: (1) Surface dissolved inorganic carbon is always close to its equilibrium value (reasonable to within a few percent), (2) fractionation of carbon isotopes during transfer across the air–sea interface and within the dissolved inorganic components is small compared to the large transient changes, and (3) atmospheric and mixed-layer gradients in dissolved inorganic carbon are small compared to the background value. Given these assumptions, the mixed-layer development of $\Delta^{14}C$ can be expressed in the following way:

$$\frac{D}{Dt}(\Delta^{14}C_m) = \alpha \frac{v_e}{h}(\Delta^{14}C_{at} - \Delta^{14}C_m) + E. \quad (2)$$

Here subscripts "m" and "at" denote mixed-layer and atmospheric values, respectively, and $D/Dt = (\partial/\partial t + \mathbf{U}\cdot\nabla)$ is the substantial derivative. The tendency due to entrainment of thermocline waters is represented by E. The parameter $\alpha = [CO_2(aq)]/\Sigma C_m$, the ratio of dissolved CO_2 gas and total inorganic carbon in the mixed layer, is assumed to be a constant ($\alpha = 0.005$). Thus the mixed-layer $\Delta^{14}C$ relaxes to the imposed atmospheric value with a timescale $\tau = h/\alpha v_e$, typically of the order of a decade for mixed layers of depth $h \sim 100$ m. We assume v_e, the piston velocity, to be a uniform 20 cm h^{-1}. The northern hemisphere tropospheric value of $\Delta^{14}C$ is prescribed, uniformly in space, from the data compilation of *Tans* [1981], displayed in Figure 1. The prescribed atmospheric perturbation of $\Delta^{14}C$ is, in fact, not entirely attributable to bomb radiocarbon, since there is a dilution due to the Suess effect (P. Duffy, personal communication, 1995). Thus the modeled fields of bomb radiocarbon displayed in the following section also contain a perturbation from the latter effect. However, this study is focused on the qualitative comparison of model responses, and the main conclusions are unaffected.

To convert a model distribution of $\Delta^{14}C$ into a column inventory of bomb-produced ^{14}C (I, atoms per square meter), we integrate vertically over the model domain:

$$I = \frac{N_A \, \gamma_s \, \Sigma C \, \rho}{1000} \int \Delta^{14}C \, dz \quad (3)$$

where N_A is Avogadro's number. Density ρ (kilograms per cubic meter) and concentration of dissolved inorganic carbon, ΣC (moles per kilogram), are here assumed uniform throughout the domain, introducing an error of about 1% in the column inventory. In the simulations presented below, the initial condition for $\Delta^{14}C$ is zero everywhere in the basin. Since we are concerned with perturbations to the prebomb state, this initial condition is arbitrary and chosen for convenience. This assumption, $\Delta^{14}C(1950) = 0$, is built into (3), factoring out the prebomb distribution of ^{14}C in the column inventory estimates.

3. Model Results

Figure 3 maps the column inventories of bomb ^{14}C, I (atoms per square centimeter), for midsummer of model year 1972 from the simulations with both the coarse and fine resolution models. In both cases, the column inventories are found to have a maximum in the western part of the subtropical gyre. In the coarse resolution case, however, this is very slight with a generally uniform distribution over the gyre. In the fine resolution case, there is a strong longitudinal gradient, with I elevated in the western region. In the remainder of the subtropical gyre we find similar values and distributions of I, though in the subpolar gyre, the fine resolution case shows slightly elevated values.

Why do the distributions in the coarse and fine resolution models show such different behavior in the western subtropical gyre? *Rhines and Young* [1982] introduced the idea that ventilation of the region of closed streamlines in the recirculating gyre must be achieved by eddy transfers. *Cox* [1985] compared coarse and fine resolu-

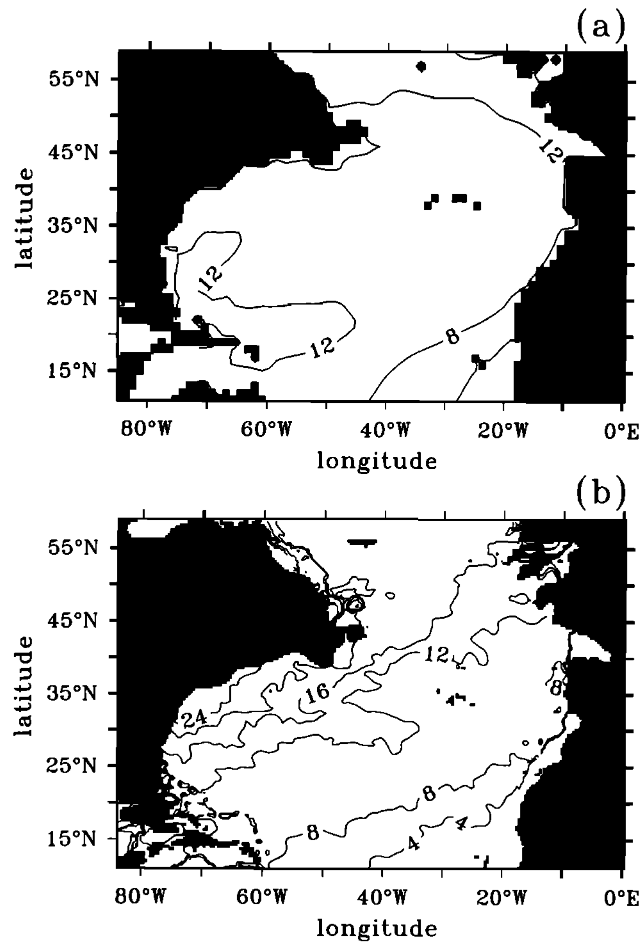

Figure 3. Vertical integral of bomb ^{14}C column inventories, I (atoms per square centimeter), over the model domain, midsummer 1972, for **(a)** the coarse resolution model and **(b)** the fine resolution model.

tion general circulation models in an idealized basin. In that study, the fine resolution case showed a homogenization of the potential vorticity field on constant density surfaces and a decreased age to the west, indicating enhanced ventilation of that region. The idealized date tracer experiments of *Williams et al.* [1995], also using the coarse and fine resolution CME models, found enhanced ventilation in the recirculating region in the eddy permitting model.

The experiments performed here indicate a similar role for eddy transfers in ventilating bomb Δ^{14}C into the western region of the density surfaces. Figure 4 illustrates the midsummer distribution of bomb Δ^{14}C on the $\sigma_\theta = 27.0$ surface for the two models. The fine resolution model shows a very strong signal of high Δ^{14}C values from the surface right across the basin. In contrast, at the coarser resolution the ventilated region is confined to the eastern part of the basin; a large unventilated pool is present in the west. The column inventories in Figure 3 simply reflect the fact that the deeper density surfaces are ventilated in the western basin in the fine resolution case, but not at coarse resolution. We suggest that in the fine resolution model, resolved eddies ventilate the pool more efficiently than the the diffusive parameterization of the coarse model. The coarse resolution case (Figure 4a) shows a tongue of high Δ^{14}C ventilating the eastern subtropical gyre consistent with the thermocline ventilation theory of *Luyten et al.* [1983]. In the fine resolution case, this tongue is smeared westward (Figure 4b), as *Cox* [1985] found for an ideal age tracer. Figure 4b suggests that high Δ^{14}C values are also being transferred into the recirculation region in the vicinity of the Gulf Stream and intergyre boundary, presumably by enhanced eddy transfer in that region.

We also observe significantly deeper mixed layers in the fine resolution case (Figure 5) which could communicate bomb ^{14}C to deeper surfaces more rapidly. We argue, however, that variations in the column inventory, I, are critically dependent on lateral transport processes and not the mixed-layer depth. Since the mixed-layer equilibration of Δ^{14}C is so slow ($\sim$ 10 years), surface ocean values are small compared to atmospheric values, during the period of the bomb-produced transient. Thus the flux of bomb ^{14}C through the ocean surface is, to a good approximation, uniform in space and given by $\alpha v_e \Delta^{14}C_{at}$. In the absence of lateral transports within the ocean, the column inventories in 1972 would be uniform and approximately equal in both model experiments. From (2) and (3), and assuming no lateral transports, the column inventory of perturbation ^{14}C, at time Δt, would be

$$I(\Delta t) \quad = \quad \frac{N_A \; \gamma_s \; \Sigma C \; \rho \; \alpha \; v_e}{1000} \int_0^{\Delta t} \Delta^{14}C_{at} \; dt \quad , \quad (4)$$

which is independent of the mixed-layer depth. Vertical transport alone, be it by convection or other means, can have no direct impact on the column inventory distributions. Any nonuniform column inventories, or differences thereof, are facilitated by lateral eddy transfers or advection. We interpret the differences between the modeled column inventories, then, to be largely a consequence of the different representation of eddy transfers in the coarse and fine resolution models.

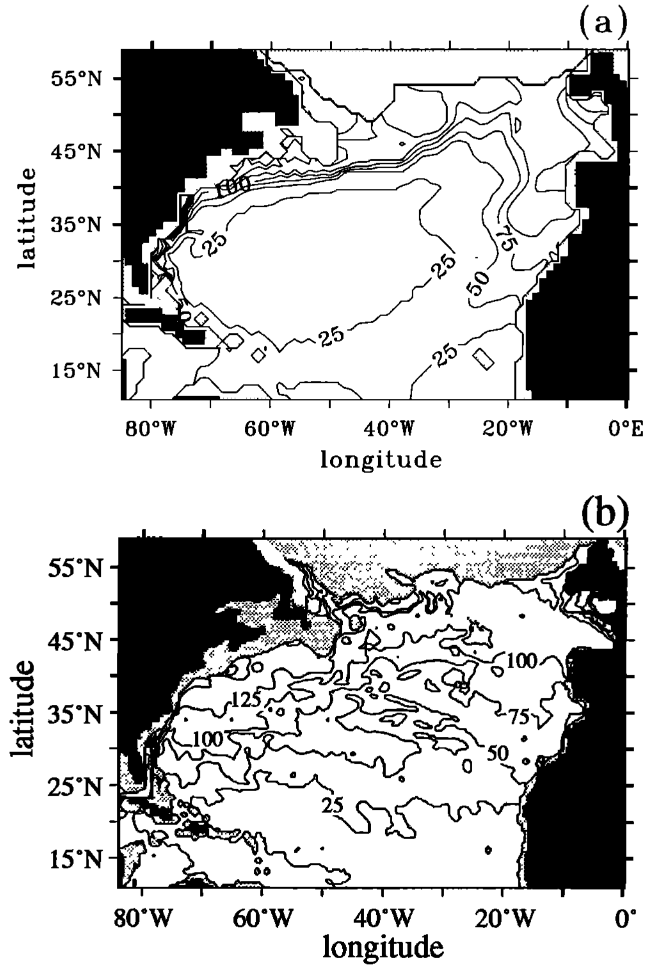

Figure 4. Bomb Δ^{14}C on the $\sigma_\theta = 27.0$ surface, midsummer 1972, for **(a)** the coarse resolution model and **(b)** the fine resolution model.

4. Summary

Global coarse resolution models of bomb-produced Δ^{14}C in the ocean produce unrealistic distributions over the subtropical gyre [*Toggweiler et al.*, 1989; *Duffy et al.*, 1995]. East-west gradients in the vertically integrated Δ^{14}C distribution are found to be reversed in the model subtropical gyres, when compared to the GEOSECS observations.

Using two North Atlantic tracer models, with an idealized, bomb Δ^{14}C tracer, one coarse resolution and one which is eddy permitting, we demonstrate that the the eddy-resolving calculation resembles the GEOSECS observations more closely, with the column inventory of the bomb ^{14}C raised to the west. This is attributed to enhanced eddy stirring by explicit eddies in the western region of the fine resolution model, ventilating the deeper isopycnals in the recirculation region. The parameter-

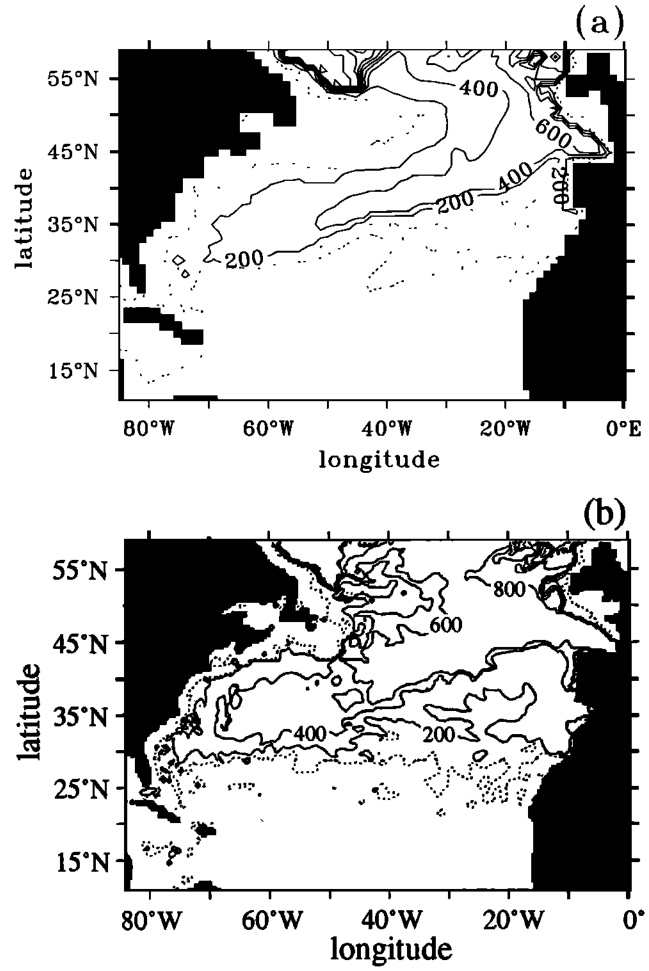

Figure 5. March mixed-layer depth (meters) in **(a)** the coarse resolution model and **(b)** the fine resolution model. Figures 5a and 5b show instantaneous diagnostic mixed-layer depths, based on a $\Delta\sigma_\theta = 0.05$ kg m^{-3} criterion. The contour interval is 200 m, and the 100 m contour is added as a dotted line.

ized eddy flux, employing constant diffusivities, in the coarse resolution model is unable to represent this. We conclude that since explicit representation of eddies is not currently feasible for global biogeochemical models, further effort to develop more realistic parameterizations of eddy tracer transfers is required.

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