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Ocean Science
Discussions

Interactive comment on "How does ocean ventilation change under global warming?" *by* A. Gnanadesikan et al.

A. Gnanadesikan et al.

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Response to Reviewers

We would like to thank the reviewers and the editor for their work on this paper. Subject to the editor's agreement, our plan is to submit a revised manuscript for publication in Ocean Science.

Reviewer 1

We thank reviewer 1 for encouraging this work. In general we agree with the reviewer's points, and we list responses to the minor comments below. However, there are four points where we disagree with the reviewer. A detailed response on these four points is provided below.

Major points: Reviewer 1

1. Isopycnal vs. depth analysis. The reviewer is certainly correct that isopycnal analysis makes sense for analyzing model fidelity. However, when looking at climate change (for which the depth of isopycnals changes) it obscures the key result. For example, in the CM2.1 model, doubling CO2 produces a reduction of age of about 16 years in the Eastern Tropical Pacific (180W-100W, 30S-20N) at a depth of 400m. When following an isopycnal associated with this depth and region however, a similar analysis shows an increase of age of about 30 years. Moreover, we are interested in these regions in part because they correspond to minima in the oxygen concentration. Insofar as remineralization of organic matter and thus consumption of oxygen are determined by depth (really distance from the euphotic zone) rather than density, analyzing things in depth makes more sense. However, we will add language saying that when Figure 1 in particular is looked at in density space, the models continue to reproduce the contrast between the PV structure of the shadow zones and that of the subtropical gyres.

2. Why use the R30 model? The fact that we see the same behavior in this model raises our confidence that the response is robust are not merely an artifact of our initialization strategy.

3. Why use the coarse PRINCE2 model? If one looks at the budget terms in these regions, it becomes rapidly clear that many terms (lateral advection and diffusion, vertical advection and diffusion) can play important roles. We do not currently have access to a coupled simulation with nutrients which has been validated with tracers and in which all relevant budget terms have been saved.

4. 1-D model. Both reviewers seem to have missed the point of this model, probably because we did not explicitly link it to classic geochemical models. The purpose of this model was to present a very simple analytical solution that illustrated the conceptual difference between a pipe model in which the age is simply the time for water to travel from an outcrop, and a more complicated picture in which the age is actually an integral of a spectrum of ages with different pathways. The simplest such example of

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the second picture is a two-source model, with bottom-water injection and diffusion of tropical waters from above. From a geochemical point of view, the water upwelling from the abyss can be thought of as "young" because it is a source of oxygen. A revised discussion that reflects these points is presented below:

In order to understand the results of the coupled model, it is necessary to distinguish between two conceptual models of the ideal age. The first may be thought of as a "pipe" model, in which the age at a point simply reflects the time required for water to reach that point from a surface outcrop. In such a picture a reduction of the advective or diffusive transport would result in an increase in the age. However, one can propose an alternative "network" model in which there are many different pathways to reach the same point. In such a model the age is actually the centroid of a spectrum of ages, reflecting many different pathways by which surface waters can reach a particular point (see Khatiawala et al., 2001 for a more detailed discussion of this issue). The age at a point can then change not only as the time associated with each pathway changes, but as the *relative proportion* of waters taking separate pathways changes.

A simple model system that illustrates the different behavior of these two pictures is a one-dimensional advective-diffusive model, of the type used in classic geochemical studies (Volk and Hoffert, 1985; Shaffer and Sarmiento, 1995). Such models typically have two pathways by which oxgyen-replete surface waters enter the ocean. One pathway involves the formation of bottom water, which flows from polar regions into the tropics and upwells into the interior, aging as it does so. The other involves the diffusion of tropical surface water from above (which in models such as the HILDA code of Shaffer and Sarmiento, 1995 is taken as a representation of the wind-driven gyre circulation as well as explicit diapycnal diffusion). The equations governing age in the model interior then are

$$w\frac{\partial A}{\partial z} - K_v\frac{\partial^2 A}{\partial z^2} = 1 \quad (1)$$

where w is the upwelling velocity and K_v is a vertical diffusion coefficient. While mod-

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els such as the HILDA code allow for lateral exchange with a well-mixed polar deep box and inject the deep water from this box, such additional complexity does not add additional insight relative to the simple condition of fixing the bottom water and top at an age of 0. With these boundary conditions the solution to 1 is

$$A = \frac{1}{w}\left(z + \frac{D(1 - e^{zw/K_v})}{1 - e^{-wD/K_v}}\right) \tag{2}$$

When wD/K_v is large, the solutions of this equation behave like a "pipe" model. As illustrated in Figure 6a,c when the wD/K_v is large, decreasing w means that the age increases throughout the water column as it takes more and more time to bring the water up from below. However, when wD/K_v is large (Figure 6b,d) decreasing w does not have such a simple impact. In the upper part of the water column, decreasing the upwelling means that the age is more dominated by the downward transport of "young" tropical waters and so the age actually decreases. Insofar as the decrease in the upwelling of the extremely old deep waters from below outstrips any decrease in the supply of younger waters from above, one can actually decrease the overall rate of ventilation while still decreasing the age in the upper water column!

(text would then continue at second paragraph on p. 813).

Response to other comments of Reviewer 1

Introduction

1. Suggestion: expand discussion of the Walker circulation and impact of the enhanced hydrological cycle on ventilation. We will add a few sentences doing this.

Description of simulations

2. We will reference the IPCC AR4 terminology for the CM2 runs. The 1860 control corresponds to the PIcntr runs, the 1990 control to the PDcntrl runs and the 1% doubling run to the 1%to2x runs in the PCMDI terminology.

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Results

3. CFC-12 age is calculated from the gridded dataset of Willey et al. (2004). This reference will be added.

4. We have increased the size of the labels and lightened the colors so that the contours and labels are visible in the printed version. Although the color scales were not harmonized in the original version as they refer to different fields, we have made them the same in the current version.

5. The discrepancy in the west Pacific appears to be due to the fact that the model produces a more symmetric equatorial circulation than is observed. When the ocean model is forced with observed winds, there is a strong North Equatorial Counter Current and a weak South Equatorial Counter Current. This means that the old, low oxygen water in the east is much more efficiently transported to the west in the Northern Hemisphere relative to the Southern. Such an asymmetry does not exist in the coupled models and is likely to be related to the well-known "double ITCZ" problem which produces a far more symmetric wind field in the Pacific than observed.

6. The top panels in Figure 6 show two profiles of age, the bottom panels the change between the two. Caption will reflect this more clearly. Zero line will be added to Figure 6d.

7. Zero line will be added for Figure 7c.

8. Discussion questions are handled above in point 4.

Conclusion

9-10 First 2 questions are handled in point 2, above.

11. The impact of using a coarse model is likely to slow down and spread out the lateral advective transports, particularly in the region of the EUC, relative to the slower diffusive upwelling. Thus we would expect any results in the coarser models would

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underestimate the true difference between the near-equatorial zone and the shadow zones.

12. Figure 9 caption will be fixed and brought into agreement with text.

Reviewer 2

We thank Reviewer 2 for forcing us to make our argument clearer and for pointing out places where we were insufficiently rigorous. As with Reviewer 1, we divide our response into major and minor points.

1. Focus on the shadow zones. We chose to focus on these regions because they correspond to the oxygen minimum zones, and have important implications for the global nitrogen cycle. We will make this more clear in the abstract and elsewhere in the paper. As outlined below, however, we will spend some time discussing the North Atlantic and Arctic as well.

2. 1d model. Again, a major part of our focus in this paper was on the oxygen minimum zones. We hope that our new discussion, which specifically links the 1D model to classic geochemical box models such as Volk and Hoffert (1985) more clearly illustrates the difference between a "pipe" and a "network" model for oxygen.

Minor points

Introduction

1. Add other references. The Sarmiento et al. paper actually shows results from 6 coupled GCMs- this fact will be added to the text. We will also add references to Washington and Meehl, 1989 and Manabe and Stouffer, 1994 both of whom demonstrated increased stratification due to global warming despite an increase in the hydrological cycle.

2. Slowing tropical winds reducing tropical ventilation. This is a reasonable point, in that a decrease in the winds could be compensated by a shift in the pattern of stress.

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However, such a change in the wind stress pattern does not occur in the results of Vecchi et al. (2006). A followup paper, (Vecchi and Harrison subm.) shows clearly that the equatorial overturning decreases in strength under global warming across the IPCC AR4 models.

3. More detail in the model description. We will add the following paragraph,

The CM2.0 model is run using the new B-grid atmosphere described in GAMDT (2004) with 24 vertical levels (including 6 in the surface boundary layer) and a horizontal resolution of 2.5° in longitude and 2° in latitude. The CM2.1 model is run using the amd atmospheric column physics as CM2.0 but with a finite-volume core (Lin, 2004) which produces a significant poleward shift in the wqinds, particularly in the Southern Hemisphere. As discussed in Gnanadesikan et al. (2006) the shift in winds produces a significant improvement in the circulation. The ocean model is based on the MOM4 code base of Griffies et al. (2005) at a nominal resolution of 1° mid latitudes, with latitudinal resolution increasing to 1/3° at the equator. Vertical resolution is high in the upper ocean, with 10m vertical resolution down to 230m, and an additional 27 layers below this depth The ocean model includes up-to-date representations of bottom topography, the free surface, the mixed layer, lateral viscosity, and advection about which more details are provided in Griffies et al. (2005). The control climate simulations are described in Delworth et al. (2006) and the simulations under idealized climate change in Stouffer et al (2006).

4. The information requested here is given in Table 1 of Delworth et al. (2006) , which we will specifically reference. As the solar irradiance, CO_2, CH_4, CFC11, CFC12, CFC22, CFC113, N2O and land use all differ between the simulations we do not feel it useful to reproduce all of these differences here.

Results

5. CFC age is calculated from dataset of Willey et al. (2004). This refernce will be added. Changes to figure have been made to improve legibility.

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6. It appears that the referee misread the plots- probably because the contours weren't very clear. In fact the age in the models is too *young* relative to the CFC age (5-10 vs around 20). As noted by the reviewer the PV (colors in b,c,and d) is on the low side in the gyre interior. The key point, in our view, is the distinction between the low-PV, low-oxygen shadow zones, high PV values in a zone along the edge of the gyre which is nonetheless better ventilated, and lower PV values in the most rapidly ventilated parts of the gyre interior. The model does capture these gradients.

7. Why is there not more discussion of other regions. As noted above, we had intended to focus our discussion on the shadow zones, which show the most robust changes across models, but as the reviewer notes, there are interesting differences in the Arctic and North Atlantic as well. We will deal with these by adding a section to the discussion section, as described below.

8. We will add a table showing the change in young water volume in the bands 90S-50S, 50S-0, 0-50N, 50N-80N, 80N-90N.

9. Why is it striking to find changes in regions with low variability? "Striking" is perhaps the wrong word here. What we were trying to point out was that the changes in the shadow zones are quite large in comparison with interannual variability, in comparison to (for example) the North Pacific.

Discussion

10. We hope that the changes made in response to Reviewer A also satisfy these comments. We note that with respect to tracers like oxygen, the deep ocean is not, in fact "old".

We will also add some discussion of the changes in other regions, and talk about whether they can be understood in similar terms as the low-latitude change. The change in the North Atlantic appears to have a similar type of explanation as the tropics (a decrease in the flow of AAIW coming from the south as the overturning spins down,

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which more than compensates for a local reduction in convection). The Arctic is more tricky. The changes in the Canada basin appear to be due to an increase in sinking within the Arctic. Under global warming, there appears to be more downwelling at intermediate depths in the Western Arctic. The increase is more dramatic in the CM2.0 model (increasing from 0.4 Sv to 1.2 Sv) than in the CM2.1 model. (-0.9 to -1.4 Sv).

Added References

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