Deep ocean heat uptake as a major source of spread in transient climate change simulations

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[1] Two main mechanisms can potentially explain the spread in the magnitude of global warming simulated by climate models: deep ocean heat uptake and climate feedbacks. Here, we show that deep oceanic heat uptake is a major source of spread in simulations of 21st century climate change. Models with deeper baseline polar mixed layers are associated with larger deep ocean warming and smaller global surface warming. Based on this result, we set forth an observational constraint on polar vertical oceanic mixing. This constraint suggests that many models may overestimate the efficiency of polar oceanic mixing and therefore may underestimate future surface warming. Thus to reduce climate change uncertainties at time-scales relevant for policy-making, improved understanding and modelling of oceanic mixing at high latitudes is crucial.
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1. Introduction

[2] A central contemporary challenge of climate science is to reduce uncertainties of climate change projections. Indeed, even the simplest possible metric of climate change – the global increase of surface air temperature in response to a given radiative forcing – remains uncertain. For example, when forced by the SRESA1B emission scenario [*Nakicenovic et al.*, 2000], the state-the-art climate models used in the last Intergovernmental Panel on Climate Change (IPCC) report [*Intergovernmental Panel on Climate Change*, 2007] simulate a globally-averaged mean surface air temperature change of 2.6 K between 2070–2099 and 1950–1999 (ΔTas), with a two-sigma range of 1.7–3.5 K. At the regional scale, the inter-model standard deviation of surface temperature change is often even larger than for the global average: For example, it is roughly two times greater over most of continental USA and locally more than four times greater over high latitude oceans.

[3] Surface warming in the transient response to a given external perturbation of the Earth's energy budget mainly depends of two factors: how much climate feedbacks dampen or enhance the initial radiative perturbation, and the rate at which heat is removed from the surface to deeper ocean [*Gregory and Mitchell*, 1997; *Forest et al.*, 2006; *Collins et al.*, 2007]. Whether deep ocean heat uptake or climate feedbacks are the main source of uncertainties in transient climate change simulations is therefore a key question.

2. Baseline Mixed Layer Depth and Deep Ocean Heat Uptake

[4] A radiative forcing in a climate model first results in a temperature anomaly in the ocean mixed layer/troposphere system that spreads progressively to the deeper ocean [*Hansen et al.*, 1984; *Manabe et al.*, 2007]. High latitudes are known to be particularly important for deep ocean heat uptake, as the deep vertical mixing characteristic of those regions may constitute a "door" to deep ocean [*Gregory*, 2000; *Russell et al.*, 2006]. During the transient response to a given radiative perturbation, it is therefore possible that the inter-model spread in baseline climatological mixed layer depth (MLD) at high latitudes is tightly linked to intermodel variations in deep ocean heat uptake, and consequently to surface air temperature change.

[5] To test this hypothesis, we computed the climatological annual maximum MLD in the 1950–1999 period in an ensemble of 19 present-day climate simulations from the Coupled Model Intercomparison Project phase 3 (CMIP3) archive, done in the context of the last IPCC report. Figures 1a and 1b show the ensemble mean and inter-model standard deviation of the MLD. Deep mixed layers are simulated in high latitudes, while shallow mixed layers are seen in the Tropics, especially in the East-Pacific and East-Atlantic. This geographical pattern is qualitatively consistent with the observations [*Monterey and Levitus*, 1997; *Kara et al.*, 2003; *de Boyer Montégut et al.*, 2004]. Deep mixed layers in polar regions are generally associated with deep water formation. The relatively large MLDs in the Southern Ocean are also linked to a deep wind-driven overturning cell [*Manabe and Stouffer*, 2007; *Held*, 1993]. The inter-model standard variation of MLD is very large at high latitudes, especially in the Ross and Weddell seas (Figure 1b).

[6] To assess the relationship between baseline climatological MLD and simulated surface warming, we correlated the models' ΔTas to their zonally-averaged MLD, for each latitude band (Figure 1c). Except in a few regions, the correlations are negative. Not surprisingly, large and statistically significant negative correlations are found only at high latitudes. In particular, very high negative inter-model correlations are obtained in the southern polar region (−0.7 to −0.8). Thus models with deeper baseline mixed layers at high latitudes are associated with smaller surface warming: the inter-model correlation between ΔTas and the spatial average of MLD south of 68°S and north of 58°N (MLDp in the following) is −0.82. The effect of deeper mixed layers at high latitudes on surface warming is global and not

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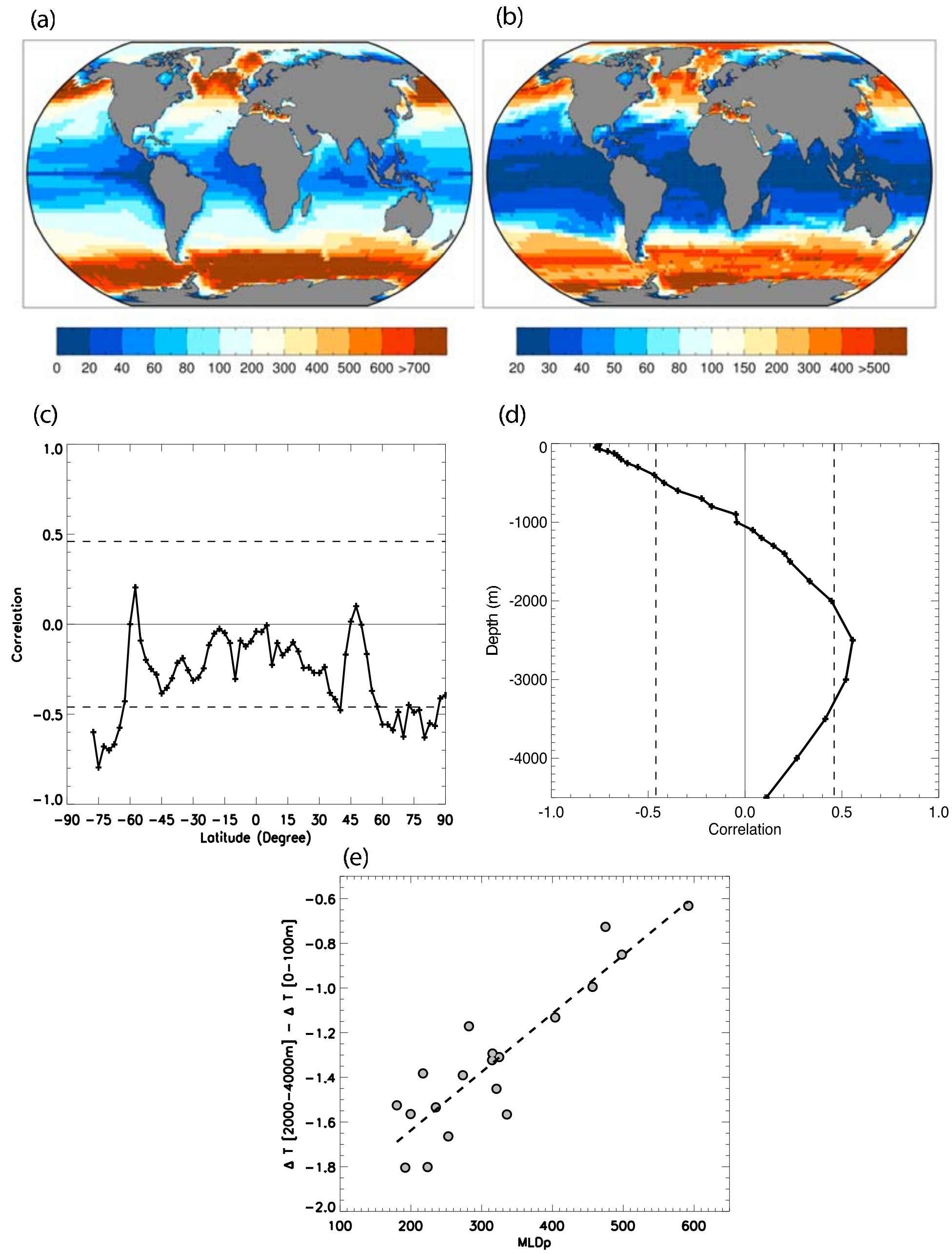

Figure 1. (a) Ensemble mean and (b) inter-model standard deviation of the climatological annual maximum Mixed Layer Depth (MLD) during the 1950–1999 period (m). The MLD is computed for the 19 models with the necessary data for this study in the CMIP3 archive, using the "20c3m" experiments [*Meehl et al.*, 2007]: bccr_bcm2_0, cccma_cgcm3_1, cccma_cgcm3_1_t63, cnrm_cm3, csiro_mk3_0, csiro_mk3_5, gfdl_cm2_0, gfdl_cm2_1, giss_aom, giss_model_e_h, giss_model_e_r, ipsl_cm4, miroc3_2_medres, mpi_echam5, miub_echo_g, mri_cgcm2_3_2a, ncar_pcm1, ncar_ccsm3_0, ukmo_hadcm3. The climatological MLD is computed for each month and then the annual maximum at each location is searched. The MLD is defined as the depth where the absolute difference with potential oceanic temperature at the first level is greater than 0.2 K, a definition for example used by *de Boyer Montégut et al.* [2004]. (c) Inter-model correlation between global air surface temperature change (between the 2070–2099 and 1950–1999 periods) and zonally-averaged baseline MLD (annual maximum) in the 1950–1999 period. The dashed lines show the 0.05 significance level. Here and in the following the SRESA1B [*Nakicenovic et al.*, 2000] scenario is used for the future climate simulations. (d) Inter-model correlation between the baseline MLD (annual maximum) averaged north of 58°N and south of 68°S (MLDp) and globally averaged oceanic temperature change between 2070–2099 and 1950–1999 at different depths. The dashed lines show the 0.05 significance level. (e) Scatter plot between the difference of oceanic temperature change between the deep ocean (2000–4000 m) and the surface (0–100 m) and MLDp.

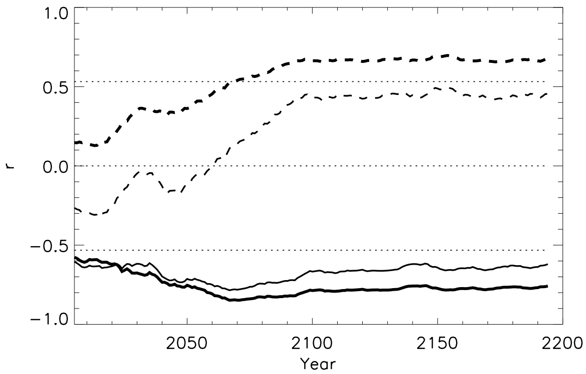

Figure 2. Running inter-model correlation between overlapping 10-year average of global surface air temperature change (1900–1949 reference) and (1) MLDp (thick solid line) and (2) ECS (thick dashed line). Running inter-model partial correlation between overlapping 10-year average of global surface air temperature change and (1) MLDp when the effect of ECS is controlled (thin solid line) and (2) ECS when the effect of MLDp is controlled (thin dashed line). The dotted lines show the 0.05 level of significance for the correlation. Only 14 models are used for this graph, as the necessary data are not available for all the models. The partial correlation between ΔTas and MLDp when the effect of ECS is controlled is the correlation between the residuals from regressing ΔTas on ECS and the residuals from regressing MLDp on ECS.

limited to polar regions. Indeed, the inter-model correlation between MLDp and surface air temperature change averaged in the region between 50°S and 50°N is −0.80.

[7] To show that the statistical relationship between MLD at high latitudes and transient surface warming is really due to deep ocean heat uptake, we computed the inter-model correlation between MLDp and globally-averaged oceanic temperature change at different depths as shown in Figure 1d. Models with deeper mixed layers at high latitudes not only exhibit smaller surface warming but also enhanced ocean warming below 1000 m depth. The difference of oceanic temperature change between the deep ocean (2000–4000 m) and the surface (0–100 m) is therefore strongly linked to MLDp (Figure 1e). This analysis shows that a relation between MLDp and ΔTas exists because models with deeper mixed layers at high latitudes in the present climate are transferring more of the radiative perturbation to the deep ocean, reducing surface warming.

3. Respective Roles of Deep Ocean Heat Uptake and Climate Feedbacks in Transient Global Warming

[8] For a given radiative forcing at equilibrium, global surface warming (or equilibrium climate sensitivity, ECS) depends only on climate feedbacks. Therefore, the role of deep oceanic heat uptake in the spread of surface warming should decrease over time, while the role of climate feedbacks – as measured by ECS – should increase. As a strong relationship between deep ocean heat uptake and MLDp exists (section 2), we study here how the roles of ECS and MLDp in the spread of global surface warming evolve over time. The values of ECS for the recent IPCC models have been estimated by undertaking equilibrium climate change experiments with the atmospheric components of the models coupled to a slab ocean [*Randall et al.*, 2007]. It is important to acknowledge that MLDp and ECS are not independent: a correlation of $r = -0.56$ ($p < 0.05$) is found between MLDp and ECS.

[9] Figure 2 shows the running correlation between ΔTas and MLDp, and between ΔTas and ECS. The anticorrelation between MLDp and ΔTas is already large and significant at the beginning of the 21st century and increases until roughly 2070. After 2070, it decreases very slowly. The correlation between ECS and ΔTas is very small at the beginning of the 21st century and then increases progressively. However, even at the end of the 22nd century, the absolute correlation between ΔTas and ECS remains smaller than that between ΔTas and MLDp, though the difference is not significant.

[10] To evaluate the impact of the fact that MLDp and ECS are not completely independent on the previous result, we show in Figure 2 the running partial correlations between ΔTas and MLDp when ECS is controlled, and between ΔTas and ECS when MLDp is controlled. The partial correlation between MLDp and ΔTas is only slightly weaker than the corresponding total correlation, especially during the 21st century. This shows that the relation between MLDp and ΔTas is not simply a result of the anticorrelation between MLDp and ECS and is therefore mainly due to deep ocean heat uptake, which is consistent with the results shown in section 2 (Figures 1d and 1e). Therefore, it is possible to conclude that deep ocean heat uptake is a major source of spread in transient climate change simulations until well into the 22nd century.

[11] This conclusion is not consistent with *Dufresne and Bony* [2008]. Using a global energy balance approach and the concept of "heat uptake efficiency", they conclude the role of ocean heat uptake in the spread of transient surface warming is limited compared to that of climate feedbacks – and in particular cloud feedback. Other studies have followed similar approach: the results of *Raper et al.* [2001] and *Gregory and Forster* [2008] are consistent with *Dufresne and Bony* [2008], while the results of M. Winton et al. (Importance of ocean heat uptake efficacy to transient climate change, submitted to *Journal of Climate*, 2009) are consistent with ours.

[12] Note that the very slow decrease of the anticorrelation between MLDp and ΔTas after the stabilization of greenhouse gas concentration in the atmosphere in 2100 in the SRES1AB forcing scenario is consistent with a millennial time scale for the climate system to return to equilibrium [*Stouffer*, 2004; *Danabasoglu and Gent*, 2009].

4. Constraining Transient Climate Change

[13] As the baseline MLD at high latitudes explains at least half of the spread in simulated global surface warming during most of the 21st century (Figure 2), it is important to evaluate its realism in current climate models. However, this is difficult because the precise value of the MLD may be sensitive to the definition of MLD and to the temporal and spatial aggregation procedure (in particular whether the MLD is computed on individual profiles or after spatial

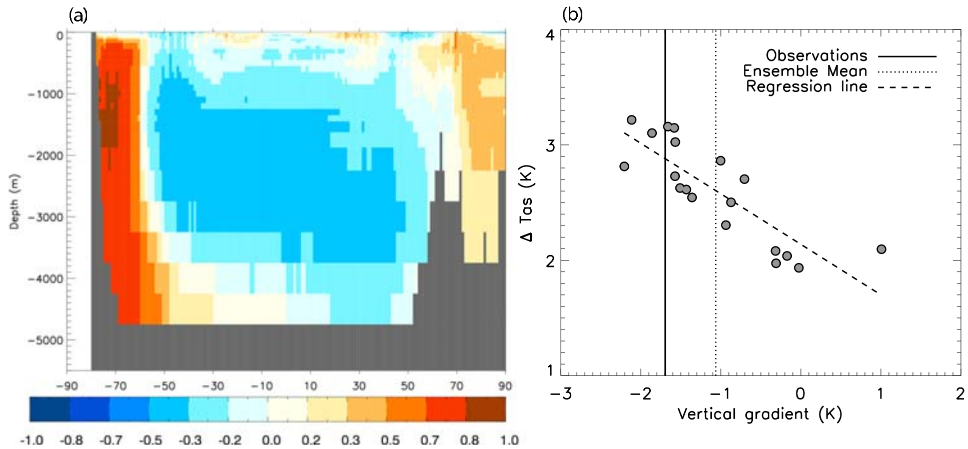

Figure 3. (a) Inter-model correlation of global air surface temperature change between the 2070–2099 and 1950–1999 periods and baseline climatological oceanic potential temperatures (1950–1999 period) in the 19 CMIP3 models. The 0.05 significance levels are 0.46 and −0.46. (b) Global surface air temperature change between the 2070–2099 and 1950–1999 periods in the 19 CMIP3 models as a function of the climatological difference of oceanic temperature between the 0–50 m and 500–1000 m depth ranges during the 1950–1999 period. The observed value based on the World Ocean Atlas 2005 dataset [*Locarnini et al.*, 2006] is given by the thick solid line.

and temporal averaging [*de Boyer Montégut et al.*, 2004]). Therefore, an alternative approach is adopted here.

[14] As shown in Figure 3a, there is a high inter-model correlation between oceanic temperature below roughly 100 m depth and south of 60°S in the present climate and future global surface warming. Results are qualitatively similar in the high latitudes of the northern hemisphere, but the correlations there are smaller. This may be an effect of the zonal-averaging of oceanic temperature, as the deep mixing responsible for heat uptake in the northern hemisphere is mostly confined to the northern North Atlantic and we do not expect deep ocean temperatures outside this sector to be predictive of surface warming. The correlation of MLDp to present-day oceanic temperature gives a very similar pattern, with an opposite sign (not shown): Colder waters below 100 m depth and south of 60°S in the present climate are climatologically associated with deeper mixed layers at high latitudes. These results show that the baseline vertical temperature structure in polar regions, in particular in the southern hemisphere, can be a skillful predictor of surface warming in transient climate change given the relationship between present-day oceanic mixing at high-latitudes and deep oceanic heat uptake.

[15] Figure 3b shows ΔTas in the models at the end of the 21st century versus the climatological present-day temperature difference south of 60°S between surface (0–50 m) and subsurface (500–1000 m) waters. As expected, a high inter-model correlation of −0.83 ($p < 0.01$) is found between the two quantities: models with smaller surface warming are associated with weaker vertical temperature gradient. Incorporating information about the vertical temperature structure in the Arctic in the predictor does not improve its correlation with ΔTas significantly. This is probably because in any particular model, mixing and associated heat uptake levels in northern and southern polar regions are not independent across models, even if the polar Northern Hemisphere is an important sink of heat.

[16] The corresponding observational estimate based on the World Ocean Atlas 2005 data [*Locarnini et al.*, 2006] is plotted in Figure 3b. Comparison of this value to the model's ensemble mean suggests that as an ensemble, current climate models may simulate excessive oceanic mixing in southern polar regions and may therefore give a biased-low estimate of global surface warming at the end of the 21st century. However, given the scarcity of observations in polar regions, the observational estimate remains uncertain and the previous conclusion must be viewed tentatively.

5. Conclusion

[17] In this paper, we have shown that deeper mixed layers at high latitudes in the present climate are associated with enhanced deep ocean heat uptake in the transient response to anthropogenic forcing and consequently lead to smaller surface warming. Our results point to a major role of deep oceanic heat uptake in transient surface warming. Improving the realism of oceanic mixing at high latitudes in climate models could therefore lead to an important decrease in the spread of global warming during the 21st century and beyond. To cope with climate change and inform policy decisions to mitigate it, reducing climate change uncertainties during this transient period is arguably more important than for longer time frames and equilibrium climate change.

[18] The role of oceanic mixing is doubly important because ocean does not simply absorb heat but also atmospheric carbon dioxide. With the introduction of the modelling of the carbon cycle in the new generation of climate models, the same inter-model variations in oceanic mixing that lead to a spread in global warming may also lead to a spread in the oceanic uptake of atmospheric carbon dioxide.

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