Ocean heat and carbon uptake in transient climate change: Identifying model uncertainty

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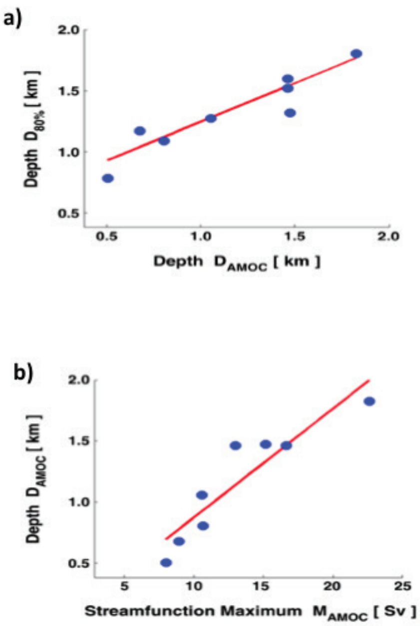
Global warming on decadal and centennial timescales is mediated and ameliorated by the ocean sequestering heat and carbon into its interior. Transient climate change is a function of the efficiency by which anthropogenic heat and carbon are transported away from the surface into the ocean interior (Hansen et al. 1985). Gregory and Mitchell (1997) and Raper et al. (2002) were the first to identify the importance of the 'ocean heat uptake efficiency' in transient climate change. Observational estimates (Schwartz 2012) and inferences from coupled atmosphere-ocean general circulation models (AOGCMs; Gregory and Forster 2008; Marotzke et al. 2015), suggest that ocean heat uptake efficiency on decadal timescales lies in the range 0.5-1.5 W m^{-2} K^{-1} and is thus comparable to the climate feedback parameter (Murphy et al. 2009). Moreover, the ocean not only plays a key role in setting the timing of warming but also its regional patterns (Marshall et al. 2014), which is crucial to our understanding of regional climate, carbon and heat uptake, and sea-level change.

This short communication is based on a presentation given by A. Romanou at a recent workshop, *Ocean's Carbon and Heat Uptake: Uncertainties and Metrics*, co-hosted by US CLIVAR and OCB. As briefly reviewed below, we have incomplete but growing knowledge of how ocean models used in climate change projections sequester heat and carbon into the interior. To understand and thence reduce errors and biases in the ocean component of coupled models, as well as elucidate the key mechanisms at work, in the final section we outline a proposed model intercomparison project named FAFMIP. In FAFMIP, coupled integrations would be carried out with prescribed "overrides" of wind stress and freshwater and heat fluxes acting at the sea surface.

Ocean's role in shaping the patterns and timing of temperature response in a warming world

Mechanisms of ocean heat uptake

What ocean processes control the efficiency of ocean heat uptake? Mixing (across and along isopycnal surfaces) was identified by Sokolov et al. (2003), who also found that this "effective diffusion" varies significantly with latitude, as being somewhat small in the tropics but fifty-fold larger at high latitudes. Huang et al. (2003) showed that heat penetration to the deep ocean could be mediated by changes in convection and eddy stirring. On the other hand, Knutti et al. (2008) did not detect notable sensitivity of ocean heat uptake to the rate of diffusive mixing in their model. In a study of many CMIP5 models, Kostov et al. (2014) showed that the modeled Atlantic meridional overturning circulation (AMOC) plays a large role in transient ocean heat uptake through its control of deep ocean ventilation. They found (see Figures 1a and b) that the AMOC depth sets the depth to which heat is sequestered, and hence the effective heat capacity of the ocean in transient climate change, and that the strength of the AMOC influences the sequestration rates. Therefore, the spread in heat uptake across the models could be largely explained by differences in their AMOC properties. The importance of the AMOC (Figure 1c) is perhaps to be expected, given that 50% of the net heat uptake in the global ocean occurs in the Atlantic north of 35°N. Distinguishing different oceanic processes, Exarchou et al. (2015) showed from global diagnostics of a suite of climate models that diapycnal diffusion (below the mixed layer) is the least important process in controlling heat uptake, as compared to mixed layer physics and convection and advection by mean circulation.



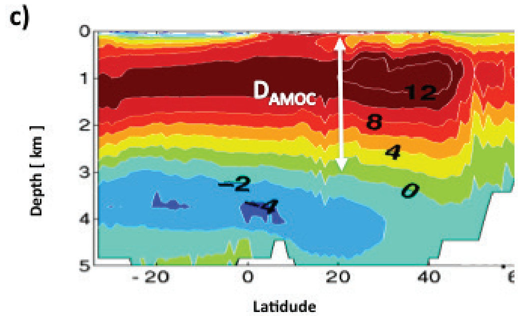


Figure 1: a) Depth of heat uptake ($D_{80\%}$) versus depth of the AMOC (D_{AMOC}); b) Depth of AMOC (D_{AMOC}) versus strength of AMOC (M_{AMOC}) (Kostov et al. 2013); and c) AMOC overturning streamfunction (Sv) from a typical climate model, with D_{AMOC} marked.

Spatial patterns and timing of SST anomalies

Marshall et al. (2014 a,b) employ a stand-alone ocean model run under Coordinated Ocean-ice Reference Experiment (CORE) forcing (Griffies et al. 2009) to study how ocean circulation shapes patterns of SST response in a warming world. They carry out "override" experiments, in which SST evolves in response to air-sea fluxes given by CORE, but augmented by a spatially uniform, constant-in-time downwelling radiative flux. Climate feedbacks are parameterized through an SST damping term at a rate that is constant in space and time. This setup, although highly idealized, is useful in investigating the role of the ocean in setting the patterns and timescales of the transient climate response. Despite the idealized model framework, both Arctic amplification and delayed warming signals in the North Atlantic and around Antarctica are captured, and in common with CMIP5 climate change experiments with complex coupled models (note the marked similarity between Figure 2a, from the override experiment, with Figure 2b from an ensemble of coupled CMIP5 models). We conclude that these patterns can largely be attributed to ocean rather than atmospheric processes. Similarly, the regional climate response is, to the first order, not due to regional feedbacks since they are kept constant and uniform in our override experiments. That said, Armour et al. (2013) and Rose et al. (2014) emphasize the importance of regional atmospheric climate feedbacks in setting the time-evolving pattern of surface warming and ocean heat uptake.

Transient CO_2 and tracer uptake

The ocean also plays an important role in CO_2 uptake, reducing the airborne greenhouse gas concentrations and thus the rate of atmospheric warming. It is not yet clear how the ocean sink of anthropogenic CO_2 will change in a warming world (Le Quéré et a.l 2009; Gloor et al. 2010). Observations indicate that the outgassing of natural CO_2 from the interior ocean has increased in the last few decades, particularly in the Southern Ocean, offsetting the anthropogenic sink. Some studies argue that this may be linked to an increase in the westerly winds blowing over the Southern Ocean, whereas other studies question whether increased outgassing is occurring. The net (natural +

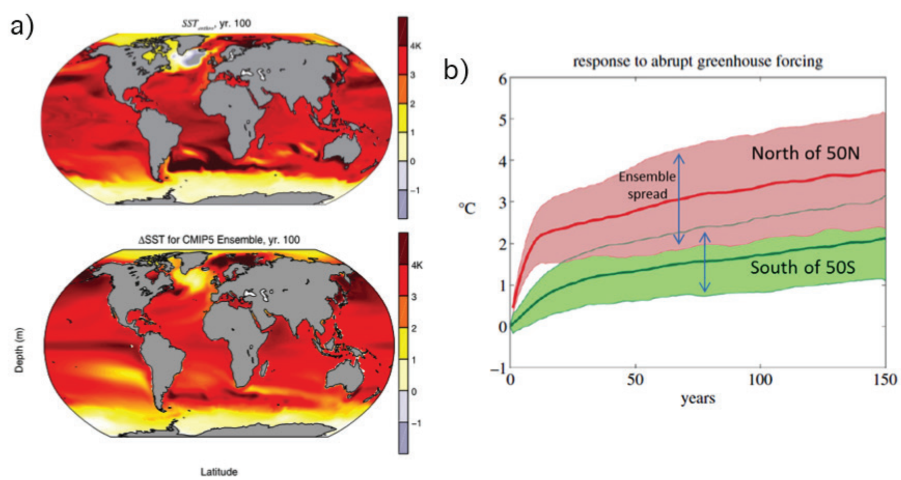


Figure 2: a) (top) SST perturbation (SST_{anthro}) from a 100-year run of a stand-alone ocean with specified, spatially uniform downwelling radiation and a linear damping of SST at the sea surface (from Marshall et al. 2014a); (bottom) SST change after 100 years from CMIP5 model runs of $4xCO_2$ forcing; b) SST conditional random fields for greenhouse gas emissions forcing computed from an ensemble of 15 CMIP5 models under quadrupling of CO_2. The Arctic is defined as north of 50° N (in red) and the Antarctic between 50° S and 70° S (in green). Thick lines denote the ensemble mean and the shaded area spans 1 s.d. (from Marshall et al. 2014b).

anthropogenic) CO_2 flux depends on the strength of the wind, upwelling, and the mixed-layer cycle of carbon and nutrients, and is thus directly related to ocean dynamics. Indeed, uptake of CO_2 in models varies substantially, mostly due to differences in physical parameterizations (structural uncertainty), increasing the uncertainty of future climate projections (Krasting et al. 2014). To address structural uncertainty, tracer uptake experiments, both realistic (CFC, SF_6, etc.) and idealized (ventilation-tracer, ocean age, and passive temperature-like tracers as in Marshall et al. 2014), can be used to highlight heat and carbon uptake processes. Figure 3, for example, shows a ventilation tracer set equal to one at the surface of the subpolar North Atlantic Ocean and subsequently integrated forward in time. The experiments only differ in the strength of the AMOC. We find that as the depth and strength of the AMOC grow, additional tracer is sequestered to greater depths (Romanou et al. *in prep*). Therefore, the AMOC controls not only the rate and depth of heat uptake, but also that of many tracers, including anthropogenic CO_2.

Proposed Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP)

A coordinated model intercomparison project could provide very useful information about how the ocean component of coupled models contributes to uncertainty in climate change projections. A focus might be regional sea-level change, coupled with global and regional SST patterns, heat and carbon uptake, AMOC change, etc. Knowledge of which ocean processes and phenomena have a large model spread may help us evaluate and refine our models. Ideally, one might couple the same atmosphere to different ocean models, but this would be difficult to organize. Alternatively, one could parameterize atmospheric climate feedbacks with a simple parameter and run ocean-only models (as in Marshall et al. 2014), but this would fail to capture the richness and the regional detail of the feedbacks. A viable way forward, we think, is to use existing coupled control runs and add air-sea flux "overrides" - i.e., wind stress, evaporation-precipitation, heat fluxes – chosen to be representative of those induced by climate change. Such experiments are proposed within the Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP, http://www.met.reading.ac.uk/~jonathan/FAFMIP/). Each modeling group would adopt the same protocol and run experiments ascribing the same override fields, computed from ensembles of CMIP5 models perturbed by climate change. We would then attempt to assess the spread in the resulting AMOC, heat and carbon uptake, and patterns of sea-level change, both regionally and globally, and identify their causes. The community has some familiarity already with override experiments – e.g., freshwater forcing (Stouffer et al. 2006); wind forcing (Gent and Danabasoglu 2011); or both heat and freshwater forcing experiments (Zhang and Vallis 2013). Due to the dominance of heat flux-SST feedbacks, it is not yet clear how to carry out meaningful heat flux override experiments. This is currently under study (http://www.met.reading.ac.uk/~jonathan/FAFMIP/FAFMIP_method_heat.pdf).

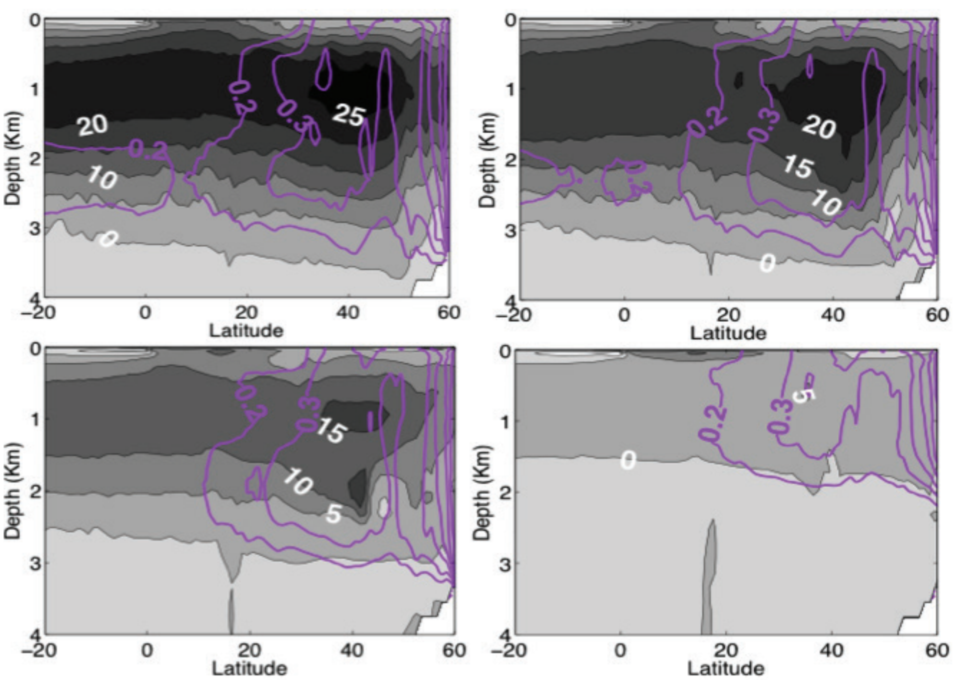


Figure 3: Zonally averaged section showing (purple contours) ventilation tracer concentration (from a stand-alone NASA GISS ocean run driven with CORE-1 forcing. The AMOC overturning streamfunction (Sv) is also plotted in gray shading with white labels.

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