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An assessment of global and regional sea level in a suite of interannual CORE-II simulations: a synopsis

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Motivation to study sea level in CORE-II simulations

There are a growing number of observation-based measures of sea level related patterns with the advent of the Argo floats (since the early 2000s) and satellite altimeters (since 1993). These measures provide a valuable means to evaluate aspects of global model simulations, such as the global ocean-sea ice simulations run as part of the interannual Coordinated Ocean-ice Reference Experiments Griffies et al. (2009), Danabasoglu et al. (2013). In addition, these CORE-II simulations provide a means for evaluating the likely mechanisms causing sea level variations, particularly when models with different skill are compared against each other and observations. We have conducted an assessment of CORE-II simulations from 13 model configurations Griffies et al. (2013), with a focus on their ability to capture observed trends in ocean heat content as well as the corresponding dynamic sea level over the period 1993-2007. Here, we provide a synopsis of the assessment.

The CORE-II simulations are designed primarily for studies of interannual variability (Doney et al., 2007, Large and Yeager, 2012). The atmospheric state of Large and Yeager (2009), used as part of the CORE-II air-sea flux calculations, contains interannual satellite-based radiation only after 1983. Over the 15 year period from 1993-2007, observed sea level variations have a large component due to natural variability e.g., Zhang and Church (2012), Meyssignac et al (2012). The CORE-II simulations thus provide a useful means to evaluate interannual variability in ocean-ice models against observations of sea level.

A notable limitation of our study is that we are not focused on sea level changes associated with melting land ice. There are complementary global model studies that consider the ocean's response to melt events (Gerdes et al., 2006, Stammer (2008), Weijer et al., 2012 and Lorbacher et al, 2012). However, there are large uncertainties with rates of observed liquid and solid runoff from Greenland and Antarctica, thus prompting us to focus on steric aspects of global and regional sea level variations.

Questions asked by the CORE-II sea level study

Ocean warming causes ocean volume to increase due to a decrease in density. According to Church et al. (2011), such changes in global mean thermosteric sea level determine about one-third to one-half of the observed global mean sea level rise during the 20th and early 21st centuries. Although limited largely to examinations of natural variability over the relatively short period of 1993-2007, our assessment is of use to determine the suitability of global ocean-ice models for capturing the longer term trends that are the focus of studies such as Church et al. (2011), and of great concern for climate impacts from anthropogenic warming. In particular, we can assess the ability of models to respect observed changes in global ocean heat content and associated sea level trends, as well as regional patterns of sea level change due to ocean dynamics.

With this motivation, we focus the assessment on two general questions:

- Do CORE-II global ocean-ice simulations reproduce the observed global mean sea level variations associated with thermosteric effects estimated from the observation-based analyses? To address this question, we focus on ocean heat content trends, and how these trends are associated with changes in thermosteric sea level.
- Do CORE-II ocean-ice simulations reproduce observation-based changes to dynamic sea level patterns? To address this question, we partition dynamic sea level trends into their halosteric and thermosteric patterns, as well as bottom pressure contributions.

Results and discussion

As part of our synopsis, we present patterns from the CORE-II ensemble mean from the suite of 13 models analyzed by Griffies et al. (2013), where again all results are computed over the years 1993-2007. Where available, we compare CORE-II simulations to observation-based analyses. We also exhibit time series of global volume integrated upper ocean heat content and thermosteric sea level.

1. Time mean and anomalous dynamic sea level

We show the time mean dynamic sea level in Figure 1 (Front cover image), both from the CORE-II simulations and from the satellite-based analysis from AVISO (Archiving, Validation, and Interpolation of Satellite Oceanographic Data) LeTraon et al. (1998), Ducet et al. (2000). The models cluster around a global root-mean-square difference from AVISO between 0.09-0.15 m, with the ensemble mean having an RMS difference of 0.10 m. The models generally are more consistent with observations in the lower latitudes, with the high latitudes leading to larger differences, particularly in regions of mode and deep water formation (40-50 degrees latitude) as well as western boundary currents in the Atlantic and Pacific. The north-south gradient of dynamical sea level accross the Southern Ocean is weaker for many of the simulations relative to AVISO, perhaps suggesting a fluctuation towards a weaker than observed zonal transport in the Antarctic Circumpolar Current, or perhaps a shift in the overall latitude of the current. In general, we conclude that each of the CORE-II simulations produces a respectable 1993-2007 time mean dynamic sea level, meeting or surpassing the accuracy of the historical simulations considered as part of the CMIP3 analysis of Yin et al. (2010).

2. Linear trend in heat content and thermosteric sea level

As shown in Griffies et al., (2013), the linear trend in CORE-II simulated dynamic sea level over years 1993-2007 is dominated by the trend in steric sea level, with changes in bottom pressure (column mass) roughly an order of magnitude smaller. To illustrate changes in the steric patterns, we show in Figure 2 the linear trend in heat content per unit horizontal area as computed over the upper 700 m of ocean, and the corresponding trends in thermosteric sea level. The thermosteric trends largely reflect the heat content trends, but with some modulation from the thermal expansion coefficient. We compare these trends to those found in observation-based analyses.

We note that the two observation-based analyses themselves have differences, particularly in the North Atlantic, where Domingues et al. (2008) show much less warming than Levitus et al. (2012), and the Southern Ocean, where Domingues et al. (2008) show a cooling absent from Levitus et al. (2012). To the leading order, models capture the observed warming of the central-west Pacific found in both observation-based analyses, as well as the strong warming in the subpolar North Atlantic as found in Levitus et al. (2012). The models show a general cooling trend in the tropical northern hemisphere for the Atlantic and Pacific, with a westward extension in this simulated trend absent from both of the observational analyses.

The mechanism for the Pacific trend in the CORE-II simulations, with general rise in the west and fall in the east, accords with that discussed in such studies as Timmermann et al. (2010), Feng et al (2010), Bromirski et al. (2011), Merrifield et al. (2012), Zhang and Church (2012), and Meyssignac et al (2012), with these studies suggesting that the west-east gradient reflects the negative phase of the Pacific Decadal Oscillation. Likewise, the increased heat content in the North Atlantic over this period is dominated by natural variability. It is associated with a decrease in surface cooling in the subpolar region related to a change in the North Atlantic Oscillation (NAO) phase in the presence of a positive Atlantic meridional overturning circulation (AMOC) anomaly. Specifically, in the 1980s and early 1990s, the NAO exhibited a persistent positive phase and the associated large negative surface fluxes acted as a pre-conditioner for enhanced AMOC. During this period, enhanced poleward oceanic heat transport associated with an enhanced AMOC was largely balanced by surface cooling due to the positive NAO. Around 1995/1996, a reduction in the surface ocean heat loss associated with a change in the NAO to its negative (or neutral) phase allowed for the northward oceanic heat transport to cause the subpolar gyre to transition to an anomalously warm phase (e.g., see the discussion in Lohmann et al., 2009, Robson et al., 2012, and Yeager et al., 2012).

3. Evolution of global mean heat content and thermosteric sea level

For many purposes, the CORE-II simulations are relatively short, with the 60 years of CORE-II atmospheric state (1948-2007) repeated five times with an aim to reduce, although admittedly insufficient to eliminate, long-term drift in the deep ocean. Notably, the repeated 60-year cycle introduces a spurious periodicity, and it also leads to a lag in the response of the simulations to potential long term trends, such as the warming of the latter portion of the 20th century. Additionally, as discussed in Griffies et al. (2013), there is a slightly weaker linear trend in the CORE-II simulations relative to the observations, with this smaller trend in CORE-II revealed by the time series in Figure 3 for the global mean heat content and thermosteric sea level. Additionally, if we remove the linear trend, the variability in the CORE-II simulations correlates more to that in Domingues et al (2008) than to Levitus et al (2012).

Conclusions

There is a general agreement between the CORE-II simulated patterns of heat content change and thermosteric sea level change with the observation-based analyses. The global mean also shows a general agreement, though with a cool bias. These results lend confidence to both the observation-based analyses and the CORE-II simulations. Yet as with any model comparison project, one is perhaps left with more questions than answers, with this situation perhaps representing the real use of comparison projects. Namely, it is critical to identify relevant questions to make steps towards understanding as well as to improve numerical models and observation-based analyses.

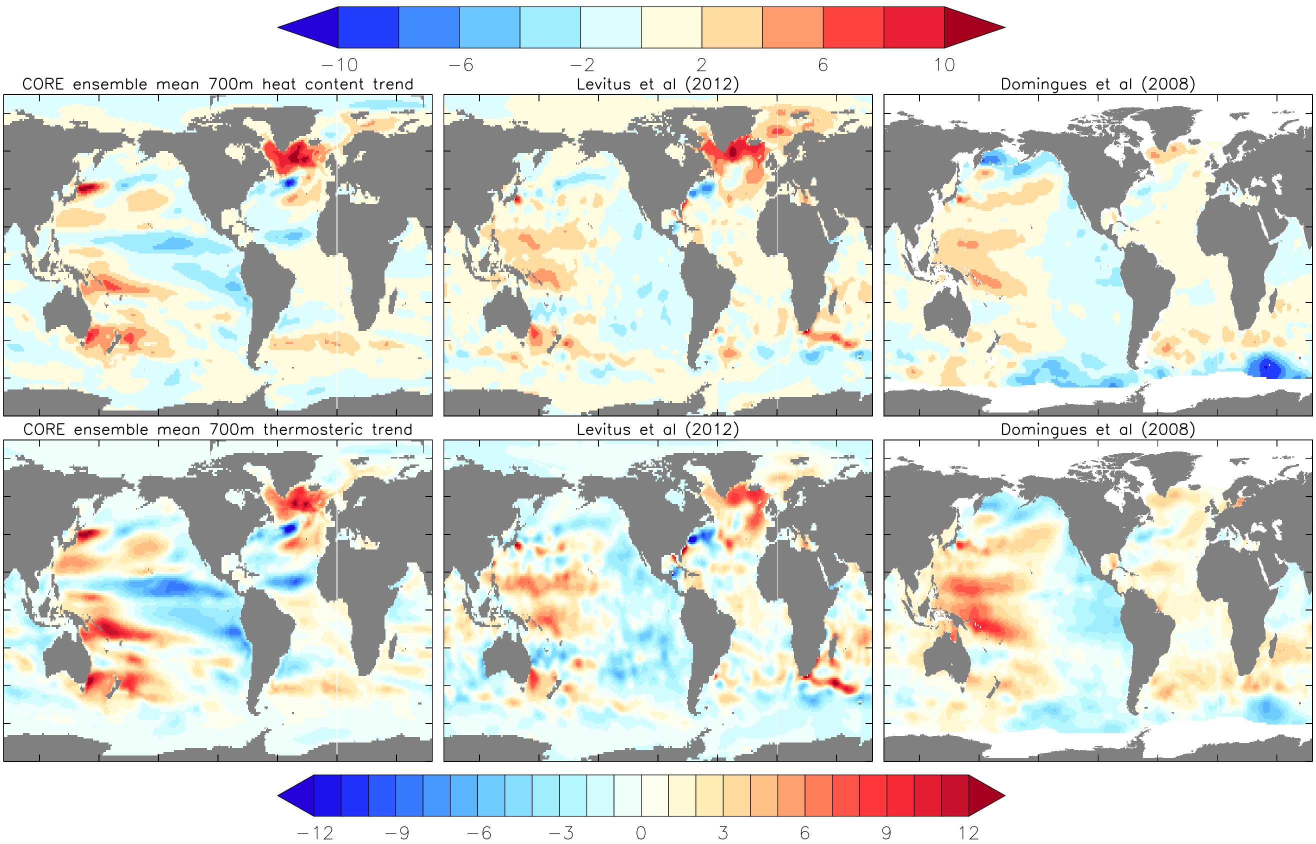

Figure 2: The upper row shows the linear trend in annual mean ocean heat content per unit horizontal ocean area as vertically integrated over the upper 700~m of ocean (W m^{-2}) for the years 1993-2007, computed from CORE-II ensemble mean as well as the observation-based analysis from Levitus et al. (2012) and an updated analysis from Domingues et al., (2008) and Church et al (2010) (see their Figure 6.3b). The lower row shows the corresponding trends in thermosteric sea level (mm yr^{-1}).

Model-model and model-observational differences may be due to model error, CORE-II atmospheric state errors, CORE-II experimental design limitations, and/or observational error or limitations Griffies et al. (2013). One avenue to make progress on these questions from the modelling perspective is to conduct detailed analyses of physical processes, term-by-term. We have in mind, for example, the analysis of Griffies and Greatbatch (2012), who decomposed the global mean sea level budget according to physical processes, as well as that from Palter et al. (2013), who decomposed the local steric sea level budget according to physical processes. Such analyses are nontrivial to perform with a single model, and logistically even more difficult across a suite of models such as the CORE-II simulations assessed here. Nonetheless, we contend that significant progress will be made to understand model-model, and to some extent model-observational, differences only when careful budget analyses are performed at the level of physical processes.

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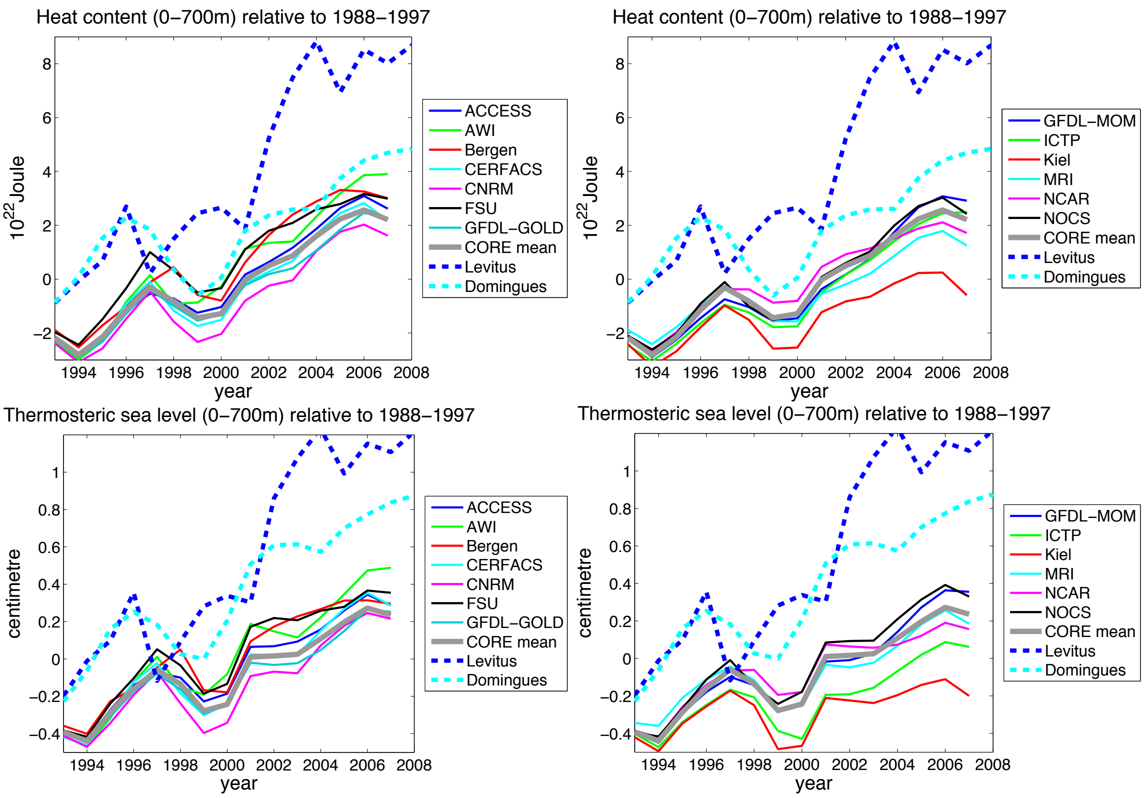

Figure 3: Time series for ocean heat content and thermosteric sea level integrated over the upper 700 m of ocean. To reduce dependence on a single chosen reference date, each result is computed with respect to the ten year mean for the respective model or observational time series, as computed over years 1988-1997. The CORE-II ensemble mean is also shown, as computed from all of the simulations. We also show estimates from observations based on analysis of Levitus et al. (2012} (global) and Domingues et al. (2008) (within the latitude range 65°S-65°N). Model results are global.

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