The importance of the deep ocean in estimating Earth's radiation balance

Matt Palmer, Doug McNeall and Nick Dunstone

The lack of global surface temperature rise over the past decade, due largely to a lack of rise in sea surface temperature (SST), has provoked much interest in the scientific community and wider media. Recent research has highlighted an apparent discrepancy between satellite estimates of net top-of-atmosphere radiation balance (TOA) and changes in ocean heat content (OHC). We carry out regression analyses using control run data from three generations of Hadley Centre climate model, to estimate the uncertainty of TOA , given SST or OHC. We show that decadal trends in SST are only weakly indicative of changes in TOA. Trends in OHC, integrated over increasingly deeper levels, provide an increasingly good indication of TOA changes. To achieve a given accuracy in TOA estimated from OHC we find that there is a trade-off between measuring for longer or deeper. Our model results suggest that there is potential for substantial improvement in our ability to monitor Earth's radiation balance by sustained observation of the deep ocean.

1. Data

The data analysed come from control integrations of three generations of coupled climate models developed at the Met Office Hadley Centre: HadCM3 (Gordon et al., 2000); HadGEM1 (Johns et al., 2006) and HadGEM2 (HadGEM2 Dev. Team, 2011). The control simulations use pre-industrial (1860) time constant external forcings and therefore represent only the unforced internal variability of the climate system. The three models have small net TOA radiation imbalances of approximately -0.1 W m^{-2}, 0.2 W m^{-2} and 0.4 W m^{-2} for HadCM3, HadGEM1 and HadGEM2, respectively.

The following annual mean model fields are used in our investigation: (i) top-of-atmosphere incoming shortwave radiation; (ii) top-of-atmosphere outgoing shortwave radiation; (iii) top-of-atmosphere outgoing longwave radiation; (iv) ocean potential temperature on all model levels Variables (i)-(iii) are globally integrated and combined to give the net top-of-atmosphere radiation (TOA). Variable (iv) is converted to ocean heat content by integrating over each model level and multiplying by the fixed values of density ($\rho0$) and heat capacity (Cp): $\rho0\ Cp$ = 4.09169 × 10^6 kg m^{-3} J K^{-1}.

	HadCM3	HadGEM1	HadGEM2
Horizontal Res. - Atmos.	2.5° × 3.75°	1.25° × 1.875°	1.25° × 1.875°
Vertical Levels - Atmos.	19	38	38
Horizontal Res. - Ocean	1.25° × 1.25°	1.0°(0.33°) × 1.0°	1.0°(0.33°) × 1.0°
Vertical Levels - Ocean	20	40	40
No. Years Analysed	3511	1298	495

Table 1: Climate model configurations used in this study.

2. Methods

Two-dimensional annual fields of TOA are temporally and spatially integrated to produce a time series of the total energy entering or leaving the model climate system each year. Similarly, annual mean values of ocean heat content for each model vertical level are computed by spatially integrating the two-dimensional fields. Since it can take many centuries for the deep ocean to reach equilibrium, it is important to remove the associated model drift from our analyses. We use a Butterworth filter with a cut-off frequency of 100 years to high-pass all of the time series. These pre-processing steps result in the following anomaly time series for each of the three models: (i) total energy anomaly of the climate system (intTOA); (ii) globally averaged sea surface temperature (SST), and (iii) ocean heat content (OHC), integrated to successively deeper model levels (see Table 1). Note that, for convenience, we will refer to the anomaly series simply as intTOA, SST and OHC hereafter.

For each model, the annual time series of intTOA, SST and OHC are separated into every possible overlapping period of length p. We perform a linear regression of all trends in intTOA against the corresponding trends in SST, or OHC integrated over successively deeper model levels This is performed for all periods of length p = 2 to 25 years. Since we are using annual mean data, the computed trends in intTOA are 6-months out-of-phase with SST and OHC. Therefore, we compute the mean trends of two consecutive p-year periods to arrive at equivalent trends in SST and OHC for a given trend in intTOA. We note that when p is only a few years this may not be a good approximation.

3. Results

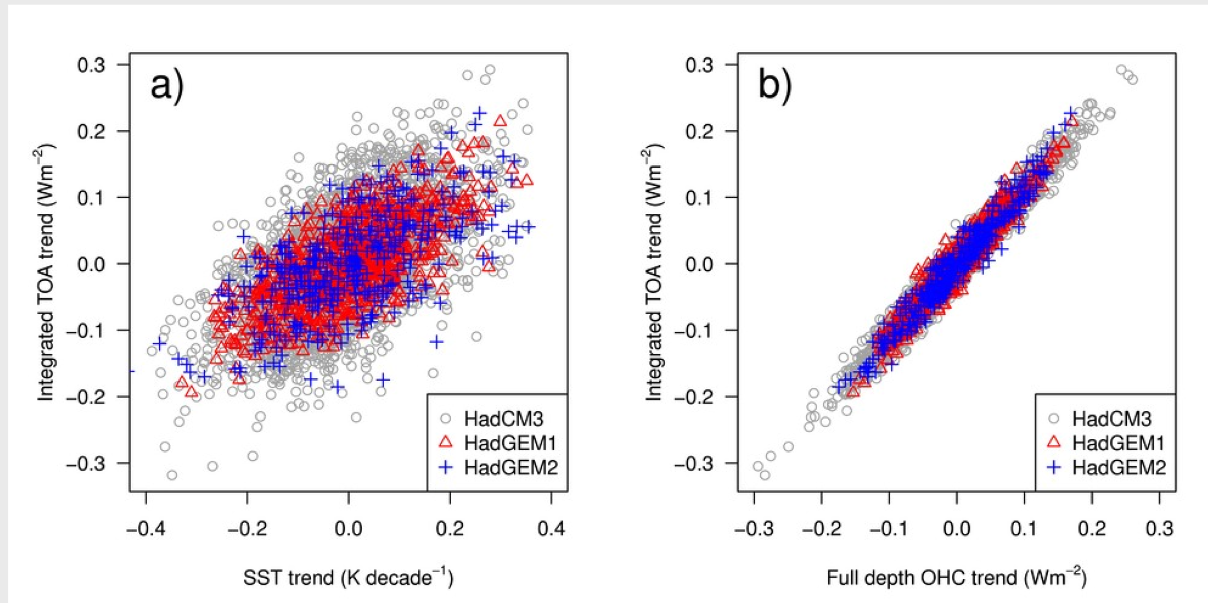

Figure 1: Plot of linear decadal trends in intTOA regressed against: a) globally averaged SST; b) full-depth OHC.

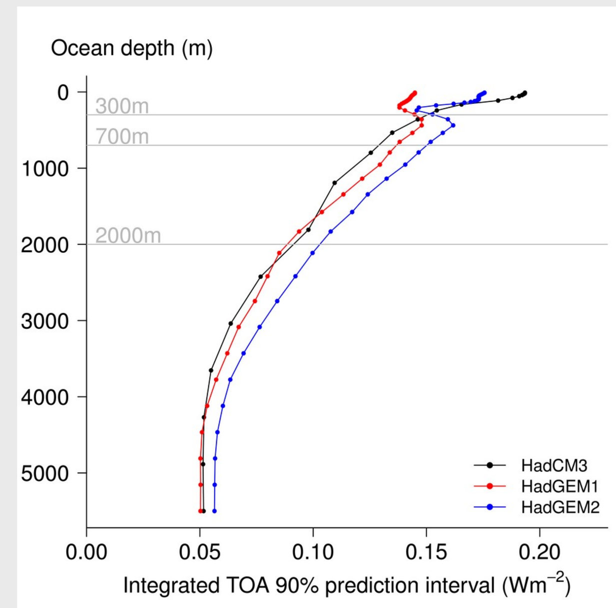

Figure 2: 90% prediction intervals for trend in intTOA associated with depth of OHC integration

For all models a decadal trend in SST places a relatively weak constraint on the intTOA trend over the same period (Figure 1a). Approximately 30% of decades show a trend in intTOA and SST that are of opposite sign. All three climate models frequently exhibit a decadal trend in SST with a magnitude greater than 02K per decade. This large internal variability in SST could easily mask the anthropogenic warming signal for a decade or more, consistent with the findings of previous studies (Easterling and Wehner 2009; Knight et al., 2009).

Compared to SST, we see a much tighter relationship between decadal trends in full-depth OHC and intTOA (Figure 1b). By carrying out similar regressions we are able to plot the relationship between intTOA trends and OHC trends integrated over successive model vertical levels. If we treat the OHC trends as a predictor of the intTOA trend over the same decade, we can express this relationship in terms of uncertainty (90% prediction interval) against integration depth (Figure 2). All three models show the same basic vertical structure, with a reduction in uncertainty with depth over the upper 4000m.

This result requires that there are mechanisms operating in the climate models that re-distribute substantial quantities of heat at all depths on a decadal time scale. It also suggests that in order to provide the best estimate of ocean heat uptake we must aim to observe over the 0-4000m layer in order to minimise the "noise" associated with internal variability.

In the final part of our analysis, we look at the relationship between OHC and intTOA over a range of different timescales (Figure 3). All three models show a qualitatively consistent picture: there is a trade-off between depth and timescale in order to achieve a given level of uncertainty. For example, in order to estimate the trend in intTOA with a 90% prediction interval of 0.1 W m^{-2}, one would need to observe SST for 15-20 years. If one were able to observe the full-depth ocean, this timescale could be reduced to about 6-7 years.

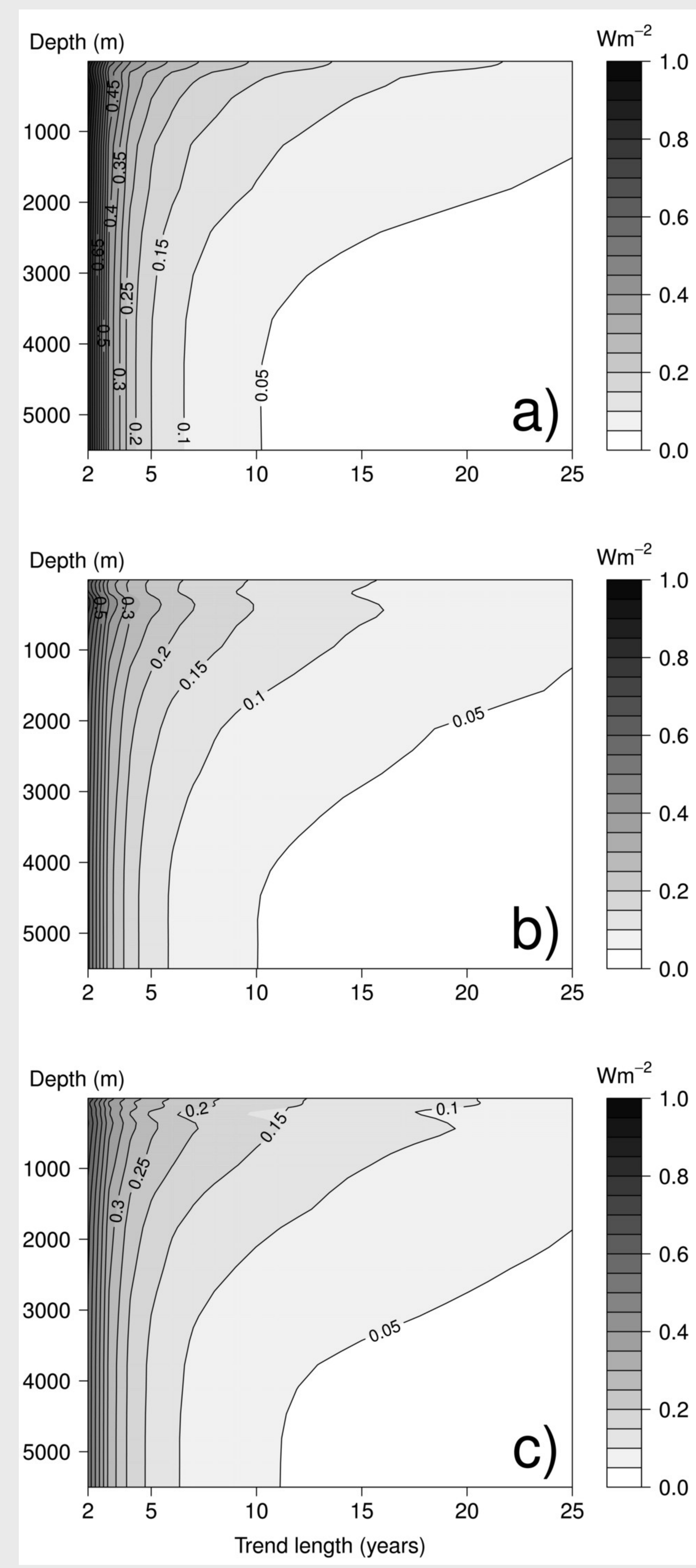

Figure 3: 90% prediction intervals for trend in intTOA (W m^{-2}) estimated by OHC measured to different depths, for: a) HadCM3; b) HadGEM1; and c) HadGEM2.

4. Summary

We have carried out analysis of the relationship between decadal trends in time-integrated TOA, SST, and OHC using annual control run data from three generations of Met Office Hadley Centre climate models. At decadal time scales, SST trends place only a weak constraint on the TOA changes over the same period. Conversely, full-depth OHC strongly constrains the TOA changes, since the ocean is the dominant heat reservoir in the system. Surprisingly, we find that one must integrate OHC to depths in excess of 4000m before the gain in information with depth becomes saturated.

Our results suggest that the potential pay off of a deep ocean observing array (e.g. Garzoli et al., 2009) is the ability to better resolve, and therefore monitor, changes in Earth's radiation balance. These findings highlight the need to sustain the Argo observations to 2000 m and provide strong motivation for the development of a deep ocean observing array.

References:

Easterling, D. R., and M. F. Wehner. Is the climate warming or cooling?. Geophys. Res. Lett., 36, L08706, doi:10.1029/2009GL037810, 2009.

Garzoli, S. et al. Progressing Towards Global Sustained Deep Ocean Observations. Proceedings of OceanObs'09. Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi:10.5270/OceanObs09.cwp.34, 2010.

Gordon, C. et al. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dyn., 16, 147–168, 2000.

HadGEM2 Development Team. HadGEM2 Family of Met Office Unified Model Climate Configurations, by The, Geosci. Mod. Dev., submitted manuscript, 2011.

Johns, T. C. et al. The New Hadley Centre Climate Model (HadGEM1): Evaluation of Coupled Simulations. J. Clim., 19, 1327-1353, 2006.

Knight, J. et al. Do global temperature trends over the last decade falsify climate predictions? [in "State of the Climate in 2009"] Bull. Amer. Meteor. Soc., 90, S20-S21.

Met Office Hadley Centre, FitzRoy Road, Exeter, Devon, EX1 3PB United Kingdom
Tel: 01392 885680 Fax: 01392 885681
Email: matthew.palmer@metoffice.gov.uk