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Impact of relative atmosphere–ocean resolution on coupled climate models

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Introduction

There are many examples of ocean processes that are important for climate simulation and which require some minimal mesh size for a believable simulation (examples include dense flow through narrow gaps, boundary currents, deep water formation, eddy processes involved in Tropical Instability Waves, Agulhas rings and the Antarctic Circumpolar Current). However, when considering the fidelity of climate models, we cannot only consider ocean model resolution; if atmospheric mesh size is insufficient to distinguish important oceanic features, then important coupling and feedback effects may be excluded. Such a situation was found by Roberts et al. (2004), in which a 1/3 degree resolution ocean model was coupled to a 280km atmosphere model. The ocean simulation is hugely improved (compared to an ocean model with 1.25° spacing), but there are rather few changes to the large-scale atmospheric and climate simulation.

Hence we need to consider the correct balance between atmospheric and oceanic mesh sizes, so that the most important processes are captured in both components, in addition to the necessary coupling and feedbacks. The purpose of this article is to show several examples where increases in ocean model resolution also require increases in atmosphere resolution in order for the coupled effect to be properly realised.

Models

The joint DEFRA/NERC-funded UK-Japan Climate Collaboration (UJCC) project, together with the NCAS-Climate UK-HiGEM project (Norton et al., 2007), have been developing coupled models based on the Met Office Hadley Centre's HadGEM1 model (Johns et al., 2006, a configuration of the Met Office Unified ModelTM(UK)), but with enhanced resolution. Using atmospheric models with 150km, 90km and 60km mesh sizes at mid-latitudes, and ocean models at 1 degree (with enhancement to 1/3 degree meridionally at the equator) and 1/3 degree, we have formed a matrix of models in which we can attempt to understand the relative importance of model resolution in a coupled framework (in a similar way to the Japanese CCSR/NIES/FRCGC groups with their MIROC3.2 coupled model (Hasumi and Emori, 2004) using T42, T106 and T213 atmosphere models and 1.4 degree and 0.25 degree ocean models). Integrating such models for 50-100 years has been made possible through use of the Japanese Earth Simulator super computer. Here we describe results from versions of the coupled HadGEM model (150km atmosphere, 1-1/3 degree ocean) and HiGEM model (90km atmosphere, 1/3 degree ocean) as well as the intermediate models.

Results

The impact of model resolution in the coupled framework can take various forms. Examples will be shown which illustrate: (a) strong local feedbacks between atmosphere and ocean as mesh size is reduced, leading to changes in the coupling of the components and potential changes to the mean state, and (b) internal ocean processes at higher resolution changing the mean ocean climate, which therefore changes the forcing to the atmosphere.

Tropical Instability Waves

Tropical instability waves (TIWs) in the eastern tropical Pacific Ocean, caused by mixed barotropic/baroclinic instability, are a highly visible sign of ocean variability in observations (e.g., Legeckis, 1977). They are often poorly represented in climate models as, although their zonal wavelength is large (1000-2000 km), the cusp of the wave is very narrow. Hence the wave breaking (the movement of cold water off the equator, and warm water onto the equator) only begins to be represented with ocean model mesh sizes of about 1 degree. The SST change across a TIW can also be large (2-5C), and hence a high resolution atmosphere is needed to resolve the SST gradients.

The impact of improved TIW representation in a coupled model is illustrated in Figure 1. The wind stress divergence field is shown for both HadGEM and HiGEM, and overlaid are the associated SST contours depicting the characteristic TIWs. It has been shown that perturbations in the wind stress divergence and curl fields are linearly related to the underlying SST gradient in the eastern equatorial Pacific (Chelton et al., 2001). Changes in SSTs are thought to modify the overlying wind field via alterations in the stability of the Atmospheric Boundary Layer (ABL) and local sea level pressure (Hayes et al., 1989). Both models resolve the oceanic TIW signature, though stronger and earlier in HiGEM with its higher zonal resolution. However, the low resolution HadGEM atmosphere is unable to capture the SST perturbed wind field on the length scales of the TIWs. The TIW perturbed wind field is apparent in HiGEM as patches of high wind stress divergence, indicated by white shading, associated with the cusp-like features of the SST contours.

Chelton et al. (2001) describes two measures of ocean-atmosphere coupling in relation to TIWs. In the first, the degree of coupling, can be derived from the amplitude of the cosine (sine) dependencies that the wind stress divergence (curl) has on the angle between the SST gradient and wind vectors on TIW length scales. In the second, the strength of coupling, is defined as the slope of fit between the downwind (crosswind) SST gradient and wind stress divergence (curl) on TIW length scales. With higher horizontal resolution in both ocean and atmosphere, HiGEM has a significantly greater degree and strength of coupling than HadGEM. However, the degree and strength of coupling is still less than that derived from satellite observations by Chelton et al. (2001). This deficiency may be accounted for by increasing the resolution yet further or it may suggest that the model is not resolving the physics of the system completely. If we degrade the resolution of the SSTs to that of the atmospheric model in HiGEM, we increase the strength of the coupling (i.e. grad(SST) is weakened thus strengthening the slope d(grad. tau) / d(grad SST)) although the degree of coupling remains relatively unaffected. By analogy, if we increase the resolution of the atmosphere in HiGEM to that of the ocean grid we are likely to resolve sharper features in the ABL, thus increasing not only the strength of coupling, but also the degree of coupling on the length scales of the TIWs.

By improving TIW representation in coupled models through refinement of the horizontal resolution (including the convergence of ocean and atmosphere mesh size) we will better resolve the effects of the TIWs on the ABL. Such a modification may manifest itself locally through, for example, cloud distribution in the eastern equatorial Pacific (Deser et al., 1993) or through an influence on the mean climate of the tropical Pacific Ocean. An illustration of the latter is described in Roberts et al. (2004), in which the ocean resolution in a coupled model is increased to resolve TIWs. It was found that the SST bias present in the model was significantly reduced, and this was shown to be due to the explicit representation of TIWs as an advective process, in which they remove cold water from the equator and replace it with warmer water from off the equator. The refinement in the SST field results in an improvement to the atmospheric winds, which in turn leads to a better simulation of the whole zonal atmospheric Walker circulation (Roberts et al., 2008). It has also been suggested that the modified ABL may feedback onto the TIWs themselves (Pezzi et al., 2004). There are many other regions where such small-scale interactions may be important to properly simulate large-scale climate (e.g. Agulhas retroflection; O'Neill et al., 2003).

Coastal effects

Coupled climate models often suffer from large biases in regions adjacent to coastlines, most prominently off the eastern boundaries of Africa and America, where complex interactions between atmospheric winds and clouds, and ocean upwelling and SST, are poorly simulated. Although these areas only occupy 0.5% of the global ocean, they account for 11% of the global primary production transported to the thermocline and 20% of global fish catch (Kearns and Carr, 2003), and hence are an important part of the carbon cycle and our food supply. Observations show that these regions are very sensitive to climate change (McGregor et al., 2007).

The impact of ocean and atmosphere mesh size on the seasonal cycle of SST in a 3x3 degree area along the North African coast, centred on 30N, 11W, is shown in Figure 2 (page 10). The thick line is based on Reynolds SST observations from 2001-2006 (Reynolds et al., 2002), and model data from the different resolution coupled models averaged over 20 years. While HadGEM shows significant but opposite-signed biases in summer and winter, the HiGEM model follows the observations more closely. Although a higher resolution in either the atmosphere or the ocean improves the simulation, both are clearly needed to give a good simulation throughout the year. The increased atmospheric resolution improves the processes that determine the radiation balance over these stratocumulus areas in summer, while the ocean resolution probably moderates the seasonal cycle through a stronger upwelling response which is important throughout the year.

Hawaiian Lee Countercurrent

Another illustration of the incremental role that ocean and atmosphere mesh size can play on the coupled climate is seen in the simulation of the Hawaiian Lee Countercurrent (HLCC), which is described in detail by Sasaki and Nonaka (2006). Simply stated, a wind stress curl caused by the trade winds interacting with the Hawaiian Islands induces a circulation in the ocean which drives a eastward countercurrent at about 20N extending from west of 160E to the Hawaiian Islands. It is thought that interaction and feedbacks between atmospheric wind stress curl and ocean SSTs and currents cause the HLCC to stretch such a distance.

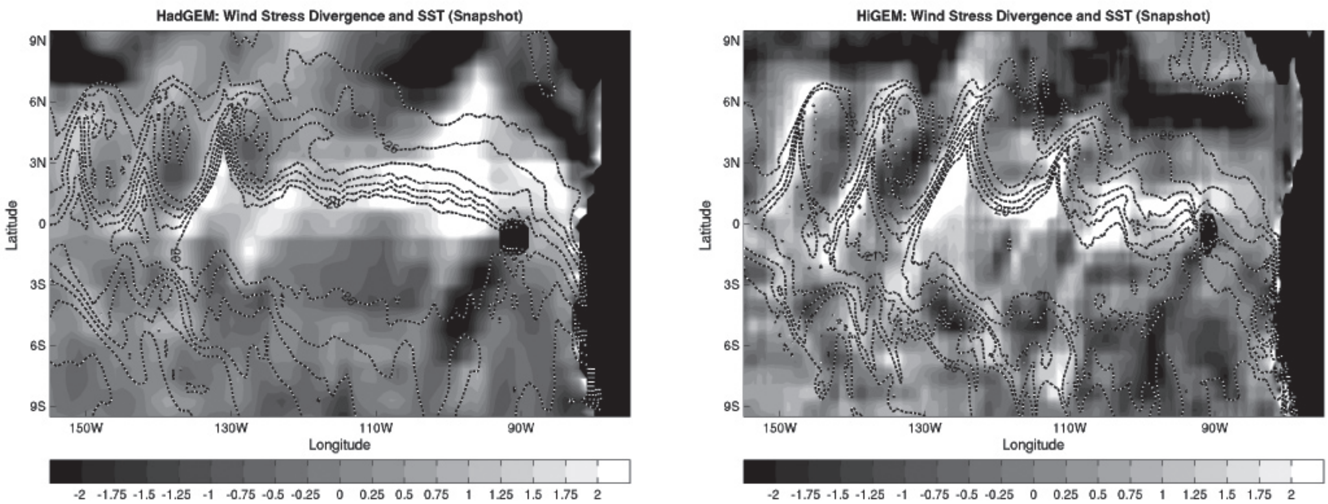

Figure 1: Atmospheric boundary layer response to Tropical Instability Waves in the ocean. Daily mean windstress divergence (Nm-2 x 10-7, shading) and daily mean sea surface temperature (black and white dashed contours, 20C to 26C every 1C) for a) HadGEM and b) HiGEM. Daily mean fields taken from the 13th and 5th September of the HadGEM and HiGEM runs respectively.

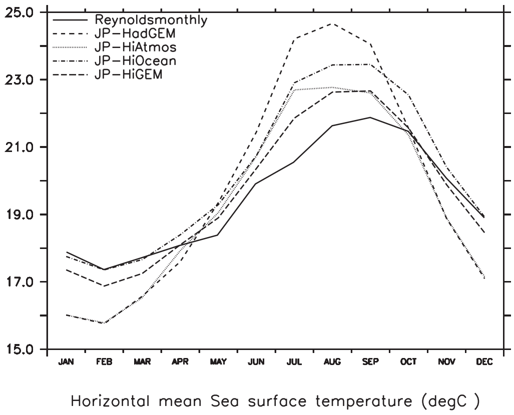

Figure 2: Seasonal cycle of SST (degree C) averaged over a 3x3 box centred on 30N, 11W along the North African coast. Solid line is Reynolds 2001-2006 observations (Reynolds et al., 2007), short dashes for the lowest resolution coupled model (HadGEM), dots for a higher resolution atmosphere, dash-dots for a higher resolution ocean, and long dashes for both high resolution atmosphere and ocean (HiGEM). All model data has been averaged over 20 years.

Using the model matrix, the relative roles of atmosphere and ocean for inducing this current can be studied. Figure 3 (page 19) shows the wind stress curl (colours) and the ocean zonal current at 35m (contours) for the four coupled models. In the low resolution HadGEM model (a), there is strong local wind stress curl over the Hawaiian Islands, and a weak zonal current. With higher resolution atmosphere (b), the wind stress curl signal stretches further west, as does the current. The higher resolution ocean with low resolution atmosphere (c) shows a current which stretches over to 160E and beyond, but with relatively modest wind stress curl, while (d) shows the high resolution coupled response, with the local maximum in wind stress curl collocating with the stronger ocean current over to 160E. Such changes to the circulation cause a warming of the local SSTs, which may be related to local changes in clouds and precipitation.

The Hawaiian Lee Countercurrent is a simple example of how higher resolution atmosphere and ocean components can lead to changes in simulated circulation. It may well be that changes to the persistent small-scale wind stress curl features (when comparing within the model matrix) found in many other regions (particularly over the Southern Ocean and boundary currents) might also lead to changes in their simulation and behaviour, but these will require more detailed analysis.

Discussion

There are many important interactions between the atmosphere and the ocean occurring on small time and space scales, and it is a challenge to represent the most important of these processes in our climate models. Systematic studies of the impact of model resolution on simulated coupled climate are a useful first step, but other methods of analysis will also be needed to isolate and identify individual processes.

For example, UJCC has performed experiments with a variety of atmosphere model resolutions, using AMIP-II SST and sea-ice forcing (Gates et al., 1999) which is nominally 1° resolution but is effectively much smoother than this in time and space. Surprisingly few differences have been found between these simulations, and it is reasonable to ask whether using such smooth forcing is partly to blame. Experiments in which higher resolution ocean SSTs have been used to force atmosphere models (e.g. Chelton et al., 2005) suggest that this can make a significant difference to model variability, and hence the development of higher resolution SST datasets (for example the Reynolds and OSTIA datasets; Reynolds et al., 2007, Stark et al., 2007) will be important tools for future experiments, particularly as atmosphere model resolution increases.

While it is clearly desirable to continue to develop higher resolution ocean models, since there are many important processes that are not properly simulated in the current generation of models, continued thought must be given to the most appropriate resolution of forcing (be it from observations or coupled to an atmospheric model) in order that the feedbacks and interactions are also represented.

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Further information on UJCC and UK-HiGEM projects can be found at http://www.earthsimulator.org.uk/index.php and http://www.higem.nerc.ac.uk/

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Figure 3: Wind stress curl (colour, Nm^{-2}/m) and ocean zonal current at 35m (contours at $5cms^{-1}$ intervals, eastward currents solid, westward currents dashed). (a) lowest resolution (HadGEM), (b) higher resolution atmosphere, (c) higher resolution ocean, and (d) high resolution atmosphere and ocean (HiGEM).