4B.5 TROPICAL CYCLONES AND CLIMATE CHANGE IN A HIGH RESOLUTION GENERAL CIRCULATION MODEL, HIGEM

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1. INTRODUCTION

There is substantial evidence that the large scale environment from which tropical cyclones form and evolve is changing as a result of anthropogenic emissions of greenhouse gases. General Circulation Models (GCMs) offer the ability to investigate future projections of tropical cyclone activity and allow for a robust diagnosis of the mechanisms involved. Most previous climate change studies of tropical cyclones have used time slice experiments to allow the highest resolution possible. These use sea surface temperatures (SSTs) taken from relatively low resolution coupled Atmosphere-Ocean GCMs (AOGCMs) as boundary conditions and typically have relatively short integration lengths. This does not allow the tropical cyclones to realistically feedback onto the SSTs and ocean heat content (Scoccimarro *et al*, 2011). In this study, we use the UK's High Resolution General Circulation Model (HiGEM) to study tropical cyclones in the current and future warmer climates. We make use of a long integration of 150 years at present day CO_2 concentrations. This is compared with idealised stabilised $2xCO_2$ and $4xCO_2$ simulations to investigate the impact of anthropogenic climate change on future tropical cyclone activity and the nonlinearities associated with the response. We show that the greatest reduction in tropical cyclone frequency occurs in the North Atlantic basin owing to the increase in vertical wind shear and atmospheric stability. The increase in vertical wind shear in the $4xCO_2$ experiment is greatly enhanced over the North East Pacific, which results in a decrease of tropical cyclone frequency, whereas, tropical cyclone frequency did not change in the $2xCO_2$ experiment. We also show that a weaker Walker circulation leads to a reduction in North West Pacific tropical cyclones and an enhancement in the North Central Pacific region, via anomalous descending and ascending air, respectively.

2. HiGEM MODEL

This study uses HiGEM1.1, a high resolution coupled climate model based on the Met Office Hadley Centre Global Environmental Model version 1 (HadGEM1). The horizontal resolution of the atmospheric component is 0.83^o latitude x 1.25^o longitude (90km at 50^oN), which is higher than the typical resolution now used in the coupled model intercomparison project (CMIP5). The atmosphere has 38 vertical levels extending to over 39km in height. The ocean component also has a higher resolution than most previous studies at 0.3^o x 0.3^o (40km at 50^oN) with 40 vertical levels. More details about HiGEM and validation of the large scale parameters can be found in Roberts *et al* (2009) and Shaffrey *et al* (2009). This model has also been used to investigate extratropical cyclones and climate change (Catto *et al*, 2011).

The HiGEM control simulation was run under present-day radiative forcings for 150 years. This period has been split into 5x30 year periods, effectively giving us a 5-member ensemble to aide our understanding of natural variability. From the control simulation, a transient climate change run was performed with CO_2 levels increasing by 2% per year. The CO_2 levels were then stabilised at $2xCO_2$ levels and run for a further

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30 years. The transient run was continued and the CO_2 levels stabilized at $4xCO_2$. Again this was run for another 30 years. The two runs with the stabilized CO_2 levels will be referred to as the $2xCO_2$ and $4xCO_2$ experiments. Tropical cyclone activity is investigated in both experiments and assessed to find out whether any changes are outside the range of natural variability given by the 5x30 year control simulation.

3. TROPICAL CYCLONE TRACKING METHODOLOGY

Feature tracking algorithms of tropical cyclones tend to be unique to each study, each basin and can be resolution dependent which makes it difficult for comparison. In our study we use an objective, feature tracking methodology to identify and track tropical cyclone-like features. The method is fully described in Bengtsson *et al* (2007). This method uses low level vorticity maxima which allows for identification of smaller spatial scales than is possible with mean sea level pressure and hence earlier storm identification. Similar criteria are applied to those in Bengtsson *et al* (2007) but with a refined warm core criteria. This has improved the identification of tropical cyclones in the North Indian basin where previously we were also identifying monsoon depressions.

4. VALIDATION OF THE MODEL

The ability of the atmospheric component of HiGEM, called HiGAM, to simulate different aspects of tropical cyclone activity, focussing on the impact of horizontal resolution, has been assessed by comparing with observed tropical cyclone activity, from the International Best Track Archive for Climate Stewardship (IBTrACS), and with tropical cyclones identified in reanalyses, using the same tracking methodology by Strachan *et al* (2012). Further research is currently being undertaken to investigate the role of ocean-atmosphere coupling, using HiGEM and HiGAM simulations. Track densities are shown in Fig. 1 and are used to investigate the spatial distribution of storms. The density distributions for the model and reanalyses can appear quite different from those provided by IBTrACS, for which the tracks are only defined in the portion of the lifetime classified as a tropical cyclone. In our tracking of models and reanalyses identification is based on vorticity, from genesis through to lysis, which allows for early identification of weak vorticity features contained, e.g., in Easterly Waves. Cool SST biases in HiGEM are responsible for a slight underestimation in North Atlantic tropical cyclone frequency and also a lack of recurvature in the North West Pacific (Fig. 1). Despite these differences, the spatial distribution of tropical cyclones in the model is in good agreement with the observed cyclone distribution. In terms of tropical cyclone frequency, the northern hemisphere basins in HiGEM show good agreement with observations. However HiGEM has an even split in tropical cyclone frequency between hemispheres unlike the observations and reanalyses, with twice as many storms identified in the southern hemisphere.

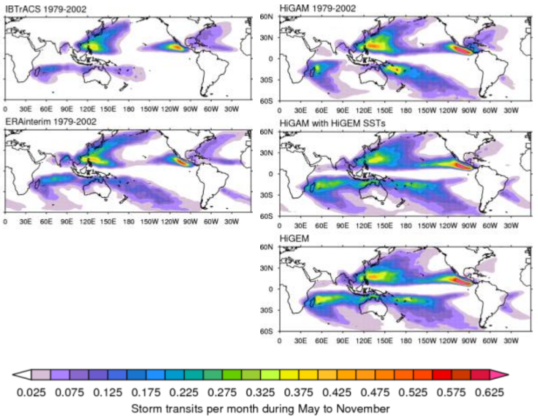

Figure 1. A comparison of tropical cyclone density (storm transits/month/10^6km^2) of IBTrACS (1979-2002), ERAinterim (1979-2002), HiGAM AMIP simulation (1979-2002), HiGAM with HiGEM SSTs and HiGEM

5. TROPICAL CYCLONES AND CLIMATE CHANGE SIMULATIONS

Tropical cyclones are shown to decrease in frequency globally by 9% in the $2xCO_2$ experiment and 26% in the $4xCO_2$ experiment (Fig. 3), similar to previous studies (Knutson *et al*, 2010). There is a larger reduction in the number of tropical cyclones in the southern hemisphere: 12% in the $2xCO_2$ experiment (30% in the $4xCO_2$ experiment) compared to 6% in the northern hemisphere in the $2xCO_2$ experiment (22% in the $4xCO_2$ experiment). The North Indian Ocean basin and North Central Pacific region are the only regions showing an increase in activity. The change in track density also shows some nonlinearities with increasing CO_2 concentration (Fig. 2). In the North East Pacific the tropical cyclones shift towards the south west part of the basin, although maintaining approximately the same number (18/year). However, in the $4xCO_2$ experiment the tropical cyclones are greatly reduced in number and outside the range of natural variability (11/year).

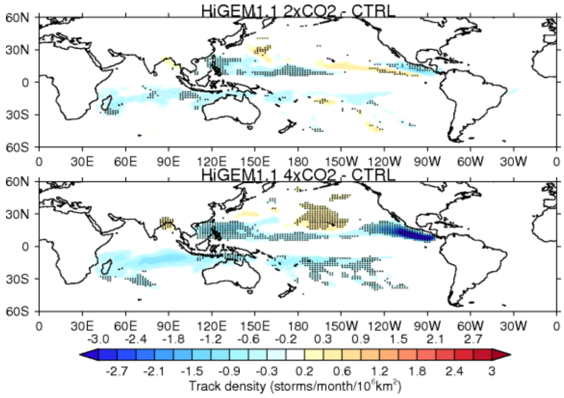

Figure 2. Tropical cyclone density differences (storms transits/month/10^6km^2) between the $2xCO_2$ and $4xCO_2$ experiments and the control simulation. Stippling shows where changes are outside the range of 5x30 year control simulation natural variability.

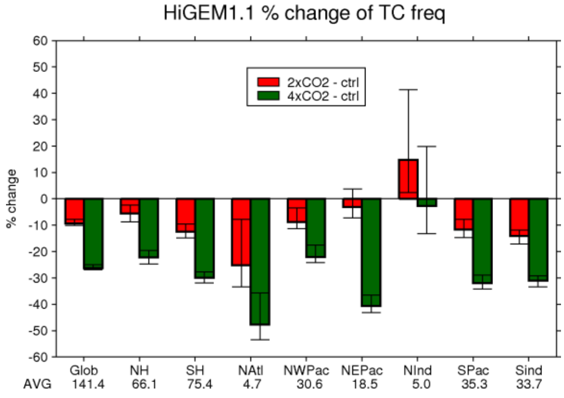

Figure 3. Tropical cyclone frequency change between the $2xCO_2$ and $4xCO_2$ experiments and the control simulation. Error bars show the range of 5x30 year natural variability. The average value in the control simulation is shown at the bottom.

6. LARGE SCALE FORCING

6.1 SST CHANGE

We similarly investigate changes in large scale parameters in the $2xCO_2$ and $4xCO_2$ experiments compared to the 5x30 years variability in the control simulation. Firstly, the change in SST during July, August, September and October (JASO) shows a warming everywhere in the tropics in line with the CMIP3 results (Zhao *et al*., 2009). The most striking feature, which occurs in both the $2xCO_2$ experiment and $4xCO_2$ experiment, is a tongue of relatively less warm water in the tropical North Atlantic as compared to the rest of the tropics (Fig. 4). This reduced SST warming, which is less than the tropical average, has a strong impact on the number of tropical cyclones that can form in the vicinity of the reduced SST (Vecchi and Soden, 2007a; Lee *et al*., 2011). Increasing evidence suggests that this SST pattern arises mainly due to aerosol forcing as opposed to ocean dynamics (Booth *et al*, 2012). Aerosol loadings were, however, not changed in our HiGEM experiments, so that changes presented in this research are indicative of an ocean response to increased greenhouse gases. The increase in SST in the North East Pacific is related to a weakening of the Walker circulation. As well as, SSTs are shown to warm more in the northern hemisphere than the southern hemisphere (Vecchi and Soden, 2007b) (not shown).

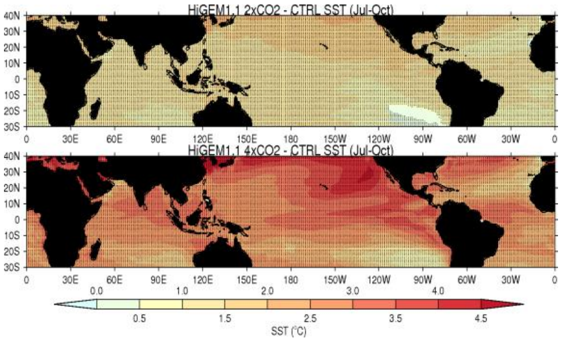

Figure 4. SST (°C) differences between the $2xCO_2$ and $4xCO_2$ experiments and the control simulation JASO. Stippling shows

where changes are outside the range of 5x30 year control natural variability.

6.2. CIRCULATION CHANGE

Catto *et al* (2011) showed that the tropics warm more in the upper troposphere compared to the lower troposphere in HiGEM, similar to other studies (Held and Soden, 2006). This increases the static stability, and reduces the strength of the tropical overturning circulation, resulting in the decrease of global tropical cyclone frequency. The region in the North West Pacific where the rising branch of the Walker circulation occurs (Fig. 5) is much weaker, the equivalent of anomalous descending motion. This subsidence reduces relative humidity, which makes the environment more hostile to tropical cyclone development. In contrast, the area of the descending branch in the Central Pacific now shows anomalous ascent, which favours the enhancement of tropical cyclones in this region (see also Li *et al* (2010) and Murakami *et al* (2011)).

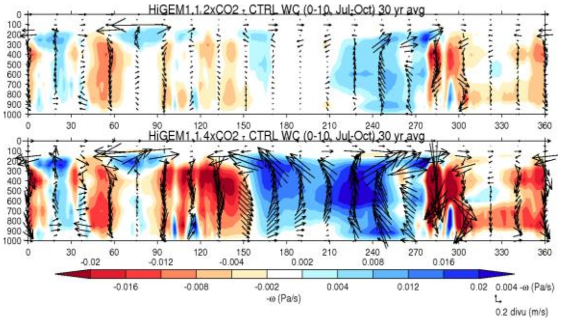

Figure 5. Walker circulation differences between the $2xCO_2$ and $4xCO_2$ experiments and the control simulation averaged from 0-10°N, JASO. Longitude is along the x-axis and pressure on the y-axis. The colours denote differences in the vertical velocity (-ω) (Pa/s). The x vector is divergence u, a change in the velocity potential (irrotational part of the wind field) with respect to latitude (m/s). The y vector is vertical velocity.

HiGEM simulates a weakening of the Hadley cell across the tropics, but shows large regional variations. The North East Pacific shows a southwards shift of the inter-tropical convergence zone (ITCZ) and an increase in subsidence in the Northern part of the basin which favours development to the South West. There is also a strong increase in subsidence in the tropical North Atlantic throughout a broad region from 10-30°N (not shown).

6.3. VERTICAL WIND SHEAR CHANGE

The weakening of the Walker circulation has previously been related to an increase in vertical wind shear over the main development region (MDR) of the North Atlantic (Vecchi and Soden *et al*, 2007b). This response is similar to that which occurs during an El Niño event although the increased vertical wind shear has a different structure. The increase in vertical wind shear is also likely to arise due to the tongue of relatively cooler water in the tropical North Atlantic (Zhang and Delworth, 2006). This creates a larger meridional temperature gradient, which in turn leads to stronger vertical wind shear over the region via thermal wind balance (Fig. 6). The influence region of this increased vertical wind shear extends to the North East Pacific in the $4xCO_2$ experiment and greatly reduces the tropical cyclone frequency. The larger increase in vertical wind shear in the southern hemisphere also gives rise to a greater reduction in tropical cyclone frequency (Vecchi and Soden, 2007b) (not shown).

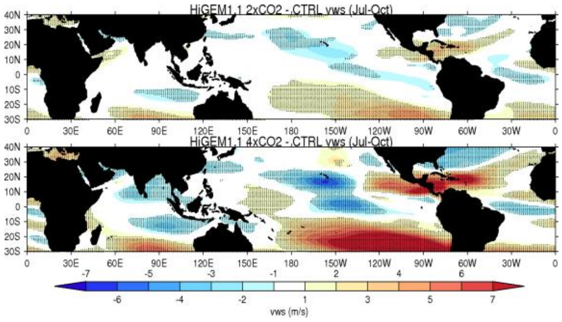

Figure 6. Vertical wind shear (m/s) differences between the $2xCO_2$ and $4xCO_2$ experiments and the control simulation JASO. Stippling shows where changes are outside the range of 5x30 year simulated control natural variability.

6.4. COMBINED CHANGE IN ENVIRONMENTAL PARAMETERS

To understand which of the changing large scale parameters are dominant in the future projections of tropical cyclones we have investigated the percentage change of SST, vertical wind shear, precipitation, relative humidity at 700hPa and upward vertical motion at 500hPa in the MDRs of the North Atlantic and the North East Pacific (similar to Held and Zhao (2011)). Fig. 7 shows the increase in stability in the North Atlantic is the largest environmental parameter change, with a linear reduction in upward motion in the $2xCO_2$ experiment (-49%) and $4xCO_2$ experiment (-105%). However, the vertical motion shows large natural variability. Most large scale parameters remain relatively unchanged in the $2xCO_2$ experiment in the North East Pacific. However, the large increase in vertical wind shear of 46% in the $4xCO_2$ experiment is likely to have caused the large reduction in tropical cyclone frequency.

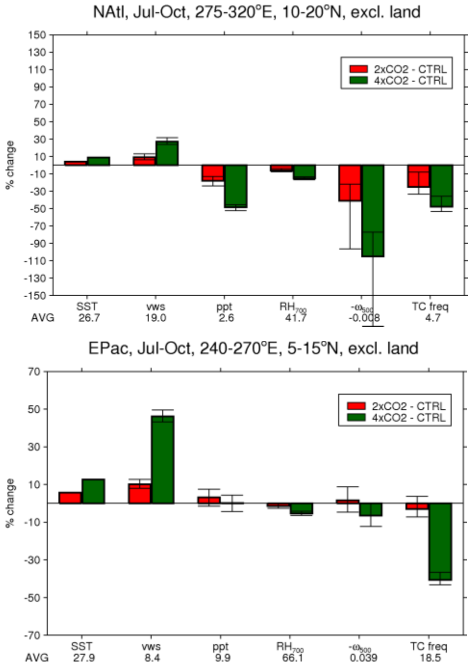

Figure 7. Percentage change of large scale forcing in the $2xCO_2$ and $4xCO_2$ experiments compared to 5x30 years control variability (shown as error bars). The average value in the control simulation is shown at the bottom. The regional and time averages are shown at the top of the plot. SST (°C), vertical wind shear (VWS, m/s), precipitation (ppt, mm/day) and relative humidity at 700hPa (RH, %), upward motion at 500hPa ($-\omega$, Pa/s). Note the difference in the scaling of the axes (percentage change) in the North Atlantic (top) and North East Pacific (bottom).

7. CONCLUSIONS

The use of a high resolution coupled GCM with a long control simulation has allowed us to gain a strong understanding of natural variability, which has been compared to idealised $2xCO_2$ and $4xCO_2$ experiments. For current climate conditions HiGEM shows a good comparison in terms of simulated geographical location of tropical cyclones and northern hemisphere tropical cyclone frequencies, when compared to IBTrACS and tropical cyclones identified in reanalyses. However, HiGEM simulates slightly less tropical cyclones in the North Atlantic and twice the number as observed in the southern hemisphere. The future simulations show that tropical cyclones decrease in frequency globally. We attribute this change to the increase in static stability and an increase in vertical wind shear over the MDRs, especially the North Atlantic. In the North East Pacific the large scale forcing remains relatively unchanged in the $2xCO_2$ experiment. However, a large increase in vertical wind shear in the $4xCO_2$ experiment is shown to have a strong detrimental effect on tropical cyclone frequency. A weaker Walker circulation is shown to reduce activity in the North West Pacific and favour activity in the North Central Pacific via anomalous descending and ascending air, respectively.

8. FUTURE WORK

Current research is being undertaken to further validate the HiGEM model similar to the robust validation of HiGAM (Strachan *et al*, 2012) both in terms of tropical cyclone metrics and large scale forcing. HiGEM's long control integration and good simulation of ENSO is being investigated further to understand whether it can capture how tropical cyclones respond to ENSO. This work will extend to investigating how a changing El

Niño may influence tropical cyclone projections. The varying HadGEM1 resolution models used in Strachan *et al* (2012) have all been run with idealised increased CO_2 forcing and will be investigated for future projections of tropical cyclone intensities.

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