U.S. CLIVAR
Fall 2013, Vol. 11, No. 3
VARIATIONS

Hurricanes in a Warming Climate

Mike Patterson, Director

How will the frequency and intensity of tropical cyclones/hurricanes change in a warmer climate? This question is being addressed by the U.S. CLIVAR Hurricane Working Group (HWG) established in 2011. The HWG has coordinated a set of global atmosphere model experiments using a common set of forcings to enable the systematic evaluation of modeled tropical cyclone climatology, responses to sea surface temperature changes, and responses to atmospheric CO_2 changes. Eleven modeling groups in the U.S. and internationally have voluntarily produced and furnished simulations for the experiments. HWG members have undertaken analysis of the simulations, presenting their findings at the U.S. CLIVAR Hurricane Workshop held at NOAA GFDL, June 5-7, 2013.

The articles in this edition of Variations derive from HWG findings and workshop presentations. Kevin Walsh and co-authors explore the fundamental reasons for model projections of decreased tropical cyclone numbers, particularly in the Southern Hemisphere. Suzana Camargo summarizes the ability of a new generation of high-resolution climate models to simulate tropical cyclone climatology, intra-seasonal to decadal variability, and response to climate change.

Changes in future Southern Hemisphere tropical cyclone numbers

Kevin Walsh*[1]*, Michael Horn*[1]*, Suzana Camargo*[2]*,
***Hiroyuki Murakami*[3]*, Hui Wang*[4]*, and Enrico Scoccimarro*[5]**

[1]*School of Earth Sciences, University of Melbourne, Australia*
[2]*Lamont-Doherty Earth Observatory/Columbia University*
[3]*University of Hawaii/MRI*
[4] *NOAA/NWS/NCEP/Climate Prediction Center*
[5]*Instituto Nazionale di Geofisica e Vulcanologia and*
Centro Euro-Mediterraneo per i Cambiamenti Climatici, Italy

There are fundamental differences between the climate of the Southern and Northern Hemispheres. Largely, these differences are dictated by the obvious differences in the geography of the two hemispheres: the Northern Hemisphere is about 50% land, whereas about 90% of the Southern Hemisphere is ocean. This asymmetry gives a much larger seasonal cycle in the Northern Hemisphere (NH) and reduces the response of Southern Hemisphere (SH) climate to imposed perturbations. This is most clearly seen in predictions of future SH climate, where predicted temperature increases caused by anthropogenic warming are considerably muted compared to changes at similar latitudes in the NH (e.g., Knutti and Sedláček 2013). Since the climate effects of anthropogenic carbon dioxide are well-mixed throughout the global atmosphere, the smaller future surface warming in the SH suggests that the future climate response to a combined forcing of surface temperature change and CO_2 increases will be different in the SH compared to the NH.

This difference may manifest itself in future projections of changes in tropical cyclone (TC) numbers, as a clear majority of climate models predict future substantial decreases in TC numbers in the SH, in excess of the decreases predicted for the NH (e.g., Knutson et al. 2010; Walsh et al. 2012). The reasons for this are at present unclear, but the idealized experiments conducted by the U.S. CLIVAR Hurricane Working Group (HWG) also indicate this tendency (see below). The reader is referred to Zhao et al. (2013; this issue) for a description of the HWG experimental design.

IN THIS ISSUE

Malcolm Roberts and co-authors present an evaluation of the HWG model experiments examining the modeled tropical cyclone response to imposed increases in sea surface temperature. Ming Zhao and co-authors examine how the role of changes in atmospheric CO_2 differs from the role played by sea surface temperatures in changing tropical cyclone characteristics.

The HWG members continue to evaluate the model experiments, with several resulting papers to be published in a Journal of Climate Special Collection on Hurricanes and Climate.

U.S. CLIVAR Science Plan Release:

In December, the U.S. CLIVAR Scientific Steering Committee will issue a new Science Plan detailing the scientific questions, goals, and research challenges to guide community-based implementation planning over the next 15 years. CLIVAR Town Halls are planned for the Fall 2013 AGU Meeting in San Francisco in December and the 2014 Ocean Sciences Conference in Honolulu next February. If attending one of these meetings, please join us to learn of the future U.S. and International CLIVAR program directions and to pick up a copy of the new U.S. Plan.

U.S. CLIVAR VARIATIONS

Editors: Mike Patterson, Director;
Jennifer Mays, Program Specialist
U.S. CLIVAR Project Office
1201 New York Ave NW 4th Floor
Washington, DC 20005
202.787.1682 www.usclivar.org

An issue not addressed by the HWG experiments to date is the substantial interannual variability in the present day and future climates. In the SH, there are strong regional interannual variations in TC formation and occurrence in the current climate (e.g., Kuleshov et al. 2008; Dowdy and Kuleshov 2012). ENSO causes substantial variations in the geographical distribution of TC numbers in the SH. El Niño conditions are characterized by increases in the formation rate east of the dateline in the South Pacific and a general expansion westward in the Indian Ocean, while incidence near the Australian coastline decreases. During La Niña conditions, more TCs strike the Australian coast, while fewer storms occur in the eastern South Pacific or the western South Indian Ocean (Kuleshov et al. 2008, Ramsay et al. 2008, 2012). Total numbers of storms forming in the SH are larger during La Niña conditions than during El Niño (Dowdy and Kuleshov 2012). Nevertheless, existing long-term trends in numbers of SH TCs are small since the beginning of the period of reliable satellite monitoring of TC formation after about 1970 (Kuleshov et al. 2010).

For the SH, it is therefore difficult to determine whether existing climate trends in this region have already had an effect on TC numbers. Even so, the response of greater decrease in TC numbers in the SH is also evident in the simulations of the HWG experiments when both CO_2 and sea surface temperature forcings are included (see Zhao et al. 2013, Fig. 3c). This combination of forcings arguably should be most similar among the HWG experiments to the simulated climate change response in a coupled climate model.

Previous work has suggested that there appear to be strong relationships between changes in the strength of the tropical circulation and changes in TC numbers (e.g., Vecchi et al. 2006). One question that arises is whether the accompanying decreases in the mid-tropospheric vertical velocities are greater in the SH than in the NH, and whether this is a potential source of explanation for the more systematic predicted decreases in SH TC numbers. Zhao et al. (2013) ascribe this result to decreases in convective mass flux, as represented by the 500 hPa vertical velocity. Examination of Fig. 3c of Zhao et al. (2013) indicates that when both forcings are included, there are more regions of increase in upward convective mass flux in the NH than in the SH, apparently associated with the overall smaller reduction in TC numbers in the NH than in the SH.

To address this issue further, we investigate whether this SH response in the HWG experiments is sensitive to the imposition of a different TC tracking scheme for comparison to the results of Zhao et al. (2013). The rationale for this analysis is that the choice of cyclone tracking scheme should not be a factor in modifying the response to the imposed perturbations, yet it is well known that different TC tracking schemes can give different detected climatologies of TCs. Here we employ the scheme of Walsh et al. (2004) with some subsequent modifications: we impose a resolution-dependent intensity threshold (Walsh et al. 2007) and we impose a restriction on TC formation, i.e., that it must occur equatorward of the subtropical ridge.

Figure 1 shows the results for the control run along with each perturbation experiments for four of the models participating in the HWG experiments. The results show that even in these idealized experiments, the SH is more likely to experience a decline in TC numbers than the NH (note that while percentage changes for the GISS model runs are large, numbers of TCs generated by this model in the control climate are low using this tracking scheme). This is also the case in the SH for the experiment where sea surface temperatures are increased uniformly by 2K, whereas globally some models give increases in numbers for this experiment. This response is also seen in the results of Zhao et al. (2013), where they analyzed a partially overlapping suite of models and a different tracking scheme. The fact that this difference in the response between the SH and NH is seen both in idealized atmospheric GCM experiments and in coupled model experiments suggests that it may be due to fundamental differences in the land-sea distribution in each hemisphere, which is one of the few factors that the HWG experiments and coupled model experiments both have in common. The modulating factor that is related to TC formation may be the resulting differences between the hemispheres in the relative proportion of convection between land and ocean induced by anthropogenic warming.

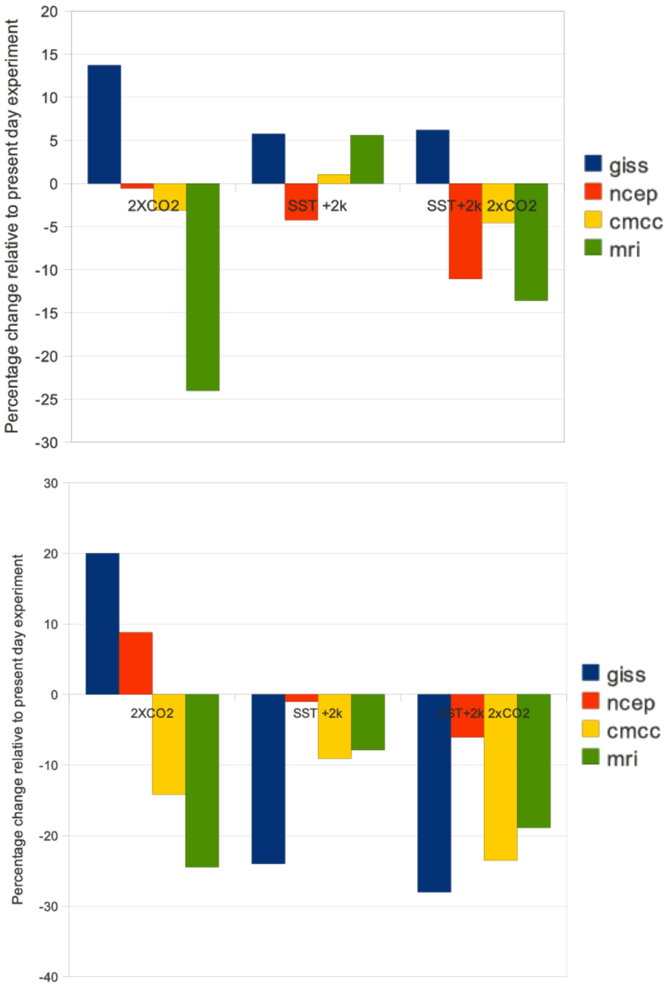

Figure 1. (top) Percentage changes in global numbers of detected tropical cyclones from the control simulation for the three perturbation experiments, for four general circulation models; (bottom) the same for the SH.

Given the strong relationship between ENSO and TC formation in the SH, the current uncertainty regarding the effect of climate change on ENSO is a serious limitation in our ability to understand the relationship between future climate and TC formation (see, for instance, Stevenson et al. 2012). Barnes et al. (2013) additionally suggest that climate change effects in the SH will be delayed due to the gradual recovery of stratospheric ozone, which model results have suggested substantially opposes the climate response to greenhouse gases. This is an additional factor that may cause a different future climate response in the SH, as is also the case for mid-latitude cyclones in the 20th century (Grise et al. 2013), as well as possible effects on TC numbers.

Acknowledgments

The authors would like to thank the Commonwealth Scientific and Industrial Research Organization for the use of their TC detection scheme.

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Tropical cyclones in high-resolution climate models

Suzana J. Camargo

Lamont-Doherty Earth Observatory/Columbia University

Introduction: The interest in the relationship between climate and tropical cyclones (hurricanes and typhoons) is very high. Tropical cyclones (TCs) are influenced by climate in various time-scales, with different climate modes responsible for the modulation of TC activity. There is variety in how the modulation occurs, with important regional distinctions. On top of the natural climate variability affecting TCs, in longer time-scales (decadal to centennial), anthropogenic climate change can also impact tropical cyclone activity.

The strong relationship between the El Niño-Southern Oscillation (ENSO) and Australian TCs and North Atlantic hurricanes led to the development of the first TC statistical seasonal forecasts (Nicholls 1979, 1984, 1985; Gray 1984a,b). The modulation of TC activity by various climate modes has been extensively studied in the literature and was summarized in recent reviews (Camargo et al. 2010; Camargo and Hsiang 2013). However, due to the short record of reliable historical TC data, it is fundamental that we use climate models in order to better understand this problem, as well as to make projections of future TC activity.

Since the 1970s, it is well known that even low-resolution climate models are able to produce vortices with characteristics very similar to TCs (Manabe et al. 1970; Bengtsson et al. 1982). These tropical cyclone-like vortices in low-resolution models typically occur in the same location as the observed TCs and typically form in the correct season, but tend to be much weaker and have much larger horizontal scale than observed ones. These biases are associated with the low-resolution of the models. Even at low-resolution, the modulation of TCs by ENSO is reproduced in climate models (Vitart et al. 1997; Camargo et al. 2005) and is the basis of the first TC dynamical seasonal forecasts that were developed in the early 2000s (Vitart and Stockdale 2001; Camargo and Barnston 2009). Early on, low-resolution climate models were used to investigate possible changes in TC activity under climate change (Broccoli and Manabe 1990; Bengtsson et al. 1996; Royer et al. 1998, Krishnamurti et al. 1998).

In recent years, the exponential improvement in the computational capacity has led to the existence of high-resolution climate models by various modeling groups.

The main effort is concentrated on the impacts of the climate change in tropical cyclone activity—however, many groups are also exploring their model skill in other time-scales, especially seasonal and intra-seasonal. The first effort of these groups is to assure the high-resolution climate models are able to simulate realistically some of the climatological characteristics of the TC activity (Bengtsson et al. 2007; Gualdi et al. 2008; Zhao et al. 2009). While some of the high-resolution models are able to simulate the global characteristics quite well, the regional characteristics can still be quite challenging. However, the regional biases can influence model projections, leading to different TC regional projections by different climate models in spite of robust global TC projections (Knutson et al. 2010).

In this paper, we will discuss (i) the state–of–the art of modeling of TCs in various time-scales from intra-seasonal to decadal and (ii) the latest projections of TC activity under climate change.

The U.S. CLIVAR Hurricane Working Group has produced a suite of simulations of with many high-resolution climate models in present and simple future scenarios, with the intent of improving the understanding of the differences between the TC simulations in high-resolution climate models. An intercomparison of the characteristic of TCs in these high-resolution climate models is currently being performed by the members of the working group.

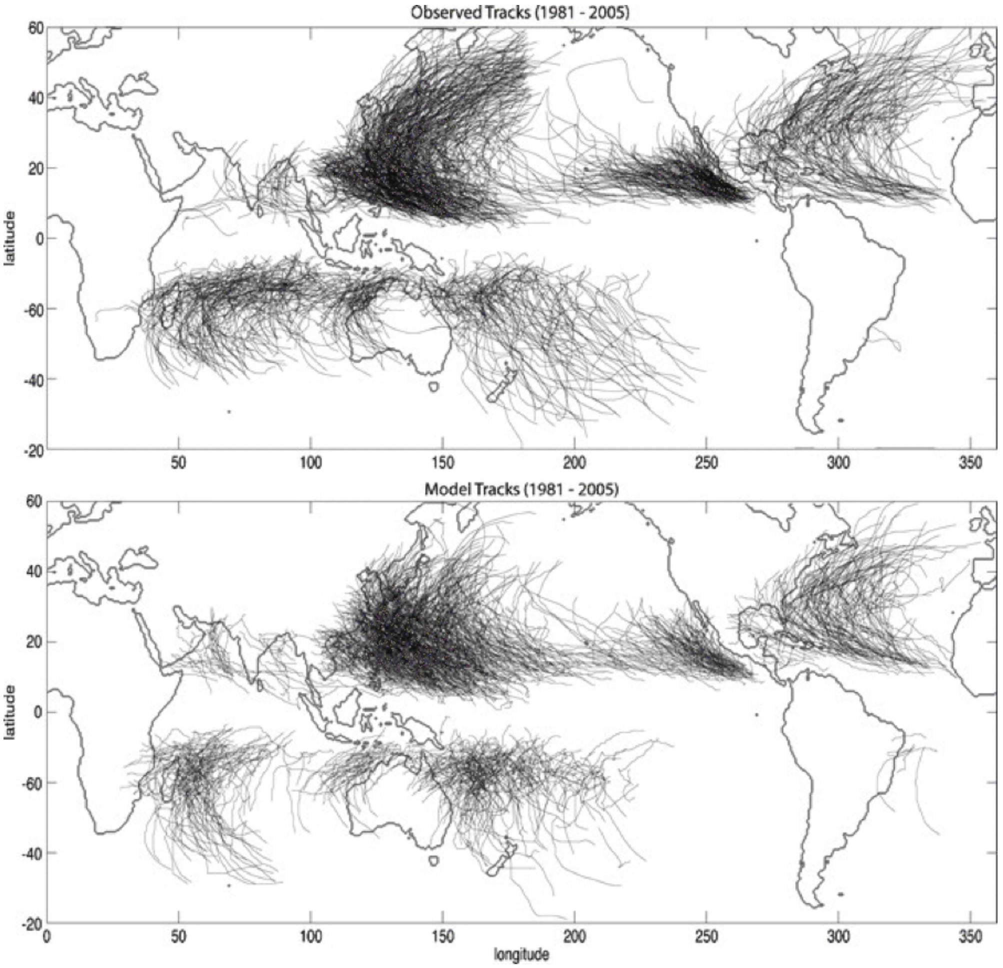

Figure 1. Tracks of observed (top) and model simulated (bottom) tropical cyclones that reached hurricane intensity in the period 1981-2005. The simulated tracks were generated by the GFDL HiRAM model forced with observed SST. Figure originally from Zhao et al. (2009).

Climatology: In low-resolution models, the global TC frequency climatology is typically much lower than observed. This is the case of the global climatology of TCs in most models of the Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5) (Meehl et al. 2007; Taylor et al. 2012). Given the scope of these model intercomparisons, most modeling centers have contributed with output from fairly low-resolution model simulations. Although the typical model resolution has increased since the previous CMIP3 assessment, model global TC frequency is still much lower than observed, with very little improvement from CMIP3 to CMIP5 in general (Camargo 2013). Examining the global genesis frequency in the CMIP3 models, it is clear that the main advantage of increasing model resolution is to produce a considerably better pattern of TC genesis (Walsh et al. 2013). Furthermore, the relationship between TC genesis and genesis indices (based on large-scale environmental fields) also improves with resolution (Walsh et al. 2013). There are still large deficiencies in the geographical patterns of the TC tracks and formation in CMIP5, with many models being relatively active in the western North Pacific, Indian Ocean, and Southern Hemisphere and inactive in the North Atlantic and eastern North Pacific (Camargo 2013).

High-resolution climate models are able to reproduce many aspects of TC climatology quite well (see, e.g., Fig. 1 from Zhao et al. 2009). Murakami and Sugi (2010) investigated the effect of model resolution on TC climatology using the same model with 4 different resolutions. They showed that present-day climatology of TC frequency (annual mean frequency and spatial distribution) shows little dependence on resolution once the model simulation reaches a critical value (120 km), with similar model biases in all resolutions. On the other hand, much higher resolution (at least 60km) is necessary for the models to start producing more intense TCs , and even at those resolutions, very intense TCs (categories 4 and 5) are still not present in the simulations (Zhao et al. 2009; Murakami and Sugi 2010). Only at resolutions around 20km are intense TCs simulated (Murakami et al. 2012). Other aspects of TC activity, such as tracks and landfall risk, are still not well reproduced in many high-resolution models (Daloz et al. 2013). Therefore, downscaling methods (statistical and dynamical) have been employed to improve model simulations and projections (Emanuel et al. 2006; Knutson et al. 2007; Bender et al. 2010; Lavender and Walsh 2011; Villarini and Vecchi 2012, 2013).

Intra-seasonal variability: In intra-seasonal time-scales, the Madden-Julian Oscillation (MJO; Madden and Julian 1972) is the strongest signal and the main source of predictability in the tropics. The MJO consists of large-scale coupled patterns of deep convection and atmospheric circulation with a 30-90 day period. The MJO modulates the TC activity in many regions (Camargo et al. 2009). When the MJO is in the enhanced convective or “active” phase in a certain region, there is a tendency for a higher frequency of TC formation in that region. Given this strong relationship between the MJO phase and tropical cyclone genesis, statistical forecast models have been developed for intra-seasonal TC activity using the MJO phase as one of the predictors (e.g., Leroy and Wheeler 2008).

Until recently, the representation of the MJO in most climate models has been quite poor (Kim et al. 2009), making the simulation of the MJO a difficult test for climate models (Slingo et al. 1996; Lin et al. 2006). Recently, a few high-resolution models have been able to simulate the MJO-TC relationship. For instance, the Japanese high-resolution cloud-resolving model NICAM has successfully simulated an MJO event and its link to tropical cyclogenesis in the western North Pacific (Oouchi et al. 2009). The European Centre for Medium Weather Forecasts (ECMWF) model is able to simulate the modulation of TC activity by the MJO as well as the relationship of landfall risk in Australia and North America with the MJO phase (Vitart 2009), while the Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) is able to reproduce the modulation of the MJO on TC activity in the eastern North Pacific quite well (Jiang et al. 2012).

Seasonal variability: In seasonal time-scales, ENSO is the main climate mode in the tropics. ENSO affects TCs in various regions in different ways: ENSO can modulate TC activity by altering TC frequency, intensity, duration, genesis location, and track types (e.g., Camargo et al. 2010). Although dominant, ENSO is not the only climate mode that influences TC activity in seasonal time-scales. Other natural modes of climate variability have been associated with seasonal TC activity, for instance the Atlantic Meridional Mode (AMM) (Vimont and Kossin 2007).

As the climate models improve, their ability to simulate and forecast TC activity on seasonal time-scales also improves. The HiRAM atmospheric model has very high skill in forecasting seasonal TC activity in the North Atlantic using 50km (Zhao et al. 2009) or 25km horizontal resolution (Chen and Lin 2011). Similarly, LaRow (2013) obtains significantly better skill in hindcasts of number of TCs in the Atlantic when using bias corrected SST (see Fig. 2). The effect of model resolution on the ability of the model in simulating interannual variability of

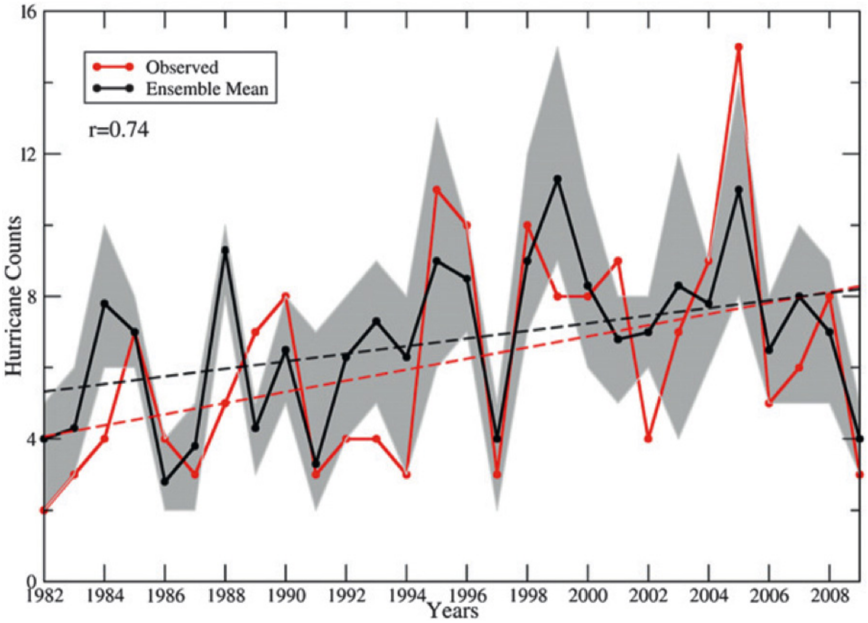

Figure 2. Interannual hurricane counts from 1982-2009. The red line is the IBTrACS observed dataset, and the solid black is the ensemble mean. The shaded region is the ensemble spread using the bias-corrected SST. The dashed lines are linear trends. The correlation coefficient is 0.74. Figure originally from LaRow (2013).

TC activity is examined in Strachan et al. (2013) using the Hadley Center Global Environmental Model (HadGEM1). In this study, a significant improvement of the model skill in interannual time-scales with resolution is found for the North Atlantic, but not for other basins. Caron et al. (2011) compares the impact of increasing resolution in TC activity in the Atlantic using the Global Environmental Multiscale (GEM) model. They find that the improvement in simulating Atlantic storms is partially due to a better representation of African Easterly waves. Coupled atmospheric-ocean models' interannual skill has improved as well. The model from the Japan Meteorological Agency with 60-km resolution is able to reproduce many of the features of the ENSO-TC relationship in the western North Pacific (Iizuka and Matsuura 2008) and North Atlantic (Iizuka and Matsuura 2009), even with the model ENSO having some deficiencies.

Decadal variability: In the last few years, decadal prediction has become a focal topic of research, with substantial effort in the climate community dedicated to this area. The decadal prediction focus is on the next 10-30 years time frame and therefore is a bridge between the seasonal predictions and the climate change projections. In this time frame, the climate is strongly influenced by both anthropogenic forcing and natural variability. Therefore, in order to have accurate decadal predictions, we must use accurate initial conditions as well as include anthropogenic greenhouse gases and aerosols forcing (Cane 2010). There are various spatial patterns of climate decadal variability identified in the observational record, such as the Atlantic Multidecadal Variability (AMV, also called in the literature Atlantic Multidecadal Oscillation or AMO), which could potentially be predicted (Goddard et al. 2012). New challenges appear in decadal predictions, such as separating the natural and forced components of the climate in these time-scales (e.g., DelSole et al. 2011). An important difference between seasonal and decadal prediction is that the main source of variability, AMV and the Pacific Decadal Variability (PDV), are mainly mid-latitude oceanic phenomena, but it is expected that their impact could be transmitted to the atmosphere through tropical SST changes (Goddard et al. 2012). Pioneer hindcast experiments using initialized coupled models showed promising results for decadal predictions (Keenlyside et al. 2008; Smith et al. 2007).

The decadal variability of tropical cyclone activity has been associated with natural modes of climate variability. The region that has attracted most attention in this topic is the North Atlantic, where the multi-decadal variability in the number of major hurricanes is associated with the AMV (see Fig. 3) through changes in vertical shear (Gray et al. 1997; Goldenberg et al. 2001; Bell and Chelliah 2006). Decadal variability in TC activity has been discussed in other regions as well. However, due to the short record of reliable observations in most regions, the results of these analyses need to be interpreted with caution. There are various studies analyzing the decadal variability of TC activity in the western North Pacific with a few of them identifying a modulation of intense typhoon occurrence and typhoon tracks by the PDV (Chan 2008; Ho et al.

2004). Interestingly Matsuura et al. (2003) and Yumoto et al. (2003) could reproduce the mechanism of decadal variability in the typhoon activity using a high-resolution coupled atmospheric-ocean model.

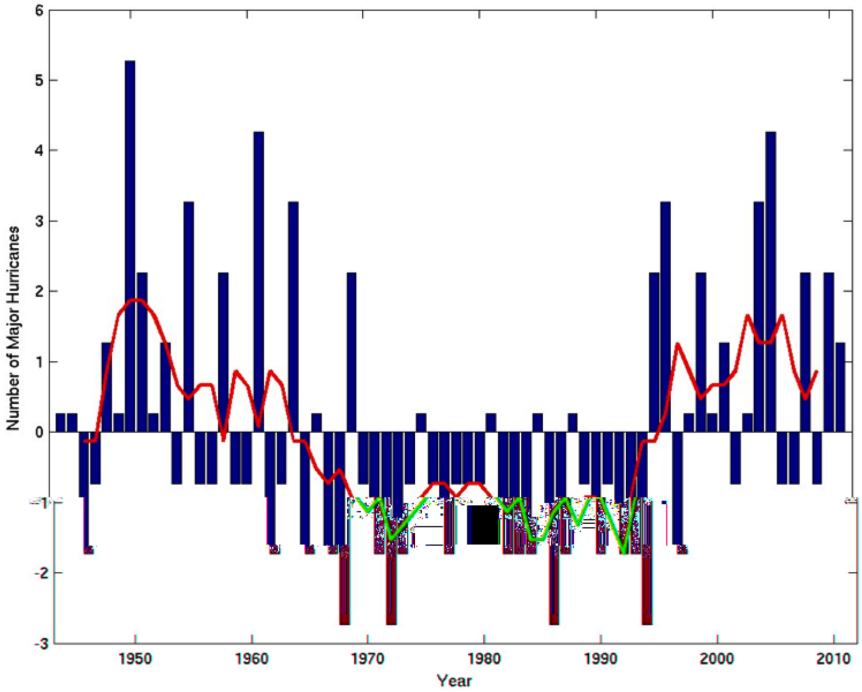

Figure 3. Difference of the number of major hurricanes per year in the North Atlantic and the mean number of major hurricanes (~2.7 per year) for the period 1944-2011 (blue bars). The 5-year running average is shown in the red line. Adapted from the original figure from Goldenberg et al. (2001).

Smith et al. (2010) explore the possibility of issuing forecasts of TC frequency in the North Atlantic many years in advance using decadal predictions. They show that their ensemble decadal prediction has skill in hindcast mode when initializing the prediction system with observed conditions. Their decadal prediction system has higher skill in predicting 5-year mean North Atlantic TC frequency than similar systems with either random initial conditions or forced with persisted SST. These encouraging results from decadal systems should be taken carefully. As discussed in Vecchi et al. (2013), the skill of the multi-year forecasts arise in large part from the persistence of the PDV phase in the initialized forecasts, rather than predicting the its evolution per se. Furthermore, the experiments are performed for a relatively short period and there is a strong correlation of the time-series, which could inflate the potential skill of these forecasts (Vecchi et al. 2013).

Future projections: There are two different issues that have been analyzed regarding changes in TC activity due to climate change. The first is the detection of long-term changes in the storm characteristics in the current observed record. The second is the projection of changes in TC activity in future climates.

Given the large fluctuations in global TC frequency and intensity, the detection and attribution of changes due to anthropogenic greenhouse gas forcing is very difficult. Furthermore, observational records of TC activity have well known quality and availability issues (e.g., Vecchi and Knutson, 2008; Landsea et al. 2010), which make the detection of statistically significant small trends very problematic. Recently, Weinkle et al. (2012) showed that there are no trends, globally or in individual basins, in the frequency and intensity of landfalling TCs with hurricane intensity of either minor (categories 1 and 2) or major (categories 3 to 5) strength.

Robust projections among a large array of models exist for global changes in TC characteristics only: a slight reduction of TC global frequency and a small increase in the percentage of the most intense storms are expected by the end of the 21st century (Knutson et al. 2010). Regional projections and other information about characteristics in TC activity in the future are still uncertain, as they are not robust across models. Even the global projections only became robust in the last few years, with the availability long climate simulations using high-resolution (50 km or less) climate models. The expected globally averaged intensity increases by 2100 are in the range of 2 – 11%, while the globally averaged frequency of storms is expected to reduce by 6 – 34% (Knutson et al. 2010). The high-resolution models also project increased precipitation rate associated to the storms on the order of 20% (Knutson et al. 2010).

Due to the low-resolution in most models, the simulation of TC activity in the CMIP5 models is not as good as in higher-resolution simulations. There are no robust changes across the CMIP5 models in global and regional TC changes in activity for future scenarios (Camargo 2013). Considering only a subset of CMIP5 models (models with a reasonable TC climatology in the present climate). there is a reduction in global TC frequency with a range of 3 – 15% (Tory et al. 2013).

Given the low-resolution of most CMIP5 models, it is fundamental to continue use a variety of downscaling methods (statistical and dynamical) to infer future projections of TC frequency, intensity, and tracks (e.g., Knutson et al. 2008; Villarini and Vecchi 2012, 2013). High-resolution models forced with fixed SST from the CMIP5 atmosphere-ocean coupled models (e.g., Zhao et al. 2009) and statistical-dynamical downscaling results (e.g., Emanuel et al. 2008) should still give a better assessment TC projections than using low-resolution models.

Emanuel (2013) downscaling of the CMIP5 models reveals an increase in the global TC frequency in the 21st century, contrasting with the decrease in the global frequency of TCs at the end of 21st century obtained when downscaling the CMIP3 models with the same technique (Emanuel et al. 2008). A dynamical downscaling of the CMIP3 and CMIP5 model projections over the North Atlantic (Knutson et al. 2013) results in a significant reduction of TC frequency by the end of the 21st century and an increase in the frequency of the very intense storms (categories 4 and 5), in agreement with previous results (Knutson et al. 2008; Bender et al. 2010).

Villarini and Vecchi (2012) examine 21st projections of North Atlantic TC activity using SST, specifically tropical Atlantic SST and mean tropical SST of the CMIP5 dataset, as predictors of a simple statistical model for the number of Atlantic tropical storms. Their results show that in the first half of the 21st century, radiative forcing changes (probably aerosols) lead to an increase in the number of North Atlantic named storms. However, trends over the entire 21st century are ambiguous and attributed the uncertainties to the climate response to radiative forcing and the chaotic nature of the climate system.

Summary: In the last few years, significant progress has been made in understanding the connection of climate and TC activity. A large reason for this progress is the existence of high-resolution global climate models simulations, which are able to simulate global TC activity with characteristics similar to that observed with exception of intensity, which requires even higher resolution. This has led to significant progress in simulating and forecasting TC activity in various time-scales from intra-seasonal to decadal as well in future TC projections.

Many global climate models project a small decrease in the global frequency of TCs and an increase in the occurrence of intense TCs by the end of the 21st century. However, significant differences are found among the models in the magnitude of these changes, and no robust predictions are made of regional changes in TC activity. Given these differences and the uncertainties still existing in projections of TC activity, it is fundamental to consider more idealized studies of TC activity under climate change. An example of idealized simulations are the ones being considered in the U.S. CLIVAR Hurricane Working Group and discussed in the articles in this edition of Variations. By considering simple uniform changes in SST and CO_2 and using the same forcing in all models, we are hoping to shed light on the reasons for the differences among models in the TC response to climate change.

Acknowledgments

SJC would like to thank all the members of the U.S. CLIVAR Hurricane Working Group for their contribution to this significant effort. SJC is partially supported by NOAA grants NA10OAR4310124 and NA11OAR4300193, NSF grants AGS 1143959 and 1064081, ONR grant N00014-12-1-0911 and NASA grant NNX13AM18G.

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Sensitivity of tropical cyclone simulation to SST forcing

Malcolm Roberts[1], Pier Luigi Vidale[2], Ray Bell[3], Kevin Hodges[4],
and the U.S. CLIVAR Hurricane Working Group (HWG) Members

[1]Met Office Hadley Centre
[2]NCAS-Climate, University of Reading
[3]Dept. of Meteorology, University of Reading
[4]NERC Centre for Earth Observation, University of Reading

Introduction: Tropical cyclones (TCs) and hurricanes have the potential to be very damaging and costly in both lives and infrastructure, with development along coastlines particularly vulnerable to wind, storm surge and precipitation extremes. Many previous studies (Emanuel 1991; Holland 1997) have shown that tropical cyclone behaviour responds strongly to changes in thermodynamic equilibrium – the simplest diagnostics of which would be sea surface temperature (SST)/moisture and upper level temperature/wind shear (Rotunno and Emanuel 1987; Emanuel 1988; Emanuel and Nolan 2004; Camargo 2007a). Our understanding of the important factors for present day TC/hurricane formation have greatly increased over the last 20 years, leading to improved forecasts of short-term tracks (Rappaport et al. 2009), seasonal-timescale activity (e.g., Vecchi et al. 2013; MacLachlin et al. 2013; Camargo et al. 2007b), and interannual variability (e.g., Strachan et al. 2013; Zhao et al. 2009; Smith et al. 2010). Likely future changes in TCs are still quite uncertain (e.g., Camargo et al. 2013; Tory et al. 2013) partly due to the complexity of possible future changes in both dynamic and thermodynamic quantities as well as in forcing factors (greenhouse gases [GHG], aerosols) and limitations in modelling.

To fully assess potential future change in TCs with climate, a global coupled model is required – only this type of tool can produce a fully consistent and representative environment with all the interacting elements (e.g., CMIP5 models; Tory et al. 2013; Camargo et al. 2013; Villirani and Vecchi 2012). However, such models often have significant mean-state biases in atmosphere and ocean, need to be spun-up to equilibrium for long periods, and are run at relatively coarse resolutions due to their complexity and length of run. Murakami et al. (2013) show how these model biases can significantly affect TC projections.

Forced present-day global atmospheric integrations are cheaper, can be shorter, do not have ocean biases due to specified SSTs, and therefore can be amenable to using much higher resolution (e.g., Yamada et al. 2010). Results can also be compared more easily with observations for a given period and to other models. However, using an imposed SST is an idealization as it effectively supplies an infinite energy source (due to the SST not being changed by surface fluxes), and SST itself is really just a tracer of the climate state, not the driver. SSTs clearly do play some role in TC formation – typically tropical deep convection only occurs when SSTs exceed about 26°C (Palmén 1946) – so any change in SSTs into the future could alter genesis regions and hence TC climatology. As discussed in Emanuel and Sobel (2013), SST is not a unique function of other variables related to TC activity, and hence we should interpret such experiments with caution. It would be better to use a coupled slab-ocean model as standard, but this does have its own problems.

The U.S. CLIVAR Hurricane Working Group decided to set up several coordinated experiments with a range of climate models, which attempt to answer questions such as:

- What is the tropical cyclone response of climate models to an imposed, common increase in SST, and is it robust across models?
- How sensitive is the simulation of tropical cyclone variability to differences in SST analysis?
- What are the factors controlling the TC changes?
- Can we learn anything to apply to likely future changes in TCs?

The methodology adopted is to add a uniform +2K increase in SST onto the HadISST (Rayner et al. 2003) repeating annual cycle (with no other changes, in order to separate the effects of SST from those of CO_2) and integrate for as many years as possible. As discussed above, this should be seen as more of a sensitivity study to understand model response to uncertainty in SST forcing than for understanding climate influences on TCs. HadISST is used since this is the standard dataset for AMIPII integrations (Taylor et al. 2000). An increase in SST of +2K is a relatively weak forcing (something near to the RCP4.5 scenario at 2100) compared to the strongest RCP8.5 scenario in CMIP5, and hence may not give a clear response (particularly without the corresponding GHG increase – see companion article on the CLIVAR HWG CO_2 experiments).

There have been various previous studies imposing a uniform SST increase with CO_2 held fixed (Held and Zhao 2011; Yoshimura and Sugi 2005). Both seem to indicate a decrease of the order 6-10% in global TC frequency. There are various effects of a uniform SST warming on the large-scale climate of relevance to TCs as measured for example by the Potential Intensity (PI) and Genesis Potential Intensity (GPI) (e.g., Camargo et al. 2007a; Emanuel 1988; Holland 1997; Bell et al. 2013). The GPI seems to increase in all basins in the +2K runs (Zhao et al. 2013), as it seems to do in other papers on CMIP5 models (Camargo 2013; Emanuel 2013). The upper troposphere warms more quickly than the lower, giving an increase in static stability, but there is typically also an increase in precipitation from more intense tropical convection – these effects seem to partially cancel. Held and Zhao link their TC changes to a reduction in deep convection as diagnosed from omega at 500hPa. Yoshimura and Sugi suggest a competition between increased tropical convection and the increased static stability, with the latter slightly dominating. These studies also indicate a slight increase in intensity of the strongest storms.

In addition to an imposed SST increase, there is also great interest in how different SSTs forcing datasets (both representing present day values and any future projections) might influence TC climatology. Since TCs are such small-scale features, a model ideally needs high resolution, which might suggest using more recent daily datasets such as Reynolds (nominally ¼ degree; Reynolds et al. 2007), OSTIA (Donlon et al. 2012), and ESA-CCI (Hollmann et al. 2013) (both nominally 1/20 degree). However, the standard forcing for the CMIP5 AMIPII experiments (Taylor et al. 2000) remains the monthly, 1° dataset based on HadISST (Rayner et al 2003), which has a much longer record than those previously mentioned.

There is also evidence from statistical modelling of TCs (e.g., Villarini et al. 2012) to suggest that different SST datasets can have an impact on the relationships between TC variability and landfalling.

Experiments to investigate future climate using atmosphere-only models must make assumptions about the projected SST change. Results from Zhao et al. (2009) and Murakami et al. (2012), in which projected SST changes (and GHG changes) from CMIP3 coupled models were used for an ensemble of sensitivity studies at high resolution, suggest a general decrease in TC frequency globally. Later papers, Murakami et al. (2013) and Zhao et al. (2009), show that projected changes in TCs are very sensitive to the different SST projections, which, given what is known about how various modes of variability (e.g., ENSO, AMM, AMO, tropical versus basin-wide SST changes) project onto TC climatology (e.g., Camargo et al. 2007b; Kossin and Vimont 2007; Goldenberg and Shapiro 1996; Vecchi and Soden 2007), is perhaps unsurprising but important.

Yet another approach is to extract a small region, use much higher resolution, and hence attempt to model the TC processes with more physical realism. Knutson et al. (2010) and Emanuel et al. (2010) and Emanuel (2013) have used this approach in different ways. Knutson et al. (2010) downscaled various CMIP3 and CMIP5 models using the ZETAC regional 18km model over the Atlantic in which the large-scale is nudged towards the climate model climatology while allowing an explicit convection model to operate on the finer scales. For the RCP 4.5 scenario a reduction is found in total storms, but a significant increase occurs in the strongest storms, particularly when further downscaling to the GFDL hurricane model. Emanuel (2013) uses daily and monthly output from global models to produce an environment for seeding proto-TCs and calculating their climatology using a beta-and-advection model. The wind field of each storm is then predicted by a deterministic coupled air-sea model (CHIPS) phrased in angular momentum coordinates to give a highly resolved inner core. This model predicts an increase in TC frequency in line with the increase in GPI.

The correct simulation of the TC genesis regions is also important in order to reproduce realistic track path and landfalling statistics (clearly of ultimate interest in terms of impacts). Kossin et al. (2010) and Daloz et al. (2013) show how clusters of TCs with different genesis regions have rather different properties. Clearly future changes to the genesis climatology through SST changes will consequently affect the TC characteristics.

In summary, forced atmosphere-land surface experiments are simpler to use and interpret but in terms of understanding future TC change should be considered as model sensitivity tests to SST perturbations.

U.S. CLIVAR HWG Model results: These results were collected from the HWG workshop at GFDL in June 2013. Data from different modelling groups has been submitted to an archive at Lamont-Doherty – both daily outputs and TC tracks extracted using each group's TC tool. Presentations are available at **http://www.usclivar.org/meetings/hurricane-workshop-agenda**. The tracking methods used are indicated in Table 1.

Ming Zhao (GFDL) showed his analysis of the +2K models. The results in Table 1 (and manuscript in preparation) show the percentage changes between P2K and control. In terms of global frequency, some models show a reduction of 10-20% (in line with some of the previous papers), some show an insignificant change, and one has a significant increase (CAM5.1 at 1°, see below). His analysis suggests that 500 hPa omega seems to best explain the behaviour of most models, with reduced ascent regions corresponding to reductions in TC genesis. It is suggested that the spread of model response might be partly due to uncertainties in how the parameterised convection responds to warmer SSTs.

Tracking method	Model	Resolution at equator (km)	+2K change	% age change	No. years	Presenter
Hodges	HadGEM-GA3	208	D	-8	20	MR
Hodges	HG3-N216	92	N	2	10	MR
Hodges	HG3-N320	62	D	-14	10	MR
Oouchi	NICAM	14	N		5 mths	KO
Orig tracks (GFDL)	CAM5.1	100	U	28	24	DS
Orig tracks	CMCC ECHAM5	84	N	-2	10	DS
Orig tracks	FSU COAPS	106	D	-10	5	DS
Orig tracks	GEOS-5	56	U	70	19	DS
Orig tracks	GISS	111	U	10	20	DS
Orig tracks	NCEP GFS	106	D	-10	20	DS
GFDL ws17	GFDL HIRAM	50	D	-13	21	MZ
GFDL ws17	GFDL C180AM2	50	N	2	20	MZ
GFDL ws12	CMCC ECHAM5	84	N	4	10	MZ
GFDL ws12	NCEP GFS	106	D	-15	20	MZ
GFDL ws12	GEOS-5	56	N	-5	19	MZ
GFDL ws12	GISS	111	D	-38	20	MZ
CSIRO new	GISS	111	U	6	20	KW
CSIRO new	NCEP GFS	106	D	-4	20	KW
CSIRO new	CMCC ECHAM5	84	N	2	10	KW
GFDL	CAM5.1	28	D	-4	17	MW

Table 1. Sign of global TC frequency change from models run with the climatology and +2K SST forcings. D = reduction, N = no significant change in relation to the standard deviation, U = increase in TC frequency with +2K warming - control. Where available, the percentage change, the number of model years, and the initials of the presenter from the GFDL meeting are noted (data from their slides). The tracking method is also noted: Orig tracks = original tracking files submitted to database, Hodges = Hodges (1995) and Bengtsson et al. (2007), GFDL = Zhao et al. (2009) (with wind stress thresholds noted in m/s), CSIRO new = an updated version of Walsh et al. (2007).

Daniel Shaevitz (Lamont–Doherty) showed his analysis of the archived output (Table 1, manuscript in preparation). It reveals an extremely mixed +2K picture, with some reduction and some increase in TC frequency.

Michael Wehner (Berkeley) showed that the 1° CAM5.1 model has a significant increase in TCs under +2K but cautioned that is likely due to the tracking algorithm and in particular the threshold used – if the storms increase in intensity, then more may be detected by the algorithm. The ¼ degree CAM5.1 shows a small reduction in frequency globally, an increase in frequency in the Atlantic basin, and a definite increase in the strength of the strongest storms.

Malcolm Roberts (Met Office Hadley Centre) showed results (Table 1) from the HadGEM3 GA3 model (Walters et al. 2012) at different resolutions (130km, 60km and 40km at mid-latitudes). For total storms the highest and lowest resolutions show a significant decrease, while the 60km has an insignificant change. Different basins give a variety of changes that have no consistency with resolution change.

Kevin Walsh (University of Melbourne) introduced an improved TC tracking algorithm from CSIRO and used it on three models with control and +2K simulations. Two models give a small increase in TC frequency, and one shows a decrease.

Kerry Emanuel (MIT) showed results from the CHIPS model (Emanuel 2013), which uses the archived model output to constrain the large-scale climatology of an idealised coupled hurricane model and then uses random seeding to derive the TC climatology. In this case all models show an increase in TC frequency in +2K climate, with this increase following the trend in GPI (although the GPI itself is of course only calibrated on the present day climate). Daloz et al. (2013) have results from using this methodology to downscale some of the HWG experiments for the Atlantic. They show an improvement in cluster climatology in the downscaled present-day integrations. No strong signal in frequency change is found with the +2K warming, there is an indication of an intensity increase.

To summarise, the +2K results for the global climate models with explicitly tracked storms present a very mixed picture:

- changes have no obvious dependence on model type and/or horizontal resolution;
- the majority of models indicate a decrease in global TC frequency, but there is certainly no consensus; and
- there is perhaps more agreement that the strongest storms in the warmer climate tend to become more intense.

In contrast, the Emanuel CHIPS model, using output from some of these models for the large-scale climatology, indicates an increase in global TC frequency in all the models tested, in agreement with the increase in GPI index found in most models.

Further work is needed to discover how to reconcile these contrasting conclusions for how TC frequency might change in the future. There are indications that some of these results are dependent on the tracking algorithm used (there is at least one model with a different signed change using a different tracker). A continued effort to compare different tracking algorithms will be important to understand how they can impact results.

Impact of different SST datasets in present day integrations: Using present day SSTs to force an atmosphere-only model is a simple way to test a model's ability to simulate tropical cyclone interannual variability at the ocean basin-scale. In addition to the caveats above over using SST, there is also a question of the sensitivity to different SST datasets used. Zhao et al. (2009) show that while the global TC frequency is relatively insensitive to the choice of HadISST or Reynolds SSTs, particular models in specific basins do have larger differences. This may be related to the warmer SSTs found in HadISST (averaging 0.2-0.3 over large areas of the ocean in JJA and particularly in the Atlantic main development region) compared to Reynolds and other recent satellite-derived products such as OSTIA (Mizielinski et al. in prep.). The difference is a significant fraction of an SST warming signal, particularly as the different datasets may go above the 26°C threshold for different lengths of time. Several sensitivity tests using the HadGEM3-GA5 model (Walters et al. in prep.) have been made to compare the Reynolds, OSTIA, and ESA-CCI datasets using single integrations between 1991-2009 (Roberts et al. in prep.). At 130km resolution there is no significant difference between the TC climatologies, while at 25km resolution there is a significant difference in the West Pacific basin only, with an increased frequency of 20% using ESA-CCI. Analysis is ongoing to understand these differences.

Given our knowledge of the sensitivity of both simulated and observed tropical cyclones to SST changes (e.g., Zhao et al. 2009; Murakami et al. 2013; Villarini et al. 2012; Saunders and Lea 2008), there is clearly more scope for investigating this sensitivity, as regards both the spatial resolution and the temporal resolution of the forcing data (i.e., monthly vs. daily). The AMIP II protocol still requires use of the monthly PCMDI/HadISST forcing. Hence, an improved knowledge of how such forcing influences the TC climatology would be valuable.

Acknowledgments:

The current figures are based on talks given at the U.S. CLIVAR Hurricane Working Group meeting at GFDL in June 2013, and can be found at **http://www.usclivar.org/meetings/hurricane-workshop-agenda.**

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Robust direct effect of increasing atmospheric CO_2 concentration on global tropical cyclone frequency: a multi-model inter-comparison

***Ming Zhao*[1]*, Isaac M. Held*[1]*, Gabriel Vecchi*[1]*, Enrico Scoccimarro*[2]*, Hui Wang*[3]*, Michael Wehner*[4]*, Y.-K. Lim*[5]*, Tim LaRow*[6]*, Suzana J. Camargo*[7]*, Kevin Walsh*[8]*, S. Gualdi*[2]*, Arun Kumar*[3]*, Siegfried Schubert*[5]*, and Kevin A. Reed*[9]**

[1]*NOAA/Geophysical Fluid Dynamics Laboratory*
[2]*Instituto Nazionale di Geofisica e Vulcanologia and*
Centro Euro-Mediterraneo per i Cambiamenti Climatici, Italy
[3]*NOAA/NWS/NCEP Climate Prediction Center*
[4]*Lawrence Berkeley National Laboratory*
[5]*NASA Goddard Space Flight Center*
[6]*Florida State University*
[7]*Lamont-Doherty Earth Observatory/Columbia University*
[8]*The University of Melbourne, Australia*
[9]*National Center for Atmospheric Research*

Rising concentration of carbon dioxide (CO_2) is expected to affect tropical cyclone (TC) intensity, frequency, and genesis locations through an increase in global mean sea surface temperature (SST). This has been an area of intensive research for the past few decades with increasing use of high-resolution global climate models (GCMs) and various downscaling approaches [see Knutson et al. (2010) for a recent review]. The assumption appears to be that the dominant effect of increasing CO_2 on TCs is through an increase in tropical mean SST. However, recent modeling studies suggest that both spatial patterns of SST warming and higher atmospheric CO_2 concentrations can significantly affect global and regional TC statistics independent of the global mean SST warming (Vecchi et al. 2008; Zhao et al. 2009; Held and Zhao 2011). In this article we focus on an examination of the direct or fast effect of CO_2 on global TC frequency from the multiple models participating in the U.S. CLIVAR Hurricane Working Group (HWG). An understanding of the direct effect of CO_2 is important for both near-term TC projections and assessing the impact of geo-engineering schemes on future TC statistics, especially if as a consequence the atmospheric CO_2 concentration increases with significantly delayed or alleviated SST warming.

In comparison to the numerous studies on the effect of global warming on TCs, the direct effect of CO_2 on TC statistics has not received enough attention. To our knowledge until the experiments carried by the US CLIVAR HWG, there were only two modeling groups who have attempted to separate and document in their models the effect of increasing CO_2 with fixed SSTs from the effect of increasing SSTs with fixed CO_2 (Yoshimura and Sugi 2005; Held and Zhao 2011). Both models show a significant reduction in global TC frequency to an increase of CO_2 with fixed SSTs. Although there are hypotheses that attempt to explain these results, the physical mechanisms of the direct effect of CO_2 are not fully understood, and conventional TC Genesis Potential indices (GPI) fail to explain the model results (Camargo et al. 2013). Moreover, it is not clear to what extent these results might be model dependent. One objective of the U.S. CLIVAR HWG is to assess the robustness of the GCM simulated TC response to increases in SST and CO_2, both in isolation and together, by conducting a well controlled, multi-model inter-comparison study in which specifications of SSTs and greenhouse-gas (GHG) concentrations are made identical across the models.

For each HWG participating model, a set of common experiments are requested. It includes one control experiment forced by monthly climatological (1981-2005 average) SSTs with present-day GHG concentrations, and three perturbed-forcing experiments that are identical to the control, except 1) SSTs are uniformly increased by 2K (P2K), 2) atmospheric CO_2 concentration is doubled (2xCO_2), and 3) a combination of 1) and 2) (BOTH). We compare the response in global TC frequency from seven models that have provided sufficient data for this analysis. The seven models include: two GFDL models (HIRAM and C180AM2), ECHAM5 simulations conducted in CMCC, NCEP GFS, USDOE/NSF CAM5H (CAM5.1 running at 25km resolution), NASA-GFSC GOES5, and COAPS simulations from FSU. Table 1 lists participating institutions, model names, resolutions, and reference papers.

To minimize the uncertainty caused by using different TC detection and tracking algorithms, a single tracking scheme (GFDL; Knutson et al. 2008; Zhao et al. 2009) is employed for all models using their 6-hourly data. Because some models, especially those with coarser resolution, tend to produce significantly weaker surface wind speed, it becomes necessary to reduce the maximum wind speed criteria in order to obtain enough TCs for reliable statistics (Walsh et al. 2007). In particular, we use 17 m/s for HIRAM, C180AM2 and CAM5H and 12 m/s for all other models. The threshold criteria for TC duration, vorticity, and warm-core are two days, 3.5E-5 1/s, and 1 °C respectively and are the same across all models. The sensitivity of TC statistics to different TC detection and tracking algorithms is currently being explored and will be reported elsewhere (Walsh et. al 2013). Except for

Institution	Model	Resolution (km)	No. years	Reference paper
GFDL	HIRAM	50km	20	Zhao et al. 2009
GFDL	C180HIRAM	50km	20	GAMDT 2004
CMCC	ECHAM5	80km	10	Roeckner et al. 2003 Scoccimarro et al. 2011
NCEP	GFS	100km	20	Saha et al. 2013
LBNL	CAM5H	25km	12	Wehner et al. 2013
NASA-GSFC	GOES5	50km	19	Rienecker et al. 2008
FSU	COAPS	100km	10	LaRow et al. 2008

Table 1. A list of institutions, model names, resolutions, integration length and reference papers for each model.

FSU COAPS, all model results reported here use GFDL tracking.

We first show that the seven models produce substantial different annual global TC frequencies and geographical distributions (Fig. 1). These differences are due to model spatial resolutions and physics parameterizations. While coarse resolution models tend to produce fewer TCs, not all high-resolution models produce more TCs than coarse resolution models do (Fig. 1 inset). For example, GEOS5 generates fewer TCs than ECHAM5 and GFS despite its higher spatial resolution (50km, same as HIRAM and C180AM2). The differences among HIRAM, C180AM2, and GEOS5 are nearly entirely in their physics parameterizations since they all use the same dynamic core and horizontal resolution. The two GFDL models differ predominantly in their convection schemes; therefore, any differences in simulated characteristics of TC statistics and their response to changed climate conditions between the two would suggest effects of convective parameterizations.

Due to the large variation in global TC frequency among the models, we compare the simulated regional differences in basin-wide TC frequency by normalizing individual basins' TC counts by each model's global counts. It is evident that the models produce distinct differences in the geographical distribution of TC frequency. [Basin definitions follow the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. 2010)]. For example, CAM5 and GFS produce relatively too few Western North. Pacific TCs and too many Eastern North Pacific TCs, while C180AM2 and ECHAM5 produce an opposite bias. An in-depth understanding of the cause of the characteristic regional biases in simulated present-day TC frequencies and its impact on future TC projections is clearly needed.

Despite the large differences in simulated present-day TC frequency, all models produce a reduction in global TC frequency when both CO_2 concentration is doubled and SSTs are uniformly increased by 2K (Fig. 2a, BOTH). However, the responses to individual forcing changes (P2K or $2xCO_2$) show a larger discrepancy among the models. In particular, only two out of the seven models produce a significant (based on 90% confidence interval) reduction in global TC frequency under 2K SST warming while the rest exhibit insignificant changes. None of the models produces a significant increase in global TC frequency. In comparison, six out of the seven models produce a significant reduction in global TC frequency in response to $2xCO_2$ with GFS being the only one that generates an insignificant change. Hence, the response of global TC frequency to CO_2 increases is more robust than its response to SST warming among these models. This result is consistent with a recent study that reveals a more robust direct effect of CO_2 on tropical circulation and regional precipitation among the CMIP5 models (Bony et. al 2013).

Held and Zhao (2011) attribute the reduction of global TC frequency to CO_2 and/or SST increases to a decrease in large-scale convective mass flux over the global TC development region. They provide a measure of the convective mass flux by using an index

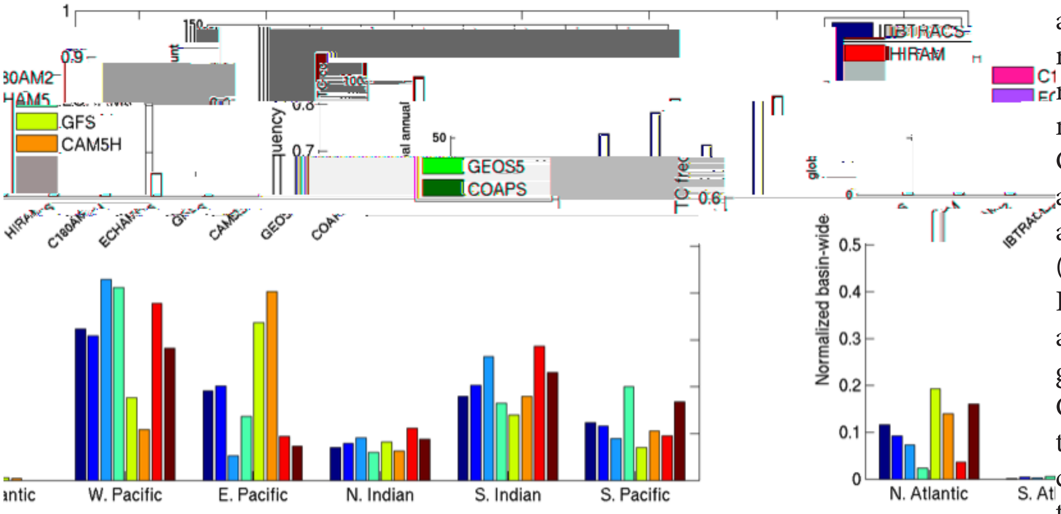

Figure 1. Geographical distribution of normalized annual basin-wide TC frequency from seven models and the observations from IBTRACS. The annual global TC number simulated by each model is shown in the inset figure and it is normalized to 1 when plotting the basin-wide TC frequency for each model. The definition of the basins follows that used in IBTRACS.

of mid-tropospheric vertical pressure velocity, $(\overline{\omega_{500}})$, defined as the spatial average of an annual mean 500hPa vertical velocity $\overline{\omega_{500}}$ over the entire TC development region (as defined by the control simulation). The annual mean vertical velocity $\overline{\omega_{500}}$ is an average of monthly mean ω_{500} weighted by monthly climatological TC genesis frequency over each 4°×5° (latitude xlongitude) grid box from the control simulation. At each grid box, the weighting by its seasonal climatological TC genesis frequency helps to objectively identify ω_{500} over the seasons most relevant to TC genesis. The global index $(\overline{\omega_{500}})$ is negative for all models, indicating that TC genesis on average occurs over regions of large-scale ascent. Fig. 2b shows fractional change in $(\overline{\omega_{500}})$ for each perturbation experiment from each model. A negative fractional change indicates an increase (less negative) in $(\overline{\omega_{500}})$, i.e., a reduction in upward convective mass flux.

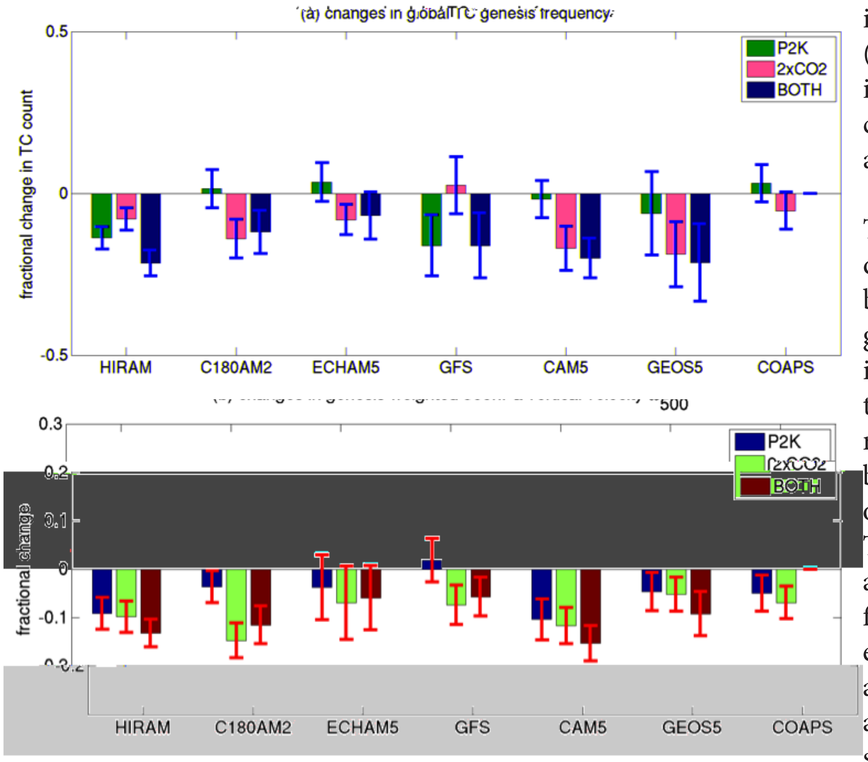

Figure 2. a) Fractional changes in global annual TC frequency between each perturbation simulation and the control. P2K: uniform 2K warming. $2xCO_2$: a doubling of CO_2 concentration, BOTH: both uniform 2K warming and a doubling of CO_2. Error bars show 90% confidence interval. Note that FSU COAPS does not provide the BOTH experiment. b) As in a) except for fractional changes in TC genesis frequency weighted 500hPa vertical pressure velocity index, $\overline{\omega_{500}}$ (see text for the definition of $\overline{\omega_{500}}$).

If $(\overline{\omega_{500}})$ is well correlated to the change in TC frequency we consider this as support for the picture that the overall level of convective activity in regions otherwise favorable for genesis controls the changes in TC frequency. The question of whether this index is affected by the TC change itself is addressed briefly by Held and Zhao (2011) where they conclude that the effect is minor in most regions, with the East Pacific being a possible exception. In general, $(\overline{\omega_{500}})$ appears to explain reasonably well changes in global TC frequency for most models although there are some exceptions. For example, a stronger reduction of global TC frequency to CO_2 doubling compared to 2K warming is qualitatively captured by changes in $(\overline{\omega_{500}})$ for most models (except GFS and HIRAM). Most models (except CAM5H) showing insignificant changes to 2K warming also display a smaller reduction in fractional change of $(\overline{\omega_{500}})$. However, $(\overline{\omega_{500}})$fails to explain the GFS results that show a larger reduction (a nominal increase) in global TC frequency despite a nominal increase (large reduction) in fractional change of $(\overline{\omega_{500}})$ for the P2K $(2xCO_2)$ experiment. These inconsistencies imply that there are other factors besides changes in overall convective activity that affect TC frequency.

To examine the changes in geographic distribution of TC genesis frequency caused by P2K and/or $2xCO_2$, we bin the local TC genesis frequencies from each experiment into 4°×5° (lattitude x longitude) grid boxes that cover the entire global tropical ocean. The responses to each perturbation are obtained by taking the differences between the results of the perturbation and control experiments. The multi-model ensemble mean changes are then computed by averaging the results from all seven models. Figs. 3a-c show the ensemble mean changes for the P2K, $2xCO_2$, and BOTH cases respectively. The stippled areas denote the grid-boxes where five of the seven models agree on the sign of the change in frequency.

For P2K, regional changes in TC genesis frequency are far from uniform and consist of areas of both increased and decreased TC

are due entirely to P2K. Comparing the figures, it is evident that the direct effect of increased atmospheric CO_2 concentration can strongly affect both global and regional changes in TC frequency. This effect appears to be more robust across models than that caused by P2K.

To understand the regional changes in TC genesis frequency, Figs. 3d-f show similar plots as Figs. 3a-c except the differences in TC genesis frequency are replaced by changes in $\overline{\omega_{500}}$. For convenience, we show the negative value of the changes (i.e., $-\Delta\overline{\omega_{500}}$) to make it easier to compare with Figs. 3a-c since a positive (negative) value in Figs. 3d-f indicates an increase (decrease) in upward mass flux and therefore would suggest an increase in TC genesis frequency. Despite some detailed regional differences, there are general similarities between the broad patterns in changes in TC genesis frequency and changes in $\overline{\omega_{500}}$. For example, in the case of P2K, the increase in TC genesis in the eastern North Pacific, part of the North Atlantic MDR and Caribbean Sea, the western portion of the West Pacific, the south-eastern portion of the South Indian Ocean, and near the dateline of the South Pacific are in reasonable agreement to the enhanced convective mass flux over those regions.

Similarly, for the $2xCO_2$ case, the reductions in TC genesis over most of the tropical oceans correspond well to reductions in convective mass flux. The large increase in TC genesis frequency north of Australia and in part of the South Pacific is also consistent with an increase in large-scale convective mass flux. Furthermore, the increase in TC genesis in the Bay of Bengal and Caribbean Sea in the BOTH case can also be explained by local changes in $\overline{\omega_{500}}$. Therefore, $\overline{\omega_{500}}$ appears to be a good index for explaining regional and global TC genesis frequency for most of the models examined here. We have also conducted similar analysis using different environmental variables (e.g., vertical wind shear, humidity). We found that $\overline{\omega_{500}}$ is the best among these variables in explaining global and regional changes in TC genesis frequency, which is consistent with the results in Held and Zhao (2011).

Despite many years of research on TC genesis processes and various environmental factors known to be important, a complete theory remains to be developed to understand the climate control of TC genesis frequency. The GCM-simulated TC frequency response to an isolated increase in SSTs and CO_2 concentration provide additional cases for testing theories as well as empirically-based TC genesis potential indices (Camargo et al. 2013). In the literature, several hypotheses have been proposed to explain the simulated global reduction in TC frequency to warming. They include: 1) an increase in the saturation deficit of mid-troposphere (e.g., Emanuel et al. 2008); 2) a weakening of the tropical circulation due to an increase in upper tropospheric static stability and a decrease in the upward convective mass flux (e.g., Yoshimura and Sugi 2005; Bengtsson et. al 2007; Chauvin et al. 2006; Gualdi et al. 2008; Held and Zhao 2011). These hypotheses may be interrelated and describe intrinsic components and signals of global warming. The results obtained by studying the individual cases of P2K and $2xCO_2$ may help distinguish the different hypotheses. For example, an increase in mid-tropospheric saturation deficit is expected to be much larger in the P2K scenario than in the $2xCO_2$ scenario. Yet, the models produce more robust and stronger reductions when $2xCO_2$ is applied. Thus, these results do not support the hypothesis that the saturation deficit is the key in determining the response of global TC frequency.

In comparison, the different results from P2K and $2xCO_2$ are consistent with the hypothesis that the upward mass flux in TC development regions are key to understanding the simulated global and regional TC frequency response to a change in climate condition. An increase in atmospheric CO_2 concentration may reduce large-scale convective mass flux over TC development regions through two super-imposing components. First, it weakens tropical large-scale convective overturning motion by weakening the atmospheric radiative cooling at the subsiding branch of the circulation (Held and Zhao 2011; Bony et al. 2013). Second, it alters large-scale distribution of tropical convection by enhancing it over land and diminishing it over the ocean (Bony et al. 2013). Both components act to reduce the global TC frequency, resulting in a robust reduction across the models. However, the two components do not act in the same direction in a P2K experiment. A reduction in tropical mean convective mass flux is also expected in a P2K experiment owing to a larger increase in boundary layer moisture than the increase of atmospheric radiative cooling rate (Held and Soden 2006). The increase in upper tropospheric static stability also leads to a weakening of tropical large-scale circulation (Vecchi et al. 2006). This should lead to a reduction in global TC frequency. However, the SST increases tend to alter the distribution of convection between land and ocean in an opposite way to that caused by CO_2 increases. It moves a significant amount of convection from tropical land to tropical oceans and therefore reduces the potential decreases in global TC frequency due to the other component. This is very likely the cause of the weaker and less robust reduction of global TC frequency response to SST increases among the models.

The hypothesis that the overall convective activity in TC development regions may largely control TC genesis frequency is also consistent with recent studies on changes in regional TC frequency in response to different patterns of SST warming (e.g., Zhao and Held 2012; Murakami et al. 2012) as well as the concept that relative SST is important in modulating regional TC frequency. Held and Zhao (2011) provide a discussion on how changes in convective mass flux might alter genesis frequency in regions that are otherwise favorable for genesis.

Acknowledgements
M. Wehner (LBNL) was supported by the Regional and Global Climate Modeling Program of the Office of Biological and Environmental Research in the Department of Energy Office of Science under contract number DE-AC02-05CH11231.

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U.S. CLIVAR acknowledges support from these U.S. agencies:

This material was developed with federal support of NASA (AGS-093735), NOAA (NA06OAR4310119), NSF (AGS-0926904), and DOE (AGS-1357212). Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsoring agencies.