Hurricanes and climate: the U.S. CLIVAR working group on hurricanes

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High-resolution climate models can now simulate many aspects of tropical cyclone climate, but a theory of tropical cyclone formation remains elusive.

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Abstract

While a quantitative climate theory of tropical cyclone formation remains elusive, considerable progress has been made recently in our ability to simulate tropical cyclone climatologies and understand the relationship between climate and tropical cyclone formation. Climate models are now able to simulate a realistic rate of global tropical cyclone formation, although simulation of the Atlantic tropical cyclone climatology remains challenging unless horizontal resolutions finer than 50 km are employed. This article summarizes published research from the idealized experiments of the Hurricane Working Group of U.S. CLIVAR (CLImate VARiability and predictability of the ocean-atmosphere system). This work, combined with results from other model simulations, has strengthened relationships between tropical cyclone formation rates and climate variables such as mid-tropospheric vertical velocity, with decreased climatological vertical velocities leading to decreased tropical cyclone formation. Systematic differences are shown between experiments in which only sea surface temperature is increased versus experiments where only atmospheric carbon dioxide is increased, with the carbon dioxide experiments more likely to demonstrate the decrease in tropical cyclone numbers previously shown to be a common response of climate models in a warmer climate. Experiments where the two effects are combined also show decreases in numbers, but these tend to be less for models that demonstrate a strong tropical cyclone response to increased sea surface temperatures. Further experiments are proposed that may improve our understanding of the relationship between climate and tropical cyclone formation, including experiments with two-way interaction between the ocean and the atmosphere and variations in atmospheric aerosols.

Introduction

The effect of climate change on tropical cyclones has been a controversial scientific issue for a number of years. Advances in our theoretical understanding of the relationship between climate and tropical cyclones have been made, enabling us to understand better the links between the mean climate and the potential intensity (PI; the theoretical maximum intensity of a tropical cyclone for a given climate condition) of tropical cyclones. Improvements in the capabilities of climate models, the main tool used to predict future climate, have enabled them to achieve a considerably improved and more credible simulation of the present-day climatology of tropical cyclones. Finally, the increasing ability of such models to predict the interannual variability of tropical cyclone formation in various regions of the globe indicates that they are capturing some of the essential physical relationships governing the links between climate and tropical cyclones.

Previous climate model simulations, however, have suggested some ambiguity in projections of future numbers of tropical cyclones in a warmer world. While many models have projected fewer tropical cyclones globally (Sugi et al. 2002; Bengtsson et al. 2007a; Gualdi et al. 2008; Knutson et al. 2010), other climate models and related downscaling methods have suggested some increase in future numbers (e.g. Broccoli and Manabe 1990; Haarsma et al. 1993; Emanuel 2013a). When future projections for individual basins are made, the issue becomes more serious: for example, for the Atlantic basin there appears to be little consensus on the future number of tropical cyclones (Knutson et al. 2010) or on the relative importance of forcing factors such as aerosols or increases in carbon dioxide (CO_2) concentration. One reason could be statistical: annual numbers of tropical cyclones in the Atlantic are relatively small, making the identification of such storms sensitive to the detection method used.

Further, there is substantial spread in projected responses of regional tropical cyclone (TC) frequency and intensity over the 21st century from downscaling studies (Knutson et al. 2007; Emanuel 2013a). Interpreting the sources of those differences is complicated by different projections of large-scale climate, and by differences in the present-day reference period and sea surface temperature (SST) datasets used. A natural question is whether the diversity in responses to projected 21st century climate of each of the studies is primarily a reflection of uncertainty arising from different large-scale forcing (as has been suggested by, e.g., Villarini et al. 2011; Villarini and Vecchi 2013b; Knutson et al. 2013) or whether this spread reflects principally different inherent sensitivities across the various downscaling techniques, even including different sensitivity of responses within the same model due to, for instance, the use of different convective parameterizations (Kim et al. 2012). A similar set of questions relate to the ability of models to generate observed changes in TC statistics when forced with a common forcing dataset.

The preceding questions motivated the design of a number of common idealized experiments to be simulated by different atmospheric general circulation models. Following on from experiments described in Yoshimura and Sugi (2005), Held and Zhao (2011) have designed a series of experiments using a high-resolution global atmospheric model (HiRAM): using present-day climatological, seasonally-varying monthly SSTs (that is, the same climatological monthly-average seasonal cycle of SSTs repeating every year; the “climo” experiment); specifying interannually-varying monthly SSTs (monthly SSTs that vary from year to year, as observed; “amip”); application of a uniform warming of 2K added to the climatological SST values (“2K”); employing SSTs at their climatological values but where the CO_2 concentration was doubled in the atmosphere (“2CO2”); and an experiment with a combined uniform 2K SST increase and doubled carbon dioxide (“2K2CO2”). The purpose of these common experiments is to determine whether responses would be robust across a number of different, high-resolution climate models (see Table 1). This would then establish better relationships between climate forcings and tropical cyclone occurrence, a key goal in work towards the development of a climate theory of tropical cyclone formation. To facilitate this goal, U.S. CLIVAR established the Hurricane Working Group (HWG). Another goal of this group is to provide a synthesis of current scientific understanding of this topic. The following sections summarize our understanding of climate controls on tropical cyclone formation and intensity and the results of the HWG experiments analyzed to date, as well as other issues such as tropical cyclone rainfall. The focus of this work is on tropical cyclone formation, due to the very fine horizontal resolutions needed to generate good simulations of tropical cyclone climatological intensity distributions. A concluding section outlines avenues for further research.

Tropical cyclone formation

At present, there is no climate theory that can predict the formation rate of tropical cyclones from the mean climate state. It has been known for many years that there are certain atmospheric conditions that either promote or inhibit the formation of tropical cyclones, but so far an ability to relate these quantitatively to mean rates of tropical cyclone formation has not been achieved, other than by statistical means through the use of semi-empirically-based genesis potential indices (GPIs; see, for instance, Menkes et al. 2012). Increasingly, numerical models of the atmosphere are being used to pose the kind of questions that need to be answered to address this issue.

The ability of climate models to simulate the present-day tropical cyclone climatology

A starting point for the simulation of changes in TC climatology is the ability of climate models (often known as general circulation models; GCMs) to simulate the current climatology of TCs in the "climo" HWG experiment or other similar current-climate simulations. In the HWG climo experiment, Figure 1 shows the simulated global TC numbers range from small values to numbers similar to observed (Zhao et al. 2013a; Shaevitz et al. 2014). Better results can also be obtained from higher-resolution versions of the HWG models (finer than 50 km horizontal resolution), including an ability to generate storms of intense tropical cyclone strength, as shown by Wehner et al. (2014a) for a higher-resolution version of the NCAR-CAM5 model than that shown in Fig. 1. In addition, the tropical cyclone formation rate in the GSFC-GEOS5 model as shown in Fig. 1 has been improved following the development of the new version of the model (see Figure 4 in Shaevitz et al. 2014).

The annual cycle of formation is reasonably well simulated in many regions, although there is a tendency for the amplitude of the simulated annual cycle to be less than observed. A common factor in many such model assessments is the poorer performance at simulating Atlantic tropical cyclone formation than for other basins, although recent finer-resolution models give an improved simulation. Figure 2 illustrates this point, showing Atlantic results from Mei et al. (2014), from a 25-km resolution version of the HiRAM model, demonstrating the performance of this higher-resolution version of the model. Strachan et al. (2013) also found that the observed inter-hemispheric asymmetry in tropical cyclone formation, with Northern Hemisphere formation rates being roughly twice those in the Southern Hemisphere, was not well captured by a high-resolution GCM.

Why do GCMs generally produce a decrease in future global tropical cyclone numbers?

Most GCM future projections indicate a decrease in global tropical cyclone numbers, particularly in the Southern Hemisphere: Knutson et al. (2010) give decreases in the Northern Hemisphere ranging from roughly zero to 30%, and in the Southern Hemisphere from 10 to 40%. Previous explanations of this result have focused on changes in tropical stability and the associated reduction in climatological upward vertical velocity (Sugi et al. 2002, 2012; Oouchi et al. 2006; Held and Zhao 2011) and on increased mid-level saturation deficits (drying) (e.g. Rappin et al. 2010). In this argument, the tropical cyclone frequency reduction is associated with a decrease in the convective mass flux and an overall related decrease in tropical cyclone numbers. Zhao et al. (2013a) compare the HWG model responses for the various simulations, using the Geophysical Fluid Dynamics Laboratory (GFDL) tropical cyclone tracking scheme (Knutson et al. 2008; Zhao et al. 2009). They find that most of the models show decreases in global tropical cyclone frequency for the 2CO2 run of 0-20%. The changes in TC numbers are most closely related to 500 hPa vertical velocity, with Figure 3 showing close agreement between changes in tropical cyclone formation and changes in this variable. Here, Figure 3b shows the annual mean vertical velocity as an average of monthly mean vertical velocity weighted by monthly climatological TC genesis frequency over each 4°×5° (latitude by longitude) grid box from the control simulation. This relationship between TC frequency and vertical velocity was the closest association found among a suite of analyzed variables that included precipitation, 600 hPa relative humidity and vertical wind shear. In addition, Camargo et al. (2014) use a number of GPIs applied to the output of the GFDL HiRAM model to show that in order to explain the reduction in TC frequency, it is necessary to include saturation deficit and potential intensity in the genesis index. While the response of the models in the other HWG experiments is more ambiguous, no model generated a substantial increase in global TC frequency for any experiment.

The simulated decrease in global tropical cyclone frequency does not appear to be sensitive to the use of a particular parameterization scheme for convection. Murakami et al. (2012) use a 60-km horizontal resolution version of the MRI atmospheric GCM to demonstrate that patterns of future SST change appear more important in causing future changes in tropical cyclone numbers rather than the choice of the convective parameterization used in their suite of experiments. As the resolution of climate models becomes finer, the need for convective parameterization will become less as microphysical representations of convective processes become more appropriate. Oouchi (2013) has reported simulations of tropical cyclones using a global non-hydrostatic model (NICAM) run without convective parameterization. It is anticipated that this type of simulation will become increasingly important in the future (e.g. Yamada and Satoh 2014).

The HWG experiments are atmosphere-only climate model experiments and do not include an interactive ocean. In general, however, ocean-atmosphere coupled climate models tend to give similar results to uncoupled atmospheric climate models' results in their response to an imposed greenhouse-induced climate change. Kim et al. (2014), using the GFDL CM2.5 coupled model at a horizontal atmospheric resolution of about 50 km, also note a strong link in their model simulations between decreases in tropical cyclone occurrence and decreases in upward mid-tropospheric vertical velocity in tropical cyclone formation regions. Like the atmosphere-only models, they also simulate too few storms in the Atlantic. The response to increased CO_2 in their model is a substantial decrease in tropical cyclone numbers in almost all basins. Other future changes include a slight increase in storm size, along with an increase in tropical cyclone rainfall. In the coordinated CMIP5 (Taylor et al. 2012) coupled ocean-atmosphere model experiments, while there is a significant increase in TC intensity (Maloney et al. 2013), TC frequency changes are not as robust and are dependent on tracking scheme (Camargo 2013, Tory et al. 2013a, Murakami et al. 2014).

Not all methods for determining TC numbers identify a decrease in future numbers, however. Emanuel (2013a,b) uses a downscaling method in which incipient tropical vortices are "seeded" into large-scale climate conditions provided from a number of different climate models, for current and future climate conditions. The number of "seeds" provided to each set of climate model output is tuned so that the model in question reproduces the observed number of tropical cyclones (about ninety) in the current climate. This same number of seeds is then provided for the future climate conditions generated by the climate models. In contrast to many models, this system generates more tropical cyclones in a warmer world when forced with the output of climate models running the CMIP5 suite, even when the host CMIP5 model itself produces reduced TC frequency (Camargo 2013; Tory et al. 2013a; Murakami et al. 2014). Analogous results are produced by the same methodology using climate fields from selected HWG model outputs (Figure 4).

In the HWG experiments, simulated tropical cyclone numbers are most likely to have a small decrease in the 2K2CO2 experiment, with a clear majority of models indicating this (Fig. 3). Numbers are also considerably more likely to decrease in the 2CO2 experiment, but in the 2K experiment, there is no genuine preferred direction of future numbers. Overall, the tendency of decreases in tropical cyclone numbers to be closely associated with changes in mid-tropospheric vertical velocity suggests a strong connection between the two, and one that many other future climate model projections of tropical cyclone numbers also demonstrate. Note that increased saturation deficit, another variable shown to be related to decreases in tropical cyclone numbers, might be expected to accompany a decrease in vertical velocity over the oceans.

Do the new generation of higher-resolution climate models simulate tropical cyclones in the North Atlantic better? Do they simulate a similar tropical cyclone response to climate change, thus giving more confidence in our prediction?

While most models predict fewer tropical cyclones globally in a warmer world, the difference in the model response becomes more significant when smaller regions of the globe are considered. This appears to be a particular issue in the Atlantic basin, where climate model performance has been often poorer than in other formation basins (e.g., Camargo et al. 2005, Walsh et al. 2013, Camargo 2013, Tory et al. 2013). Since good model performance in simulating the current climate has usually been considered an essential pre-condition for the skilful simulation of future climate, this poor Atlantic performance poses an issue for the confidence of future tropical cyclone climate in the Atlantic region.

The most recent climate models have begun to simulate this region better, however, most likely due to improved horizontal resolution (Manganello et al.2012; Strachan et al. 2013; Roberts et al.,2014; Zarzycki and Jablonowski 2014). Best results appear to be achieved at horizontal resolutions finer than 50 km. Roberts et al. (2014) suggest that this may be related to the ability of the higher resolution models to generate easterly waves with higher values of vorticity than at lower resolution (see also Daloz et al. 2012a). Zhao et al. (2013) note that more than one of the HWG models produced a reasonable number of tropical cyclones in the Atlantic. Even so, Daloz et al. (2014) showed that the ability of the HWG models to represent the clusters of Atlantic tropical cyclones tracks is inconsistent and varies from model to model, especially for the tracks with genesis over the eastern part of the basin.

Knutson et al. (2013) and Knutson (2013) employ the ZETAC regional climate model and global HiRAM model, combined with the GFDL hurricane model, to show that in addition to simulating well the present-day climatology of tropical cyclone formation in the Atlantic, they are also able to simulate a reasonably realistic distribution of tropical cyclone intensity. Manganello et al. (2012) showed a similar ability in a high-resolution GCM (see below for more on intensity). These simulations mostly show a decrease in future numbers of Atlantic storms.

Substantial increases in observed Atlantic tropical cyclone numbers have already occurred in the past 20 years, likely driven by changes in the Atlantic Meridional Mode (AMM; Servain et al. 1999; Vimont and Kossin 2007; Kossin et al. 2010) on decadal time scales and the Atlantic Multidecadal Oscillation (AMO; Delworth and Mann, 2000) on multi-decadal timescales. A number of detailed explanations of changes in TC numbers related to these climate variations have been suggested, ranging from changes in upper-tropospheric temperatures (Emanuel et al. 2013, Vecchi et al. 2013) to the "relative-SST" argument of Vecchi and Soden (2007), namely that increases in TC numbers are related to whether local SSTs are increasing faster than the tropical average. Changes in tropospheric aerosols have also been implicated (Villarini and Vecchi 2013b). Camargo et al. (2013) and Ting et al. (2013, 2014) show that the effect of Atlantic SST increases alone on Atlantic basin potential intensity is considerably greater than the effect on Atlantic basin PI of global SST changes. Figure 5 shows that regression coefficients that indicate the strength of this relationship are considerably larger for SSTs forced by the AMO (left panels) than for the global climate change signal (right panels), for a range of both current climate and future climate simulations. This suggests that increases in local PI are likely related to whether the local SST is increasing faster than the global average or not. Ting et al. (2014) show that by the end of this century, the change in PI due to climate change should dominate the decadal variability signal in the Atlantic, but that this climate change signal is not necessarily well predicted by the amplitude in the relative SST signal. Knutson (2013) finds that relative SST appears to explain the predicted evolution of future Atlantic TC numbers reasonably well (see also Villarini et al. 2011).

The issue of the relative importance of large-scale climate variations for tropical cyclone formation in the Atlantic region is related to the ability of dynamical seasonal forecasting systems to predict year-to-year tropical cyclone numbers in the Atlantic. In general, despite the challenges of simulating tropical cyclone climatology in this basin, such models have good skill in this region (LaRow et al. 2011; Schemm and Long 2013; Saravanan et al. 2013).

This skill is clearly assisted by models being well able to simulate the observed interannual variability of tropical cyclone formation in this region, as shown by Emanuel et al. (2008), LaRow et al. (2008), Knutson et al. (2007), Zhao et al. (2009), LaRow et al. (2011), Knutson (2013), Patricola et al. (2014), Roberts et al. (2014) and Wang et al. (2014). This suggests that tropical cyclone formation in the Atlantic basin is highly related to the climate variability of the environmental variables in the basin rather than to the stochastic variability of the generation of precursor disturbances in the basin. This also suggests that provided the challenge of simulating the tropical cyclone climatology in this region can be overcome, and provided that the relative contributions of the existing substantial decadal variability and the climate change signal can be well quantified, simulations in this basin may achieve more accurate predictions of the effect of climate change on tropical cyclone numbers.

While the Atlantic basin has been a particular focus of this work, the basin with the greatest annual number of tropical cyclones is the northwest Pacific. The HWG simulations mostly show decreases in numbers in this basin for the 2K2CO2 experiment. This is in general agreement with results from previous model simulations of the effect of anthropogenic warming on tropical cyclone numbers. Some recent results for predictions in other regions of the globe suggest some consensus among model predictions. For instance, Li et al. (2010), Murakami et al. (2013), Murakami et al. (2014), Kim et al. (2014) and Roberts et al. (2014) suggest that the region near Hawaii may experience an increase in future tropical cyclone numbers. Walsh et al. (2013) and Zhao et al. (2013) indicate that HWG and other model projections tend to produce more consistent decreases in TC numbers in the Southern Hemisphere than in the Northern Hemisphere. The cause of this interhemispheric inhomogeneity is currently uncertain but it is speculated that it is due to fundamental differences caused by the land-sea distribution in the two hemispheres.

What is the tropical cyclone response of climate models to an imposed, common increase in SST? How sensitive is the simulation of tropical cyclone variability to differences in SST analysis?

Previous work has shown that tropical cyclone numbers decrease in response to the imposition of a uniform ocean warming (Yoshimura and Sugi 2005; Held and Zhao 2011). The relevant experiment here is the 2K experiment of the HWG modelling suite. In general, of those HWG models that generate a substantial number of tropical cyclones, slightly more models show global numbers that decrease rather than increase, although the difference is not large.

Some insight has been previously provided into the issue of the sensitivity of GCM results to the specification of the forcing SST data set. Po-Chedley and Fu (2012) conduct an analysis of the CMIP5 AMIP simulations and it is noted that the HWG models participating in the CMIP5 AMIP experiments used a different SST data set (HadISST, Rayner et al. 2003 – the one used for the HWG experiments) than the one recommended for the CMIP5 AMIP experiments (the "Reynolds" data set; Reynolds et al. 2002). These HWG models have a weaker and more realistic upper tropospheric warming over the historical period of the AMIP runs, suggesting that there is some sensitivity to the specification of the SST data sets. This difference in SST data sets could conceivably have an effect on tropical cyclones in these models, through changes in either formation rates due to changes in stability or through changes in intensity caused by effects on PI. This issue remains unresolved at present.

How does the role of changes in atmospheric carbon dioxide differ from the role played by SSTs in changing tropical cyclone characteristics in a warmer world?

The HWG experiments indicate that it was more likely for tropical cyclone numbers to decrease in the 2CO2 experiments than in the 2K experiments (Fig. 3a). Zhao et al. (2013a) show that, for several of the HWG models, decreases in mid-tropospheric vertical velocity are generally larger for the 2CO2 experiments than for the 2K experiments (Fig. 3b). For the 2CO2 experiment, the decrease in upward mass flux has previously been explained by Sugi and Yoshimura (2004) as being related to a decrease in precipitation caused by the decrease in radiative cooling aloft. This is caused by the overlap of CO2 and water vapour absorption bands, whereby an increase in CO2 will reduce the dominant radiative cooling due to water vapor. This argument assumes that tropical precipitation rates are controlled by a balance between convective heating and radiative cooling (Allen and Ingram 2002). The simulated decrease in precipitation was combined with little change in stability. In contrast, in their 2K experiment, precipitation increased but static stability also increased, which was attributed to a substantial increase in upper troposphere temperature due to increased convective heating. Yoshimura and Sugi (2005) note that these effects counteract each other and may lead to little change in the upward mass flux, thus leading to little change in tropical cyclone formation rates for the 2K experiment, as seen in their results. A thorough analysis of the HWG experiments along these lines has yet to be performed, however.

The 2K and 2CO2 may also have different effects on the intensity of storms. If fine-resolution models are used, it is possible to simulate reasonably well the observed distribution of intensity (see below). The model resolutions of the HWG experiments are in general too coarse to produce a very realistic simulation of the observed tropical cyclone intensity distribution. Nevertheless, some insight into the overall effects of these forcings on intensity of storms can be obtained, particularly when compared with the almost resolution-independent PI theory. First, Held and Zhao (2011) showed that one of the largest differences between the results of the 2K and 2CO2 experiments conducted for that paper was that PI increased in the 2K experiments but decreased in the 2CO2 experiment, due to the relative changes in surface and upper tropospheric temperatures in the two cases. In addition, directly-simulated intense tropical cyclone (hurricane) numbers decrease more as a fraction of their total numbers in the 2CO2 experiment than they did in the 2K experiment, consistent with the PI results. A similar behavior is seen in the HWG experiments, although apart from the HiRAM model results, there is a general suppression of storms across all intensity categories rather than a preferential suppression of hurricane-intensity storms (Zhao et al., 2013a). In contrast, previous model simulations at higher resolutions than employed for the HWG experiments have tended to indicate an increase in the number of more intense storms (e.g. Knutson et al. 2010).

How does air-sea interaction modify the climate response of tropical cyclones?

If the SST field from a coupled ocean atmosphere is applied as the lower boundary condition for a specified-SST "time slice" AGCM run, it has been shown previously that the resulting atmospheric climate differs from the original atmospheric climate of the corresponding coupled ocean-atmosphere model run (Timbal et al. 1997). Thus, the presence of air-sea interaction itself appears to be important for the generation of a particular climate.

This issue is not addressed directly through the design of the HWG experiments. Emanuel and Sobel (2013) show by an analysis of thermodynamic parameters associated with tropical cyclone intensity that SST should not be considered a control variable for tropical cyclone intensity on time scales longer than about two years, rather it is a quantity that tends to co-vary with the same control variables (surface wind, surface radiative fluxes, and ocean lateral heat fluxes) that control potential intensity. Thus it can be argued that simulations that used specified SSTs risk making large errors in potential intensity, related to their lack of surface energy balance. Nevertheless, Kim et al. (2014) use the GFDL coupled model running at a resolution of 50 km to show that the inclusion of coupling does not necessarily change the direction of the tropical cyclone frequency response. As a result, these runs also show decreases in the global number of tropical cyclones and also under-simulate current climate numbers in the Atlantic. It is noted that this might be due to a cold bias in the SST simulation in the Atlantic. Daloz et al. (2012b), using a stretched configuration of CNRM-CM5 with a resolution of up to 60 km over the Atlantic, also showed an underestimate of tropical cyclone activity when coupling was introduced.

Are the results sensitive to the choice of cyclone tracking scheme?

An essential first step in the analysis of any tropical cyclone detection scheme is to select a method for detecting and tracking the storms in the model output. A number of such schemes have been developed over the years; they share many common characteristics but also have some important differences. They fall into five main categories, although some schemes contain elements of more than one category:

(1) Structure-based threshold schemes, whereby thresholds of various structural parameters are set based on independent information, and storms detected with parameter values above these thresholds are declared to be tropical cyclones (e.g., Walsh et al. 2007);
(2) Variable threshold schemes, in which the thresholds are set so that the global number of storms generated by the model is equal to the current-climate observed annual mean (e.g. Murakami et al. 2011);
(3) Schemes in which model output is first interpolated onto a common grid before tracking (e.g., the feature tracking scheme of Bengtsson et al. 2007b; Strachan et al. 2013);
(4) Model-threshold dependent schemes, in which the detection thresholds are adjusted statistically, depending upon the formation rate in a particular model, originally

developed for seasonal forecasting with basin-dependent thresholds (e.g., Camargo and Zebiak 2002); and

(5) Circulation based schemes, in which regions of closed circulations and enhanced vorticity with low deformation are identified based on the Okubo-Weiss-Zeta diagnostic (Tory et al. 2013b).

It is possible to make arguments for and against each type of scheme, but clearly the change in tropical cyclone numbers of the climate model simulations should not be highly dependent on the tracking scheme used, and if the direction of the predicted change is sensitive to this, this would imply that the choice of the tracking scheme is another source of uncertainty in the analysis. To examine this issue, results from the HWG simulations are compared for different tracking schemes. In general, after correction is made for differences in user-defined thresholds between the schemes, there is much more agreement than disagreement on the sign of the model response between different tracking schemes (Horn et al. 2014; Fig. 6). Nevertheless, it is possible to obtain a different sign of the response for the same experiment by using a different tracking scheme. In the case of CMIP5 models, changes in TC frequency in future climates was clearly dependent on the tracking routine used, especially for the models with poor TC climatology (see Camargo 2013, Tory et al. 2013a, Murakami et al. 2014). This could simply be a sampling issue caused by insufficient storm numbers in the various intensity categories rather than any fundamental difference between the model responses as estimated by the different tracking schemes or the effect of user-specific threshold detection criteria. This may still imply that results from such simulations should be examined using more than one tracking scheme.

Climatological controls on formation

It has been recognized for some time that one consequence of a warmer climate is an increase in the typical threshold of the initiation of deep convection, a precursor of tropical cyclone formation (Dutton et al. 2000; Evans and Waters 2012; Evans 2013). This threshold varies within the current climate as well (Evans 2013). The search for relevant diagnostics of tropical cyclone formation that can be derived from the mean climate has led to the formulation of GPI parameters that statistically relate tropical cyclone formation to climatological mean values of parameters that are known to influence tropical cyclone formation (Gray 1979; Royer et al. 1998; Emanuel and Nolan 2004; Emanuel 2010; Tippett et al. 2011; Bruyère et al. 2012; Menkes et al. 2012; Korty et al. 2012). GPIs usually include values of atmospheric variables such as vertical wind shear, PI, mid-tropospheric relative humidity and SST. Another large-scale environmental factor that should be considered is the ventilation, the import of cooler, drier air, which was shown to have an important influence in both tropical cyclogenesis and intensification (Tang and Emanuel 2012). Changes in TC frequency in future climates have also been related to the ventilation index for the CMIP5 models (Tang and Camargo 2014).

The potential of such a technique is obvious: it could serve as a diagnostic tool to determine the reasons for changes in tropical cyclone numbers in a particular climate simulation, without the need to perform numerous sensitivity experiments, or (ultimately) it could enable the diagnosis of changes in tropical cyclone formation rate from different climates without the need to run a high-resolution GCM to simulate the storms directly, similar to what was done in the present climate for diagnostics of TC genesis modulation by the El Niño-Southern Oscillation (Camargo et al. 2007a) and the Madden-Julian Oscillation (Camargo et al. 2009). Korty et al. (2013) and Korty et al. (2012a,b) show results where the GPI is used to diagnose the rate of tropical cyclone formation for a period 6,000 years before the present, showing considerable changes in GPI, with mostly decreases in the Northern Hemisphere and increases in the Southern Hemisphere. It is noted, however, that while GPIs appear to have some skill in estimating the observed spatial and temporal variations in the number of tropical cyclones (Menkes et al. 2012), there are still important discrepancies between their estimates and observations. In addition, there can be similar differences between GPI estimates and directly-simulated tropical cyclone numbers, which appears to be better in models with higher resolution (Camargo et al. 2007b; Walsh et al. 2013; Camargo 2013). A potential limitation of the GPI methodology for application to a different climate is that it is trained on present-day climate. This was demonstrated in the 25km version of the CAM5 GCM, where decreases in GPI estimated for the 2CO2 experiment were consistent with the direct simulation but increases in GPI estimated for the 2K and 2K2CO2 were inconsistent with the direct simulation of changes in tropical cyclone numbers (Wehner et al 2014b; see also Camargo 2013 and Camargo et al. 2014).

The role of idealized simulations in understanding the influence of climate on tropical cyclones is highlighted by Merlis et al. (2013). A series of idealized experiments with land areas removed (so-called “aquaplanet” simulations) show that the position of the Intertropical Convergence Zone (ITCZ) is crucial for the rate of generation of tropical cyclones. If the position of the ITCZ is not changed, a warmer climate leads to a decrease in tropical cyclone numbers, but a poleward shift in the ITCZ leads to an increase in tropical cyclone numbers. With a new generation of climate models being better able to simulate tropical cyclone characteristics, there appears to be increased scope for using models to understand fundamental aspects of the relationship between climate and tropical cyclones.

Sensitivity of results to choice of convection scheme

Murakami et al. (2012) shows experiments investigating the sensitivity of the response of TCs to future warming using time slice experiments. Decreases in future numbers of tropical cyclones are shown for all experiments irrespective of the choice of convection scheme. Note that there also appears to be a considerable sensitivity of tropical cyclone formation to the specification of the minimum entrainment rate (Lim et al. 2014). As this is decreased (equivalent to turning off the cumulus parameterization), the number of tropical cyclones increases. The sensitivity of the TC frequency to other convection scheme parameters (fractional entrainment rate and rate of rain reevaporation) was also shown in Kim et al. (2012) with the GISS model, with a larger entrainment rate causing fewer TCs but an increase in rain reevaporation substantially increasing TC numbers. One issue that needs to be examined is that an increase in tropical storm numbers due to changes in the convective scheme to more realistic values is not necessarily accompanied by an improvement in the simulation of the mean climate state. A similar issue occurs in the simulation of the intraseasonal variability in climate models, where there is a systematic relationship between the amplitude of the intraseasonal variability in the models and mean state biases in climate simulations (Kim et al. 2011).

Tropical cyclone intensity

Work in the past couple of decades has led to the generally accepted theory that the potential intensity of tropical cyclones (PI) can be quantified by thermodynamic arguments (Emanuel 1986; Emanuel 1988; Holland 1997; see also Knutson et al. 2010). While the focus of the HWG has been on numerical model simulation, the use of theoretical diagnostics such PI has been an important part of efforts to understand the results produced by the models.

Emanuel and Sobel (2011, 2013) outline some of the important unresolved theoretical issues related to maximum tropical cyclone intensity, including the physics of air-sea interaction at very high wind speeds, the existence and magnitude of super-gradient winds in the hurricane boundary layer, horizontal mixing by eddies, and the radial structure and characteristics of the outflow temperature (see also Wang et al. 2014; Ramsay 2014). In addition, most tropical cyclones do not reach their maximum intensities (Wing et al. 2007, Kossin and Camargo 2009), and while factors that inhibit their intensification are well known (e.g., vertical wind shear, dry mid-tropospheric air, and land surfaces), less certain is the precise quantitative response of tropical cyclones to changes in these quantities. Ideally, there should be a strong correspondence between the theoretical PI and the simulated maximum intensity of storms in a model climatology of tropical cyclones.

Simulation of the intensity distribution of tropical cyclones

While it is clear that simply increasing the resolution does not necessarily improve intensity distribution (Shaevitz et al. 2014), results from the HWG simulations indicate that a very significant improvement in a GCM's ability to simulate both TC formation and intensity occurs at resolutions finer than 50km, with good results shown at 25 km (Strachan et al. 2013; Roberts et al. 2014; Lim et al. 2014; Wehner et al. 2014b; Mei et al. 2014). In addition, if such high resolution is employed, it is possible to simulate reasonably well the observed intensity distribution of tropical cyclones (Bender et al. 2010; Lavender and Walsh 2011; Murakami et al. 2012; Knutson 2013; Chen et al. 2013; Zarzycki and Jablonowski 2014). Figure 7 illustrates this for the 25 km version of the CAM-SE model, with typical simulated wind speeds (red crosses) for intense storms being only slightly lower for the same central pressure than in the observations (blue crosses). This is due to the model at this resolution not being quite able to simulate pressure gradients that are as large as those observed. Nevertheless, Manganello et al. (2012) showed that there remained some discrepancies in the wind-pressure relationship between observations and even very high horizontal resolution (10 km) simulations.

Other issues

Future TC precipitation

Previous work has shown a robust signal of increasing amounts of precipitation per storm in a warmer world (Knutson and Tuleya 2004; Manganello et al. 2012; Knutson 2013; Kim et al. 2014; Roberts et al. 2014). The size of this signal varies a little between simulations, from approximately 10% to 30%. Knutson (2013) shows that this increase in precipitation close to the center of the storm appears to be greater than the Clausius-Clapeyron rate of 7% per degree of warming, due to the additional source of moisture supplied by the secondary circulation (inflow) of the tropical cyclone.

Villarini et al. (2014) and Scoccimarro et al. (2014) have investigated the response of precipitation from landfalling tropical cyclones in the HWG experiments (Fig. 8). Scoccimarro et al. (2014) find that compared to the present day simulation, there is an increase in TC precipitation for the scenarios involving SST increases. For the 2CO2 run, the changes in TC rainfall are small and it was found that, on average, TC rainfall for that experiment tends to decrease compared to the present day climate. The results of Villarini et al. (2014) also indicate a reduction in TC daily precipitation rates in the 2CO2 scenario, of the order of 5% globally, and an increase in TC rainfall rates when SST is increased, both in the 2K and 2K2CO2 runs, about 10-20% globally. The authors propose an explanation of the decrease in precipitation in the 2CO2 runs is similar to that described by Sugi and Yoshimura (2004) above, while the increases in the 2K runs are a result of increased surface evaporation.

A number of issues are identified for future work, including the need to stratify the rainfall rate by intensity categories and an examination of the extra-tropical rainfall of former TCs.

Novel analysis techniques

Strazzo et al. (2013a,b) present results in which a hexagonal regridding of the model output variables and tracks enable some analysis of their interrelationships to be performed efficiently. Once this is done for the HWG experiments, it is noted that one can define a “limiting intensity” that is the asymptotic intensity for high return periods. The sensitivity of this limiting intensity to SST is lower in the models than in the observations, perhaps a reflection of the lack of high-intensity storms in most HWG model simulations. This technique can also be used to establish performance metrics for the model output in a way that can be easily analyzed statistically.

Strazzo et al. (2013a, b) and Elsner et al. (2013) use this novel analysis technique to show that the sensitivity of limiting intensity to SST is 8 m/s/K in observations and about 2 m/s/K in the HiRAM and FSU models (Figure 9). They speculate that the lower sensitivity is due to the inability of the model-derived TCs to operate as idealized heat engines, likely due to unresolved inner-core thermodynamics that then limit the positive feedback process between convection and surface heat fluxes that is responsible for TC intensification. They further speculate that GCM temperatures near the tropopause do not match those in the real atmosphere, which would likely influence the sensitivity estimates.

Gaps in our understanding and future work

In summary, the HWG experiments have shown systematic differences between experiments in which only sea surface temperature is increased versus experiments where only atmospheric carbon dioxide is increased, with the carbon dioxide experiments more likely to demonstrate the decrease in tropical cyclone numbers previously shown to be a common response of climate models in a warmer climate. Experiments where the two effects are combined also show decreases in numbers, but these tend to be less for those models that demonstrate a strong tropical cyclone response to increase sea surface temperatures. Analysis of the results has established firmer links between tropical cyclone formation rates and climate variables such as mid-tropospheric vertical velocity, with decreased climatological vertical velocities leading to decreased tropical cyclone formation. Some sensitivity in the experimental results has been shown to the choice of tropical cyclone detection and tracking scheme chosen, suggesting that at the current state of the art, it would be useful to employ more than one tracking scheme in routine analysis of such experiments. Diagnosis of tropical cyclone rainfall in the experiments shows support for previously-proposed theoretical arguments that relate changes in warmer-world rainfall to the competing influences of increases in sea surface temperatures and increased carbon dioxide, providing further support for future projections of increased rainfall from tropical cyclones. Higher-resolution versions of some of the HWG models are now able to generate a good simulation of climatological Atlantic tropical cyclone formation, previously a difficult challenge for most models, and models of even higher resolution are now also able to simulate good climatological distributions of observed intensities.

A number of issues are identified by the HWG as requiring further investigation. The influence of the inclusion of an interactive ocean clearly is a further step needed to improve the realism of the results of the HWG experiments. Designing common experiments for models that include air-sea interaction is challenging, but may be aided by the addition of a simple slab or mixed-layer ocean with specific lateral fluxes to represent advective processes as a boundary condition. The inclusion of this simplified form of air-sea interaction will partially address the important issue of the inconsistency of the surface flux balance in experiments that employ specified SSTs and the resulting effects on variables such as potential intensity. Additionally, there is scope for the use of coupled ocean/atmosphere models in tropical cyclone simulation experiments (e.g. Vecchi et al. 2014). These experiments might be performed with or without selected modifications to the coupling methods, using so-called “partial coupling” (e.g. Ding et al. 2014), to enable a better understanding of how hurricanes influence the climate, as opposed to an understanding of how the climate influences hurricanes, as examined in the HWG experiments. There is also some scope for the use of ocean-only models in this topic (e.g. Vincent et al. 2012; Bueti et al. 2014).

A series of systematic experiments could be devised to examine the relative role of Atlantic versus global SST anomalies on the generation of tropical cyclones in the Atlantic basin (see Lee et al. 2011). Some results presented at the workshop indicate some support for the “relative SST” explanation of increases in tropical cyclone activity in the Atlantic in the past two decades, which could be further investigated by such experiments. A related topic is the relative role of future decadal and interannual variability in this basin when combined with the effects of anthropogenic warming. Patricola et al. (2014) investigate the possible effects of combinations of extreme phases of the AMM and ENSO. Figure 10 shows that strongly negative AMM activity, combined with strong El Niño conditions, inhibits Atlantic TC activity, but even with very positive AMM conditions, strong El Niño conditions still lead only to average Atlantic TC activity. Thus any future climate change projection would ideally need to include information on changes in the periodicity and amplitude of the AMM and ENSO. Similarly, a factor that is not investigated in the HWG experiments is the role of changing atmospheric aerosols in the Atlantic basin (e.g., Villarini and Vecchi 2013a,b). It would be possible to design a series of experiments to investigate this, similar to the HWG experiments.

Now that there is a critical mass of HWG experiments available for analysis, there may be some scope for using the experiments in an inter-comparison process, to determine if there are common factors that lead to improved simulations of both the mean atmospheric climate and of tropical cyclone climatology. This would be facilitated by the use of novel analysis techniques associating the changes in tropical cyclone occurrence simulated in these experiments with changes in fundamental climate variables, along the lines of those already established by existing analysis of the HWG suite. Strong links between changes in tropical cyclone formation rate and fundamental measures of tropical circulation, and stronger quantification of these links, will ultimately lead to a clearer understanding of the relationship between tropical cyclones and climate.

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Table 1: List of participating modeling centers, models, horizontal resolution and experiments performed.

Center	Model	Horizontal resolution (km at equator)	Experiments run
LBNL	CAM5.1	222, 111, 25	climo, amip, 2CO2, 2K,2K2CO2
CMCC	CMCC/ECHAM5	84	climo, 2CO2, 2K,2K2CO2
CNRM	CNRM	50	amip
FSU	FSU/COAPS	106	climo, amip, 2CO2, 2K
NOAA GFDL	HiRAM	50	climo, amip, 2CO2, 2K,2K2CO2
NOAA GFDL	C180AM2	50	climo, 2CO2, 2K,2K2CO2
NASA-GISS/Columbia	GISS	111	climo, amip, 2CO2, 2K,2K2CO2
NASA GSFC	GEOS5	56	climo, amip, 2CO2, 2KSST, 2K2CO2
Hadley Centre	HadGEM3	208	climo, 2K, 2CO2
Hadley Centre	HG3-N216	92	climo, 2K, 2CO2
Hadley Centre	HG3-N320	62	climo, 2K, 2CO2
JAMSTEC	NICAM	14	control and greenhouse runs
MRI	MRI-AGCM3.1H	50	amip-style, 2K, 2CO2 and greenhouse runs
NCEP	GFS	106	climo, amip, 2CO2, 2K,2K2CO2
TAMU	WRF	27	climo, amip, 2K2CO2
MIT	CHIPS (downscaling)	Variable	climo, 2CO2, 2K,2K2CO2

LBNL: Lawrence Livermore National Laboratories; CMCC: Centro Euro-Mediterraneo per i Cambiamenti Climatici; FSU: Florida State University; NOAA GFDL: National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory; NASA-GISS: NASA Goddard Institute for Space Studies; JAMSTEC: Japan Agency for Marine-Earth Science and Technology; MRI: Meteorological Research Institute of Japan; NCEP: National Centers for Environmental Prediction; TAMU: Texas A&M University; MIT: Massachusetts Institute of Technology

Figure Captions

Figure 1. Tropical cyclone formation rates from IBTrACS (Knapp et al. 2010) observations and the “climo” run of the HWG experiments, using the GFDL tropical cyclone tracking scheme: relative distribution (shaded) and total annual-mean numbers (in panel titles). From Zhao et al. (2013).

Figure 2. (a) Observed and (b) simulated geographical distribution of the climatological TC track density (unit: days per year) during the North Atlantic hurricane season calculated at each 8^{o}x8^{o} grid. From Mei et al. (2014).

Figure 3. Comparison between changes in (a) tropical cyclone formation for various models for the 2K (here labelled P2K) and 2CO2 experiments versus (b) TC genesis as weighted by changes in mid-tropospheric vertical velocity, as described in the text. From Zhao et al. (2013b).

Figure 4. Global tropical cyclone frequency using the downscaling methodology of Emanuel (2013) forced by climate fields derived from the HWG model output, for the HWG models and experiments as indicated.

Figure 5. Regression of PI on Atlantic Multidecadal Oscillation (left panels) and climate change signals for the CMIP5 multi-model ensemble (right panels), for historical and two future climate simulations using the rcp4.5 and rcp8.5 greenhouse gas emissions scenarios (van Vuuren et al. 2011). Units are $ms^{-1}K^{-1}$ of SST index (AMO or CMIP5). From Ting et al. (2014).

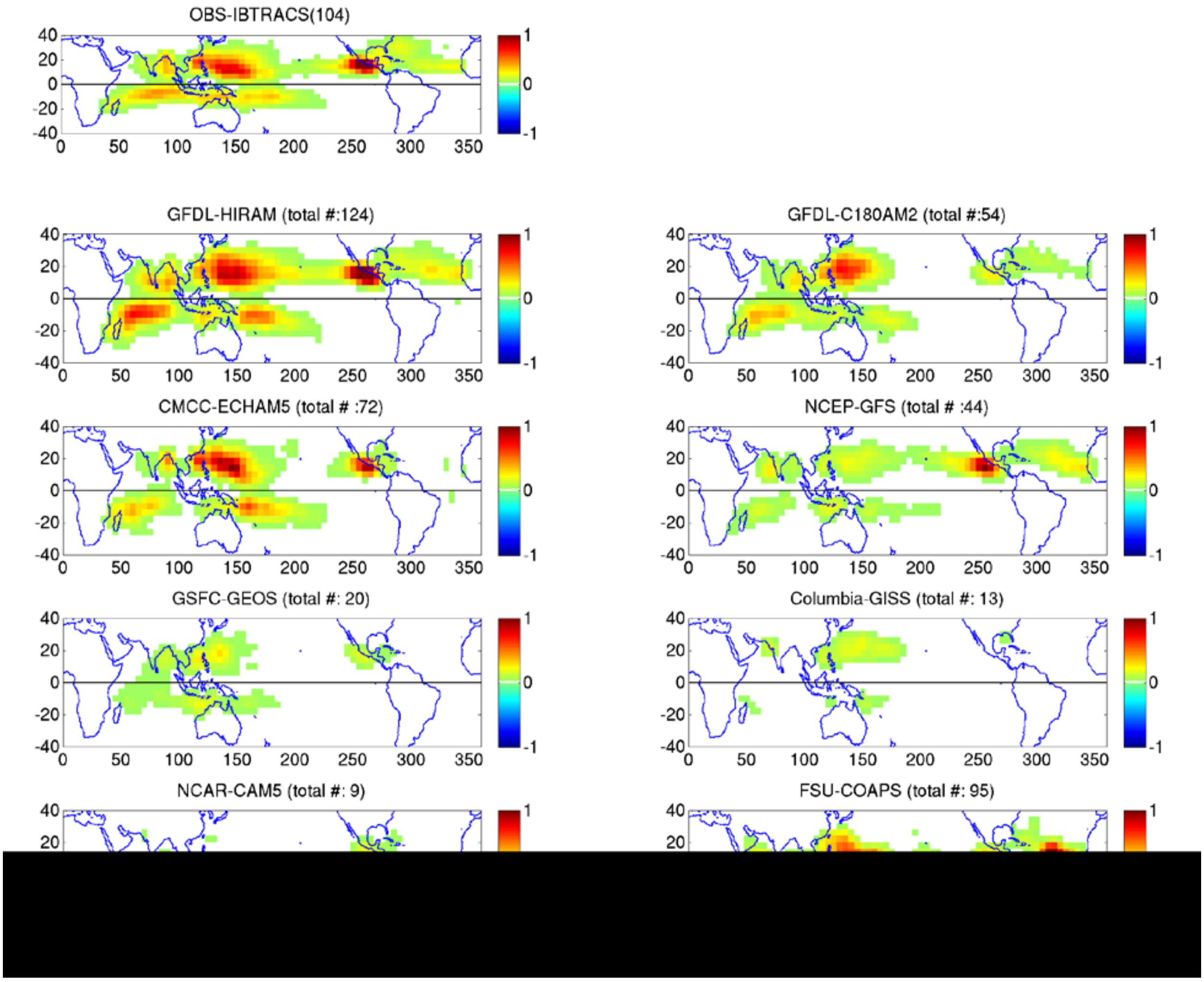
Figure 6. Percentage change in TC numbers in each model for the three altered climate experiments relative to the present-day experiment, as tracked by the CSIRO, Zhao, and individual group tracking schemes, after homogenisation in duration, wind speed, and latitude of formation. Asterisks indicate statistical significance to at least the $p = 0.05$ level.

Figure 7. Comparison between North Atlantic observed (blue) and simulated (red) wind-pressure relationships during the 1980-2002 period for the high-resolution (0.25^o) CAM-SE model, for central tropical cyclone pressure and 10 m wind speed. From Zarzycki and Jablonowski (2014).

Figure 8. Changes in TC related precipitation amount in the 2CO2 (blue), 2K (green) and 2K2CO2 (red) experiments as a function of latitude. Results are shown with respect to the climo experiment. Solid thin lines represent CMCC results. Dashed thin lines represent GFDL results. The solid thick lines represent the average of the two models. Units are [%].The amount of rainfall associated TCs is computed by considering the daily precipitation in a $10^o \times 10^o$ box around the center of the storm (right panel), and a smaller window closer to the storm center ($6^o \times 6^o$, left panel). From Scoccimarro et al. (2014).

Figure 9. The sensitivity of limiting intensity to SST ($m\ s^{-1}\ °C^{-1}$) for observed TCs (top left panel) and three runs of the GFDL HiRAM model, indicated by the slope of the blue line. The gray shading represents the 95% confidence interval while the vertical black bars depict uncertainty, obtained through a bootstrapping technique, about the limiting intensity estimates.

Figure 10. Seasonal Accumulated Cyclone Energy (ACE;10^4 kt^2 , denoted next to mark) of Atlantic tropical cyclones from regional climate model (RCM) simulations forced by the imposed lower boundary conditions and Pacific SST of the 1999 La Niña (filled circle) and 1987 El Niño (open circle) and Atlantic SST (corresponding August-October averaged AMM index on the x-axis), with the RCM 1980-2000 mean Atlantic ACE (dash). Each mark represents one season-long integration. From Patricola et al. (2014).



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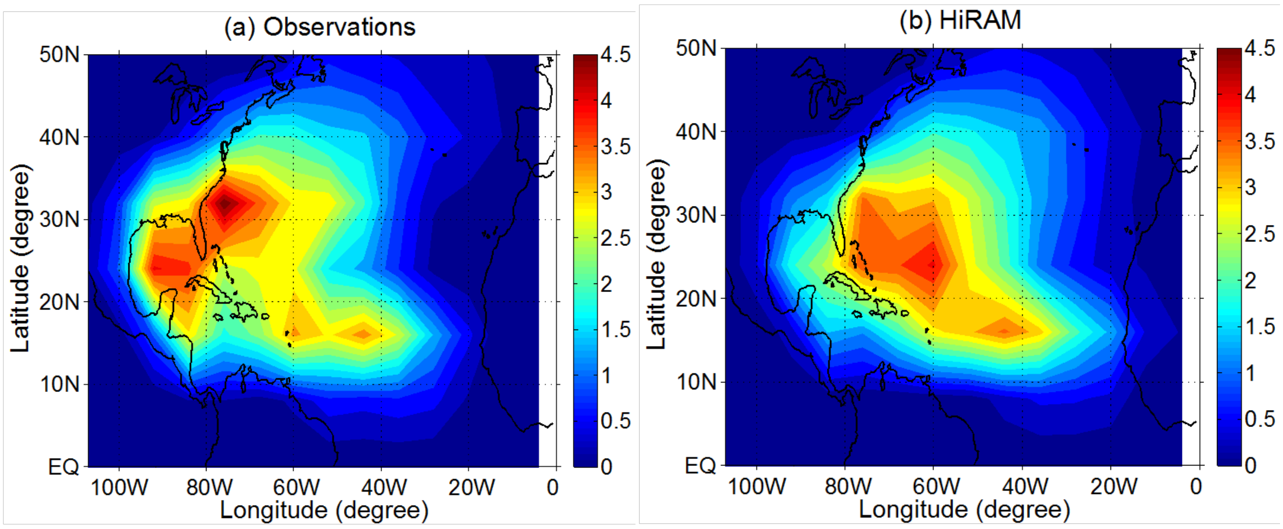

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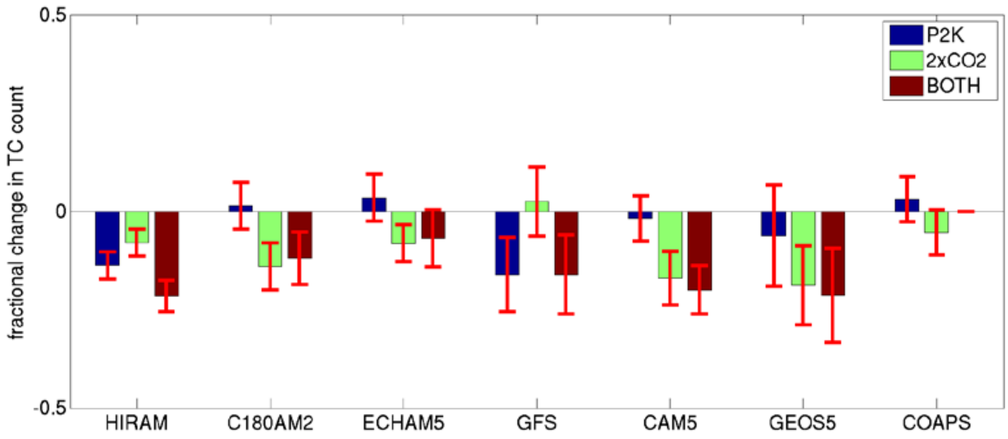

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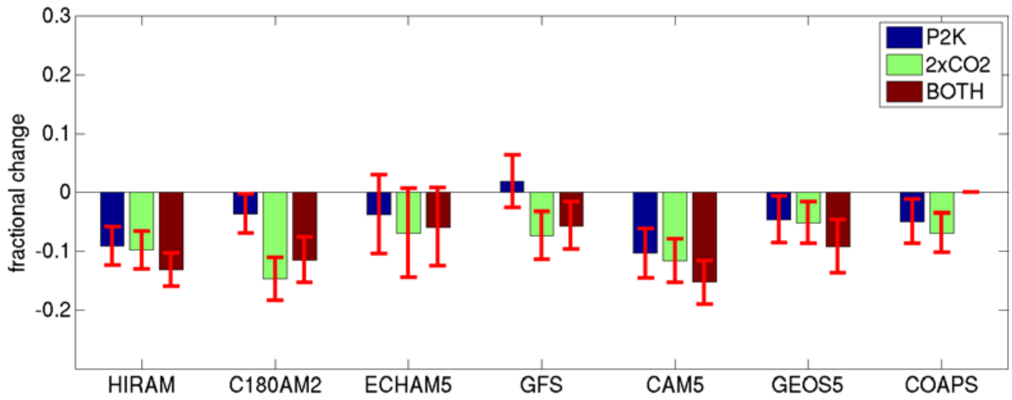

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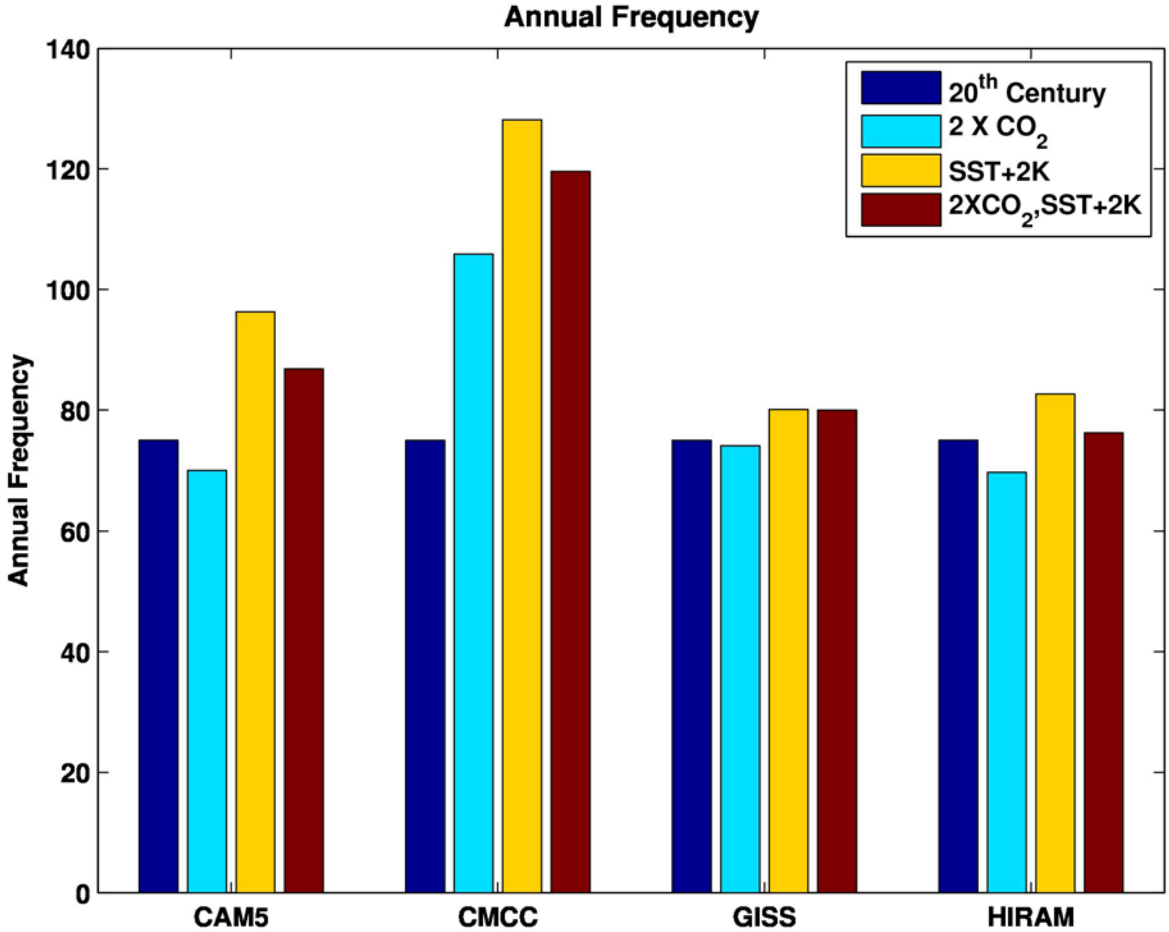

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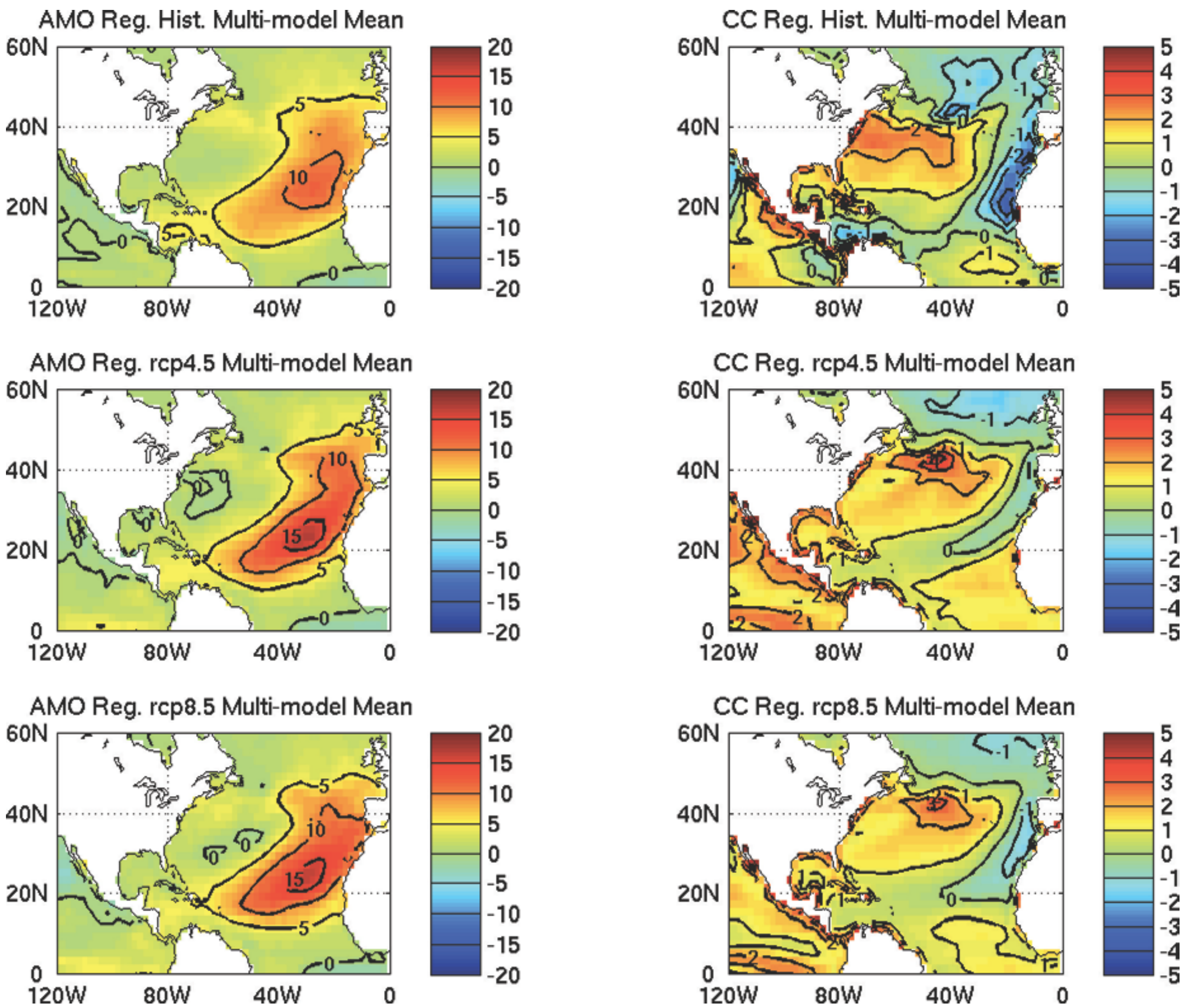

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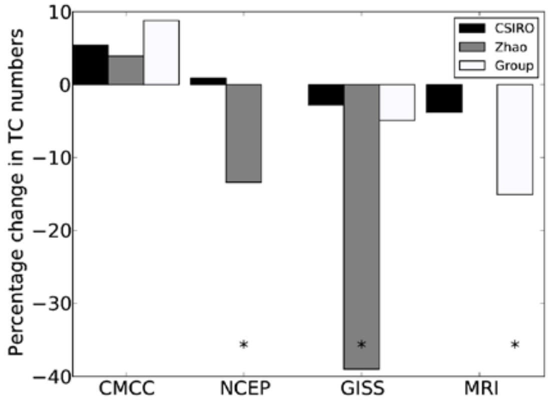

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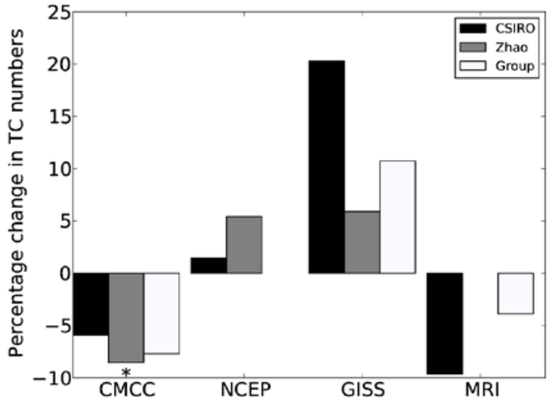

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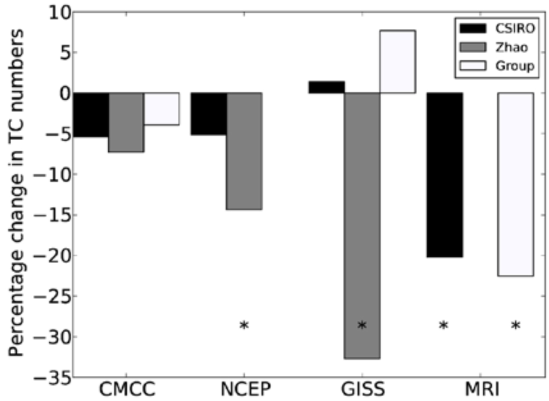

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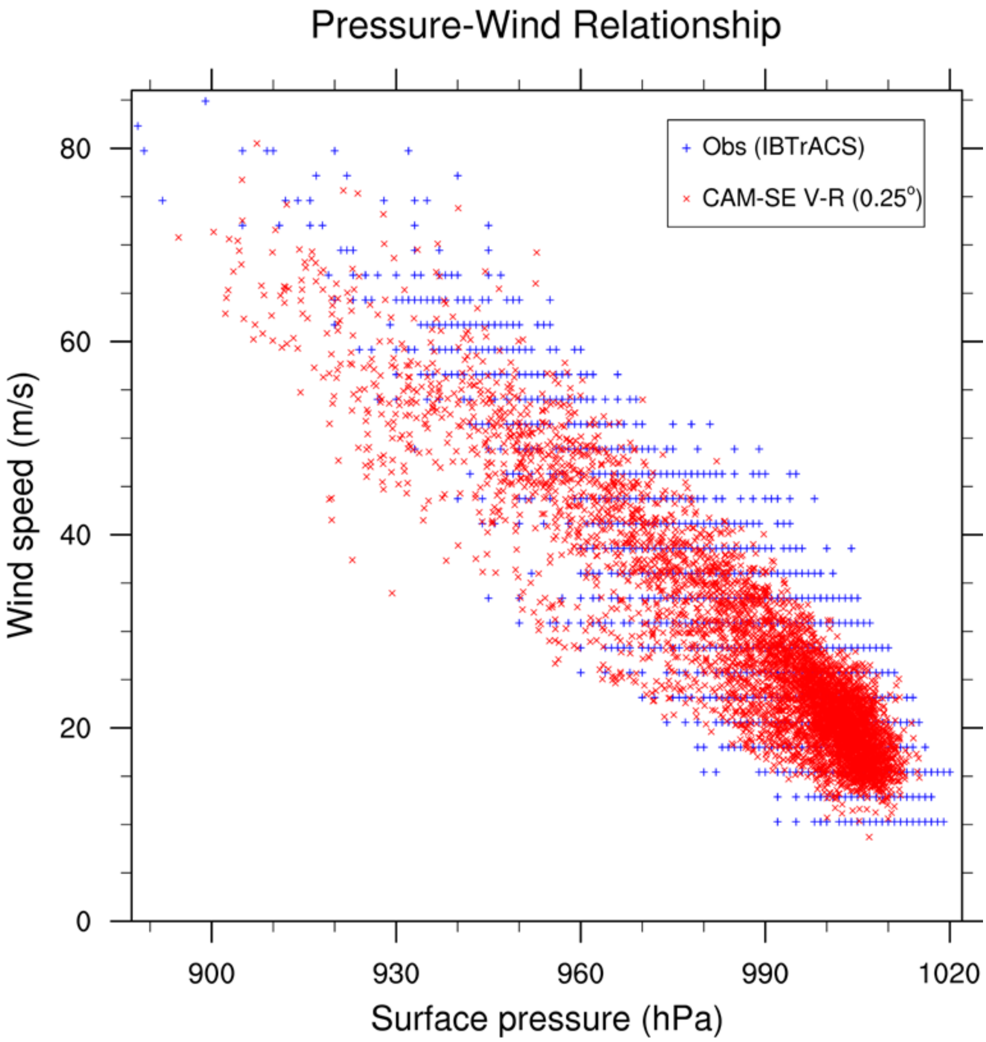

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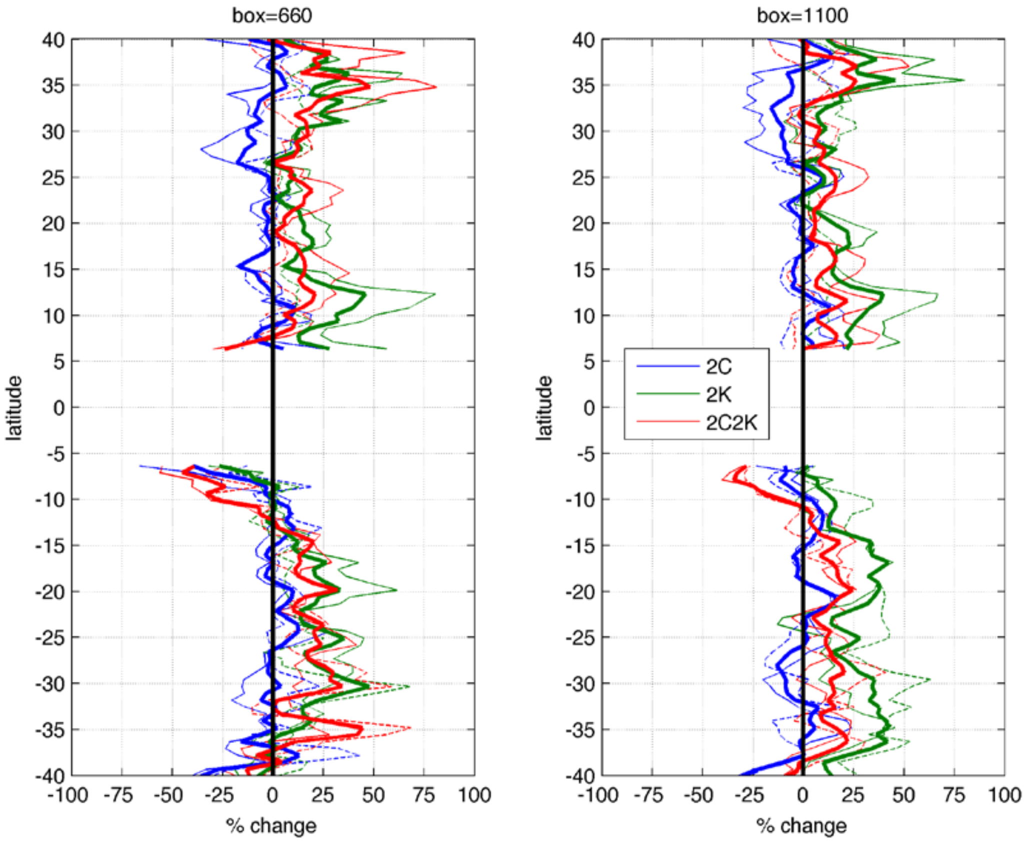

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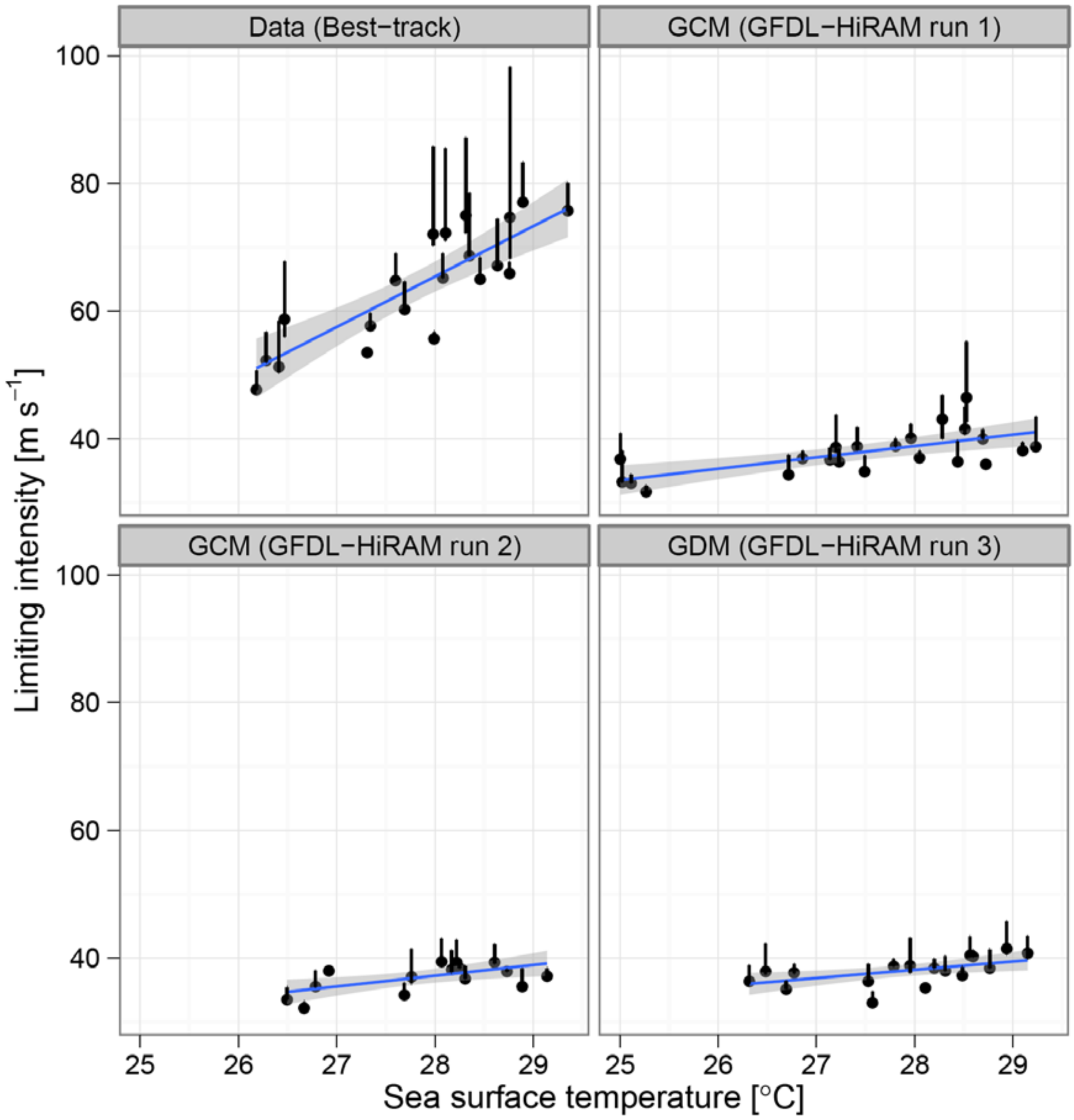

Figure 9. The sensitivity of limiting intensity to SST (m s^{-1} $°C^{-1}$) for observed TCs (top left panel) and three runs of the GFDL HiRAM model, indicated by the slope of the blue line. The gray shading represents the 95% confidence interval while the vertical black bars depict uncertainty, obtained through a bootstrapping technique, about the limiting intensity estimates.

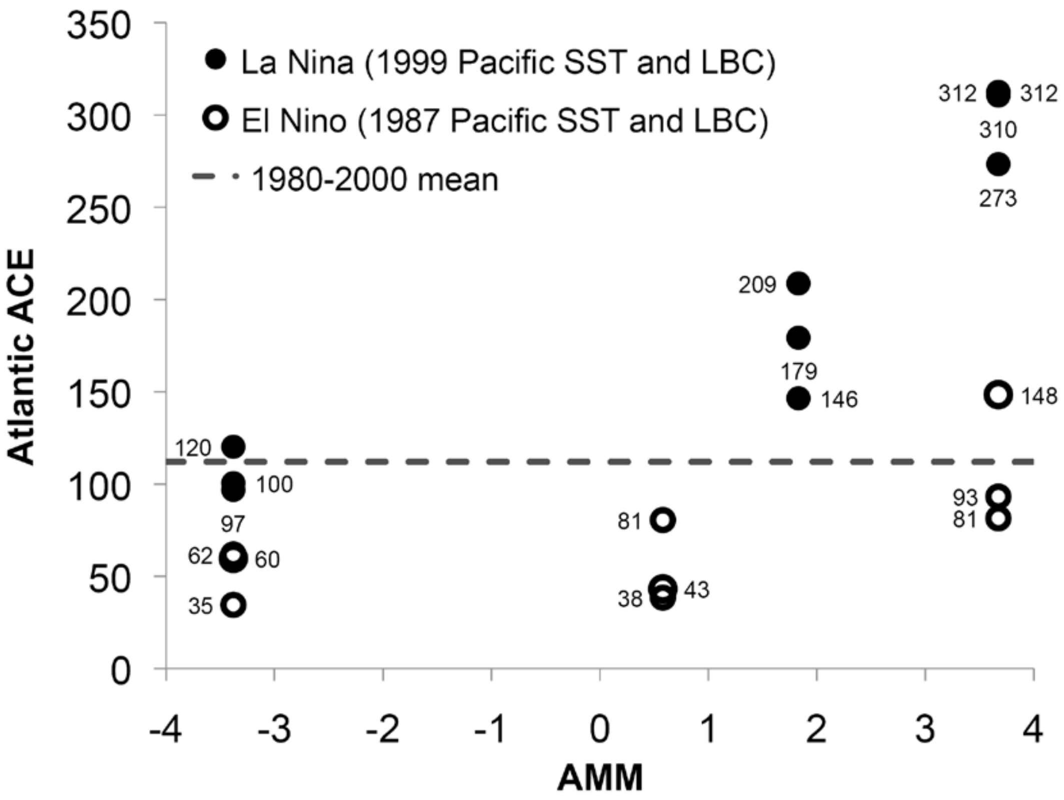

Figure 10. Seasonal Accumulated Cyclone Energy (ACE;10^4 kt^2 , denoted next to mark) of Atlantic tropical cyclones from regional climate model (RCM) simulations forced by the imposed lower boundary conditions and Pacific SST of the 1999 La Niña (filled circle) and 1987 El Niño (open circle) and Atlantic SST (corresponding August-October averaged AMM index on the x-axis), with the RCM 1980-2000 mean Atlantic ACE (dash). Each mark represents one season-long integration. From Patricola et al. (2014).