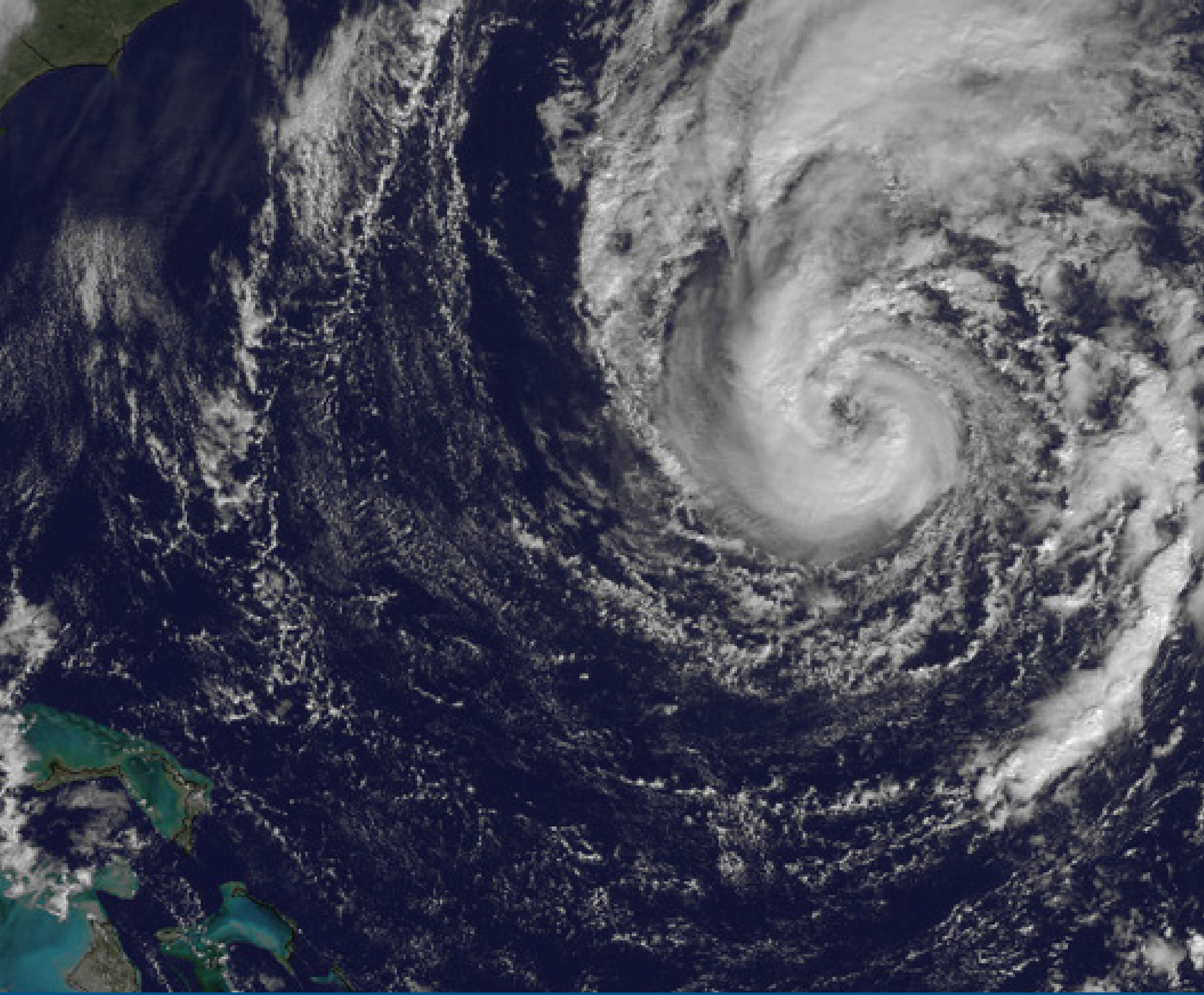
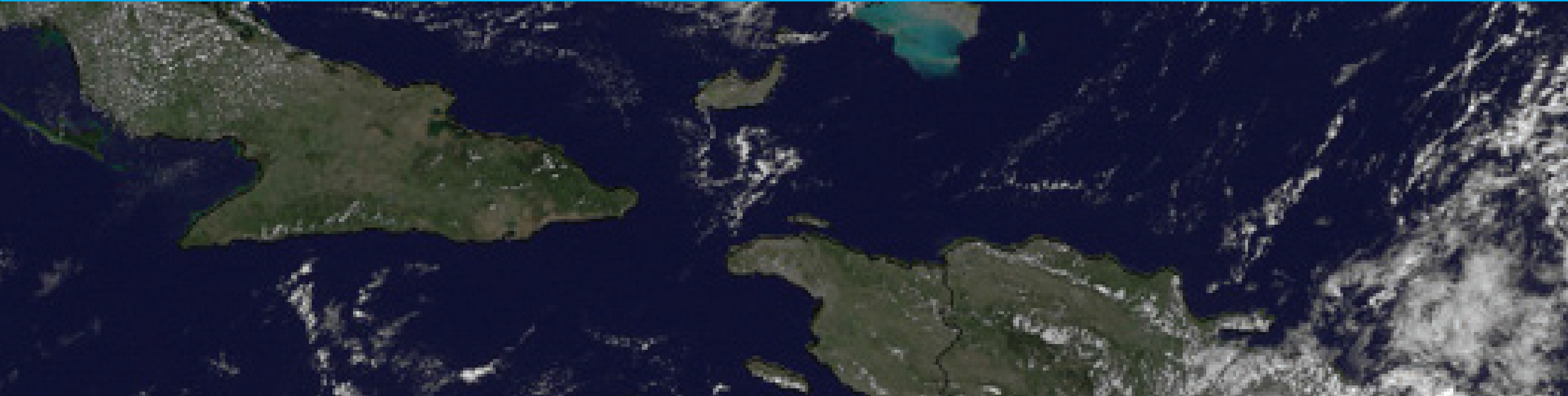


US CLIVAR HURRICANE WORKSHOP REPORT

June 5-7, 2013

Geophysical Fluid Dynamics Laboratory

Princeton, New Jersey



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http://www.usclivar.org/meetings/hurricane-workshop

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I Introduction

The effect of climate change on tropical cyclones has been a controversial scientific issue for a number of years. A number of techniques have been employed to address this issue in the recent past. First, advances in our theoretical understanding of the relationship between climate and tropical cyclones have been made, enabling us to better understand the links between the mean climate and the potential intensity (PI) of tropical cyclones. Second, 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. Third, 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. 2007b; Knutson et al. 2010), others have suggested some increase in future numbers (e.g., 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 concentration. One reason could be statistical: annual numbers of tropical cyclones in the Atlantic are small, making the identification of such storms sensitive to the detection method used.

Following from experiments described in Yoshimura and Sugi (2005), Held and Zhao (2011) have designed a series of idealized experiments using a high-resolution global atmospheric model (HIRAM): one using present-day climatological, seasonally-varying SSTs (climo); one with a uniform warming of 2K added to the climatological values (2K); one in which the SSTs were kept at their climatological values but the carbon dioxide (CO_2) concentration was doubled in the atmosphere (2CO2); and one with a combined uniform 2K SST increase and doubled carbon dioxide (2K2CO2). They find that HIRAM simulated a 20% decrease in global TC frequency in the 2K2CO2 run, with equal contributions from the 2K and 2CO2 runs. An important issue, given the current diversity of climate models, is whether such a response would be robust across a number of different, high-resolution climate models.

Further, there is substantial spread in projected responses of regional TC frequency and intensity over the 21st century from downscaling studies in the literature (Emanuel 2013; Knutson et al. 2007). Interpreting the sources of those differences is complicated by the different projections of large-scale climate that each study has explored, and by differences in the present-day reference period and SST forcing dataset across the studies. 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; 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. A related set of questions relate to the ability of models to recover 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 a number of atmospheric general circulation models following both idealized perturbations using the methodology of Held and Zhao (2011), as well as a historical forcing experiment using well-defined monthly SST and radiative forcing (HIST). A workshop was held at GFDL, June 5-7, 2013, at which progress was discussed on the analysis of these simulations for the US CLIVAR Hurricane Working Group (HWG). In addition, presentations were made on more general topics on the relationship between climate and tropical cyclone formation and characteristics.

Workshop presentations are available online at:
http://www.usclivar.org/meetings/hurricane-workshop-agenda

2 Science Synthesis

This section provides an overview of a number of the main issues discussed at the workshop along with a synthesis of our current understanding of these issues.

2.1 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 (see, for instance, Menkes et al. 2012). Increasingly, numerical models of the atmosphere are being used to pose the kind of the questions that need to be answered to address this issue.

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

A starting point for the simulation of changes in TC climatology is the ability of these models to simulate the current climatology of TCs in the "climo" HWG experiment or other similar current-climate simulations. There are many aspects of the current climate simulation in high-resolution GCMs that are realistic. In the HWG climo experiment, the simulated global TC numbers range from small values to numbers similar to the observed ones (Shaevitz et al. 2013; Zhao et al. 2013). Higher-resolution versions of some of the models used for the HWG experiments simulate global tropical cyclone formation considerably better (Wehner et al. 2013). 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. Most models simulate the observed double peak in the seasonal cycle of North Indian Ocean tropical cyclone formation, which has a minimum in TC formation during the monsoon season due to the high values of vertical wind shear in the region during that season (Dwyer et al. 2013). A common factor in many such model assessments is the poorer performance at simulating Atlantic tropical cyclone formation than for other basins. Strachan et al. (2013) found that the observed interhemispheric 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. A question that arises is whether the suite of model simulations performed for the HWG experiments, combined with other, similar experiments at higher resolution, could be used for an inter-comparison experiment to determine reasons for model performance by examining common features among models.

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 small 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. (2013) compare the HWG model responses for the various simulations, using the GFDL tropical cyclone tracking scheme (Knutson et al. 2008; Zhao et al. 2009). They find that almost all of the models show decreases of 0-20% in global tropical cyclone frequency for the 2K2CO2 run. The changes in TC numbers are most closely related to 500 hPa vertical velocity, among a suite of analyzed variables that included precipitation, 600 hPa relative humidity and vertical wind shear. While the response of the models in the other experiments is more ambiguous, no model generated a substantial increase in global TC frequency for any experiment.

The 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. (2012a) use a 60-km horizontal resolution version of the MRI AGCM to demonstrate that patterns of future SST change, rather than the choice of the convective parameterization used in their suite of experiments, appears more important in causing future changes in tropical cyclone numbers. 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) shows 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.

In general, 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. (2013), 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 is a substantial decrease in tropical cyclone numbers in almost all basins. Other changes include a slight increase in storm size, along with an increase in tropical cyclone rainfall.

Not all models simulations generate a decrease in future TC 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 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 CMIP5 climate models.

Overall, in the HWG experiments tropical cyclone numbers are most likely to have a small decrease in the 2K2CO2 experiment, with a clear majority of models indicating such. 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. Analysis of the results is preliminary but this suggests a link between tropical cyclone formation and tropical instability, which would be more likely to increase in the 2K experiment.

Do the new generation of higher-resolution climate models simulate the 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 model performance has been often poorer than in other formations basins (e.g., Walsh 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 poses an issue for the confidence of future tropical cyclone climate in this region.

The most recent GCMs have begun to simulate this region better, however. Zhao et al. (2013) note that more than one of the HWG models produced a reasonable number of tropical cyclones in the Atlantic. Manganello et al. (2012), Strahan et al. (2013), Roberts et al. (2013) and Zarzycki and Jablonowski (2013) show that increased horizontal resolution is an important factor in improving the simulation of Atlantic tropical cyclone climatology. Best results appear to be achieved at horizontal resolutions of finer than 50 km. Roberts et al. (2013) 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. 2012). 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, they are also able to simulate a reasonably realistic distribution of tropical cyclone intensity. Manganello et al. (2012) show 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. Daloz et al. (2013) use a cluster analysis technique to show that recent models give an improved simulation of tracks and intensities in the Atlantic basin.

Substantial increases in observed Atlantic tropical cyclone numbers have already occurred in the past 20 years. A number of explanations of this have been suggested, ranging from changes in upper-tropospheric temperatures (Emanuel et al. 2013) to the "relative-SST" argument of Vecchi and Soden (2007) to changes in tropospheric aerosols (Villarini and Vecchi 2013b). Camargo et al. (2013) and Ting et al. (2013) show that the effect of Atlantic SST increases alone on Atlantic basin potential intensity (PI) is considerably greater than the effect on Atlantic basin PI of global SST changes, thus suggesting that increases in local PI may be related to whether the local SST is increasing faster than the global average or not. Ting et al. (2013) show that by the end of this century, the change in PI due to climate change would 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 that relative SST appears to explain the evolution of future Atlantic TC numbers reasonably well. The HWG experiments have the potential to make a useful contribution to this debate, but at present there has been insufficient regional analysis (as opposed to global) performed on the model results.

The issue of the dynamical controls on tropical cyclone formation in the Atlantic region is related to the ability of 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. (2013), Wang et al. (2013) and Roberts et al. (2013). In general, this skill tends to exceed that seen in other basins. This suggests that tropical cyclone formation in the Atlantic basin is highly related to the climate variability of 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, this basin may have some advantages over other regions of the globe for more accurate predictions of the effect of climate change on tropical cyclone numbers.

Of particular interest is the difference in the projected changes in tropical cyclone numbers between the northern and southern hemispheres. Global model results consistently show a larger decrease in numbers in the southern hemisphere. Another consistent projection of global models is that SSTs in this hemisphere will increase slower than northern hemisphere SSTs, which, through the "relative SST" argument, may then be related to the projected decreases in tropical cyclone numbers. There is not yet a scientific consensus on this issue, however.

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 (2013), Kim et al. (2013) and Roberts et al. (2013) suggest that the region near Hawaii may experience an increase in future tropical cyclone numbers. Further regional analysis of the HWG results is under way.

What is the tropical cyclone response of climate models to an imposed, common increase in sea surface temperature? 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 warming (Yoshimura and Sugi 2005; Held and Zhao 2011). The relevant experiment here is the 2K experiment of the HWG modeling suite. In general, of those models that generate a substantial number of tropical cyclones, slightly more models show 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 would 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 maximum Potential Intensity (PI). These factors have not yet been considered quantitatively.

How does the role of changes in atmospheric carbon dioxide differ from the role played by sea surface temperatures 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. Zhao et al. (2013) 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. 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, assuming that tropical precipitation rates are controlled by a balance between convective heating and radiative cooling (Allen and Ingram 2002). This 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 two experiments may also have different effects on the intensity of storms. It is possible using fine resolution 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. 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. 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. A similar behavior is seen in the HWG experiments, although apart from the HIRAM model results, in general this suppression is part of a more general suppression of storms across all intensity categories rather than a preferential suppression of hurricane-intensity storms (Zhao, workshop presentation). Previous model simulations at higher resolutions than employed for the HWG experiments has 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.

While this issue is not addressed directly through the design of the HWG experiments, it is the subject of considerable discussion. Emanuel (2013a,b) shows by an analysis of thermodynamic parameters associated with tropical cyclone intensity that SST should not be considered a control variable for tropical cyclone intensity. Nevertheless, Kim et al. (2013) show results from the GFDL coupled model running at a resolution of 50 km, indicating 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-simulated 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.

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 four main categories:

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. 2007a; Strachan et al. 2013); and
4. Basin-dependent schemes, in which the detection thresholds are adjusted statistically, depending upon the formation rate in a particular basin (e.g., Camargo and Zebiak 2002)

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, there is much more agreement than disagreement on the sign of the model response between different tracking schemes (Horn et al. 2013). Nevertheless, it is possible to obtain a different sign of the response for the same experiment by using a different tracking scheme. 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.

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 diagnostics of tropical cyclone formation that are applicable to the mean climate has led to the formulation of parameters that statistically relate tropical cyclone formation to climatological mean values of parameters that are known to influence tropical cyclone formation, known as genesis potential indices (GPIs; Gray 1979; Royer et al. 1998; Emanuel and Nolan 2004; Emanuel 2010; Tippett et al. 2011; Bruyère et al. 2012; Menkes et al. 2012). GPIs usually include values of atmospheric variables such as vertical wind shear, PI, mid-tropospheric relative humidity, and SST. The potential of such a technique is obvious: it can 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) 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. Korty (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 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 (Walsh et al. 2013; Camargo 2013). In addition, a potential limitation of the GPI methodology for application to a different climate is that it is trained on present-day climate.

The role of idealized simulations in understanding the influence of climate on tropical cyclones is highlighted by Merlis et al. (2013). A series of aquaplanet simulations show that the position of the 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.

Future changes in seasonal cycle of tropical cyclone formation

Dwyer et al. (2013) analyze a subset of the HWG experiments to determine whether there are phase changes in the seasonal cycle of tropical cyclone formation. In these results, there appears to be a hemispheric asymmetry in the response, with phase delays in the Northern Hemisphere but phase advances in the Southern Hemisphere.

Sensitivity of results to choice of convection scheme

Murakami (2013) 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. Note that there also appears to be a considerable sensitivity of tropical cyclone formation to the specification of the minimum entrainment rate (Lim and Schubert 2013). As this is decreased (equivalent to turning off the cumulus parameterization), the number of tropical cyclones increases. 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.

2.2 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 based on the Carnot cycle (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 of the outflow temperature. In addition, most tropical cyclones do not reach their maximum intensities, and while factors that inhibit their intensification are well known (e.g., vertical wind shear, cold ocean surfaces, 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. In general, however, the HWG experiments are of insufficient horizontal resolution to produce a good representation of the intensity distribution of observed storms. Finer-resolution models, though, have recently been shown to be able to do this (see below), leading to the possibility of stronger linkages between numerical climate experiments and our existing climate theory of tropical cyclone intensity.

Simulation of the intensity distribution of tropical cyclones

A number of talks at the workshop discussed the question of intensity distribution. While it is clear that simply increasing the resolution does not necessarily improve intensity distribution (Shaevitz et al. 2013), results shown during the workshop indicate that a very significant improvement in a model'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. 2013; Lim and Schubert 2013; Wehner et al. 2013). In addition, if 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. 2012a; Knutson 2013; Chen et al. 2013; Zarzycki and Jablonowski 2013). Manganello et al. (2012) show that there remain some discrepancies in the wind-pressure relationship between observations and even very high horizontal resolution (10 km) simulations, however.

A number of different formulations of PI have been developed. The relationships between them and with convective available potential energy (CAPE) are detailed by Garner (workshop presentation). Some differences in formulation depend upon assumptions made about the relationship between CAPE and the outflow trajectories in the storm. It is possible, however, to recover the various specifications of PI employed in the literature by making some simple assumptions about the relationship between CAPE and PI. Uncertainties remain in specification of the ratio of exchange coefficients to drag coefficients, a crucial variable in PI formulations.

2.3 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. 2013; Roberts et al. 2013). The size of this signal varies a little between simulations, from approximately 10% to 30%. Knutson (workshop presentation) 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 of the tropical cyclone.

Lavers et al. (2013) and Scoccimarro et al. (2013) are investigating the response of precipitation from landfalling tropical cyclones in the HWG experiments. Preliminary results show that there are considerable differences between HWG models for the landfalling TC precipitation response. A number of issues are identified for future work, including a stratification of the rainfall rate by intensity categories and an examination of the extra-tropical rainfall of the former TC.

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. They speculate that the lower sensitivity is due to the inability of the model-derived TCs to operate as idealized heat engine likely due to unresolved inner-core thermodynamics. They further speculate that GCM temperatures near the tropopause do not match those in the real atmosphere, which would likely influence the sensitivity estimates.

3 Gaps in Our Understanding and Future Work

A number of issues are identified by the HWG as needing 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 use of a mixed-layer ocean as a boundary condition rather than using a full ocean GCM.

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. (2013) show that long-term variations in TC formation in the Atlantic appear to be dominated by the Atlantic Meridional Mode (e.g., Vimont and Kossin 2007), and so any future climate change projection would ideally need to include information on changes in the periodicity and amplitude of the AMM.

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.

Analysis of the model experiments and comparison of the results would be aided by a set of common diagnostics. While suggested model outputs were specified for the experiments, it would be useful to take the next step to specify the generation of more elaborate common diagnostics that are relevant to the physical factors identified as important for explaining the model results, e.g., PI.

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.

4 Acknowledgements

The workshop organizers wish to thank the participants for their informative presentations and active engagement in discussion. We also wish to take this opportunity to recognize the essential contributions from participating modeling groups (NCAR CAM5.1, CMCC ECHAM5, CNRM, FSU COAPS, NOAA GFDL HIRAM, NASA GISS-Columbia U., NASA GSFC GEOS5, Hadley Center HadGEM3, JAMSTEC NICAM, MRI CGCM3, NCEP GFS and WRF) that ran model experiments and furnished their data for analysis. We also appreciate the contributions of NOAA GFDL for hosting the meeting, the US CLIVAR Project Office and UCAR JOSS for logistics support, and the US CLIVAR funding agencies, NASA, NOAA, NSF, and DoE for their sponsorship.

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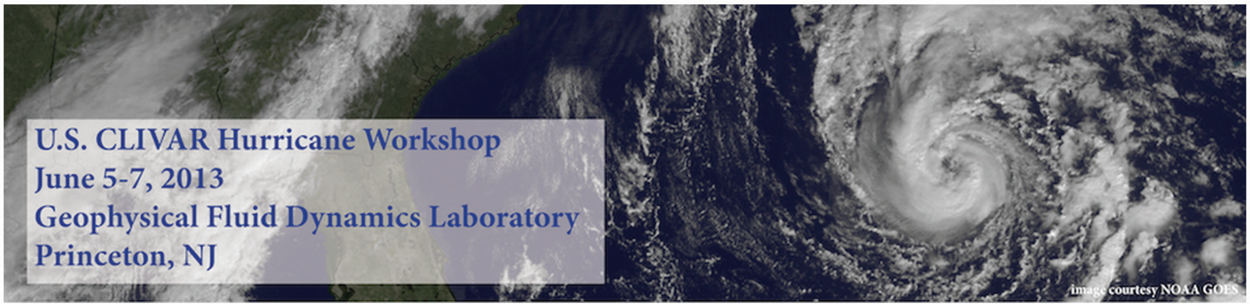
Appendix A: Scientific Organizing Committee

Gabriel Vecchi
NOAA Geophysical Fluid Dynamics Laboratory

Suzana Camargo
Columbia University/Lamont-Doherty Earth Observatory

Kevin Walsh
University of Melbourne, Australia

Appendix B: Workshop Agenda



Summary

In recent years, global climate models have become an increasingly important tool for simulating the effects of climate change on tropical storms and hurricanes. The increasing horizontal resolution of these models has enabled them to provide an improved representation of tropical cyclone formation rates and their regional variation. This is particularly important when these models are used to estimate the possible effects of climate change on tropical cyclone behavior.

Several research questions remain to be resolved in this work:

- Many models predict a decrease in global tropical cyclone numbers, particularly in the Southern Hemisphere. What is the fundamental reason for this change?
- Prediction of future tropical cyclone behavior in the Atlantic Ocean is of crucial importance, yet tropical cyclones in this basin have typically been less well simulated. Do the new generation of higher-resolution climate models simulate the Atlantic better? Do they simulate a similar tropical cyclone response to climate change, thus giving more confidence in our prediction?
- Many studies have shown that tropical cyclone behavior responds strongly to changes in sea surface temperature. What is the tropical cyclone response of climate models to an imposed, common increase in sea surface temperature? How sensitive is the simulation of tropical cyclone variability to differences in SST analysis?
- What is the relationship between local versus remote forcing and hurricane formation in the North Atlantic? How does tropical cyclone frequency respond to an increase in tropical mean sea surface temperature versus an increase in the Atlantic alone? What about the response of tropical cyclones to local and remote forcing in other regions of tropical cyclone formation, is it similar to or different from that in the Atlantic?
- How does the role of changes in atmospheric carbon dioxide differ from the role played by sea surface temperatures in changing tropical cyclone characteristics in a warmer world?
- How does air-sea interaction modify the climate response of tropical cyclones?

This workshop will review current progress in these issues, through presentations based on results of common climate model experiments already produced by group members. In addition, discussion will focus on novel syntheses of these results, as well as applicable analytical techniques, and how they might be applied to address some of the fundamental issues mentioned above.

Wednesday, June 5th

8:30am – *US-CLIVAR Hurricane WG: How we got here - where are we going?* **Gabriel Vecchi**

9:00am – *Characteristics of tropical cyclones in high-resolution models of the present climate*, by **Daniel A. Shaevitz**, S.J. Camargo, A.H. Sobel and the US CLIVAR hurricane working group.

9:30am – *Response of global tropical cyclone frequency to a doubling of CO_2 and a uniform SST warming – a multi-model intercomparison*, by **Ming Zhao**, G. Vecchi, E. Scoccimarro, S. Gualdi, H. Wang, A. Kumar, Y.-K. Lim, and S. Schubert.

10:00am – Coffee Break

10:30am– *Response of downscaled tropical cyclones to climate forcing: Results and interpretation*, by **Kerry Emanuel**.

11:00am – *Cluster analysis of explicitly and downscaled simulated North Atlantic tropical cyclone tracks*, by A.S. Daloz, **Suzana J. Camargo**, J. Kossin, K. Emanuel, and US CLIVAR hurricane working group

11:30am – *A comparison of observed and model-generated tropical cyclone climatologies using a spatial lattice*, by **Sarah Strazzo**, J.B. Elsner, T. LaRow, and M. Zhao

12:00pm – Lunch

1:00pm – *Projected changes in the seasonal cycle of tropical cyclones*, by **John G. Dwyer**, S.J. Camargo, A.H. Sobel, M. Biasutti, K.A. Emanuel, G.A. Vecchi, and M. Zhao.

1:30pm – *Warming sea-surface temperature raises the bar for tropical cyclogenesis*, by **Jenni Evans**

2:00pm – *North Atlantic hurricane potential intensity in CMIP5 models: Anthropogenic forcing versus Atlantic multi-decadal variability*, **Mingfang Ting**, S.J. Camargo and Y. Kushnir.

2:30pm – *On the relationship between potential intensity and CAPE*, by **Stephen Garner**

3:00pm – Coffee Break

3:30pm – Discussion

4:00pm – Dynamic hurricane prediction with the NCEP CFS CGCM, by **Jae K. E. Schemm** and L. Long

4:30pm – *Uncertainties in future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments*, by **Hiroyuki Murakami**

5:00pm – *Tropical cyclone characteristics in response to different cumulus convective activity in a high-resolution climate model*, by **Young-Kwon Lim** and S. Schubert

6:30pm – 8pm: Reception at Salt Creek Grille with appetizers and beverages

Thursday, June 6th 2013

8:30am - *Dynamical downscaling of tropical cyclone activity: An update on the use of the GFDL Hurricane model in multiple basins*, by **Thomas R. Knutson**

9:00am – *Tropical cyclone simulation and response to CO2 doubling in GFDL CM2.5 high-resolution coupled model*, by **Hyeong-Seog Kim**, G. Vecchi, T.R. Knutson, T.L. Delworth, and M. Zhao.

9:30am - *Tropical cyclone studies with a hierarchy of climate model resolutions from the UPSCALE project*, by **Malcolm Roberts**, M. Mizielinski, J. Strachan, P.L. Vidale, M.E. Demory, and R. Schiemann

10:00am – Coffee Break

10:30am – *Hurricane simulations in a regional climate model*, by **R. Saravanan**, C.M. Patricola and P. Chang

11:00am – *Tropical cyclone simulations in the very high-resolution global climate models*, **Cheng-Ta Chen**, T.-P. Tzeng, M. Wehner, Prabhat, and A. Kitoh

11:30am – Discussion

12:00pm – Lunch

1:00pm – *High resolution, multi-decadal tropical cyclone simulations using a variable-resolution general circulation model*, by **Colin M. Zarzycki** and C. Jablonowski

1:30pm – Results from the Community Atmosphere Model CAM5.1, by **Michael Wehner**, Prabhat, K. Reed, C.-T. Cheng, and D. Stone

2:00pm – *Tropical cyclone research with a global non-hydrostatic model*, by **Kazuyoshi Oouchi**

2:30pm – *Environmental control of tropical cyclone genesis in paleoclimate simulations*, by **Robert Korty**, S.J. Camargo and J. Galewsky

3:00pm – Coffee Break

3:30pm – *Intense precipitation events associated with landfalling storms in a warmer climate*, by **Enrico Scoccimarro**, S. Gualdi, G. Villarini, A. Navarra, and modelers of the US CLIVAR hurricane working group

4:00pm – *Sensitivity of tropical cyclone rainfall to different warming scenarios*, by D.A. Lavers, **Gabriele Villarini**, E. Scoccimarro, G.A. Vecchi and modelers of the US CLIVAR hurricane working group

4:30pm – *Impact of stratospheric temperature on hurricane intensity: An idealized modeling study*, by **Shuguang Wang**, S.J. Camargo, A.H. Sobel and L.M. Polvani

5:00pm - Discussion

Friday, June 7th, 2013

8:30am – *Detection of tropical cyclones using a phenomenon-based cyclone tracking scheme*, by M. Horn, **Kevin Walsh** and A. Ballinger

9:00am – H*ow well can we detect tropical cyclone tracks in the Reanalyses data*, by **Cheng-Ta Chen**, T.-P. Tzeng, M. Wehner and Prabhat

9:30am - *The impact of the El Niño-Southern Oscillation and Atlantic Meridional Mode on Atlantic tropical cyclone activity*, by **Christina Patricola**, R. Saravanan and P. Chang

10:00am – Coffee Break

10:30am – How well do global climate models simulate the variability of Atlantic tropical cyclones associated with ENSO? by **Hui Wang**, L. Long, A. Kumar, W. Wang, and J.-K. E. Schemm

11:00am – *Isentropic analysis of hurricanes*, by **Agnieszka Mrowiec**, O. Pauluis and F. Zhang

<u>11:30am – Discussion</u>

<u>12:30pm – End of the workshop</u>

Appendix C: List of Participants

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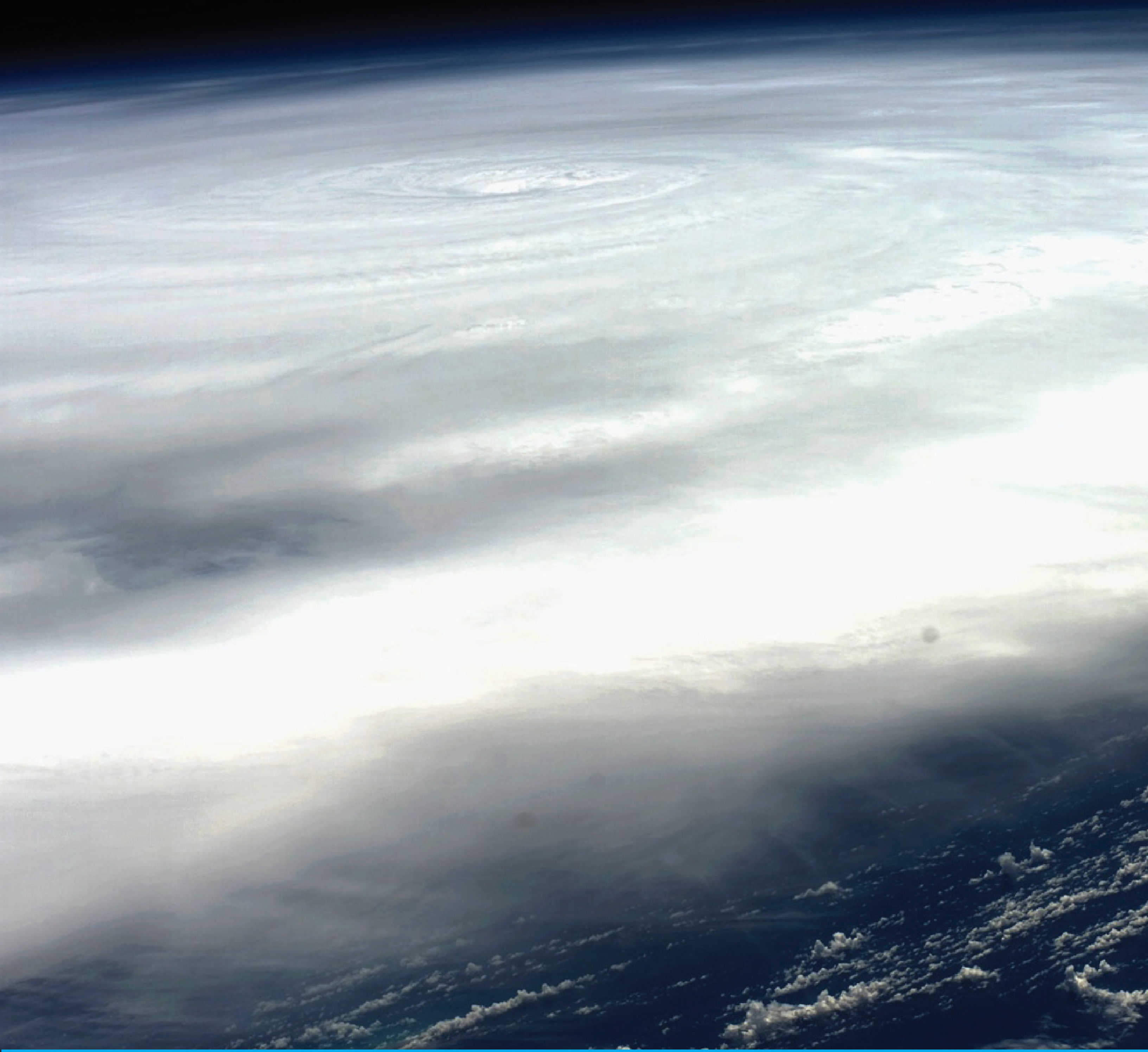

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