Hurricanes and Climate Change

James B. Elsner • Thomas H. Jagger
Editors

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Preface

Tropical cyclones are becoming more powerful with the most dramatic increase occurring over the North Atlantic. The increase is correlated with an increase in ocean temperature. A debate concerns the nature of this increase with some researchers attributing it to natural climate fluctuations while other researchers attributing it to anthropogenic increases in forcing from greenhouse gases. A Summit on Hurricanes and Climate Change held May 27–30, 2007 at the Aldemar Knossos Royal Village in Hersonissos, Crete brought together leading academics and researchers to discuss the issues and to address what research is needed to advance the science of hurricane climate.

The Summit was hosted by Aegean Conferences and supported by the Bermuda Institute for Ocean Sciences (BIOS) Risk Prediction Initiative and by the U.S. National Science Foundation. It was organized to provide a venue for encouraging a lively, spirited exchange of ideas. In this spirit, it was appropriate to convene at the birthplace of the Socratic method. This volume is a collection of research papers from participants of the Summit.

Tropical cyclones are typically analyzed as a passive response to climate forcing: the hurricane as a product of its environment. A warm ocean provides sustenance, a calm atmosphere nurturing, and a subtropical high-pressure cell forward direction. An increase in oceanic heat will raise a hurricane's potential intensity, yet an increase in shearing winds could counter by dispersing the heat in a fledgling storm. This perspective is useful for identifying the mechanisms responsible for making some seasons active while others inactive. A point of emphasis at the Summit was that statistical modeling is superior to data analysis (trend lines, etc) as it avoids cherry-picking the evidence and provides a framework for making use of older, less reliable data.

For example, a Poisson distribution is useful for modeling tropical storm counts over time. The benefit of a statistical approach is that it provides a context that is consistent with the nature of the underlying physical process, analogous to the way the laws of physics provide a context for studying meteorology. It was shown at the Summit that smoothing (filtering) the hurricane count data introduces low frequency patterns that may not be significant and that a statistical model of Atlantic hurricanes indicates a recent upswing in the number of strongest hurricanes with little or no multidecadal variation.

Although the question of whether we can ascribe a change in tropical cyclone intensity to anthropogenic climate change (attribution) is still open, it was argued based on statistical models for extreme winds that the difference in hurricane intensity for storms near the U.S. coast between globally warm and cool years is consistent in sign and magnitude with theory and simulations. In this regard it was noted that the discrepancy between numerical model results and observations is likely due to a reliance on data analysis rather than statistical models.

The collective role that hurricanes play in changing the climate was another point of emphasis at the Summit. Over the Atlantic Ocean, heat and moisture transport out of the tropics by an ensemble of hurricanes moving poleward in a given season was shown to have a detectable influence on the baroclinic activity at high latitudes the following winter, which in turn influences the preferred hurricane track type (recurving or straight-moving) during the subsequent hurricane season. Thus a communication between the tropics and the middle latitudes on the biennial time scale is accomplished through tropical cyclone track changes and middle latitude baroclinicity. This finding has important implications for financial markets because it provides a way to hedge risk through diversification.

Also, the relationship between global warming and ENSO was explained in terms of warming rather than warmth. A warming planet is associated with more El Nino events, which on the biennial time scale leads to cooling. These are intriguing hypotheses about climate change and tropical cyclones that merit further investigation. It was also shown that super typhoons in the western North Pacific need a deep ocean mixed layer for rapid intensification only in regions where the sub surface water temperatures are marginally supportive of tropical cyclone intensification. It was demonstrated that high aerosol concentrations lead to an invigoration of the convection in tropical cyclones through enhancement of the ice/water microphysical processes inside the clouds.

Another important theme of the Summit was paleotempestology—the study of prehistoric storms from geological and biological evidence. For instance, coastal wetlands and lakes are subject to overwash processes during hurricane strikes when barrier sand dunes are overtopped by storm surge. The assumption is that during landfall the waves and wind-driven storm surge reach high enough over the barrier to deposit sand in the lake. In a sediment core taken from the lake bottom, a sand layer will appear distinct from the fine organic mud that accumulates slowly under normal conditions. Sediment cores taken from the northeastern Caribbean show more sand layers during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees C cooler than today providing some evidence that today's warmth is not needed for increased storminess. Not surprisingly intervals of more hurricanes correspond with periods of fewer El Nino events. It was shown that sedimentary ridges in Australia left behind by ancient tropical cyclones indicate activity from the last century under represents the continent's stormy past. It was argued that proxy techniques based on oxygen isotopes from tree rings and cave deposits show promise for studying prehistoric tropical cyclone events because of the signature left in the annual layers by the isotopically lighter tropical cyclone rainwater.

It was mentioned that a spatially limited set of proxies or historical records are not able to resolve changes in overall activity from changes in local activity due to shifts in tracks. While the northeastern Caribbean region is in the direct path of today's hurricanes, was it always? Network analysis of hurricane activity might be able to shed light on this question. The answer is important as more hurricanes locally could mean changes in steering rather than changes in abundance. Proxy data from the U.S. Gulf coast show a pattern of frequent hurricanes between 3800 and 1000 years ago followed by relatively few hurricanes during the most recent millennium which is explained in terms of the position of the subtropical North Atlantic High. Moreover it was shown that recent increases in typhoon intensities affecting Korea can be explained by an eastward shift in the subtropical North Pacific High allowing the storms to recurve over the warmer waters of the Kuroshio Current rather than over the colder subsurface waters of the Yellow Sea. In order to understand how climate influences local changes in tropical cyclone activity, it was remarked that more research is needed to identify factors influencing tropical cyclone tracks.

Results from high-resolution numerical models, including a 20 km-mesh model, were consistent in showing stronger tropical cyclones in a warmer future. Most models indicate an overall decrease in the number of storms, attributable in one study to greater atmospheric stability and a decrease in the vertical mass flux. Not all models agree on the change in individual basin numbers with some models showing an increase in the Atlantic and others a decrease. It was shown that models without tropical cyclones remove the oceanic heat in the tropics through stronger trade winds. It was noted that models may be better at identifying changes to the large-scale genesis fields and that models still do not have the resolution to be useful to society. Climate model projections can be downscaled to construct tropical cyclone climatologies using a method that combines rejection sampling by numerical models to determine genesis points with simple physical models for storm motion and winds. A few participants focused on the perception and politics of tropical cyclone risk in a changing climate.

This volume provides a cross-section of the topics that were covered during the Summit. It is broadly organized around study type with empirical analyses first followed by statistical models, then by numerical simulations.

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March 2008 *Thomas H. Jagger*

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Detection and Attribution of Climate Change Effects on Tropical Cyclones

Kevin Walsh, David Karoly, and Neville Nicholls

Abstract The status of attempts to detect climate trends in tropical cyclone data and the possible attribution of such trends to anthropogenic climate change are reviewed. A number of trends have been detected in tropical cyclone data but some of these are likely due to data inhomogeneities. Where the data is good, for instance in the Atlantic basin, detected trends are more likely to be real. Whether such trends can be attributed at this time to anthropogenic climate change relies not only upon good data but also upon the physical basis of the hypothesized links between global warming and variables related to tropical cyclone characteristics. These links may be made stronger through the use of numerical models and theoretically-based parameters. A process is outlined by which this might be achieved.

Introduction

The detection and attribution of the possible effects of anthropogenic climate change on tropical cyclones is one of the most controversial topics in present-day science. The increase in tropical cyclone numbers in the Atlantic since the mid 1990s, combined with the devastating impacts of individual hurricanes such as Katrina in 2005, has led to an urgent examination of trends in the available tropical cyclone data to see if these can be explained by man's effect on the climate.

To examine these issues, numerous recent studies have been performed to analyze the data record, to simulate future occurrence and intensity of tropical cyclones and to determine the influence of various environmental parameters on tropical cyclone characteristics. But no study has yet applied the standard, formal methodology to tropical cyclones that has been used previously to conclude, with high confidence, that a particular change in atmospheric or oceanic behavior is likely due to anthropogenic climate change. The formal process of detection and attribution is the most powerful tool available to climate scientists to build confidence in ascribing detected climate trends to man-made influences. This article discusses the relevance of this methodology for studies of tropical cyclones, outlines the current issues that limit its application to tropical cyclones and suggests

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ways in which these limitations can be addressed. The formal process of detection and attribution is first described and examples are given of its successful application in providing robust, high-confidence conclusions regarding the effects of anthropogenic climate change.

Detection and Attribution

Definition

Detection is the process of determining whether a climate signal has emerged from the background noise of the data. Typically this “noise” constitutes the natural climate variability of the atmosphere-ocean system., particularly variability on decadal time scales which can often be aliased onto longer-time scales trends such as those associated with global warming, thus making these trends difficult to detect unambiguously. A recent summary of the detection process is provided in Hegerl et al. (2007). Detection is largely a statistical issue and is usually determined by statistical techniques, ranging from simple trend analyses to multi-variate analysis.

For a signal to be detected unambiguously, good data for both the signal and the noise must exist. Like all good climate data, cyclone data must be free of inhomogeneities caused by changes in observing practices. The data must also be complete in that the data sample being analysed must be consistently collected at similar time intervals over the entire period of record. To estimate the magnitude of the climate noise in a particular climate parameter, it may not be possible to just use the available observational record, as this may be too short to fully characterize the long-term variability due to noise alone. In principle, data records much longer than the duration of the climate change signal are required to estimate the range of long-term variability that may occur due to climate noise alone (Santer et al., 1995). In practice, such lengthy observational records do not exist for any climate variables and so alternative approaches must be used to estimate the long term variability due to noise. Often, long control simulations from coupled ocean-atmosphere climate models performed with no changes in external forcing factors are used to estimate the long-term variability of climate variables due to climate noise alone, assuming that the models provide realistic simulations of the noise in such variables.

It is clear that the mere detection of a signal is not an indication of its cause. Further analysis needs to be undertaken to ascribe causes for any detected signals; this is known as the process of attribution. In the case of anthropogenic climate change, we are interested in whether the detected signal can be attributed to man-made global warming. As defined by the IPCC, in order for high confidence attribution conclusions to be reached, a signal needs to be detected that is not only of the expected pattern of change but also of the correct magnitude expected from the response to anthropogenic climate forcing. This response is usually estimated using simulations with climate models forced by increases in atmospheric concentrations of greenhouse gases and aerosols, although theoretically-based approaches have also been used in some instances. Inherent in this process is the assumption that the simulations of climate models have reasonable skill, an assumption that is not justified at present for some small-scale, complex phenomena such as tropical cyclones (e.g. Randall et al. 2007; Walsh 2008).

Therefore, based on the formal Intergovernmental Panel on Climate Change (IPCC) definition of detection and attribution, the following conditions must be satisfied for successful detection and attribution:

- A signal must be detected;
- The signal must be consistent with the esimated response from modeling or theoretical techniques of a given combination of anthropogenic and natural forcings; and
- The detected signal must be inconsistent with alternative, plausible explanations that exclude important elements of the given combination of proposed forcings.

The last point is particularly important in that it provides a means of eliminating alternative explanations to a signal that might otherwise appear completely consistent with anthropogenic warming.

Attribution can also be achieved, but with considerably less confidence, by using statistical techniques to relate well-attributed variables to other climate phenomena. In this case, the confidence of the attribution would depend upon the plausibility of the hypothesized physical association between the variables. The current controversy regarding the influence to date of anthropogenic warming on tropical cyclones arises from this lower level of confidence.

Confident attribution of an anthropogenic effect depends on the likely magnitude of the anthropogenic effect as well as on the data and model simulations and theoretical understanding available for testing. Thus, if over the next few years a series of strong tropical cyclones were observed in the South Atlantic (a region where such events have been exceedingly rare in the past), we would be justified in concluding, with little formal studies, that this was likely the result of anthropogenic climate change. Similarly, if tropical cyclones off the east coast of Australia regularly started to retain their tropical characteristics as far away from the equator as, say, Sydney, we would again be justified in concluding that this was the result of anthropogenic changes. However, we do not expect such massive changes any time soon. So the question of attribution, given the expected degree of change from anthropogenic causes, is more difficult. This means that it is essential that we contrast the various formal and less-formal approaches to detection and attribution, so that we present balanced expressions of our confidence in any attribution statement. Quite simply, there are approaches than can yield strong statements about attribution, and others that can only yield weaker statements of confidence, given the tools and data available and the expected degree of change due to anthropogenic causes.

Examples of Detection and Attribution Studies

Before detailing the numerous obstacles facing detection and attribution studies of tropical cyclone behavior, we illustrate the process of detection and attribution through the use of a few examples. One of the easiest variables that can be used to demonstrate successful detection and attribution is global mean near-surface air temperature. Such a study is relatively straightforward for a number of reasons. The detected signal for global mean temperature increase in the past 100 years is highly statistically significant (e.g. Trenberth et al. 2007). The data used to estimate this trend have been extensively analyzed over many years and have small error bars. The main tool used for attributing this trend to man-made climate change, the global climate model, simulates global average temperature variability well (Randall et al. 2007). When global climate models are driven by the best available estimates of the radiative forcing of the 20th century, they reproduce well the observed temperature global average increase in the latter part of that century. Finally, when the key man-made elements of the forcing are removed, leaving only the naturally-varying components such as solar forcing, the models fail to reproduce the observed temperature increase. Thus the observed increase in global average temperature in the 20th century can be confidently ascribed to man-made global warming (Hegerl et al. 2007). Numerous earlier studies showed this (e.g Tett et al. 1999; Stott et al. 2001); more recently (Hegerl et al. 2007), this work has been extended to continental-average temperatures over most areas of the globe, demonstrating that these temperature increases can also be attributed to anthropogenic climate change.

Other observed climate trends have been formally ascribed to anthropogenic climate change. Barnett et al. (2005) and Pierce et al. (2006) analyzed trends in upper ocean temperatures in various ocean basins over the period 1960–2000, examining the observed change of temperature with depth and comparing it with the results of climate model simulations. They found that the oceanic warming over this period had been most pronounced in the upper part of the ocean and that this profile of temperature change was well simulated by numerical models using anthropogenic forcing, and could not be simulated when this forcing was removed. An increasing number of attribution studies have considered variables other than temperature. An anthropogenic influence has been formally identified in the increasing height of the tropopause over the last 3 decades (Santer et al. 2003), associated with stratospheric cooling due to ozone depletion and tropospheric warming due to increasing greenhouse gases. Observed multi-decadal changes in global patterns of mean sea level pressure have been attributed to anthropogenic forcing (Gillett 2005), as the observed changes cannot be explained by natural variability and are consistent with the response to anthropogenic forcing. However, the simulated pressure response to anthropogenic forcing is much weaker than the observed pressure trends, even though there is general agreement in the large scale spatial pattern of pressure changes.

These standard techniques have not been successfully applied to all climate variables, however. Problems have been encountered in detection and attribution studies of variables such as precipitation, due to the generally poor ability of models to simulate precipitation trends, the expected strong regional variations in trends due to climate change and large interannual variability in current and future climates (e.g. Lambert et al. 2004). Similar problems would be encountered in any similar formal attribution studies for tropical cyclones, beginning with the effect of data quality on signal detection.

Detected Trends in Tropical Cyclone Characteristics

Tropical Cyclone Data

The data that are typically used in trend analyses of tropical cyclones are the so-called "best track" data (Neumann et al. 1993). The process of compiling the best track data involves a review of the available tropical cyclone data by tropical cyclone forecasters, usually at the end of the tropical cyclone season, using all data sources available at the time that the review is performed. Thus for climate analysis there are immediate issues regarding the homogeneity of such data, particularly for less well-estimated variables such as tropical cyclone intensity, as the best available techniques for estimating this have changed over time (Landsea et al. 2006).

There are really two questions that need to be addressed in a reanalysis of the best track data, depending on the ultimate use of the data. The data can be made as accurate as possible for each storm, using all data available at the time and our present-day improved knowledge of tropical cyclones to update earlier estimates of variables contained in the data sets. Nevertheless, a data set that was reanalyzed in this fashion would not be homogeneous, as observational data and techniques have improved over time, thus potentially introducing spurious trends into the data. An argument can therefore be made for the creation of a "degraded" but uniform data set, one in which only a base level of data is used, combined with present-day analysis techniques (e.g. Kossin et al. 2007).

There are good reasons to believe that inhomogeneities have been introduced into the tropical cyclone best track record (e.g. Harper 2006; Kepert 2006). A very obvious change was the introduction of weather satellites in the 1960s; before this, many storms would have gone unrecorded. By the 1970s, these polar-orbiting satellites were providing regular, twice-daily visible and infrared images. By the 1980s, geostationary satellites provided 3-hourly coverage. The introduction of passive microwave sensors, followed by scatterometer data and cloud drift winds in the 1990s, provided improved delineation of tropical cyclone structure. Finally, in recent years, 3-axis stabilized geostationary satellites have provided rapid interval scans of tropical cyclones.

Moreover, analysis techniques have themselves changed. The gradual introduction and evolution of the Dvorak (1975, 1984) technique (Velden et al. 2006) of estimating tropical cyclone intensity from the appearance of the satellite image will have led to changes in estimated tropical cyclone intensities. This is particularly important in regions of the globe where there is no ground truthing of this technique as there is in the Atlantic ocean. More recently, objective techniques (Olander and Velden 2006) have further improved our ability to estimate tropical cyclone intensity.

It can be easily argued that even recent tropical cyclone records are not free from data inhomogeneities. The most telling example of this so far is the analysis of Kamahori et al. (2006) and Wu et al. (2006). Wu et al. (2006) examine trends in severe tropical cyclone numbers in different competing "best-track" data sets in the northwest Pacific region, those of the Joint Typhoon Warning Center, the Hong Kong Observatory and the Japanese Regional Specialized Meteorological Center (RSMC). The JTWC analyzed substantially greater numbers of intense cyclones than the other two forecast offices even in very recent times, when the data should be best. Wu et al. (2006) ascribe this result to the different analysis techniques used in the rival data sets; Kamahori et al. (2006) attribute these differences to modifications made by the Japan Meteorological Agency (JMA) to the original Dvorak technique so that it agreed better with surface observations. At present, it is not clear which data set best represents reality. Other best track data sets have similar issues. In the Australian best data set, three different versions of the Atkinson and Holliday (1977) wind-pressure relationship have been used at various times (Harper 2002; Kepert 2006).

In recognition of these problems, reanalyses of the tropical cylone record have been performed (Landsea et al. 2004; Harper 2006). Recent partial reanalyses of the tropical cyclone record have shown substantial corrections in trends compared with studies that have analysed existing best-track data. Kossin et al. (2007) use geostationary satellite images degraded to a consistent horizontal resolution over the period 1983 to 2005 to remove time-dependent biases, finding that detected changes in a measure of cyclone intensity in basins other than the Atlantic are smaller than in previous analyses. A recent reanalysis of the record in the western Australian region (Harper 2006) has also found that increases in severe tropical cyclone numbers are less than previously estimated using best track data. Landsea et al. (2006) use modern intensity estimation methods applied to satellite images of non-Atlantic tropical cyclones from the late 70s and early 80s to show that the intensities of the storms are likely significantly underestimated in the best track data that were compiled at that time.

There is a limit, however, to the ability of such studies to recreate completely the tropical cyclone record. Clearly, cyclones that have never been observed are lost forever and only estimates can be made of the numbers of storms that have been missed from the record. Landsea (2007) make such an estimate for the Atlantic basin, noting that although this region has been monitored by aircraft reconnaissance since 1944, such observations would not have covered the portion of the Atlantic east of 55W. Landsea (2007) estimates that about 2.2 storms per year would have been missed over the period 1900–1965, before the advent of routine satellite monitoring. In contrast, Holland and Webster (2007) estimate considerably smaller numbers of missing storms. Moreover, Holland (2007) questions Landsea's (2007) assumption that the ratio of landfalling storms to oceanic storms has been constant over this period, showing that this ratio may have changed due to cyclical variations in the formation locations of tropical cyclones. This conclusion was reinforced by Chang and Guo (2007), who estimate about 1.2 missing storms per year over the same period. In any event, the magnitude of the detected trend in Atlantic tropical cyclone numbers appears only to be reduced, not eliminated entirely when missing storm numbers similar to those assumed by Landsea (2007) are included in the data record (Mann et al. 2007). Any trend analyses of best track data would need to consider this and other data issues.

Trend Analyses

Numerous studies have analyzed tropical cyclone best track data for trends in tropical cyclone numbers and various measures of tropical cyclone intntensity. All recent work suggests that there is no current detectable trend in global tropical cyclone numbers, with numbers typically 80–90 per year (Emanuel 2005; Webster et al. 2005). Regional trends are somewhat more difficult to analyze, given the lower signal to noise ratio due to the high interannual variability of tropical cyclone numbers in many formation basins (e.g. McBride 1995). Analyses that have been performed show different trends in different basins. Most work has been performed in the Atlantic, since this is the basin with the best data. Trends in tropical cyclone indicators in the Atlantic have shown substantial positive trends since 1980, and these trends appear to be real (e.g. Mann et al. 2007). Kossin et al. (2007) show that since 1980, the Atlantic has experienced very large upward trends in an intensity-related variable, the Power Dissipation Index (PDI), a measure of the total integrated power in the storm. According to Kossin et al. (2007), trends in the northwest Pacific have been modest, have been downwards in the northeast Pacific and approximately flat in the other regions.

In other basins, where the data are poorer, there is more dispute regarding trends, particularly of variables like intensity that are more difficult to estimate, leading to uncertainty in detected trends. Intensity trends in the Australian region differ by geographical location, with the northwest region showing some increases in intensity since 1980, but the eastern region exhibiting no trend (Harper 2006; Hassim and Walsh 2008).

In contrast, Webster et al. (2005) found large trends in global tropical cyclone intensities in the period from 1970 to 2004, noting a doubling in the global number of intense category 4 and 5 storms over this period. The value of this paper was that it identified that there *were* such unexplained trends in the best track cyclone data, a fact that was not previously generally appreciated. Nevertheless, subsequent worked showed that these detected trends were likely at least partly the result of artifacts of the data. Kossin et al. (2007) showed that there was no apparent trend in global tropical cyclone intensity over that period, a time during which there was a substantial increase in category 4 and 5 storms numbers analysed by Webster et al. (2005). Instead, large decadal variations in global numbers of intense hurricanes were found. As already stated, there are a number of reasons to suspect that the best track data analysed by Webster et al. (2005) has artificial trends within it due to changes in observing practices. However, it is not clear to what extent correcting the existing data for inhomogeneities would alter the trends detected by Webster et al. (2005) and others: in other words, whether the trends would be eliminated, reversed or only modified.

In summary, the analysis of tropical cyclone trends is complicated by a lack of consensus regarding the state of the current tropical cyclone data used to determine such trends. The detected trends in the Atlantic ocean basin since 1980 appear to be real, however.

Attribution of Detected Trends in Tropical Cyclones

If a real trend is detected, attribution of such trends could be accomplished in a number of ways. A well-tested theory of tropical cyclone numbers or intensities could be compared with observed trends. Alternatively, a numerical simulation of tropical cyclones could be performed analogous to previously performed simulations of 20th century climate and the results with and without anthropogenic forcing compared with observations. Less confidently, statistical links could be made between well-attributed variables and tropical cyclone characteristics.

Studies that are largely statistical can give indications of associations that need to be investigated, but as tools for attribution they naturally provide less confident results. For example, Holland and Webster (2007) demonstrate a very plausible causal connection between the observed global warming, the warming of sea surface temperatures (SSTs) in the Atlantic and the subsequent changes in tropical cyclone behaviour in that region. A mechanism for this is proposed by Vimont and Kossin (2007), who show that there are apparent strong relationships between variations in tropical cyclone characteristics and the Atlantic Meridional Mode (AMM; see the review by Xie and Carton 2004). This is due to the circulation changes induced by the AMM, including changes to SST anomalies, whereby the main genesis regions of tropical cyclones tend to move equatorward to regions where the MPI is larger and where they are more likely to reach their MPI due to lower wind shear during positive phases of the AMM. One way to improve the confidence of the attribution to global warming in the analysis of Holland and Webster (2007) would be to employ physically-based modelling studies to show that a consequence of warming in the late 20th century is that changes in atmospheric circulation in models forced by changes in anthropogenic factors are consistent with a southward move in the main Atlantic tropical cyclone genesis regions, and that such circulation changes do not occur in unforced simulations. In this way, confidence would be improved in the Holland and Webster (2007) conclusion that tropical cyclone trends in the Atlantic are due to global warming. Thus such attribution studies need not take the form of direct simulation of tropical cyclones in climate models – and, given the current state of the art, this would be difficult (Walsh 2008). But they should include, where possible, an assessment of how anthropogenic climate change is likely to affect the crucial variables used in detected statistical relationships, employing either simulations or theoretical techniques to do so.

Theoretical Techniques

Tropical Cyclone Numbers

One difficulty with applying theoretical concepts to predict tropical cyclone formation for this purpose is that there is no widely accepted quantitative theory of tropical cyclone formation (Emanuel 1986; Rotunno and Emanuel 1987; Bister and Emanuel 1997; Simpson et al. 1997; Ritchie and Holland 1997; Ritchie et al. 2003; Montgomery and Enagonio 1998; Reasor et al. 2005; Tory et al. 2006). In the absence of such a theory, tropical cyclone genesis parameters have been developed that statistically relate large-scale atmospheric and oceanic fields to formation of tropical cyclones. The earlier work of Gray (1975) and the more recent parameters of Royer et al. (1998), DeMaria et al (2001) and Emanuel and Nolan (2004) all show an ability to diagnose tropical cyclone formation when forced by large-scale fields, but since they are diagnostic parameters, none of them necessarily constitute a predictive theory of formation that would be valid in a changed climate. In particular, Gray's parameter is unrealistically sensitive to changes in SST (Ryan et al. 1992), which severely limits its application to climate change studies.

One way to build confidence that these parameters may be useful in a changed climate would be to compare their predictions with the number of tropical cyclones directly simulated by a climate model in current and enhanced greenhouse climates, applying the large-scale fields generated by the models to the genesis parameters. This approach was employed by McDonald et al. (2005), who found reasonable agreement between the predictions of the Royer et al. (1998) Convective Yearly Genesis Parameter (CYGP) and the model simulation of tropical cyclone formation. Chauvin et al. (2006) reached a similar conclusion, while Camargo et al. (2007) showed mixed results. Royer et al. (2008; this volume) apply the CYGP to the enhanced greenhouse predictions of fifteen general circulation models, finding a wide variation of responses of the CYGP, due to the considerable differences in the models' SST predictions in a warmer world. These conclusions are also subject to the criteria used to identify tropical cyclones in the output of climate models (Walsh et al. 2007); if different selection criteria are used, different numbers of tropical cyclones would be detected. One potential use of these cyclone genesis parameters in a detection and attribution study would be to apply them to a suite of forced and unforced model simulations to determine whether there are any systematic differences in the genesis potential between the two and compare the differences to observed trends.

Tropical Cyclone Intensities

In contrast to tropical cyclone numbers, the theory of tropical cyclone intensities appears to be on a firmer foundation. The theory of tropical cyclone maximum potential intensity (MPI; Emanuel 1986, 1988) suggests that a tropical cyclone may be viewed as a Carnot cycle heat engine, with the warm reservoir being the sea surface temperature (or upper ocean heat content) and the cold reservoir being the upper tropospheric outflow temperature. The alternative, thermodynamic adjustment theory of Holland (1997) gives similar results. The application of earlier versions of these theories to the output of GCM simulations has suggested that increases in peak tropical cyclone intensities of 5–10% could occur some time after 2050 (Emanuel 1987; Henderson-Sellers et al. 1998; Walsh 2004).

Emanuel (2007) points out that the MPI predictions of Emanuel (1987) for the rate of change of intensity increase in the Atlantic since the 1970s, based upon the observed increase in SST, are considerably less than the observed changes in intensity in the Atlantic during that time. Emanuel (2007) has presented a new calculation based on the revised technique of Bister and Emanuel (2002). This version results in much better agreement with the observed intensity change in the Atlantic. Emanuel (2007) investigated the causes of the observed increase of tropical cyclone power dissipation index (PDI) over the period since 1950. He also created a diagnostic parameter that included the effects of changes in potential intensity, low-level vorticity and vertical wind shear. The results showed that the observed increase of PDI in the Atlantic since 1980 was consistent with changes in these three factors, including increases in low-level vorticity and potential intensity. The increases in potential intensity since 1980 were caused by increases in SST and decreases in upper troposphere temperature in the tropical Atlantic, thus increasing the thermodynamic efficiency of tropical cyclones. Note that the PDI is an integrated measure of cyclone characteristics and as such may not be the most sensitive variable for use in studies of detection and attribution.

Thus these results appear to indicate, with good skill, relationships between trends in large-scale variables and tropical cyclone PDI. Regarding attribution of these trends, it is clear that there is a relationship between the increases in Atlantic tropical SST and similar increases in global temperatures that have been well ascribed to global warming (Elsner 2006; Mann and Emanuel 2006; Trenberth and Shea 2006; Elsner 2007). In particular, Santer et al. (2006) showed this by using the standard formal attribution methodology in which a number of model simulations of 20th century climate were run with and without greenhouse gas forcings, so this is a conclusion with high confidence. It is also true that a number of studies have demonstrated a plausible statistical relationship between SST increases and intense tropical cyclone numbers in the Atlantic (Hoyos et al. 2006; Holland and

Webster 2007) and increases in SST are an expected consequence of global warming. Nevertheless, the decreases in tropical upper troposphere (100 hPa) temperature, which Emanuel (2007) found contributed to increased Atlantic tropical cyclone intensity, are not expected consequences of global warming. Meehl et al. (2007), among many others, show that tropical temperatures are expected to warm at this altitude in the 21st century, which is inconsistent with an anthropogenic cause for the observed cooling. It is also not clear why the low-level vorticity in the tropical Atlantic has been increasing. Nor is it clear what the relationship is between low-level vorticity and global warming. Thus the attribution of the increases in Atlantic tropical cyclone PDI to factors related to global warming is of less confidence as a result. For increased confidence, one would have to examine the simulation of Emanuel's (2007) diagnostic PDI in climate models forced with and without anthropogenic factors over the late 20th century. Additionally, the relationship between SST and PDI is much weaker in the northwest Pacific than in the Atlantic, where SSTs have also been increasing since 1980, but where the trend in PDI is not pronounced (Klotzbach 2006; Emanuel 2007). This is due to different trends in vertical wind shear and vorticity in this region. These different regional trends would also have to be seen in 20th-century climate simulations for confident attribution.

Simulation Techniques

Numerous studies have employed climate models to directly simulate the formation and intensification of tropical cyclones. Since the early work of Manabe et al. (1970), the ability of climate models to generate lows that resemble tropical cyclones has developed considerably. Currently, numerous groups worldwide are developing a capability to perform these types of simulations. A recent review is given in Walsh (2008).

Climate models have varying abilities to simulate tropical cyclone characteristics. In general, though, they usually do not simulate numbers that are very close to observed formation rates. One difficulty, as detailed in Walsh et al. (2007), is that the storm detection schemes used to determine the rate of formation within the models are often tuned to the observed formation rate, thus making it impossible to determine the actual ability of the model to generate tropical cyclones in the current amount.

The situation is even worse for intensities, with climate models having an inadequate simulation of the observed cyclone intensity distribution, mostly simulating tropical cyclones that are considerably weaker than observed. Thus simulating observed intensity trends as part of a model-based attribution study would be problematic.

Nevertheless, in general agreement with the earlier predictions of MPI theory, direct simulations of the effect of global warming on tropical cyclones suggest intensity increases of 5–10% by some time after 2050 (Knutson and Tuleya 1999; Walsh and Ryan 2000; Knutson et al. 2001; Knutson and Tuleya 2004).

Thus at present direct simulation as a tool for detection and attribution studies is in its infancy. Recently, though, Knutson et al. (2007) showed that a modeling system could reproduce the observed trend in Atlantic tropical cyclone numbers over the period 1980–2005. Emanuel et al. (2008) use a downscaling methodology employing a synthetic track generator to produce climatologies of tropical cyclones from climate model output. Similar modeling systems have the potential to elucidate the causes of the increase in numbers in the Atlantic by performing attribution experiments that change aspects of the simulation and examine their effects on simulated formation rates.

What is Required to Improve Detection and Attribution?

At present, the possibility that anthropogenic warming has affected tropical cyclone behavior in the Atlantic is a plausible hypothesis. Hegerl et al. (2007) indicate that it is more likely than not that anthropogenic warming has affected tropical cyclone behavior. This is a fairly weak conclusion but it is the best that we can obtain at present. It should be noted that the detection and attribution of a human influence on global climate has been an evolutionary process, with relatively weaker conclusions based on less formal approaches reached in the IPCC Second Assessment (Santer et al 1995). The Summary for Policymakers of that assessment concluded "The balance of evidence suggests a discernible human influence on global climate" (Houghton et al. 1995), which is much weaker than the conclusions of the IPCC Fourth Assessment: "Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations" (Hegerl et al. 2007).

The formal attribution process as clearly defined by the IPCC is the best way to make strong conclusions about climate change effects. Due to the current inadequacies of tropical cyclone models and theories, formal attribution following the IPCC approach is not possible at this time. Therefore we must also employ other methods, as has been done in the past for assessing the possible effects of global warming on the future behavior of tropical cyclones (e.g. Henderson–Sellers et al. 1998; Walsh 2004). It is inevitable that this will involve making hypotheses about the physical reality of statistical relationships between variations in variables that have already been formally attributed and variations in tropical cyclone characteristics. The level of confidence for attribution of these statistical relationships is directly related to the level of confidence that we have in the hypothesized physical relationship that explains them. If these physical relationships are well-established, either by theory, simulation or observation at shorter time scales, then this confidence can be reasonably high. Moreover, there must also be some reason to believe that this physical relationship will remain the same in a warmer world. These ideas could provide the basis for a more structured approach to attribution until such time as simulations and theory improve to the point when the much stronger formal attribution process becomes possible.

The first step in any attribution process, formal or otherwise, is detection of a trend. Improved tropical cyclone data records would increase our confidence that trends had actually been detected and were simply not due to data inhomogeneities. There are a number of approaches that could be undertaken: a consistent reanalysis of the polar-orbiting satellite record, for instance, could be performed similar to the method used Kossin et al. (2007) for the geostationary satellite data. Given the finer resolution or the polar-orbiting satellites, this may lead to a more accurate determination of intensity trends. There are a number of limitations of any reanalysis procedure, however. As mentioned previously, storms that were never observed by anyone are gone forever, and only estimates can be made of their effect on any detected trends. For a reanalysed tropical cyclone data set to most useful for climate analysis, there have to be no artificial trends in the data caused by changes in observing practices. The reanalysis of Kossin et al. (2007) attempts this but at the cost of a degraded resolution of recent satellite data. One possibility would be instead to create a best track dataset with all available data but include error estimates that are larger for earlier storms. In this way, climate trends could still be analysed with statistical techniques that take into account the change in the error distribution with time when statistical significance of trends is calculated. Additionally, change points in the observing systems should have created change points in the data, and these can be corrected using well-established methods (e.g. Lanzante et al. 2003).

Once a robust trend is detected, the attribution step would ideally utilize an excellent climate model that produces tropical cyclones of about the right intensity and numbers, run with and without anthropogenic forcing, that would reproduce with reasonable fidelity the observed intensity trends, particularly in the Atlantic. The work of Knutson et al. (2007) is an important step in this direction, as their results imply that the increase in tropical cyclone numbers in the Atlantic is related to the pattern of the observed SSTs that were used to force their model. Since the SST anomalies are likely related to global warming, at first glance this suggests a causal link between global warming and tropical cyclone numbers in the Atlantic. Similar models will be used to run coupled climate runs that could then help identify the anthropogenically-forced transient climate response of tropical cyclones in the Atlantic and elsewhere.

In the absence of excellent climate model simulations, studies such as those of Emanuel (2007) could be further analysed to strengthen their conclusions. Specifically, it is presently unclear whether all of the individual components of his PDI parameter (MPI, vorticity and vertical wind shear) are varying in a manner consistent with an anthropogenic cause. An anthropogenic influence on MPI is likely, based on its formulation and our theoretical understanding of influences on tropical cyclone intensity, but this is not clear for vorticity or vertical wind shear. For instance, Vecchi and Soden (2007) show that multi-model projections of vertical wind shear trends in the Atlantic over the 21st century are strongly positive in parts of the tropical Atlantic (i.e. more hostile to cyclone formation), although trends are neutral in the main development region. This issue can be addressed by examining changes in the large-scale atmospheric fields between two sets of GCM simulations, with and without anthropogenic forcing, to determine whether the observed trends in vorticity and vertical wind shear are similar to those expected from anthropogenic forcing. Similar studies could be performed with other hypothesized combinations of variables. If a quantitative theory of tropical cyclone formation were to be developed, studies along these lines could also address the issue of the relative responses of formation and intensification to anthropogenic forcing. Important in all of these type of studies is whether there are good reasons to believe that relationships between parameters will remain the same in a warmer world. Such reasons would include a theory successfully tested at shorter time scales, such as the Emanuel MPI theory or a well-established observed relationship that is not expected to change in a warmer world, such as that between vertical wind shear and tropical cyclone intensification (e.g. Vecchi and Soden 2007).

Excellent climate model simulations have the potential to suggest where and when the detection of an anthropogenically-forced tropical cyclone signal might be achieved. Leslie and Karoly (2007) examine this issue using multi-member ensembles of simulations with a variable-resolution climate model, including both control and climate change simulations. They show that there is large natural decadal variability in the simulated number of strong tropical cyclones per decade in the northeast Australian region but that the simulated increase in strong tropical cyclones due to anthropogenic climate change should appear above the noise some time in the 2020s or later. The confidence of this prediction would be substantially increased if other independent models were to make similar predictions.

The formal detection and attribution methods described above and in Hegerl et al. (2007) use a null hypothesis of no expected change in the climate variable being considered, apart from that due to natural internal climate variations. Now that there is a substantial body of scientific research supporting the conclusion that most of the observed global average temperature increase since the mid-20th century is very likely (more than 90% certain) due to the increase in anthropogenic greenhouse gases in the atmosphere (Hegerl et al., 2007), it may be more appropriate to use a different null hypothesis. It is now appropriate to use a null hypothesis that global scale temperature increases, including sea surface temperature increases, over the past fifty years have a significant anthropogenic influence and then apply the same attribution methods to detect and attribute an anthropogenic climate change influence on tropical cyclones. The problem is substantially changed, now making use of the prior information that anthropogenic climate change is causing large scale warming and then seeking to quantify the specific changes expected to occur in the frequency and intensity of tropical cyclones. This is essentially a Bayesian statistical approach (e.g. Lee et al. 2005).

The use of Bayesian statistics has the potential to increase the sensitivity of detection and attribution studies and make it easier to increase the confidence that observed changes are due to anthropogenic influences. Bayesian techniques are being increasingly employed in atmospheric and oceanic statistical models (Wikle 2000; Berliner et al. 2002; Katz 2002). Elsner et al. (2004) apply Bayesian statistics to detect discontinuities ("change points") in hurricane data, while Elsner and Jagger (2004) show that the inclusion of 19th century data as priors improved the significance of relationships between indices of ENSO and the NAO and 20th century North American coastal hurricane incidence. Jagger and Elsner (2006) used Bayesian extreme value statistics to show that warmer global temperatures were associated with larger numbers of intense hurricanes, although this result was not highly significant. Their results could also be interpreted to show that observed increases in global temperature and increases in maximum hurricane intensity are consistent with MPI theory.

Conclusion

Fundamentally, the main issue here is that the more sound, physically-based methods there are that make the same prediction, the more confidence that can be placed in that prediction. Formal detection and attribution of a climate change signal requires more than a plausible physical association between variables; it requires that predictive tools are employed to distinguish anthropogenic effects from natural variability. Current studies clearly show a detected signal of tropical cyclone changes in the Atlantic and there have been plausible arguments relating these changes to global warming. But formal attribution of these trends, quantifying the fraction of the observed change due to anthropogenic climate change and the fraction due to natural climate variations, has not taken place—yet. For this to occur, climate model simulations and theories of tropical cyclones need to improve. In the meantime, improved inferences can be made using a combination of large-scale numerical simulation and statistical methods. Such a process is vital in increasing the confidence of future projections of climate change.

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