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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 4.2 : **Possible Relationships Between Climate Change and Tropical Cyclone Activity**

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4.2.1 **Introduction**

This report reviews the current science on possible relationships between climate change and tropical cyclone (TC) activity/intensity on different time scales. Since variability of tropical cyclone activity/intensity on intraseasonal, interannual, interdecadal and multi-decadal scales is a topic addressed separately in another section of this report (Subtopic 4.1), the emphasis of this chapter will be on climate change (specifically meaning long-term trends in climate) as opposed to cyclical variations. An earlier review and assessment of this topic was presented in Henderson-Sellers et al. (1998). They concluded: i) there was no clear evidence for long-term trends in TC activity; ii) the potential intensity (PI) of storms would remain the same or increase by 10-20%, in terms of central pressure fall, for a doubling of CO_2, although uncertainties remained with PI approaches; iii) little could be said about the future distribution of intensities or about future frequencies of TCs; and iv) the broad geographic regions of cyclogenesis and of occurrence of TCs were unlikely to change significantly. A 10-20% increase in central pressure fall would correspond to a smaller (roughly 5-10%) percentage increase in terms of maximum surface wind speeds. Walsh (2004) presents a more recent overview of the TC/climate change problem. The present report attempts to briefly summarize earlier work, but with a greater emphasis on work published since the Henderson-Sellers et al. assessment was completed, including recent published work on trends in observed TC metrics.

A few statements in this report are non-peer-reviewed critiques of existing papers from our writing team. Since there was not agreement among the writing team about whether these types of critiques should be included in the report, we have identified such statements with square brackets [].

4.2.2. **Background on tropical climate changes relevant to tropical cyclone activity**

There is substantial evidence that the large-scale environment in which hurricanes form and evolve is changing as a result of anthropogenic emissions of greenhouse gases and aerosols. A recent review of the climate change detection and attribution field (IADAG 2005) concluded that there is increasing evidence that “most of the global warming over the past 50 years is likely due to the increase in greenhouse gases.” A study of subsurface ocean data by Barnett et al. (2005) concluded that an anthropogenic warming signal is penetrating the world oceans, in broad agreement with model simulations that include the greenhouse gas forcing. Model-based attribution of early 20th century global warming (e.g. 1900-1944) to specific causes is more ambiguous, with various studies suggesting significant contributions from multiple factors, including increased greenhouse gases, solar variability, decreasing volcanic activity, and internal climate variability (e.g., Stott et al. 2000; Delworth and

Knutson 2000; Meehl et al. 2004; Knutson et al. 2006).

On the regional scale of most relevance to local hurricane interaction, some aspects of the tropical climate appear to be changing in a trend-like fashion. There is increasing evidence that tropical sea surface temperature increases, as reported in recent studies (Emanuel 2005a; Webster et al. 2005), are at least partly a response to long-term increases in greenhouse gas concentrations. For example, Santer et al. (2006) find that observed SST increases in the Atlantic and North Pacific tropical cyclogenesis regions during the 20th century are unlikely to be due solely to unforced variability of the climate system, but are more realistically simulated in experiments using estimated historical climate forcing. Their internal climate variability assessment and external forcing results are made more robust by their use of 22 different climate models and two observed SST reconstructions. In the models in which individual forcing experiments were available, they find that the human-induced change in greenhouse gas forcing is the main cause of the 20th century warming, and particularly of the late 20th century warming. Their results support earlier regional surface temperature trend assessments based on a more limited set (two) of models (Knutson et al. 2006) or on a more limited set of forcings (Karoly and Wu 2005) both of which found model-based support for anthropogenically forced 20th century warming trends in the tropics and other regions. In Knutson et al., the simulations where anthropogenic and natural forcing agents were evaluated separately indicated significantly closer agreement with observed trends over much of the tropical oceans in the anthropogenic forcing runs than in the natural forcing or internal climate variability runs. The anthropogenic forcings in these experiments included changes in well-mixed greenhouse gases, ozone, and aerosols, as well as land use change, whereas natural forcings included solar variations and aerosols from volcanic eruptions.

For the tropical North Atlantic, the roles of naturally occurring oscillations versus radiative forcing variability and trends on tropical Atlantic SSTs have also been evaluated using statistical modeling approaches. The potential importance of a naturally occurring large-scale oscillation of SSTs known as the Atlantic Multi-decadal Oscillation (AMO) was noted by Goldenberg et al. (2001), who found that multi-decadal variations in Atlantic major hurricane counts since the 1940s covaried with fluctuations in both Main Development Region (MDR) vertical wind shear as well as an AMO index derived from detrended SST data. Mann and Emanuel (2006) noted that late summer SSTs in the Atlantic Main Development Region (MDR) closely track, on long time scales, surface temperatures averaged over the entire Northern Hemisphere, with substantial warming over the 20th century. Using a statistical modeling approach, they suggested that most of the low-frequency (multi-decadal) variation and warming trend in MDR SSTs is being driven primarily by changing radiative forcing, as opposed to being part of the AMO. Their approach used terms proportional to global mean SST and to aerosol forcing, the latter of which they argued was justified by a regionally enhanced cooling response to aerosols over the tropical Atlantic during late summer. In general, climate forcing from aerosols is much more uncertain than the forcing due to increasing greenhouse gases (e.g., IPCC 2001).

In another recent statistical analysis, Trenberth and Shea (2006) show that the method of construction of AMO indices can have a significant impact on AMO anomaly values for various time periods. They proposed that the index be constructed as a residual after removal of a near-global (60N-60S) SST component, as opposed to residual from a linear trend (as in Goldenberg et al. 2001). Using this approach, they derive a revised AMO index with smoothed anomaly values of about +/- 0.2 C and a transition from negative to positive values in the mid 1990s. However, the contribution of their low-pass-filtered AMO anomalies to the record summer of 2005 values is quite small (<0.1C), and the anomalies from 1870 to 1900, are also much smaller (closer to zero) compared to those using the method of Goldenberg et al. [In removing the global or near-global mean SST from the Atlantic SST series, both Mann and Emanuel (2006) and Trenberth and Shea (2006) include the Atlantic SST in their computation of the global or near-global mean. This procedure could have the effect of artificially damping the AMO amplitude.]

Enfield and Mestas Nuñez (2000) have previously published a means of deriving an “Atlantic Multidecadal Mode” based not on linear trend removal, but on a complex empirical orthogonal function

(CEOF) decomposition, in which a “Global Warming Mode” is distinguished from the Atlantic Multidecadal and Pacific interdecadal modes based on the CEOF modal decomposition. In their analysis the AMO is the third CEOF in a dataset from which an ENSO-related CEOF had previously been removed (i.e., in practical terms, the AMO is their fourth CEOF). It should be noted that different SST reconstructions have been used by various investigators, which may also contribute to differences seen in the resulting analyses (e.g., Santer et al. 2006).

The existence of a robust AMO-like internal mode of the climate system is supported by some climate models, which simulate internal modes of variability that resemble the observed AMO signal in several respects (Delworth and Mann 2001; Knight et al. 2005) Model based studies also indicate that such multidecadal variations of Atlantic SSTs can have important impacts on vertical wind shear in the Atlantic MDR (Zhang and Delworth, 2006; Knight et al. 2006), which Goldenberg et al. (2001) proposed can then affect Atlantic hurricane activity.

Elsner (2006) uses Granger causality statistical analysis to demonstrate that global mean temperature can be used to predict North Atlantic SST but not the other way around. This, he argues, supports the hypothesis that greenhouse gases are the causal forcing agent for global temperatures and thus for North Atlantic SSTs and hurricanes. To eliminate nonstationarity in the data, Elsner time differences both the global temperature and North Atlantic SST series before performing the causality tests. [Time differencing acts as a strong high-pass filter on the data, and thus his conclusions about Granger causality strictly apply only to the higher frequency fluctuations that remain in the data. The inference that global temperature Granger causes North Atlantic SST fluctuations on multidecadal time scales thus depends on the assumption that the direction of causality for the high frequency fluctuations also applies to the lower (filtered) frequencies, which has not yet been demonstrated by his analysis.]

Trenberth et al. (2005) have reported a substantial increase (1.3% +/- 0.3% per decade) in column-integrated atmospheric water vapor over the global oceans (1988 to 2003) as derived from the special sensor microwave imager (SSM/I) satellite data set. Thus, it appears that tropical precipitable water vapor is increasing in a manner consistent with the notion of approximately constant relative humidity, and in accord with model simulations of tropical relative humidity under warming conditions (e.g., Knutson and Tuleya 2004). As noted by Trenberth et al., the relatively short available record in their study is a limitation with regard to inferring an anthropogenic climate change signal.

The vertical profile of historical tropospheric temperature trends in the tropics has been a subject of considerable debate in the climate change community. In a recent study, Santer et al. (2005) examined the profile of temperature changes for the period 1979-1999 produced by a large ensemble of climate models, all incorporating a range of historical forcings including greenhouse gases and aerosols, with some of the models incorporating volcanic eruptions. The climate models generally simulate an enhanced warming of the tropical upper troposphere relative to the surface. In contrast, the observed vertical profile of radiosonde-derived temperature trends over this period has a distinctly different character from the model simulations, with the observations showing much smaller tropospheric warming trends relative to the surface. Finally, Santer et al. showed that both models and observations have interannual variations in upper tropospheric temperatures that are enhanced relative to the surface variations. Thus the vertical structure of interannual variations is similar to that of modeled trends (1979-1999), but is in sharp contrast with the vertical structure of observed trends (1979-1999) in tropical tropospheric temperatures. Their results are suggestive of serious remaining problems with radiosonde-derived and satellite-derived temperature trends--a conclusion also receiving some support from two other recent studies which examined issues with radiosonde-based observations (Sherwood et al. 2005) and satellite-based analyses (Mears and Wentz 2005).

The possibility that tropospheric trend estimates from radiosonde-based observations (including reanalyses) may be unreliable should be considered as a caveat when reviewing other published reports on related trend measures. Other measures of tropical climate relevant to hurricane formation which have been examined for possible trends include CAPE and potential intensity. For example, Gettleman et al. (2002) found a preponderance of upward trends in tropical CAPE since roughly the early 1960s. DeMott and Randall (2004) examined a larger number of tropical stations over a shorter period (1973-1999) and reported a more evenly divided mixture of increasing and decreasing CAPE trends. Trenberth (2005) questioned the reliability of the radiosonde data in DeMott and Randall's larger sample. Free et al. (2004), using a selected set of 14 tropical island radiosonde stations, found only small, statistically insignificant trends in potential intensity over the periods 1975 to 1995 and 1980 to 1995. Emanuel (2006) reported a 10% increase in Atlantic MDR potential intensity since 1982 based on HadISST and NCEP reanalysis data.

Concerning large-scale circulation indices, Bell and Chelliah (2006) have statistically linked multi-decadal changes in Atlantic hurricane activity to a series of large-scale circulation features, all correlated to a multi-decadal circulation signal derived from empirical orthogonal function (EOF) analysis of upper tropospheric velocity potential. The indices of Bell and Chelliah's modes are of insufficient length to determine whether they have a cyclical or trend-like character, or some combination of trend and cycle. No published studies to date have linked pronounced historical circulation changes such as Bell and Chelliah's multi-decadal signal or Goldenberg et al.'s (2001) index of Atlantic MDR vertical shear to a radiative forcing mechanism. Similarly, Saunders and Lea (2005) and Elsner et al.(2000; 2006) find statistical links between U.S. landfalling hurricane activity and large-scale circulation anomalies, although long-term climate trends in their predictors have not been firmly established. In the Southern Hemisphere, observed trends in the Southern Annular Mode have been at least partly attributed to anthropogenic forcing (Marshall et al. 2004). Pezza and Simmonds (2005), commenting on the rare atmospheric conditions associated with the first reported hurricane in the South Atlantic (Catarina, 2004), suggested that observed and predicted trends in the Southern Annular Mode could increase the probability of such conditions in the future.

Two recent studies (Rotstayn and Lohmann 2002; Held et al. 2005) have found that 20th century trends in Sahel rainfall may have been at least partially forced by anthropogenic forcing, albeit through different physical mechanisms in the two studies. In Rotstayn and Lohmann's study, anthropogenic indirect aerosol forcing through the interaction of sulfate aerosol with cloud and precipitation processes, causes a pronounced decrease in rainfall in the Sahel, whereas in Held et al. (2005) the Sahel drying from the 1950s to the 1980s is simulated by approximately equal contributions of internal climate variability and radiative forcing (the latter being primarily anthropogenic "direct effect-only"aerosol forcing and increasing greenhouse gases). Vecchi et al. (2006) report evidence for a century-scale weakening trend in the Walker Circulation in the Pacific, similar to that which occurs during El Niño, and consistent with the slightly El Nino-like warming trends predicted by some climate models. Both West African monsoon activity and El Niño have been statistically linked to Atlantic hurricane activity (e.g., Gray 1990; Bell and Chelliah 2006). The Southern Annular Mode, Pacific Walker circulation, and Sahel drought studies cited above serve as reminders that the relationship between radiative climate forcing and hurricane response may involve a variety of complex tropics-wide or even global-scale phenomena.

4.2.3 **Observed trends and low-frequency variability of tropical cyclone activity**

In the past year, two observational studies of low-frequency variability and trends in several measures of tropical cyclone activity (Emanuel 2005a; Webster et al. 2005) have attracted considerable attention in the hurricane research community.

Emanuel (2005a) developed a "Power Dissipation Index" (PDI) of tropical cyclones, based on the time integrated cube of the estimated maximum sustained surface wind speeds, some of which are inferred from central pressure reports, for the Atlantic and Northwest Pacific tropical cyclone basins from the late 1940s to 2003. After adjusting for time-dependent biases due to changes in measurement and reporting practices, Emanuel reported an approximate doubling of the PDI over the period of record, with contributions from apparent increases in both intensity and mean storm duration. The low-pass filtered PDI series in his study were significantly correlated with large-scale tropical SST indices for both basins. Pielke (2005) noted that there are no evident trends in observed damage in the North Atlantic region, though Emanuel (2005b) notes that a PDI series such as Landsea's (2005) based on only U.S. landfalling data, contains only about 1 percent of the data that Emanuel's (2005a) PDI contains, which is based on all storms over their entire lifetimes. Thus a trend in basin-wide PDI may not be detectable in U.S. landfalling PDI since the former index has a factor of 10 advantage in signal to noise ratio.

A subsequent comment by Landsea (2005) resulted in adjustments, particularly removing much of the large post-2000 upswing in the Atlantic PDI series through 2003, although Emanuel (2005b) reported that these adjustments had minimal impact on the Northwest Pacific results. In particular, Landsea’s (2005) PDI analysis for the Atlantic basin shows no evidence for a trend from 1949-2004, similar to time series of major hurricane counts or Accumulated Cyclone Energy (ACE, Bell and Chelliah 2006), provided that wind speeds early in the record are not adjusted, as Landsea (2005) now recommends. Landsea’s (2005) PDI for U.S. landfalling Atlantic tropical cyclones (1900 to 2004) also shows no evidence of an upward trend, with the past two seasons (2004 and 2005) being strong positive outliers, with similar magnitude to that estimated for 1886. As noted by Emanuel (2005b), this is not necessarily inconsistent with the observed trends in basin-wide statistics.

Recently Emanuel (2006) presented an alternative PDI measure for the Atlantic basin, the storm maximum PDI, which was extended back into the late 1800s. This measure tracks the long-term variation in Atlantic MDR SST—particularly the century-scale warming trend--fairly closely, and is also notably well-correlated with MDR SST, particularly after 1970 (r^2 = 0.83 from 1970 onwards, using low-pass (1-3-4-3-1) filtered data). A similar behavior is seen for TC counts for the Atlantic basin (e.g., Mann and Emanuel 2006). The reliability of Atlantic basin-wide TC measures prior to the 1940s is highly debatable, as Landsea (2005) argues that the PDI values even from the more recent 1940s to the 1960s are likely to be substantially undercounted due to lack of routine aircraft reconnaissance and geostationary satellite monitoring of TCs far from land. Mann and Emanuel (2006) argue that detection of the existence of TCs in the years prior to the 1940s was less problematic than TC intensity estimates, since in the absence of aircraft and satellites based guidance to warn them off, ships often encountered TCs at sea, at least peripherally. On the other hand, Landsea et al. (2004) had earlier estimated the number of “missed” Atlantic basin tropical storms and hurricanes per year to be on the order of 0-6 for the period 1851-85 and 0-4 for the period 1886-1910. They argued that the TC record over the Atlantic should by no means be considered complete for either frequency or intensity of tropical storms and hurricanes for the years 1851 to 1910, in contrast to the more complete and accurate information available for landfalling TCs along much of the U.S. coastline.

In a more regionally focused study, Mock (2004) analyzed records of TC activity from 1769 to 2003 for the state of South Carolina in an effort to assess a relatively homogeneous multi-century record of tropical storm and hurricane strikes. This analysis suggests pronounced multidecadal variability, but no long-term trends. Given the well-established communities along the South Carolina coastal regions since the 18th century, it is unlikely that any significant hurricanes were not captured in this record.

Webster et al. (2005) reported that the number of category 4 and 5 hurricanes has almost doubled globally over the past three decades. Although their analysis spans a shorter time period than Emanuel's, due to their decision to limit the analysis to the satellite era, their results indicate that a substantial increase has occurred in all six tropical storm basins. They found no trend in the numbers of tropical storms and hurricanes or in the maximum wind speed observed globally each year. While they did also find an increasing trend in the duration of Atlantic tropical cyclones over this period, no significant trend was identified in the remaining global basins for duration. In a follow-on study, Hoyos et al. (2006) found that the increasing trends in category 4 and 5 tropical cyclones are principally correlated with SST as opposed to other environmental factors.

The recent Emanuel and Webster et al. studies continue to be the subject of much debate in the hurricane research community, particularly with regard to homogeneity of the tropical cyclone data over time and the required adjustments. For example, Knaff and Sampson (2006) reanalyzed the maximum intensities of Northwest Pacific tropical cyclones over the period 1966-1987 and found a much reduced upward trend in annual numbers of category 4 and 5 storms in their reanalyzed data relative to the original best track data. Chan (2006) extended the analysis of Webster et al. for the Northwest Pacific basin back to earlier years and argued that the "trend" in that basin is part of a large interdecadal variation (see also Webster et al. 2006; Chan and Liu 2004). Chan used unadjusted data from the earlier part of the record, in contrast to the adjustments for this period proposed by Emanuel (2005a) for the basin.

Landsea et al. (2006) propose that much – perhaps the majority – of the global increase in Category 4 and 5 TCs since 1970 may be due to data reliability issues in that strong TCs are more accurately monitored in the more recent years. They documented six additional Category 4 and 5 TCs in the North Indian Ocean during the 1970s and 1980s, which were not counted as such in the Webster et al. (2005) study. The inclusion of these extreme TCs make the trend found in the North Indian Ocean much weaker, perhaps insignificantly so. They argue that such systematic undercounts are endemic in the global TC records, especially in basins that rely primarily upon satellite imagery for intensity monitoring (that is, all but the Atlantic).

Using a different approach, Sriver and Huber (2006) computed power dissipation statistics from ECMWF (ERA-40) reanalysis data from 1958 to 2001. Despite the coarse resolution of the reanalysis data (1.125^o longitude by 1.125^o latitude), their resulting global indices, normalized by their standard deviations, are well-correlated with Emanuel's (2005a) Atlantic + Western North Pacific PDI, particularly after 1978. Sriver and Huber estimated a sensitivity of global power dissipation of roughly 60% per 0.25 degree Celsius SST increase. [The ERA-40 reanalysis has benefited from improvements in the observing systems over the years, which conceivably could have led to inhomogeneities or artificial increasing trends in the PDI measures derived by Sriver and Huber, particularly considering trends involving the pre-1979 era, when the agreement with Emanuel's PDI is less compelling. For example, Special Sensor Microwave/Imager (SSM/I – 1987), European Remote Sensing Satellite (ERS – 1991) and increased cloud motion winds (1970s through 1990s) should contribute to better defined surface winds in the tropics and thus may cause some artificial increasing trend in ERA-based PDI values.] Of possible relevance to the tropical storm issue, Hoskins and Hodges (2005) discuss problems with using the ERA40 and other reanalyses for examining past Southern Hemisphere extratropical cyclone numbers and intensity.

Michaels et al. (2006) hypothesized that Atlantic tropical cyclones respond to an SST threshold such that major hurricanes are possible only for storms experiencing SSTs above the threshold value at some point in their lifetime. Using a statistical-analog approach, they infer an intensity sensitivity of about 6.3% in wind speed for a 2 degree Celsius SST rise. In comparing these sensitivities, note that PDI depends on the cube of the wind speed and includes effects of storm duration and frequency. Nonetheless, a much higher intensity sensitivity is likely implied by Sriver and Huber's analysis than by Michaels et al. For example, if we assume based on Emanuel (2005) that the PDI change is half due to intensity increase and half to duration increase with no frequency change, the above sensitivity estimates still differ from each other by more than a factor of 10.

Over the period 1986-2005, Klotzbach (2006) finds no significant change in global net tropical cyclone activity, and a small trend (~+10%) in category 4 and 5 TC frequencies. He restricted his analysis to this 20-yr period owing to data quality concerns. In particular, while he finds a large increase in TC activity in the Atlantic from 1986-2005, there is a nearly commensurate decrease in the Northeast Pacific, and the remaining global basins show negligible changes in the 20 year period. Klotzbach's Fig. 2 shows a tropical SST warming trend of roughly 0.2^{o}C during this period. It should be noted that climate change detection studies in a variety of contexts have found that the ability to detect significant trends in climate records is reduced as the record length is shortened, and Klotzbach's analysis is based on a relatively short record compared with other analyses. On the other hand, Klotzbach's conclusion that there have been only minor alterations in global TC activity in the last 20 years is consistent with Landsea et al.'s (2006) assertions that monitoring changes in the 1970s and 1980s, rather than true climate changes, may be responsible for the increased extreme TC occurrence during from 1990s and early 2000s found in Webster et al. (2005). Klotzbach's analysis included a portion (1986 to 1990) of the period whose intensity estimates were questioned by Landsea et al. (2006).

Using a partial correlation statistical analysis, Elsner et al. (2006) examined the relationships between global temperature, tropical Atlantic SST, and Atlantic PDI on high-frequency interannual time scales. They concluded that the positive influence of global temperature on PDI was limited to an indirect connection through the tropical Atlantic SSTs. After controlling for the effect of tropical Atlantic SSTs on PDI, the correlation of PDI with global temperatures was slightly negative. This result was consistent with idealized modeling studies (Shen et al. 2000) and with statistical analyses of ENSO-Atlantic TC relationships (Tang and Neelin 2004), both indicating inhibiting effects of tropospheric stabilization on TC intensity or frequency.

Kamahori et al. (2006) examine how the records of typhoon days compare between the Japanese Meteorological Agency (JMA) typhoon best tracks and those from the Joint Typhoon Warning Center (JWTC, which were used in Emanuel (2005a) and Webster et al. 2005)) from 1977 until 2004. They found a 15-30% increase in TC days with an intensity of category 2 or higher in both data sets, although with pronounced differences between the two data sources as to the distribution of storms within the category 2-5 range. For example, they found that the number of Category 4 and 5 typhoon days decreased from 7.2 per year in 1977-90 to 4.3 per year in 1991-2004 in the JMA database. This contrasts with the JWTC dataset, which showed for Category 4 and 5 typhoon days 9.8 per year from 1977-90 and 16.9 per year from 1991-2004. Undoubtedly, the discrepancy relates to JMA vs JWTC satellite treatment of TC intensities once aircraft reconnaissance was discontinued there in 1987. There is currently no guidance as to which dataset is more reasonable in assessing true extreme TC climate trends.

Some regional trends in prevailing typhoon tracks in the western North Pacific for the period 1965 to 2003 have been reported by Wu et al. (2005), although they were not able to distinguish between anthropogenic impacts or long-term natural variability. The changes in tracks were found to be consistent with expected changes based on large scale circulation (steering flow) changes.

4.2.4. **Paleoclimate proxy studies of past TC activity**

Paleotempestology is the term for an emerging field of science that attempts to reconstruct past tropical cyclone activity using geological proxy evidence or historical documents. This work attempts to expand knowledge about hurricane occurrence back in time beyond the limits of conventional instrumental records, which cover roughly the last 150 years. A long-term record of hurricane activity on timescales of centuries to millennia is especially important in understanding the spatial and temporal variability of the rare but most intense landfalling hurricanes like Camille (1969) or Andrew (1992), which may have return periods of longer than 150 years. A broader goal of paleotempestology is to help researchers explore physically based linkages between prehistoric TC activity and other aspects of past climate. This would provide important independent evidence for causes of changes in hurricane activity, and possibly assist in understanding the potential for future climate changes to affect hurricane activity, or vice versa (e.g., Section 7).

Among the geologically based proxies, overwash sand layers deposited in coastal lakes and marshes have proven to be quite useful (Liu and Fearn, 1993, 2000; Liu 2004; Donnelly and Webb 2004). The storm surge plus wave run-up during an intense hurricane can overwash a beach barrier, eroding sand and depositing a layer of the eroded sand material in a lake or marsh behind the barrier. These layers can then form a stratified record through time of intense storm overwash events. Cores of these layers can be retrieved and the layers analyzed in terms of their thickness, composition, age, and frequency of occurrence. The age of deposits is estimated through various radiometric dating techniques applied to the surrounding organic matter, supplemented by other information.

By comparison of the characteristics of these deposits with those of well-observed storms in the historical record, inferences about past storm events can be made. For example, Liu and Fearn (1993; 2000) have constructed a 5,000-year paleo record of inferred category 4 and 5 hurricane strikes in Alabama and northwestern Florida using this technique. Similar methods have been used to produce proxy records of hurricane strikes from back-barrier marshes in Rhode Island and New Jersey extending back about 700 years (Donnelly et al. 2001a, 2001b; Donnelly et al. 2004; Donnelly and Webb 2004), and more recently in the Caribbean (Donnelly 2005). In interpreting these records, long-term changes in sea level must also be taken into account. The frequency of cyclone or "super-cyclone" occurrence in the Australia region over the past 5000 years has been inferred from chronostratigraphic series of shelly beach ridges (Nott and Hayne, 2001; Hayne and Chappell 2001).

Stable isotope signals in tree rings (Miller et al. 2003), cave deposits (Frappier et al. 2006) and coral reef materials are also being actively explored for their utility in providing paleoclimate information on tropical cyclone activity. These methods attempt to exploit an oxygen isotope signal that distinguishes rain originating in hurricanes from that in low-latitude thunderstorms (Lawrence and Gedzelman, 1996). Rainwater from a hurricane is eventually incorporated into the tree-ring, cave deposit, or reef material where it may be preserved as a long-term proxy record. The above studies are beginning to show some promise as a method of inferring aspects of past tropical cyclone activity.

Historical documents apart from traditional weather service records can also be used to reconstruct some aspects of past tropical cyclone activity. For example, investigators have used sources such as newspapers, plantation diaries, various instrumental weather records, and annals in the Carribbean to reconstruct past tropical cyclone activity in the U.S., Caribbean, Gulf of Mexico, and Atlantic basin for up to several centuries before present (Ludlam, 1963; Millas, 1968; Fernandez-Partagas and Diaz, 1996; Chenoweth, 2003; Mock 2004). Spanish and British historical archives may be a useful source for further investigation (Garcia Herrera et al. 2004; 2005). Even longer documentary records of tropical cyclone activity, extending back for more than 1000 years, have been found and investigated in China (Liu et al. 2001; Louie and Liu 2003; Louie and Liu 2004).

Paleoclimate researchers are continuing to investigate these multiple sources of information on pre-historic tropical cyclone activity, and to validate where possible, the paleoclimate proxy records against hurricane observations from the more recent, well-observed part of the historical record. These studies should provide an increasingly useful independent source of information on the tropical cyclone-climate connection, as well as a better-constrained long-term perspective on hurricane risk from rare but extreme hurricanes. Future efforts will include expansion of geographical coverage, development of new proxies, coupling of multiple proxy sources, improved calibration, and integration with modeling and advanced statistical techniques.

4.2.5. **Use of theory and models to understand past variations in tropical cyclone activity**

Theory and models of tropical cyclone activity may provide useful information both on the interpretation of past changes in activity and on possible future changes due to such factors as greenhouse gas-induced global warming or natural climate variability. In this section, the utility of the theoretical and modeling approaches is assessed based on analyses of climatological (seasonal) variations and past interannual to interdecadal variations and trends. The theories include potential intensity theories as well as empirical indices which attempt to relate tropical cyclone frequency to large-scale environmental conditions. The models range from global climate models to higher resolution regional models aimed at simulating hurricane structure in more detail.

a) Assessment of simulated TC climatologies and seasonal cycles

Extended integrations of global climate models in principle allow for an assessment of the frequency, intensity, duration, structure, and tracks of tropical cyclone-like features in the model. In practice, simulation of realistic intensities and detailed structures of the TC's is hampered by the coarse resolution generally required of such global models, as discussed below. In addition, the fidelity of the global model's TC genesis process compared to the real world has not been well established.

In the global models, TCs are located and tracked in model data using objective techniques that are usually based on a local maximum of cyclonic relative vorticity at 850 hPa and often involve other criteria such as: life-time; warm core; maximum winds above a threshold; and local minimum MSLP (e.g. Tsutsui and Kasahara 1996; Vitart et al. 1997; Sugi et al. 2002; McDonald et al. 2005). The location and tracking method tends to be unique to each study which makes it difficult to compare the results of the different studies directly. Walsh et al. (2006) provide recommendations for providing homogeneous comparisons of various resolution models for determining tropical cyclone frequencies. They base this upon an analysis of how minimal tropical storms (with maximum winds at 17.5 m/s) would be depicted under various resolutions. Use of such resolution-based criteria for determining tropical cyclone occurrence should allow for more rigorous quantitative comparisons of global (and regional) climate model output of tropical cyclones frequencies.

The global climate models used for tropical cyclone analysis have tended to be of low (300km) horizontal resolution (e.g. Vitart et al. 1997; Tsutsui 2002; Bengtsson et al. 2006) or of medium (120km) resolution (e.g. Sugi et al. 2002; McDonald et al. 2005; Hasegawa and Emori 2005; Yoshimura and Sugi 2005). The grid-scale of the low and medium resolution models is larger than the typical scale of tropical cyclones and this can lead to a poor simulation of tropical cyclones (e.g. Vitart et al. 1997; McDonald et al. 2005). The cyclones tend to have a larger horizontal scale, and although they have warm cores, the intense inner core is not well-simulated. Thus, the cyclones have lower wind speeds than observed tropical cyclones (Vitart et al. 1997). Minimum central pressures tend to be better simulated than the maximum surface wind speeds. Recent studies studies have used higher resolutions of 50km (Chauvin et al. 2006) and 20km (Oouchi et al. 2006), but models of this resolution are too expensive for most modeling centers to use for long climate change experiments. An alternative approached is to use a global model with a stretched grid (i.e. higher resolution) over the region of interest (e.g. Chauvin et at. 2006) although this limits the study to the region where the resolution is high. Even at that resolution, the highest simulated TC intensity reported by Oouchi et al. was about 932 hPa, compared with the observed record of 870 hPa, indicating the limitation of their global model in simulating very intense TCs.

More realistic maximum intensity levels, including their geographic distribution in the NW Pacific basin, have been simulated by downscaling individual storm cases from a coarse-grid global model into an operational regional high-resolution hurricane prediction system (Knutson et al. 1998) or into a regional climate model (Walsh and Ryan 2000; Walsh et al. 2004).

Even though smaller-scale features of the individual cyclones are typically not well simulated in the global models, these models are able to reproduce some aspects of the observed climatology and inter-annual variability of tropical cyclones (Tsutsui and Kasahara 1996; Sugi et al. 2002; Camargo et al. 2005; McDonald et al. 2005). Most models are able to simulate tropical cyclone-like disturbances in roughly the correct location and at the correct time of year, although all models exhibit some biases. Several models simulate tropical cyclones in the South Atlantic (Vitart et al. 1997; Sugi et al. 2002; McDonald et al. 2005; Oouchi et al. 2006) where they are rarely observed (Pezza and Simmonds 2005), although not all models simulate storms there (Camargo et al. 2005).

The global models' simulated TC tracks are sometimes shorter than observed (Tsutsui and Kasahara

1996; Sugi et al. 2002; Camargo et al. 2005) but those in the high resolution model of Oouchi et al (2006) are better simulated, whereas those in the low resolution models ECHAM3 and ECHAM4 are too long (Camargo et al 2005). Some of these differences in length may be due to the objective techniques used to identify and track the cyclones in the model data.

The simulated global annual frequency of TCs in global models varies, with some models simulating too many TCs (e.g., McDonald et al. 2005) while others simulate too few (Camargo et al. 2005). Both from comparing results between different models (e.g., Carmago et al. 2005) and from sensitivity experiments with a given model (Vitart et al. 2001; Emori et al. 2005), it is evident that both model resolution and model physics can play important roles in determining the frequency of TC occurrence in the global models. While models in many existing studies have demonstrated an ability to simulate many aspects of the seasonal variability of tropical cyclone frequency in each basin, all of the models have some errors in both frequency and timings. These errors are basin-, season- and model-dependent.

Increasing the horizontal resolution of the global models typically improves the simulation of the individual cyclones (Bengtsson et al. 1995) but may not improve the tropical cyclone climatology and interannual variability, as it is also important that the models have a good simulation of the large-scale circulation for the latter. Tropical cyclone occurrence is observed to be correlated to the phase of ENSO (Chan 1985). This implies that climate models also must simulate realistic ENSO and decadal variability under present day and future climate conditions as a necessary condition for providing reliable future projections of TC activity in these regions (e.g. Nguyen and Walsh 2001; Chan and Liu 2004). Chan and Evans (2002) examine CCM3 and GISS ensemble simulations of the structure of the East Asian summer monsoon in the present climate. Since tropical cyclogenesis in the western North Pacific is dominated by the monsoon, realistic simulations of the monsoon and is variability are necessary for accurate representation of genesis. Chan and Evans demonstrate that there is more variability of monsoon behavior among individual members of the ensembles than between ENSO extremes.

An alternative approach to explicit global model simulation is to use an empirical “seasonal genesis parameter” (e.g. Ryan et al. 1992; Watterson et al. 1995) to infer a genesis frequency from climate model data (Tsutsui and Kasahara 1996; Royer et al. 1998; McDonald et al. 2005; Chauvin et al. 2006). Great caution is required when applying a parameter developed for present day climate to future predictions as the statistical relationships may not be valid under altered climate conditions (Ryan et al. 1992). Royer et al. (1998) and Emanuel and Nolan (2004) (see also Nolan et al. 2006) have proposed a refined versions of Gray’s (1979) genesis index that avoid the use of factors such as threshold SSTs that themselves may well vary in an altered climate (e.g., Henderson-Sellers et al. 1998). These methods typically produce plausible maps and seasonal cycles of TC genesis. Recent efforts have begun in assessing performance of the Emanuel and Nolan scheme with regard to interannual (ENSO) variability (Carmargo et al. 2006).

Wu and Wang (2004) showed that TC track climatologies can be inferred from global model data using the climatological mean velocity fields as input to a TC trajectory model. In an initial application of this technique in the Northwest Pacific, Wu and Wang demonstrated that the main characteristics of the current climatology of TC tracks can be reproduced using this approach with the mean circulation data from NCEP-NCAR reanalyses. Since any systematic changes in TC tracks could have important impacts on TC-related damage, this approach provides an alternative means of exploring potentially important climate-change-induced TC impacts.

The present-climate performance of theoretical frameworks such as hurricane potential intensity theory has been assessed to some degree based on geographical or seasonal variations of real-world tropical cyclone intensities (e.g., Emanuel, 1987; Emanuel 2000; Holland 1997; Tonkin et al. 2000). These assessments show that the theories have some skill at hindcasting seasonal and geographical variations of maximum intensities similar to those in the real world, although shortcomings can also be identified (e.g., Tonkin et al. 2000). Camp and Montgomery (2001) and Holland (1997) have noted that the Emanuel and Holland potential intensity theories have somewhat different sensitivities to certain environmental factors, such as relative humidity. The current climate-based assessments to date suggest that potential intensity theories are a plausible means of relating real-world intensities of TCs to the large-scale environmental thermodynamic conditions in which the storms form and develop.

The capability of models to simulate realistic intensities can also be assessed based on experience with operational TC prediction. Using a simplified numerical modeling framework, Emanuel (1999) showed several cases of successful hindcasts of hurricane intensity, derived from each storm's initial intensity, the large-scale atmospheric thermodynamic environment (which also determines the potential intensity), and a representation of ocean mixing (potentially creating a cool wake) beneath the storm. Knutson and Tuleya (2004) used an idealized hurricane model derived from an operational hurricane prediction system to assess possible impacts of climate change on hurricane intensity in the absence of wind shear effects. The operational performance of the GFDL hurricane model for intensity prediction and the relevance of its performance for the climate change/hurricane intensity problem has been a subject of debate (Michaels et al. 2005; Knutson and Tuleya 2005). As noted by Knutson and Tuleya (2004) their results should be interpreted as analogous to potential intensity.

Emanuel et al. (2006) recently introduced a new statistical-deterministic TC simulation approach based on combination of synthetically generated storm tracks and a TC intensity prediction framework which is applied along the path of the TC. The TC intensity scheme includes the impact of the large-scale thermodynamic environment, along with representations of wind shear and ocean interaction effects, through a simple axisymmetric balance hurricane model coupled to a one-dimensional ocean model. Being highly simplified and computationally efficient compared with full three-dimensional atmosphere/ocean models, the approach has been used to generate TC statistics based on thousands of synthetic tracks, under various assumptions about genesis locations. The method produces a reasonable histogram of maximum wind speed occurrence for the Atlantic basin as a whole, and to some degree for two U.S. coastal cities that were examined (Miami and Boston). This method was then applied by Emanuel (2006b) to controlled climate changes. Using a sample of 3000 synthetic Atlantic storm tracks and holding the tracks themselves fixed, Emanuel re-ran the intensity model with 10% spatially uniform increases, in succession, in potential intensity, vertical wind shear, and ocean mixed layer thickness. These led, respectively, to changes in net tropical cyclone power dissipation of +65%, -12% and +4%.

b. Assessment of simulated interannual to decadal variability of TC activity

The interannual variability of TC occurrence in global models can be tested by comparing cyclones simulated in models forced with observed SSTs to tropical cyclone observations from the same period (Tsutsui and Kasahara 1996; Vitart et al. 1997; Sugi et al. 2002; McDonald et al. 2005; Camargo et al. 2005). The nine-member ensemble of Vitart et al. 1997 and the 40 yr experiments used by Camargo et al. (2005) are better suited for analysis of the inter-annual variability than are the shorter experiments used by Tsutsui and Kasahara (1996), Sugi et al. (2002) and McDonald et al. (2005) because of the larger sample sizes. The correlation of the global annual number of tropical cyclones with the observed varies from 0.15 in the JMA model (Sugi et al. 2002) to 0.41 in GFDL model (Vitart et al. 1997). The correlations are better in some seasons, basins and models than in others. The correlations tend to be highest in the west North Pacific and North Atlantic basins (Vitart et al. 1997; Carmago et al. 2005), possibly because of the importance of ENSO in those regions. The interannual variability performance of the 20 km grid global model of Oouchi et al. (2006) has not yet been assessed.

In a coarse-grid global model investigation of interdecadal variability of tropical storm occurrence in the Atlantic, Vitart and Anderson (2001) were able to simulate a decrease in tropical storm frequency for the 1970s in comparison to the 1950s, similar to observations, by specifying the observed SST changes for the globe (and specifically for the tropical North Atlantic) in their model. The decreased frequency in their model was linked to increased vertical wind shear and reduced CAPE in the tropical storm formation regions. A correlation of hurricane activity with tropical vertical wind shear has also been noted in observational studies of Atlantic TC variability (e.g., Goldenberg et al. 2001; Bell and Chelliah 2006).

c. Assessment of observed trends in TC activity and related measures

The substantial increases in tropical cyclone Power Dissipation Indices (PDIs) reported by Emanuel (2005a; 2006) and the reported increases in the numbers and percentages of TCs attaining category 4 or 5 intensity (Webster et al. 2005; Hoyos et al. 2006) raise the question of whether these changes can be reconciled with existing theory or modeling work. A caveat to such comparisons is that existing modeling work, such as Knutson and Tuleya (2004) is highly idealized in terms of both climate forcings (CO2 only vs a mixture of known historical forcings) and in neglect of potentially important factors such as vertical wind shear. Therefore, such existing studies can only provide a rough guide as to expected responses of hurricanes to both past and future climate changes.

Emanuel (2005a; 2006) provided some discussion of the discrepancy between observed and theoretical results, in particular noting the importance of considering potential intensity and not simply SST in attempting such comparisons. Emanuel (2005a) noted that the doubling of the North Atlantic plus western North Pacific PDI in the last 30 years implied in his analysis was due to increases in both the accumulated annual duration of storms and the peak intensities of TCs. The annual average storm peak wind speed summed over the Atlantic and North Pacific basins (in terms of V^3) increased by about 50% during the period, implying roughly 30% per degree Celsius sensitivity of wind intensity. Emanuel (2005a) reported that the potential intensity as estimated from atmospheric re-analysis data had increased by about 10% rather than the predicted 2-3% over the period, owing to the failure of atmospheric temperature warming to keep pace with the SST warming. Emanuel noted that predicted peak intensity sensitivity to SST from theory was only about 5% per degree Celsius, which, for an SST increase of 0.5°C, implied a PDI increase of only about 8-12%. In an analysis of more recent (post-1979) Atlantic basin data Emanuel (2006) suggested that the 10% increase in potential intensity in that region was partly attributable to decreases in mean surface wind speeds over the basin as well as SST increases of about 0.5 °C, implying about 20% per degree Celsius sensitivity to SST alone. The modeling study of Knutson and Tuleya (2004; 2005) found a peak wind speed sensitivity of about 3.3% per degree Celsius (or 3.7% per degree Celsius if maximum winds are inferred from central pressures following Landsea 1993). Thus while highly idealized, their results imply a discrepancy of roughly a factor of 5 to 8 between observations and model estimates of intensity sensitivity to SST increases.

Mann and Emanuel's (2006) analysis of Atlantic basin data extending back to the late 19th century indicated a pronounced increase of TC frequency in the Atlantic since that time. This reported increase of TC frequency has not as yet been reconciled with existing theory or modeling of storm frequency. As noted previously, Landsea et al. (2004) maintain that TC counts for the Atlantic basin were likely undercounted in the earlier parts of the record, with the number of "missed" Atlantic basin tropical storms and hurricanes per year estimated to be on the order of 0-6 for the period 1851-85 and 0-4 for the period 1886-1910.

4.2.6. Simulations of future TC behavior

a. Global and regional nested models

Future changes in tropical storms projected by global or regional climate models (RCMs) are subject to many sources of uncertainty including: the future climate forcing scenario; initial conditions; regional patterns and magnitudes of future climate change for various fields; model physics and dynamics; and so forth. Since tropical storms are relatively rare events, large samples sizes (i.e. many years) are typically required to test the significance of any changes against natural variability, depending upon the metric being examined. The changes in frequency of storms simulated by models are often smaller than the climatological bias of the models. These errors in the tropical storm climatology add to the uncertainty of the future changes in tropical storms projected by the models.

The combined effect of all the sources of uncertainty is that there is large overall uncertainty in future changes in tropical cyclone frequency as projected by climate models forced with future greenhouse gases. The IPCC Third Assessment Report concluded that the TC frequency results of GCM experiments are inconclusive (see Giorgi et al. 2001). The most recent results obtained from medium and high resolution (120km-20km) GCMs (Table 1) indicate a consistent signal of fewer tropical cyclones globally in a warmer climate, though this finding is still not conclusive. While, these models consistently show a global decrease in frequency (e.g. Sugi et al. 2002; McDonald et al. 2005; Bengtsson et al. 2006; Oouchi et al. 2006), there are regional variations in the sign of the changes, and these vary substantially between models (Table 1). For example, more storms are projected in the North Atlantic region in some models, despite a large reduction globally (Sugi et al. 2002; Oouchi et al. 2006), while fewer Atlantic TCs are projected by the N144 HadAM3 atmosphere only model (McDonald et al. 2005). Chauvin et al. (2006) found that the sign of the changes in tropical cyclone frequency in the north Atlantic basin depended on the SST anomaly pattern in their stretched grid global model experiments (50km over Atlantic region). Walsh et al. (2004) using a 30 km grid nested regional model for the Australia region, found little change in frequency of tropical cyclones near Australia in their 3xCO_2 RCM experiments. All of these results should be treated with caution, as it is not always clear that these changes are greater than the model's natural variability, or that natural variability or the TC genesis process is properly simulated in the models.

Concerning future changes in TC intensity, there is substantial disagreement among recent global and regional modeling studies, although the highest resolution models available show evidence for some increase of intensity. As discussed earlier, simulated future changes of intensity in current global models may not be reliable, since these models do not simulate the very intense TCs observed in the present climate, even in the case of the relatively high resolution (20km grid) simulation of Oouchi et al. (2006). Given this caveat, Tsutsui (2002), Walsh et al. (2004), McDonald et al. (2005) and Oouchi et al. (2006) all report evidence for intensity increases, while Sugi et al. (2002), Bengtsson et al. (2006), and Hasegawa and Emori (2005; western North Pacific only) , and Chauvin et al. (2006; North Atlantic only) found either no increase or a decrease of intensity. Among these studies, Tsutsui and Bengtsson et al. used relatively low resolution models; McDonald et al., Sugi et al., and Hasegawa and Emori used medium (~120km) grid spacing models; and Oouchi et al. and Walsh et al used relatively high resolution models. The Oouchi et al. (2006) study reports that the number of the most intense cyclones increases globally in their 20 km grid warming climate simulation, despite a large decrease in overall TC numbers. However, statistically significant intensity increases in their study were confined to only one or two individual basins. Walsh et al. (2004), focussing on the Australia region with a nested regional model, found little change in overall TC frequency under 3xCO_2 conditions, but a 56% increase in the number of storms with relatively high maximum winds (>30 m/sec in their model), and a 26% increase in the number of storms with central pressures less than 970mb. Similarly, Knutson et al. (1998) simulated a significant CO_2 warming-induced increase of typhoon intensities in the NW Pacific basin, based on downscaling a sample of 51 tropical storms from a high CO2 scenario of a global climate model into a regional nested hurricane model.

Regarding TC precipitation based on global models, Hasegawa and Emori (2005) found an increase in TC-related precipitation in the western North Pacific, despite a decrease in TC intensity in their model. Chauvin et al (2006) found a similar result in the North Atlantic in their model. Yoshimura et al. (2006) found a similar result on a global domain. Hasegawa and Emori interpret the increase in hurricane-related precipitation as being due to enhanced atmospheric moisture in the warmer climate--a mechanism which has been discussed in the context of extreme precipitation in general by Trenberth (1999), Allen and Ingram (2002), and Emori and Brown (2005). Note that enhanced latent heating associated with increased TC precipitation does not necessarily lead to intensification of the TC, since the enhanced heating is balanced to some degree by enhanced adiabatic cooling for given updraft due to the increased dry static stability in the simulated warmer climate (e.g., Sugi et al. 2002).

Concerning observed changes in hurricane-related precipitation, Groisman et al. (2004) report finding no increasing trend in the total seasonal hurricane-related precipitation along the U.S. Southeast coast, despite finding that the frequency of very heavy precipitation unrelated to TCs has increased significantly in the same region and over the conterminous U.S. during the 20th century. They have not yet examined the behavior of hurricane-related precipitation on a per storm basis, and thus the time series they examine are influenced by changes in U.S. TC activity which has exhibited substantial multidecadal variability but no trend (Goldenberg et al. 2001; Landsea 2005).

An important issue is to identify the underlying mechanisms producing changes in future TC behavior in the GCMs simulation. Sugi et al. (2002) report that the simulated reduction of global TC frequency in their model was closely related to the weakening of tropical circulation, which in turn resulted from a considerable increase in the dry static stability, coupled with relatively little increase in the precipitation. Yoshimura and Sugi (2005) performed a series of experiments to test the relative effects of SST changes and changes in CO_2 on changes in TC frequency in their model. They found that the decrease in tropical storm frequency in their model was due to the increased CO_2 (see also Sugi and Yoshimura 2004), with the SST changes having a relatively small direct impact. Regarding the regional variations in projected TC frequencies, the results of Sugi et al (2002) and McDonald et al (2005) and Chauvin et al. (2006) suggest that dynamical factors such as low level vorticity and vertical wind shear play a more important role than thermodynamical factors such as SST and moist instability. Knutson and Tuleya (2004) examined the mean vertical wind shear of the zonal wind for the tropical Atlantic basin in different coupled models. Their analysis showed a slight preference for increased vertical shear under high CO2 conditions if all of the models are considered, and a somewhat greater preference for increased shear if the three models with the poorest present-day simulation of shear in the basin are excluded.

Examination of the trends in deep convection in the tropics provides some guidance on potential changes in tropical cyclogenesis regions. Dutton et al. (2000) examine changes in tropical convection in a fully coupled, transient CO_2 simulation using the NCAR CSM1. They find that the SST threshold for tropical deep convection is about 25°C in the $1\times CO_2$ climate, consistent with observational studies. This SST threshold increases as the level of CO_2 and the global mean surface temperature increase in the model, to 26.0°C for $2\times CO_2$ and 26.7°C for $3.4\times CO_2$ (at the end of the 134 year simulation). Throughout this simulation, the area of convection between 40°N and 40°S remains approximately constant, however the precipitation intensity increases ~2%.

b. Theoretical or idealized modeling frameworks

Thus far, almost all theoretical or idealized modeling frameworks have focused on potential future changes in the intensities of TCs. Emanuel (1987) and later Tonkin et al. (1997) first presented evidence, based on potential intensity theory, that CO_2-induced climate change as simulated by several GCMs implied significant increases in future TC intensities. Limitations of their approach were discussed in Henderson-Sellers et al. (1998). These theory-based assessments received model-based support from Knutson and Tuleya (2004), who used an idealized hurricane model framework to evaluate tropical climate warming scenarios from nine different coupled climate models, all forced by increasing CO_2 levels. They reported a tropical cyclone intensity increase of about 3.3% per degree Celsius SST increase, which was roughly comparable to the increase predicted by the Emanuel and Holland potential intensity theories for those environments.

The above methods account for changes in atmospheric temperature above the warming sea surface—an effect which acts to limit the increase of intensity for a given SST increase compared to the rate in the absence of the atmospheric temperature increases (e.g., Shen et al. 2000). Knutson et al. (2001) found that the CO_2-warming-induced intensification of tropical cyclones in their idealized model framework was robust to the inclusion of ocean coupling beneath the storms. Knutson and Tuleya (2004) reported that near-storm (100km radius) rainfall increased by about 10% per degree Celsius in their experiments.

Wu and Wang (2004) performed an initial assessment of the potential impact of greenhouse gas-induced climate change on TC tracks using a trajectory modeling approach for the NW Pacific basin. Based on experiments derived from a particular climate model, they found evidence for inferred track changes, although the pattern of changes was fairly complex, as opposed to a more simply described, systematic change. Royer (1998) illustrated the use of a modified genesis parameter, based on a measure of convective rainfall as opposed to SST or oceanic heat content, and showed that TC frequency results for a future climate scenario depended strongly on whether the modified or unmodified genesis parameter approach was used.

The empirical genesis index developed by Emanuel and Nolan (2004) and Nolan et al. (2006) implies a positive relation between potential intensity and the likelihood of tropical cyclogenesis. This finding, coupled to the increased potential intensity as inferred from increased CO_2 climate model simulations (e.g., Emanuel 1987; Tonkin et al. 1997; Knutson and Tuleya 2004) implies a possible increase in tropical storm frequency in a warmer climate, unless other factors in their index (e.g., wind shear, vorticity, or relative humidity) change in ways to offset the impact of the potential intensity increase. In further recent work aimed at increasing the realism of simulated TC genesis, Nolan et al. (2006) have undertaken a very high-resolution (4 km grid) idealized modeling approach, using the Weather Research and Forecast Model (WRF) to explore the relationship between local values of potential intensity, the Coriolis parameter, and the likelihood of tropical cyclogenesis. Their initial results show that, in radiative-convective equilibrium (RCE), the potential for TC genesis increases with increasing values of SST. As the environmental surface wind is increased from zero, the genesis potential increases at first due to a substantial increase in the mid-level humidity, even though PI decreases. As the mean surface winds increase beyond 3 m s-1, both the PI and the genesis potential rapidly decline due to increased warming aloft by stronger and wetter convection. Additionally, Nolan et al. observed “spontaneous” TC genesis from random convection in RCE, suggesting that in very ideal environments, the absence of significant precursors such as easterly waves may not be a limiting factor on TC genesis.

4.2.7. **The role of TCs in the climate system**

The possibility that tropical cyclones play an active as opposed to essentially passive role in the climate system was proposed by Emanuel (2001). According to this hypothesis, tropical cyclones, through wind-induced mixing of tropical ocean waters and subsequent re-heating of the cold wakes, make a potentially important contribution to the meridional heat transport by the oceans. Boos et al. (2004) provide additional support for this idea through idealized ocean modeling experiments. If in a warming climate, increased tropical storm activity substantially increases the poleward heat transport by the ocean through this mechanism, this process may then help explain the occurrence of distant past climates, such as the Eocene, characterized by strongly reduced equator-to-pole temperature gradients. With enhanced poleward oceanic heat transport, the high latitudes would warm more than otherwise, while the warming in tropical latitudes would be moderated. This in turn would moderate any projected increases in tropical cyclone intensity relative to those predicted on the basis of current global climate model simulations of future climates.

In another example of the possible role of TC activity on climate, Hart (2006) has explored the impact of recurving tropical cyclone activity on the subsequent winter climate. He demonstrates that, for years with anomalously high numbers of recurving tropical cyclones in the Northern Hemisphere, the baroclinicity of the subsequent winter season is substantially reduced. It is hypothesized that this reduction in hemispheric baroclinicity is tied to snow cover (Hart et al. 2006).

4.2.8. **Roadblocks to further advancements**

There are substantial roadblocks both in making reliable future projections about TC activity and in determining whether a trend can be detected in historical TC data.

a. Data homogeneity in TC databases.

For the climate change detection problem, a large hurdle is the quality of the tropical cyclone historical databases. The databases were populated over time without a focus on maintaining data homogeneity, a key requirement for databases which are to be used to assess possible climate-related trends. In some cases, such as the NW Pacific basin, our ability to monitor TC intensity has diminished over time. For example, aircraft reconnaissance was conducted in the NW Pacific basin beginning in the 1940s, but was discontinued in 1987. Experience with reanalysis of the HURDAT database for the Atlantic basin (Landsea et al. 2004) indicates that considerable effort and analysis is required to identify and attempt to correct, where possible, past problems with the TC databases. Indeed, even in 2006, operational satellite-based estimates of the intensity of TS Chris were found to be off by a full storm category when reconnaissance aircraft surveyed the storm. The possibility of such errors across all of the other ocean basins is real and problematic from both operational and climate perspectives.

While reanalysis may help provide a more uniform assessment based upon consistent use of pressure-wind relationships and flight level to surface wind analyses, it will not recover hurricanes that were never observed. For example, over the open oceans before that advent of satellite coverage in the 1960s, there will never be a complete, reliable TC dataset for any of the basins. Even in the Atlantic, aircraft reconnaissance typically monitors about half of the tropical cyclones. However, it may be possible to have a high quality, global analysis of TC intensities and frequencies from about 1970 onward with substantial effort. One method that may be able to provide longer, reliable records is to focus upon analyses of landfalling tropical cyclones that have occurred along coastal regions with substantial populations. The tradeoff with this approach to get longer time series is that one only samples a much smaller number of tropical cyclones compared to the entire basin.

The widespread concerns about problems in the TC databases reduces confidence in trends derived from those databases, and thus is an important roadblock to further advancement on the topic of historical TC trends.

b. Data homogeneity concerns with other TC-related climate variables

Improved understanding of the causes of past variations or trends in TC activity will depend on the existence of reliable climate-quality data sets for related variables, such as SST, atmospheric temperature, moisture, wind shear, etc. Although reanalysis efforts by NCEP/NCAR and ECMWF have led to important improvements in this regard, recent studies of upper-air data sets (e.g., Santer et al. 2005) identify likely remaining problems that could substantially affect efforts to reconcile historical TC behavior with various environmental influences. These data quality issues therefore also remain as an important roadblock for further advancement.

[In using global reanalysis datasets such as NCAR/NCEP and ECMWF for TC-related studies (e.g., Sriver and Huber 2006), inclusion of new observations over time complicates monitoring of trends of tropical cyclone statistics, as improved observations should lead to better identification of tropical cyclones. While the circulation of larger tropical cyclones can be identified on the synoptic scale, some systems remain smaller scale (mesoscale) and the region in which intensity is defined (the maximum sustained surface winds in the eyewall) is always on the mesoscale, which implies that these features typically cannot be well-represented in low resolution reanalysis products.]

c. Limitations of climate models

Climate models contain hypotheses for how the climate system works in a framework which allows experiments to be performed to test various hypotheses or compare the model's historical simulations against historical observations. Nonetheless there are important uncertainties in climate models and the radiative forcings used for such experiments. For example, past aerosol forcing due to the interaction of aerosols with cloud and precipitation processes (indirect aerosol effects) remain quite uncertain. Many inferences about relative contributions of internal climate variability to past observed climate fluctuations rely on climate model simulations of internal variability, although paleo reconstructions provide important contributions to this question. Climate models have known limitations in simulating important internal modes of variability of the climate system (such as ENSO), although more recent models are improving in that regard (e.g., Wittenberg et al. 2006).

The climate sensitivity to past and future radiative forcing is another important area of uncertainty, both on the global scale and with respect to important regional details, as evidenced by the wide range of likely global climate sensitivity to CO_2 doubling (1.5-4.5^o C) reported in the IPCC 3rd Assessment Report (IPCC 2001). In addition to climate sensitivity, there is considerable uncertainty in projections of future warming due to uncertainties in the rate of future ocean heat uptake as well as uncertainties in various climate forcing agents (IPCC 2001), including but not limited to greenhouse gas concentrations. These uncertainties combined lead to a wide range (1.4-5.8^{o}C) in projected global warming by 2100 according to the IPCC (2001). Although the projected warming of tropical SSTs is generally smaller than the global mean warming, the above range provides an indication of the relative degree of uncertainty that also applies to future projections of tropical storm basin SSTs when forcing uncertainties are considered. The forcing-related uncertainty has not yet been formally assessed in detail at the tropical storm basin scale.

The limited resolution of global climate models implies that many aspects of TC-like storms as simulated by the current models will not be very realistic, including the intensity and important smaller-scale structure such as the eye and eye-wall. This situation will gradually improve as available computing power increases (e.g., Oouchi et al. 2006). Meanwhile, questions remain about the realism of the TC genesis process in the global models. Generally, atmosphere-only models have been used for the global model-based TC-change assessments, as available computing power has been used for increasing atmospheric resolution rather than addition of ocean coupling. Eventually, this simplification will need to be relaxed, particularly in order to explore impacts of ocean coupling on TC genesis and intensity, as well as the possible role of TCs on the climate system (Section 7). The important impact of model physics and physical parameterizations, even in high-resolution models, means that future progress will depend on both increased scientific understanding and increased computing power.

d. Limitations of high-resolution idealized models and theory

While high-resolution idealized models can address the problem of limited resolution to some degree, this approach has limitations and uncertainties to be addressed. For example, the nested model used for the down-scaling may have a substantially different climatology and climate sensitivity from the "parent" global model, raising questions about the effect of such model incompatibilities on the reliability of the overall results obtained. The simulations can also be affected by the chosen domain (e.g., Landman et al. 2005). Clearly a preferred approach would be to avoid the downscaling issue altogether by using the TC statistics from the original GCM.

The potential feedback of the TC activity on the climate system (section 7) also cannot be modeled using the simple one-way nesting approaches employed to date in TC/climate studies, nor can it be reliably inferred from the present generation of global models due to resolution limitations.

In contrast to the theory of potential intensity of TCs, which is more well-established, a comparable theory of TC frequency is not well-developed at this time. (We note that even the current theories of potential TC intensity include many assumptions and for example do not consider any dynamical limitations on TC intensity.) The lack of theoretical underpinning of TC genesis and frequency of occurrence remains as an important roadblock to progress in this area, apart from global model limitations.

4.2.9. **Proposals for moving forward**

In general, hurricane-climate research is expected to progress most rapidly when a combination of theory, modeling, and observations are brought to bear on the problem.

a. Improved paleoclimate, historical, and future TC databases

The need for improved climate-quality tropical cyclone databases seems clear. These will provide better information for assessing future changes, and more reliable statistical assessments of past changes in hurricane activity, including land fall, in all basins. Specific examples include the need to reanalyze historical tropical cyclone databases in all basins, and not just the Atlantic. Such efforts should be encouraged and supported. Greater efforts should be made to provide researchers with access to original “raw” historical observations (i.e., ship, station, buoy, radar, aircraft, and satellite data) rather than derived quantities, concerning past tropical cyclones.

Concerning future measurement systems, we advocate a comprehensive analysis of the optimal mix of observing systems in support of tropical cyclone measurement (for climate, forecasting, and other needs). Such an analysis should include consideration of both the overall costs and benefits of different mixes of observing platforms, with researchers and forecasters providing hard data on the benefits that a given mix of platforms can provide. As an example, aircraft reconnaissance was conducted in the NW Pacific basin beginning in the 1940s, but was discontinued in 1987 in favor of satellite-only intensity estimation. Is a resumption or initiation of manned or unmanned aircraft reconnaissance in various basins now justifiable in terms of costs, benefits, and alternative measurement techniques?

A related issue is that future improvements in observing systems will lead, unfortunately, to more discontinuities and biases unless recognized and corrected for. For example, in 2007 the U.S. Air Force reconnaissance aircraft will be outfitted with Stepped Frequency Microwave Radiometers to more provide continuous surface wind estimates for the first time (Uhlhorn and Black 2003). Researchers need to be cognizant that large monitoring changes have occurred in the past and will continue to occur in the future, which can make determining actual climate-related trends problematic.

Studies of how sampling can alter monitoring of both frequency and intensity of tropical cyclones are one approach to investigating the data homogeneity issue. For example, what would the 2005 Atlantic hurricane season look like using only the monitoring capabilities available in 1970, 1950, or 1900? Until better quantitative estimates of how the current observational network influences the determination of numbers and intensities of tropical cyclones, climate trends may be difficult to distinguish from changes induced by monitoring improvements.

Paleotempestology research, which attempts to use information in the geological record to infer pre-historic hurricane activity, should continue to receive support from funding agencies. As the techniques themselves mature, thought should be given to a transition from technique-development research to systematic surveys designed to produce a comprehensive long-term record of tropical cyclone climatology.

b. Improved TC modeling

Tropical cyclone/climate modeling studies will benefit from efforts to improve global climate modeling in general. In addition, studies which focus on simulation or downscaling of TCs could benefit from more rigorous testing of model performance with simulating a wider range of TC metrics. For example, the ability of models to simulate known interannual or interdecadal TC variability characteristics identified in various basins (e.g., Bell and Chelliah, 2006; Chan and Liu 2004) could be further exploited. A similar recommendation would also apply to studies using empirical approaches such as seasonal genesis parameters (see below).

In TC climate change experiments with climate models, statistical significance testing should be emphasized to ensure that reported changes are not simply due to limited sampling. This may be particularly important in basins such as the Atlantic which feature large multi-decadal variations in some observed TC metrics. By analyzing several models using a common tropical storm metric, perhaps with common adjustments for resolution effects (e.g., Walsh et al. 2006), intercomparisons of sensitivity results between different models will be more informative. Such a procedure would help reduce differences between model results arising from differing analysis techniques alone. Analysis of individual models with perturbed physics experiments can be useful in isolating mechanisms producing model behavior. In general, there is a need to improve understanding of the physical mechanisms producing the climate-induced changes in TC behavior in the models.

c. Improved empirical approaches to TC activity

Exploration of empirical approaches, such as seasonal genesis parameters, should be encouraged, including testing/evaluation and improvements aimed at reproducing characteristics of historical TC activity in different basins from both observations and climate model simulations. Based on these results, these approaches may be useful for making climate change projections of TC activity, although caution must be exercised (e.g. Ryan et al. 1992).

A similar recommendation would apply to studies leading to the development of empirical approaches for tropical cyclone potential intensity. Such empirical approaches should include not only thermodynamic parameters, such as the SST and outflow temperature, but also the environmental dynamical parameters that control TC intensity, such as the vertical wind shear and translational speed (Zeng et al. 2006). Current global climate models can simulate the large-scale circulation much more realistically than the individual TCs. Thus empirical approaches with environmental parameters as input to estimate TC potential intensity should be further exploited in this area.

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Table 1. Summary of future changes in tropical storm frequency as simulated by climate GCMs under global warming conditions

Reference	Model	Resolution	Experiment	Ratio (%) of number of storms in global warming experiment to number in control experiment								
				Global	NH	SH	Ocean basin					
							N Atlantic	NW Pacific	NE Pacific	N Indian	S Indian	SW Pacific
Sugi et al. 2002	JMA timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	**66**	**72**	**61**	**161**	**34**	33	109	**43**	**69**
Tsutsui 2002	NCAR CCM2	T42 L18	10y 1xCO2 2xCO2 from 115y CO2 1% pa	102			86	111	91	116	124	99
McDonald et al. 2005	HadAM3 timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	**94**	97	**90**	**75**	**70**	**180**	**142**	110	**82**
Hasegawa and Emori 2005	CCSR/NIES/ FRCGC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2					96				
Yoshimura et al. 2006	JMA timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	**85**								
Bengtsson et al. 2006	ECHAM5-OM	T63 L31 1.5° L40	A1B 3 members 30y 20C and 21C	94								
Oouchi et al. 2006	MRI/JMA timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	**70**	**72**	**68**	**134**	**62**	**66**	**48**	**72**	**57**

Red = significantly **more** tropical storms in the future simulation

Blue = significantly **fewer** tropical storms in the future simulation

Black = not significant or significance level not tested