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6.3. Tropical Cyclones

The IPCC contends that global warming is likely to increase the frequency and intensity of hurricanes. For example, it states “it is *likely* that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures [italics in the original]” (IPCC, 2007-I, p. 15). However, numerous peer-reviewed studies suggest otherwise. In the following sections we examine such claims as they pertain to hurricane activity in the Atlantic, Pacific, and Indian Ocean basins, and the globe as a whole.

Reference

IPCC. 2007-I. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.) Cambridge University Press, Cambridge, UK.

6.3.1. Atlantic Ocean

6.3.1.1. Intensity

Free *et al*. (2004) write that “increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al*., 1998; Knutson *et al*., 1998),” but that “because the predicted increase in intensity for doubled CO_2 is only 5%-20%, changes over the past 50 years would likely be less than 2%—too small to be detected easily.” They report that “studies of observed frequencies and maximum intensities of tropical cyclones show no consistent upward trend (Landsea *et al*., 1996; Henderson-Sellers *et al*., 1998; Solow and Moore, 2002),” and set out to find increases in what they call “potential” hurricane intensity, because, as they describe it, “changes in potential intensity (PI) can be estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs [sea surface temperatures] and profiles of atmospheric temperature and humidity.” Using radiosonde and SST data from 14 island radiosonde stations in the tropical Atlantic and Pacific Oceans, they compare their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They report that their results “show no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995.” What is more, they report that between 1975 and 1980, “while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone.”

In the following year, some important new studies once again promoted the IPCC’s claim that warming would enhance tropical cyclone intensity (Emanuel, 2005; Webster *et al*., 2005), but a new review of the subject once again cast doubt on this contention. Pielke *et al*. (2005) began their discussion by noting that "globally there has been no increase in tropical cyclone frequency over at least the past several decades," citing the studies of Lander and Guard (1998), Elsner and Kocher (2000) and Webster *et al*. (2005). They noted that research on possible future changes in hurricane frequency due to global warming has produced studies that "give such contradictory results as to suggest that the state of understanding of tropical cyclogenesis provides too poor a foundation to base any projections about the future."

With respect to hurricane intensity, Pielke *et al*. noted that Emanuel (2005) claimed to have found "a very substantial upward trend in power dissipation (i.e., the sum over the life-time of the storm of the maximum wind speed cubed) in the North Atlantic and western North Pacific." However, they report that "other studies that have addressed tropical cyclone intensity variations (Landsea *et al*., 1999; Chan and Liu, 2004) show no significant secular trends during the decades of reliable records." In addition, they indicate that although early theoretical work by Emanuel (1987) "suggested an increase of about 10% in wind speed for a 2°C increase in tropical sea surface temperature," more recent work by Knutson and Tuleya (2004) points to only a 5 percent increase in hurricane windspeeds by 2080, and that Michaels *et al*. (2005) conclude that even this projection is likely twice as great as it should be.

By 2050, Pielke *et al*. report that "for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between $22 and $60 of increase in damage due to population growth and wealth," citing the findings of Pielke *et al*. (2000) in this regard. Based on this evidence, they state without equivocation that "the primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms."

In concluding their review, Pielke *et al*. note that massive reductions of anthropogenic CO_2 emissions "simply will not be effective with respect to addressing future hurricane impacts," and that "there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997)."

Michaels *et al*. (2006) subsequently analyzed Emanuel's (2005) and Webster *et al*.'s (2005) claims that "rising sea surface temperatures (SSTs) in the North Atlantic hurricane formation region are linked to recent increases in hurricane intensity, and that the trend of rising SSTs during the past 3 to 4 decades bears a strong resemblance to that projected to occur from increasing greenhouse gas concentrations." The researchers used weekly averaged 1° latitude by 1° longitude SST data together with hurricane track data of the National Hurricane Center that provide hurricane-center locations (latitude and longitude in tenths of a degree) and maximum 1-minute surface wind speeds (both at six-hour intervals) for all tropical storms and hurricanes in the Atlantic basin that occurred between 1982 (when the SST dataset begins) through 2005. Plotting maximum cyclone wind speed against the maximum SST that occurred prior to (or concurrent with) the maximum wind speed of each of the 270 Atlantic tropical cyclones of their study period, they found that for each 1°C increase in SST between 21.5°C and 28.25°C, the maximum wind speed attained by Atlantic basin cyclones rises, in the mean, by 2.8 m/s, and that thereafter, as SSTs rise still further, the first category-3-or-greater storms begin to appear. However, they report "there is no significant relationship between SST and maximum winds at SST exceeding 28.25°C."

From these observations, Michaels *et al*. conclude that "while crossing the 28.25°C threshold is a virtual necessity for attaining category 3 or higher winds, SST greater than 28.25°C does not act to further increase the intensity of tropical cyclones." The comparison of SSTs actually encountered by individual storms performed by Michaels *et al*.—as opposed to the comparisons of Emanuel (2005) and Webster *et al*. (2005), which utilized basin-wide averaged monthly or seasonal SSTs—refutes the idea that anthropogenic activity has detectably influenced the severity of Atlantic basin hurricanes over the past quarter-century.

Simultaneously, Balling and Cerveny (2006) examined temporal patterns in the frequency of intense tropical cyclones (TCs), the rates of rapid intensification of TCs, and the average rate of intensification of hurricanes in the North Atlantic Basin, including the tropical and subtropical North Atlantic, Caribbean Sea, and Gulf of Mexico, where they say there was "a highly statistically significant warming of 0.12°C decade^{-1} over the period 1970-2003 ... based on linear regression analysis and confirmed by a variety of other popular trend identification techniques." In doing so, they found "no increase in a variety of TC intensification indices," and that "TC intensification and/or hurricane intensification rates ... are not explained by current month or antecedent sea surface temperatures (despite observed surface warming over the study period)." They concluded that "while some researchers have hypothesized that increases in long-term sea surface temperature may lead to marked increases in TC storm intensity, our findings demonstrate that various indicators of TC intensification show no significant trend over the recent three decades."

Klotzbach and Gray (2006) note that still other papers question the validity of the findings of Emanuel (2005) and Webster *et al*. (2005) "due to potential bias-correction errors in the earlier part of the data record for the Atlantic basin (Landsea, 2005)," and that "while major hurricane activity in the Atlantic has shown a large increase since 1995, global tropical-cyclone activity, as measured by the accumulated cyclone energy index, has decreased slightly during the past 16 years (Klotzbach, 2006)." And as a result of these and other data and reasoning described in their paper, they "attribute the heightened Atlantic major hurricane activity of the 2004 season as well as the increased Atlantic major hurricane activity of the previous nine years to be a consequence of multidecadal fluctuations in the strength of the Atlantic multidecadal mode and strength of the Atlantic Ocean thermohaline circulation." In this regard, they say "historical records indicate that positive and negative phases of the Atlantic multidecadal mode and thermohaline circulation last about 25-30 years (typical period ~50-60 years; Gray *et al*., 1997; Latif *et al*., 2004)," and "since we have been in this new active thermohaline circulation period for about 11 years, we can likely expect that most of the next 15-20 hurricane seasons will also be active, particularly with regard to increased major hurricane activity."

Vecchi and Soden (2007a) explored twenty first century projected changes in vertical wind shear (VS) over the tropical Atlantic and its ties to the Pacific Walker circulation via a suite of coupled ocean-atmosphere models forced by emissions scenario A1B (atmospheric CO_2 stabilization at 720 ppm by 2100) of the Intergovernmental Panel on Climate Change's Fourth Assessment Report, where VS is defined as the magnitude of the vector difference between monthly mean winds at 850 and 200 hPa, and where changes are computed between the two 20-year periods 2001-2020 and 2081-2100. The 18-model mean result indicated a prominent increase in VS over the topical Atlantic and East Pacific (10°N-25°N). Noting that "the relative amplitude of the shear increase in these models is comparable to or larger than model-projected changes in other large-scale parameters related to tropical cyclone activity," the two researchers went on to state that the projected changes "would not suggest a strong anthropogenic increase in tropical Atlantic or Pacific hurricane activity during the 21st Century," and that "in addition to impacting cyclogenesis, the increase in SER [shear enhancement region] shear could act to inhibit the intensification of tropical cyclones as they traverse from the MDR [main development region] to the Caribbean and North America." Consequently, and in addition to the growing body of empirical evidence that indicates global warming has little to no impact on the intensity of hurricanes (Donnelly and Woodruff, 2007; Nyberg *et al*., 2007), there is now considerable up-to-date model-based evidence for the same conclusion.

In a closely related paper, Vecchi and Soden (2007b) used both climate models and observational reconstructions "to explore the relationship between changes in sea surface temperature and tropical cyclone 'potential intensity'—a measure that provides an upper bound on cyclone intensity and can also reflect the likelihood of cyclone development." They found "changes in local sea surface temperature are inadequate for characterizing *even the sign* [our italics] of changes in potential intensity." Instead, they report that "long-term changes in potential intensity are closely related to the regional structure of warming," such that "regions that warm more than the tropical average are characterized by increased potential intensity, and vice versa." Using this relationship to reconstruct changes in potential intensity over the twentieth century, based on observational reconstructions of sea surface temperature, they further found that "even though tropical Atlantic sea surface temperatures are currently at a historical high, Atlantic potential intensity probably peaked in the 1930s and 1950s," noting that "recent values are near the historical average." The two scientists' conclusion was that the response of tropical cyclone activity to natural climate variations "may be larger than the response to the more uniform patterns of greenhouse-gas-induced warming."

Also in the year 2007, and at the same time Vecchi and Soden were conducting their studies of the subject, Latif *et al*. (2007) were analyzing the 1851-2005 history of Accumulated Cyclone Energy

(ACE) Index for the Atlantic basin, which parameter, in their words, "takes into account the number, strength and duration of all tropical storms in a season," after which they "analyzed the results of an atmospheric general circulation model forced by the history of observed global monthly sea surface temperatures for the period 1870-2003."

With respect to the first part of their study, they report that "the ACE Index shows pronounced multidecadal variability, with enhanced tropical storm activity during the 1890s, 1950s and at present, and mostly reduced activity in between, but no sustained long-term trend," while with respect to the second part of their study, they report that "a clear warming trend is seen in the tropical North Atlantic sea surface temperature," but that this warming trend "does not seem to influence the tropical storm activity."

This state of affairs seemed puzzling at first, because a warming of the tropical North Atlantic is known to reduce vertical wind shear there and thus promote the development of tropical storms. However, Latif *et al*.'s modeling work revealed that a warming of the tropical Pacific enhances the vertical wind shear over the Atlantic, as does a warming of the tropical Indian Ocean. Consequently, they learned, as they describe it, that "the response of the vertical wind shear over the tropical Atlantic to a warming of all three tropical oceans, as observed during the last decades, will depend on the warming of the Indo-Pacific relative to that of the tropical North Atlantic," and "apparently," as they continue, "the warming trends of the three tropical oceans cancel with respect to their effects on the vertical wind shear over the tropical North Atlantic, so that the tropical cyclone activity [has] remained rather stable and mostly within the range of the natural multidecadal variability."

Nevertheless, a striking exception to this general state of affairs occurred in 2005, when the researchers report that "the tropical North Atlantic warmed more rapidly than the Indo-Pacific," which reduced vertical wind shear over the North Atlantic, producing the most intense Atlantic hurricane season of the historical record. By contrast, they say that the summer and fall of 2006 were "characterized by El Niño conditions in the Indo-Pacific, leading to a rather small temperature difference between the tropical North Atlantic and the tropical Indian and Pacific Oceans," and they say that "this explains the weak tropical storm activity [of that year]."

Latif *et al*. say "the future evolution of Atlantic tropical storm activity will critically depend on the warming of the tropical North Atlantic relative to that in the Indo-Pacific region," and "changes in the meridianal overturning circulation and their effect on tropical Atlantic sea surface temperatures have to be considered," and that "changes in ENSO statistics in the tropical Pacific may become important." Consequently, it is anyone's guess as to what would actually occur in the real world if the earth were to experience additional substantial warming. However, since the global temperature rise of the twentieth century—which the IPCC contends was unprecedented over the past two millennia—did not lead to a sustained long-term increase in hurricane intensity, there is little reason to believe any further warming would do so.

In one final concurrent study, Scileppi and Donnelly (2007) note that "when a hurricane makes landfall, waves and storm surge can overtop coastal barriers, depositing sandy overwash fans on backbarrier salt marshes and tidal flats," and that long-term records of hurricane activity are thus formed "as organic-rich sediments accumulate over storm-induced deposits, preserving coarse overwash layers." Based on this knowledge, they refined and lengthened the hurricane record of the New York City area by first calibrating the sedimentary record of surrounding backbarrier environments to documented hurricanes—including those of 1893, 1821, 1788, and 1693—and then extracting several thousand additional years of hurricane history from this important sedimentary archive.

As a result of these efforts, the two researchers determined that "alternating periods of quiescent conditions and frequent hurricane landfall are recorded in the sedimentary record and likely indicate that climate conditions may have modulated hurricane activity on millennial timescales." Of special interest in this regard, as they describe it, is the fact that "several major hurricanes occur in the western Long Island record during the latter part of the Little Ice Age (~1550-1850 AD) when sea surface temperatures were generally colder than present," but that "no major hurricanes have impacted this area since 1893," when the earth experienced the warming that took it from the Little Ice Age to the Current Warm Period.

Noting that Emanuel (2005) and Webster *et al*. (2005) had produced analyses that suggest that "cooler climate conditions in the past may have resulted in fewer strong hurricanes," but that their own findings suggest just the opposite, Scileppe and Donnelly concluded that "other climate phenomena, such as atmospheric circulation, may have been favorable for intense hurricane development despite lower sea surface temperatures" prior to the development of the Current Warm Period.

Last, Briggs (2008) developed Bayesian statistical models for the number of tropical cyclones, the rate at which these cyclones became hurricanes, and the rate at which the hurricanes became category 4+ storms in the North Atlantic, based on data from 1966 to 2006; this work led him to conclude that there is "no evidence that the distributional mean of individual storm intensity, measured by storm days, track length, or individual storm power dissipation index, has changed (increased or decreased) through time."

In light of the many real-world observations (as well as certain modeling work) discussed above, it would appear that even the supposedly unprecedented global warming of the past century or more has not led to an increase in the intensity of Atlantic hurricanes.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlanintensity.php.

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6.3.1.2. Frequency

6.3.1.2.1. The Past Few Millennia

Has the warming of the past century increased the yearly number of intense Atlantic Basin hurricanes? We offer a brief review of some studies that have explored this question via thousand-year reconstructions of the region's intense hurricane activity.

Liu and Fearn (1993) analyzed sediment cores retrieved from the center of Lake Shelby in Alabama (USA) to determine the history of intense (category 4 and 5) hurricane activity there over the past 3,500 years. This work revealed that over the period of their study, "major hurricanes of category 4 or 5 intensity directly struck the Alabama coast ... with an average recurrence interval of ~600 years." They also report that the last of these hurricane strikes occurred about 700 years ago. Hence, it would appear that twentieth century global warming has not accelerated the occurrence of such severe storm activity.

Seven years later, Liu and Fearn (2000) conducted a similar study based on 16 sediment cores retrieved from Western Lake, Florida (USA), which they used to produce a proxy record of intense hurricane strikes for this region of the Gulf of Mexico that covered the past 7,000 years. In this study, 12 major hurricanes of category 4 or 5 intensity were found to have struck the Western Lake region. Nearly all of these events were centered on a 2,400-year period between 1,000 and 3,400 years ago, when 11 of the 12 events were recorded. In contrast, between 0 to 1,000 and 3,400 to 7,000 years ago, only one and zero major hurricane strikes were recorded, respectively. According to the two researchers, a probable explanation for the "remarkable increase in hurricane frequency and intensity" that affected the Florida Panhandle and the Gulf Coast after 1400 BC would have been a continental-scale shift in circulation patterns that caused the jet stream to shift south and the Bermuda High southwest of their earlier Holocene positions, such as would be expected with global cooling, giving strength to their contention that "paleohurricane records from the past century or even the past millennium are not long enough to capture the full range of variability of catastrophic hurricane activities inherent in the Holocene climatic regime."

Last, we have the study of Donnelly and Woodruff (2007), who state that "it has been proposed that an increase in sea surface temperatures caused by anthropogenic climate change has led to an increase in the frequency of intense tropical cyclones," citing the studies of Emanuel (2005) and Webster *et al*. (2005). Donnelly and Woodruff developed "a record of intense [category 4 and greater] hurricane activity in the western North Atlantic Ocean over the past 5,000 years based on sediment cores from a Caribbean lagoon [Laguna Playa Grande on the island of Vieques, Puerto Rico] that contains coarse-grained deposits associated with intense hurricane landfalls."

Based on this work, the two researchers from the Woods Hole Oceanographic Institution detected three major intervals of intense hurricane strikes: one between 5,400 and 3,600 calendar years before present (yr BP, where "present" is AD 1950), one between 2,500 and 1,000 yr BP, and one after 250 yr BP. They also report that coral-based sea surface temperature (SST) data from Puerto Rico "indicate that mean annual Little Ice Age (250-135 yr BP or AD 1700-1815) SSTs were 2-3°C cooler than they are now," and they say that "an analysis of Caribbean hurricanes documented in Spanish archives indicates that 1766-1780 was one of the most active intervals in the period between 1500 and 1800 (Garcia-Herrera *et al*., 2005), when tree-ring-based reconstructions indicate a negative (cooler) phase of the Atlantic Multidecadal Oscillation (Gray *et al*., 2004)."

In light of these findings, Donnelly and Woodruff concluded that "the information available suggests that tropical Atlantic SSTs were probably not the principal driver of intense hurricane activity over the past several millennia." Indeed, there is no compelling reason to believe that the current level of intense hurricane activity is in any way unprecedented or that it has been caused by global warming. Quite to the contrary, the two researchers write that "studies relying on recent climatology indicate that North Atlantic hurricane activity is greater during [cooler] La Niña years and suppressed during [warmer] El Niño years (Gray, 1984; Bove *et al*., 1998), due primarily to increased vertical wind shear in strong El Niño years hindering hurricane development."

In summary, millennial-scale reconstructions of intense hurricane activity within the Atlantic Basin provide no support for the claim that global warming will lead to the creation of more intense Atlantic hurricanes that will batter the east, southeast, and southern coasts of the United States. In fact, they suggest just the opposite.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlanmill.php.

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6.3.1.2.2. The Past Few Centuries

Has the warming of the past century, which rescued the world from the extreme cold of the Little Ice Age, led to the formation of more numerous Atlantic Basin tropical storms and hurricanes? We review several studies that have broached this question with sufficiently long databases to provide reliable answers.

Elsner *et al*. (2000) provided a statistical and physical basis for understanding regional variations in major hurricane activity along the U.S. coastline on long timescales; in doing so, they presented data on major hurricane occurrences in 50-year intervals for Bermuda, Jamaica, and Puerto Rico. These data revealed that hurricanes occurred at lower frequencies in the last half of the twentieth century than they did in the preceding five 50-year periods, at all three of the locations studied. From 1701 to 1850, for example, when the earth was locked in the icy grip of the Little Ice Age, major hurricane frequency was 2.77 times greater at Bermuda, Jamaica, and Puerto Rico than it was from 1951 to 1998; from 1851 to 1950, when the planet was in transition from Little Ice Age to current conditions, the three locations experienced a mean hurricane frequency that was 2.15 times greater than what they experienced from 1951 to 1998.

Boose *et al*. (2001) used historical records to reconstruct hurricane damage regimes for an area composed of the six New England states plus adjoining New York City and Long Island for the period 1620-1997. In describing their findings, they wrote that "there was no clear century-scale trend in the number of major hurricanes." At lower damage levels, however, fewer hurricanes were recorded in the seventeenth and eighteenth centuries than in the nineteenth and twentieth centuries; but the three researchers concluded that "this difference is probably the result of improvements in meteorological observations and records since the early 19th century." Confining ourselves to the better records of the past 200 years, we note that the cooler nineteenth century had five of the highest-damage storms, while the warmer twentieth century had only one such storm.

Nyberg *et al*. (2007) developed a history of major (category 3-5) Atlantic hurricanes over the past 270 years based on proxy records of vertical wind shear and sea surface temperature that they derived from corals and a marine sediment core. These parameters are the primary controlling forces that set the stage for the formation of major hurricanes in the main development region westward of Africa across the tropical Atlantic and Caribbean Sea between latitudes 10 and 20°N, where 85 percent of all major hurricanes and 60 percent of all non-major hurricanes and tropical storms of the Atlantic are formed. This effort resulted in their discovering that the average frequency of major Atlantic hurricanes "decreased gradually from the 1760s until the early 1990s, reaching anomalously low values during the 1970s and 1980s." More specifically, they note that "a gradual downward trend is evident from an average of ~4.1 (1775-1785) to ~1.5 major hurricanes [per year] during the late 1960s to early 1990s," and that "the current active phase (1995-2005) is unexceptional compared to the other high-activity periods of ~1756-1774, 1780-1785, 1801-1812, 1840-1850, 1873-1890 and 1928-1933." They conclude that the recent ratcheting up of Atlantic major hurricane activity appears to be simply "a recovery to normal hurricane activity." In a commentary on Nyberg *et al*.'s paper, Elsner (2007) states that "the assumption that hurricanes are simply passive responders to climate change should be challenged."

Also noting that "global warming is postulated by some researchers to increase hurricane intensity in the north basin of the Atlantic Ocean," with the implication that "a warming ocean may increase the frequency, intensity, or timing of storms of tropical origin that reach New York State," Vermette (2007) employed the Historical Hurricane Tracks tool of the National Oceanic and Atmospheric Administration's Coastal Service Center to document all Atlantic Basin tropical cyclones that reached New York State between 1851 and 2005, in order to assess the degree of likelihood that twentieth century global warming might be influencing these storms, particularly for hurricanes but also for tropical storms, tropical depressions and extratropical storms.

This work revealed, in Vermette's words, that "a total of 76 storms of tropical origin passed over New York State between 1851 and 2005," and that of these storms, 14 were hurricanes, 27 were tropical storms, seven were tropical depressions and 28 were extratropical storms. For Long Island, he further reports that "the average frequency of hurricanes and storms of tropical origin (all types) is one in every 11 years and one in every 2 years, respectively." Also of note is his finding that storm activity was greatest in both the late nineteenth century and the late twentieth century, and the fact that "the frequency and intensity of storms in the late 20th century are similar to those of the late 19th century.” As a result, Vermette concludes that “rather than a linear change, that may be associated with a global warming, the changes in recent time are following a multidecadal cycle and returning to conditions of the latter half of the 19th century.” He also concludes that “yet unanswered is whether a warmer global climate of the future will take hurricane activity beyond what has been experienced in the observed record.”

In a similar study, Mock (2008) developed a “unique documentary reconstruction of tropical cyclones for Louisiana, U.S.A. that extends continuously back to 1799 for tropical cyclones, and to 1779 for hurricanes.” This record—which was derived from daily newspaper accounts, private diaries, plantation diaries, journals, letters, and ship records, and which was augmented “with the North Atlantic hurricane database as it pertains to all Louisiana tropical cyclones up through 2007”—is, in Mock’s words, “the longest continuous tropical cyclone reconstruction conducted to date for the United States Gulf Coast.” And this record reveals that “the 1820s/early 1830s and the early 1860s are the most active periods for the entire record.”

In discussing his findings, the University of South Carolina researcher says that “the modern records which cover just a little over a hundred years is too short to provide a full spectrum of tropical cyclone variability, both in terms of frequency and magnitude.” In addition, he states that “if a higher frequency of major hurricanes occurred in the near future in a similar manner as the early 1800s or in single years such as in 1812, 1831, and 1860, [they] would have devastating consequences for New Orleans, perhaps equaling or exceeding the impacts such as in hurricane Katrina in 2005.” We also observe that the new record clearly indicates that the planet’s current high levels of air temperature and CO_2 concentration cannot be blamed for the 2005 Katrina catastrophe, as both parameters were much lower when tropical cyclone and hurricane activity in that region were much higher in the early- to mid-1800s.

Around the same time, Wang and Lee (2008) used the “improved extended reconstructed” sea surface temperature (SST) data described by Smith and Reynolds (2004) for the period 1854-2006 to examine historical temperature changes over the global ocean, after which they regressed vertical wind shear—“calculated as the magnitude of the vector difference between winds at 200 mb and 850 mb during the Atlantic hurricane season (June to November), using NCEP-NCAR reanalysis data”—onto a temporal variation of global warming defined by the SST data. This work led to their discovery that warming of the surface of the global ocean is typically associated with a secular increase of tropospheric vertical wind shear in the main development region (MDR) for Atlantic hurricanes, and that the long-term increased wind shear of that region has coincided with a weak but robust downward trend in U.S. landfalling hurricanes. However, this relationship has a pattern to it, whereby local ocean warming in the Atlantic MDR actually reduces the vertical wind shear there, while “warmings in the tropical Pacific and Indian Oceans produce an opposite effect, i.e., they increase the vertical wind shear in the MDR for Atlantic hurricanes.”

In light of these findings, the two researchers conclude that “the tropical oceans compete with one another for their impacts on the vertical wind shear over the MDR for Atlantic hurricanes,” and they say that to this point in time, “warmings in the tropical Pacific and Indian Oceans win the competition and produce increased wind shear which reduces U.S. landfalling hurricanes.” As for the years and decades ahead, they write that “whether future global warming increases the vertical wind shear in the MDR for Atlantic hurricanes will depend on the relative role induced by secular warmings over the tropical oceans.”

Vecchi and Knutson (2008) write in the introduction to their study of the subject that “there is currently disagreement within the hurricane/climate community on whether anthropogenic forcing (greenhouse gases, aerosols, ozone depletion, etc.) has caused an increase in Atlantic tropical storm or hurricane frequency.” In further exploring this question, they derived an estimate of the expected number of North Atlantic tropical cyclones (TCs) that were missed by the observing system in the pre-satellite era (1878-1965), after which they analyzed trends of both reconstructed TC numbers and duration over various time periods and looked at how they may or may not have been related to trends in sea surface temperature over the main development region of North Atlantic TCs. This work revealed, in their words, that “the estimated trend for 1900-2006 is highly significant (+~4.2 storms century^{-1}),” but they say that the trend “is strongly influenced by a minimum in 1910-30, perhaps artificially enhancing significance.” When using their base case adjustment for missed TCs and considering the entire 1878-2006 record, they find that the trend in the number of TCs is only "weakly positive" and "not statistically significant," while they note that the trend in average TC duration over the 1878-2006 period "is negative and highly significant."

Elsner (2008), in his summary of the *International Summit on Hurricanes and Climate Change* held in May 2007 on the Greek island of Crete, said the presence of more hurricanes in the northeastern Caribbean Sea "during the second half of the Little Ice Age when sea temperatures near Puerto Rico were a few degrees (Celsius) cooler than today" provides evidence that "today's warmth is not needed for increased storminess."

In conclusion, the bulk of the evidence that has been accumulated to date over multi-century timescales indicates that late twentieth century yearly hurricane numbers were considerably lower than those observed in colder prior centuries. It is by no means clear that further global warming, due to any cause, would lead to an increase or decrease in U.S. landfalling hurricanes. All we can say is that up to this point in time, global warming appears to have had a weak negative impact on their numbers.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlancent.php.

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6.3.1.2.3. The Past Century

Have tropical storms and hurricanes of the Atlantic Ocean become more numerous over the past century, in response to what the IPCC describes as unprecedented global warming? This became a matter of intense speculation following a spike of storm occurrences in 2004-2005, but once again it is instructive to approach the question by starting with the findings of earlier research.

Bove *et al*. (1998) examined the characteristics of all recorded landfalling U.S. Gulf Coast hurricanes—defined as those whose eyes made landfall between Cape Sable, Florida and Brownsville, Texas—from 1896 to 1995. They found that the first half of this period saw considerably more hurricanes than the last half: 11.8 per decade vs. 9.4 per decade. The same was true for intense hurricanes of category 3 or more on the Saffir-Simpson storm scale: 4.8 vs. 3.6. The numbers of all hurricanes and the numbers of intense hurricanes both tended downward from 1966 to the end of the period investigated, with the decade 1986-1995 exhibiting the fewest intense hurricanes of the entire century. The three researchers concluded that "fears of increased hurricane activity in the Gulf of Mexico are premature."

Noting that the 1995 Atlantic hurricane season was one of near-record tropical storm and hurricane activity, but that during the preceding four years (1991-94) such activity over the Atlantic basin was the lowest since the keeping of reliable records began in the mid-1940s, Landsea *et al*. (1998) studied the meteorological characteristics of the two periods to determine what might have caused the remarkable upswing in storm activity in 1995. In doing so, they found that "perhaps the primary factor for the increased hurricane activity during 1995 can be attributed to a favorable large-scale pattern of extremely low vertical wind shear throughout the main development region." They also noted that "in addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea-level pressure, abnormally warm ocean waters, and very humid values of total precipitable water."

An additional factor that may have contributed to the enhanced activity of the 1995 Atlantic hurricane season was the westerly phase of the stratospheric quasi-biennial oscillation, which is known to enhance Atlantic basin storm activity. Possibly the most important factor of all, however, was what Landsea *et al*. called the "dramatic transition from the prolonged late 1991-early 1995 warm episode (El Niño) to cold episode (La Niña) conditions," which contributed to what they described as "the dramatic reversal" of weather characteristics "which dominated during the [prior] four hurricane seasons."

"Some have asked," in the words of the four researchers, "whether the increase in hurricanes during 1995 is related to the global surface temperature increases that have been observed over the last century, some contribution of which is often ascribed to increases in anthropogenic 'greenhouse' gases." In reply, they stated that "such an interpretation is not warranted," because the various factors noted above seem sufficient to explain the observations. "Additionally," as they further wrote, "Atlantic hurricane activity has actually decreased significantly in both frequency of intense hurricanes and mean intensity of all named storms over the past few decades," and "this holds true even with the inclusion of 1995's Atlantic hurricane season."

In a major synthesis of Atlantic basin hurricane indices published the following year, Landsea *et al*. (1999) reported long-term variations in tropical cyclone activity for this region (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea). Over the period 1944-1996, decreasing trends were found for (1) the total number of hurricanes, (2) the number of intense hurricanes, (3) the annual number of hurricane days, (4) the maximum attained wind speed of all hurricane storms averaged over the course of a year, and (5) the highest wind speed associated with the strongest hurricane recorded in each year. In addition, they reported that the total number of Atlantic hurricanes making landfall in the United States had decreased over the 1899-1996 time period, and that normalized trends in hurricane damage in the United States between 1925 and 1996 revealed such damage to be decreasing at a rate of $728 million per decade.

In a similar study that included a slightly longer period of record (1935-1998), Parisi and Lund (2000) conducted a number of statistical tests on all Atlantic Basin hurricanes that made landfall in the contiguous United States, finding that "a simple linear regression of the yearly number of landfalling hurricanes on the years of study produces a trend slope estimate of -0.011 ± 0.0086 storms per year." To drive home the significance of that result, they expressly called attention to the fact that "the estimated trend slope is negative," which means, of course, that the yearly number of such storms is decreasing, which is just the opposite of what they described as the "frequent hypothesis ... that global warming is causing increased storm activity." Their statistical analysis indicates that "the trend slope is not significantly different from zero."

Contemporaneously, Easterling *et al.* (2000) noted that the mean temperature of the globe rose by about 0.6°C over the past century, and they thus looked for possible impacts of this phenomenon on extreme weather events, which if found to be increasing, as they describe it, "would add to the body of evidence that there is a discernable human affect on the climate." Their search, however, revealed few changes of significance, although they did determine that "the number of intense and landfalling Atlantic hurricanes has declined."

Lupo and Johnston (2000) found "there has been relatively little trend in the overall occurrence of hurricanes within the Atlantic Ocean Basin (62 year period)," reflecting an upward trend in category 1 hurricanes which is countered by downward or weak trends in the occurrence of category 2-5 hurricanes. Stratifying by hurricane genesis region indicated the tendency for more hurricanes to form in La Niña years during PDO1 (1977-1999) was strongly influenced by more storms being generated in the Caribbean and Eastern Atlantic. Only two storms formed in these regions during El Niño years. During PDO2 (1947-1976) there was a weak tendency for more (fewer) storms forming in the Gulf and Caribbean (West and East Atlantic) sub-regions during La Niña years, while the reverse occurred for El Niño years.

Three years later, Balling and Cerveny (2003) wrote that "many numerical modeling papers have appeared showing that a warmer world with higher sea surface temperatures and elevated atmospheric moisture levels could increase the frequency, intensity, or duration of future tropical cyclones," but that empirical studies had failed to reveal any such relationships. They also noted that "some scientists have suggested that the buildup of greenhouse gases can ultimately alter other characteristics of tropical cyclones, ranging from timing of the active season to the location of the events," and that these relationships have not been thoroughly studied with historical real-world data. They proceeded to fill this void by conducting such a study for tropical storms in the Caribbean Sea, the Gulf of Mexico, and the western North Atlantic Ocean.

More specifically, the two Arizona State University climatologists constructed a daily database of tropical storms that occurred within their study area over the period 1950-2002, generating "a variety of parameters dealing with duration, timing, and location of storm season," after which they tested for trends in these characteristics, attempting to explain the observed variances in the variables using regional, hemispheric, and global temperatures. In doing so, they "found no trends related to timing and duration of the hurricane season and geographic position of storms in the Caribbean Sea, Gulf of Mexico and tropical sector of the western North Atlantic Ocean." Likewise, they said they "could find no significant trends in these variables and generally no association with them and the local ocean, hemispheric, and global temperatures."

Elsner *et al*. (2004) conducted a changepoint analysis of time series of annual major North Atlantic hurricane counts and annual major U.S. hurricane counts for the twentieth century, which technique, in their words, "quantitatively identifies temporal shifts in the mean value of the observations." This work revealed that "major North Atlantic hurricanes have become more frequent since 1995," but at "a level reminiscent of the 1940s and 1950s." In actuality, however, they had not quite reached that level, nor had they maintained it for as long a time. Their data indicate that the mean annual hurricane count for the seven-year period 1995-2001 was 3.86, while the mean count for the 14-year period 1948-1961 was 4.14. They also reported that, "in general, twentieth-century U.S. hurricane activity shows no abrupt shifts," noting, however, that there was an exception over Florida, "where activity decreased during the early 1950s and again during the late 1960s." Last, they found that "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

In contradiction of the IPCC's claim that global warming leads to more intense hurricane activity, the results of Elsner *et al*.'s study found that not only did North Atlantic hurricane activity not increase over the entire twentieth century, hurricane activity also did not increase in response to the more sporadic warming associated with periodic El Niño conditions.

Two years later, things got a bit more interesting. "The 2005 hurricane season," in the words of Virmani and Weisberg (2006), "saw an unprecedented number of named tropical storms since records began in 1851." Moreover, they said it followed "on the heels of the unusual 2004 hurricane season when, in addition to the first South Atlantic hurricane, a record-breaking number of major hurricanes made landfall in the United States, also causing destruction on the Caribbean islands in their path." The question they thus posed was whether these things occurred in response to recent global warming or if they bore sufficient similarities with hurricane seasons of years past to preclude such an attribution.

The two researchers determined that "latent heat loss from the tropical Atlantic and Caribbean was less in late spring and early summer 2005 than preceding years due to anomalously weak trade winds associated with weaker sea-level pressure," which phenomenon "resulted in anomalously high sea surface temperatures" that "contributed to earlier and more intense hurricanes in 2005." However, they went on to note that "these conditions in the Atlantic and Caribbean during 2004 and 2005 were not unprecedented and were equally favorable during the active hurricane seasons of 1958, 1969, 1980, 1995 and 1998." In addition, they said there was "not a clear link between the Atlantic Multidecadal Oscillation or the long term trend [of temperature] and individual active hurricane years, confirming the importance of other factors in hurricane formation."

The following year, Mann and Emanuel (2006) used quantitative records stretching back to the mid-nineteenth century to develop a positive correlation between sea surface temperatures and Atlantic basin tropical cyclone frequency for the period 1871-2005, while Holland and Webster (2007) had analyzed Atlantic tropical cyclone frequency back to 1855 and found a doubling of the number of tropical cyclones over the past 100 years. Both of these papers linked these changes to anthropogenic greenhouse warming. In a compelling rebuttal of those conclusions, however, Landsea (2007) cited a number of possible biases that may exist in the cyclone frequency trends derived in the two studies, concluding that "improved monitoring in recent years is responsible for most, if not all, of the observed trend in increasing frequency of tropical cyclones."

Parisi and Lund (2008) calculated return periods of Atlantic-basin U.S. landfalling hurricanes based on "historical data from the 1900 to 2006 period via extreme value methods and Poisson regression techniques" for each of the categories (1-5) of the Saffir-Simpson Hurricane Scale. This work revealed that return periods (in years) for these hurricanes were, in ascending Saffir-Simpson Scale category order: (1) 0.9, (2) 1.3, (3) 2.0, (4) 4.7, and (5) 23.1. In addition, the two researchers reported that corresponding non-encounter probabilities in any one hurricane season were calculated to be (1) 0.17, (2) 0.37, (3) 0.55, (4) 0.78, and (5) 0.95. They stated that the hypothesis that U.S. hurricane strike frequencies are "increasing in time" is "statistically rejected."

Lupo *et al.* (2008) added data for seven more years to the data originally analyzed by Lupo and Johnston (2000) and found it "did not change the major findings." The authors hypothesized that the Atlantic hurricane season of 2005 was so active, not only because of the recent increase in hurricane activity which may be associated with the PDO, but also possibly due to decreased upper tropospheric shear over the Atlantic which may have been associated with a stronger easterly phase of the quasi-biennial oscillation along with warmer-than-normal SSTs.

In light of the long history of multi-decadal to century-scale analyses that have come to the same conclusion, we must reject the oft-heard claim that Atlantic hurricanes have increased in frequency in response to twentieth century global warming.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlangwe.php.

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6.3.1.2.4. The El Niño Effect

How does the frequency of Atlantic basin hurricanes respond to increases in ocean temperature? In exploring this important question one has to look not only at Atlantic Ocean temperatures, but also those in the eastern tropical Pacific, in particular during La Niña and El Niño conditions. Wilson (1999) utilized data from the last half of the twentieth century to determine that the probability of having three or more intense Atlantic hurricanes was only 14 percent during an El Niño year (warm temperatures in the eastern tropical Pacific), but fully 53 percent during a La Niña year (cold ocean temperatures in the eastern tropical Pacific). When ocean temperatures warm in the eastern tropical Pacific, they cause stronger upper level winds in the tropical Atlantic and a greater likelihood that storms would become sheared, and hence weaker. The opposite (weaker upper level winds) occurs during La Niña years.

Muller and Stone (2001) conducted a similar study of tropical storm and hurricane strikes along the southeast U.S. coast from South Padre Island (Texas) to Cape Hatteras (North Carolina), using data from the entire past century. For tropical storms and hurricanes together, they found an average of 3.3 strikes per La Niña season, 2.6 strikes per neutral season, and 1.7 strikes per El Niño season. For hurricanes alone, the average rate of strike occurrence ranged from 1.7 per La Niña season to 0.5 per El Niño season, which represents a frequency-of-occurrence decline of fully 70 percent in going from cooler La Niña conditions to warmer El Niño conditions. Likewise, Elsner *et al*. (2001)—who also worked with data from the entire past century—found that when there are below normal sea surface temperatures in the equatorial Pacific, "the probability of a U.S. hurricane increases."

Lyons (2004) also conducted a number of analyses of U.S. landfalling tropical storms and hurricanes, dividing them into three different groupings: the 10 highest storm and hurricane landfall years, the nine lowest such years, and all other years. These groupings revealed, in Lyons' words, that "La Niña conditions occurred 19% more often during high U.S. landfall years than during remaining years," and that "El Niño conditions occurred 10% more often during low U.S. landfall years than during remaining years." In addition, it was determined that "La Niña (El Niño) conditions were 18% (25%) more frequent during high (low) U.S. landfall years than during low (high) U.S. landfall years."

An analogous approach was used by Pielke and Landsea (1999) to study the effect of warming on the intensity of Atlantic basin hurricanes, using data from the period 1925 to 1997. In their analysis, they first determined that 22 years of this period were El Niño years, 22 were La Niña years, and 29 were neither El Niño nor La Niña years. Then, they compared the average hurricane wind speed of the cooler La Niña years with that of the warmer El Niño years, finding that in going from the cooler climatic state to the warmer climatic state, average hurricane wind speed dropped by about 6 meters per second.

Independent confirmation of these findings was provided by Pielke and Landsea's assessment of concurrent hurricane damage in the United States: El Niño years experienced only half the damage of La Niña years. And in a 10-year study of a Mediterranean waterbird (Cory's Shearwater) carried out on the other side of the Atlantic, Brichetti *et al*. (2000) determined—contrary to their own expectation—that survival rates during warmer El Niño years were greater than during cooler La Niña years.

In another pertinent study, Landsea *et al*. (1998) analyzed the meteorological circumstances associated with the development of the 1995 Atlantic hurricane season, which was characterized by near-record tropical storm and hurricane activity after four years (1991-94) that had exhibited the lowest such activity since the keeping of reliable records began. They determined that the most important factor behind this dramatic transition from extreme low to extreme high tropical storm and hurricane activity was what they called the "dramatic transition from the prolonged late 1991-early 1995 warm episode (El Niño) to cold episode (La Niña) conditions."

Last, in a twentieth century changepoint analysis of time series of major North Atlantic and U.S. annual hurricane counts, which in the words of its authors, "quantitatively identifies temporal shifts in the mean value of the observations," Elsner *et al*. (2004) found that "El Niño events tend to suppress hurricane activity along the entire coast with the most pronounced effects over Florida."

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurratlanelnino.php.

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6.3.2. Indian Ocean

Singh *et al*. (2000, 2001) analyzed 122 years of tropical cyclone data from the North Indian Ocean over the period 1877-1998. Since this was the period of time during which the planet recovered from the global chill of the Little Ice Age, it is logical to assume that their findings would be indicative of changes in hurricane characteristics we might expect if the earth were to warm by that amount again, which is what the IPCC is projecting.

Singh *et al*. found that on an annual basis, there was a slight decrease in tropical cyclone frequency, such that the North Indian Ocean, on average, experienced about one less hurricane per year at the end of the 122-year record in 1998 than it did at its start in 1877. In addition, based on data from the Bay of Bengal, they found that tropical cyclone numbers dropped during the months of most severe cyclone formation (November and May), when the El Niño-Southern Oscillation was in a warm phase. In light of these real-world observations, it would thus appear that if tropical cyclones of the North Indian Ocean were to change at all in response to global warming, their overall frequency and the frequency of the most intense such storms would likely decrease.

Hall (2004) analyzed characteristics of cyclones occurring south of the equator from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001-2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This work revealed that "the 2001-2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, Hall determined that "the overall number of depressions and tropical cyclones was below the long-term mean." Further east, he found that broad-scale convection was near or slightly above normal, but that "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which result represented "a continuation of the trend of the previous few seasons." What is more, Hall writes that "in the eastern Australian region, the four-year period up to 2001-2002 was by far the quietest recorded in the past 41 years."

Raghavan and Rajesh (2003) reviewed the general state of scientific knowledge relative to trends in the frequency and intensity of tropical cyclones throughout the world, giving special attention to the Indian state of Andhra Pradesh, which borders on the Bay of Bengal. For the North Indian Ocean (NIO), comprising both the Bay of Bengal and the Arabian Sea, they report that for the period 1891-1997 there was a significant decreasing trend (at the 99 percent confidence level) in the frequency of cyclones with the designation of "cyclonic storm" and above, and that "the maximum decrease was in the last four decades," citing the work of Srivastava *et al*. (2000). In addition, they note that Singh and Khan (1999), who studied 122 years of data, also found the annual frequency of NIO-basin tropical cyclones to be decreasing.

As in other parts of the world, they found increasing impacts of tropical cyclones; but their economic analysis led them to conclude that "increasing damage due to tropical cyclones over Andhra Pradesh, India, is attributable mainly to economic and demographic factors and not to any increase in frequency or intensity of cyclones." With no equivocation, they state that "inflation, growth in population, and the increased wealth of people in the coastal areas (and not global warming) are the factors contributing to the increased impact."

Commenting on their findings, the researchers say "there is a common perception in the media, and even government and management circles, that [increased property damage from tropical cyclones] is due to an increase in tropical cyclone frequency and perhaps in intensity, probably as a result of global climate change." However, as they continue, "studies all over the world show that though there are decadal variations, there is no definite long-term trend in the frequency or intensity of tropical cyclones." They confidently state that "the specter of tropical cyclones increasing alarmingly due to global climate change, portrayed in the popular media and even in some more serious publications, does not therefore have a sound scientific basis."

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurricaneindian.php.

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6.3.3. Pacific Ocean

Chu and Clark (1999) analyzed the frequency and intensity of tropical cyclones that either originated in or entered the central North Pacific (0-70°N, 140-180°W) over the 32-year period 1966-1997. They determined that "tropical cyclone activity (tropical depressions, tropical storms, and hurricanes combined) in the central North Pacific [was] on the rise." This increase, however, appears to have been due to a step-change that led to the creation of "fewer cyclones during the first half of the record (1966-81) and more during the second half of the record (1982-1997)," and accompanying the abrupt rise in tropical cyclone numbers was a similar abrupt increase in maximum hurricane intensity. Chu and Clark say the observed increase in tropical cyclone activity cannot be due to CO_2-induced global warming, because, in their words, "global warming is a gradual process" and "it cannot explain why there is a steplike change in the tropical cyclone incidences in the early 1980s."

Clearly, a much longer record of tropical cyclone activity is needed to better understand the nature of the variations documented by Chu and Clark, as well as their relationship to mean global air temperature. The beginnings of such a history were presented by Liu *et al*. (2001), who meticulously waded through a wealth of weather records from Guangdong Province in southern China, extracting data pertaining to the landfall of typhoons there since AD 975. Calibrating the historical data against instrumental observations over the period 1884-1909, they found the trends of the two datasets to be significantly correlated (r = 0.71). This observation led them to conclude that "the time series reconstructed from historical documentary evidence contains a reliable record of variability in typhoon landfalls." They proceeded to conduct a spectral analysis of the Guangdong time series and discovered an approximate 50-year cycle in the frequency of typhoon landfall that "suggests an external forcing mechanism, which remains to be identified." They also found that "the two periods of most frequent typhoon strikes in Guangdong (AD 1660-1680, 1850-1880) coincide with two of the coldest and driest periods in northern and central China during the Little Ice Age."

Looking even further back in time into the Southern Hemisphere, Hayne and Chappell (2001) studied a series of storm ridges at Curacoa Island, which were deposited over the past 5,000 years on the central Queensland shelf (18°40'S; 146°33'E), in an attempt to create a long-term history of major cyclonic events that have impacted that area. One of their stated reasons for doing so was to test the climate-model-based hypothesis that "global warming leads to an increase of cyclone frequency or intensity." They found that "cyclone frequency was statistically constant over the last 5,000 years." In addition, they could find "no indication that cyclones have changed in intensity," a finding that is inconsistent with the climate-model-based hypothesis.

In a similar study, Nott and Hayne (2001) produced a 5,000-year record of tropical cyclone frequency and intensity along a 1,500-km stretch of coastline in northeast Australia located between latitudes 13 and 24°S by geologically dating and tropographically surveying landform features left by historic hurricanes, and running numerical models to estimate storm surge and wave heights necessary to reach the landform locations. These efforts revealed that several "super-cyclones" with central pressures less than 920 hPa and wind speeds in excess of 182 kilometers per hour had occurred over the past 5,000 years at intervals of roughly 200 to 300 years in all parts of the region of their study. They also report that the Great Barrier Reef "experienced at least five such storms over the past 200 years, with the area now occupied by Cairns experiencing two super-cyclones between 1800 and 1870." The twentieth century, however, was *totally devoid* of such storms, "with only one such event (1899) since European settlement in the mid-nineteenth century."

Also noting that "many researchers have suggested that the buildup of greenhouse gases (Watson *et al*., 2001) will likely result in a rise in sea surface temperature (SST), subsequently increasing both the number and maximum intensity of tropical cyclones (TCs)," Chan and Liu (2004) explored the validity of this assertion via an examination of pertinent real-world data. As they put it, "if the frequency of TC occurrence were to increase with increasing global air temperature, one would expect to see an increase in the number of TCs during the past few decades." Their efforts, which focused on the last four decades of the twentieth century, resulted in their finding that a number of parameters related to SST and TC activity in the Western North Pacific (WNP) "have gone through large interannual as well as interdecadal variations," and that "they also show a slight decreasing trend." In addition, they say that "no significant correlation was found between the typhoon activity parameters and local SST," and "an increase in local SST does not lead to a significant change of the number of intense TCs in the WNP, which is contrary to the results produced by many of the numerical climate models." Instead, they found that "the interannual variation of annual typhoon activity is mainly constrained by the ENSO phenomenon through the alteration of the large-scale circulation induced by the ENSO event."

In discussing their results, Chan and Liu write that the reason for the discrepancies between their real-world results and those of many of the numerical climate models likely lies in the fact that the models assume TCs are generated primarily from energy from the oceans and that a higher SST therefore would lead to more energy being transferred from the ocean to the atmosphere. "In other words," as they say, "the typhoon activity predicted in these models is almost solely determined by thermodynamic processes, as advocated by Emanuel (1999)," whereas "in the real atmosphere, dynamic factors, such as the vertical variation of the atmospheric flow (vertical wind shear) and the juxtaposition of various flow patterns that lead to different angular momentum transports, often outweigh the thermodynamic control in limiting the intensification process." Their final conclusion is that "at least for the western North Pacific, observational evidence does not support the notion that increased typhoon activity will occur with higher local SSTs."

Much the same thing was found by Free *et al*. (2004), who looked for increases in potential hurricane intensity, as they put it, "estimated from thermodynamic principles as shown in Emanuel (1986, 1995) given a record of SSTs and profiles of atmospheric temperature and humidity." This they did using radiosonde and SST data from 14 island radiosonde stations in both the tropical Pacific and Atlantic Oceans, after which they compared their results with those of Bister and Emanuel (2002) at grid points near the selected stations. They found "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

Hall (2004) reviewed the characteristics of cyclones occurring south of the equator and eastward from longitude 90°E to 120°W in the South Pacific and southeast Indian Oceans, concentrating on the 2001-2002 cyclone season and comparing the results with those of the preceding four years and the 36 years before that. This analysis indicated that "the 2001-2002 tropical cyclone season in the South Pacific and southeast Indian Ocean was one of the quietest on record, in terms of both the number of cyclones that formed, and the impact of those systems on human affairs." In the southeast Indian Ocean, for example, he writes that "the overall number of depressions and tropical cyclones was below the long-term mean," while further east he found that broad-scale convection was near or slightly above normal, but that "the proportion of tropical depressions and weak cyclones developing into severe cyclones was well below average," which result represented "a continuation of the trend of the previous few seasons." Hall writes that "in the eastern Australian region, the four-year period up to 2001-2002 was by far the quietest recorded in the past 41 years."

Noting that "according to Walsh and Ryan (2000), future global climate trends may result in an increased incidence of cyclones," and realizing that "understanding the behavior and frequency of severe storms in the past is crucial for the prediction of future events," Yu *et al*. (2004) devised a way to decipher the history of severe storms in the southern South China Sea. Working at Youngshu Reef (9°32'-9°42'N, 112°52 -113°04'E), they used standard radiocarbon dating together with TIMS U-series dating to determine the times of occurrence of storms that were strong enough to relocate large *Porites* coral blocks that are widespread on the reef flats there. This program revealed that "during the past 1000 years, at least six exceptionally strong storms occurred," which they dated to approximately AD 1064 ± 30, 1218 ± 5, 1336 ± 9, 1443 ± 9, 1682 ± 7, and 1872 ± 15, yielding an average recurrence time of 160 years. Interestingly, none of these six severe storms occurred during the past millennium's last century, which the IPCC claims was the warmest such period of that thousand-year interval.

Noting that Emanuel (2005) and Webster *et al*. (2005) have claimed that "tropical cyclone intensity has increased markedly in recent decades," and saying that because they specifically argued that "tropical cyclone activity over the western North Pacific has been changed in response to the ongoing global warming," Ren *et al*. (2006) decided to see if any increases in tropical cyclone activity had occurred over China between 1957 and 2004. This they did by analyzing tropical cyclone (TC) precipitation (P) data from 677 Chinese weather stations for the period 1957 to 2004, searching for evidence of long-term changes in TCP and TC-induced torrential precipitation events. This search indicated, in their words, that "significant downward trends are found in the TCP volume, the annual frequency of torrential TCP events, and the contribution of TCP to the annual precipitation over the past 48 years." Also, they say that the downward trends were accompanied by "decreases in the numbers of TCs and typhoons that affected China during the period 1957-2004." In a conclusion that consequently differs dramatically from the claims of Emanuel (2005) and Webster *et al*. (2005) relative to inferred increases in tropical cyclone activity over the western North Pacific in recent decades, Ren *et al*. say their findings "strongly suggest that China has experienced decreasing TC influence over the past 48 years, especially in terms of the TCP."

Nott *et al*. (2007) developed a 777-year-long annually resolved record of landfalling tropical cyclones in northeast Australia based on analyses of isotope records of tropical cyclone rainfall in an annually layered carbonate stalagmite from Chillagoe (17.2°S, 144.6°E) in northeast Queensland. Perhaps their most important discovery in doing so was their finding that "the period between AD 1600 to 1800"—when the Little Ice Age held sway throughout the world—"had many more intense or hazardous cyclones impacting the site than the post AD 1800 period," when the planet gradually began to warm.

Li *et al*. (2007) analyzed real-world tropical cyclone data pertaining to the western North Pacific basin archived in the *Yearbook of Typhoon* published by the China Meteorological Administration for the period 1949-2003, together with contemporaneous atmospheric information obtained from the National Center for Environmental Protection reanalysis dataset for the period 1951-2003. Following this endeavor, they used their empirical findings to infer future tropical cyclone activity in the region based upon climate-model simulations of the state of the general circulation of the atmosphere over the next half-century. This protocol revealed, first, that there were "more tropical cyclones generated over the western North Pacific from the early 1950s to the early 1970s in the 20th century and less tropical cyclones from the mid-1970s to the present." They further found that "the decadal changes of tropical cyclone activities are closely related to the decadal changes of atmospheric general circulation in the troposphere, which provide favorable or unfavorable conditions for the formation of tropical cyclones." Based on simulations of future occurrences of these favorable and unfavorable conditions derived from "a coupled climate model under the [A2 and B2] schemes of the Intergovernmental Panel on Climate Change special report on emission scenarios," they then determined that "the general circulation of the atmosphere would become unfavorable for the formation of tropical cyclones as a whole and the frequency of tropical cyclone formation would likely decrease by 5% within the next half century, although more tropical cyclones would appear during a short period of it."

Last, an analysis by Lupo *et al*. (2008) of 69 years of East Pacific tropical cyclone activity (1970 – 2007) found that there were 16.3 storms per year (9.0 hurricanes and 7.3 tropical storms), which was a greater amount of activity than found in the Atlantic Ocean basin. The long-term trend showed a slight decrease (not statistically significant) in East Pacific tropical cyclone activity. An examination of the interannual variability demonstrated that there were more East Pacific tropical cyclones during El Niño years, and that this was mainly accounted for by more storms becoming intense hurricanes than during La Niña years. The tropical cyclone season was one or two months longer in El Niño years, while more storms formed in the southeast and southwest part of the East Pacific Ocean Basin. This is likely due to the fact that ENSO years bring warmer waters to the East Pacific region. When breaking down the ENSO years by phase of the PDO, the ENSO-related differences in occurrence and intensity and geographic formation region are accentuated in PDO1 years (1977-1999), but were blurred in PDO2 (1947-1976) years. This ENSO and PDO related variability is similar to that occurring in the Atlantic (LJ00), except that in the Atlantic more storms occurred in La Niña years and they were more intense.

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurricanepacific.php.

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6.3.4. Global

Although some climate models suggest the intensity and frequency of tropical cyclones on a global scale may be significantly reduced in response to global warming (Bengtsson *et al*., 1996), thus implying a "decrease in the global total number of tropical cyclones on doubling CO_2," as noted by Sugi *et al*. (2002), most of them suggest otherwise. Free *et al*. (2004) state that "increases in hurricane intensity are expected to result from increases in sea surface temperature and decreases in tropopause-level temperature accompanying greenhouse warming (Emanuel, 1987; Henderson-Sellers *et al*., 1998; Knutson *et al*., 1998)."

In an early review of empirical evidence related to the subject, Walsh and Pittock (1998) concluded that "the effect of global warming on the number of tropical cyclones is presently unknown," and "there is little relationship between SST (sea surface temperature) and tropical cyclone numbers in several regions of the globe." They opined there was "little evidence that changes in SSTs, by themselves, could cause change in tropical cyclone numbers."

In a second early analysis of the topic, Henderson-Sellers *et al*. (1998) determined that (1) "there are no discernible global trends in tropical cyclone number, intensity, or location from historical data analyses," (2) "global and mesoscale-model-based predictions for tropical cyclones in greenhouse conditions have not yet demonstrated prediction skill," and (3) "the popular belief that the region of cyclogenesis will expand with the 26°C SST isotherm is a fallacy."

Six years later, Free *et al*. (2004) looked for increases in "potential" hurricane intensity and found "no significant trend in potential intensity from 1980 to 1995 and no consistent trend from 1975 to 1995." What is more, they report that between 1975 and 1980, "while SSTs rose, PI decreased, illustrating the hazards of predicting changes in hurricane intensity from projected SST changes alone."

In another review of what real-world data have to say about the subject, Walsh (2004) was once again forced to report "there is as yet no convincing evidence in the observed record of changes in tropical cyclone behavior that can be ascribed to global warming." Nevertheless, Walsh continued to believe that (1) "there is likely to be some increase in maximum tropical cyclone intensities in a warmer world," (2) "it is probable that this would be accompanied by increases in mean tropical cyclone intensities," and (3) "these increases in intensities are likely to be accompanied by increases in peak precipitation rates of about 25%," putting the date of possible detection of these increases "some time after 2050," little knowing that two such claims would actually be made the very next year.

Emanuel (2005) claimed to have found that a hurricane power dissipation index had increased by approximately 50 percent for both the Atlantic basin and the Northwest Pacific basin since the mid 1970s, and Webster *et al*. (2005) contended the numbers of Category 4 and 5 hurricanes for all tropical cyclone basins had nearly doubled between an earlier (1975-1989) and a more recent (1990-2004) 15-year period. However, in a challenge to both of these claims, Klotzbach (2006) wrote that "many questions have been raised regarding the data quality in the earlier part of their analysis periods," and he thus proceeded to perform a new analysis based on a "near-homogeneous" global dataset for the period 1986-2005.

Klotzbach first tabulated global tropical cyclone (TC) activity using best track data—which he describes as "the best estimates of the locations and intensities of TCs at six-hour intervals produced by the international warning centers"—for all TC basins (North Atlantic, Northeast Pacific, Northwest Pacific, North Indian, South Indian, and South Pacific), after which he determined trends of worldwide TC frequency and intensity over the period 1986-2005, during which time global SSTs are purported to have risen by about 0.2-0.4°C. This work did indeed indicate, in his words, "a large increasing trend in tropical cyclone intensity and longevity for the North Atlantic basin," but it also indicated "a considerable decreasing trend for the Northeast Pacific." Combining these observations with the fact that "all other basins showed small trends," he determined there had been "no significant change in global net tropical cyclone activity" over the past two decades. With respect to Category 4 and 5 hurricanes, however, he found there had been a "small increase" in their numbers from the first half of the study period (1986-1995) to the last half (1996-2005); but he noted that "most of this increase is likely due to improved observational technology." Klotzbach said his findings were "contradictory to the conclusions drawn by Emanuel (2005) and Webster *et al*. (2005)," in that the global TC data did "not support the argument that global TC frequency, intensity and longevity have undergone increases in recent years."

Following close on the heels of Klotzbach's study came the paper of Kossin *et al*. (2007), who wrote that "the variability of the available data combined with long time-scale changes in the availability and quality of observing systems, reporting policies, and the methods utilized to analyze the data make the best track records inhomogeneous," and stated that this "known lack of homogeneity in both the data and techniques applied in the post-analyses has resulted in skepticism regarding the consistency of the best track intensity estimates." Consequently, as an important first step in resolving this problem, Kossin *et al*. "constructed a more homogeneous data record of hurricane intensity by first creating a new consistently analyzed global satellite data archive from 1983 to 2005 and then applying a new objective algorithm to the satellite data to form hurricane intensity estimates," after which they analyzed the resultant homogenized data for temporal trends over the period 1984-2004 for all major ocean basins and the global ocean as a whole.

The five scientists who conducted the work said that "using a homogeneous record, we were not able to corroborate the presence of upward trends in hurricane intensity over the past two decades in any basin other than the Atlantic." Therefore, noting that "the Atlantic basin accounts for less than 15% of global hurricane activity," they concluded that "this result poses a challenge to hypotheses that directly relate globally increasing tropical sea surface temperatures to increases in long-term mean global hurricane intensity." They deliver another major blow to the contentions of Emanuel (2005) and Webster *et al*. (2005) when they say "the question of whether hurricane intensity is globally trending upwards in a warming climate will likely remain a point of debate in the foreseeable future."

As a result of the many investigations of the subject that have been conducted over the past several years, there currently appears to be no factual basis for claiming that planet-wide hurricane frequency and/or intensity will rise in response to potential future global warming. Nevertheless, parties pushing for restrictions on anthropogenic CO_2 emissions continue to do so, citing the now-rebutted claims of Emanuel (2005) and Webster *et al*. (2005).

Additional information on this topic, including reviews of newer publications as they become available, can be found at http://www.co2science.org/subject/h/hurricaneglobal.php.

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6.4. ENSO

Computer model simulations have given rise to three claims regarding the influence of global warming on El Niño/Southern Oscillation (ENSO) events: (1) global warming will increase the frequency of ENSO events, (2) global warming will increase the intensity of ENSO events, and (3) weather-related disasters will be exacerbated under El Niño conditions. Here, we test the validity of these assertions, demonstrating they are in conflict with the observational record. We begin by highlighting studies that suggest the virtual world of ENSO, as simulated by state-of-the-art climate models, is at variance with reality.

Additional information on this topic, including reviews on ENSO not discussed here, can be found at http://www.co2science.org/subject/e/subject_e.php under the heading ENSO.

6.4.1. Model Inadequacies

In a comparison of 24 coupled ocean-atmosphere climate models, Latif *et al*. (2001) report that "almost all models (even those employing flux corrections) still have problems in simulating the SST [sea surface temperature] climatology." They also note that "only a few of the coupled models simulate the El Niño/Southern Oscillation (ENSO) in terms of gross equatorial SST anomalies realistically." And they state that "no model has been found that simulates realistically all aspects of the interannual SST variability." Because "changes in sea surface temperature are both the cause and consequence of wind fluctuations," and because these phenomena figure prominently in the El Niño-La Niña oscillation, it is not surprising that Fedorov and Philander (2000) conclude that current climate models do not do a good job of determining the potential effects of global warming on ENSO.

Human ignorance likely also plays a role in the models' failure to simulate ENSO. According to Overpeck and Webb (2000), there is evidence that "ENSO may change in ways that we do not yet understand," which "ways" have clearly not yet been modeled. White *et al*. (2001), for example, found that "global warming and cooling during earth's internal mode of interannual climate variability [the ENSO cycle] arise from fluctuations in the global hydrological balance, not the global radiation balance," and that these fluctuations are the result of no known forcing of either anthropogenic or extraterrestrial origin, although Cerveny and Shaffer (2001) make a case for a lunar forcing of ENSO activity, which also is not included in any climate model.

Another example of the inability of today's most sophisticated climate models to properly describe El Niño events is provided by Landsea and Knaff (2000), who employed a simple statistical tool to evaluate the skill of 12 state-of-the-art climate models in real-time predictions of the development of the 1997-98 El Niño. They found that the models exhibited essentially no skill in forecasting this very strong event at lead times ranging from 0 to eight months. They also determined that no models were able to anticipate even one-half of the actual amplitude of the El Niño's peak at a medium range lead-time of six to 11 months. They state that "since no models were able to provide useful predictions at the medium and long ranges, *there were no models that provided both useful and skillful forecasts for the entirety of the 1997-98 El Niño*" [italics in the original].

Given the inadequacies listed above, it is little wonder several scientists have criticized model simulations of current ENSO behavior, including Walsh and Pittock (1998), who say "there is insufficient confidence in the predictions of current models regarding any changes in ENSO," and Fedorov and Philander (2000), who say "at this time, it is impossible to decide which, if any, are correct." As a result, there is also little reason to believe that