

Hurricanes and Global Warming— Potential Linkages and Consequences

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The potential relationships between tropical cyclones and global climate change are scientifically and socially complex, with great implications for society. The exceptional nature of the 2005 North Atlantic hurricane season alone provides great incentives for better understanding the full range of interactions and causes and effects thereof. The 2005 season saw the largest number (27) of named storms (sustained winds over 17 m s^{-1}) and the largest number (14) of hurricanes (sustained winds over 33 m s^{-1}), and it was the only year with three category 5 storms (maximum sustained winds over 67 m s^{-1}). Also recorded was the most intense storm on record (Wilma,

minimum pressure 882 hPa), the most intense storm ever in the Gulf of Mexico (Rita, 897 hPa), and the most costly storm on record (Katrina; some estimates put the cost of Katrina at as high as \$200 billion; see information online at www.rms.com/Publications/KatrinaReport_LessonsandImplications.pdf). (Please see www.ncdc.noaa.gov/oa/climate/research/2005/hurricanes05.html for additional details.)

The climate is in the process of a rapid warming, caused in part by human activities, including emission of greenhouse gases (GHGs) and aerosols, and changes in land use (Houghton et al. 2001; Karl and Trenberth 2003). These climate changes may well be changing the properties of tropical cyclones, yet the potential relationships between climate change and tropical cyclones and the consequences for humans have been downplayed or dismissed by a number of recent articles, testimonies, and press releases (e.g., Michaels et al. 2005;¹ Pielke et al. 2005; Mayfield 2005). For example, the recent article with the all-encompassing title “Hurricanes and global warming” by Pielke et al. (2005) raises several important points, yet it is incomplete and misleading because it 1) omits any mention of several of the most important aspects of the potential relationships between hurricanes and global warming, including rainfall, sea level, and storm surge; 2) leaves the impression that there is no significant connection between recent climate change caused by human activities and hurricane characteristics and impacts; and 3) does not take full account of the significance of recently identified trends and variations in tropical storms in causing impacts as compared to increasing societal vulnerability. In a similar vein, public statements and testimonies by prominent hurricane forecasters have denied or minimized important connections between global warming and tropical cyclones, attributing interannual variations in tropical cyclones only to natural variability (e.g., Mayfield 2005).

It is true that society’s vulnerability to hurricane damage is increasing rapidly, predominantly because of the rise in population and property values near

coastlines. Yet, it is this very increase in vulnerability that makes it even more important to identify and understand both interannual variability and possible relationships between tropical cyclones and climate change. Although there remains much uncertainty about these relationships, there are many reasons for concern. It is thus important to consider the full range of relationships and scenarios and to take them seriously.

CHANGES IN CLIMATE AND TROPICAL CYCLONES. Global and tropical atmospheric temperatures near the surface and aloft (Parker et al. 2004; Jones and Moberg 2003; Smith and Reynolds 2005; Santer et al. 2005) are increasing, as is water vapor (Trenberth et al. 2005). Tropical oceans have warmed about 0.6°C over the instrumental record, including about 0.5°C since 1970 (Fig. 1), and sea levels are rising (Cazenave and Nerem 2004; Lombard et al. 2005). There is little doubt that the recent observed increases are due to anthropogenic effects (Meehl et al. 2004), and models project these increases to continue well into this century under all plausible scenarios of greenhouse gas emissions (Houghton et al. 2001). It is well known that tropical cyclones form only over warm oceans from which they gain their energy, largely from the latent heat of condensation (e.g., Anthes 1982; Emanuel 1987; Holland 1997). Thus, it would not be surprising if a warmer and moister world contained enhanced overall hurricane activity. Indeed, a gathering of hurricane specialists concluded in 1998 that the most likely projection was that intensity (as measured by maximum winds) would increase by the order of 10% for a doubled CO₂ environment (Henderson-Sellers et al. 1998). Houghton et al. (2001) similarly projected

that tropical cyclones' peak winds and precipitation were likely to increase during this century.

Recent observational work has indicated that overall intensity has increased substantially since the 1970s (Emanuel 2005a,b; Webster et al. 2005), and modeling studies indicate that both wind speeds and rainfall are projected to rise as well (Knutson and Tuleya 2004). This broad consistency between observations, models, and theory is a powerful indicator that we are likely already experiencing more intense tropical cyclones as a result of global warming. Furthermore, as discussed below, there is increasing evidence that the atmospheric general circulation patterns are changing, and it is likely that the number, tracks, and other characteristics of tropical cyclones will change under the new circulation patterns in a warmer world. With a rising sea level due to warmer oceans and melting glaciers and ice sheets, moreover, beach and wetland erosion and storm surges associated with tropical cyclones will cause greater impacts even if other aspects of tropical cyclones were to remain the same. Although rainfall-induced inland flooding and storm surge are the leading causes of damage and loss of life in hurricanes (Simpson and Riehl 1981; Pielke and Pielke 1997; Rappaport 2000; Negri et al. 2005), possible increases in these due to global warming are not considered by Pielke et al. (2005).

Knutson and Tuleya (2004) ran several versions of The National Oceanic and Atmospheric Administration's (NOAA's) Geophysical Fluid Dynamics Laboratory hurricane model in a CO₂-enriched world. The large-scale thermodynamic boundary conditions for the experiments, specifically sea surface temperature (SST) and atmospheric profiles of temperature and moisture, were based on 80-year linear trends from 1% yr⁻¹ CO₂ increase experiments from nine different climate model simulations. The projected SST changes in the three tropical cyclone basins studied ranged from +0.8° to +2.4°C. The aggregate results, averaged across all model simulations, indicated a 6% increase in maximum tropical cyclone wind speed. While this may appear to be a relatively insignificant increase, nonlinear effects can make even a small increase important in causing damage, because damage is proportional to the cube of the wind speed. A recent study by Emanuel (2005a,b) shows a 70% increase since the mid-1970s of an index of hurricane activity related to the total power dissipation, which is proportional to the cube of the maximum wind speed, integrated over the lifetime of the storm. Moreover this index is very strongly correlated with SSTs. Another study by Webster et al. (2005) indicates

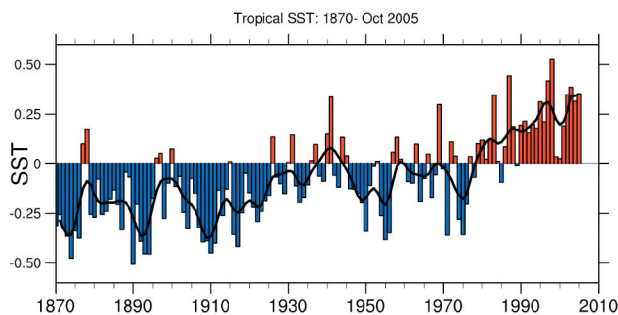


FIG. 1. Time series of global annual SST anomalies (°C) over the Tropics from 20°N to 20°S (bars) and with a seven-point filter (solid line) that emphasizes decadal variations. The values are departures from the 1961–90 climatological annual average from the Rayner et al. (2003) dataset. [Figure courtesy John Fasullo, NCAR.]

a large increase over the past 35 years in the number and proportion of intense hurricanes (those reaching categories 4 and 5) in all hurricane basins, although there is no significant change in the total number of tropical cyclones over this period.

The role of building codes is also relevant. Codes vary with location, but they typically require buildings to withstand winds up to some threshold speed, such as 120 mph (Pielke and Pielke 1997). Thus, even relatively small increases in mean maximum wind speeds may shift the probability distribution function and cause a significant increase in the number of occurrences of winds exceeding a given threshold, resulting in catastrophic failures for infrastructure designed to the threshold. Further, experience with Hurricane Andrew (1992) showed only too well that building codes are not always strictly enforced.

Modeling results also indicate that increasing ocean temperatures will lead to a significantly larger percentage change in the number and characteristics of heavy precipitation events. Knutson and Tuleya (2004) found on average an 18% increase in peak tropical cyclone precipitation rates at the time of CO₂ doubling. While tropical cyclone rainfall is highly variable and dependent on many factors, there is evidence that the frequency of heavy rainfall events is increasing worldwide (Trenberth et al. 2003; Trenberth 2005), and water vapor over the oceans is estimated to have increased by 4% since 1970 (Trenberth et al. 2005). Thus, it is quite plausible that tropical cyclone rainfall will increase with time as the climate warms and moistens. Higher precipitation rates and amounts, especially in mountainous regions, would significantly increase flooding, leading to more extensive damage and loss of life, because virtually all additional precipitation on water-saturated soils goes into runoff.

Another critical issue is that of the impacts of hurricanes and sea level rise, which is often ignored (e.g., Pielke et al. 2005). Douglas et al. (2001) describe how even a minimal rise in sea level can have catastrophic consequences when intense storms strike.² Global warming is leading to sea level rise, averaging 3 mm yr⁻¹ over the past decade (when satellite altimetry provides greater confidence; Cazenave and Nerem 2004), and the midrange projection is for a further 0.5 m rise over the twenty-first century (Houghton

et al. 2001; Meehl et al. 2005). Even without the projected increase in hurricane winds, the higher sea level will result in greatly increased coastal erosion, shrinking protective beaches and wetlands. In addition, storm-induced flooding and storm surges will reach farther inland, and damage can be projected to be considerably more extensive. Louisiana's coast is the poster child of what the accelerated sea level rise rate will mean to many other locations in the United States and around the world, for example, Bangladesh (Glantz 1988). As summarized in the Working Group II assessment of McCarthy et al. (2001), model projections of the mean annual number of people who would be flooded by coastal storm surges increase several-fold (75–200 million, depending on the adaptive response) for midrange scenarios of a 0.4-m sea level rise by the 2080s relative to scenarios with no sea level rise. It is also important to note that local changes in sea level can be much greater than global mean changes due to land subsidence and changes in large-scale ocean and atmosphere circulations (NRC 1990; McCarthy et al. 2001).

Several studies (Landsea et al. 1998, Pielke et al. 2005) have concluded that the recent observed increases in Atlantic hurricane frequency and intensity are within the range of observed multidecadal variability. A number of multi-year-scale atmospheric and oceanic patterns of variability, including the El Niño–Southern Oscillation phenomenon, the quasi-biennial oscillation, the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO), have a large impact on hurricane frequency, intensity, and tracks. But to therefore assume that all of the variability during the twentieth century has been natural is not valid (e.g., Houghton et al. 2001; Feldstein 2002; Gillett et al. 2003; Hoerling et al. 2004; Gillett et al. 2005). In particular, the impact on tropical cyclones of multidecadal variations tends to be specific to each ocean basin and compensated globally by opposite fluctuations elsewhere. However, the study by Webster et al. (2005) shows an increase of category 4 and 5 hurricanes in all ocean basins, and an overall global increase thereof. Although there is uncertainty in the global tropical cyclone best-track dataset used in their study, this is the type of signature that would be expected from global warming changes rather than from natural variability alone.

Recent detection and attribution studies indicate that human influences have, over the past 35 years, caused both regional increases and decreases in temperature due to greenhouse gases and sulfate aerosols, respectively (Houghton et al. 2001; Barnett et al. 2005; Hansen et al. 2005). The time-varying latitudinal and

² For example, models and observations show that long-term sandy beach erosion is two orders of magnitude larger than the rate of sea level rise, because “increased sea level enables high-energy, short-period storm waves to attack farther up the beach and transport sand offshore” (Douglas et al. 2001, p. 190).

regional patterns of radiative forcing caused by the globally well-mixed greenhouse gases and the spatially heterogeneous concentrations of sulfate aerosol have already disturbed the atmospheric and oceanic circulation. For instance, it is possible that the AMO, which plays a large role in Atlantic hurricane frequency and tracks (Kerr 2005) as well as the intensity and duration (Emanuel 2005a,b), is being affected by human-induced climate change. The AMO describes multidecadal variations in SSTs that are likely driven by variations in the Atlantic meridional overturning circulation (MOC; Delworth and Mann 2000; Knight et al. 2005). Further, as shown by Dickson et al. (2002) and Curry et al. (2003), changes in the freshwater balance of the Atlantic Ocean over the past four decades include freshening in the North Atlantic and also south of 25°S, while salinity has increased in the Tropics and subtropics, especially in the upper 500 m. The implication is that there have been substantial increases in moisture transport by the atmosphere from the subtropics to higher latitudes, in association with changes in atmospheric circulation, such as the NAO, and global climate change. Such changes impact the ocean currents and likely the AMO. Most global coupled ocean–atmosphere models project some weakening of the Atlantic MOC in response to increasing GHG concentrations (e.g., Houghton et al. 2001), and a recent study by Bryden et al. (2005) indicates that the thermohaline circulation has slowed by up to 30%. A reasonable conclusion is that the observed warming of the tropical oceans in recent decades (Fig. 1) and related changes in atmospheric and oceanic circulations contain an anthropogenic component (e.g., Knutson et al. 1999; Hurrell et al. 2004; Barnett et al. 2005).

CONCLUDING REMARKS. Because of natural variability, no one event or a single season like 2005 can be attributed solely to changes in climate. However, it is equally inappropriate to declare or imply that the current observed global changes and seasons with storms of unusually high frequency or intensity are not related to global warming and that there will not be a significant change in climate in the future. It should be recognized that the issue is not black or white, but rather that global warming has a pervasive influence on ocean SST and heat content, atmospheric temperature, water vapor, and atmospheric and oceanic general circulation patterns, all of which affect tropical cyclones in complex, not yet fully understood ways.

However, while there are obvious large and natural oscillations, in our view the growing body

of evidence suggests a direct and growing trend in several important aspects of tropical cyclones, such as intensity, rainfall, and sea level, all of which can be attributed to global warming. Aspects of the association between global warming and tropical cyclones and other extreme atmospheric events are uncertain, in part because climate change is continuous, yet irregular. However, in a warmer, moister world with higher SSTs, higher sea level, altered atmospheric and oceanic circulations, and increased societal vulnerability, it would be surprising if there were no significant changes in tropical cyclone characteristics and their impacts on society. Indeed, the broad agreement between theoretical and modeling studies, together with the strong evidence from observational analysis, suggests that not only will tropical cyclone intensity increase with anthropogenic warming, but that this process has already commenced. The precautionary principle argues for further scientific study and better planning and adaptation. Research is needed to enhance understanding and long-term projections, to improve forecasting and warnings of tropical cyclones worldwide, and to better assess vulnerability. Based on what is already known and can be projected into the future, it would be prudent to improve planning and carry out mitigation measures such as trying to minimize possible losses through enhanced building codes, restrictions on where to build, and improving infrastructure to cope with winds and floods, even if some of the more extreme scenarios do not eventuate.

REFERENCES

- Anthes, R. A., 1982: *Tropical cyclones: Their Evolution Structure and Effects*. Meteor. Monograph, No. 41, Amer. Meteor. Soc., 208 pp.
- Barnett, T. P., D. W. Pierce, K. M. AchutaRao, P. J. Gleckler, B. D. Santer, J. M. Gregory, and W. M. Washington, 2005: Penetration of human-induced warming into the world's oceans. *Science*, **309**, 284–287.
- Bryden, H. R., H. R. Longworth, and S. A. Cunningham, 2005: Slowing of the Atlantic meridional overturning circulation at 25°N. *Nature*, **438**, 655–657.
- Cazenave, A., and R. S. Nerem, 2004: Present-day sea level change: Observations and causes. *Rev. Geophys.*, **42**, RG3001, doi:3010.1029/2003RG000139.
- Curry, R., B. Dickson, and I. Yashayaev, 2003: A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, **426**, 826–829.
- Delworth, T. L., and M. E. Mann, 2000: Observed and simulated multidecadal variability in the Northern Hemisphere. *Climate Dyn.*, **16**, 661–676.

- Dickson B., I. Yashayaev, J. Meincke, B. Turrell, S. Dye, and J. Holtfort, 2002: Rapid freshening of the deep North Atlantic Ocean over the past four decades. *Nature*, **416**, 832–837.
- Douglas, B. C., M. S. Kearney, and S. P. Leatherman, 2001: *Sea Level Rise: History and Consequences*. Academic Press, 232 pp.
- Emanuel, K. A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483–485.
- , 2005a: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686–688.
- , 2005b: Emanuel replies. *Nature*, **438**, E13, doi:10.1038/nature04427.
- Feldstein, S. B., 2002: The recent trend and variance increase of the Annular Mode. *J. Climate*, **15**, 88–94.
- Gillett, N. P., F. W. Zwiers, A. J. Weaver, and P. A. Stott, 2003: Detection of human influence on sea-level pressure. *Nature*, **422**, 292–294.
- , R. J. Allan, and T. J. Ansell, 2005: Detection of external influence on sea level pressure with a multi-model ensemble. *Geophys. Res. Lett.*, **32**, L19714, doi:10.1029/2005GL023640.
- Glantz, M. H., 1988: *Societal Responses to Regional Climate Change: Forecasting by Analogy*. Westview Press, 428 pp.
- Hansen, J., and Coauthors, 2005: Earth's energy imbalance: Confirmation and implications. *Science*, **308**, 1431–1435.
- Henderson-Sellers, A., and Coauthors, 1998: Tropical cyclones and global climate change: A post-IPCC assessment. *Bull. Amer. Meteor. Soc.*, **79**, 19–38.
- Hoerling, M. P., J. W. Hurrell, T. Xu, G. Bates, and A. Phillips, 2004: Twentieth century North Atlantic climate change. Part II: Understanding the effects of Indian Ocean warming. *Climate Dyn.*, **23**, 391–405.
- Holland, G. J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.*, **54**, 2519–2541.
- Houghton, J. H., Y. Ding, D. J. Griggs, M. Nogue, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, 881 pp.
- Hurrell, J. W., M. P. Hoerling, A. Phillips, and T. Xu, 2004: Twentieth century North Atlantic climate change. Part I: Assessing determinism. *Climate Dyn.*, **23**, 371–389.
- Jones, P. D., and A. Moberg, 2003: Hemispheric and large-scale surface air temperature variations: An extensive revision and update to 2001. *J. Climate*, **16**, 206–223.
- Karl, T. R., and K. E. Trenberth, 2003: Modern global climate change. *Science*, **302**, 1719–1723.
- Kerr, R. A., 2005: Atlantic climate pacemaker for millennia past, decades hence? *Science*, **309**, 41–42.
- Knight, J. T., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann, 2005: A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Res. Lett.*, **32**, L20708, doi:10.1029/2005GL024233.
- Knutson, T. R., and R. E. Tuleya, 2004: Impact of CO₂-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. *J. Climate*, **17**, 3477–3495.
- , and —, 2005: Reply. *J. Climate*, **18**, 5183–5187.
- , T. L. Delworth, K. W. Dixon, and R. J. Stouffer, 1999: Model assessment of regional surface temperature trends (1949–1997). *J. Geophys. Res.*, **104**, 30 981–30 996.
- Landsea, C. W., G. D. Bell, W. M. Gray, and S. B. Goldenberg, 1998: The extremely active 1995 Atlantic hurricane season: Environmental conditions and verification of seasonal forecasts. *Mon. Wea. Rev.*, **126**, 1174–1193.
- Lombard, A., A. Cazenave, P.-Y. Le Traon, and M. Ishii, 2005: Contribution of thermal expansion to present-day sea-level change revisited. *Global Planet. Change*, **47**, 1–16.
- McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White, Eds., 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, 1032 pp.
- Mayfield, M., 2005: *The Lifesaving Role of Accurate Hurricane Prediction*. Oversight Hearing before the Committee on Commerce, Science and Technology Subcommittee on Disaster Prevention and Prediction, U. S. Senate, 20 September 2005, 13 pp. [Available online at www.legislative.noaa.gov/Testimony/mayfieldfinal092005.pdf]
- Meehl, G. A., W. M. Washington, C. M. Ammann, J. M. Arblaster, T. M. L. Wigley, and C. Tebaldi, 2004: Combinations of natural and anthropogenic forcings in twentieth-century climate. *J. Climate*, **17**, 3721–3727.
- , —, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buja, W. G. Strand, and H. Teng, 2005: How much more global warming and sea level rise? *Science*, **307**, 1769–1772.
- Michaels, P. J., P. C. Knappenberger, and C. Landsea, 2005: Comments on “Impacts of CO₂-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective scheme.” *J. Climate*, **18**, 5179–5182.
- Negri, A. J., and Coauthors, 2005: The hurricane–flood–landslide continuum. *Bull. Amer. Meteor. Soc.*, **86**, 1241–1247.

- NRC, 1990: *Sea-Level Change*. National Academy Press, 234 pp.
- Parker, D. E., L. V. Alexander, and J. Kennedy, 2004: Global and regional climate in 2003. *Weather*, **59**, 145–152.
- Pielke, R. A., Jr., and Pielke, R. A. Sr., 1997: *Hurricanes: Their Nature and Impacts on Society*. Wiley, 279 pp.
- , Jr., C. Landsea, M. Mayfield, J. Laver, and R. Pasch, 2005: Hurricanes and global warming. *Bull. Amer. Meteor. Soc.*, **86**, 1571–1575.
- Rappaport, E. N., 2000: Loss of life in the United States associated with recent tropical cyclones. *Bull. Amer. Meteor. Soc.*, **81**, 2065–2074.
- Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, 4407, doi:10.1029/2002JD002670.
- Santer, B. D., and Coauthors, 2005: Amplification of surface temperature trends and variability in the tropical atmosphere. *Science*, **309**, 1551–1556.
- Simpson, R. H., and H. Riehl, 1981: *The hurricane and Its Impact*. Louisiana State University Press, 398 pp.
- Smith, T. M., and R. W. Reynolds, 2005: A global merged land and sea surface temperature reconstruction based on historical observations (1880–1997). *J. Climate*, **18**, 2021–2036.
- Trenberth, K., 2005: Uncertainty in hurricanes and global warming. *Science*, **308**, 1753–1754.
- , A. Dai, R. M. Rasmussen, and D. B. Parsons, 2003: The changing character of precipitation. *Bull. Amer. Meteor. Soc.*, **84**, 1205–1217.
- , J. Fasullo, and L. Smith, 2005: Trends and variability in column integrated atmospheric water vapor. *Climate Dyn.*, **24**, 741–758.
- Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, **309**, 1844–1846.
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