

Mixing Politics and Science in Testing the Hypothesis That Greenhouse Warming Is Causing a Global Increase in Hurricane Intensity

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This complex hypothesis has been muddied frequently in recent public debate, yet can be clarified by laying bare the underlying causal chain and potential approach to verification.

“Science is what we have learned about how to keep from fooling ourselves.”—RICHARD FEYNMAN

The incidence of seven major hurricanes threatening or directly affecting the United States during 2005, associated with warmer-than-average surface waters, has fueled the debate regarding the role of greenhouse warming in increasing hurricane intensity. The exceptional damage caused by Hurricane Katrina, estimated at exceeding \$100 billion, and a death toll exceeding 1,300, has raised important policy issues on the vulnerability of the United States

to the intense hurricanes and rising sea level associated with the emission of greenhouse gases.

Prior to the 2005 North Atlantic hurricane season, Trenberth (2005) published a commentary in *Science* raising the issue as to whether the increase in North Atlantic hurricane activity since 1995 could be attributed to global warming. This paper motivated us to begin looking at global hurricane data. In August, Emanuel (2005) published a paper in *Nature* associating the increase in sea surface temperature (SST) with an increase in maximum hurricane potential intensity and the destructive capacity of hurricanes, focusing on hurricanes in the North Atlantic and North Pacific. Webster et al. (2005; hereafter WHCC), in an article in *Science*, showed that since 1970 the total number of hurricanes has not increased globally, but the proportion of category-4 and -5 hurricanes had doubled, implying that the distribution of hurricane intensity has shifted toward being more intense. The timing of the publication of the Emanuel (2005) paper early in the 2005 North Atlantic hurricane season and the publication of WHCC between the landfalls of Hurricanes Katrina and Rita focused intense media attention on the topic of greenhouse warming and increasing hurricane intensity, although neither

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Emanuel (2005) nor WHCC directly attributed the tropical cyclone changes to greenhouse warming. The intense public interest in these papers is reflected by *Discover* magazine's "Top 100 Stories for 2005" ranking of these articles as number 1 on hurricanes and global warming (available online at www.discover.com/issues/jan-06/cover).

The debate surrounding these papers has been particularly intense owing to the implications of this research for the global warming debate. During the month following publication of WHCC, we cataloged a total of 14 distinct issues raised in rebuttal to the paper, ranging from ad hominem attacks to legitimate scientific questions and issues. In addition to critiques by well-known global warming deniers, the issue of hurricanes and global warming has been debated intensely within the meteorological community, identifying clear differences in the prevailing views on this subject, especially between climate researchers and hurricane forecasters. Some of this debate reflects healthy skepticism in the scientific community that will move the research forward, while other aspects of the debate are convoluted with denial of global warming.

We therefore have the following several objectives in writing this paper:

- to clarify the debate surrounding the subject as to whether or not global warming is causing an increase in global hurricane intensity, by sorting out the valid from the fallacious criticisms, addressing the valid criticisms, assessing alternative hypotheses, and identifying the outstanding uncertainties;
- to illustrate a methodology of hypothesis testing to address multiple criticisms of a complex hypothesis that involves a causal chain; and
- to provide a case study of the impact of politics, the media, and the World Wide Web on the scientific process.

THE HYPOTHESES. The central hypothesis addressed in this paper is that greenhouse warming is causing an increase in global hurricane intensity.

Ideally, testing this hypothesis would require a much longer global dataset on hurricane intensity than is available, together with global climate model simulations that resolve the critical hurricane processes. Because the central hypothesis cannot be evaluated unambiguously, given the limitations of the data and models, we formulate the central hypothesis as a causal chain consisting of the following three subhypotheses, each of which subsequently is more easily evaluated:

- 1) the frequency of the most intense hurricanes is increasing globally;
- 2) average hurricane intensity increases with increasing tropical SST;
- 3) global tropical SST is increasing as a result of greenhouse warming.

The central hypothesis implies a causal chain $3 \rightarrow 2 \rightarrow 1$ and therefore depends upon the validity of each of the three subhypotheses. We note that the WHCC and Emanuel (2005) papers addressed subhypotheses 1–2 and the causal chain $2 \rightarrow 1$.

Assessing the issues raised in rebuttal in the hypotheses. We have identified a total of 14 distinct critiques reported in the media that have been made in rebuttal to the central hypothesis and subhypotheses. These 14 issues are divided into the following three categories, reflecting whether there are logical fallacies involved:

- 1) issues having obvious logical fallacies,
- 2) arguments having logical fallacies, but nevertheless raising ancillary issues that need to be addressed, and
- 3) concerns based on logically valid arguments.

Sorting the issues into these three categories allows us to assess which of these issues can be dismissed, which can be rebutted through logical argument, and which require further scientific investigation.

In the first category (possessing obvious logical fallacies), we identify three separate issues:

- i) The central hypothesis disagrees with official statements from the National Hurricane Center. **Logical fallacy:** appeal to authority.
- ii) The authors are not qualified to analyze the hurricane data. **Logical fallacy:** ad hominem.
- iii) The proponents of the connection between hurricanes and global warming are motivated by obtaining funding for their research. **Logical fallacy:** appeal to motive.

The second category (arguments having logical fallacies, but raising valid ancillary points) includes arguments that have been persuasive to the public and other nonexperts:

- iv) Atlantic hurricane variations follow a natural cycle that is not influenced by greenhouse warming. **Logical fallacies:** hasty conclusions; fallacy of multiple causes.

- v) Observations of major U.S. landfalling hurricanes over the last 100 years show a minimum during the 1970s, and higher frequencies earlier in the century, and therefore there is no increase associated with global warming. **Logical fallacy:** fallacy of distribution of the compositional type; unrepresentative sample.
- vi) There is no relationship between global tropical SST increase and hurricane intensity, because some storms do not intensify over warm water. **Logical fallacy:** fallacy of the single cause; fallacy of distribution of the divisional type.
- vii) Model simulations of greenhouse warming show a much slower increase of hurricane intensity than do the data, and therefore greenhouse warming cannot explain the increased intensity. **Logical fallacy:** begging the question; statistically special pleading.

In the third category (logically valid arguments), we divide the concerns into three areas:

Concerns about the quality and length of the hurricane dataset and its analysis (related to subhypothesis 1):

- viii) The quality of the data was poor in the 1970s and 1980s.
- ix) If the statistics were redone with categories 3+4+5 hurricanes (instead of 4+5), there would

be a decrease in the number of intense storms during this period.

- x) Data not collected directly by the United States have been processed inconsistently in terms of wind speed determination, and therefore any trends in regions outside the North Atlantic and North Pacific are spurious.

Concerns about the relationship between increasing SST and increasing hurricane intensity (related to subhypothesis 2):

- xi) The correlation between SST and hurricane intensity does not prove that higher SST values produce more intense hurricanes.
- xii) Factors other than SST contribute to hurricane intensity.

Alternative hypotheses for the cause of the increase of SST (related to subhypothesis 3):

- xiii) The increase in surface temperature is caused by solar variability.
- xiv) The recent increase in tropical ocean surface temperature is caused by multidecadal internal oscillations of the climate system.

Methods of testing hypotheses. Scientific hypotheses are plausible only if they can survive stringent challenges that their originators or their peers design

LOGICAL FALLACIES

The logical fallacies discussed in the context of attacks on the hypotheses are summarized here, following elementary texts in logic, such as Damer (2004) [the Wikipedia is an excellent online source describing these fallacies (online at http://en.wikipedia.org/wiki/Logical_fallacy)].

- An *ad hominem fallacy* consists of asserting that someone's argument is wrong because of something discreditable/not authoritative about the person or persons cited by them rather than addressing the soundness of the argument itself.
- *Appeal to authority* cites a person or organization who is an authority in the relevant field and therefore should carry more weight, but given the possibility of mistake, should not be compelling. Direct evidence must be provided by the expert and the expert should be reasonably unbiased.
- *Appeal to motive* is a pattern of argument that consists of challenging a thesis by calling into question the motives of its proposer.
- An *unrepresentative sample* is one that is falsely taken to be typical of a population from which it is drawn.
- *Begging the question* is a fallacy occurring in deductive reasoning in which the proposition to be proved is assumed implicitly or explicitly in one of the premises.
- *Correlation implies causation* is a logical fallacy by which two events that occur together are claimed to be cause and effect.
- A *fallacy of distribution* occurs when an argument assumes that what is true of the members is true of the class (composition), or what is true of the class is true of its members (division).
- *Hasty generalization* is the logical fallacy of reaching an inductive generalization based on too little evidence.
- *Statistical special pleading* occurs when the interpretation of the relevant statistic is "massaged" by looking for ways to reclassify or requantify data from one portion of results, but not applying the same scrutiny to other categories.
- *Fallacy of the single cause* occurs when it is assumed that there is one simple cause of an outcome when in reality it may have been caused by a number of only jointly sufficient causes.

by which to test them. This has been the fundamental basis of scientific discovery since it was first expounded by Francis Bacon (1620). In his landmark book, *The Logic of Scientific Discovery*, Popper (1959) describes a scientific method based on falsification, whereby scientists should attempt to disprove their theory rather than attempt to continually prove it. Science can help us approach the truth progressively, but we can never be certain that we have arrived at the final explanation.

Inferential statistics based upon frequentist methods, such as null hypothesis testing and confidence intervals, are used to attempt to falsify hypotheses. There is no doubt that a hypothesis should be rejected or modified if it is not capable of explaining experimental results. However, if it is impossible to determine with certainty that a hypothesis is true, it becomes impossible to identify a preferred hypothesis among the infinite number of hypotheses that have not been falsified. Probabilistic methods, such as maximum likelihood and Bayesian methods, allow for a scale of credibility to be provided for classifying all hypotheses taken into account. Investigative scientists bring prior experience, understanding, and prejudice to their investigation. Among a group of investigators, if these priors are so different that the investigators genuinely reach divergent conclusions from the available sparse data, then none of the hypotheses can be raised to the status of a theory.

TESTING THE HYPOTHESES. Based upon the analysis in the “Assessing the issues raised in rebuttal to the hypotheses” section, we evaluate the subhypotheses in the causal chain. No attempt is made here to present fundamental new research on the topic; rather, we conduct simple data analyses and hypothesis tests that clarify the support for the hypotheses and indi-

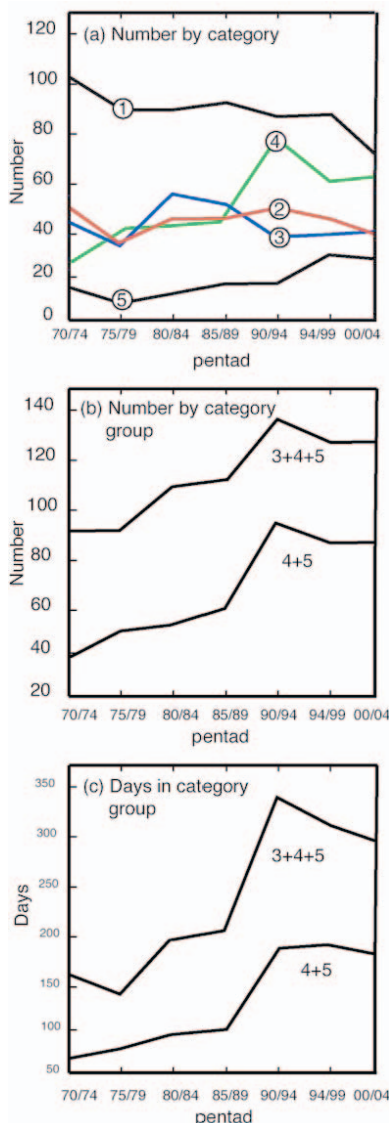


FIG. 1. Global time series for 1970–2004 of (a) number of hurricanes by category and (b) number of hurricanes by category group (3+4+5 and 4+5), and (c) number of storm days for hurricanes by category group. The dataset used here is described by WHCC.

cate major areas of uncertainty and needs for further research.

Frequency of the most intense hurricanes is increasing globally. The satellite-derived dataset of WHCC showed a global increase in the number of category-4 and -5 hurricanes since 1970; this increase was seen in each of the ocean basins where hurricanes occur (Fig. 1). Several concerns have been raised about the quality of the dataset by Landsea (2005) and Klotzbach (2006). While random errors in the dataset are unlikely to influence the trend, systematic errors in the early portion of the dataset would influence the trend. While the details of the issues being raised about the data quality are beyond the scope of this paper, we provide a simple analysis that illustrates how doubtful it is that this hypothesis can be rejected based upon documented uncertainties in the data. We do this by considering the following null hypothesis: *There has been no global increase in hurricane intensity over the period of 1970–2004.*

- **Argument 1:** Category-3 hurricanes cannot be distinguished from category 4 and 5 in the database, therefore the null hypothesis cannot be rejected.

This issue can be clarified by simple analysis. Figure 1a shows the global trends for each hurricane category, and Fig. 1b shows

the global trends for 3+4+5 and 4+5 hurricanes. The comparison in Fig. 1b indicates that an inability to discriminate between category-3, -4, and -5 hurricanes introduces a maximum uncertainty of $\pm 30\%$ to WHCC's finding of a 100% increase in the proportion of category-4+5 hurricanes. Hence, the null hypothesis must be rejected unless we cannot distinguish category-1 from category-4 storms. More specifically, 50% of the storms classified as category-1 and -2 storms would need to be in actuality category-4

or -5 storms. There is no evidence that we cannot, for the vast majority of hurricanes since 1970, distinguish between category-4 and -5 hurricanes and category-1 and -2 hurricanes. Thus, while there are uncertainties and heterogeneities in the global hurricane dataset, the magnitude of the trend identified by WHCC is sufficiently large that the null hypothesis must be rejected based upon the currently documented uncertainties in the dataset.

WHCC represents the first effort to undertake a global climate data analysis of hurricanes. There is an obvious need for an improved climate data record for hurricane characteristics and efforts, such as the Atlantic Basin Hurricane Database (HURDAT) reanalysis (available online at www.aoml.noaa.gov/hrd/hurdat), to be attempted worldwide. A recent report (NAS 2004) provides advice on steps for generating reanalyses of satellite climate data. In the context of the hurricane dataset, there is a clear need for the involvement of the national hurricane centers and hurricane forecasters that are most familiar with these data, the national and international climatic data centers, and both hurricane forecasters and climate researchers in the reprocessing and evaluation of the dataset.

- **Argument 2:** Observations of major U.S. land-falling hurricanes over the last 100 years show a minima during the 1970s and higher frequencies earlier in the century, and therefore there is no increase associated with global warming.

Logical fallacies of distribution and unrepresentative samples arise from the sample of U.S. landfalling hurricanes not being representative of the population of global hurricanes. The sampling errors associated with using statistics on U.S. landfalling hurricanes to infer statistics on global hurricanes or the cause of changes in hurricane intensity can be assessed directly by using the same global dataset employed by WHCC for the period of 1970–2004. Atlantic hurricanes comprise only 11% of global hurricanes, and U.S. landfalling hurricanes comprise only 25% of North Atlantic hurricanes, and therefore only 3% of global hurricanes. Of the U.S. landfalling hurricanes during this period, only three were category 4 and 5, compared to a total of 43 category-4 and -5 storms occurring in the Atlantic. Thus, the number of category-4 and -5 landfalling hurricanes does not represent the total number of similar hurricanes in the Atlantic, owing to sampling errors. While regional data records are useful for documenting regional change and supporting some aspects of re-

gional decision making, understanding the causes of the variability requires that global, regional, and local processes all be analyzed to interpret the mechanisms responsible for the change. Thus, while the relatively short dataset used by WHCC brings into question inferences of longer-term trends, regional datasets cannot, by their very nature, be used to reject the hypothesis that the frequency of the most intense hurricanes is increasing globally.

Average hurricane intensity increases with increasing sea surface temperature. To assess the validity of this hypothesis, we again consider the null hypothesis: *Average hurricane intensity does not increase with increasing SST.*

- **Argument 3:** The observed correlation between SST and hurricane intensity does not prove that higher SST values produce more intense hurricanes.

The correlation fallacy notes that it is dangerous to deduce causation from a statistical correlation. However, robust correlations often imply some sort of causal story, whether it be either a common cause or something more complicated. The challenge is to establish the correct causal structure through rational argument based upon the physical understanding of tropical cyclone intensification.

The role of SST in determining hurricane intensity is generally understood and is supported by case studies of individual storms and by the theory of potential intensity. The causal link between SST and hurricane intensity was established over 50 years ago, when it was observed that tropical cyclones do not form unless the underlying SST exceeds 26.5°C and that warm sea surface temperatures are needed to supply the energy to support the development of hurricane winds (e.g., Gray 1968). SST, or more precisely ocean thermal energy, has a prominent role in theories to estimate the upper bounds on tropical cyclone intensity (e.g., Holland 1997; Emanuel 1999). These theories, which are backed by solid observational evidence, indicate that there is a strong relationship between ocean thermal energy and the maximum potential intensity that can be achieved. Hoyos et al. (2006) have clarified the relationship between seasonally averaged hurricane intensity and seasonally averaged tropical SST on an individual ocean basis. By isolating the trend from the shorter modes of variability and applying a methodology based on information theory, Hoyos et al. found that the global increase in category-4 and -5 hurricanes for the period of 1970–2004 is

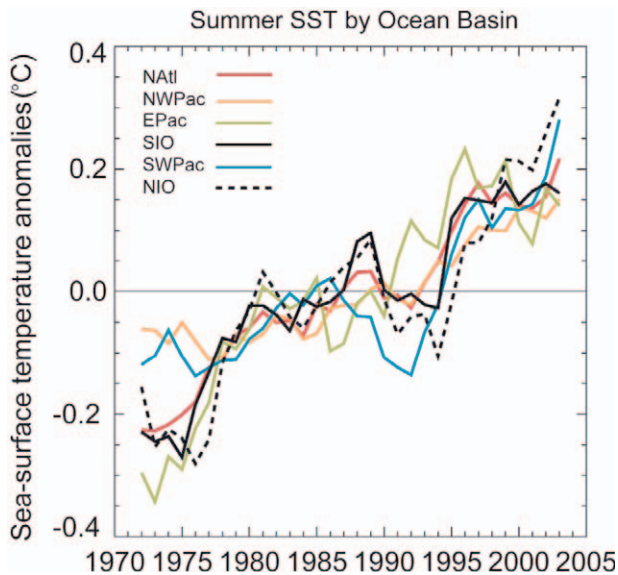


FIG. 2. Evolution of the sea surface temperature anomalies relative to the 1970–2004 period for the North Atlantic, western Pacific, east Pacific, South Indian Ocean, southwest Pacific, and North Indian Ocean basins as defined by WHCC.

directly linked to the trends in SST. Hence, we reject the null hypothesis, and find considerable support for the hypothesis that average hurricane intensity increases with increasing SST.

- **Argument 4:** Model simulations of greenhouse warming show a much slower increase of hurricane intensity than do the data, and therefore greenhouse warming cannot explain the increased intensity.

The theoretically based models used by Henderson-Sellers et al. (1998) provided the conservative estimate that a 10%–20% decrease in central pressure deviation was a likely result from using climate model projections of a warmed world with an around 2°C change in SST. More recently, Knutson and Tuleya (2004) found that a similar decrease of 14% in the central pressure deviation leads to an estimate of a 5%–10% increase in maximum wind speeds for a 2°C change in SST. The increase in intensity found by WHCC is equivalent to a 5% increase in maximum wind speeds for a 0.5°C SST increase, which is a factor of 2–4 larger than that estimated from theory and determined from the model simulations of Knutson and Tuleya (2004). Recent simulations using the Japanese Earth Simulator (Oouchi et al. 2006) found a 10.7% increase in intensity for a 2.5°C increase in SST, which scales linearly to a 2.1% increase in intensity for a

0.5°C increase in SST, which is approximately a factor of 2 smaller than the increase found by WHCC.

Skeptics have used this inconsistency in two ways: first, to argue that the observed trend cannot be associated with greenhouse warming, because it does not agree with the model and theoretical results (Landsea 2005); and second, to argue that the model results are wrong, because they are not supported by the observations (Michaels et al. 2005). The appropriate way to interpret the finding that the model simulations show a slower increase of hurricane intensity than do the data is to recognize that the models may be underestimating the impact of global warming on hurricane intensity or that there are additional mechanisms whereby SST indirectly influences hurricane intensity in ways that are not accounted for by theories of potential intensity or the climate models. Michaels et al. (2006) argues for a steplike, rather than continuous, influence of SST on tropical cyclone intensification.

- **Argument 5:** Factors other than SST contribute to hurricane intensity.

Hurricanes are complex dynamical systems whose intensities are affected by a variety of interactions between the storms, the underlying ocean, and the atmospheric environment, and physical processes internal to the storm (for a recent summary see Bell and Chelliah 2006). Many of these processes are poorly understood, and there is presently little skill in forecasts of the intensity of individual storms. Among the other environmental factors is vertical wind shear, which has a negative impact on intensity (Wang and Holland 1996; DeMaria 1996). Internal dynamics, such as the eye wall replacement cycle (Shapiro and Willoughby 1982), also cause fluctuations in intensity and may ultimately limit tropical cyclone intensity.

Depending on how this argument is used, it may or may not be valid. When presented as a cautionary note on factors that may have an influence not yet fully understood or accountable, it represents legitimate scientific concern. A critical issue in examining such arguments in the context of the hypothesis is to examine relationships that contribute to the trend rather than merely to interannual variability. Chan (2006), in comments on aspects of WHCC that examined tropical cyclones in the western North Pacific, pointed out that seasonal values of SST and NCAT45 (the frequency of number of category-4 and -5 storms) were anticorrelated over the period of 1960–2004, and that positive correlations are seen with wind shear, low-level vorticity, and moist static energy. Webster

et al. (2006; in reply to Chan 2006) and Hoyos et al. (2006) find that there is no global trend in wind shear and vorticity, and that the positive correlations with these variables are associated primarily with shorter-term variability (e.g., ENSO). To date, there has been no convincing evidence presented of a global long-term trend in any of these factors that can be associated with the trend in NCAT45 since 1970.

Global tropical SST is increasing as a result of greenhouse warming. Greenhouse warming deniers have invoked potential issues related to solar variability and climate feedbacks. Several hurricane forecasters and researchers have also invoked natural variability as the source of the variations in both hurricane characteristics and SST, most specifically in the North Atlantic and North Pacific (e.g., Landsea et al. 1999; Goldenberg et al. 2001; Xie et al. 2002; Molinari and Mestas-Nuñez 2003). To address these arguments, we consider the null hypothesis: *Recent trends in tropical surface temperatures are not a response to greenhouse warming.*

A number of natural internal oscillations of the atmosphere–ocean system have a large impact on SST (e.g., El Niño, North Atlantic Oscillation). However, decadal-scale oscillations tend to be specific to each ocean basin and are often anticorrelated from one basin to another. WHCC specifically shows that the tropical SST increase is global in nature and occurs consistently in each of the ocean basins (Fig. 2). This tropical warming is consistent with a similar increase in global surface temperatures (Fig. 3).

External forcing factors, such as volcanic eruptions and solar variability, which are also natural causes, are known to produce global responses. The surface temperature trends over the last century have been extensively studied as summarized in the Houghton et al. (2001) Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) and detailed in subsequent climate modeling studies (e.g., Tett et al. 2005; Hurrell et al. 2004; Meehl et al. 2004). The unanimous conclusions of these studies are

- for the 1910s through 1930s: solar activity contributed to a warming trend;
- for the 1940s through 1960s: as industrial activity increased, sun-blocking sulfates and other aerosols from both volcanic and anthropogenic sources contributed to a slight cooling;
- since 1970: the increase in anthropogenic greenhouse gas emissions has overwhelmed the aerosol effect to produce global warming.

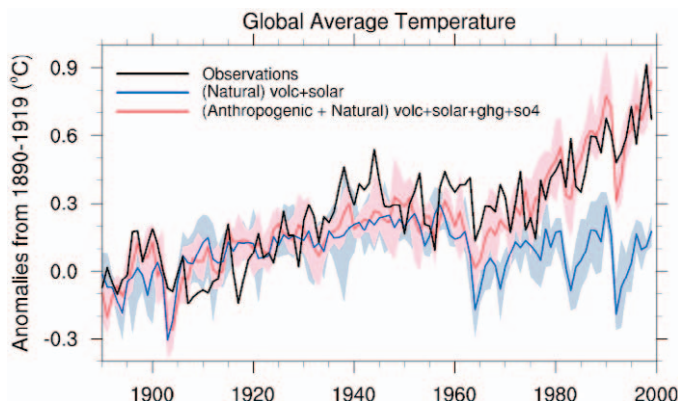


FIG. 3. The four-member ensemble mean (red line) and ensemble member range (pink shading) for globally averaged surface air temperature anomalies ($^{\circ}\text{C}$; anomalies are formed by subtracting the 1890–1919 mean for each run from its time series of annual values) for all forcing [(volcano + solar + GHG + sulfate + ozone)]; the solid blue line is the ensemble mean and the light blue shading is the ensemble range for globally averaged temperature response to natural forcing calculated as a residual [(volcano + solar)]; the black line is the observations after Folland et al. (2001). Taken from Meehl et al. (2004).

These simulations and analyses provide solid evidence that the global surface temperature trend since 1970 (including the trend in tropical SSTs) cannot be reproduced in climate models without the inclusion of anthropogenic greenhouse gases. Knutson et al. (2006) specifically attributed the increase in global tropical sea surface temperatures to greenhouse warming. Hence, the null hypothesis is rejected because the trend in tropical SST cannot be explained by natural internal variability and/or volcanic eruptions or solar variability, and the observed trend is consistent with model simulations associated with forcing from greenhouse gases.

Elevation to theory? If the central hypothesis is to be elevated to a theory, it must pass the following three tests:

- 1) survive scrutiny and debate, including attacks by skeptics,
- 2) be the best existing explanation (physical and statistical) for the particular phenomenon, and
- 3) demonstrate predictive capability.

The framework we have adopted to test the central hypothesis is to break it down into a causal chain of three subhypotheses, with the validity of each being a requirement for the validity of the central hypothesis. In the “The hypotheses” and “Testing

TABLE 1. Comparison of North Atlantic hurricane statistics for the periods 1945–55 and 1995–2005 (data from www.aoml.noaa.gov/hrd/hurdat and <http://weather.unisys.com/hurricane/atlantic>).

	1945–55	1995–2005
No. of tropical storms	115	165
No. of hurricanes	74	112
No. of category 3+4+5	41	45
No. of category 4+5	19	28

the hypotheses” sections, the hypotheses were subject to considerable scrutiny and examination, with an emphasis on trying to prove the alternative, or null, of each hypothesis. While uncertainties remain and further research is needed, none of the skeptical arguments made thus far has resulted in the rejection of any of the subhypotheses. We submit that each of the subhypotheses also provides the best existing explanation to date for the existing data.

Given the way in which the subhypotheses are posed, it can be argued that each of the subhypotheses, and hence the central hypothesis, should also hold for the individual ocean basins. The North Atlantic hurricanes deserve special discussion in light of the relatively long historical record of hurricanes. There is no question that natural internal variability is associated with variations in North Atlantic hurricane frequency and intensity. The Atlantic Multidecadal Oscillation (AMO; Delworth and Mann 2000; Knight et al. 2005; Kerr 2005) is of particular relevance to the central hypothesis because

- the AMO has a period nominally of 70 years (Knight et al. 2005);
- the AMO is reflected strongly in the tropical SSTs of the North Atlantic (Delworth and Mann 2000)—in fact, the North Atlantic SST is used to define the periods of the AMO; and
- data on the frequency of North Atlantic tropical storms going back to 1851 show strong minima of hurricane activity in the periods centered around 1850, 1915, and 1980 and maxima centered around 1875, 1950, and at the end of the time series (Elsner et al. 1999)—these variations are approximately in phase with the AMO (Knight et al. 2005).

Given the above, it would seem to be impossible to sort out whether the increase in North Atlantic hurricane frequency and intensity since 1995 is associated

with the AMO or with greenhouse warming. However, there are four arguments that support a strong component of greenhouse warming in the enhanced North Atlantic hurricane activity of the past decade:

- An argument provided by WHCC notes that the global increase in tropical SST since 1970 cannot be explained solely by internal oscillations in individual ocean basins.
- Identification of the phase of the AMO over the past 50 years is complicated by the convolution of the global warming signal and the AMO; this suggests that analyses that rely solely on SST to identify the AMO may have aliased the phase and amplitude of the AMO signal (Mann and Emanuel 2006). Mann and Emanuel further posit that there is no evidence for a signal from the AMO in tropical North Atlantic sea surface temperatures.
- The observations of Bryden et al. (2005), whereby the North Atlantic thermohaline circulation has decreased during the period since 1950, suggesting that there is no rationale for supposing that the AMO, has moved into an anomalously positive phase.
- The strength of the tropical storm activity during the period of 1995–2005 (which is at least a decade away from the expected peak of the current AMO cycle), relative to the previous maximum 11-year period of 1945–55 (Table 1), shows a 50% increase in the total number of tropical storms, number of hurricanes, and number of category-4 and -5 storms.

Based upon the hypothesis that natural internal variability is the cause of the high hurricane activity in the North Atlantic since 1995, there have been several predictions of a forthcoming downturn in hurricane activity—Goldenberg et al. (2001) imply a downturn in 10–40 years; Molinari and Mestas-Nuñez (2003) anticipate a downturn associated with decadal cycles; and Gray (2006) anticipates a downturn in 3–8 years.

In summary, the central hypothesis and subhypotheses cannot be invalidated by the available evidence. We anticipate that it may take a decade for the observations to clarify the situation as to whether the hypothesis has predictive ability. In short, time will tell.

CASE STUDY: MIXING POLITICS, CLIMATE SCIENCE, THE WORLD WIDE WEB, AND THE MEDIA. A case study is presented of the recent experiences of the authors of WHCC with the media

and the policy process. Our experience has not been unique; topics such as acid rain, nuclear winter, ozone depletion, and global warming have all engendered substantial media attention and policy debates, with some similar experiences for the scientists involved there with. However, there are several relative unique aspects to the case discussed here.

Once WHCC was accepted for publication and Georgia Institute of Technology, University Corporation for Atmospheric Research, and the American Association for the Advancement of Science (AAAS) prepared to issue press releases, it became apparent that this research would receive some significant media attention. In our AAAS press release (available online at www.aaas.org/news/releases/2005/0915hurricaneIntro.shtml), given the recent devastation associated with Hurricane Katrina, the main public message that we wanted to communicate was

The key inference from our study of relevance here is that storms like Katrina should not be regarded as a “once-in-a-lifetime” event in the coming decades, but may become more frequent. This suggests that risk assessment is needed for all coastal cities in the southern and southeastern U.S. . . . The southeastern U.S. needs to begin planning to manage the increased risk of category-5 hurricanes.

WHCC did not address explicitly the issue of global warming or the cause of increase in SST of the global tropical oceans. We considered including something on this topic in the article, but at the time the manuscript was submitted the authors did not agree on what, if anything, should be included. Hence, we adopted the fairly neutral stance of stating that the observed trend was “consistent with that which would be expected from greenhouse warming.” However, during the week prior to publication of WHCC, it became apparent that the main issue of media interest and policy relevance associated with our research would be whether or not greenhouse warming was causing the increase in hurricane intensity; the catastrophe of Katrina had arguably focused public concern about global warming more than any other issue or event hitherto. For context, prior to the publication of WHCC none of the authors had previously made any public statements about greenhouse warming or other environmental issues. Substantial media attention ensued, and we were rapidly embroiled in the greenhouse-warming debate. We made the conscious decision to present any information from the peer-reviewed literature in

our media interviews, although this often placed us at a considerable debating disadvantage.

Our recent experiences with the media and the policy process have caused us to reflect on the following issues:

- the role of the media in promoting divisiveness among the scientists and legitimizing disinformation;
- implications of the media, politics, and the World Wide Web for the scientific process; and
- the value gap among climate scientists, policy makers, and reporters.

Boykoff and Boykoff (2004) demonstrated that superficial balance in coverage of global warming by the U.S. “prestige press” (e.g., *New York Times*, *Washington Post*, *Los Angeles Times*, *Wall Street Journal*) can actually be a form of informational bias. Boykoff and Boykoff state that by giving equal time to opposing views, the major newspapers are significantly downplaying scientific understanding of the role humans play in global warming. Pitting what “some scientists have found” against what “skeptics contend” implies a roughly even division within the scientific community. In the media debate on global warming and hurricanes, greenhouse-warming deniers (which, in addition to scientists, includes lawyers and others with at best minimal scientific credentials) are set side by side with scientists who have actually done the work and published papers on the subject.

In addition to debate with greenhouse-warming deniers, considerable debate has also occurred among members of the meteorological community in a variety of venues, including the media. In the beginning, we assumed that “we scientists” would collegially agree to disagree and continue with our research and see where it led, looking occasionally in amusement at the media as they tried to sensationalize this. That is not how it has played out. Acrimony generated by the media debate has contributed to disruption of legitimate debates sponsored by professional societies by the cancellation and removal of panel members. The media has played a significant role in inflaming this situation by reporters’ recitations of what people on the other side of the debate are allegedly saying. One reporter manufactured a personal conflict between the first author of this paper (including an egregious misquote) and a scientist on the other side of the debate who have had no personal contact in several years. This illustrates the role that the media can play in inflaming a scientific debate and the values gap between scientists and journalists.

While responsible journalists and respected scientists share some similarities in their “pursuit of truth,” they have different and sometimes incompatible goals, missions, and responsibilities. Journalists are not simply looking for information; they are looking to develop stories that are timely and relevant, are wide in scope, have a particular thematic angle, reflect conflict, and demonstrate human drama. Reporters have different backgrounds, different assignments (e.g., a science reporter versus a political reporter), and different deadline frameworks. As reported in the summary for the 2003 workshop on Journalists’/Scientists’ Science Communications and the News Media (online at www.gso.uri.edu/metcalf/programs/MetcalfNS-FNov_03.pdf), “Some journalists complain that scientists sometimes see the media as an extension of their own scientific work, promoting rather than reporting on that work; and many scientists express concerns that journalists too often look for conflict or for an artificial or misleading balance in reporting on science issues.”

The best science journalists do an extremely careful job in researching their stories and work to develop a relationship of trust with the scientists (including protecting the reputation of the scientist) so that reporter can continue to use the scientist as a source in future stories. On the other hand, political reporters addressing a science story often work with much shorter deadlines, are highly motivated to have an article published on the front page of the prestige press, are less aware of the scientific culture, and are more likely to “burn” a scientific source that they are unlikely to use again. As pointed out by the 2003 workshop, the process of building trust between scientists and journalists proceeds “one person at a time.” However, the destruction of trust can happen much more rapidly, and one instance of a scientist getting burned by a reporter can have a widespread impact on the willingness of scientists, who are naturally concerned about being misquoted and quoted out of context, to communicate with reporters.

How can scientists avoid such pitfalls associated with the media? There are several sources of practical advice and useful information that are easily accessible by scientists. Many institutions offer some sort of media training for scientists to help them communicate to the public more effectively and avoid common pitfalls. One example of an excellent online source of practical advice for scientists can be found at www.scripps.edu/newsandviews/e_20040621/science.html. Effectively working with the media requires conscious effort and attention, and few scientists

and universities adequately invest in this activity (although many government research laboratories do make this effort) or are even aware of such a need. Our field could definitely benefit from such an investment.

Some of the most relevant scientific debate on this topic is not being undertaken at meetings sponsored by the relevant professional societies and government agencies, but rather in the media and via blogs, and only slowly in the professional scientific journals. After reading *The World is Flat: A Brief History of the Twenty-First Century* (Friedman 2005), we were prompted to reflect on how broadly the new technologies are influencing the scientific process on topics of high relevance. As the media debate proceeded, and certainly in the process of researching the material for this paper, we made extensive use of online media articles, blogs, Wikipedia.com, and other Web sites. As pointed out by Friedman, the challenge is how to think about the new technologies and the associated changes that have irreversibly changed the intellectual commons and manage it to maximum effect. The new scientific process will eventually sort itself out among the new technologies, the need for the scientific review process, and the need for information by the public and policymakers. However, during this sorting-out period (which may end up being a period of continual evolution as new technologies emerge), the use of science to inform policy, particularly on issues of high relevance, will almost certainly become confused with the decentralization of scientific authority previously vested in scientists that have published on the subject in refereed journals. While this decentralization provides a better guarantee that the best possible information and analysis is out there somewhere, it becomes increasingly difficult to identify the best information and analysis in this new environment, providing more fodder for the politicization of science.

As aptly summarized by Engel-Cox and Hoff (2005), “Public acrimonious debate, the use of scientific results in a political fashion, and the feeling that the process is not rational, can dissuade scientists from participating directly in the policy process. Scientists (particularly young researchers) that join this process do so at their own risk.” For a scientist whose reputation is largely invested in peer-reviewed publications and the citations thereof, there is little professional payoff for getting involved in debates that mix science and politics. Scientists becoming involved in policy debates and with the media may put their scientific reputations at risk in this process. Many scientists would rather remain above the fray

and not get involved in this process, but a majority of scientists feel that they have a responsibility to communicate their research and its social and ethical implications to policy makers and the nonspecialist public (e.g., MORI 2001). Scientists also have varying skills and self-perceptions of their effectiveness at communicating science to the public. The case for scientists to be active in the public debate on climate change has been made eloquently by S. Schneider in his essay on “Mediarology” (available online at <http://stephenschneider.stanford.edu/Mediarology/Mediarology.html>).

SUMMARY. The focus of this paper has been the scientific debate surrounding hurricanes and global warming, and the influence of the media and the World Wide Web on this debate and on the scientific process itself. Because of the high relevance of this topic, particularly in light of the North Atlantic hurricane activity in 2005, the intense media attention associated with the politicization of this issue has resulted in public confusion. A case study was presented of the recent experiences of the authors of WHCC, highlighting that even senior scientists are ill prepared for their first major experience with mixing politics, science, and the media. We hope that this chronicle of our experiences will help others navigate this minefield, and will help our community become more effective in educating the public and informing policy.

We presented an analysis of the scientific issues surrounding the Emanuel (2005) and WHCC papers in a manner designed to identify the most important critiques and focus the scientific debate. We formulated the central hypothesis that greenhouse warming is causing an increase in hurricane intensity as a causal chain consisting of three subhypotheses that are individually and collectively more easily evaluated than the central hypothesis. Assessing each of these subhypotheses against logically valid critiques has clarified the support for the hypotheses and the outstanding uncertainties. Progress on this topic requires multidisciplinary collaboration that includes hurricane researchers and forecasters, climate researchers and modelers, and oceanographers to address this complex scientific problem.

The debate has clearly shown that some of the most challenging issues in our field that are also of the highest policy relevance are at the interface of climate change and weather extremes. The operational and research communities need to work together on these issues, and the National Oceanic and Atmospheric Administration (NOAA) and the American

Meteorological Society (AMS) can play a major role in facilitating this collaboration.

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