The Spin on Greenhouse Hurricanes

ROBERT C. BALLING, JR.

The cover of *Newsweek* for January 22, 1996 shows a man walking through the white-out of a snowstorm. Curiously, the headline on the cover proclaims "THE HOT ZONE: Blizzards, Floods & Hurricanes: Blame Global Warming." To emphasize the point, "HOT" and "Global Warming" appear in bright red letters against the white background of blowing snow. This is not unusual. News reports of hurricanes (also called typhoons or simply tropical cyclones) around the world are often accompanied by statements mentioning global warming, the greenhouse effect, and the influence of human activity on climate. The public has been convinced that the future includes an increasing number of intense hurricanes that will do more and more damage throughout the world and that worries about hurricanes should be added to concerns we have regarding future heat stress, rising sea levels, droughts, pestilence, crop failures, water shortages, wildfires, and all the other components of the greenhouse disaster. This prediction is especially frightening since, in many parts of the world, hurricanes are among the most devastating natural disasters and suggestions that hurricane activity may increase should be taken seriously and deserve critical analysis by scientists and policy-makers.

What is most surprising about the claims regarding the increase in the numbers and intensity of hurricanes in the greenhouse world is the lack of empirical evidence or theory to support of these claims. In fact, much of the evidence offered to date indicates there is no link between global warming and increased hurricane activity. International scientific bodies have divorced themselves from popularized predictions and the most recent research shows that, in the future, there may be fewer hurricanes of less intensity doing less damage.

Like so many other elements of the greenhouse debate, the theoretical and empirical evidence do not matter to individuals interested in spreading the gloom and doom of global warming. I spent nearly one hour with the *Newsweek* editors explaining the information in this chapter but, despite this discussion, they planned a cover story in which hurricanes were blamed on global warming. This was not a matter of confusion regarding a complex scientific issue—I fully believe that *Newsweek* chose to ignore the facts and present the scariest possible story regarding global warming.

Building the link

If observations and theory do not support a link between greenhouse gases, global warming, and the intensification of hurricane activity, one may fairly question how this link became such a permanent feature of the global warming debate. An amazing set of circumstances lies behind our fear of future hurricanes.

In 1986, Kerry Emanuel, a noted hurricane scientist at MIT, published a highly technical and complex paper in the prestigious *Journal of the Atmospheric Sciences* (Emanuel 1986). This article, which deals with air-sea interactions and hurricane activity shows that if the sea-surface temperature falls below approximately 26°C, intense hurricanes become a physical impossibility. The cooler sea-surface temperatures strengthen the inversion that exists in the trade winds of the subtropical to tropical latitudes, thereby limiting the growth of convective clouds in the hurricane system. Emanuel further showed that the intensity of a hurricane has a well-defined upper limit that is governed, in part, by the degree of thermodynamic disequilibrium between the atmosphere and the underlying ocean. In simple terms, a warmer sea-surface could theoretically increase the upper limit of a storm's intensity. Only a few storms actually approach this theoretical upper limit but they are the most destructive and dangerous. Whether he realized it or not, Emanuel had set a foundation for one of the more interesting misconceptions in the greenhouse debate.

This 1986 publication set the stage for several more important papers by Emanuel that ultimately would have a large impact on the link between greenhouse gases and increased hurricane activity. The following year, Emanuel published another article in *Nature* (Emanuel 1987) on the dependence of hurricane activity on climate. He showed that a numerical model altered to simulate an increase in greenhouse gases shows an increased thermodynamic disequilibrium between the ocean surface and the overlying atmosphere, and an increase in the theoretical upper limit of storm intensity. This is not to say that there would necessarily be more hurricanes or even more intense hurricanes, but the upper limit of intensity could increase. For a 3°C increase in sea-surface temperatures, the potential destructive power (as measured by the square of the wind speed) of storms approaching this theoretical limit could increase by 40 percent to 50 percent. From the outset, Emanuel acknowledged that there are many reasons to be skeptical about his conclusions regarding this limit of storm intensity, particularly as this value is determined for future climatic conditions.

Several more papers in 1988 encouraged the inclusion of hurricanes into all future gloomy greenhouse predictions. An article in the *Journal of the Atmospheric Sciences* (Emanuel 1988a) developed further the relationship between the upper limit of storm intensity and the warming occurring in the atmosphere and introduced the important term "hypercane" into the vocabulary of the atmospheric scientists. Not many people understood that, when he spoke of hypercanes, Emanuel was talking about the upper limit of storm intensity. He suggests that a warming of the sea surface by 6°C to 10°C (and with conditions in the lower stratosphere held constant) would make a supersized, ultrapowerful hypercane a *theoretical* possibility. Although no computer model has ever predicted a greenhouse-induced temperature rise of 6°C for the tropical and subtropical sea surfaces that spawn hurricanes, Emanuel had produced some interesting and valuable information about the physics of hurricane development and persistence.

These ideas were presented to a broader audience in a paper for the *American Scientist* (Emanuel 1988b) and, not surprisingly, the notion of hypercanes gained a wide-spread and credulous audience since a world-class scientist at a first-rate institution had published articles in the finest journals providing a link between atmospheric concentrations of greenhouse gases, global warming, and the development of these extraordinary hypercanes. Other scientists (e.g., Merrill 1988) published articles that supported Emanuel's work. Hobgood and Cerveny (1988) used a numerical hurricane model to simulate conditions during the height of an ice age and found a significant reduction in the intensity of the storms that developed in the model. If hurricanes weaken in ice age conditions, it is logical to assume they may strengthen during a time of increased planetary temperature.

The summer of 1988 was a period when the greenhouse effect and global warming made headline news day after day. On June 23, James Hansen made his the famous statement to the United States Congress that scientists were "99 percent certain" that the greenhouse effect produced by human activity is having an impact on the global climate system (Hansen 1988). There followed a series of climatic calamities in many parts of the world, including North America: there was a severe drought in the southeastern United States; parts of the Mississippi River dried up; there were record-breaking heat waves; and, in the American West, there were wildfires like the fires in Yellowstone National Park.

The apparent link between the greenhouse effect and hurricanes seemed even more credible when, in September of 1988, the storm of the century hit North Americans, who had suffered through a summer like no other. Just as the weather seemed to be quieting down, a tropical storm named Gilbert appeared south of the Virgin Islands. Unlike other storms that season, Gilbert grew at an alarming rate and its center pressure dropped to 885 millibars, the lowest pressure ever recorded for a hurricane in the western hemisphere; winds in Gilbert were sustained at 280 km/hr (175 mph) when it smashed into the area around Cancún in the Yucatán of Mexico. Gilbert then headed north and arrived in southern Texas on September 16th; prayers for an end to the drought were more than answered as Gilbert dropped more than 4 inches of rain to many locations in the souther Great Plains before dying in the interior of the United States.

The image of hurricanes—even hypercanes—was added to the popular vision of the greenhouse world; this enormous hurricane confirmed people's worst fears about the future. Emanuel's work was cited as proof that solid theoretical and empirical arguments existed linking global warming to super-sized hurricanes. Selling the greenhouse scare became easy—the proof was the incredible images of destruction caused by Hurricane Gilbert. When Hurricane Hugo struck the southeast coast of the United States the following year, all skepticism came to an end and people came to believe that, because of the greenhouse effect, hurricanes were increasing in intensity, magnitude, areal extent, duration, and ability to devastate our coastlines. Bookstores and newsstands were filled with new issues proclaiming the coming disaster that would be caused, in part, by the increase in hurricane damage. Anyone even remotely skeptical on the issue found the most credible professional organizations issuing statements about hurricane activity in the future: the governing council of the American Meteorological Society and the Board of Trustees of the University Corporation for Atmospheric Research issued a policy statement suggesting that greenhouse-induced global warming over the next 50 years would likely lead to "a higher frequency and greater intensity of hurricanes" (1988: 1436). By the end of the 1980s, the public was convinced that the scientific community was reasonably certain of this prediction and, on this authority, anyone could construct a powerful case that humans were facing a world of greenhouse-related perils, including the nearly certain threat of hypercanes.

Debate begins

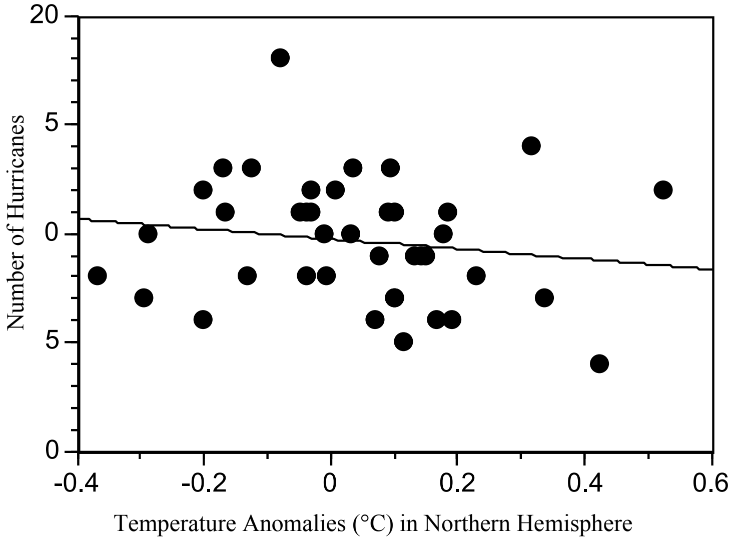
As with so many facets of the greenhouse debate, the hurricane story might seem an open and shut case: Emanuel had supplied theoretical reasons to expect an increase in hurricane activity given the buildup of greenhouse gases and an easily remembered and frightening new name, hypercane; the world seemed to be warming; hurricanes Gilbert and Hugo appeared to provide the final proof. However, this simplistic interpretation came into question since some scientists understood that Kerry Emanuel had never made a prediction of increased hurricane activity but, rather, had provided a theoretical discussion of the upper limit of hurricane intensity given a very large increase in sea-surface temperatures. They regarded the loud and public proclamations predicting increased hurricane activity with quiet skepticism.

In 1990, three articles appeared in the professional literature that made no headlines in the public outlets but that raised serious doubts about the notion that hurricane activity was increasing. Noted hurricane scientist William Gray published an article in *Science* dealing with the landfall of intense hurricanes in the United States and its relation to rainfall in West Africa. He revealed that Atlantic hurricane activity from 1970 to 1987 was less than half of the activity observed from 1947 to 1969. The greenhouse gas concentration was going up exponentially and, yet, Gray found that hurricanes were showing not the expected increase but, rather, a decrease in number or intensity.

Another research project published in 1990 in *Meteorology and Atmospheric Physics* by a group of greenhouse skeptics at Arizona State University challenged the prediction of increasing numbers and intensities of hurricanes due to a greenhouse effect (Idso *et al*. 1990). They gathered hurricane data for the central Atlantic, the east coast of the United States, the Gulf of Mexico, and the Caribbean Sea for the period from 1947 to 1987 (data prior to 1947 are unreliable and potentially biased because of the hurricane assessment procedures used prior to the end of World War II. They carefully collected information on the number of hurricanes observed each year in the study area, the number of days with hurricanes, and the number of storms within various categories of hurricane intensity. Rather than assessing trends in these hurricane variables over the 41-year period, Idso *et al*. compared the hurricane data to estimates of the surface temperature in the northern hemisphere since they saw that the northern hemisphere had shown considerable variation (nearly 1°C) in temperature from 1947 to 1987 and wondered how hurricanes had responded to these observed temperature variations.

Idso *et al*. found that “there is basically no trend of any sort in the number of hurricanes experienced in any of the four regions with respect to variations in temperature” (1990: 261). The number of hurricane days is negatively related to the northern hemispheric temperatures: warmer years produced the lowest numbers of hurricane days while the cooler years had more than average numbers of hurricane days. The number of storms within the various intensity classes is also inversely correlated with the hemispheric temperature values (figure 1). Idso *et al*. examined the trends with different intensity classes and concluded:

Figure 1 Number of Atlantic/Caribbean hurricanes verses northern hemispheric near-surface air temperature anomalies (°C) for each year from 1948 to 1987.



"For global warming on the order of one-half to one degree Centigrade, then, our analyses suggest that there would be no change in the frequency of occurrence of Atlantic/Caribbean hurricanes, but that there would be a significant decrease in the intensities of such storms" (1990: 262).

The work by Idso *et al.* had some impact on the debate but their findings were never publicized in outlets that reach large numbers of people around the world.[1] However, more research appeared to raise doubts on the connection between the greenhouse effect and hurricanes. Broccoli and Manabe, in an article entitled, Can existing climate models be used to study anthropogenic changes in tropical cyclone intensity? (1990), explained that, when they allowed certain cloud-related feedbacks to be included in their numerical modeling experiments, they found a 15 percent reduction in the number of days with hurricanes given a doubling of the concentration of atmospheric carbon dioxide. Their numerical simulation with cloud feedbacks suggested a reduction in hurricane number and/or duration for a world in which there was higher concentrations of greenhouse gases. Broccoli and Manabe noted that their results were a bit unstable and highly dependent upon how they represented cloud processes within the model.

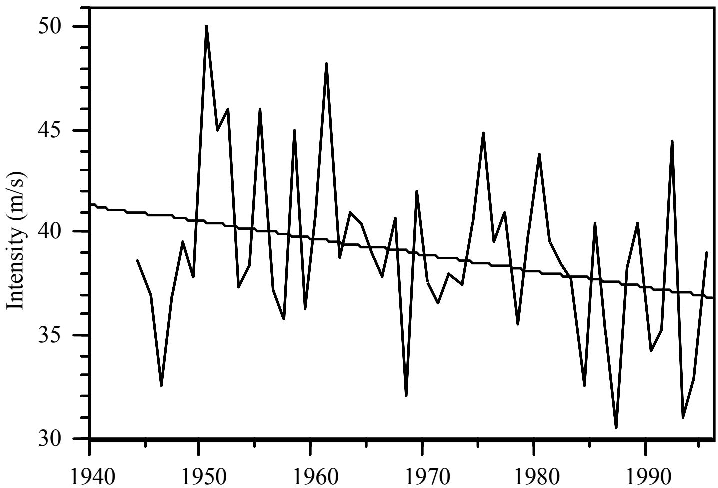
The first scientific assessment from the Intergovernmental Panel on Climate Change (IPCC 1990) was also published in 1990. The Policymakers Summary of this widely distributed and highly praised document explained: "climate models give no consistent indication whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades" (IPCC 1990: xxv). By the end of 1990, the issue of hurricanes and climate change had become a part of the heated debate about the greenhouse effect.

Ebb and flow in the 1990s

Throughout the 1990s, articles appeared in major journals both supporting and challenging the prediction of increased hurricane activity due to the greenhouse effect. In an article dealing with impacts on tropical forests, O'Brien *et al.* (1992) assumes that doubling the concentration of atmospheric carbon dioxide increases tropical sea surface temperatures from 1°C to 4°C, doubles the number of hurricanes, increases their strength by 40 percent to 60 percent, and extends the hurricane season. Although the authors' interest was forests, their unhesitating acceptance of the predictions of changes in the numbers and intensities of hurricanes had the effect of adding weight and credibility to those predictions. In addition, research by Ryan *et al.* (1992) suggested that areas conducive to hurricane generation could expand substantially in a warming world, although they fully acknowledged that their results gave an overestimation of the area in which hurricanes could arise.

Haarsma *et al.* (1993) used an 11-layered, global general-circulation model coupled with an ocean model and found that a doubling of the concentration of greenhouse gases would increase the frequency of hurricanes by 50 percent, increase the mean intensity of the storms by 20 percent, and increase the number of intense hurricanes developing due to the greenhouse effect. Conversely, Landsea (1993) reports that the intensity of Atlantic hurricanes has been decreasing since the middle of this century. Landsea carefully screened his data to remove known

Figure 2 Time series of Atlantic basin mean intensity (m/s) as determined from maximum sustained wind speeds of all hurricanes in each year from 1944 to 1995 (from Landsea *et al.*, 1996)



biases, and the decreasing trend remained an identifiable pattern in the intensity estimates (figure 2).

Further, 8 scientists who collaborated on a major review piece that appeared in the *Bulletin of the American Meteorological Society* (Lighthill *et al.* 1994) took two basic approaches. Both led to the conclusion that "even though the possibility of some minor effects of global warming on tropical cyclone frequency and intensity cannot be excluded, they must effectively be 'swamped' by large natural variability" (Lighthill *et al.* 1994: 214). Thus, they do not endorse the notion that any future increases in hurricanes can be expected or blamed on the buildup of greenhouse gases.

One approach taken by Lighthill *et al.* involved an examination of a widely accepted list of conditions that permit the formation and development of hurricanes. The list includes some simple conditions such as a sea-surface temperature above 26°C, distance from the equator of at least 5° of latitude, and fairly high relative humidity levels surrounding the storm. Other entries on the list dealt with more complex conditions such as the vertical temperature structure of the atmosphere, the change in wind velocity with height, and horizontal rotation of the system. Their analyses led to the conclusion that we should not expect any direct effects of changing sea-surface conditions on hurricane frequency and intensity. The authors point out that many unknowns and indirect effects could occur but that most impacts of rising sea-surface temperature are self-limiting. Second, Lighthill *et al*. examined the empirical records of hurricane activity since 1944 in the Atlantic and since 1970 in the Pacific. They noted great year-to-year variability in the hurricane data but could not find evidence to link hemispheric temperatures to variations in hurricane activity.

Not surprisingly, this article stirred-up the debate on the hurricane question. Emanuel (1995) fired back and questioned their evaluation, arguing that both the basic physics and the empirical records of hurricane activity suggest that warming in the tropical oceans would be accompanied by an increase in the limiting intensity of actual hurricanes. Broccoli *et al*. (1995) questioned the pessimistic view of Lighthill *et al*. of the usefulness of numerical climate models in this debate and suggested that current and future simulations hold enormous promise in providing answers to the questions surrounding future tropical storms. Pielke (1995) reported to the insurance industry that recent decades have been unusually quiet in terms of the number of hurricanes making landfall in Florida, and he suggested that a return to normal conditions would substantially increase hurricanes in Florida.

Lennart Bengtsson, member of Germany's Max Planck Institut für Meteorologie and one of the authors of Broccoli *et al*. 1995, published a paper in *Tellus* (Bengtsson *et al*. 1996) in which high-resolution numerical simulations with a coupled ocean-atmosphere model were used to show that greenhouse-induced changes would weaken the Hadley circulation that dominates the tropics but strengthen the upper-level westerlies in the vicinity of hurricane development. This strengthening of the upper-level winds should inhibit hurricane activity during the entire hurricane season. When compared to present day global distribution and seasonality of hurricanes, they found no changes for a doubling a greenhouse gases. However, the number of hurricanes in the northern hemisphere fell from 56.2

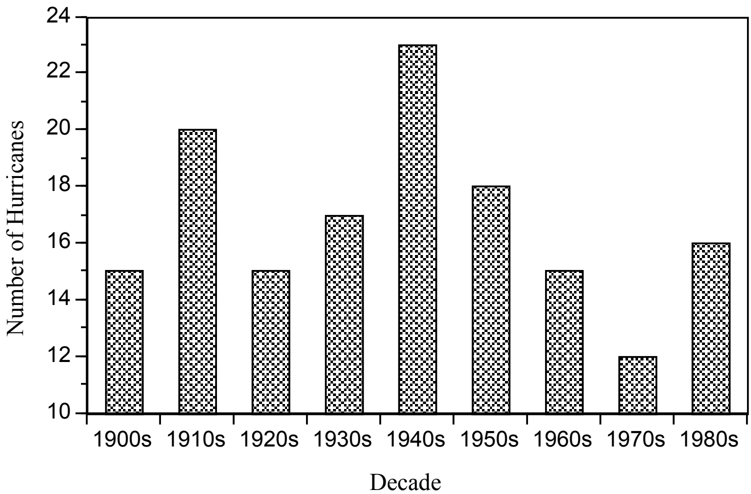
storms per year in the present-day climate simulation (the observed value from 1958 to 1977 is 54.6) to 42.0 storms per year in the case where the concentration of atmospheric CO_2 is doubled. In the southern hemisphere, the number of hurricanes dropped from 26.8 in the present-day climate simulation (24.5 is the observed value) to only 11.6 storms per year. Their results on intensity were less conclusive, but they did find a tendency for reduced wind speeds in the simulation where the concentration of atmospheric CO_2 is doubled.

Another article by Landsea *et al.* (1996) confirmed once more the view that hurricane frequency and intensity were not increasing during the past five decades. Landsea *et al.* examined Atlantic hurricanes from 1944, when aircraft reconnaissance began in the Atlantic, to the present. They found that "a long-term (five decade) downward trend continues to be evident primarily in the frequency of intense hurricanes. In addition, the mean maximum intensity (i.e., averaged over all cyclones in a season) has decreased" (Landsea *et al.* 1996: 1700). A plot of the mean intensity (figure 2) clearly shows this downward trend during a time of greatest buildup of greenhouse gases.[2]

This downward trend in Atlantic hurricane basin over the past 5 decades is interesting but it raises the question about trends prior to the 1940s. Hard evidence is difficult to find for storms that moved through the Atlantic prior to the World War II. Nevertheless, Karl *et al.* (1995, 1996) examined records of the number and intensity of hurricanes that made landfall on the continental United States over the past century and found that their number decreased from the 1940s through the 1980s. The records also show an increase in storms in the first half of the record (figure 3) and, over the twentieth century, no overall trend was discernible in the records. Elsner *et al.* (1996) looked at Atlantic hurricanes in the tropics from 1896 to 1990 and noted a drop in the number of tropical hurricanes in the 1960s; the trend in tropical hurricanes was clearly downward during the past 50 years of most reliable records.

The Intergovernmental Panel on Climate Change published its second scientific assessment in 1996 (IPCC I 1996) and in the Technical Summary they state: "Although some models now represent tropical storms with some realism for present day climate, the state of the science does not allow assessment of future changes" (IPCC I 1996: 44). Similarly, Karl *et al.* (1997)

Figure 3 Number of hurricanes making landfall in the conterminous United States (from Karl *et al.* 1995, 1996)



reported in *Scientific American* that "Overall, it seems unlikely that tropical cyclones will increase significantly on a global scale. In some regions, activity may escalate; in others, it will lessen" (Karl *et al.* 1997: 83). These summary statements do not endorse the popular claim that we should blame hurricanes on global warming.

Saunders and Harris (1997) summarized the literature on the environmental factors affecting the number of tropical cyclones in the North Atlantic basin. The major factors include tropospheric wind shear, El Niño/Southern Oscillation, the stratospheric quasi-biennial oscillation, monsoon rainfall in the western Sahel, Carribean sea-level pressure anomalies, and sea-surface temperatures in the tropical latitudes where hurricanes are spawned. They used regression analysis to link data on these environmental factors to the number of tropical cyclones, and they found that the sea-surface temperatures played a dominating role. Saunders and Harris concluded that unusually warm sea-surface temperatures were largely responsible for the large number of tropical storms and hurricanes observed in the North Atlantic during 1995. The implication from their work is that warming of the sea surface, for any reason, could result in a larger number of tropical cyclones. Their work also reminds us that the debate on future hurricanes is far from over.

Blaming warming?

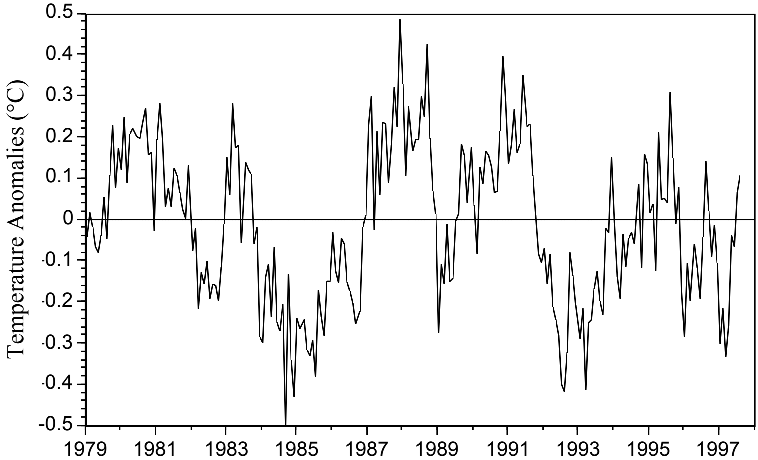
One of the most interesting ironies in the claims that recent hurricane activity is linked to warming is that the warming itself may not have occurred—there is strong evidence from satellite measurements that the planet has actually cooled over the past few decades (see figure 4). Each day, measurements of microwave emissions from molecular oxygen in the lower eight kilometers of the atmosphere are made by instruments on board satellites in polar orbit. The results provide an excellent measure of lower-tropospheric temperatures (Spencer and Christy 1990). Microwaves are able to penetrate the atmosphere with little attenuation, and the amount of energy received by the satellites is directly proportional to the temperature in the lower atmosphere. The 53.74 GHz channel is highly sensitive to the thermal emission of molecule oxygen in the middle troposphere, and has little sensitivity to water vapor, the earth's surface properties, or cloud variations. The polar orbits of the satellites assure that the entire earth, including remote and oceanic areas of the earth are covered as fully as other parts of the planet.

The satellites have not observed any warming since the measurement program began in 1979 (figure 4). Over the period from January 1979 to August 1997, the satellites have actually observed a statistically significant *cooling* of 0.08°C! Furthermore, the first 6 months of 1997 were usually cold on the global scale given that period of El Niño development. Blaming hurricanes on recent warming is flawed on all fronts—not only is there little to no link between global warming and hurricane activity, but there seems to have been no warming in recent decades either. But, as we see from the *Newsweek* cover, these facts simply make little difference in the greenhouse debate.

The future

There has developed, then, the highly popular view that the build-up of greenhouse gases will cause the sea surface and atmospheric temperatures to rise, and that this will result in an increase in the number and intensity of damaging hurricanes around the world. But, as with other aspects of the greenhouse debate, neither

Figure 4 Satellite-based monthly planetary temperature anomalies from January 1979 to August 1997 (updated from Spencer and Christy 1990).



theory nor empirical evidence provide much support for this claim. Indeed, there is plenty of evidence from which to argue that the greenhouse effect will suppress hurricane activity.

The information that we have today does not predict any increase in the number of hurricanes in the future. Similarly, the mean intensity of the hurricanes that develop is not likely to increase. On the other hand, Emanuel's research has survived a decade of debate and, should there be a substantial warming in the tropical sea surface, the upper limit of hurricane intensity probably will rise and, over a long time period, a few very powerful hurricanes may develop.

A compounding factor exists that may make detection of any changes more difficult than ever. It is well known that interannual variations in El Niño and La Niña have a significant impact on hurricane activity (Gray 1984). During El Niño periods, when there is warm water off the Pacific coast of South America, the upper-level winds over the Atlantic increase, hurricane development and persistence are inhibited, and the number of hurricanes as well as the length of the hurricane season are reduced. During La Niña periods, when there is cold water off the Pacific coast of South America, there tends to be increased hurricane activity in the Atlantic. The overriding problem here is that Meehl and Washington (1996) have presented results from climate model simulations showing that an increase in the atmospheric concentration of greenhouse gases could lead to climatic anomalies in the tropical Pacific that are similar to the quasi-periodic (and natural) El Niño events. This finding further complicates the problem of untangling natural variations in hurricane activity from those caused by the effects of increases in the concentration of greenhouse gases resulting from human activity.

More research will provide the answers to these and other related questions—the month-by-month information flow in the greenhouse debate gives it a flavour unlike similar debates in science. As the debate develops, we can go along with the simplistic and alarmist popular view presented by news magazines like *Newsweek* or we can recognize that at the present stage of this complex research, there is little reason to expect an increase in hurricane activity throughout the upcoming century.

Notes

1 A few critics pointed to what they considered a damaging aspect of the research by Idso and colleagues: in an acknowledgment in the article, they thanked the president of Cyprus Minerals Company for financial support for the project. Funding from many other sources (e.g., National Science Foundation, Environmental Protection Agency, National Oceanic and Atmospheric Administration) was acceptable to the critics but they felt that funding from a mineral company involved with coal prejudiced the results presented by Idso *et al*.

2 Landsea *et al*. are fully aware that hurricanes occur in other ocean basins but the data quality problems from other parts of the world preclude similar analyses from other locations.

References

American Meteorological Society Council and the Board of Trustees of the University Corporation for Atmospheric Research (1988). The changing atmosphere—challenge and opportunities. *Bulletin of the American Meteorological Society* 69: 1434–40.

Bengtsson, L., M. Botzet, and M. Esch (1996). Will greenhouse gas-induced warming over the next 50 years lead to a higher frequency and greater intensity of hurricanes? *Tellus* 48A: 57–73.

Broccoli, A.J., and S. Manabe (1990). Can existing climate models be used to study anthropogenic changes in tropical cyclone intensity? *Geophysical Research Letters* 17: 1917–20.

Broccoli, A.J., S. Manabe, J.F.B. Mitchell, and L. Bengtsson (1995). Comments on "Global climate change and tropical cyclones": Part II. *Bulletin of the American Meteorological Society* 76: 2243–45.

Elsner, J.B., G.S. Lehmiller, and T.B. Kimberlain (1996). Objective classification of Atlantic hurricanes. *Journal of Climate* 9: 2880–88.

Emanuel, K.A. (1986). An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *Journal of the Atmospheric Sciences* 43: 585–604.

——— (1987). The dependence of hurricane intensity on climate. *Nature* 326: 483–85.

——— (1988a). The maximum intensity of hurricanes. *Journal of the Atmospheric Sciences* 45: 1143–56.

——— (1988b). Toward a general theory of hurricanes. *American Scientist* 76: 370–79.

——— (1995). Comments on "Global climate change and tropical cyclones": Part I. *Bulletin of the American Meteorological Society* 76: 2241–43.

Gray, W.M. (1984). Atlantic seasonal hurricane frequency. Part 1: El Niño and 30 mb quasi-biennial oscillation influences. *Monthly Weather Review* 112: 1649–68.

——— (1990). Strong association between West African rainfall and U.S. landfall of intense hurricanes. *Science* 249: 1251–56.

Haarsma, R.J., J.F.B. Mitchell, and C.A. Senior (1993). Tropical disturbances in a GCM. *Climate Dynamics* 8: 247–57.

Hansen, J.E. (1988). Testimony to the United States Senate, Committee on Energy and Natural Resources (June 23).

Hobgood, J.S., and R.S. Cerveny (1988). Ice-age hurricanes and tropical storms. *Nature* 333: 243–45.

Idso, S.B., R.C. Balling Jr., and R.S. Cerveny (1990). Carbon dioxide and hurricanes: implications of Northern Hemispheric warming for Atlantic/Caribbean storms. *Meteorology and Atmospheric Physics* 42: 259–63.

Intergovernmental Panel on Climate Change (IPCC) (1990). *Climate Change: The IPCC Scientific Assessment*. Report prepared for IPCC by Working Group I. John T. Houghton *et al.* (eds). Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change, Working Group I (IPCC I) (1996). *Climate Change 1995: The Science of Climate Change*. Contribution of Working Group I to the Second Assessment Report of the

Intergovernmental Panel on Climate Change. John T. Houghton *et al.* (eds). Cambridge: Cambridge University Press.
Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle (1995). Trends in U.S. climate during the twentieth century. *Consequences* 1: 3–12.
——— (1996). Indices of climate change for the United States. *Bulletin of the American Meteorological Society* **77**: 279–92.
Karl, T.R., N. Nicholls, and J. Gregory (1997). The coming climate. *Scientific American* 276: 79–83.
Landsea, C.W. (1993). A climatology of intense (or major) Atlantic hurricanes. *Monthly Weather Review* 121: 1703–13.
Landsea, C.W., N. Nicholls, W.M. Gray, and L.A. Avila (1996). Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters* 23: 1697–700.
Lighthill, J., G. Holland, W. Gray, C. Landsea, G. Craig, J. Evans, Y. Kurihara, and C. Guard (1994). Global climate change and tropical cyclones. *Bulletin of the American Meteorological Society* 75: 2147–57.
Meehl, G.A., and W.M. Washington (1996). El Niño-like climate change in a model with increased atmospheric CO_2 concentrations. *Nature* 382: 56–60.
Merrill, R.T. (1988). Environmental influences on hurricane intensification. *Journal of the Atmospheric Sciences* 45: 1678–87.
O'Brien, S.T., B.P. Hayden, and H.H. Shugart (1992). Global climatic change, hurricanes, and a tropical forest. *Climatic Change* 22: 175–90.
Pielke, R.A., Jr. (1995). Preparing for the past: global warming and response to hurricanes in the U.S. *Insurance Specialist* 1: 14–15.
Saunders, M.A., and A.R. Harris (1997). Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming. *Geophysical Research Letters* 24: 1255–58.
Spencer, R.W., and J.R. Christy (1990). Precise monitoring of global temperature trends from satellites. Science 247: 1558–62.
Ryan, B.F., I.G. Watterson, and J.L. Evans (1992). Tropical cyclone frequencies inferred from Gray's yearly genesis parameter: validation of GCM tropical climates. *Geophysical Research Letters* 19: 1831–34.