Anthropogenic Effects on Tropical Cyclone Activity

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1. Introduction

Among the more consequential effects of global climate change is the possible change in the level of activity of tropical cyclones. We are most concerned with three aspects of hurricane activity: their frequency, their intensity, and their geographical distribution. Any change in the frequency with which hurricanes strike populated land is of obvious concern. But the amount of damage increases roughly as the square of the intensity of the storms, as measured by their maximum wind speed, so in practice we are concerned more with the intense storms. If some aspect of climate variation were to lead to fewer hurricanes, but more intense ones, we might expect more losses. We would also be concerned if climate change were to cause hurricanes to be experienced in parts of the world now free from them, or to cease to be experienced in regions they now trouble. From a scientific standpoint, these issue are quite separate. The factors that control the intensity of hurricanes appear to be quite different from those that govern their frequency of occurrence, and this is reflected in the observation that some seasons produce very few but very intense storms. (The 1992 season had few storms, but it produced Hurricane Andrew.)

http://wind.mit.edu/~emanuel/anthro.html

The geographical distribution of hurricanes over a statistically large sample is determined by features of the large-scale circulation of the atmosphere and oceans which can, in principle, be simulated by global circulation models.

A fourth characteristic of hurricanes, their geometric size, has received less attention. The radial dimension of tropical cyclones ranges over nearly a factor of ten: the smallest observed storms can be placed entirely within the eyes of the largest. A storm whose radial dimension is twice the size of another will cause perhaps as much as four times the damage (all other things being equal) since the damage track will be twice as wide and each point within it will experience damaging winds for twice as long. (The magnitude and area covered by oceans waves and the storm surge will also be greater.) But so little is now known about the factors that determine the geometric size of individual storms that we are not able to discuss the matter here. In the following sections, we focus instead on the factors affecting the intensity, frequency and geographical distribution of hurricanes. We then discuss new efforts to empirically relate tropical cyclone activity to climate by reconstructing past storm activity from the geological record. **2**

. Intensity

The intensity of an individual hurricane, as measured conventionally by its maximum surface wind speeds or minimum surface pressure, is affected at any given time by a large and complex array of physical processes governing the interaction of the storm with the underlying ocean and with its atmospheric environment. Few of these processes are well understood. For a given ocean temperature and atmospheric thermodynamic environment, there is an upper bound on the intensity that a storm may achieve, but very few storms achieve this bound in practice. This limit is useful nevertheless, because it may tell us how intense the most intense hurricanes of a given climate are likely to be. Judging from the existing record of Atlantic hurricanes, we may expect a storm approaching its limiting intensity once every few years across the entire basin, but for an area the size of the state of Florida, this may happen only once or twice in a century. A more accurate climatology of hurricane intensity, ranked as a fraction of the limiting intensity, is needed. For a more complete discussion of the theory of limiting intensity, click here .

There are reasons to be concerned that the anthropogenic addition of greenhouse gases to the atmosphere might lead to an increase in the energy available to tropical cyclones and therefore to an increase in their limiting intensity; these are discussed in a previous paper by the author (Emanuel, 1987). Greenhouse gases reduce the amount of infrared radiation leaving the earth's surface, and unless there is a compensating decrease in the amount of solar radiation reaching the surface by clouds (but this is complicated because clouds also trap outgoing infrared radiation), the ocean must lose the excess heat by increased evaporation of sea water. There are only two ways to achieve this: either the thermodynamic disequilibrium between the tropical oceans and atmosphere must increase or the average surface wind speed must increase. If the thermodynamic disquilibrium increases, then so does the potential intensity of hurricanes (unless the thermodynamic efficiency were to decrease, but in fact, the efficiency also increases when greenhouse gases are added to the atmosphere. Not only does the input temperature (the sea surface temperature) increase, for the reasons given above, but the temperature of the tropopause decreases, because the extra greenhouse gas at high levels leads to more efficient emission of infrared radiation and thus to more cooling).

There must be considerable doubt, however, about the magnitude of the increase in potential intensity of hurricanes accompanying increases in anthropogenic greenhouse gases. The main source of uncertainty plaguing calculations of the increase have to do with uncertainties in the principal feedback in the climate system: the amount of water vapor in the atmosphere. Were the water vapor content to remain fixed, doubling atmospheric carbon dioxide would yield a tropical sea surface temperature increase of only about 0.5 C and a barely perceptible rise in the potential intensity of tropical cyclones. Most climate model simulations give much larger increases than this, owing to a positive feedback loop involving increasing atmospheric water vapor. But the physics of the processes controlling water vapor in the atmosphere are poorly understood and even more poorly represented in climate models, and what actually happens in the atmosphere is largely unknown because of poor measurements. It is now widely recognized that improvements in understanding and predicting climate hinge largely on a better understanding of the processes controlling atmospheric water vapor. While it is certainly useful to know the limiting intensity of tropical cyclones, any attempts to relate tropical cyclone intensity distributions to the state of the climate will have to reckon with the processes that prevent most storms from reaching their potential. What are these processes? Before discussing them, it must be noted that all potential intensity estimates to date have relied on climatological estimates of the parameters that are used in the estimate. While it is possible, in principle, to use real-time data to estimate potential intensity, this has only been tried quite recently. There is particular sensitivity to the environmental temperature near the top of the storm. Small differences in the temperature at fixed altitudes can cause the hurricane outflow to occur at very different altitudes, and thus at different temperatures. The climatological value of this quantity may therefore not be representative of the value that occurs in the actual storm environment.

Among the environmental factors known to affect hurricane intensity is vertical wind shear. This is just the rate at which the background horizontal wind varies with altitude. Even modest magnitudes of shear prevent weak disturbances from intensifying and may also limit the intensity of mature storms. Vertical shear affects the storm dynamics in numerous ways, few of which are well understood. It acts to tilt the circulation of the storm, possibly disrupting the flow of air in, up and out through it. Also, through a complex dynamical interaction, it forces a couplet of up-down motion, straddling the storm center. This in turn causes an asymmetrical distribution of clouds and rain and may also disrupt the essential process of heat transfer from the ocean, which is particularly important under the eye wall. Finally, vertical shear causes dry air from the environment to penetrate inward closer to the core of the storm. This may lead to the formation of cold, dry downdrafts in the eyewall, partially or completely offsetting the critical moistening of the boundary layer air by the ocean.

Not all dynamical interactions of tropical cyclones with their environment are detrimental to storm intensity. Tropical meteorologists in the 1940's noticed that interactions between cyclones and certain features of the flow at very high altitudes could cause intensification. Recent work by Bosart and Bartlo (1991) and by Molinari et al. (1995) have recast the analyses of such interactions in a modern dynamical framework, making the physics of the interaction somewhat more clear. It appears from this work that, under the right circumstances, the approach of a high altitude cyclonic circulation can cause an existing tropical cyclone to intensify, or a nascent one to develop. There are also several examples of strong high level cyclonic anomalies leading to the development of strong surface cyclones with some of the characteristics of tropical storms, even over relatively cool ocean water. One such storm occurred over the western North Atlantic in October, 1992, and caused extensive coastal damage in the northeastern U.S.

Interaction of hurricanes with the underlying ocean can cause substantial reduction of the storm's intensity. This has now been well documented in modeling studies (e.g. Khain and Ginis, 1991; Schade, 1994). Hurricanes stir cold water up to the surface, reducing the amount of heat that flows into the storm. The magnitude of the effect depends on the thickness of the warm layer of water at the top of the ocean, on the forward speed of the storm, and on its geometric size. Typical reductions of intensity from the potential intensity are on the order of 30%.

Clearly, there are many and diverse processes that affect the intensity of individual hurricanes. We would like to know how all of these affect the statistical distributions of hurricane intensity in a given climate, but this will require a far better understanding of hurricane dynamics than we have at present. One factor limiting progress is the enormous computational demands of simulating in three dimensions the full array of scales and physics that characterize tropical cyclones. Computers are barely fast enough to simulate the interaction of a hurricane with its environment with a spatial resolution sufficient to simulate the individual cumulonimbus clouds that are the real agents of vertical heat transport in hurricanes. But we can expect vast improvements in computer capability, if the recent past is any guide.

3. Frequency

Very few atmospheric processes are as poorly understood as tropical cyclogenesis. In spite of years of study, it remains largely a matter of guesswork as to whether a particular tropical disturbance will become a hurricane. Thanks largely to the work of Gray (e.g. Gray, 1988), we now know the atmospheric conditions that must prevail for genesis to occur, but the existence of such conditions, which are not uncommon in the tropics, is by no means a guarantee of genesis. It has been known for many years that tropical cyclones do not arise spontaneously, as do other types of storms, but must literally be triggered by disturbances of independent origin. The frequency of tropical cyclogenesis is a product of the prevalence of Gray's necessary conditions and the frequency of suitable initiating disturbances. But we do not yet know what makes one disturbance suitable and another unsuitable.

Nor is there some physical constraint on the number of tropical cyclones occurring every year around the globe. As evidenced by years in which there are virtually no hurricanes in the North Atlantic, the tropical atmosphere seems to be able to live quite happily without hurricanes. Truly, these storms are accidents of nature.

Some recent developments do offer hope, however, that we may soon understand genesis well enough to be able to predict the statistical frequency of cyclone occurrence given the state of the climate. One such development is the detection by Landsea and Gray (1992) of certain strong empirical relationships between Atlantic hurricane activity and other signals in the climate system. (These are discussed fully elsewhere in this volume.) The existence of such signals clearly offers clues about the physics of genesis, but these clues have yet to be unraveled. Another development stems from some recent work with numerical hurricane simulation models and from a series of field experiments performed in the early 1990's in the western and eastern tropical Pacific. It appears that a necessary and perhaps sufficient condition for genesis is the establishment of a pillar of very humid air that extends through the entire depth of the tropical troposphere and is about 50-100 miles wide. (Normally, the tropical atmosphere is somewhat dry in middle levels.) Thunderstorms that then develop within this humid pillar do not produce the dry, cold downdrafts that characterize most such storms and which oppose the tendency of evaporation from the ocean to humidify the atmosphere. These cold, dry downdrafts are driven by the partial evaporation of falling rain, but within the humid pillar, evaporation is reduced and downdraft formation is inhibited. The formation of these humid pillars appears to be possible through a number of different mechanisms, including the lifting of the tropical boundary layer within a tropical disturbance such as an easterly wave. Humid pillars also form naturally within tropical cloud clusters, by mechanisms that have yet to be elucidated.

The problem of predicting how tropical cyclone frequency might respond to climate change can be broken into two parts: predicting how the prevalence of Gray's necessary conditions will change, and predicting how the frequency and strength of potential initiating disturbances will change. Elementary considerations suggest that anthropogenic increases in greenhouse gases will reduce the former and increase the latter. Very briefly, the strength of very large scale tropical circulations such as monsoons and the trade winds are expected to increase. (Although the pole-to-equator surface temperature gradient decreases, gradients at higher altitudes increase and, in the net, the strength of thermally direct circulations increases.) In general, this would be accompanied by an increase in vertical wind shear, particularly in the upper troposphere (wind shear in the lower troposphere actually decreases). This would weigh in favor of fewer cases of tropical cyclogenesis. On the other hand, the more vigorous large-scale circulation might favor more and stronger potential initiating disturbances, such as easterly waves. This would weight in favor of more tropical cyclones. Thus the problem is complex, and simple reasoning produces ambiguous results.

General circulation models (GCM's) have been used by a number of groups to explore changes in tropical cyclone activity in a double CO2 world. To date, each of these groups has examined changes in the activity of tropical cyclones produced explicitly by the models. This approach is problematic, because neither the spatial resolution nor the physics of the models is sufficient to simulate tropical cyclones scrupulously. While the physics of mature model storms may be close to that of real hurricanes, it is very unlikely that genesis, which recent field experiments show to occur on scales as small as 30 miles, is being mimicked at all realistically by the GCM's, whose spatial resolution is more like 200 miles. For what they are worth, the GCM's produce conflicting results. The study of Haarsma et al. (1992), using the GCM run by the British Meteorological Office, shows an increase in both the intensity and frequency of tropical cyclones, but the analysis by Broccoli and Manabe (1990), using the Princeton/GFDL model, shows ambiguous results, with an increase in tropical cyclone activity if cloud-radiation feedback is not included and a decrease in activity otherwise.

Perhaps a better strategy would be to use GCM's to assess the prevalence of Gray's necessary conditions and of potential initiating disturbances. This would circumvent the need to actually simulate genesis and would be within the bounds of what the models should be capable of. (One would have to exercise some care in doing this, since not all of Gray's conditions can be expected to be invariant with climate change. For example, the SST threshold of 26 C would change with global mean temperature.) At present, however, there is very little basis for taking seriously quantitative estimates of climate change produced by GCM's, if for no other reason than that there is no basis for believing that they handle water vapor correctly. But there is also good reason to be optimistic about solving the problems that plague the present generation of models, and future GCM's should prove to be valuable tools for assessing the effects of climate change on hurricane activity.

I believe that a thorough, physically-based understanding of tropical cyclogenesis is a prerequisite for developing an ability to relate tropical cyclone frequency to the state of the climate. Empirical studies are enormously useful, but cannot lead to a completely general understanding of the problem. Even so, it must be admitted that such studies are far ahead of theory and modeling, which must now make an effort to catch up.

4. Geographical Distribution

In the current climate, hurricanes develop over tropical ocean waters whose sea surface temperature (SST) exceeds about 26 C, but, once developed, they may move considerably poleward of these zones. An oft-stated misconception about tropical cyclones is that were the area enclosed by the 26 C SST isotherm to increase, so too would the area experiencing tropical cyclogenesis. Regions prone to tropical cyclogenesis are better characterized as places where the atmosphere is slowly ascending on the largest scales. Since about as much atmosphere is descending as ascending, it is hard to change the total area experiencing ascent. Thus there is little basis for believing that there would be any substantial expansion or contraction of the area of the world prone to tropical cyclogenesis. This is borne out by the GCM simulations performed by Haarsma et al. (1992), who show that while there is a substantial increase in the area enclosed by the 26 C SST isotherm is a double CO2 environment, there is no perceptible increase in the area experiencing tropical cyclones.

It is conceivable, though, that changes in the large-scale circulation of the atmosphere would increase or decrease the rate of movement of tropical cyclones out of their genesis regions and into higher latitudes. It is also likely that changes in atmospheric circulation and SST distribution within the tropics would be associated with variations in the distribution of storms.

5. Paleotempestology

In the past few years, several efforts have been initiated to use geological records to quantify tropical cyclone activity going back as far as the end of the last glacial episode, about 10,000 years ago. One such effort, described by Liu and Fearn (1993), is based on the record of hurricane activity in sediments in the bottom of near-shore freshwater lakes. When Category 4 or 5 hurricanes pass over such lakes, ocean water breaches the sandbars that separate the lakes from the sea, leaving a deposit of relatively coarse sediments in the lake bed. Sediment cores ectracted from the lake bed reveal episodic layers of coarse sediments which can then be dated using carbon 14 techniques. The most recent of these layers correspond exactly to known historical category 4 and 5 hurricanes. To date, this technique has only been applied using sediment cores from Lake Shelby in coastal Alabama, USA. The stratigraphic record reveals that Category 4 or 5 storms affect Lake Shelby at 3400, 2800, 2200, 1300, and 700 years ago, implying a recurrence interval of about 600 years. Oddly, there is no indication of Category 4 or 5 hurricanes in the sediment record before about 3400 years ago, suggesting that there may have been a change in the climate of the region at about that time.

Although the long term record of intense hurricane activity at one point on the shores of the Gulf of Mexico cannot be considered enough to make deductions about the relationship between hurricane activity and climate, the technique could be applied to many more near-shore lakebeds to construct a broader climatology.

Tropical cyclones also cause strong currents that affect sediments in shallow ocean water. Records of these sediments can then be dated and used to infer past tropical cyclone activity (Keen and Slingerland, 1993). Although this technique has not been widely applied to date, it appears that it may be possible to use it to construct very long-period records of tropical cyclone activity.

Another technique that has been developed recently involves an aspect of hurricane rainfall that has received comparatively little attention. In the 1980's, it was discovered that rainfall from the eywalls of tropical cyclones have relatively little concentration of the oxygen isotope O18 compared to normal tropical rainfall (Lawarence and Gedzelman, 1996). This is probably a result of the unusually small rates of evaporation of eywall rain, given the nearly saturated environment through which the rain falls. (Evaporation concentrates O18 in the liquid water left behind.) David Malmquist (Personal communication, 1996) has shown that the oxygen isotope ratio of rainfall can be recorded in the carbonate deposits in cave stalagtites, which can then be sectioned and 14C dated. He has started to perform analyses of stalagtites in Bermuda. There is hope that this technique can be applied to a variety of deposits to deduce long-term records of tropical cyclone activity.

The field of paleotempestology is in its infancy, but there is hope that it can be used to push back the record of tropical cyclone activity well into the prehistoric past. This may offer the best hope for an empirical deduction about the relationship between tropical cyclones and climate.

6. Summary

The theory of tropical cyclones, in its present state of development, yields some useful insights into the relationship between tropical cyclone activity and climate. There is a rigorous upper limit to the intensity that hurricanes can achieve, and this limit can be easily determined from known states of the atmosphere and ocean. Elementary considerations show that this limit increases with the amount of greenhouse gas in the atmosphere, but the magnitude of the increase that would result from the present injection of anthropogenic greenhouse gases into the atmosphere is unknown, owing to large uncertainties about feedbacks in the climate system. Moreover, very few storms approach their limiting intensity, and the processes responsible for keeping storm intensities below their limiting value are poorly understood and not likely to be well simulated by present GCM's. The frequency with which tropical cyclones occur is a product of the prevalence of known necessary conditions for their formation and the frequency and strength of disturbances that have the potential of initiating tropical cyclones. Neither basic theory nor numerical climate simulation is well enough advanced to predict how tropical cyclone frequency might change with changing climate, and both give conflicting results on the change of tropical cyclone frequency on doubling atmospheric . There is no physical basis, however, for claims that the total area prone to tropical cyclogenesis would increase. The new field of paleotempestology entails the use of a variety of techniques for deducing the long-term history of hurricane activity from the geological record. Pushing the record of landfalling tropical cyclones well back into prehistory, perhaps even to the last ice age, may be the key to understanding from an empirical standpoint the relationship between tropical cyclone activity and climate. We should do what we can to encourage this endeavor.

Further progress in confronting the important relationship between tropical cyclone activity and climate will be limited unless there are fundamental advances in understanding the basic physics of hurricanes. An important limitation to making such advances is social and political in nature: There are remarkably few scientists working on the problem (when compared to the numbers working on, say, earthquakes, a phenomenon of comparable social significance). This is a complex matter of history and of the professional tastes that guide scientists in their choice of research problems. There is a potential for accelerating progress by taking measures to attract more scientific interest to the problem.

References

Bosart, L.F. and J.A. Bartlo, 1991: Tropical storm formation in a baroclinic environment. *Mon. Wea. Rev.*, **119**, 1979-2013.

Broccoli, A.J. and S. Manabe, 1990: Can existing climate models be used to study anthropogenic changes in tropical cyclone climate? *Geophys. Res. Lett.* , **17**, 1917-1920.

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. *Nature*, **326**, 483-485.

Gray, W. M. 1988: Environmental influences on tropical cyclones. *Aust. Met. Mag.*, **36**, 127-139.

Haarsma, R.J., J.F.B. Mitchell and C.A. Senior, 1992: Tropical disturbances in a GCM. *Climate Dyn.*, **8**, 247-257.

Keen, T. R., and R.L. Slingerland, 1993: Four storm-event beds and the tropical cyclones that produced them: A numerical hindcast. *J. Sed. Petro.*, **63**, 218

Khain, A., and I. Ginis, 1991: The mutual response of a moving tropical cyclone and the ocean. *Beitr. Phys. Atmosph.*, **64**, 125-141.

Landsea, C.W., and W. M. Gray, 1992: The strong association between western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate*, **5**, 435-453.

Lawrence, J.R. and S. D. Gedzelman, 1996: Low stable isotope ratios of tropical cyclone rains. *Geophys. Res. Let.*, **23**, 527

Liu, K-B, and M. L. Fearn, 1993: Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology*, **21**, 793-796.

Molinari, J., S. Skubis and D. Vollaro, 1995: External influences on hurricane intensity. Part III: Potential vorticity evolution. *J. Atmos. Sci.*, **52**, 3593.

Schade, L. R., 1994: The ocean's effect on hurricane intensity. Ph.D. thesis, Mass. Inst. Tech., Cambridge, MA, 127 pp.