PERSPECTIVES: WEATHER

Hurricane Threats

Lennart Bengtsson

Tropical cyclones are among the most devastating natural disasters, frequently causing loss of human lives and serious economic damage through ocean storm surges in coastal regions, destructive winds, and flash flooding due to excessive precipitation. The annual costs for the United States, presently estimated at some $5 billion (*1*), are expected to rise as a result of growing population and increasing wealth in coastal areas. Other regions of the world can be even more exposed to tropical cyclones. In 1998, Hurricane Mitch killed at least 10,000 people in Central America and caused enormous economic damage. The average annual economic loss in the Philippines is estimated at some 5% of the gross national income.

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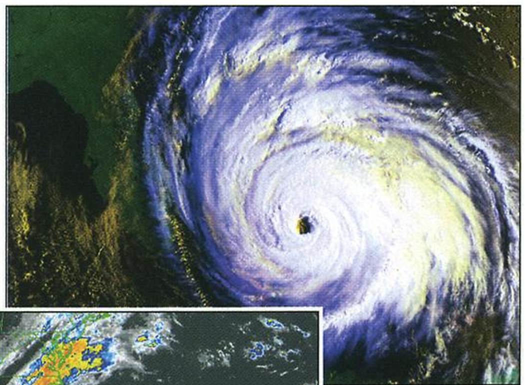
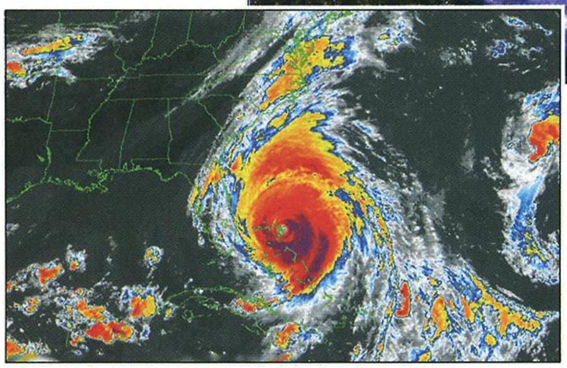
Tropical cyclones are low-pressure systems that originate over tropical or subtropical oceans (*2*) and have organized convection and a well-defined cyclonic circulation at the surface. At maximum sustained surface wind velocities of 17 m/s, they are called tropical storms or tropical cyclones. At 33 m/s or more, they are referred to as hurricanes (North Atlantic, northeast Pacific), typhoons (northwest Pacific), or severe tropical cyclones (southwest Pacific, Indian Ocean).

On page 474 of this issue, Goldenberg *et al.* (*3*) report an analysis of tropical cyclones in the Atlantic and Caribbean during much of the 20th century. Their results suggest that there may be long-term variations in the number of hurricanes. If true, this would have important implications for those regions within the storm track of these Atlantic storms.

The initial dynamics leading to a tropical cyclone are not well understood because data are limited and complex interactions between many scales of motion are involved. Once a weak cyclonic circulation exists, however, it may intensify into a hurricane as follows: Near the sea surface, friction causes the air to spiral inward toward the storm center. Clouds near the center become organized into spiral rainbands and eventually into an eye wall by the strong rotation in the vortex. As the winds strengthen and surface pressure decreases, increasing amounts of water are extracted from the warm ocean.





A dangerous storm. (Top) Hurricane Floyd on 14 September 1999 at 1244 UTC (Universal Time Coordinated) over the Bahamas on a northwesterly course toward the mainland United States. This multispectral false color image was taken by the NOAA-15 polar orbiting satellite. **(Bottom)** The same hurricane 7 hours later as seen by the GOES-8 geostationary weather satellite in a colorized infrared image. The dark red colors reflect areas of intense convective activity. Because of its size and intensity, Floyd constituted a very serious threat to the East Coast of the United States. It struck the coast of North Carolina (fortunately substantially below its maximum speed) and moved up into New England. River flooding caused 57 deaths (56 in the United States). The total damage has been estimated at $3 billion to over $6 billion. See www.nhc.noaa.gov/1999floyd_text.html.

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The air rises and cools and water vapor condenses, releasing latent heat. The heating of the center of the storm leads to its intensification, thereby further increasing the surface wind and evaporation. The storm will continue to intensify in this way until the energy input by surface evaporation is balanced by the frictional dissipation.

Tropical cyclones thus derive energy primarily from the evaporation of seawater and the associated condensation in convective clouds concentrated near the center of the storm. A well-developed tropical cyclone (hurricane) converts ocean heat energy into the mechanical energy of the winds, like a heat engine or Carnot engine (*4–6*). In contrast, extratropical cyclones primarily obtain energy from the redistribution of air masses at different potential temperatures.

Observations indicate (*7*) that the empirical relations based on the concept of a Carnot engine developed in (*6*) provide a good measure of the upper bound on the possible wind speed and intensity of a hurricane as can be determined from the sea surface temperature and the state of the atmosphere. However, the conditions responsible for the development of tropical cyclones are poorly understood because of a lack of good observations in areas where they develop. Empirical assessment (*3*) and results from comprehensive climate models (*8*) are in broad agreement that the following key conditions must be met: First, tropical storms will only develop over ocean areas where the sea surface temperature is ~26°C or more because a minimum amount of ocean heat supply is required. Second, low vertical wind shear is required, presumably because the convective cloud cells that provide the energy for the storm can only do so if their vertical structure is maintained. A strong wind shear will distort the structure of the convective cells and prevent them from systematically driving the storm.

A few other patterns have been found in connection with the development of tropical cyclones. Large-scale cyclonic circulation systems in the lower troposphere (onset vortices) and an unstable moist stratification through the depth of the atmosphere commonly occur over the ocean areas where tropical storms develop. Observations (*9*) and modeling results (*10*) indicate that El Niño events influence the frequency of hurricanes in the Atlantic. The suggested mechanism is that during an El Niño warm event, vertical wind shear is increased over the tropical Atlantic through changes in the large-scale tropical

The author is in the Max Planck Institute for Meteorology, Bundesstr. 55, 20146 Hamburg, Germany, and the Environmental Systems Science Centre, University of Reading, Reading RG6 6AL, UK. E-mail: bengtsson@dkrz.de or olb@mail.nerc-essc.ac.uk

circulation. Other remote factors have been suggested, such as rainfall variability over the western Sahara (*11*) or influences by the quasi-biennial circulation in the stratosphere (*12*), but these are empirical and lack a clear physical understanding.

Why some disturbances intensify to a hurricane while others do not is not well understood although they can be simulated and predicted reasonably realistically with numerical models (*8*). Neither is it clear why some tropical cyclones almost reach their maximum potential and others do not. It is the major hurricanes, reaching wind speeds above 50 m/s, that produce 80 to 90% of the damage in the United States, although they account for only 20% of all land-falling tropical cyclones (*1*).

On average, 45 tropical storms reach hurricane strength each year, 30% of them in the western North Pacific. Because of the short period of reliable observations—about 60 years in the Atlantic and the western North Pacific and only about 30 years elsewhere—it is not yet feasible to determine a trend or reliable low-frequency variations. Goldenberg *et al.* (*3*) suggest that there is evidence of long-term (multidecadal) shifts in the number of major hurricanes in the Atlantic and the Caribbean. A high level of activity from 1920 to 1960 is followed by reduced activity from the mid-1960s to the early 1990s. Thereafter, the authors report a return to a more active period. Superimposed on this slow variability are substantial variations from year to year, often influenced by El Niño–Southern Oscillation (ENSO) events.

Other tropical storm areas show no conclusive trend or variation (*13*). In some regions, the numbers of tropical storms have increased, in other regions they have decreased, and in some regions they are unchanged. The lack of long reliable records and a systematic classification of the storms in previous years makes it impossible to identify trends or clearly defined fluctuations.

Tropical cyclones usually form and spend most of their time over remote ocean areas. It was therefore not until the advent of space observations in the 1970s that the detection and systematic monitoring of the storms became possible. Additional observations come from reconnaissance aircraft, coastal radar, ships, buoys, and land stations. The combined use of better observations and advanced numerical modeling and data assimilation has gradually improved the forecasting of tropical storms (*14*), which is now increasingly done with comprehensive high-resolution atmospheric models (*1*), with some success even on the time scale of a week (*15*).

Predictions of seasonal hurricane activity have demonstrated modest forecast skill. Since the mid-1980s, these empirically based forecasts (*1*) have been able to anticipate nearly 20% of the variance of hurricane frequencies. The phase of ENSO, vertical wind shear, and Atlantic sea surface temperatures are the most important factors. The most promising approach for future development is the use of advanced climate models, which a priori incorporate these different factors.

How tropical cyclone frequency and intensity might respond to climate change is still a very open question (*13*). The above discussion on the mechanisms for hurricane development suggests that ocean warming would enhance tropical cyclone development. From this, one may be led to infer that if the area enclosed by the 26°C sea surface temperature isotherm increases, so too would the area experiencing tropical cyclogenesis. However, this is incorrect, as has been shown in (*16*): Cyclone development in a warmer climate occurs at higher oceanic temperatures, particularly in the case of intense tropical cyclones, because upper atmosphere warming compensates to some extent for the increased energy potential from the warmer ocean. This result is supported by modeling studies (*17*).

The broad geographical regions affected by tropical cyclones are thus not expected to change substantially. In particular, there is no reason to expect that the region of cyclone development will expand with the 26°C isoterm. However, although the number of cyclones may not increase substantially in the near future, this does not necessarily mean that the strength of the most powerful and dangerous cyclones will remain the same. Given optimum conditions in a future warmer climate, with an atmosphere potentially holding more moisture, the development of more intense cyclones cannot be excluded. This notion is supported by a high-resolution climate modeling study (*18*).

The societal vulnerability to hurricanes has increased substantially in recent decades, mainly because of (*19*) increased population in hurricane-exposed areas all around the world and, in some areas such as the U.S. coastal regions, increased wealth and advanced infrastructure. It has been estimated that if the hurricanes of 1925 had occurred in the late 1990s, the damage would have cost some $75 billion instead of a few billion if normalized for inflation, coastal county population changes, and changes in wealth (*20*).

The situation in the coastal United States is particularly precarious because the population increased substantially between 1960 and the 1990s. During this time, major hurricanes were rather rare, and this may have created a sense of false security. A change to what was typical, say, for 1920 to 1960 would create a potentially serious situation requiring most urgent attention (*3*).

The high hurricane activity during the last couple of years is as typical as the previous quiescent period, but the records are too short and incomplete to claim that the coastal United States may be in for a longer period of higher hurricane activity. Neither are there any indications that the climate warming may increase the frequencies of hurricanes in the area although the risk of very powerful storms may slowly mount. The risk of human losses is likely to remain low, however, because of a well-established warning and rescue system and ongoing improvements in hurricane prediction. A main concern is the risks of high damage costs (up to $100 billion in a single event) because of ongoing population increases in coastal areas and increasing investment in buildings and extensive infrastructure in general.

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