HANDBOOK OF WEATHER, CLIMATE, AND WATER

Atmospheric Chemistry, Hydrology, and Societal Impacts

Edited by

THOMAS D. POTTER

BRADLEY R. COLMAN

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CHAPTER 42

HURRICANE AS AN EXTREME METEOROLOGICAL EVENT

ROGER A. PIELKE, JR. AND ROGER A. PIELKE, SR.

1 INTRODUCTION: UNDERSTANDING SOCIETAL RESPONSES TO EXTREME WEATHER EVENTS

In the 1970s, many decision makers became increasingly interested in climate because of numerous weather-related impacts around the world. Events that helped to stimulate this interest included the failed Peruvian anchovy harvest in 1972 and 1973, the 1968 to 1973 drought in the African Sahel, a severe winter freeze in 1972 in the Soviet Union, and in 1974 floods, drought, and early frost in the U.S. Midwest. In 1977, winter in the eastern United States was the coldest ever recorded and summer was one of the three hottest in a century. As a consequence of these extreme events and their impacts, decision makers began paying more attention to the relation of weather and climate to human affairs.

Understanding societal responses to weather and climate requires an understanding of the terms *weather* and *climate*. The 1979 World Climate Conference adopted the following definitions of weather and climate:

> *Weather* is associated with the complete state of the atmosphere at a particular instant in time, and with the evolution of this state through the generation, growth and decay of individual disturbances.

> *Climate* is the synthesis of weather events over the whole of a period statistically long enough to establish its statistical ensemble properties (mean value, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state.

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Climate refers to more than "average weather" (Gibbs, 1987). Climate is, in statistical terminology, the distribution of weather events and their component properties (e.g., rainfall) over some period of time, typically a few months to thousands of years. In general, climate statistics are based on actual (e.g., weather station) or proxy (e.g., ice core) records of weather observations. Such a record of weather events can be used to create a frequency distribution that will have a central tendency, which can be expressed as an average, but it will also have a variance (i.e., spread around an average). Often, variability is more important to decision makers than the average state (Katz and Brown, 1992).

How society thinks about "extreme" weather is, of course, related to what is defined as "normal" weather. What, then, is a "normal" weather event? There are different ways to define normal weather. Of course, it is possible to argue that on planet Earth all weather events are in some sense normal; however, such a definition has little practical utility for decision makers. One way to refine the concept is to define normal weather events as those events that occur within a certain range within a distribution, such as, for instance, all events that fall within one standard deviation of the mean. In practice, historical records of various lengths and reliabilities have been collected around the world for temperature, precipitation, storm events, and others. When data is available, such a statistical definition lends itself to equating normal weather with "expected" weather, where expectations are set according to the amount of the distribution defined as normal. For example, about 68% of all events fall within one standard deviation of the mean of a bell-shaped distribution.

A change in the statistical distribution of a weather variable—such as that associated with a change in climate—is troubling because decision makers may no longer expect that the future will resemble the past. For the insurance industry, as well as other decision makers who rely on actuarial information, such a possibility of a changing climate is particularly troubling. A climate change is thus a variation or change in the shape or location (e.g., mean) of a distribution of discrete events (Katz, 1993).

"Extreme" weather events can simply be defined as those not normal, however normal is chosen to be defined. For instance, if normal weather events are those that occur within 2 standard deviations of the mean, then about 5% of all events will be classified as extreme.

While it is possible to classify hurricanes as either "normal" or "extreme" in this manner, the simple fact is that for most communities any landfalling hurricane would qualify as an extreme event because of their rarity at particular locations along the coast.

From the standpoint of those human activities sensitive to hurricane impacts, it is often the case that decisions are made and decision processes established based on some set of expectations about what future weather or climate will be like. Building codes, land-use regulations, insurance rates, disaster contingency funds are each an example of decisions that are dependent upon an expectation of the frequency and magnitude of future normal and extreme events.

In short, decision makers typically establish policies based upon an expectation of normal weather. Yet for most coastal communities normal weather has historically (or at least over the time of a human memory) meant no hurricanes! Consequently, people are often surprised when a hurricane does strike and then overwhelms response capabilities. Because decision makers do not always consider the possibility of extreme weather, when such events occur, they often reveal society's vulnerabilities and sometimes lead to human disaster. A fundamental challenge facing society is to incorporate information about weather and climate risks into decision making in order to take advantage of normal weather and to prepare for the extreme. The degree to which society exploits normal weather and reduces its vulnerabilities to extreme weather is a function of how society organizes itself in the face of what is known about various typical and extreme weather events. The challenge is made more difficult by variability at all measurable time scales in the underlying climate, and hence in the frequency, magnitude, and location of various weather events. And, of course, decisions that have a weather or climate component also are laden with all of the political, practical, and social factors that influence policy.

2 HURRICANES DEFINED

One of the most powerful natural phenomena on the face of Earth, the hurricane is a member of a broader class of phenomena called cyclones.* The term *cyclone* refers to any weather system that circulates in a counterclockwise direction in the Northern Hemisphere and in a clockwise direction in the Southern Hemisphere. "Tropical cyclones" typically form over ocean waters of the tropics. The tropics are the area on Earth's surface between the Tropic of Capricorn and the Tropic of Cancer, 23° 27″ south and north of the equator, respectively. Extratropical cyclones, for comparison, form as a result of the temperature contrast between the colder air at higher latitudes and warmer air closer to the equator. Extratropical storms form over both the ocean and land.

Tropical cyclones have been given different names depending on their region of origin. In the western north Pacific, they are called typhoons, while in the Bay of Bengal they are referred to as severe cyclonic storms of hurricane intensity. In the Atlantic, Gulf of Mexico, Caribbean, and Pacific north of the equator and east of the international dateline they are hurricanes. Evidence of tropical cyclones has been documented in a variety of other geographic locations including Europe and North Africa at earlier geologic times (Ager, 1993). Figure 1 shows the tracks of all tropical cyclones with winds greater than 39 mph for the 10-year period 1979 to 1988.

The meteorological community uses a number of terms to classify the various stages in the life cycle of tropical cyclones. The following are definitions of tropical cyclones used in the Atlantic Ocean basin (Pielke and Pielke, 1997):

*This chapter considers hurricanes as an extreme meteorological event. It first discusses the physical aspects of hurricanes, including their development and impacts on ocean and land. It then overviews societal impacts.

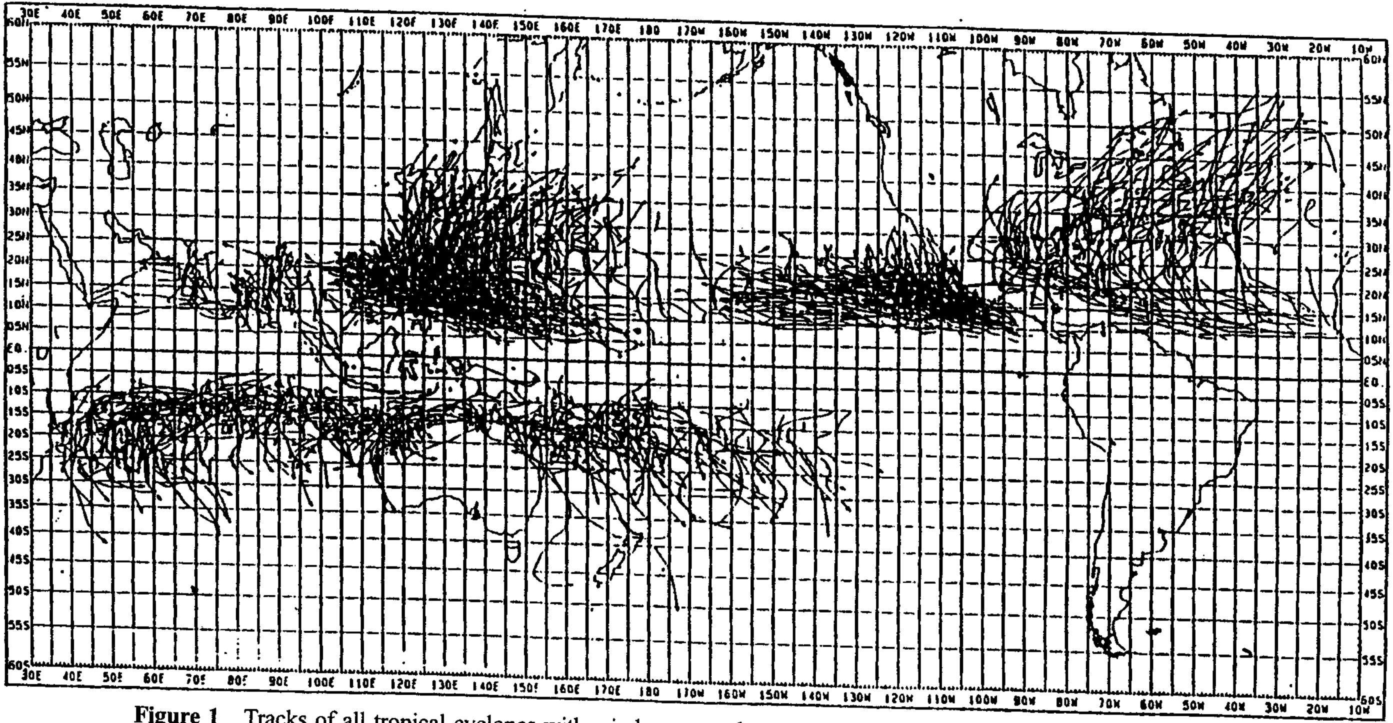

Figure 1 Tracks of all tropical cyclones with winds greater than 39 mph for a 10-year period (Neumann, 1993).

Tropical low	A surface low-pressure system in the tropical latitudes.
Tropical disturbance	A tropical low and an associated cluster of thunderstorms that has, at most, only a weak surface wind circulation.
Tropical depression	A tropical low with a wind circulation of sustained 1-min surface winds of less than 34 knots (kt) [39 miles per hour (mph), 18 meters per second [m/s] circulating around the center of the low]. [A knot (i.e., a nautical mile per hour) equals about 1.15 mph. A nautical mile is the length of 1 min of arc of latitude.]
Tropical storm	A tropical cyclone with maximum sustained surface winds of 34 to less than 64 kt (39 to 74 mph, 18 to 33 m/s).
Hurricane	A tropical cyclone with maximum sustained surface winds of 64 kt (74 mph, 33 m/s) or greater. (In the Pacific Ocean west of the international date line, hurricanes are called typhoons. They are the same phenomenon.)

3 HURRICANES IN NORTH AMERICAN HISTORY

The word *hurricane* derives from the Spanish *huracán*, itself derived from the dialects of indigenous peoples of the Caribbean and Latin America (Dunn and Miller, 1964). 'Hunraken' was the name of the Mayan storm god, and 'Huraken' was the god of thunder and lightning for the Quiche of southern Guatemala (Henry et al., 1994). The Tainos and Caribe tribes of the Caribbean called their God of Evil by the name Huracan. Other indigenous dialects included words such as *aracan*, *urican*, and *hurivanvucan* to refer to "Big Wind." The deification of the hurricane and the connection of indigenous referents with evil and violence is an indication that hurricanes had a significant impact on the lives of many peoples of the Caribbean and Latin America.

The historical record of documented hurricane events begins with the European conquest of North America. Columbus, in his four voyages to North America, experienced direct contact with an Atlantic hurricane only in his fourth voyage. Meteorological historian David Ludlam notes that Columbus' good fortune in his first voyage leads one to wonder "what the course of history in the West Indies might have been if, in the autumn of 1492, a full-blown tropical storm had dashed the frail craft of the Admiral's fleet to the bottom of the sea or flung them shipwreck on some tiny cay" (Ludlam, 1963, p. 1). Others did not experience such good fortune. Shakespeare's play, *The Tempest*, was loosely based on reports of a 1609 hurricane near Bermuda that sunk the vessel *Sea Venture* and stranded the passengers, including John Rolf, future husband of Pocahontas, on the island for 10 months. This storm's movement was among the first successfully anticipated by the colonists. During the course of the storm's trek through the Caribbean, a skipper in the Royal Navy cautioned the British fleet to move out of the storm's path, based on his experience with the movement of past hurricanes. During the 1700s and 1800s numerous coastal locations were struck by severe hurricanes. Charleston (South Carolina), New Orleans (Louisiana), and Boston (Massachusetts) were particularly hard hit a number of times. In 1772 in the West Indies, teenaged Alexander Hamilton wrote about a hurricane's impact for a local newspaper. His writing caught the attention of the local gentry who then raised money to send him to the mainland colonies to further his education, thus setting the stage for his political career.

Tropical storms were once named after the particular "saint's day" that fell nearest the hurricane event (Tannehill, 1952). For instance, "Hurricane Santa Ana" hit Puerto Rico on 26 July 1825 (see Rodriguez, 1997). Today, tropical cyclones are "named" when they reach tropical storm strength. According to one explanation, this practice dates to the 1950s, following the publication of George R. Stewart's *Storm*, a book that featured a forecaster who named storms (Williams, 1992). Another explanation has the origin of the hurricane naming convention beginning with a military radio operator who, during World War II, ended each hurricane warning singing "Every little breeze seems to whisper Louise," prompting the naming of a particular hurricane Louise (Henry et al., 1994). Whatever the origin, the practice caught on because it proved useful in identifying different storms that existed simultaneously. The personification of the extreme event was also found to be a valuable practice by the various user communities. Until 1979, tropical storms were given only women's names in English. In 1979 forecasters began to use men's, French, and Spanish names as well. The repeating, 6-year list of names assigned to tropical cyclones in the Atlantic was put together by the World Meteorological Organization. It can be found at the National Hurricane Center's website at *http://www.nhc.noaa.gov/names.html*. Hurricanes that cause significant damage or are particularly memorable, such as Andrew (1992), Camille (1969), or Gilbert (1988), are retired and those names are not used again. Table 1 lists retired hurricanes through 1995 and notes death and damages associated with each.

4 GEOGRAPHIC AND SEASONAL DISTRIBUTION: ORIGIN

Typically, in the Atlantic Ocean basin tropical storms and hurricanes develop over warm water between around 10°N to 35°N, generally, during the summer and fall. During an average year about 16 tropical cyclones develop in the eastern Pacific and approximately 10 in the Atlantic including the Gulf of Mexico and Caribbean Sea (Neumann, 1993). During the period of record, tropical cyclones fail to develop south of the equator in the Western Hemisphere east of 130 W because of one or more of the following factors: the relatively cold ocean temperature, typically strong winds in the upper troposphere, or the absence of an initiation area for tropical low-pressure systems with an associated cluster of thunderstorms (Gray, 1968).* Elsewhere these storms develop in the Indian Ocean, western Pacific, and eastern Pacific

*McAdie and Rappaport (1991), however, discussed the formation of a weak tropical cyclone in the south Atlantic west of tropical Africa in 1991.

TABLE 1 "Retired" Atlantic Hurricane Names through 1994

Year	Name	Location	U.S. Costs (1990$) and Total Casualties, etc.
1954	Carol	Louisiana, Mississippi, and Alabama	$2.37 billion, 60 deaths
1954	Hazel	Antilles, North and South Carolina	$144 billion, 1000 deaths
1955	Connie	North Carolina	25 deaths
1955	Diane	Mid-Atlantic and Northeast U.S.	$4.20 billion, 184 deaths
1955	Ione	North Carolina	$444 million
1955	Janet	Lesser Antilles, Belize, and Mexico	538 deaths
1957	Audrey	Louisiana and North Texas	$696 million, 550 deaths
1960	Donna	Bahamas, Florida, and eastern U.S.	$1.82 billion, 364 deaths
1961	Carla	Texas	$1.93 billion, 46 deaths
1963	Flora	Haiti and Cuba	8000 deaths
1964	Cleo	Lesser Antilles, Haiti, Cuba, southeast Florida	$595 million, 213 deaths
1964	Dora	Northeast Florida	$1.16 billion
1964	Hilda	Louisiana	$579 million, 304 deaths
1965	Betsy	Bahamas, southeast Florida, southeast Louisiana	$6.46 billion, 75 deaths
1966	Inez	Lesser Antilles, Hispaniola, Cuba, Florida Keys, Mexico	1000 deaths
1967	Beulah	Antilles, Mexico, South Texas	$844 million; most tornadoes, 115, ever associated with a hurricane
1969	Camille	Louisiana, Mississippi, and Alabama	$5.24 billion, 256 deaths
1970	Celia	South Texas	$1.56 billion
1972	Agnes	Florida, northeast U.S.	$5.24 billion, 122 deaths
1975	Eloise	Antilles, northwest Florida, and Alabama	$1.08 billion
1979	David	Lesser Antilles, Hispaniola, Florida, and eastern U.S.	$487 million, 2000 deaths
1988	Joan	Curacao, Venezuela, Columbia, and Nicaragua	216 deaths; crossed into Pacific and was renamed Miriam
1989	Hugo	Antilles and South Carolina	$7.16 billion, 56 deaths
1990	Diana	Mexico	96 deaths
1990	Klaus	Martinique	
1991	Bob	North Carolina and northeast U.S.	$1.5 billion
1992	Andrew	Bahamas, South Florida, and Louisiana	> $25 billion
1995	Luis	Leeward Islands	$2.5 billion, 16 deaths
1995	Marilyn	Virgin Islands	$1.5 billion, 8 deaths
1995	Opal	Mexico, Florida	$3 billion, 59 deaths
1995	Roxanne	Mexico	$1.5 billion, 14 deaths

After Pielke and Pielke (1997).

TABLE 2 Saffir/Simpson Hurricane Scale

Category	Central Pressure (mbars)	Central Pressure (inches)	Winds (mph)	Surge (ft)	Damage
1	⩾980	⩾28.94	74–95	4–5	Minimal
2	965–979	28.50–28.91	96–110	6–8	Moderate
3	945–964	27.91–28.47	111–130	9–12	Extensive
4	920–944	27.17–27.88	131–155	13–18	Extreme
5	<920	<27.17	>155	>18	Catastrophic

See Pielke and Pielke (1997, p. 17).

north of the equator (Fig. 1). The western north Pacific is the most active area with an annual average of more than 26 tropical cyclones. Globally, there are about 84 tropical cyclones each year with an annual average of 45 that reach hurricane strength (Neumann, 1993).

Hurricanes are classified by their damage potential according to a scale developed in the 1970s by Robert Simpson, a meteorologist and then-director of the National Hurricane Center, and Herbert Saffir, a consulting engineer in Dade County, Florida (Simpson and Riehl, 1981). The Saffir/Simpson scale was developed by the National Weather Service to give public officials information on the magnitude of a storm in progress and is now widely used by producers and users of hurricane forecasts. The scale has five categories, with category 1 representing the least intense hurricane and category 5 the most intense. Table 2 shows the Saffir/Simpson scale and the corresponding criteria for classification.

5 HURRICANE IMPACTS ON OCEAN AND LAND

When a hurricane forms, it poses a significant danger to society. The importance and danger of tropical cyclones differ between land and water. Over the oceans, the human activities and assets at risk are primarily oil rigs, shipping, and air traffic. On land, particularly along the coast, cities, towns, and industrial activities become threatened. Hurricanes also have ecological and geological impacts.

Ocean Impacts

Winds of hurricane speed over the ocean can create monstrous waves. For example, in 1995, the cruise ship *Queen Elizabeth II* was rocked by a 70-ft (21-m) wave caused by distant hurricane Luis. The sea near a hurricane is chaotic, and an extreme hazard to shipping can occur in response to wave motion moving in many directions.

For comparison, strong winds, of course, also occur in winter storms over the open ocean. The risk to shipping and other activities from wave action, however, is generally less serious in such storms for two reasons. First, the wind blows primarily in one direction in a given sector of a winter storm. Hence the waves move in concert with the wind. A ship can thus orient itself to minimize the effect of the waves. In a hurricane, winds change direction rapidly around the eye. The result is a chaotic sea with swells and waves propagating in a myriad of directions. A ship cannot simply steer into the running sea to reduce its risk since there is no one direction from which the waves come. Large waves also superimpose on top of each other, producing enormous swells.

Land Impacts at the Coast and a Short Distance Inland

At the coast, the major impacts of either a landfalling hurricane or one paralleling the coast are:

- Storm surge
- Winds
- Rainfall
- Tornadoes

Of these weather features, the storm surge has accounted for over 90% of the deaths in a hurricane. In recent years, and particularly in the aftermath of hurricane Andrew, more attention has been paid to the effects of hurricane winds.

Storm Surge

"Storm surge" refers to a rapid rise of sea level that occurs as a storm approaches a coastline. This is in addition to changes in variations in sea level due to tides. Thus, a storm surge causes greatest inundation at high tide. A very strong hurricane may produce a storm surge of 20 ft (6 m), of which about 3 ft (1 m) is due to the lower atmospheric pressure at the center of a hurricane. The remaining storm surge is due to: (i) the piling up of water at the coast, generated by the strong onshore winds and (ii) a decreased ocean depth near the coast, which steepens the surge. A common misconception is that the lower pressure at the center of a storm is the primary cause of the storm surge.

At landfall, storm surge is highest in the front right quadrant of a westward-moving tropical cyclone (in the Northern Hemisphere), where the onshore winds are the strongest. It is also large where ocean bottom bathymetry focuses the wave energy (e.g., as in a narrowing embayment). Peak storm surge from a landfalling cyclone increases with greater wind speeds and the areal extent of the storm's maximum winds, out to about 30 miles (48 km).

Storm surge also occurs when a storm parallels the coast without making landfall. The storm surge will precede the passage of the storm's center when winds blow onshore preceding passage of the eye. Similarly, the surge will lag the storm's center when the hurricane is moving such that onshore winds follow the passage of the eye.

Offshore winds that are associated with a storm can produce a negative surge, as the sea level is lowered by the strong winds blowing out from the coast.

Storm surge is estimated to generally diminish in depth by 1 to 2 ft (0.3 to 0.6 m) for every mile (1.6 km) that it moves inland. Even if the inland elevation were only 4 to 6 ft (1.2 to 1.8 m) above mean sea level, a storm surge of 20 ft (6 m) might typically reach no more than 7 to 10 miles (11 to 16 km) inland. Thus, the most destructive effect of the storm surge hazard is on beaches and offshore islands.

Storm Surge Hazards. A storm surge can be deadly. In 1900, up to 12,000 deaths occurred in Galveston, Texas, primarily as a result of the storm surge that was associated with a Gulf of Mexico hurricane. In 1957, a storm surge was the major cause of death for 390 people in Louisiana. The storm surge, associated with hurricane Audrey, was over 12 ft (3.5 m) in depth and extended as far inland as 25 miles (40 km) in this particularly low-lying region. In September 1928, the waters of Lake Okeechobee, FL driven by hurricane winds, overflowed the banks of the lake and were the main cause of more than 1800 deaths.

Areas to be evacuated due to storm surge in the case of hurricane landfall are determined through a model developed by the National Weather Service (NWS) called SLOSH (sea, lake, and overland surges from hurricanes; Jarvinen and Lawrence, 1985). The SLOSH model is used to define flood-prone areas in 31 "SLOSH basins" along the U.S. Gulf of Mexico and Atlantic coasts (Fig. 2). Determination of storm surge vulnerabilities is the result of an interagency and intergovernmental process funded by the National Oceanic and Atmospheric Administration (NOAA), the Federal Emergency Management Agency (FEMA), Army Corps of Engineers, and various state and local governments (BTFFDR, 1995). From development through application the SLOSH process for a particular location takes about 2 years. Because coastlines are constantly changing due to human and natural forces, the SLOSH process is an ongoing challenge.

Winds

The strong winds of a hurricane can produce considerable structural damage and risk to life from flying debris, even inland from the coast. The damage caused by hurricane Andrew was predominantly due to wind. Although winds reduce after landfall, as the central pressure increases, and the intensity of the storm lessens, destructive winds can still occur far inland.

The damage from winds is proportional to the energy of the airflow, i.e., to the velocity squared; thus, a wind of 100 mph is four times as effective at causing damage as a wind of 50 mph. Maximum gusts, of course, are even stronger than reported sustained winds (which are measured in the United States by averaging wind speed over 1 min). In a hurricane over the open ocean at about 36 ft (11 m) a gust averaged over 2 s is generally about 25% greater than the 1 min average. For flat grassland, the 2-s speed is around 35% larger, while in woods or cities, this measure of gust speeds is 65% greater. Thus a 1 min average wind of 100 mph would be expected to have gusts to 125 mph over the ocean and 165 mph over a forest.

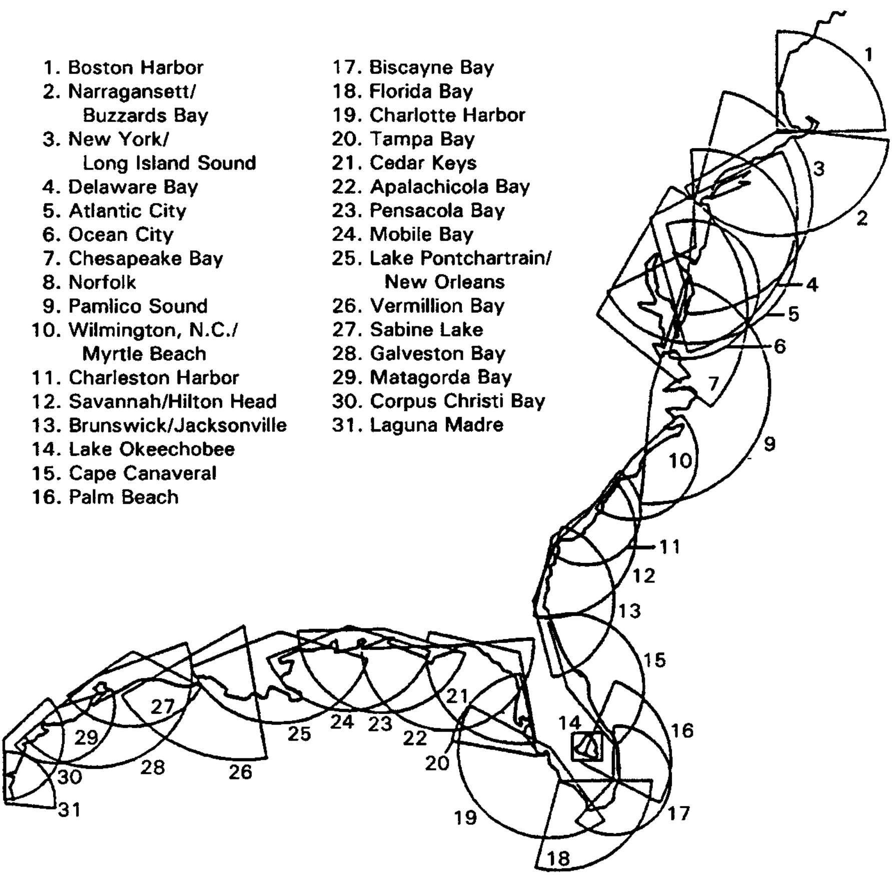

Figure 2 The 31 SLOSH basins along the U.S. Gulf and Atlantic coasts.

Rainfall. Rainfall from hurricanes is beneficial to agriculture, such as the rains from hurricane Dolly (1995) in southern Texas and northeastern Mexico that relieved a drought (Rippey, 1997; cf. Sugg, 1967). Even relatively weak tropical-like disturbances can result in extreme rainfall, as seen, for example, over coastal Texas in September 1979 in which upwards of 19 inches (483 mm) of rain inundated the area over a period of several days (Bosart, 1984). Occasionally, for reasons not completely understood, rainfall is light in the vicinity of hurricanes. Hurricane Inez in 1966, for instance, resulted in only a few drops of rain in Miami for several hours when the center was south and south-southwest of Miami and at its closest point to the city. At the time, Miami was under the storm and, normally, torrential rains would have been expected. As a result of the absence of rain, the strong winds blew salt spray many miles inland, causing severe damage to vegetation from salt accumulation. Homestead Air Force Base, south of Miami and closer to the path traveled by the hurricane's center, received only 0.62 inches (15.7 mm) of rain during the entire storm.

Tornadoes. Tornadoes are also a threat from tropical cyclones. Much of the damage of Andrew was associated with tornadic vortices whose wind speeds were added onto the large-scale hurricane winds (Black and Wakimoto, 1994). These rapidly rotating small-scale vortices are spawned in squalls, usually in the front right quadrant of the storm with respect to the storm's track.

Wind damage and tornadoes also can occur well inland associated with tropical cyclones. In 1959, hurricane Gracie caused 12 deaths in central Virginia 24 h after landfall on the South Carolina coast. Hurricane Hugo in 1989 caused significant damage in Charlotte, North Carolina, after landfall.

Inland Impacts

Inland, away from the coast, the largest threat to life and property occurs as a result of flash flooding and large-scale riverine flooding from excessive rainfall. Particularly dangerous are tropical cyclones whose rainfall is initially light and benign after landfall only to erupt a couple of days later into torrential downpours when the environment becomes favorable for precipitation of the large quantities of tropical moisture that have moved inland with the storm.

A particularly extreme example of such a system is hurricane Camille of 1969. After killing 139 people along the Gulf coast on August 17, the storm rapidly weakened after moving inland across Mississippi, into Tennessee and Kentucky. There was relatively little concern expressed by the National Weather Service and certainly no hint of the tragedy that was to happen on the night of August 19, 1969, in central Virginia. The 24-h and 12-h precipitation forecasts for the area, for example, indicated that only slightly more than 2 inches (50 mm) were expected. In fact, a deluge occurred in one part of Virginia as the remnants of Camille began to rejuvenate through interaction with a cold front and when the associated moist tropical air was lifted by the mountains. The rainfall of almost 30 inches (760 mm) in 6 h liquefied soils on the mountainous slopes and flooded drainage basins, burying and drowning 109 individuals. As a result of this tragedy, a radar site was installed in southern Virginia. One of the justifications of the new National Weather Service U.S. Doppler radar network (the WSR-D-88 system) is to detect heavy rainfall events.

Such excessive rains well inland from landfalling tropical cyclones should be expected occasionally as occurred over Georgia associated with tropical storm Alberto in 1994. The environment of a storm is a localized region of the atmosphere that is enriched with water vapor, well in excess of even the average tropical environment. After landfall, this rich reservoir of moisture moves inland and can be copiously precipitated when it is lifted through a mechanism such as a mountain barrier and/or ascent over a weather front. Hurricane Agnes in 1972, for instance, produced enormous rainfalls over large areas of the middle Atlantic states because of strong large-scale atmospheric lifting and the movement of the moist air up and over the Appalachian mountains, resulting in disaster.

Even snowfall has been reported to be associated with the inland portion of a hurricane circulation. In 1963, hurricane Ginny left more than 14 inches (36 cm) of snow in northern Maine as the hurricane moved into Nova Scotia with winds of around 100 mph (45 m/s).

Societal Impacts

When they strike the U.S. coast, hurricanes cost lives and dollars and disrupt communities. Category 3, 4, and 5 storms—intense hurricanes—are responsible for more than 80% of hurricane-related damages. Loss of life, however, occurs from storms of various intensities. Due largely to better warning systems, hurricane-related loss of life has decreased dramatically in the twentieth century (NRC 1989). Yet, in spite of reduced hurricane-related casualties "-a large death toll in a U.S. hurricane is still possible. The decreased death totals in recent years may be as much a result of lack of major hurricanes striking the most vulnerable areas as they are of any fail-proof forecasting, warning, and observing systems" (Hebert et al., 1993, p. 14).

While loss of life has decreased, the economic and social costs of hurricanes are large and rising. A rough calculation shows that annual losses to hurricanes have been in the billions of dollars. In the United States alone, after adjusting for inflation, tropical cyclones were responsible for an annual average of $1.6 billion for the period 1950 to 1989, $2.2 billion over 1950 to 1995, and $6.2 billion over 1989 to 1995 (Hebert et al., 1996). For a comparison, China suffered an average $1.3 billion (unadjusted) in damages related to typhoons over the period 1986 to 1994 (World Meteorological Organization, various years). Significant tropical cyclone damages are also experienced by other countries including those in East Asia (including Japan, China, and Korea) and Southeast Asia, those along the Indian Ocean (including Australia, Madagascar, and the southeast African coast), islands of the Caribbean, and in Central America (including Mexico). While a full accounting of global damages has yet to be documented and made accessible, it is surely in the tens of billions of dollars annually. Other estimates range to $15 billion annually (e.g., Southern, 1992).

Experts have estimated that tropical cyclones result in approximately 12,000 to 23,000 deaths worldwide (Southern, 1992; Smith, 1992; Bryant, 1991). Tropical cyclones have been responsible for a number of the largest losses of life due to a natural disaster. For instance, in April 1991, a cyclone made landfall in Bangladesh resulting in the loss of more than 140,000 lives and disrupting more than 10 million people (and leading to $2 billion in damages; Southern, 1992). A similar storm resulted in the loss of more than 250,000 lives November 1970. China, India, Thailand, and the Philippines have also seen loss of life in the thousands in recent years.

While the hurricane threat to the U.S. Atlantic and Gulf coasts has been widely recognized, it has only been in recent years, following hurricane Andrew, that many public and private decision makers have sought to better understand the economic and social magnitude of the threat.

One study has sought to "normalize" U.S. hurricane damages to assess the impact that past storms would have had in 1995 (Pielke and Landsea, 1997). The study adjusted past damages to account for changes in population, inflation, and wealth. The study found a total of $366 billion in losses over the period 1925 to 1995, or about $5 billion annually. Interestingly, the normalized data show a trend of *decreasing* losses from the 1940s through the early 1990s, which is contrary to the non-normalized data (Figs. 3 and 4). This highlights the good fortune experienced by the U.S. with respect to hurricane landfalls in recent decades (Landsea et al., 1996).

6 CONCLUSION

Tropical cyclones affect hundreds of millions of people every year around the world. While the rainfall produced by these storms often provides valuable societal and environmental benefits, these storms also have the potential to inflict great harm and suffering. Recent history suggests that communities in the Atlantic basin have been fortunate in recent decades, due to an extended period of relatively fewer hurricanes (Landsea et al., 1996). However, simply because hurricanes have been depressed in

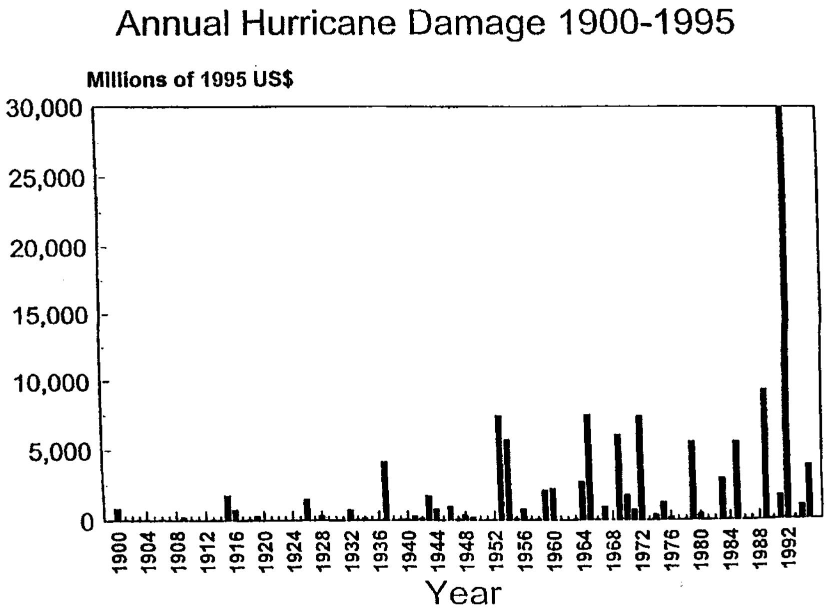

Figure 3 Inflation adjusted hurricane damages of the 20th century. (Pielke and Landsea, 1997).

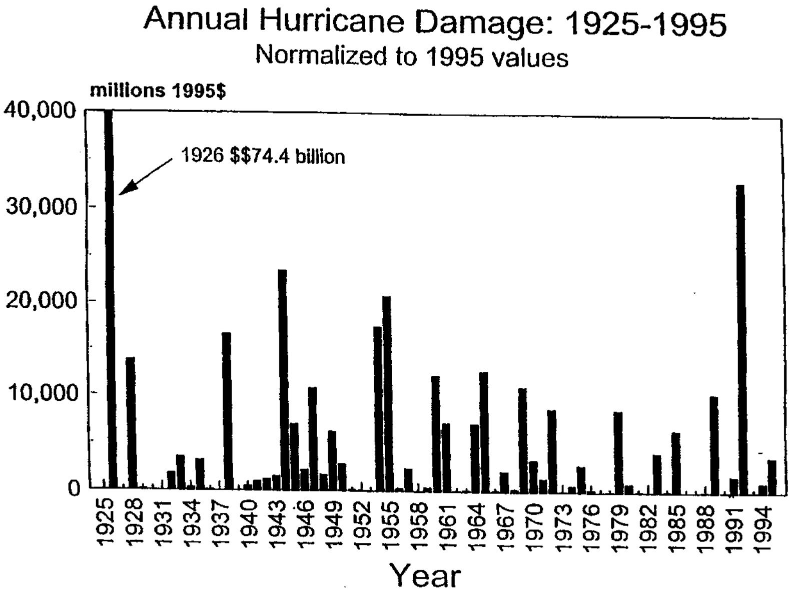

Figure 4 Hurricane damages adjusted for inflation, wealth, and population 1925 to 1995 (Pielke and Landsea, 1997).

recent decades does not eliminate the possibility of large impacts, as shown by hurricane Andrew, which occurred during the quietest 4-year period of hurricane activity since 1950. The $30 billion hurricane Andrew was the costliest tropical cyclone ever (Landsea et al., 1996; Pielke and Pielke, 1997).

Tropical cyclones occur every year around the world. In this most basic sense, they are "normal" climatological events on planet Earth. But from a human perspective, even a weak tropical cyclone can be an "extreme" occurrence. The challenge of effectively reducing societal vulnerability to hurricanes is made more difficult by the relative infrequency with which storms affect particular communities. Consider that the last major hurricane to strike Dade County, Florida, prior to Andrew was in 1950! Thus, one important step any decision maker should take is to understand the risks and potential consequences of choices made in tropical cyclone-prone regions. Damaging losses associated with tropical cyclones can never be eliminated, but with close attention to those factors that increase our vulnerability—where we live, how we live, etc.—we can hope to live in greater harmony with one of nature's most powerful forces.

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