TROPICAL CYCLONES
Their Evolution, Structure and Effects

Richard A. Anthes

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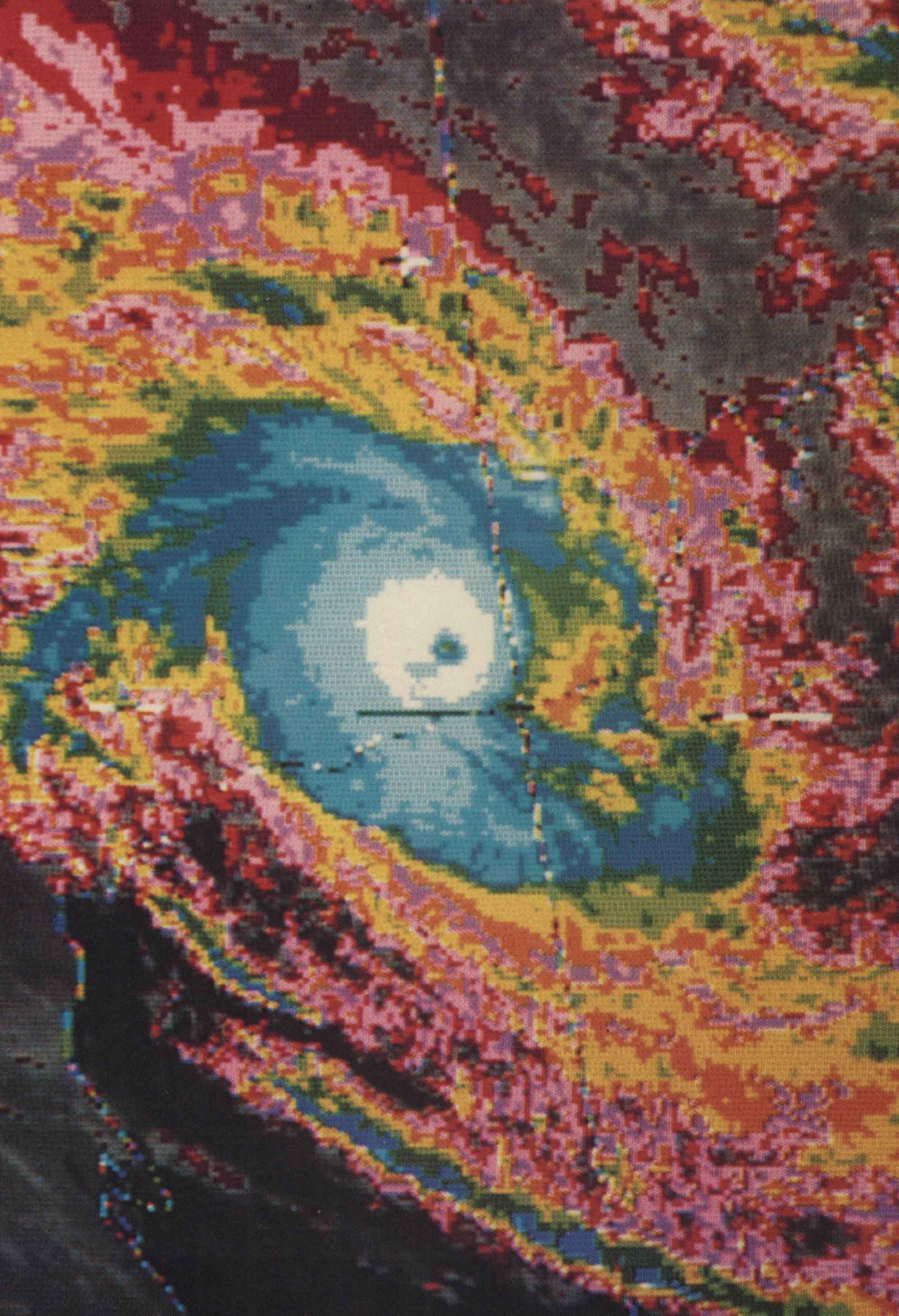
"Then up and spake an old sailor,
had sailed the Spanish Main,
'I pray thee, put into yonder port,
for I fear a hurricane.
Last night the moon had a golden ring,
and tonight no moon we see!'
The skipper, he blew a whiff from his pipe
and a scornful laugh laughed he."

Longfellow,
The Wreck of the Hesperus

Frontispiece

Infrared photograph of Tropical Cyclone Amy going inland near Port Hedland, Australia, at 0600 GMT 9 January 1980. The central pressure was about 915 mb. The color scale is in 7°C intervals and ranges from black (temperature greater than 30°C) to white (temperatures less than −80°C). Photograph supplied by Gordon J. Bell, Royal Observatory, Hong Kong.



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CHAPTER 1

Introduction

Conceived over warm tropical oceans, born amid torrential thundershowers, and nurtured by water vapor drawn inward from far away, the mature tropical cyclone is an offspring of the atmosphere with both negative and positive consequences for life. Severe cyclones are among the most destructive of all natural disasters, capable of annihilating coastal towns and killing hundreds of thousands of people. On the positive though less dramatic side, they provide essential rainfall over much of the lands they cross. Smaller than extratropical cyclones which are spawned by and follow the perturbations in the westerly flow in middle latitudes, hurricanes are associated with violent winds near the center (by definition at least 32 m s^{-1} or 115 km h^{-1}) and copious rainfall amounts. The highest sustained (1 min average) winds ever recorded were 88 m s^{-1} (317 km h^{-1}) in Hurricane Inez of 1966 (Colon, 1966). Maximum gusts have exceeded 100 m s^{-1} (360 km h^{-1}). In most storms, however, the maximum sustained wind speed is approximately 50 m s^{-1} (180 km h^{-1}).

It is difficult to convey to those who have never experienced a tropical cyclone the horror that great hurricanes can bring to ships at sea or people living near the coast. In *Early American Hurricanes,* David Ludlum (1963) has assembled a comprehensive list of accounts of hurricanes affecting the Atlantic, Caribbean and Gulf of Mexico from 1492–1870. One summary, written by Major General Vaughan of *The Great Hurricane* of October 1780, describes the desolation and misery brought by this storm to the sugar island of Barbados (Ludlum, 1963, p. 69):

> "I am much concerned to inform your Lordship, that this island was almost entirely destroyed by a most violent hurricane, which began on Tuesday the 10th instant, and continued almost without intermission for nearly forty-eight hours. It is impossible for me to attempt a description of the storm; suffice it to say, that few families have escaped the general ruin, and I do not believe that 10 houses are saved in the whole island: scarse a house is standing in Bridgetown; whole families were buried in the ruins of their habitations; and many, in attempting to escape, were maimed and disabled: a general convulsion of nature seemed to take place, and an universal destruction ensured. The strongest colours could not paint to your Lordship the miseries of the inhabitants: on the one hand, the ground covered with the mangled bodies of their friends and relations, and on the other, reputable families, wandering through the ruins, seeking for food and shelter: in short, imagination can form but a faint idea of the horrors of this dreadful scene."

Writing of the same storm, the governor of Barbados described the devastating loss of property, livestock and trees (Ludlum, 1963, p. 70):

> "Anxiously did they wait the break of day, flattering themselves, that with the light they would see a cessation of the storm; yet when it appeared, little was the tempest abated, and the day served but to exhibit the most melancholy prospect imaginable; nothing can compare with the terrible devastation that presented itself on all sides; not a building standing; the trees, if not torn up by their roots, deprived of their leaves and branches; and the most luxuriant spring changes in this one night to the dreariest winter. In vain was it to look round for shelter; houses, that from their situation it was to have been imagined would have been in a degree protected, were all flat with the earth, and the miserable owners, if they were so fortunate as to escape with their lives, were left without a covering for themselves and family."

In the same account, the governor made an interesting statement that seemed to value some human lives above others:

> "It is as yet impossible to make any accurate calculation of the number of souls that have perished in this dreadful calamity; whites and blacks together, it is imagined to exceed some thousands, *but fortunately few people of consequences are among the number.*"

Not all hurricanes are accompanied by lightning and thunder, but those that do contain special horrors. At the age of 15, Alexander Hamilton lived through a hurricane that struck St. Croix Island in the West Indies on September 6, 1772. In a letter to his father, Hamilton wrote (Hughes, 1976):

> "Good God! what horror and destruction! It is impossible for me to describe it or for you to form any idea of it. It seemed as if a total dissolution of nature was taking place. The roaring of the sea and wind, fiery meteors flying about in the air, the prodigious glare of almost perpetual lightning, the crash of falling houses, and the earpiercing shrieks of the distressed were sufficient to strike astonishment into Angels. A great part of the buildings throughout the island are levelled to the ground; almost all the rest very much shattered, several persons killed and numbers utterly ruined—whole families roaming about the streets, unknowing where to find a place of shelter—the sick exposed to the keenness of water and air, without a bed to lie upon, or a dry covering to their bodies, and our harbors entirely bare. In a word, misery, in its most hideous shapes, spread over the whole face of the country."

Terrifying as it must be to experience a hurricane on land, nothing can compare to the desolation felt by those unlucky enough to be caught at sea. Columbus, who had unusually good luck in avoiding tropical cyclones during his first three voyages, was not so fortunate on his fourth. Caught in a hurricane-force wind near the present entrance to the Panama Canal, Columbus wrote of the despair of those caught in the maelstrom of wind, rain and lightning (Ludlum, 1963, p. 7):

> The tempest arose and wearied me so that I knew not where to turn; my old wounds opened up, and for nine days I was as lost without hope of life; eyes never beheld the seas so high, angry and covered by foam. The wind not only prevented our

progress, but offered no opportunity to run behind any headland for shelter; hence we were forced to keep out in this bloody ocean, seething like a pot on a hot fire. Never did the sky look more terrible; for one whole day and night it blazed like a furnace, and the lightning broke forth with such violence that each time I wondered if it had carried off my spars and sails; the flashes came with such fury and frightfulness that we all thought the ships would be blasted. All this time the water never ceased to fall from the sky; I don't say it rained, because it was like another deluge. The people were so worn out that they longed for death to end their suffering."

Much of the early knowledge about hurricanes came from William Redfield (1789–1852) who compiled notes from ships' logs and other sources and deduced both the rotary nature of the winds around a center and the concept that the whole storm system translated along a regular path. In his first paper, published in 1831, Redfield made his classic conclusion following his study of the Long Island, NY Hurricane of 1821:

"In reviewing these facts, we are led to inquire how, or in what manner it could happen, that the mass of atmosphere should be found passing over Middletown for some hours, with such exceeding swiftness, toward a point apparently within thirty minutes distance, and yet never reach it; but a portion of the same or a similar mass of air, be found returning from that point with equal velocity? And how were all the most violent portions of these atmospheric movements which occurred at the same point of time, confined within a circuit whose diameter does not appear to have greatly exceeded one hundred miles? To the writer there appears but one satisfactory explication of these phenomena. *This storm was exhibited in the form of a great whirlwind."* (Redfield, 1831)

In the same year of Redfield's historic paper, Lt. Col. William Reid investigated the Great Barbados Hurricane of 1831. In later years, Reid studied individual storms and compared his findings with Redfield's. Another early meteorologist who made important contributions to the understanding of hurricanes was James Espy, who recognized the release of latent heat as the source of the storm's energy (Espy, 1841).

Tropical cyclones are known by different names in different parts of the world. In the Atlantic and eastern Pacific they are called "hurricanes," a name which comes from an ancient tribe of aborigines in Central America known as the Tainos. For the Tainos, "Huracan" was a "God of Evil," and from him the tropical storm acquired its name. In the western Pacific hurricanes are known as "typhoons," in the Philippines as "bagiuos," a named derived from the city of Baguio in the Philippine Islands where 46 inches (116.8 cm) of rain fell in a 24 h period in July, 1911 (Huschke, 1959). Contrary to popular opinion outside of Australia, they are not known as "willy-willies" in Australia. "Willy-willies" instead refer to small dust storms.

The naming of hurricanes is a common practice in parts of the world in order to facilitate communication and warnings. For many years hurricanes over the Caribbean were named in Spanish after the Saints. Until 1978, hurricanes in the Atlantic and typhoons in the Pacific were given women's names; but in response to complaints about sexual bias men's names are now used as well.

TABLE 1.1. Natural disasters (1964–1978) (Compiled from Encyclopaedia Britannica by Southern, 1979).

Disaster	Total deaths in 14 years	Greatest single event
Tropical cyclones	416 972	300 000 (Bangladesh, 1970)
Earthquakes and tidal waves	195 328	66 794 (Peru, 1969)
Floods	26 724	8000 (S. Vietnam, 1964)
Tornadoes, severe local storms	4062	540 (Bangladesh, 1969)
Avalanches and landslides	5790	1450 (Peru, 1974)
Volcanic eruptions	2572	2000 (Zaire, 1973)
Extratropical cyclones	1860	166 (USA, 1966)
Heat (cold) waves	505	291 (India, 1973)

The 80–100 tropical cyclones that occur each year cause an average number of 20 000 deaths and a total economic loss of $6–7 billion (Southern, 1979). Table 1.1 compares the deaths caused by tropical cyclones with deaths caused by other natural disasters during the period 1964–78 as chronicled in the annual books of Encyclopaedia Britannica (Southern, 1979). Tropical cyclones were far ahead of any other disaster as killers, accounting for about 64% of the total lives lost. Individual tropical cyclones are capable of causing catastrophic losses of life, as shown in Table 1.2.

TABLE 1.2. Deaths in tropical cyclone/flood catastrophes (Southern, 1979).

Year		Cyclone	Flood
1281	Kyushu-Japan	100 000	
1642	Kaifong-China		300 000
1737	Calcutta	300 000	
1851–66	Yangtze R.		40–50 million
1876	Chittagong	300 000	
1881	Haiphong-Vietnam	300 000	
1882	Bombay	100 000	
1887	Yangtze R.		1.5 million
1911	Yangtze R.		100 000
1915	Canton		100 000
1931	Hwang Ho R.		3–4 million
1931	Yangtze R.		140 000
1939	China		200 000
1970	Bangladesh	300 000	
1971	N. Vietnam		100 000

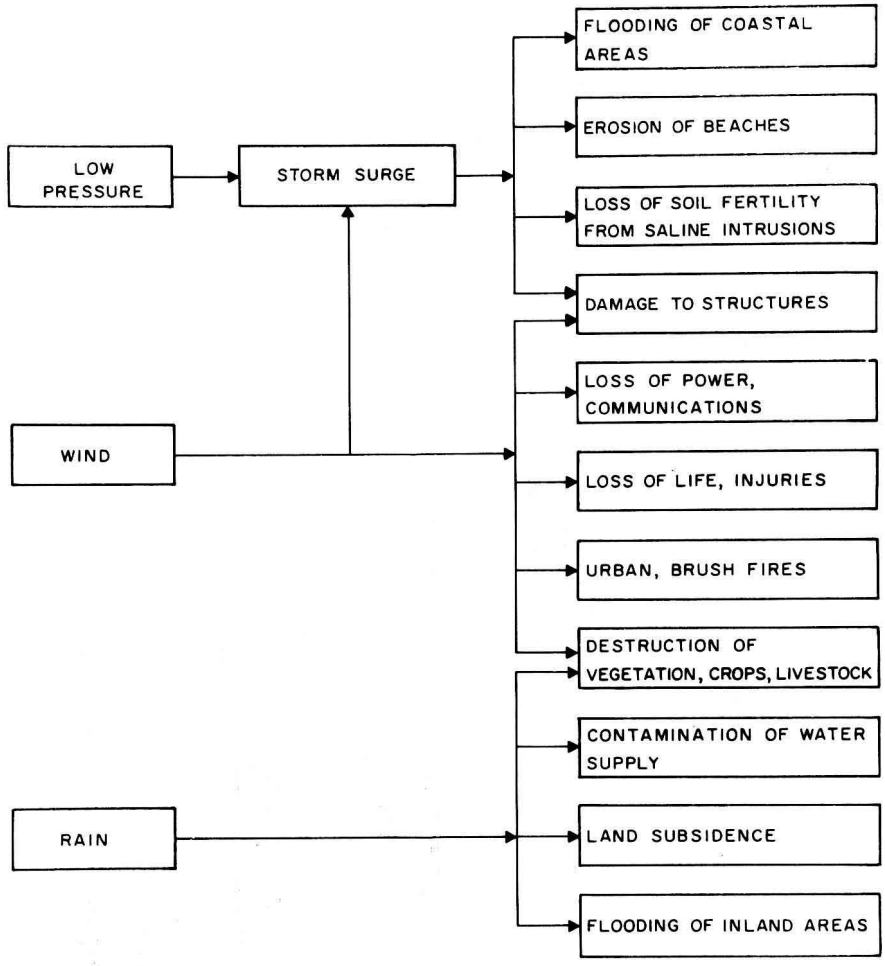

FIG. 1.1. Types of potential damage accompanying tropical cyclones (Southern, 1979).

Tropical cyclones cause a variety of damage, as indicated in Fig. 1.1. The major causes of damage are the strong winds, storm surges and heavy precipitation. The property damage caused by the wind alone varies primarily with the quality of the construction and the maximum speed of the wind. Fig. 1.2 shows the increase of damage as a function of maximum gust velocity, for buildings in Australia (Leicester and Beresford, 1978). The damage index, which is the ratio of the repair cost to the initial cost of the building (assuming constant building cost), increases nonlinearly with the wind speed. For the estimates in Fig. 1.2, the damage increases approximately as the cube of the wind speed. While even minimal hurricane wind speeds can cause property damage, especially to construction of low quality, most [90% in the United States according to the American Meteorological Society (1973)] of the

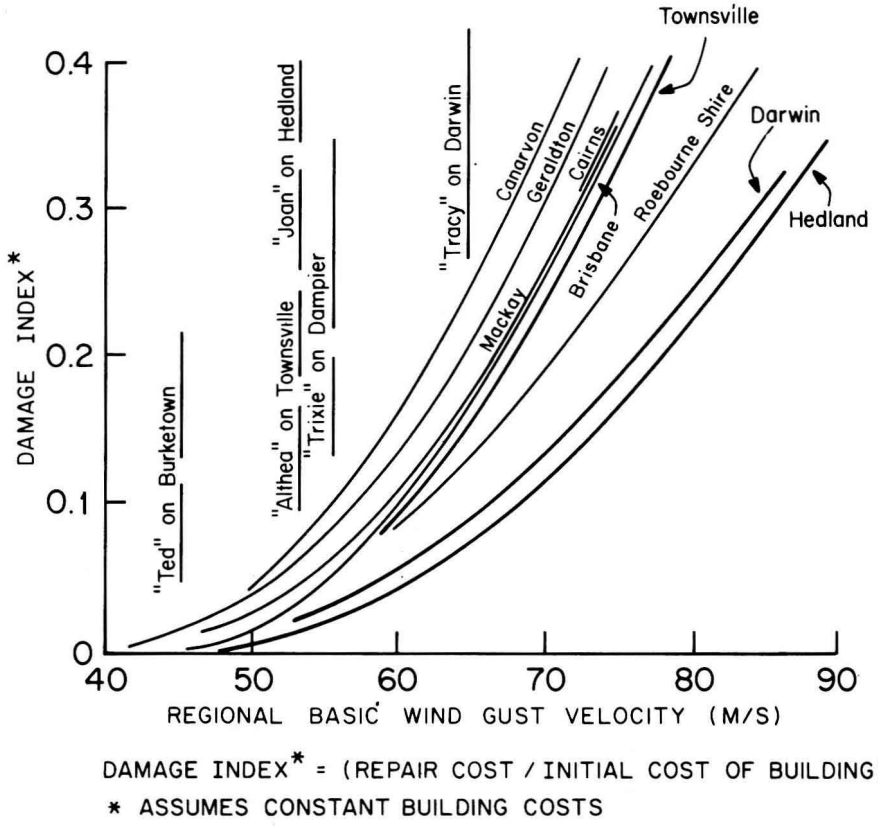

FIG. 1.2. Damage index (repair cost/initial cost of building) (Leicester and Beresford, 1978). Assumes constant building costs.

damage associated with tropical cyclones as they make landfall is caused by the storm surge. The storm surge is a rapid increase in sea level along the coast and is caused primarily by the winds driving the water ashore. Rises of several meters are not uncommon, while in extreme cases the rise may be 10 meters. One of the worst tropical cyclone disasters, which occurred in Bangladesh on 13 November 1970, was caused primarily by a storm surge estimated between 6 and 9 meters. In this cyclone, between 200 000 and 300 000 people were drowned. This exceptional surge was not because the cyclone was near-record intensity, in fact, its minimum pressure was only around 950 mb. This value is considerably higher than the lowest pressures recorded in tropical cyclones (Table 1.3) and higher than the value of 930 mb in the 31 October 1876 "bakergani" cyclone which killed 100 000 to 400 000 people (*Mariners Weather Log,* 1971). What made the 1970 cyclone so devastating was that it made landfall at almost exactly the same time of high tide. In addition to the storm surge, flooding was caused by over 25 cm of rain falling over the flat region. The enormous