

CHAPTER 39

TROPICAL CYCLONES

DESCRIPTION AND CAUSES

3900. Introduction

Tropical cyclone is a general term for a cyclone originating over the tropical oceans, although technical definitions differ across the globe. Over the North Atlantic, and eastern North Pacific Oceans, for example, a tropical cyclone is defined by the National Hurricane Center (NHC) as “a warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center.” Similar definitions are in use by the various global operational forecast centers.

For access to the *Glossary of NHC Terms* see the link provided in Figure 3900.



Figure 3900. Link to the *Glossary of NHC Terms*.
<http://www.nhc.noaa.gov/aboutgloss.shtml>

Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at high temperature and heat export at the low temperatures of the upper atmosphere. In this they differ from the extratropical cyclones of higher latitudes, which derive their energy from horizontal temperature contrasts in the atmosphere. As a result of their different energy sources, tropical cyclones tend to be more circularly symmetric than extratropical cyclones, tend to be smaller, and have their fiercest winds and rains located closer to the area of lowest pressure. Tropical cyclones are infrequent in comparison with middle- and high-latitude storms, but they have a record of destruction far exceeding that of any other type of storm. Because of their fury, and because they are predominantly oceanic, they merit special attention by mariners. The rapidity with which the weather can deteriorate with approach of the storm, and the violence of the fully developed tropical cyclone are difficult to imagine if they have not been experienced.

On his second voyage to the New World, Columbus

encountered a tropical storm. Although his vessels suffered no damage, this experience proved valuable during his fourth voyage when his ships were threatened by a fully developed hurricane. Columbus read the signs of an approaching storm from the appearance of a southeasterly swell, the direction of the high cirrus clouds, and the hazy appearance of the atmosphere. He directed his vessels to shelter. The commander of another group, who did not heed the signs, lost most of his ships and more than 500 men perished.

3901. Definitions

Tropical cyclones are classified by the intensity of their highest associated winds, usually measured by a 1-minute or a 10-minute average. The following terms apply in the North Atlantic and eastern North Pacific Oceans:

- (1) Tropical depression - a tropical cyclone in which the maximum sustained (1-minute mean) surface wind speed is 33 kts or less.
- (2) Tropical storm - a tropical cyclone in which the maximum sustained (1-minute mean) surface wind speed ranges from 34 to 63 kts.
- (3) Hurricane - a tropical cyclone in which the maximum sustained (1-minute mean) surface wind is 64 kts or more.
- (4) Major hurricane - a tropical cyclone in which the maximum sustained (1-minute mean) surface wind is 96 kts or more.

When cyclones no longer possess sufficient tropical characteristics to be considered a tropical cyclone, they may be referred to as “post tropical.” These cyclones may continue to produce heavy rains, high winds, and large seas. A remnant low is a post-tropical cyclone that no longer possesses the convective organization required of a tropical cyclone and has maximum sustained winds of less than 34 knots.

Other terms are used globally. In the western North Pacific, **typhoon** is synonymous with the Atlantic term hurricane, while **super typhoon** refers to a **tropical cyclone** with maximum sustained winds of 130 kts or more. In the Philippines, a typhoon is also known as a **bagyo**. In the North Indian Ocean, a tropical cyclone with winds of 34

knots or greater is called a **cyclonic storm**, while in the South Indian Ocean, a tropical cyclone with winds of 34 knots or greater is called a **cyclone**. A severe tropical cyclone originating in the Timor Sea and moving southwest and then southeast across the interior of northwestern Australia is called a **willy-willy**.

The term **tropical disturbance** refers to a discrete system of apparently organized convection, generally 100 to 300 miles in diameter, having a non-frontal migratory character, and must have maintained its identity for 24 hours or

more. These systems generally do not have strong winds or closed isobars (i.e., isobars that completely enclose the low). Tropical disturbances can develop into tropical cyclones.

3902. Areas of Occurrence

Tropical cyclones occur almost entirely in six distinct areas: the North Atlantic Ocean (including the Caribbean Sea and Gulf of Mexico), the eastern North Pacific (includ-

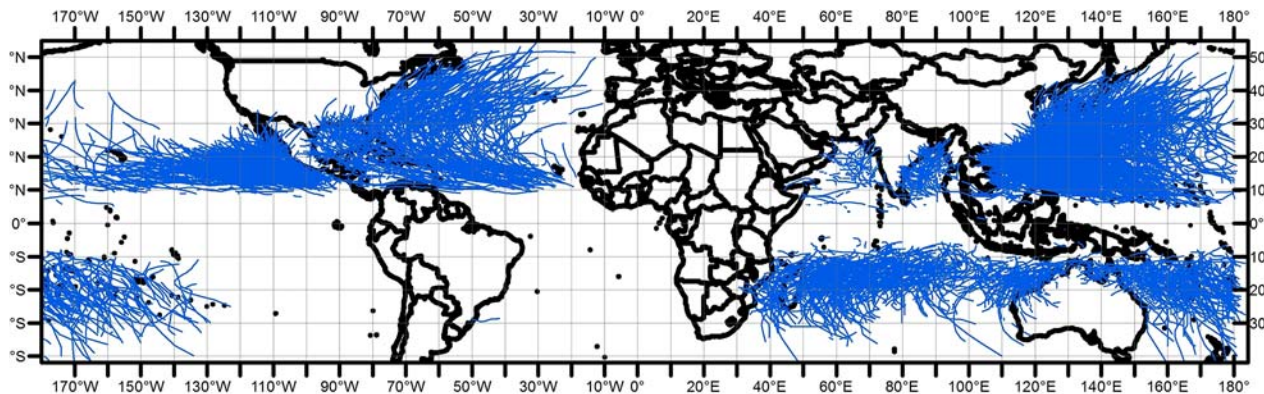


Figure 3902a. Tracks of all tropical cyclones with maximum 1-minute mean wind speed of 34 kts or greater during the period 1981-2010 (data sources National Hurricane Center, Central Pacific Hurricane Center, Joint Typhoon Warning Center; image credit Colorado State University).

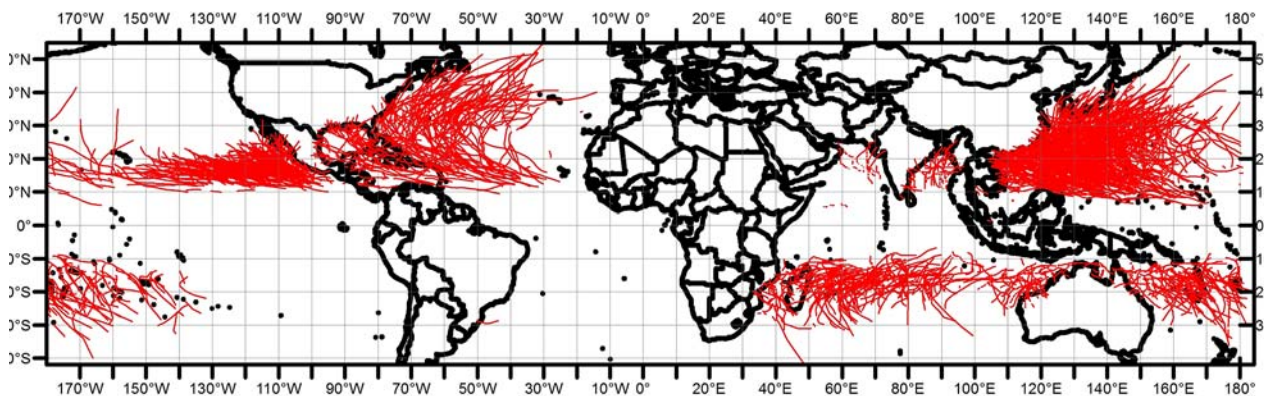


Figure 3902b. Tracks of all tropical cyclones with maximum 1-minute mean wind speed of 64 kts or greater during the period 1981-2010 (sources National Hurricane Center, Joint Typhoon Warning Center and Colorado State University).

ing the central North Pacific to the Date Line), the western North Pacific, the North Indian Ocean (including the Bay of Bengal and the Arabian Sea), the south Indian Ocean, and the Southwest Pacific/Australia area. The south Atlantic Ocean is nearly devoid of tropical cyclones, and none have been observed in the South Pacific east of 120°W. Figure 3902a shows the global tracks of all tropical cyclones of at least tropical storm strength during the period 1981-2010, while Figure 3902b shows the global track of all tropical

cyclones of hurricane strength during the same period.

3903. Origin, Season and Frequency

Table 3903 describes the frequency of formation for tropical cyclones of tropical storm and hurricane intensity in each of the six primary tropical cyclone basins worldwide. The general character of each basin's activity is described below.

North Atlantic: Tropical cyclones have formed in every month of the year; however, they are mostly a threat south of about 35°N from June through November, the official months of the Atlantic hurricane season. August, September, and October are the months of highest incidence. About 12 tropical storms form each season, and roughly 6 reach hurricane intensity. Early and late-season storms usually develop west of 50°W, although during August and September the spawning ground extends to the Cape Verde Islands. In the lower latitudes, tropical cyclones typically move westward or west-northwestward at speeds of less than 15 knots. After moving into the northern Caribbean Sea or near the Greater Antilles, they usually either move toward the Gulf of Mexico or recurve and accelerate northeastward in the North Atlantic. Some will recurve after reaching the Gulf of Mexico, while others will continue westward to a landfall in Texas, Mexico,

or central America.

Eastern North Pacific: The official season runs from May 15th through the end of November, although a storm can form in any month of the year. An average of 17 tropical cyclones forms annually in this basin, with about 9 typically reaching hurricane strength. The most intense storms are often the late-season ones; these can form close to the coast and relatively far to the south. Mid-season storms form anywhere in a wide band from the Mexican coast to the Hawaiian Islands. August and September are the months of highest incidence. Although eastern North Pacific storms are often smaller than their North Atlantic counterparts, they can be just as intense (and in fact the strongest tropical cyclone on record in the western hemisphere, 2015's Hurricane Patricia, formed in this basin).

Western North Pacific: More tropical cyclones form

AREA AND STAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
NORTH ATLANTIC													
TROPICAL STORMS				0.1	0.1	0.6	1.0	3.2	4.1	2.1	0.7	0.1	12.1
HURRICANES						0.1	.05	1.6	2.6	1.2	0.5		6.4
EASTERN NORTH PACIFIC													
TROPICAL STORMS					0.7	1.9	3.5	4.3	3.7	2.2	0.3	0.1	16.6
HURRICANES					0.3	0.8	1.8	2.1	2.5	1.3	0.2		8.9
WESTERN NORTH PACIFIC													
TROPICAL STORMS	0.4	0.2	0.4	0.7	1.2	1.6	3.7	5.8	5.0	3.8	2.6	1.4	26.6
TYPHOONS	0.2		0.2	0.4	0.7	1.0	2.2	3.5	3.4	2.9	1.6	0.7	16.7
SOUTHWEST PACIFIC AND AUSTRALIAN AREA													
TROPICAL STORMS	3.5	3.8	3.2	1.7	0.3	0.1				0.2	0.5	2.2	15.6
HURRICANES	1.5	1.9	2.0	1.0	0.1						0.3	1.2	8.0
SOUTH INDIAN OCEAN													
TROPICAL STORMS	2.7	2.5	2.0	1.2	0.4	0.1	0.2	0.1	0.3	0.5	1.2	1.4	12.5
HURRICANES	1.5	1.5	1.3	0.7	0.2					0.1	0.6	0.6	6.6
NORTH INDIAN OCEAN													
TROPICAL STORMS	0.1	0.1		0.2	0.8	0.6	0.1		0.3	1.0	1.3	0.6	4.9
CYCLONES				0.1	0.4	0.1				0.1	0.6	0.2	1.6

Table 3903. Monthly and annual numbers of tropical cyclones formed for each major cyclone basin for the period 1981-2010. For all basins, tropical storm refers to systems with maximum 1-minute sustained winds of 34 kts or greater, and hurricane refers to systems with maximum 1-minute sustained winds of 64 kts or greater (sources National Hurricane Center, Joint Typhoon Warning Center and Colorado State University).

in the tropical western North Pacific than in any other global tropical cyclone basin. On average, more than 25 tropical storms develop annually, and about 17 reach hurricane (typhoon) strength. Western North Pacific typhoons are the largest and most intense tropical cyclones in the world. An average of five generate maximum winds over 130 knots annually, and cyclonic circulations of more than 600 miles in diameter are not uncommon. Most of these storms form east of the Philippines, and move across the Pacific toward the Philippines, Japan, and China; a few storms form in the South China Sea. The primary season extends from April through December, although off-season formations are more common in this area than in any other basin. The peak of the season is July through October, when nearly 70 percent of all typhoons develop. The basin features a noticeable seasonal shift in storms; July through September storms tend to move north of the Philippines and recurve, while early- and late-season typhoons typically take on a more westerly track through the Philippines before recurving. Because of

their relative high frequency, it is not uncommon for one tropical cyclone to be influenced by a nearby cyclone, an interaction that often produces very erratic tracks for both systems.

North Indian Ocean—Tropical cyclones develop in the Bay of Bengal and Arabian Sea during the spring and fall. Tropical cyclones in this area form between latitudes 8°N and 15°N, except from June through September, when the little activity that does occur is confined north of about 15°N. Although these storms are usually short-lived and weak, winds of 130 knots or more have been encountered. North Indian Ocean cyclones often develop as disturbances within the monsoon trough, which inhibits summertime development since the monsoon trough is usually over land during the monsoon season. However, the trough is sometimes displaced southward, and when this occurs storms will form over the monsoon-flooded plains of Bengal. On average, about five tropical storms form each year, with about two reaching hurricane strength. Within the basin, the

Bay of Bengal is the area of highest incidence. It is not unusual for a storm to move across southern India and re-intensify in the Arabian Sea, and this is particularly true during October and November, the months of highest incidence. It is also during this period that torrential rains from these storms, dumped over already rain-soaked areas, are most likely to cause disastrous floods.

South Indian Ocean—Over the waters west of 100°E to the east African coast, an average of 11 tropical storms form each season, with about 4 reaching hurricane intensity. The season is from December through March, although it is possible for a storm to form in any month. Tropical cyclones in this region usually form south of 10°S. The latitude of re-curve usually migrates from about 20°S in January to around 15°S in April. After crossing 30°S, these storms sometimes become intense extratropical lows.

Southwest Pacific and Australian Area—These

tropical waters spawn an annual average of 15 tropical storms, of which 4 reach hurricane intensity. The main season extends from about December through April, although storms can form in any month. Activity is widespread in January and February, and it is in these months that tropical cyclones are most likely to affect Fiji, Samoa, and the other eastern islands. Tropical cyclones usually form in the waters from 105°E to 160°W, between 5° and 20°S. Storms affecting northern and western Australia often develop in the Timor or Arafura Sea, while those that affect the east coast form in the Coral Sea. These storms are often small, but can develop winds in excess of 130 knots. New Zealand is sometimes reached by decaying Coral Sea storms, and occasionally by an intense hurricane. In general, tropical cyclones in this region move southwestward and then recurve southeastward.

TROPICAL CYCLONE BASICS

3904. Formation

Tropical cyclones form from pre-existing disturbances that are typically convective cloud clusters associated with a low-level cyclonic vorticity maximum, such as a tropical wave (although tropical cyclones can also form from non-tropical precursor disturbances, such as old frontal boundaries or upper-level lows). Low-level vorticity maxima are also areas of low pressure at the surface, and due to the pressure gradient force, air will flow inward toward the low pressure area. As a result of the Coriolis force, the inward-flowing air is deflected to the right (left in the Southern Hemisphere) and this creates a counter-clockwise (clockwise in the Southern Hemisphere) circulation. The inflow of air produces low-level convergence that in turn results in rising motion and deep convection (showers and thunderstorms) near the area of lowest pressure. The tropical cyclone is essentially a heat engine, with the heat source being the underlying ocean. Water vapor from the ocean condenses in rising columns of air, releasing the latent heat of condensation. In these near-saturated air columns, which ultimately become the eyewall and rain bands of the cyclone, the latent heating is offset by adiabatic cooling. Unsaturated air sinks in the eye, and adiabatic warming of the subsiding air results, through hydrostatic balance, in a fall in central pressure and an intensification of the cyclonic circulation.

The development and intensification of a tropical cyclone requires an unstable air mass and a deep layer of moist air extending through the middle troposphere. Atmospheric instability is required to produce deep convection, which produces the latent heating. Although it had been previously thought that sea surface temperatures of at least 79-80 degrees Fahrenheit were a necessary condition, tropical cyclone formation has been observed over waters in the

low 70s. This implies that the vertical lapse rate, i.e., the change of temperature with height, can be large enough to provide the needed instability even over cooler waters. A deep layer of humid air is needed to prevent the development of cold downdrafts, which would result in low-level divergence that would disrupt the development process. An additional requirement is that the vertical wind shear, i.e., the change of the wind with height, be sufficiently low, say less than 15 to 20 kts from the surface to the upper troposphere. Strong shear would significantly tilt the developing vortex from the vertical and this loss of vertical coherence of the circulation prevents intensification. The environmental factors needed for tropical cyclone formation are met over much of the tropical oceanic regions, including the Atlantic, Caribbean Sea, Gulf of Mexico, the Northern Hemispheric Pacific, the waters around Australia, and both the Northern and Southern Hemispheric Indian Ocean.

3905. Structure

Figure 3904 shows an idealized cross-section through a mature hurricane. The overall cyclonic circulation in the lower troposphere can vary greatly in expanse, but is typically a few hundred miles in diameter. The extent of hurricane-force winds outward from the center can also vary greatly, with diameters ranging from no more than 20 miles to 200 miles or more. The cyclonic spiral is marked by heavy cloud bands from which torrential rains fall, separated by areas of light rain or no rain at all. These spiral bands ascend in decks of cumulus and cumulonimbus clouds to the convective limit of cloud formation, where condensing water vapor is swept off as ice-crystal wisps of cirrus clouds.

In the lower few thousand feet, the cyclonic flow has a net component toward the center, which drives ascent with-

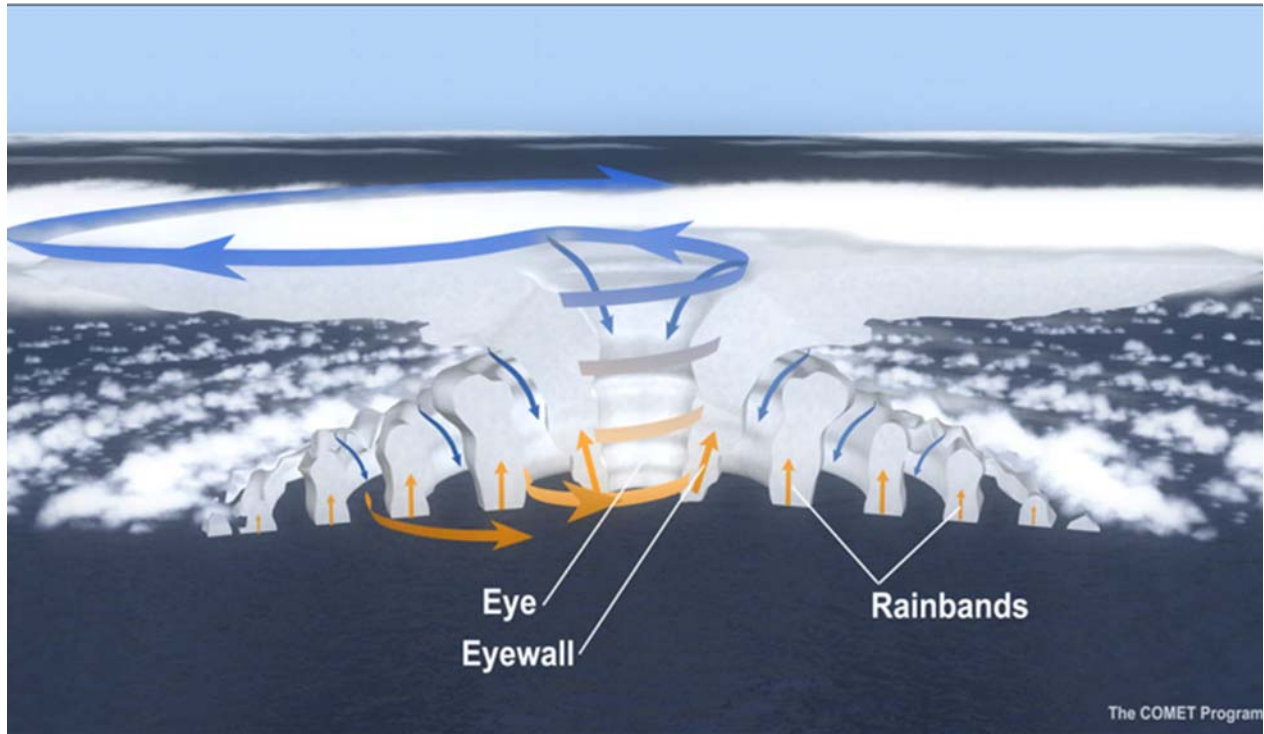


Figure 3904. Schematic cross-section of a mature hurricane. Used with permission of © UCAR/COMET Program.

in the eyewall and convective rainbands. Compensating downdrafts occur in the moat regions in between rainbands and in the eye, which at upper levels becomes much warmer than the surrounding air, and in the near environment of the cyclone. The intensity of the cyclonic flow is strongest just above the boundary layer, generally 1500-3000 feet in altitude, decreasing below that level due to surface friction and above that level because of the warm-core nature of the tropical cyclone. The cyclonic convergent flow through most of the troposphere becomes gradually replaced above 40,000 feet by anticyclonic divergent flow, which serves as the exhaust system of the hurricane heat engine. A satellite view of Hurricane Wilma (2005) is shown Figure 3905.

At the surface, winds generally increase inward as the eyewall is approached, although the increase is uneven, with stronger winds occurring within the rainbands and lighter winds in between them. In the eyewall, the typical mature hurricane is more likely to have sustained winds of 100-130 kts; however, sustained surface winds in excess of 180 kts have been recorded by remote sensing instruments onboard hurricane hunter aircraft. The winds then decrease to a near calm within the eye.

The diameter of the relatively calm eye can vary widely. In some of the most violent tropical cyclones, the eye might be just a few miles across, while in others the calm central region might cover 60-100 miles. Eye diameters of 15-30 miles are common. From the heated tower of maximum winds and cumulonimbus clouds, winds diminish rapidly to something less than 15 miles per hour in the eye; at the opposite wall, winds increase again, but come from

the opposite direction because of the cyclonic circulation of the storm. This sudden transformation of storm into comparative calm, and from calm into violence from another quarter is spectacular. The eye's abrupt existence in the midst of opaque rain squalls and hurricane winds, the intermittent bursts of blue sky and sunlight through light clouds in the core of the cyclone, and the galleried walls of cumulus and cumulonimbus clouds are unforgettable.

3906. Life Cycle

It is important to remember that tropical cyclones vary widely in nearly all their various aspects, and this is also true of their life cycle. Most take days or a week to evolve from a disorganized cluster of thunderstorms to hurricane strength, but this transition has also occurred in less than a day (e.g., 2007's Atlantic Hurricane Humberto). Once formed, a tropical cyclone may maintain itself in that status for as little as a day or as long as a month.

In this prototypical example, the precursor disturbance is a tropical wave that moves from Africa over the tropical Atlantic. The wave, or surface trough of low pressure, typically moves westward at 15 to 20 kts, with maximum winds of 20-30 kts (although some fast-moving tropical waves can have winds of 30-45 kts - these would not be considered tropical cyclones because they lack a closed surface circulation). If the environmental conditions are suitable, convective bands become organized into bands and pressure begins to fall, eventually causing west winds to develop to the south of a developing closed

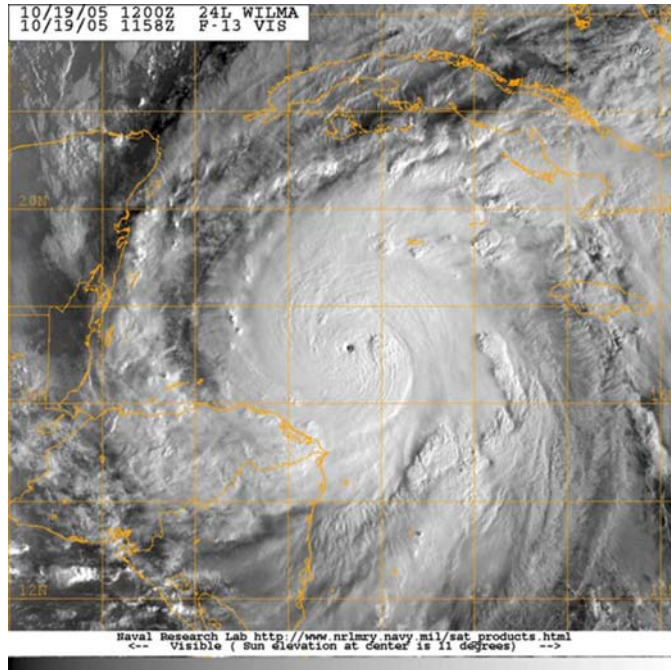


Figure 3905. Visible satellite image of 2005 Atlantic Hurricane Wilma (image courtesy Naval Research Laboratory)

low center, which marks the formation of a tropical cyclone.

Over the next several days, as the newly formed tropical depression moves west-northwestward, intensification occurs, at a rate largely governed by environmental factors that include vertical wind shear, ambient moisture, and sea-surface temperature. Large-scale weather features in the environment, such as the subtropical ridge or approaching mid-latitude troughs in the middle and upper troposphere, determine how far west the cyclone progresses before it begins to move out of the tropics. Within a few days the depression has become a hurricane, and may be approaching the North American continent or be moving through the Lesser or Greater Antilles. As it strengthens, the size of the cyclonic circulation and area of tropical storm force winds generally expands.

Once the hurricane begins to move out of the tropics, interactions with mid-latitude features increase. Typically, the cyclone will turn to the north (poleward) and often reaches its peak intensity near the most westernmost point in its track (the point of recurvature). After this, the mature hurricane usually encounters stronger wind shear and decreasing sea-surface temperatures below and may begin to interact with frontal systems. The cyclone turns northeastward and weakens while its circulation expands. The defining tropical characteristics of deep convection, strong pressure gradient and winds near the center, and warm core diminish as the system accelerates into the mid-latitudes, and the system either transitions to an extratropical low or becomes absorbed into one. See Figure 3906.

3907. Hazards

The high winds of a tropical cyclone inflict widespread damage when such a storm leaves the ocean and crosses land. Aids to navigation may be blown out of position or destroyed. Craft in harbors, often lifted by the storm surge, break moorings or drag anchor and are blown ashore and against obstructions. Ashore, trees are blown over, houses are damaged, power lines are blown down, etc. In a well-developed hurricane, the greatest damage usually occurs in the **right semicircle** a short distance from the center in the **eyewall**, where the strongest winds occur. As the storm continues on across land, its fury subsides faster than it would if it had remained over water. Wind gusts over water are usually 20-25% higher than the 1-minute mean winds. Higher gust ratios occur over land.

Tropical cyclones have produced some of the world's heaviest rainfalls. While average amounts range from 6 to 10 inches, totals near 100 inches over a 4-day period have been observed. A 24-hour world's record of 73.62 inches fell at Reunion Island during a tropical cyclone in 1952. Forward movement of the storm and land topography have a considerable influence on rainfall totals. Torrential rains can occur when a storm moves against a mountain range; this is common in the Philippines and Japan, where even weak tropical depressions produce considerable rainfall. A 24-hour total of 46 inches was recorded in the Philippines during a typhoon in 1911. As the remnants of Hurricane Camille crossed southern Virginia's Blue Ridge Mountains in August of 1969, there was nearly 30 inches of rain in about 8 hours. This caused some of the most disastrous floods in the state's history. In 2001, Tropical

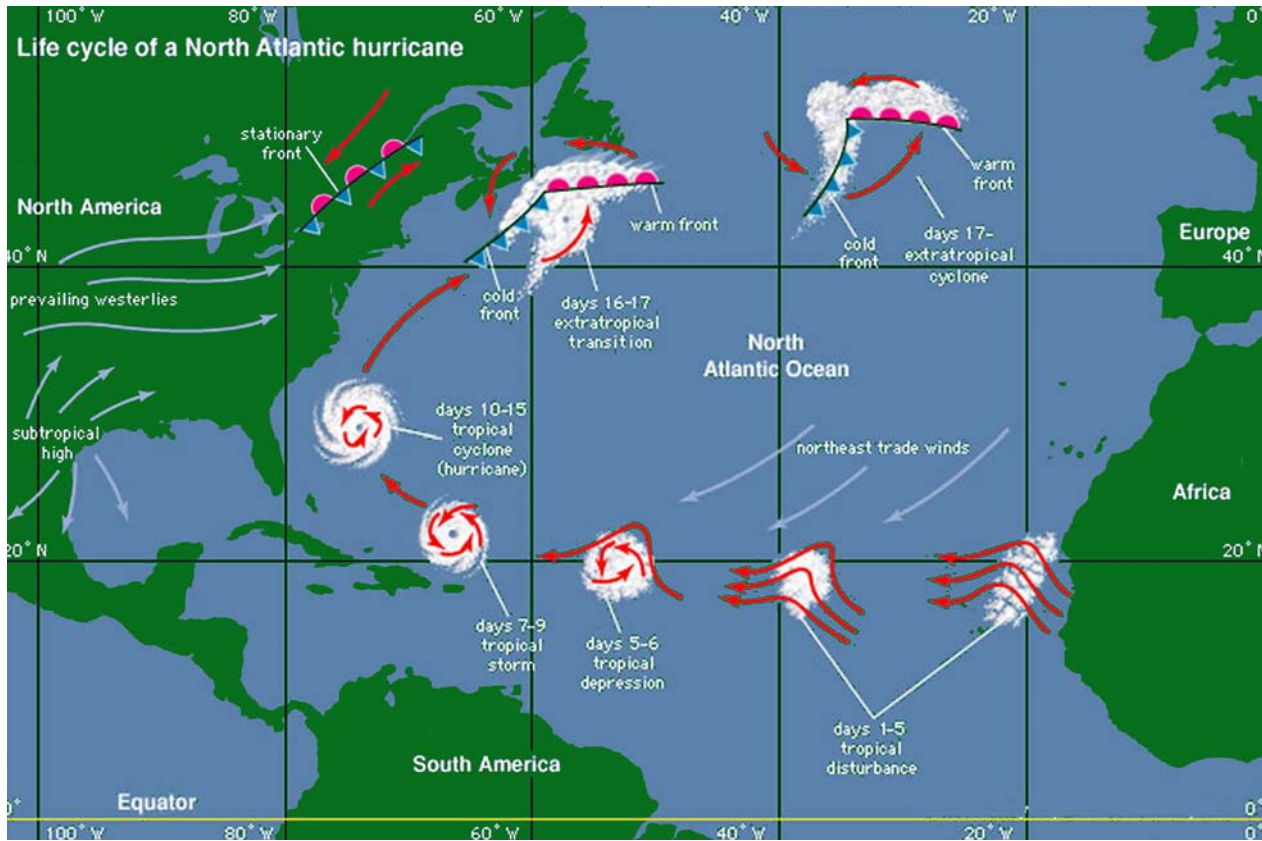


Figure 3906. Hurricane life cycle for the North Atlantic.

Storm Allison produced more than 30 inches of rain in the Houston, Texas area.

Flooding is an extremely destructive by-product of the tropical cyclone's torrential rains. Whether an area will be flooded depends on the physical characteristics of the drainage basin, rate and accumulation of precipitation, and river stages at the time the rains begin. When heavy rains fall over flat terrain, the countryside may lie under water for a month or so, and while buildings, furnishings, and underground power lines may be damaged, there are usually few fatalities. In mountainous or hill country, disastrous floods develop rapidly and can cause a great loss of life.

There have been reports in tropical cyclones of waves of up to 80 feet in height (e.g., Atlantic Hurricane Ivan in 2004) and numerous reports in the 30- to 40-foot category. However, in tropical cyclones, strong winds rarely persist for a sufficiently long time or over a large enough area to permit enormous wave heights to develop. The direction and speed of the wind changes more rapidly in tropical cyclones than in extratropical storms. Thus, the maximum duration and fetch for any wind condition is often less in tropical cyclones than in extratropical storms and the waves accompanying any given local wind condition are generally not so high as those expected with similar local wind conditions in the high-latitude storms. In Hurricane

Camille (1969), significant waves of 43 feet were recorded; an extreme wave height reached 72 feet.

Exceptional conditions may arise when waves of certain dimensions travel within the storm at a speed equal to the storm's speed, thus, in effect, extending the duration and fetch of the wave and significantly increasing its height. This occurs most often to the right of the track in the Northern Hemisphere (left of the track in the Southern Hemisphere). Another condition that may give rise to exceptional wave heights is the intersection of waves from two or more distinct directions. This may lead to a zone of confused seas in which the heights of some waves will equal the sums of each individual wave train. This process can occur in any quadrant of the storm, so it should not be assumed that the highest waves will always be encountered to the right of the storm track in the Northern Hemisphere (left of the track in the Southern Hemisphere).

When these waves move beyond the influence of the generating winds, they become known as **swell**. They are recognized by their smooth, undulating form, in contrast to the steep, ragged crests of wind waves. This swell, particularly that generated by the right side of the storm, can travel a thousand miles or more and may produce tides 3 or 4 feet above normal along several hundred miles of coastline. It may also produce tremendous surf over offshore reefs that normally are calm.

When a tropical cyclone moves close to a coast, wind often causes a rise in water level along the coast known as **storm surge**. This surge is usually confined to the right of the track in the Northern Hemisphere (left of the track in the Southern Hemisphere) or to areas with prolonged periods of onshore flow. It most often occurs with the approach of the storm, but in some cases, where a surge moves into a long channel, the effect may be delayed. Occasionally, the greatest rise in water is observed on the opposite side of the track, when northerly winds funnel into a partially land-locked harbor. The surge could be 3 feet or less, or it could be 20 feet or more, depending on the combination of factors involved. Factors that determine the amount of storm surge include the local bathymetry and topography, the intensity of the cyclone, the size of the wind field, and the forward speed and direction of motion of the cyclone. The highest storm surges are caused by a slow-moving tropical cyclone of large diameter because both of these effects result in greater duration of wind in the same direction. The effect is greatest in a partly enclosed body of water, such as the Gulf of Mexico, where the concave coastline does not readily permit the escape of water. It is least on small islands, which present little obstruction to the flow of water.

A hurricane's storm surge has occasionally been described as a wall of water that moves rapidly toward the coastline. Authenticated cases of such a rapid rise are rare, but regardless, some of the world's greatest natural disasters have occurred as a result of storm surge. In India, such a disaster occurred in 1876, between Calcutta and Chittagong, and drowned more than 100,000 persons.

There have been many instances of **tornadoes** occurring within the circulation of tropical cyclones. Most of

these have been associated with tropical cyclones of the North Atlantic Ocean and have occurred in the West Indies and along the gulf and Atlantic coasts of the United States. They are usually observed in the forward semicircle or along the advancing periphery of the storm. These tornadoes are usually short-lived and less intense than those that occur in the Midwestern United States. In 2004, Hurricane Ivan was associated with 117 tornadoes.

When proceeding along a shore recently visited by a tropical cyclone, a navigator should remember that time is required to restore aids to navigation which have been blown out of position or destroyed. In some instances, the aid may remain but its light, sound apparatus, or radio beacon may be inoperative. Landmarks may have been damaged or destroyed and in some instances the coastline and hydrography *may be changed*.

3908. Saffir-Simpson Hurricane Wind Scale

The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained winds (see Table 3908). This scale estimates potential shore side property damage and is provided here in Bowditch as a reference for mariners.

Hurricanes reaching Category 3 and higher are considered major hurricanes because of their potential for significant loss of life and property damage. Category 1 and 2 storms are still dangerous and require preventative measures. In the Western Pacific, the term "*super typhoon*" is used for tropical cyclones with sustained winds exceeding 150 mph.

Category	Sustained Winds	Description
1	74-95 mph	Very dangerous winds will produce some damage: Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph	Extremely dangerous winds will cause extensive damage: Well-constructed frame homes could sustain major roof, shingles, and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3	111-129 mph	Devastating damage will occur: Well-built framed homes may incur major damage or removal or roof, decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.

Table 3908. Saffir-Simpson Hurricane Wind Scale.

Category	Sustained Winds	Description
4	130-156 mph	Catastrophic damage will occur: Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5	157 mph or higher	Catastrophic damage will occur: A high percentage of framed houses will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

Table 3908. Saffir-Simpson Hurricane Wind Scale.

3909. A Tropical Cyclone Encounter from the Mariner's Perspective

An early indication of the approach of a **tropical cyclone** is the presence of a long **swell**. In the absence of a tropical cyclone, the crests of swell in the deep waters of the Atlantic pass at the rate of perhaps eight per minute. Swell generated by a hurricane is about twice as long, the crests passing at the rate of perhaps four per minute. Swell may be observed several days before arrival of the storm.

When the storm center is 500 to 1,000 miles away, the barometer usually rises a little, and the skies are relatively clear. **Cumulus** clouds, if present at all, are few in number and their vertical development appears suppressed. The barometer usually appears restless, pumping up and down a few hundredths of an inch.

As the tropical cyclone comes nearer, a cloud sequence begins (Figure 3909) that resembles what is typically associated with the approach of a warm front in middle latitudes. Snow-white, fibrous "**mare's tails**" (cirrus) appear when the storm is about 300 to 600 miles away. Usually these seem to converge, more or less, in the direction from which the storm is approaching. This convergence is particularly apparent at about the time of sunrise and sunset.

Shortly after the cirrus appears, but sometimes before, the barometer starts a long, slow fall. At first the fall is so gradual that it only appears to alter somewhat the normal daily cycle (two maxima and two minima in the Tropics). As the rate of fall increases, the daily pattern is completely lost in the more or less steady fall.

The cirrus becomes more confused and tangled, and then gradually gives way to a continuous veil of **cirrostratus**. Below this veil, **altostratus** forms, and then **stratocumulus**. These clouds gradually become more dense, and as they do so, the weather becomes unsettled. A fine, mist-like rain begins to fall, interrupted from time to time by rain showers. The barometer has fallen perhaps a tenth of an inch.

As the fall becomes more rapid, the wind increases in

gustiness and its speed becomes greater, reaching perhaps 22 to 40 knots (**Beaufort** 6-8). On the horizon appears a dark wall of heavy **cumulonimbus**, called the **bar of the storm**. This is the heavy bank of clouds comprising the main mass of the cyclone. Portions of this heavy cloud become detached from time to time, and drift across the sky, accompanied by rain squalls and wind of increasing speed. Between squalls, the cirrostratus can be seen through breaks in the stratocumulus.

As the bar approaches, the barometer falls more rapidly and wind speed increases. The seas, which have been gradually mounting, become tempestuous. Squall lines, one after the other, sweep past in ever increasing number and intensity.

With the arrival of the bar, the day becomes very dark, squalls become virtually continuous, and the barometer falls precipitously, with a rapid increase in wind speed. The center may still be 100 to 200 miles away in a fully developed tropical cyclone. As the center of the storm comes closer, the ever-stronger wind shrieks through the rigging and about the superstructure of the vessel. As the center approaches, rain falls in torrents. The wind fury increases. The seas become mountainous. The tops of huge waves are blown off to mingle with the rain and fill the air with water. Visibility is virtually zero in blinding rain and spray. Even the largest and most seaworthy vessels become virtually unmanageable and may sustain heavy damage. Less sturdy vessels may not survive. Navigation virtually stops as safety of the vessel becomes the only consideration. The awesome fury of this condition can only be experienced. Words are inadequate to describe it.

If the **eye of the storm** passes over the vessel, the winds suddenly drop to a breeze as the wall of the eye passes. The rain stops, and the skies clear sufficiently to permit the sun or stars to shine through holes in the comparatively thin cloud cover. Visibility improves. Mountainous seas approach from all sides in complete confusion. The barometer reaches its lowest point, which may be 1.5 or 2 inches below normal in fully developed tropical cyclones. As the wall on the opposite side of the eye arrives, the full fury of



Figure 3909. Typical cloud structures associated with a tropical cyclone.

the wind strikes as suddenly as it ceased, but from the opposite direction. The sequence of conditions that occurred during approach of the storm is reversed, and passes more

quickly, as the various parts of the storm are not as wide in the rear of a storm as on its forward side.

TROPICAL CYCLONE FORECASTS

3910. Tropical Cyclone Forecasts

Forecasting the path of tropical cyclones has advanced tremendously over the past several decades, as has the sophistication of the guidance products generated by operational forecast centers worldwide. The **World Meteorological Organization (WMO)** recognizes several **Regional Specialized Meteorological Centers (RSMCs)** with responsibility for issuing tropical cyclone forecasts and warnings. Products from these centers are the most important tools for avoiding tropical cyclones. These RSMCs and their areas of responsibilities (Figure 3910a) are outlined below.

Caribbean Sea, Gulf of Mexico, North Atlantic and eastern North Pacific Oceans: **RSMC Miami** - NOAA/NWS National Hurricane Center, USA. See Figure 3910b for a link to current forecasts from the RSMC Miami.

Central North Pacific Ocean: **RSMC Honolulu** - NOAA/NWS/Central Pacific Hurricane Center, USA. See Figure 3910c for a link to current forecasts from the RSMC Honolulu.

Western North Pacific Ocean and South China Sea: **RSMC Tokyo** - Typhoon Center/Japan Meteorological Agency. See Figure 3910d for a link to current forecasts

from the RSMC Tokyo.

Bay of Bengal and the Arabian Sea: **RSMC Tropical Cyclones New Delhi/India** Meteorological Department. See Figure 3910e for a link to current forecasts from the RSMC New Delhi.

South-West Indian Ocean: **RSMC La Reunion** - Tropical Cyclone Centre/Météo-France. See Figure 3910f for a link to current forecasts from the RSMC La Reunion.

South-West Pacific Ocean: **RSMC Nadi** - Tropical Cyclone Centre/Fiji Meteorological Service. See Figure 3910h for a link to current forecasts from the RSMC Nadi.

In addition, the following WMO-recognized **Tropical Cyclone Warning Centers (TCWC)** have regional forecast responsibilities:

South-East Indian Ocean: **TCWC-Perth**/Bureau of Meteorology (Western Australia region), Australia.

Arafura Sea and the Gulf of Carpentaria: **TCWC-Darwin**/Bureau of Meteorology, Australia.

Coral Sea: **TCWC-Brisbane**/Bureau of Meteorology, Australia. See Figure 3910i for a link to the Australian TCWCs. See Figure 3910g for a map depicting the Australian Bureau of Meteorology regions.

Solomon Sea and Gulf of Papua: **TCWC-Port Moresby**/National Weather Service, Papua New Guinea, (website under construction).

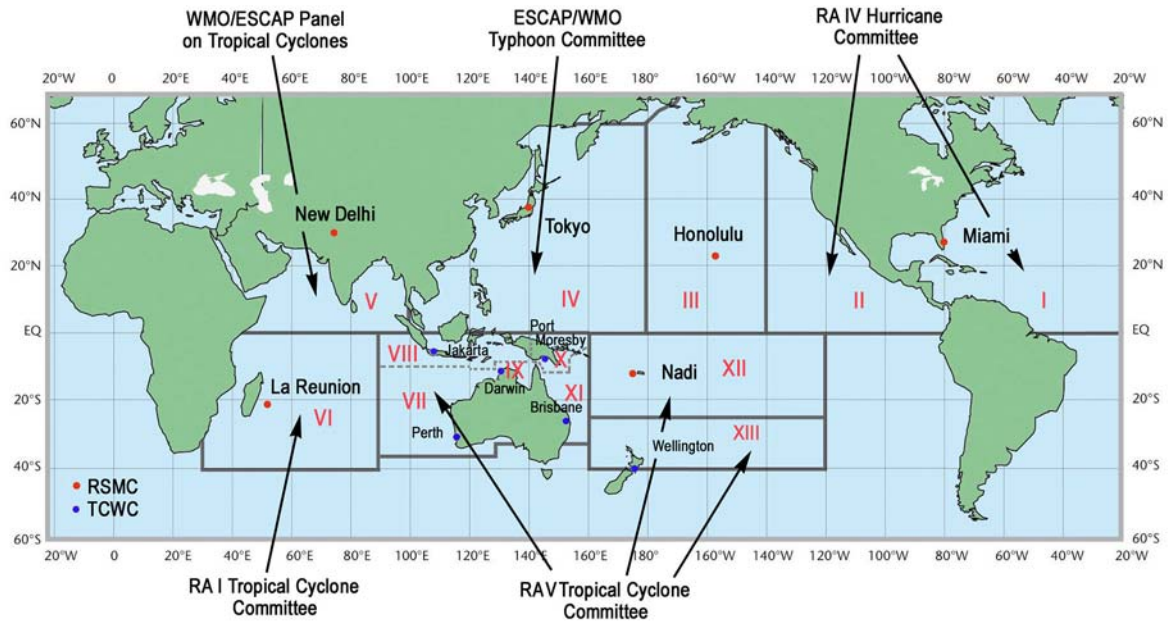


Figure 3910a. Location and area of responsibility for the WMO-recognized tropical cyclone Regional Specialized Meteorological Centers and Tropical Cyclone Warning Centers (WMO).

Tasman Sea: **TCWC-Wellington**/Meteorological Service of New Zealand, Ltd. See Figure 3910j for a link to current forecasts from the TCWC- Wellington.

TCWC-Jakarta/ Indonesian Meteorological and Geophysical Agency, Indonesia. See Figure 3910k for a link to current forecasts from the TCWC Jakarta.

And lastly, the **U.S. Joint Typhoon Warning Center** (<https://metoc.ndbc.noaa.gov/JTWC/>) provides certain products worldwide for use by U.S. government agencies. See Figure 3910l for a link to current forecasts from the JTWC.

For mariners lacking access to the internet, marine weather broadcasts and radio facsimile weather maps are an important source of information. In the Atlantic basin, the USCG broadcasts are available via high frequency (HF) voice from Chesapeake (NMN) and New Orleans (NMG). In the Pacific basin, HF voice broadcasts are made from Pt. Reyes (NMC), Kodiak (NOJ), Honolulu (NMO) and Guam (NRV). Some marine facsimile charts intentionally overlap basins with broadcasts on several frequencies from Boston (NMF), New Orleans (NMG), Kodiak (NOJ), Pt. Reyes (NMC), and Honolulu (KVM70). Other sources include VHF, HF Simplex Teletype Over Radio (SITOR) or Narrow Band Direct Printing (NBDP), Global Maritime Distress and Safety System (GMDSS) programs, Navigational Telex (NAVTEX) and amateur ham radio weather nets.

Faster computers, improvements in modeling, and increases in the amount of satellite-based atmospheric observations have resulted in greatly improved tropical cy-

clone track forecasts. Figure 3910m shows the progress made in predicting the path of tropical cyclones by the National Hurricane Center (RSMC-Miami); similar progress has been noted by other RSMCs. In the decade of the 1970s, the average 72-hour Atlantic basin tropical storm or hurricane forecast error was more than 350 nautical miles, but today that average error is only a little over 100 nautical miles.



Figure 3910b. RSMC Miami
<http://www.nhc.noaa.gov/index.shtml>



Figure 3910c. RSMC Honolulu
<http://www.prh.noaa.gov/cphc/>



Figure 3910d. RSMC Tokyo <http://www.jma.go.jp/en/typh/>



Figure 3910h. RSMC Nadi
http://www.met.gov.fj/current_warnings.php



Figure 3910e. RSMC Tropical Cyclones New Delhi/India
<http://www.imd.gov.in/>



Figure 3910i. TCWC Australia Bureau of Meteorology
<http://www.bom.gov.au/weather/cyclone/?ref=ifr>



Figure 3910f. RSMC La Reunion
<http://www.meteofrance.re/cyclone/activite-cyclonique-en-cours>



Figure 3910j. TCWC Wellington
http://www.metservice.co.nz/forecasts/severe_weather.asp

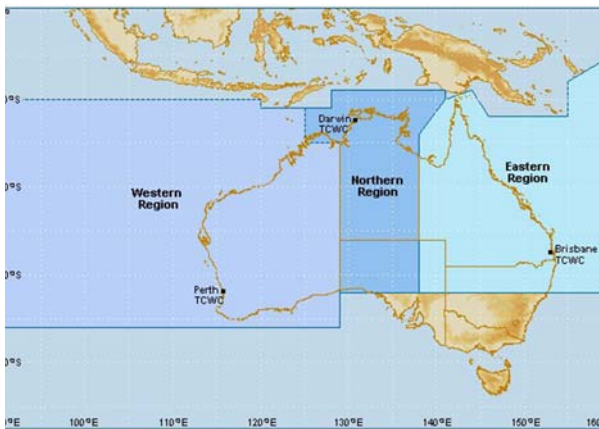


Figure 3910g. Australian Bureau of Meteorology regions.



Figure 3910k. TCWC Jakarta <http://www.bmkg.go.id/>



Figure 3910l. U.S. Joint Typhoon Warning Center.
<https://metoc.ndbc.noaa.gov/JTWC/>

This is not to say that such forecasts are without error; in the Atlantic basin 10% of the National Hurricane Center's 72-hr forecasts are currently off by 200 nautical miles or more. To help quantify forecast uncertainty in a manner

most helpful to users, many tropical cyclone forecasts are now expressed in a probabilistic framework mentioned in the following paragraphs.

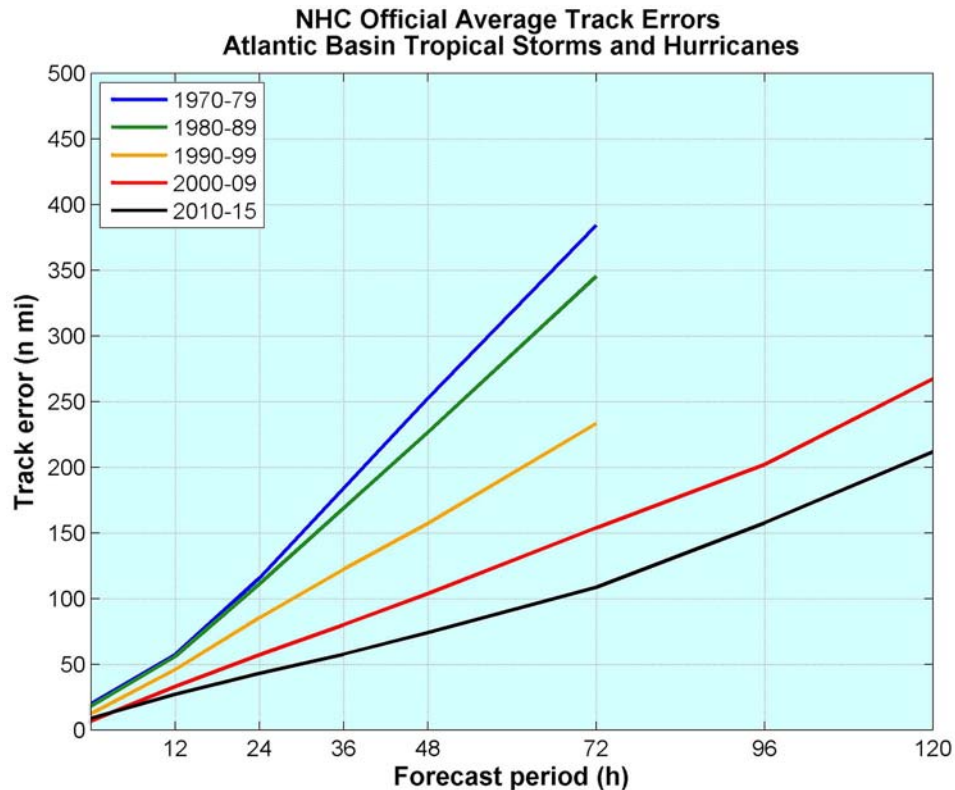


Figure 3910m. National Hurricane Center official track forecast accuracy for Atlantic basin tropical storms and hurricanes by decade.

3911. Tropical Cyclone Forecast Products

Each RSMC has its own collection of forecast and



Figure 3911a. Link to the NHC User's Guide for their tropical cyclone products.

http://www.nhc.noaa.gov/pdf/NHC_Product_Description.pdf

warning products. Responsible mariners will become familiar with the offerings of the RSMCs overseeing the areas in which they operate. Here, we discuss some of the tropical cyclone products prepared by the **National Hurricane**

Center (NHC). See Figure 3911a for a link to the User's Guide to tropical cyclone products prepared by the National Hurricane Center (NHC).

Whenever a tropical cyclone is active, the NHC issues tropical cyclone advisory packages comprising several official text and graphical products. This suite of advisory products is issued every 6 hours at 0300, 0900, 1500, and 2100 UTC. The primary text products are the **Public Advisory**, the **Forecast/Advisory**, the **Tropical Cyclone Discussion**, and the **Wind Speed Probability** product. Graphical products include the track forecast cone/watch-warning graphic, wind speed probability graphics, the maximum intensity probability table, the tropical cyclone wind field graphic, and a cumulative wind history graphic. A potential storm surge flooding map, tropical cyclone storm surge probabilities, and exceedance probability graphics are also issued with each advisory, whenever a hurricane watch or hurricane warning is in effect for any portion of the Gulf or Atlantic coasts of the continental United States

and on a case by case basis for tropical storm watches and warnings. When a tropical cyclone dissipates, advisories are discontinued. If a tropical cyclone becomes a post-tropical cyclone, NHC may continue issuing advisories if necessary to protect life and property.

The *Tropical Weather Outlook* discusses significant areas of disturbed weather and their potential for development into a tropical cyclone during the next 5 days, including a categorical forecast of the probability of tropical cyclone formation during the first 48 hours and during the entire 5-day forecast period. The 48 hour and 5-day probabilities of formation for each disturbance are given to the nearest 10% and expressed in terms of one of the following categories: low probability of development (0-30%), medium probability (40-60%), and high probability of development (70-100%). The Outlook also includes a general description of locations of any active cyclones during the first 24 hours of their existence. Tropical Weather Outlooks are issued every six hours from 1 June - 30 November for the Atlantic basin and from 15 May-30 November for the eastern North Pacific basin at 0000, 0600, 1200, and 1800 UTC.

The *Tropical Cyclone Public Advisory* is the primary tropical cyclone information product intended for a general audience. It provides critical tropical cyclone watch, warning, and forecast information for the protection of life and property. The Public Advisory has five sections:

1) This section contains the cyclone position in latitude and longitude coordinates, its distance from a well-known reference point, the maximum sustained winds, the cyclone's current direction and speed of motion, and the estimated or measured minimum central pressure.

2) A summary of all current coastal watches and warnings for the cyclone with recent changes to the watches and warnings highlighted at the top.

3) A discussion of the cyclone's current characteristics, including location, motion, intensity, and pressure and a general description of the predicted track and intensity of the cyclone over the next 24 to 48 hours. Any pertinent weather observations will also be included in this section.

4) A section that includes information on hazards to land such as storm surge/tide, wind, rainfall, tornadoes, and rip currents associated with the cyclone.

5) A section that states the time of the next advisory issuance.

Public Advisories are part of the suite of products issued for active cyclones every six hours at 0300, 0900, 1500, and 2100 UTC. When coastal watches or warnings are in effect, *Intermediate Public Advisories* are issued at 3-hour intervals between the regular *Public Advisories*. *Special Public Advisories* may be issued at any time to advise of an unexpected significant change in the cyclone or when watches or warnings for the United States are to be issued.

The *Tropical Cyclone Forecast/Advisory* (formerly known as the *Marine Advisory*) contains current and forecasted storm information. It contains a list of all current

coastal watches and warnings, cyclone position, intensity, and direction and speed of motion. It also includes the current maximum radial extent of 12-ft seas, as well as the maximum radial extent of winds of 34, 50, and 64 kt in each of four quadrants around the storm. The *Forecast/Advisory* contains quantitative forecast information on the track and intensity of the cyclone valid 12, 24, 36, 48, 72, 96, and 120 hours from the forecast's nominal initial time, with size information forecast out to 72 hours.

The *Forecast/Advisory* also contains the predicted status of the cyclone for each forecast time. This status may include any of the following: inland, dissipating, dissipated, or post tropical advisories. An **extratropical cyclone** is a cyclone of any intensity for which the primary energy source results from the temperature contrast between warm and cold air masses. Forecast/Advisories are issued for active cyclones every six hours at 0300, 0900, 1500, and 2100 UTC. *Special Forecast/Advisories* may be issued at any time to advise of an unexpected significant change in the cyclone or when coastal watches or warnings are to be issued.

The *Tropical Cyclone Discussion* describes the rationale for the forecaster's analysis and forecast of a tropical cyclone. It will typically discuss the observations justifying the analyzed intensity of the cyclone, a description of the environmental factors expected to influence the cyclone's future track and intensity, and a description of the numerical guidance models. It may also describe the forecaster's degree of confidence in the official forecast, discuss possible alternate scenarios, and highlight unusual hazards. The product also includes a table of forecast positions and intensities in knots and miles per hour out to 120 hours. This table also indicates the forecast status of the cyclone. Tropical Cyclone Discussions are issued for active cyclones every six hours at 0300, 0900, 1500, and 2100 UTC. *Special Discussions* may be issued at any time to advise of an unexpected significant change in the cyclone or when coastal watches or warnings are to be issued.

The *Tropical Cyclone Surface Wind Speed Probability* product provides the likelihood (expressed as a percentage) of sustained (1-min average) winds meeting or exceeding specific thresholds at particular locations. This product is available in text and graphical formats (example shown in Figure 3911b). These probabilities are based on the track, intensity, and wind structure (size) forecasts from the National Hurricane Center and their historical error characteristics. In addition, they consider the amount of agreement or disagreement among the primary tropical cyclone track models.

Location-specific information is given in the form of probabilities of sustained winds occurring at or above the thresholds of 34, 50 and 64 kts over specific periods of time as discussed below. These probabilities are provided for coastal and inland cities as well as for offshore locations (e.g., buoys). These probabilities are based on the track, intensity, and wind structure (size) forecasts from the

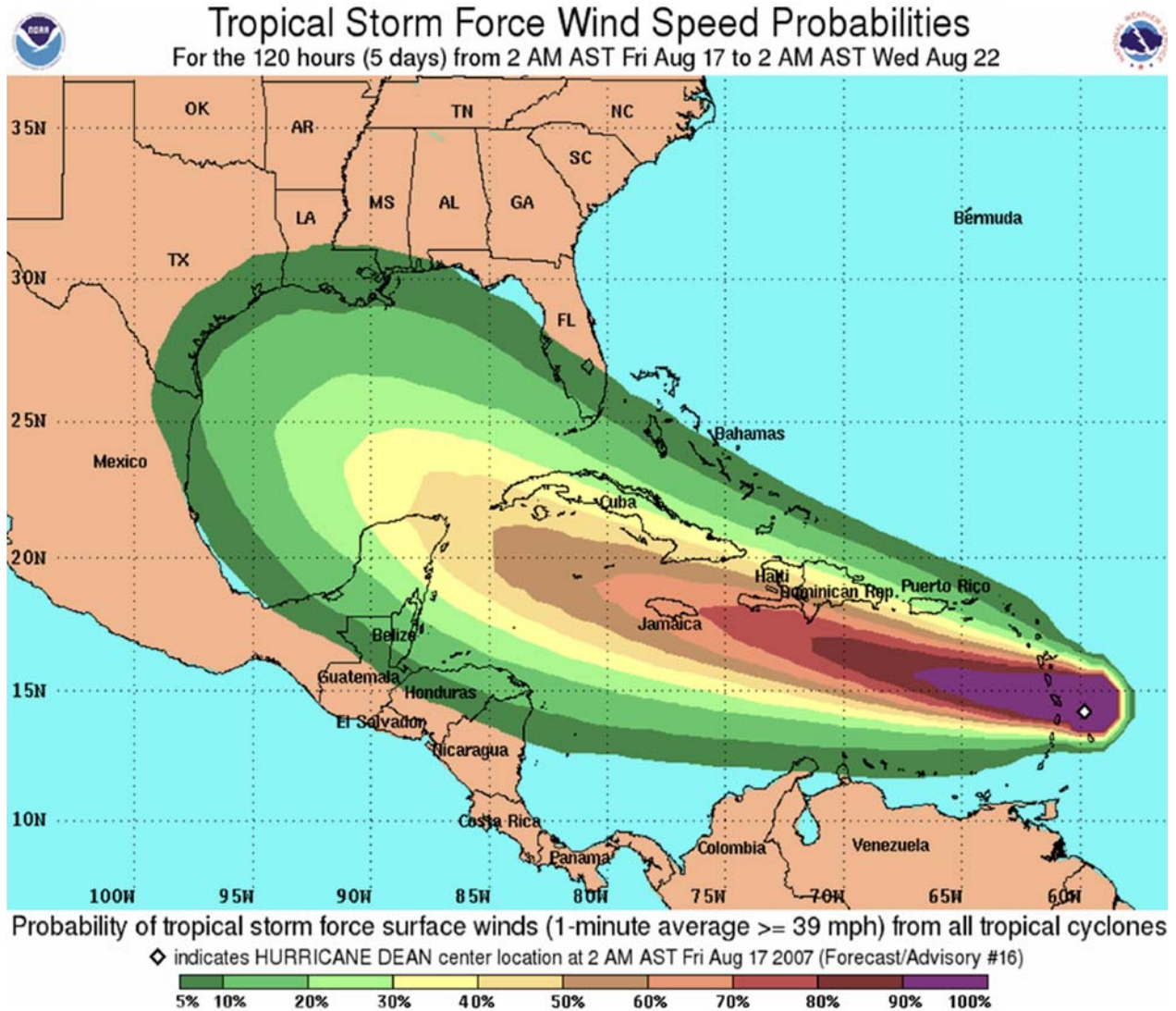


Figure 3911b. Tropical cyclone surface wind speed probability graphic.

National Hurricane Center and their historical error characteristics.

There are two kinds of location-specific probabilities used in this product: *cumulative occurrence* and *onset probabilities*.

Cumulative occurrence probabilities - these values tell you the probability the wind event will occur sometime during the specified cumulative forecast period (0-12, 0-24, 0-36 hours, etc.) at each specific point. These values are provided in both the text and graphical form of the *Surface Wind Speed Probability* product (see Figure 3911b). In the text product, the cumulative probabilities appear in parentheses. The graphical products depict only cumulative values.

Onset probabilities - These values tell you the probability the wind event will start sometime during the specified individual forecast period (0-12, 12-24, 24-36 hours, etc.) at each specific point. These values are provided

only in the text NHC product. They are the values outside of the parentheses.

This product is issued for active cyclones every six hours at 0300, 0900, 1500, and 2100 UTC. Special Wind Speed Probability products may be issued at any time to advise of an unexpected significant change in the cyclone or when coastal watches or warnings are to be issued.

It is important for users to realize that probabilities that may seem relatively small (e.g., 5-10%) may still be quite significant. Users are urged to consider the potentially large costs (in terms of lives, property, etc.) of not preparing for an extreme event.

The *Tropical Cyclone Update (TCU)* is issued to inform users of significant changes in a tropical cyclone between regularly scheduled public advisories. Such uses include:

- To provide timely information of an unusual nature,

such as the time and location of landfall, or to announce an expected change in intensity that results in an upgrade or downgrade of status (e.g., from a tropical storm to a hurricane).

- To provide a continuous flow of information regarding the center location of a tropical cyclone when watches or warnings are in effect and the center can be easily tracked with land-based radar.
- To provide advance notice that significant changes to storm information will be conveyed shortly, either through a subsequent TCU or through a *Special Advisory*.
- To announce changes to international watches or warnings made by other countries, or to cancel U.S. watches or warnings.
- To issue a U.S. watch or warning, but only if the TCU precedes a special advisory that will contain the same watch/warning information, and indicates the special advisory will be issued shortly.

When a TCU is issued and any storm summary information has changed from the previous *Public Advisory* (e.g., upgrade from tropical storm to hurricane), a storm summary section identical in format to that found in the *Public Advisory* will also be included. TCUs issued to provide updated center position information when watches/warnings are in effect are issued in between scheduled TCUs near the beginning of each hour. All other TCUs are issued on an event-driven basis.

In addition to the text products described above, the National Hurricane Center website (see Figure 3911c for link) also contains a number of tropical cyclone graphical products. The most important of these are described below.



Figure 3911c. National Hurricane Center (NHC) website.
<http://www.nhc.noaa.gov>

The *Tropical Cyclone Track Forecast Cone and Watch/Warning Graphic* (Figure 3911d) depicts the most recent NHC track forecast of the center of a tropical cyclone along with an approximate representation of associated coastal areas under a hurricane warning (red), hurricane watch (pink), tropical storm warning (blue) and tropical storm watch (yellow). The orange circle indicates the current position of the center of the tropical cyclone. The black dots show the NHC forecast position of the center at the times indicated. The letter inside the dot indicates the forecast strength of the cyclone category: (D)epression,

(S)torm, (H)urricane, (M)ajor hurricane, or remnant (L)ow. Systems forecast to be post-tropical are indicated by white dots with black letters indicating intensity using the thresholds given above. For example, a post-tropical system forecast to have winds of 65 kts would be depicted by a black H inside a white dot, even though it is not a hurricane.

The cone represents the probable track of the center of a tropical cyclone, and is formed by enclosing the area swept out by a set of circles (not shown) along the forecast track (at 12, 24, 36 hours, etc.). The size of each circle is set so that two-thirds of historical official forecast errors over a 5-year sample fall within the circle.

The *5-day Graphical Tropical Weather Outlook* (Figure 3911e) provides formation potential for individual disturbances during the next 5-day period. The areas enclosed on the graph represent the potential formation area during the forecast period. The areas are color-coded based on the potential for tropical cyclone formation during the next 5-days. Areas in yellow indicate a low probability of development (0-30%), orange indicates medium likelihood (40-60%), and red indicates a high likelihood of development (70-100%). The location of existing disturbances is indicated by an X. If the formation potential of an existing disturbance does not include the area in which the disturbance is currently located, an arrow will connect the current location of the disturbance to its area of potential formation. Areas without an X or connected by an arrow to an X indicate that the disturbance does not currently exist, but is expected to develop during the 5-day period. On the NHC website the graphic is interactive; users can mouse over disturbances in the graphic and pop-up windows will appear with the text Outlook discussion for that disturbance. Clicking on a disturbance will take the user to a graphic that shows only that disturbance. Active tropical cyclones are not depicted on this graphic. Graphical Tropical Weather Outlooks are issued every six hours from 1 June-30 November for the Atlantic basin and from 15 May-30 November for the eastern North Pacific basin, at 0000, 0600, 1200, and 1800 UTC. The Graphical Tropical Weather Outlook is also updated whenever a Special Tropical Weather Outlook is issued.

3912. Marine Forecast Products

The *Tropical Cyclone Danger Graphic* is an NHC product traditionally based on the “Mariner’s 1-2-3 rule”. The graphics (one for the North Atlantic and one for the eastern North Pacific) depict the danger area associated with tropical cyclones within the area from the equator to 60°N between 0° and 100°W, including the Pacific east of 100°W, and from the equator to 40°N between 80°W and 175°W, including the Gulf of Mexico and Western Caribbean. These graphics are posted on the NHC webpage, and are also transmitted by radio fax via Boston, New Orleans, and Pt. Reyes transmitters.

The tropical cyclone danger graphic is intended to de-

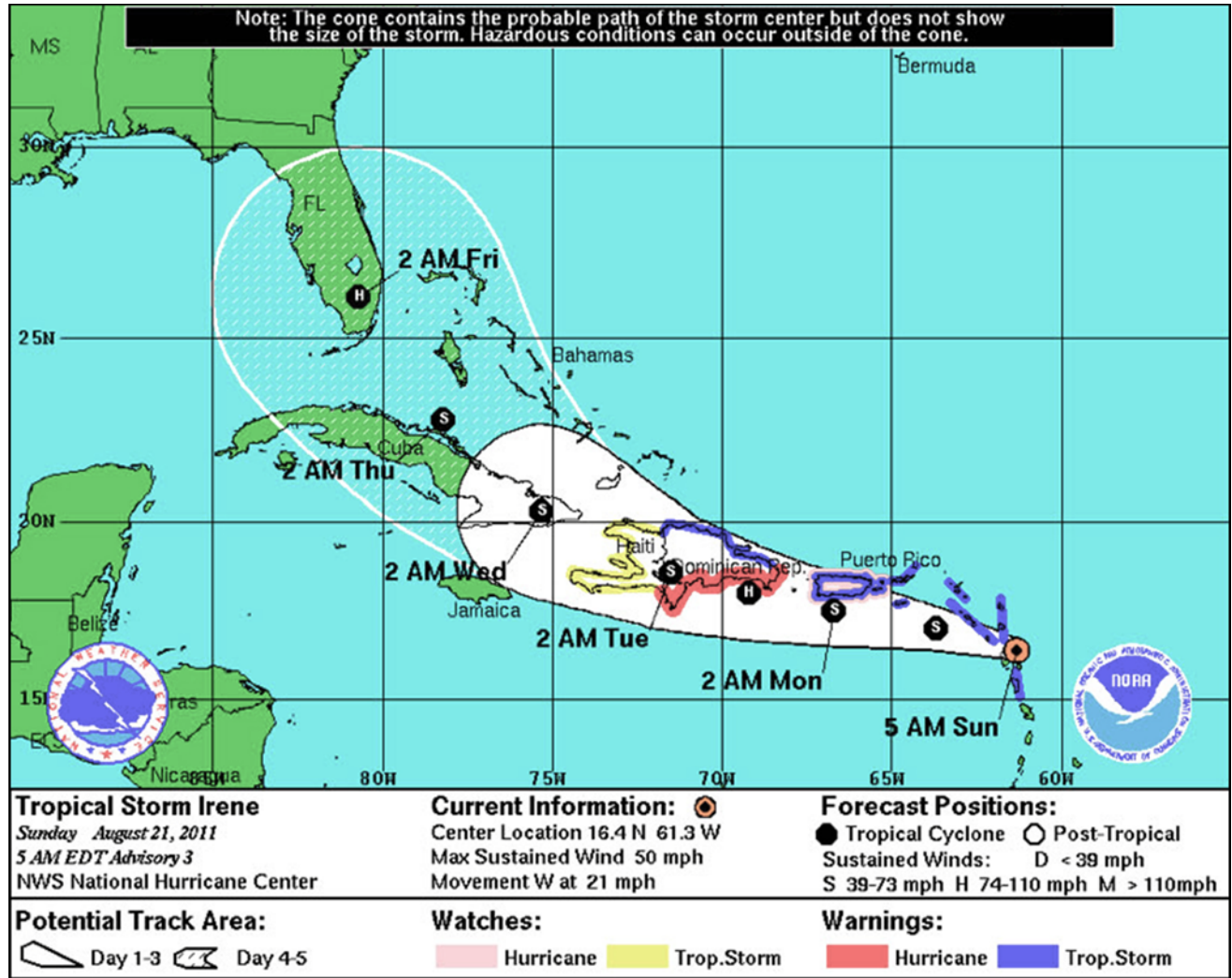


Figure 3911d. Tropical cyclone track forecast cone and watch/warning graphic.

predict the forecast track and corresponding area of avoidance for all active tropical cyclones and to depict areas for which tropical cyclone formation is possible within the next 72 hours over the Atlantic and East Pacific waters between May 15 and November 30. Traditionally, the three-day forecast track of each active tropical cyclone is depicted along with a shaded “danger” region, or area of avoidance. The danger area is determined by adding 100, 200, and 300 nautical miles to the tropical storm force radii (34 knots) at the 24, 48, and 72-hour forecast positions, respectively (hence the “1-2-3” nomenclature).

Because of advances in tropical cyclone prediction, the 1-2-3 rule (see Figure 3912a) has become outdated and the Danger Graphic based on that rule depicts excessively large potential tropical cyclone danger areas. In 2012, the National Hurricane Center developed an alternative experimental version of the graphic based on the wind

speed probability calculations discussed above. One advantage of this approach is that it allows the depiction of any particular desired level of risk. In addition, the calculation considers the spread of the model guidance and therefore has some situational variability. It also considers uncertainty in the forecasts of tropical cyclone size and intensity as well as the track of the cyclone.

NHC discontinued use of the Mariner's 1-2-3 rule in 2016. Tropical cyclone danger areas are now depicted to show the areas encompassed by the 5% and 50% 34-knots wind speed probability contours - the 5% contour is meant to highlight areas where-tropical-storm force winds are possible and the 50% contour is meant to highlight areas where those winds are likely. An example of the new Danger Graphic is given in Figure 3912b.

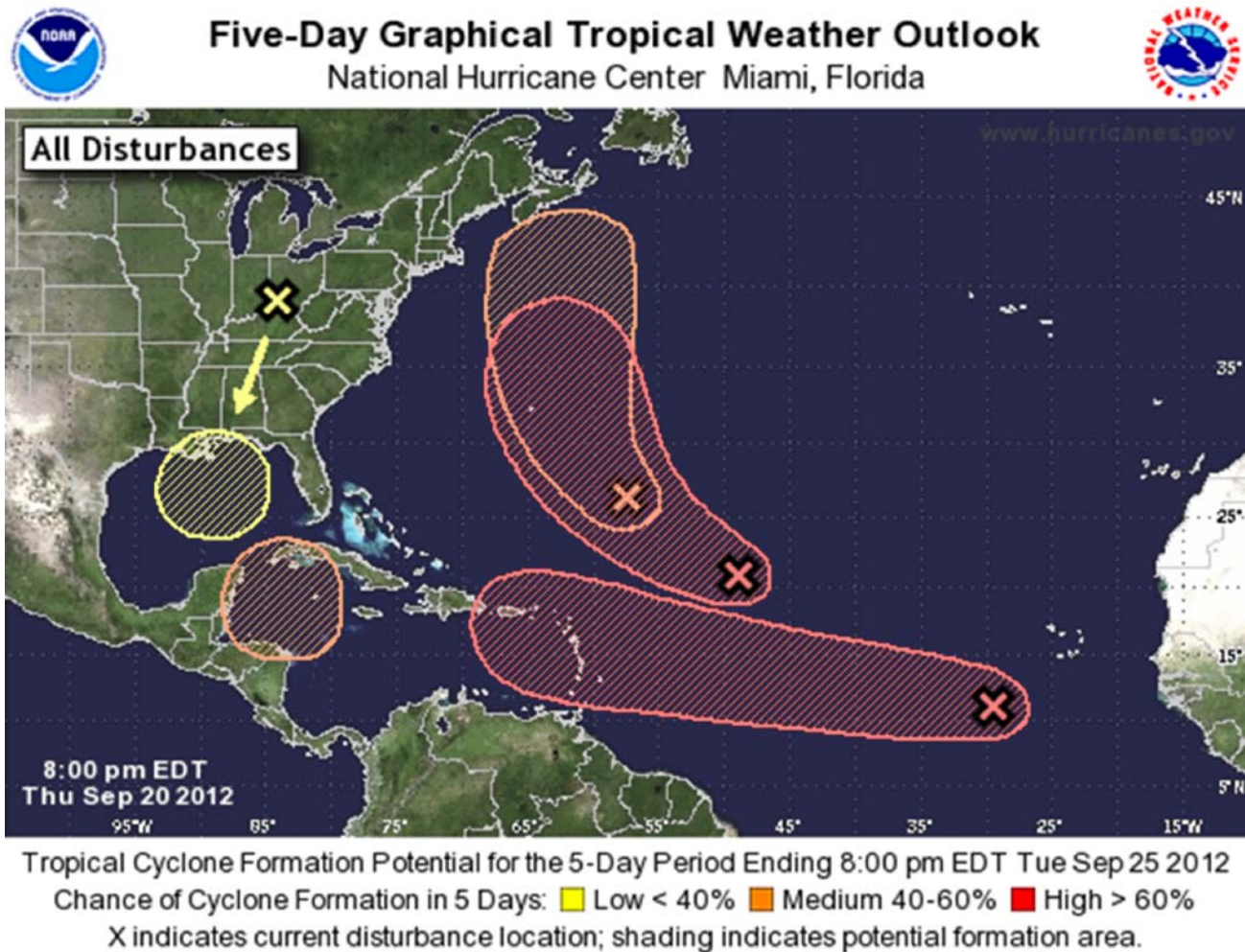


Figure 3911e. Five-day graphical tropical weather outlook.

AVOIDING TROPICAL CYCLONES

3913. Approach and Passage of a Tropical Cyclone

Given the improvements in forecasting and the growing availability of receiving these forecasts at sea, the best way to avoid an encounter with a tropical cyclone is to monitor the forecast products from the appropriate RSMC or TCWC and take early action. Early action means determining the tropical cyclone's location and direction of travel relative to the vessel and maneuvering the vessel appropriately.

A mariner should be well versed in identifying and characterizing environmental changes to maintain situational awareness and safety around these storms. The below rules of thumb should be used alongside the official forecasts to identify and maneuver around tropical cyclones.

The presence of an exceptionally long swell is usually

the first visible indication of the existence of a tropical cyclone. In deep water it approaches from the general direction of origin (the position of the storm center when the swell was generated). However, in shoaling water this is a less reliable indication because the direction is changed by refraction, the crests being more nearly parallel to the bottom contours.

When the cirrus clouds appear, their point of convergence provides an indication of the direction of the storm center. If the storm is to pass well to one side of the observer, the point of convergence shifts slowly in the direction of storm movement. If the storm center will pass near the observer, this point remains steady. When the bar becomes visible, it appears to rest upon the horizon for several hours. The darkest part of this cloud is in the direction of the storm center. If the storm is to pass to one side, the bar appears to drift slowly along the horizon. If the storm is heading di-

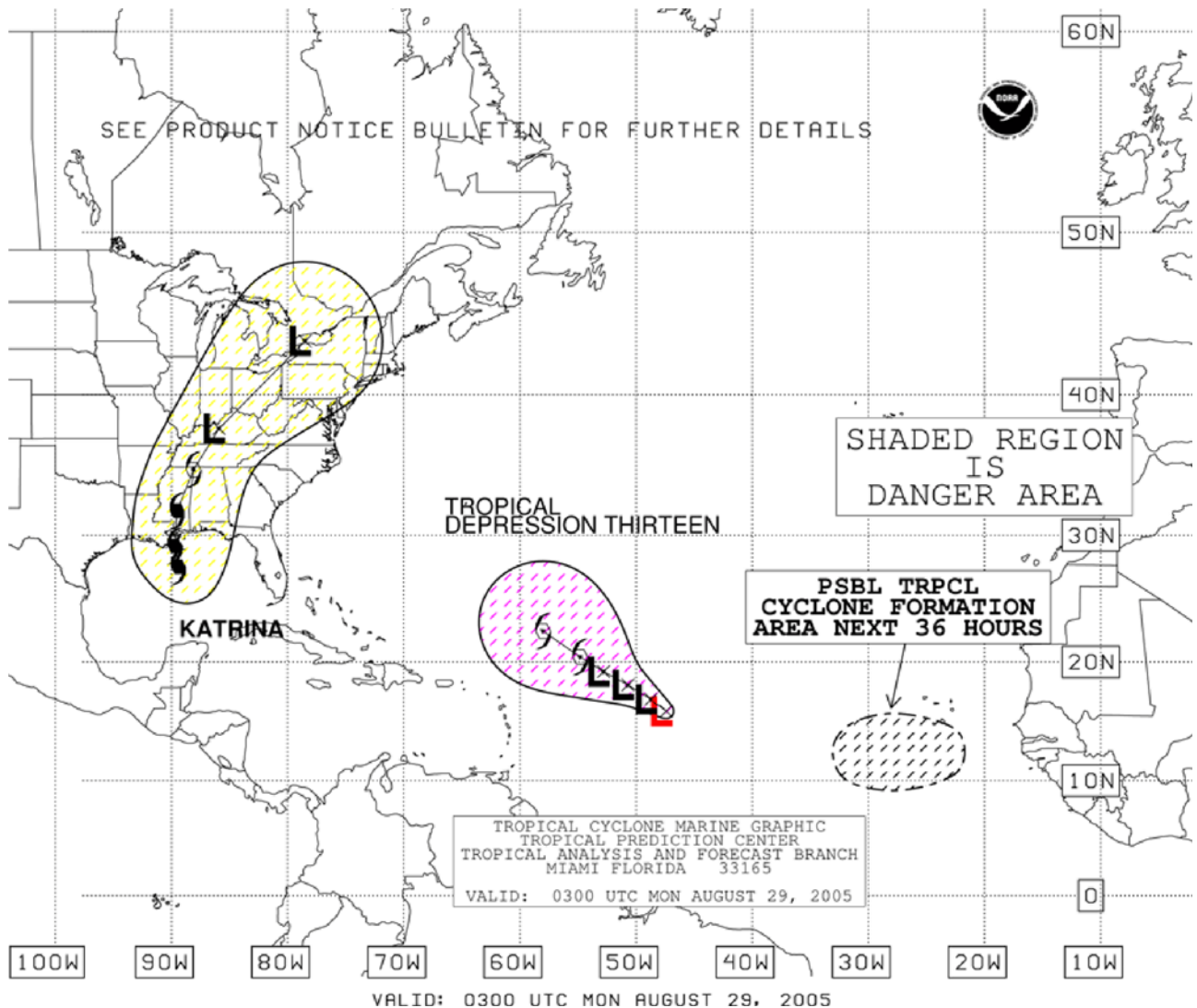


Figure 3912a. Former Tropical Cyclone Danger Graphic based on the Mariner's 1-2-3 rule.

rectly toward the observer, the position of the bar remains fixed. Once within the area of the dense, low clouds, one should observe their direction of movement, which is almost exactly along the isobars, with the center of the storm being 90° from the direction of cloud movement (left of direction of movement in the Northern Hemisphere and right in the Southern Hemisphere). The winds are probably the best guide to the direction of the center of a tropical cyclone. The circulation is cyclonic, but because of the steep pressure gradient near the center, the winds there blow with greater violence and are more nearly circular than in extratropical cyclones.

According to **Buys Ballot's law**, an observer whose back is to the wind has the low pressure on his left in the Northern Hemisphere and on his right in the Southern Hemisphere. If the wind followed circular isobars exactly, the center would be exactly 90° from behind when facing away from the wind. However, the track of the wind is usu-

ally inclined somewhat toward the center, so that the angle from dead astern varies between perhaps 90° to 135° . The inclination varies in different parts of the same storm. It is least in front of the storm and greatest in the rear, since the actual wind is the vector sum of the pressure gradient and the motion of the storm along the track. A good average is perhaps 110° in front and 120 - 135° in the rear. These values apply when the storm center is still several hundred miles away. Closer to the center, the wind blows more nearly along the isobars, the inclination being reduced by one or two points at the wall of the eye. Since wind direction usually shifts temporarily during a squall, its direction at this time should not be used for determining the position of the center. The approximate relationship of wind to isobars and storm center in the Northern Hemisphere is shown Figure 3913a.

When the center is within a vessel's radar range, it will probably be visible on the scope. However, since the radar

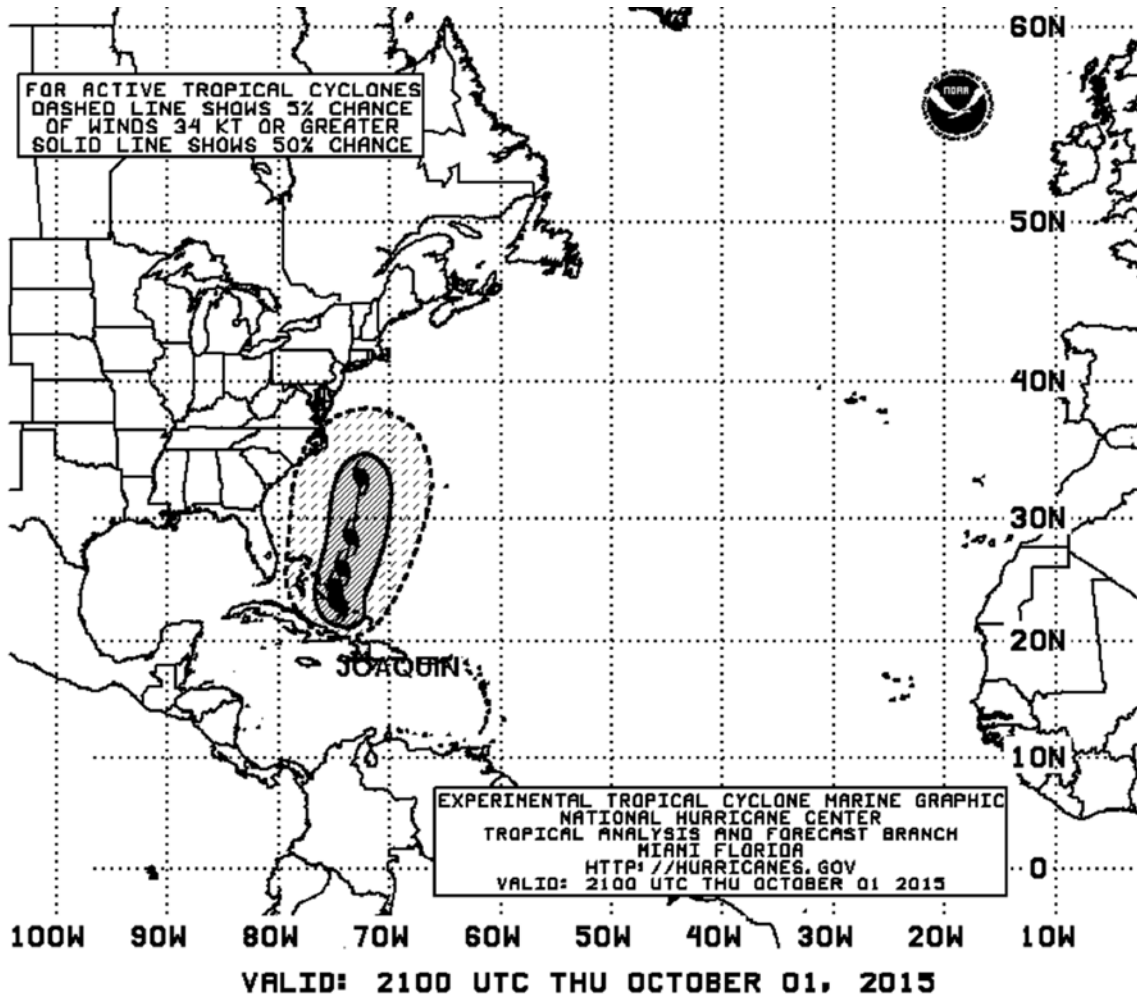


Figure 3912b. Probability-based Tropical Cyclone Danger Graphic.

return is predominantly from the rain, results can be deceptive, and other indications should not be neglected. Figure 3913b shows a radar presentation of a tropical cyclone. If the eye is out of range, the spiral bands may indicate its direction from the vessel. Tracking the eye or upwind portion of the spiral bands enables determining the direction and speed of movement; this should be done for at least 1 hour because the eye tends to oscillate. The tracking of individual cells, which tend to move tangentially around the eye, for 15 minutes or more, either at the end of the band or between bands, will provide an indication of the wind speed in that area of the storm.

Distance from the storm center is more difficult to determine than direction. Radar is perhaps the best guide. However, the rate of fall of the barometer is some indication.

3914. Statistical Analysis of Barometric Pressure

The lowest sea level pressure ever recorded was 870 mb in Super Typhoon Tip in October 1979. In the Atlantic

basin, Hurricane Wilma produced a minimum central pressure of 882 mb in 2005, and 2015's Hurricane Patricia in the eastern North Pacific deepened to a pressure of 872 mb. During a 1927 typhoon, the S.S. SAPOEROEA recorded a pressure of 886.6 mb, the lowest sea-level pressure reported from a ship. In Patricia, a pressure gradient of 24 mb per nautical mile was estimated from aircraft reconnaissance data.

In the absence of any information from an RSMC or TCWC, a method for alerting the mariner to possible tropical cyclone formation involves a statistical comparison of observed weather parameters with the climatology (30-year averaged conditions) for those parameters. Significant fluctuations away from these average conditions could mean the onset of severe weather. One such statistical method involves a comparison of mean surface pressure in the tropics with the standard deviation of surface pressure. Any significant deviation from the norm could indicate proximity to a tropical cyclone. Analysis shows that surface pressure can be expected to be lower than the mean minus 1 standard deviation less than 16% of the time, lower than the mean

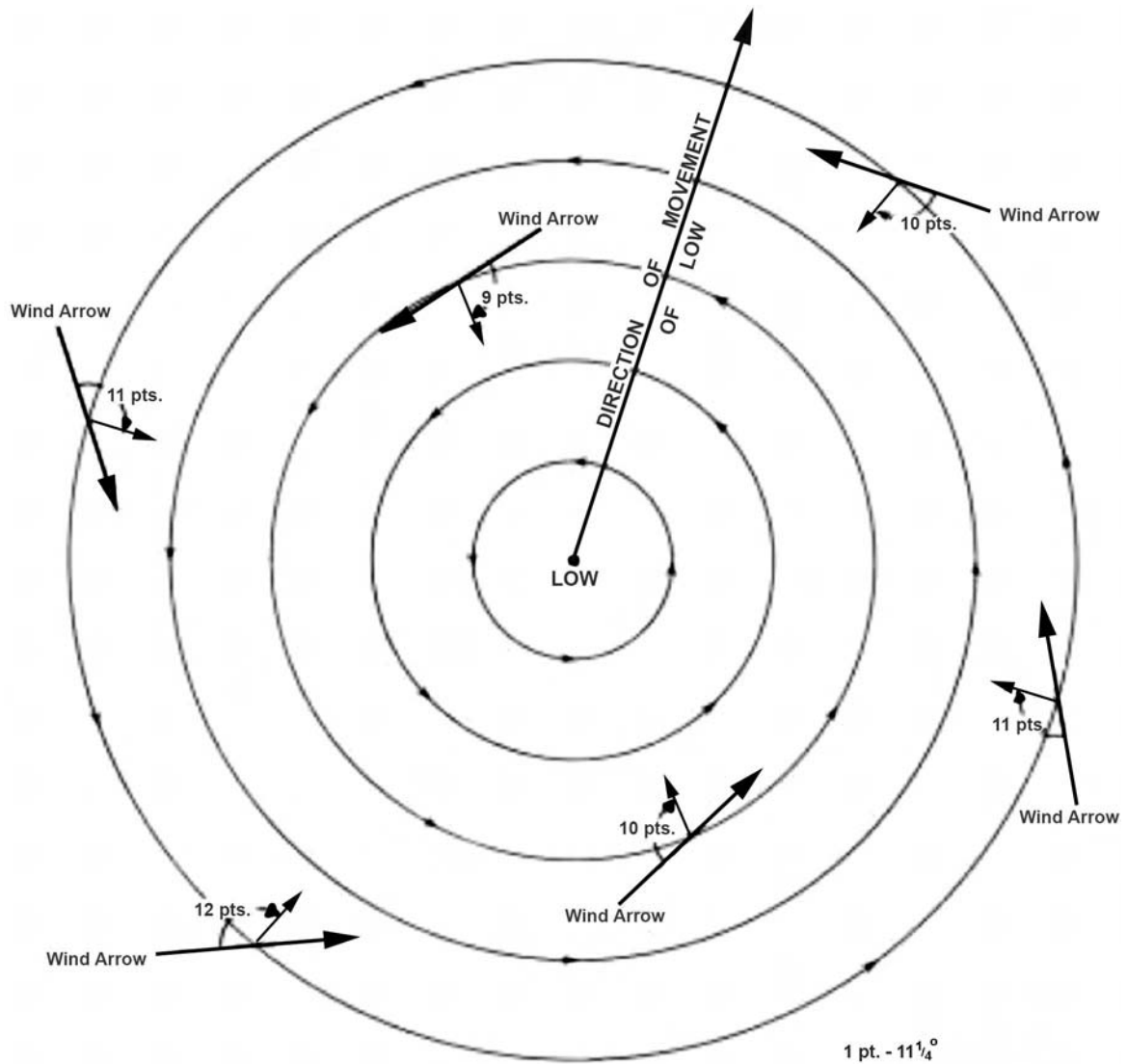


Figure 3913a. Approximate relationship of wind to isobars and storm center in the Northern Hemisphere.

minus 1.5 standard deviations less than 7% of the time, and lower than the mean minus 2 standard deviations less than 3% of the time. Comparison of the observed pressure with the mean will indicate how unusual the present conditions are.

As an example, assume the mean surface pressure in the South China Sea to be about 1005 mb during August with a standard deviation of about 2 mb. Therefore, surface pressure can be expected to fall below 1003 mb about 16% of the time and below 1000 mb about 7% of the time. Ambient pressure any lower than that would alert the mariner to the possible onset of heavy weather. Charts showing the mean surface pressure and the standard deviation of surface pressure for various global regions can be found in the U.S. Navy Marine Climatic Atlas of the World.

3915. Maneuvering to Avoid the Storm Center

The safest procedure with respect to tropical cyclones is to avoid them. If action is taken sufficiently early, this is simply a matter of setting a course that will take the vessel well to one side of the probable track of the storm, and then continuing to plot the positions of the storm center as given in the weather bulletins, revising the course as needed.

However, this is not always possible. If the ship is found to be within the storm area, the proper action to take depends in part upon its position relative to the storm center and its direction of travel. It is customary to divide the circular area of the storm into two parts.

In the Northern Hemisphere, that part to the right of the storm track (facing in the direction toward which the storm is moving) is called the dangerous semicircle. It is considered dangerous because (1) the actual wind speed is greater

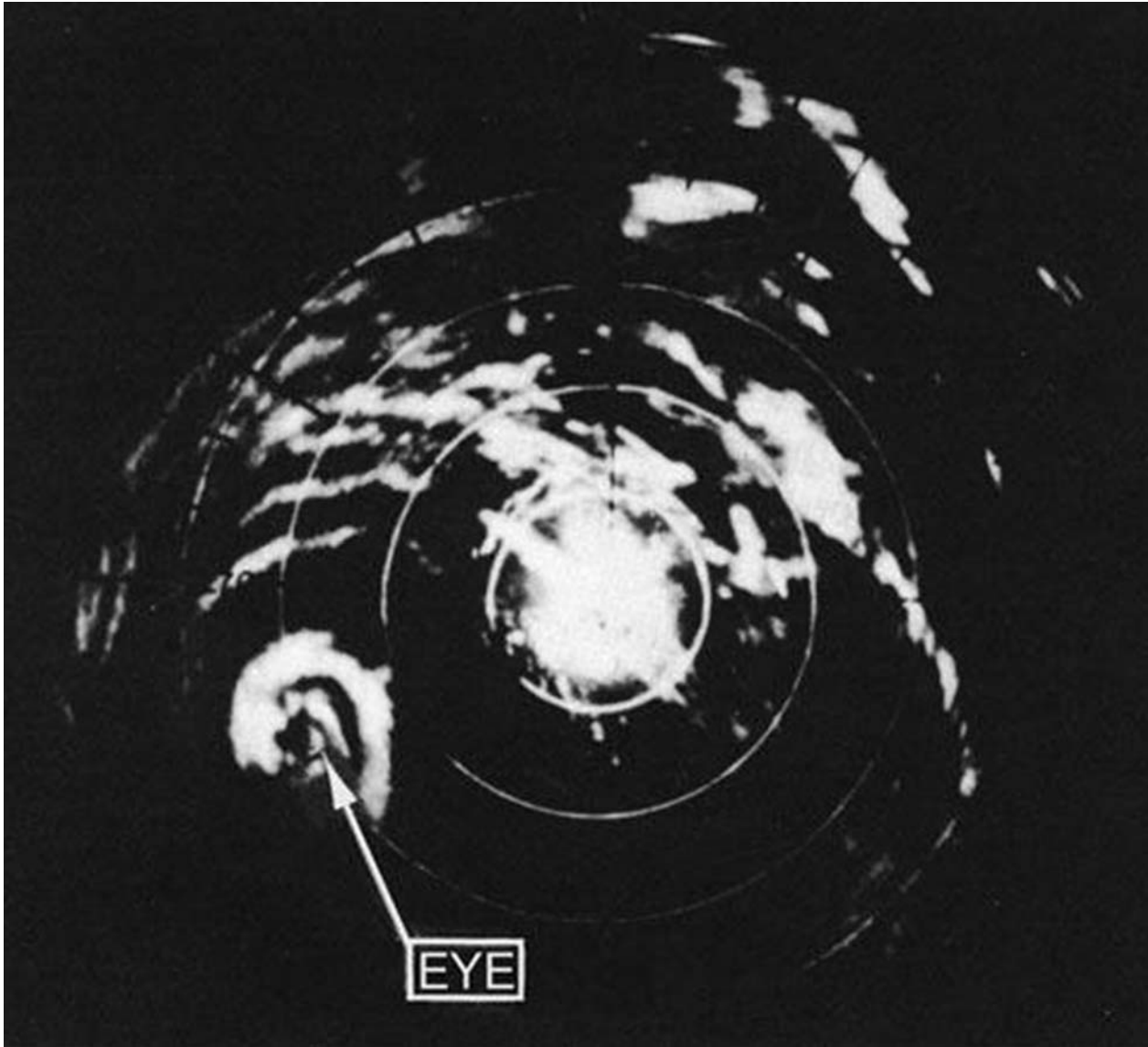


Figure 3913b. Radar PPI presentation of a tropical cyclone.

than that due to the pressure gradient alone, since it is augmented by the forward motion of the storm, and (2) the direction of the wind and sea is such as to carry a vessel into the path of the storm (in the forward part of the semicircle).

The part to the left of the storm track is called the less dangerous semicircle, or navigable semicircle. In this part, the wind is decreased by the forward motion of the storm, and the wind blows vessels away from the storm track (in the forward part). Because of the greater wind speed in the dangerous semicircle, the seas are higher than in the less dangerous semicircle. In the Southern Hemisphere, the dangerous semicircle is to the left of the storm track, and the less dangerous semicircle is to the right of the storm track.

A plot of successive positions of the storm center should indicate the semicircle in which a vessel is located. However, if this is based upon weather bulletins, it may not be a reliable guide because of the lag between the observa-

tions upon which the bulletin is based and the time of reception of the bulletin, with the ever-present possibility of a change in the direction of the storm. The use of radar eliminates this lag at short range, but the return may not be a true indication of the center. Perhaps the most reliable guide is the wind. Within the cyclonic circulation, a wind shifting to the right in the northern hemisphere and to the left in the southern hemisphere indicates the vessel is probably in the dangerous semicircle. A steady wind shift opposite to this indicates the vessel is probably in the less dangerous semicircle.

However, if a vessel is underway, its own motion should be considered. If it is outrunning the storm or pulling rapidly toward one side (which is not difficult during the early stages of a storm, when its speed is low), the opposite effect occurs. This should usually be accompanied by a rise in atmospheric pressure, but if motion of the vessel is nearly

along an isobar, this may not be a reliable indication. If in doubt, the safest action is usually to stop long enough to define the proper semicircle. The loss in time may be more than offset by the minimizing of the possibility of taking the wrong action, increasing the danger to the vessel. If the wind direction remains steady (for a vessel which is stopped), with increasing speed and falling barometer, the vessel is in or near the path of the storm. If it remains steady with decreasing speed and rising barometer, the vessel is near the storm track, behind the center.

The first action to take if the ship is within the cyclonic circulation is to determine the position of the vessel with respect to the storm center. While the vessel can still make considerable way through the water, a course should be selected to take it as far as possible from the center. If the vessel can move faster than the storm, it is a relatively simple matter to outrun the storm if sea room permits. But when the storm is faster, the solution is not as simple. In this case, the vessel, if ahead of the storm, will approach nearer to the center. The problem is to select a course that will produce the greatest possible minimum distance. This is best determined by means of a relative movement plot, as shown in the following example solved on a maneuvering board.

Example: A tropical cyclone is estimated to be moving in direction 320° at 19 knots. Its center bears 170° , at an estimated distance of 200 miles from a vessel which has a maximum speed of 12 knots.

Required:

- (1) The course to steer at 12 knots to produce the greatest possible minimum distance between the vessel and the storm center.
- (2) The distance to the center at nearest approach.
- (3) Elapsed time until nearest approach.

Solution: (Figure 3915a) Consider the vessel remaining

at the center of the plot throughout the solution, as on a radar PPI.

(1) To locate the position of the storm center relative to the vessel, plot point C at a distance of 200 miles (scale 20:1) in direction 170° from the center of the diagram. From the center of the diagram, draw RA, the speed vector of the storm center, in direction 320° , speed 19 knots (scale 2:1). From A draw a line tangent to the 12-knot speed circle (labeled 6 at scale 2:1) on the side opposite the storm center. From the center of the diagram, draw a perpendicular to this tangent line, locating point B. The line RB is the required speed vector for the vessel. Its direction, 011° , is the required course.

(2) The path of the storm center relative to the vessel will be along a line from C in the direction BA, if both storm and vessel maintain course and speed. The point of nearest approach will be at D, the foot of a perpendicular from the center of the diagram. This distance, at scale 20:1, is 187 miles.

(3) The length of the vector BA (14.8 knots) is the speed of the storm with respect to the vessel. Mark this on the lowest scale of the nomogram at the bottom of the diagram. The relative distance CD is 72 miles, by measurement. Mark this (scale 10:1) on the middle scale at the bottom of the diagram. Draw a line between the two points and extend it to intersect the top scale at 29.2 (292 at 10:1 scale). The elapsed time is therefore 292 minutes, or 4 hours 52 minutes.

Answers: (1) C 011° , (2) D 187 mi., (3) 4^h 52^m.

The storm center will be dead astern at its nearest approach.

As a general rule, for a vessel in the Northern Hemisphere, safety lies in placing the wind on the starboard bow in the dangerous semicircle and on the starboard quarter in the less dangerous semicircle. If on the storm track ahead of the storm, the wind should be put about 160° on the starboard quarter until the vessel is well within the less dangerous semicircle, and the rule for that semicircle then followed. In the Southern Hemisphere the same rules hold, but with respect to the port side. With a faster than average vessel, the wind can be brought a little farther aft in each case. However, as the speed of the storm increases along its track, the wind should be brought farther forward. If land interferes with what would otherwise be the best maneuver, the solution should be altered to fit the circumstances.

If the vessel is faster than the storm, it is possible to overtake it. In this case, the only action usually needed is to slow enough to let the storm pull ahead.

In all cases, one should be alert to changes in the direction of movement of the storm center, particularly in the area where the track normally curves toward the pole. If the storm maintains its direction and speed, the ship's course should be maintained as the wind shifts.

If it becomes necessary for a vessel to heave to, the characteristics of the vessel should be considered. A power vessel is concerned primarily with damage by direct action of the sea. A good general rule is to heave to with head to the sea in the dangerous semicircle, or stern to the sea in the less dangerous semicircle. This will result in greatest amount of headway away from the storm center, and least amount of leeway toward it. If a vessel handles better with the sea astern or on the quarter, it may be placed in this position in the less dangerous semicircle or in the rear half of the dangerous semicircle, but never in the forward half of the dangerous semicircle. It has been reported that when the wind reaches hurricane speed and the seas become confused, some ships ride out the storm best if the engines are stopped, and the vessel is left to seek its own position, or lie ahull. In this way, it is said, the ship rides with the storm instead of fighting against it.

In a sailing vessel attempting to avoid a storm center, one should steer courses as near as possible to those prescribed above for power vessels. However, if it

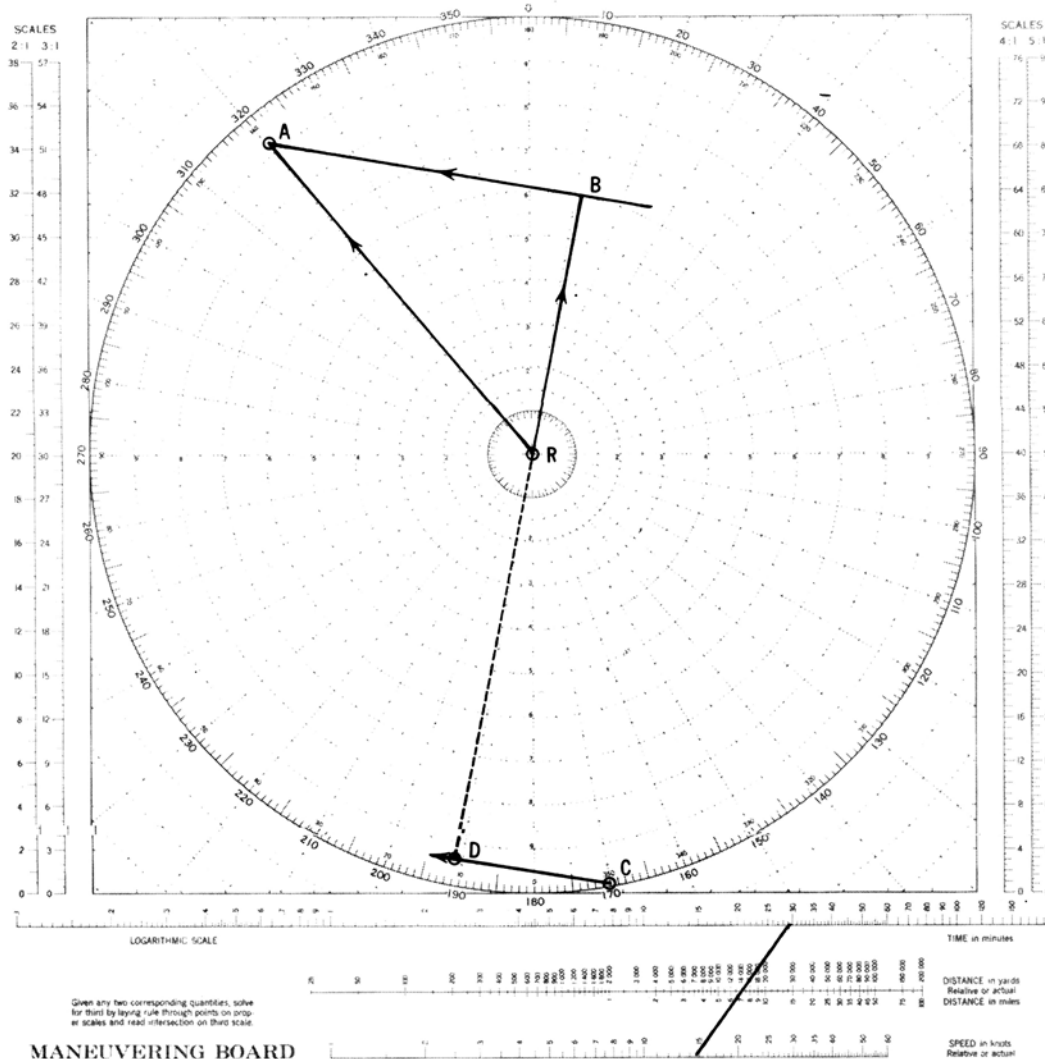


Figure 3915a. Determining the course to avoid the storm center.

becomes necessary for such a vessel to heave to, the wind is of greater concern than the sea. A good general rule always is to heave to on whichever tack permits the shifting wind to draw aft. In the Northern Hemisphere, this is the starboard tack in the dangerous semicircle, and the port tack in the less dangerous semicircle. In the Southern Hemisphere these are reversed.

While each storm requires its own analysis, and frequent or continual resurvey of the situation, the general rules for a steamer may be summarized as follows:

Northern Hemisphere

Right or dangerous semicircle: Bring the wind on the starboard bow (045° relative), hold course and make as much way as possible. If necessary, heave to with head to the sea.

Left or less dangerous semicircle: Bring the wind on

the starboard quarter (135° relative), hold course and make as much way as possible. If necessary, heave to with stern to the sea.

On storm track, ahead of center: Bring the wind 2 points on the starboard quarter (about 160° relative), hold course and make as much way as possible. When well within the less dangerous semicircle, maneuver as indicated above.

On storm track, behind center: Avoid the center by the best practicable course, keeping in mind the tendency of tropical cyclones to curve northward and eastward.

Southern Hemisphere

Left or dangerous semicircle: Bring the wind on the port bow (315° relative), hold course and make as much way as possible. If necessary, heave to with

head to the sea.

Right or less dangerous semicircle: Bring the wind on the port quarter (225° relative), hold course and make as much way as possible. If necessary, heave to with stern to the sea.

On storm track, ahead of center: Bring the wind about 200° relative, hold course and make as much way as possible. When well within the less dangerous semicircle, maneuver as indicated above.

On storm track, behind center: Avoid the center by the best practicable course, keeping in mind the tendency of tropical cyclones to curve southward and eastward.

It is possible, particularly in temperate latitudes after the storm has recurved, that the dangerous semicircle is the left one in the Northern Hemisphere (right one in the Southern Hemisphere). This can occur if a large high lies north of the storm and causes a tightening of the pressure gradient in the region.

The *Typhoon Havens Handbook* for the Western Pacific and Indian Oceans is published by the Naval Oceanographic and Atmospheric Research Lab

(NOARL) Monterey, California, as an aid to captains and commanding officers of ships in evaluating a typhoon situation, and to assist them in deciding whether to sortie, to evade, to remain in port, or to head for the shelter of a specific harbor. See Figure 3915b for a link to this handbook.



Figure 3915b. *Typhoon Havens Handbook*.
http://www.nrlmry.navy.mil/port_studies/thh-nc/0start.htm

3916. References

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