MARINE METEOROLOGY

10

CHAPTER 38

WEATHER ELEMENTS

GENERAL DESCRIPTION OF THE ATMOSPHERE

3800. Introduction

Weather is the state of the Earth's atmosphere with respect to temperature, humidity, precipitation, visibility, cloudiness, and other factors. **Climate** refers to the average long-term meteorological conditions of a place or region.

All weather may be traced to the effect of the Sun on the Earth. Most changes in weather involve large-scale horizontal motion of air. Air in motion is called **wind**. This motion is produced by differences in atmospheric pressure, which are attributable both to differences in temperature and the nature of the motion itself.

Weather is of vital importance to the mariner. The wind and state of the sea affect dead reckoning. Reduced visibility limits piloting. The state of the atmosphere affects electronic navigation and radio communication. If the skies are overcast, celestial observations are not available. Under certain conditions, refraction and dip are disturbed. When wind was the primary motive power, knowledge of the areas of favorable winds was of great importance. Modern vessels are still affected considerably by wind and sea.

3801. The Atmosphere

The **atmosphere** is a relatively thin shell of air, water vapor, and suspended particulates surrounding the Earth. Air is a mixture of gases and, like any gas, is elastic and highly compressible. Although extremely light, it has a definite weight which can be measured. A cubic foot of air at standard sea-level temperature and pressure weighs 1.22 ounces, or about $^{1}/_{817}$th the weight of an equal volume of water. Because of this weight, the atmosphere exerts a pressure upon the surface of the Earth of about 15 pounds per square inch.

As altitude increases, air pressure decreases due to the decreased weight of air above. With less pressure, the density decreases. More than three-fourths of the air is concentrated within a layer averaging about 7 statute miles thick, called the **troposphere**. This is the region of most "weather," as the term is commonly understood.

The top of the troposphere is marked by a thin transition zone called the **tropopause**, immediately above which is the **stratosphere**. Beyond this lie several other layers having distinctive characteristics. The average height of the tropopause ranges from about 5 miles or less at high latitudes to about 10 miles at low latitudes.

The **standard atmosphere** is a conventional vertical structure of the atmosphere characterized by a standard sea-level pressure of 1013.25 hectopascals of mercury (29.92 inches) and a sea-level air temperature of 15° C (59° F). The temperature decreases with height at the **standard lapse rate**, a uniform 2° C (3.6° F) per thousand feet to 11 kilometers (36,089 feet), and above that remains constant at -56.5° C (-69.7° F).

The **jet stream** refers to relatively strong (greater than 60 knots) quasi-horizontal winds, usually concentrated within a restricted layer of the atmosphere. Research has indicated that the jet stream is important in relation to the sequence of weather. There are two commonly known jet streams. The **sub-tropical jet stream (STJ)** occurs in the region of 30°N during the northern hemisphere winter, decreasing in summer. The core of highest winds in the STJ is found at about 12km altitude (40,000 feet) in the region of 70°W, 40°E, and 150°E, although considerable variability is common. The **polar frontal jet stream (PFJ)** is found in middle to upper-middle latitudes and is discontinuous and variable. Maximum jet stream winds have been measured by weather balloons at 291 knots.

3802. General Circulation of the Atmosphere

The heat required to warm the air is supplied originally by the Sun. As radiant energy from the Sun arrives at the Earth, about 29 percent is reflected back into space by the Earth and its atmosphere, 19 percent is absorbed by the atmosphere, and the remaining 52 percent is absorbed by the surface of the Earth. Much of the Earth's absorbed heat is radiated back into space. Earth's radiation is in comparatively long waves relative to the short-wave radiation from the Sun because it emanates from a cooler body. Long-wave radiation, readily absorbed by the water vapor in the air, is primarily responsible for the warmth of the atmosphere near the Earth's surface. Thus, the atmosphere acts much like the glass on the roof of a greenhouse. It allows part of the incoming solar radiation to reach the surface of the Earth but is heated by the terrestrial radiation passing outward. Over the entire Earth and for long periods of time, the total outgoing energy must be equivalent to the incoming energy (minus any converted to another form and retained), or the temperature of the Earth and its atmosphere would steadily increase or decrease. In local areas, or over relatively short periods of time, such a balance is not required. In fact it does not exist, resulting in changes such as those occurring from one year to another, in different seasons and in different parts of the day.

The more nearly perpendicular the rays of the Sun strike the surface of the Earth, the more heat energy per unit area is received at that place. Physical measurements show that in the tropics, more heat per unit area is received than is radiated away, and that in polar regions, the opposite is true. Unless there were some process to transfer heat from the tropics to polar regions, the tropics would be much warmer than they are, and the polar regions would be much colder. Atmospheric motions bring about the required transfer of heat. The oceans also participate in the process, but to a lesser degree.

If the Earth had a uniform surface and did not rotate on its axis, with the Sun following its normal path across the sky (solar heating increasing with decreasing latitude), a simple circulation would result, as shown in Figure 3802a. However, the surface of the Earth is far from uniform, being covered with an irregular distribution of land and water. Additionally, the Earth rotates about its axis so that the portion heated by the Sun continually changes. In addition, the axis of rotation is tilted so that as the Earth moves along its orbit about the Sun, seasonal changes occur in the exposure of specific areas to the Sun's rays, resulting in variations in the heat balance of these areas. These factors, coupled with others, result in constantly changing large-scale movements of air. For example, the rotation of the Earth exerts an apparent force, known as **Coriolis force**, which diverts the air from a direct path between high and low pressure areas. The diversion of the air is toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere. At some distance above the surface of the Earth, the wind tends to blow along lines connecting points of equal pressure called **isobars**. The wind is called a **geostrophic wind** if it blows parallel to the isobars. This normally occurs when the isobars are straight (great circles). However, isobars curve around highs and lows, and the air is not generally able to maintain itself parallel to these. The resulting cross-isobar flow is called a **gradient wind**. Near the surface of the Earth, friction tends to divert the wind from the isobars toward the center of low pressure. At sea, where friction is less than on land, the wind follows the isobars more closely.

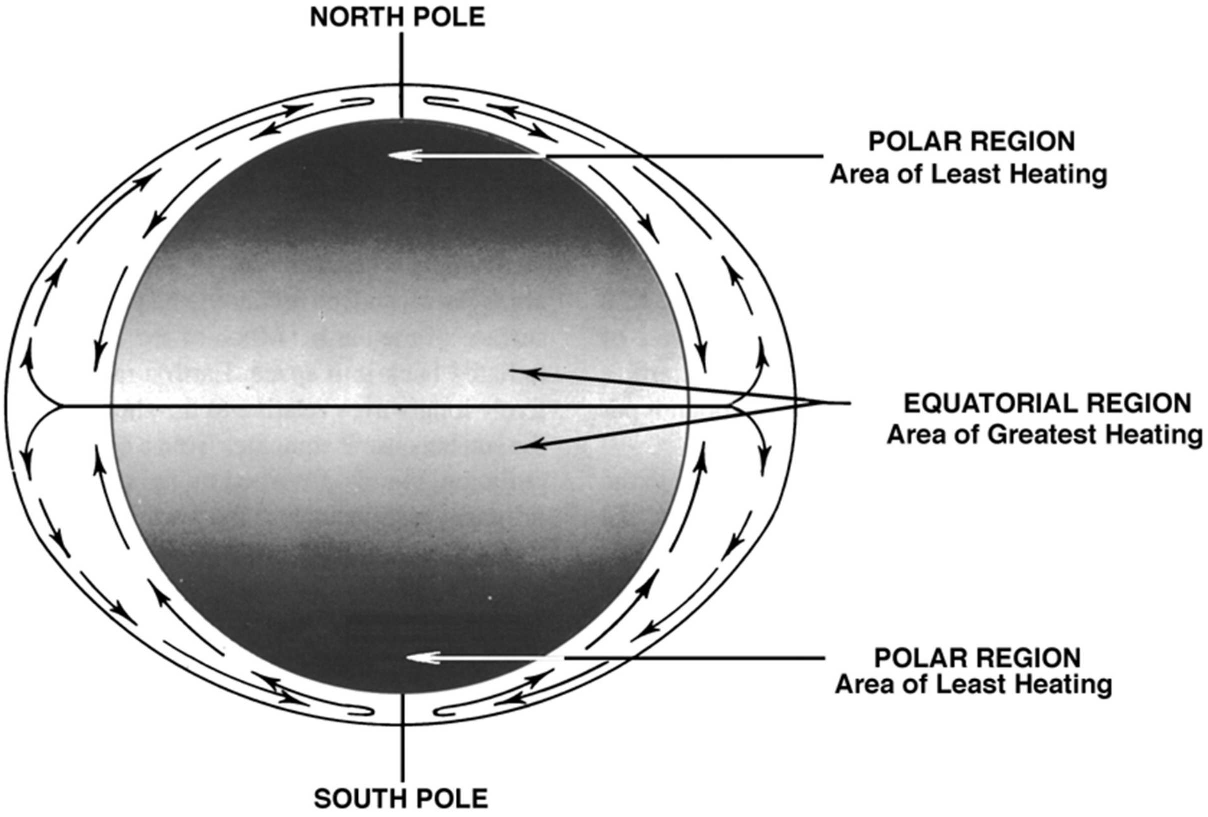

Figure 3802a. Ideal atmospheric circulation for a uniform and non-rotating Earth.

A simplified diagram of the general circulation pattern is shown in Figure 3802b. Figure 3802c and Figure 3802d give a generalized picture of the world's pressure distribution and wind systems as actually observed.

A change in pressure with horizontal distance is called a **pressure gradient**. It is maximum along a normal (per-

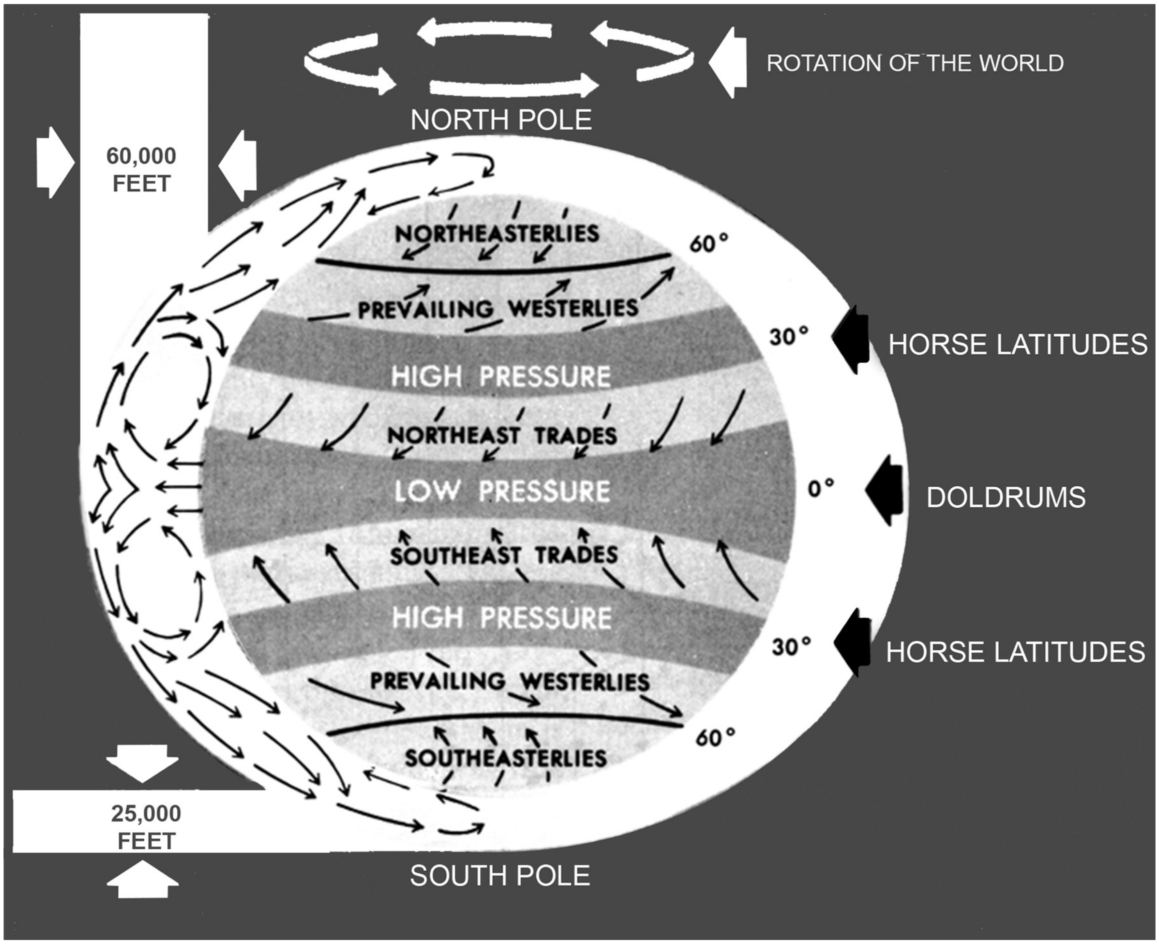

Figure 3802b. Simplified diagram of the general circulation of the atmosphere.

pendicular) to the isobars. A force results which is called **pressure gradient force** and is always directed from high to low pressure. Speed of the wind is approximately proportional to this pressure gradient.

MAJOR WIND PATTERNS

3803. The Doldrums

A belt of low pressure at the Earth's surface near the equator, known as the **doldrums**, occupies a position approximately midway between high pressure belts at about latitude 30° to 35° on each side. Except for significant intradiurnal changes, the atmospheric pressure along the equatorial low is almost uniform. With minimal pressure gradient, wind speeds are light and directions are variable. Hot, sultry days are common. The sky is often overcast, and showers and thundershowers are relatively frequent. In these atmospherically unstable areas, brief periods of strong wind occur.

The doldrums occupy a thin belt near the equator, the eastern part in both the Atlantic and Pacific being wider than the western part. However, both the position and extent of the belt vary with longitude and season. During all seasons in the Northern Hemisphere, the belt is centered in the eastern Atlantic and Pacific; however, there are wide excursions of the doldrum regions at longitudes with considerable landmass. On the average, the position is at 5°N, frequently called the **meteorological equator**.

3804. The Trade Winds

The trade winds at the surface blow from the belts of high pressure toward the equatorial belts of low pressure. Because of the rotation of the Earth, the moving air is deflected toward the west. Therefore, the trade winds in the Northern Hemisphere are from the northeast and are called the **northeast trades**, while those in the Southern Hemisphere are from the southeast and are called the **southeast trades**. The trade-wind directions are best defined over eastern ocean areas.

The trade winds are generally considered among the

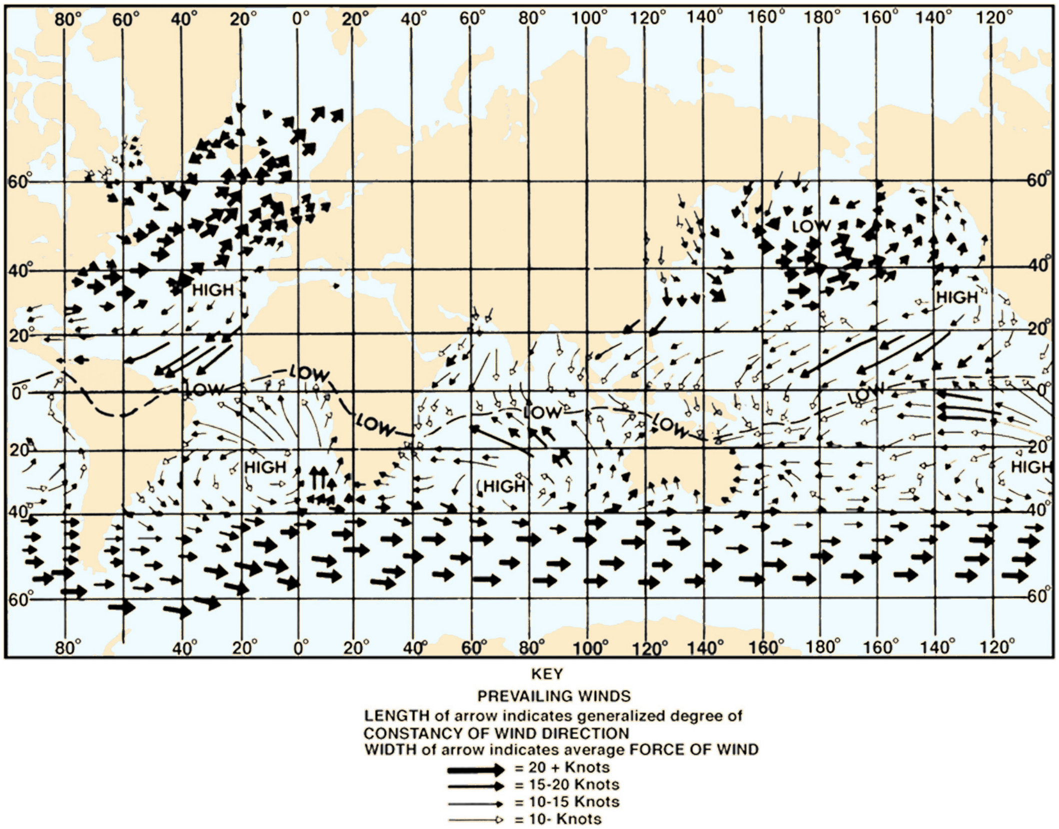

Figure 3802c. Generalized pattern of actual surface winds in January and February.

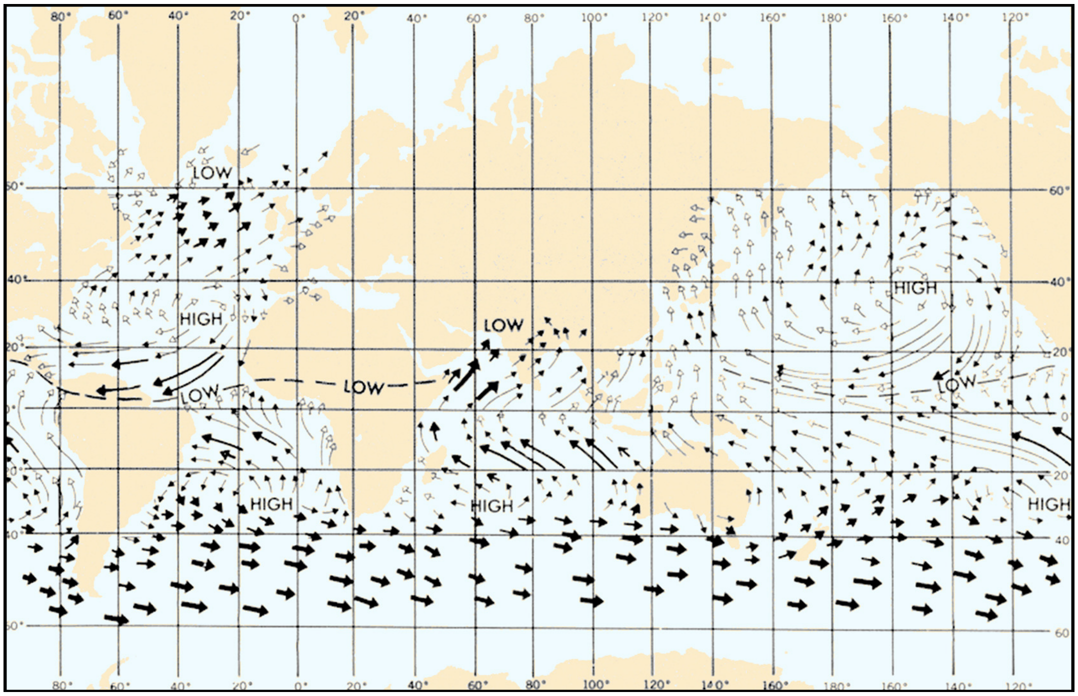

Figure 3802d. Generalized pattern of actual surface winds in July and August. (See key with Figure 3402c).

most constant of winds, blowing for days or even weeks with little change of direction or speed. However, at times they weaken or shift direction, and there are regions where the general pattern is disrupted. A notable example is found in the island groups of the South Pacific, where the trades are practically nonexistent during January and February. Their best development is attained in the South Atlantic and in the South Indian Ocean. In general, they are stronger during the winter than during the summer season.

In July and August, when the belt of equatorial low pressure moves to a position some distance north of the equator, the southeast trades blow across the equator, into the Northern Hemisphere, where the Earth's rotation diverts them toward the right, causing them to be southerly and southwesterly winds. The “southwest monsoons” of the African and Central American coasts originate partly in these diverted southeast trades.

Cyclones from the middle latitudes rarely enter the regions of the trade winds, although tropical cyclones originate within these areas.

3805. The Horse Latitudes

Along the poleward side of each trade-wind belt and corresponding approximately with the belt of high pressure in each hemisphere, is another region with weak pressure gradients and correspondingly light, variable winds. These are called the **horse latitudes**, apparently so named because becalmed sailing ships threw horses overboard in this region when water supplies ran short. The weather is generally good although low clouds are common. Compared to the doldrums, periods of stagnation in the horse latitudes are less persistent. The difference is due primarily to the rising currents of warm air in the equatorial low, which carries large amounts of moisture. This moisture condenses as the air cools at higher levels, while in the horse latitudes the air is apparently descending and becoming less humid as it is warmed at lower heights.

3806. The Prevailing Westerlies

On the poleward side of the high pressure belt in each hemisphere, the atmospheric pressure again diminishes. The currents of air set in motion along these gradients toward the poles are diverted by the Earth's rotation toward the east, becoming southwesterly winds in the Northern Hemisphere and northwesterly in the Southern Hemisphere. These two wind systems are known as the **prevailing westerlies** of the temperate zones.

In the Northern Hemisphere this relatively simple pattern is distorted considerably by secondary wind circulations, due primarily to the presence of large landmasses. In the North Atlantic, between latitudes 40° and 50°, winds blow from some direction between south and northwest during 74 percent of the time, being somewhat more persistent in winter than in summer. They are stronger in winter, too, averaging about 25 knots (Beaufort 6) as compared with 14 knots (Beaufort 4) in the summer.

In the Southern Hemisphere the westerlies blow throughout the year with a steadiness approaching that of the trade winds. The speed, though variable, is generally between 17 and 27 knots (Beaufort 5 and 6). Latitudes 40°S to 50°S, where these boisterous winds occur, are called the **roaring forties**. These winds are strongest at about latitude 50°S.

The greater speed and persistence of the westerlies in the Southern Hemisphere are due to the difference in the atmospheric pressure pattern, and its variations, from the Northern Hemisphere. In the comparatively landless Southern Hemisphere, the average yearly atmospheric pressure diminishes much more rapidly on the poleward side of the high pressure belt, and has fewer irregularities due to continental interference, than in the Northern Hemisphere.

3807. Polar Winds

Partly because of the low temperatures near the geographical poles of the Earth, the surface pressure tends to remain higher than in surrounding regions, since cold air is more dense than warm air. Consequently, the winds blow outward from the poles and are deflected westward by the rotation of the Earth, to become **northeasterlies** in the Arctic, and **southeasterlies** in the Antarctic. Where the polar easterlies meet the prevailing westerlies, near 50°N and 50°S on the average, a discontinuity in temperature and wind exists. This discontinuity is called the **polar front**. Here the warmer low-latitude air ascends over the colder polar air creating a zone of cloudiness and precipitation.

In the Arctic, the general circulation is greatly modified by surrounding landmasses. Winds over the Arctic Ocean are somewhat variable, and strong surface winds are rarely encountered.

In the Antarctic, on the other hand, a high central landmass is surrounded by water, a condition which augments, rather than diminishes, the general circulation. A high pressure, although weaker than in the horse latitudes, is stronger than in the Arctic and of great persistence especially in eastern Antarctica. The cold air from the plateau areas moves outward and downward toward the sea and is deflected toward the west by the Earth's rotation. The winds remain strong throughout the year, frequently attaining hurricane force near the base of the mountains. These are some of the strongest surface winds encountered anywhere in the world, with the possible exception of those in well-developed tropical cyclones.

3808. Modifications of the General Circulation

The general circulation of the atmosphere is greatly modified by various conditions. The high pressure in the horse latitudes is not uniformly distributed around the belts, but tends to be accentuated at several points, as shown in Figure 3802c and Figure 3802d. These semi-permanent highs remain at about the same places with great persistence.

Semi-permanent lows also occur in various places, the most prominent ones being west of Iceland and over the Aleutians (winter only) in the Northern Hemisphere, and in the Ross Sea and Weddell Sea in the Antarctic areas. The regions occupied by these semi-permanent lows are sometimes called the graveyards of the lows, since many lows move directly into these areas and lose their identity as they merge with and reinforce the semi-permanent lows. The low pressure in these areas is maintained largely by the migratory lows which stall there, with topography also important, especially in Antarctica.

Another modifying influence is land, which undergoes greater temperature changes than does the sea. During the summer, a continent is warmer that its adjacent oceans. Therefore, low pressures tend to prevail over the land. If a climatological belt of high pressure encounters a continent, its pattern is distorted or interrupted, whereas a belt of low pressure is intensified over the same area. In winter, the opposite effect takes place, belts of high pressure being intensified over land and those of low pressure being weakened.

The most striking example of a wind system produced by the alternate heating and cooling of a landmass is the **monsoon** (seasonal wind) of the South China Sea and Indian Ocean. A portion of this effect is shown in Figure 3808. In the summer, low pressure prevails over the warm continent of Asia, and relatively higher pressure prevails over the adjacent, cooler sea. Between these two systems the wind blows in a nearly steady direction. The lower portion of the pattern is in the Southern Hemisphere, extending to about 10° south latitude. Here the rotation of the Earth causes a deflection to the left, resulting in southeasterly winds. As they cross the equator, the deflection is in the opposite direction, causing them to curve toward the right, becoming southwesterly winds. In the winter, the positions of high and low pressure areas are interchanged, and the direction of flow is reversed.

In the South China Sea, the summer monsoon blows from the southwest, usually from May to September. The strong winds are accompanied by heavy squalls and thunderstorms, the rainfall being much heavier than during the winter monsoon. As the season advances, squalls and rain become less frequent. In some places the wind becomes a light breeze which is unsteady in direction, or stops altogether, while in other places it continues almost undiminished, with changes in direction or calms being infrequent. The winter monsoon blows from the northeast, usually from October to April. It blows with a steadiness similar to that of the trade winds, often attaining the speed of a moderate gale (28-33 knots). Skies are generally clear during this season, and there is relatively little rain.

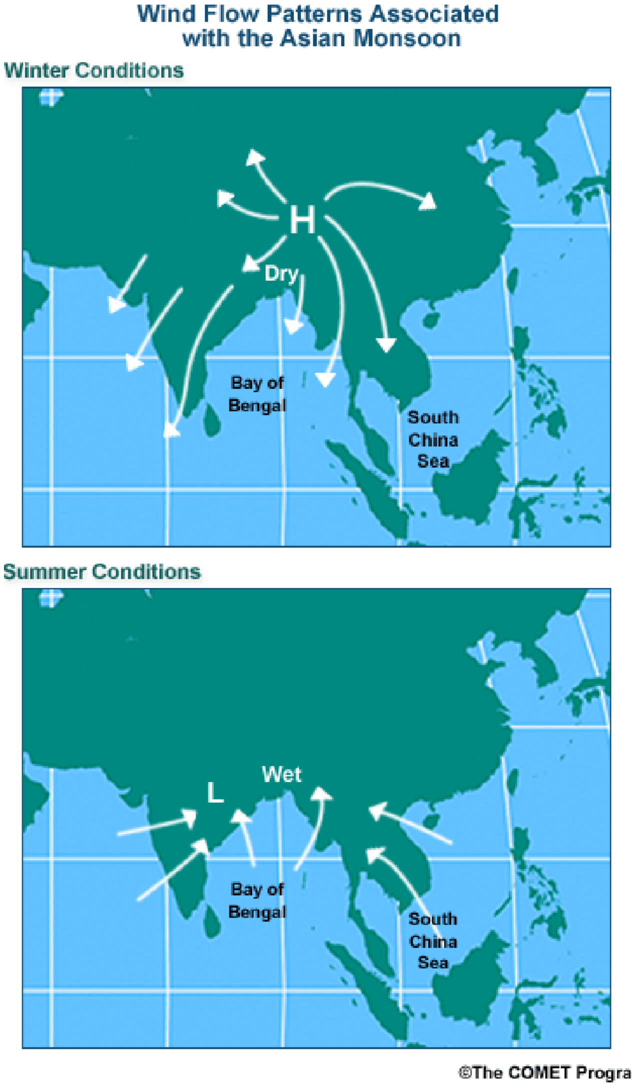

Figure 3808. The winter and summer monsoon. Used with permission of UCAR/COMET Program.

The general circulation is further modified by winds of cyclonic origin and various local winds. Some common local winds are listed by **local name** below:

Abroholos	A squall frequent from May through August between Cabo de Sao Tome and Cabo Frio on the coast of Brazil.
Bali wind	A strong east wind at the eastern end of Java.

Barat	A heavy northwest squall in Manado Bay on the north coast of the island of Celebes, prevalent from December to February.
Barber	A strong wind carrying damp snow or sleet and spray that freezes upon contact with objects, especially the beard and hair.
Bayamo	A violent wind blowing from the land on the south coast of Cuba, especially near the Bight of Bayamo.
Bentu de Soli	An east wind on the coast of Sardinia.
Bora	A cold, northerly wind blowing from the Hungarian basin into the Adriatic Sea. See also FALL WIND.
Borasco	A thunderstorm or violent squall, especially in the Mediterranean.
Brisa, Briza	1. A northeast wind which blows on the coast of South America or an east wind which blows on Puerto Rico during the trade wind season. 2. The northeast monsoon in the Philippines.
Brisote	The northeast trade wind when it is blowing stronger than usual on Cuba.
Brubu	A name for a squall in the East Indies.
Bull’s Eye Squall	A fair weather squall characteristic of the ocean off the coast of South Africa. It is named for the peculiar appearance of the small isolated cloud marking the top of the invisible vortex of the storm.
Cape Doctor	The strong southeast wind which blows on the South African coast. Also called the DOCTOR.
Caver, Kaver	A gentle breeze in the Hebrides.
Chubasco	A violent squall with thunder and lightning, encountered during the rainy season along the west coast of Central America.
Churada	A severe rain squall in the Mariana Islands during the northeast monsoon. They occur from November to April or May, especially from January through March.
Cierzo	See MISTRAL.
Contrastes	Winds a short distance apart blowing from opposite quadrants, frequent in the spring and fall in the western Mediterranean.
Cordonazo	The “Lash of St. Francis.” Name applied locally to southerly hurricane winds along the west coast of Mexico. It is associated with tropical cyclones in the southeastern North Pacific Ocean. These storms may occur from May to November, but ordinarily affect the coastal areas most severely near or after the Feast of St. Francis, October 4.
Coromell	A night land breeze prevailing from November to May at La Paz, near the southern extremity of the Gulf of California.
Doctor	1. A cooling sea breeze in the Tropics. 2. See HARMATTAN. 3. The strong SE wind which blows on the south African coast. Usually called CAPE DOCTOR.
Elephanta	A strong southerly or southeasterly wind which blows on the Malabar coast of India during the months of September and October and marks the end of the southwest monsoon.
Etesian	A refreshing northerly summer wind of the Mediterranean, especially over the Aegean Sea.
Gregale	A strong northeast wind of the central Mediterranean.
Harmattan	The dry, dusty trade wind blowing off the Sahara Desert across the Gulf of Guinea and the Cape Verde Islands. Sometimes called the DOCTOR because of its supposed healthful properties.
Knik Wind	A strong southeast wind in the vicinity of Palmer, Alaska, most frequent in the winter.
Kona Storm	A storm over the Hawaiian Islands, characterized by strong southerly or southwesterly winds and heavy rains.
Leste	A hot, dry, easterly wind of the Madeira and Canary Islands.

Levanter	A strong easterly wind of the Mediterranean, especially in the Strait of Gibraltar, attended by cloudy, foggy, and sometimes rainy weather especially in winter.
Levantera	A persistent east wind of the Adriatic, usually accompanied by cloudy weather.
Levanto	A hot southeasterly wind which blows over the Canary Islands.
Leveche	A warm wind in Spain, either a foehn or a hot southerly wind in advance of a low pressure area moving from the Sahara Desert. Called a SIROCCO in other parts of the Mediterranean area.
Maestro	A northwesterly wind with fine weather which blows, especially in summer, in the Adriatic. It is most frequent on the western shore. This wind is also found on the coasts of Corsica and Sardinia.
Matanuska Wind	A strong, gusty, northeast wind which occasionally occurs during the winter in the vicinity of Palmer, Alaska.
Mistral	A cold, dry wind blowing from the north over the northwest coast of the Mediterranean Sea, particularly over the Gulf of Lions. Also called CIERZO. See also FALL WIND.
Morning Glory	A rare meteorological phenomenon consisting of a low-level atmospheric solitary wave and associated cloud, occasionally observed in different locations around the world. The wave often occurs as an amplitude-ordered series of waves forming bands of roll clouds. Regularly occurs in the southern part of the Gulf of Carpentaria.
Norte	A strong cold northeasterly wind which blows in Mexico and on the shores of the Gulf of Mexico. It results from an outbreak of cold air from the north. It is the Mexican extension of a norther.
Nashi, N'aschi	A northeast wind which occurs in winter on the Iranian coast of the Persian Gulf, especially near the entrance to the gulf, and also on the Makran coast. It is probably associated with an outflow from the central Asiatic anticyclone which extends over the high land of Iran. It is similar in character but less severe than the BORA.
Papagayo	A violent northeasterly fall wind on the Pacific coast of Nicaragua and Guatemala. It consists of the cold air mass of a *norte* which has overridden the mountains of Central America. See also TEHUANTEPECER.
Pampero	A fall wind of the Argentine coast.
Santa Ana	A strong, hot, dry wind blowing out into San Pedro Channel from the southern California desert through Santa Ana Pass.
Shamal	A summer northwesterly wind blowing over Iraq and the Persian Gulf, often strong during the day, but decreasing at night.
Sharki	A southeasterly wind which sometimes blows in the Persian Gulf.
Sirocco	A warm wind of the Mediterranean area, either a foehn or a hot southerly wind in advance of a low pressure area moving from the Sahara or Arabian deserts. Called LEVECHE in Spain.
Squamish	A strong and often violent wind occurring in many of the fjords of British Columbia. Squamishes occur in those fjords oriented in a northeast-southwest or east-west direction where cold polar air can be funneled westward. They are notable in Jervis, Toba, and Bute inlets and in Dean Channel and Portland Canal. Squamishes lose their strength when free of the confining fjords and are not noticeable 15 to 20 miles offshore.
Suestado	A storm with southeast gales, caused by intense cyclonic activity off the coasts of Argentina and Uruguay, which affects the southern part of the coast of Brazil in the winter.
Sumatra	A squall with violent thunder, lightning, and rain, which blows at night in the Malacca Straits, especially during the southwest monsoon. It is intensified by strong mountain breezes.
Taku Wind	A strong, gusty, east-northeast wind, occurring in the vicinity of Juneau, Alaska, between October and March. At the mouth of the Taku River, after which it is named, it sometimes attains hurricane force.

Tehuantepecer	A violent squally wind from north or north-northeast in the Gulf of Tehuantepec (south of southern Mexico) in winter. It originates in the Gulf of Mexico as a norther which crosses the isthmus and blows through the gap between the Mexican and Guatamalan mountains. It may be felt up to 100 miles out to sea. See also PAPAGAYO.
Tramontana	A northeasterly or northerly winter wind off the west coast of Italy. It is a fresh wind of the fine weather mistral type.
Vardar	A cold fall wind blowing from the northwest down the Vardar valley in Greece to the Gulf of Salonica. It occurs when atmospheric pressure over eastern Europe is higher than over the Aegean Sea, as is often the case in winter. Also called VARDARAC.
Warm Braw	A foehn wind in the Schouten Islands, north of New Guinea.
Williwaw	A sudden blast of wind descending from a mountainous coast to the sea, in the Strait of Magellan or the Aleutian Islands.
White Squall	A sudden, strong gust of wind coming up without warning, noted by whitecaps or white, broken water; usually seen in whirlwind form in clear weather in the tropics.

AIR MASSES

3809. Types of Air Masses

Because of large differences in physical characteristics of the Earth's surface, particularly the oceanic and continental contrasts, the air overlying these surfaces acquires differing values of temperature and moisture. The processes of radiation and convection in the lower portions of the troposphere act in differing characteristic manners for a number of well-defined regions of the Earth. The air overlying these regions acquires characteristics common to the particular area, but contrasts those of other areas. Each distinctive part of the atmosphere, within which common characteristics prevail over a reasonably large area, is called an **air mass**.

Air masses are named according to their source regions. Four regions are generally recognized: (1) equatorial (E), the doldrums area between the north and south trades; (2) tropical (T), the trade wind and lower temperate regions; (3) polar (P), the higher temperate latitudes; and (4) Arctic or Antarctic (A), the north or south polar regions of ice and snow. This classification is a general indication of relative temperature, as well as latitude of origin.

Air masses are further classified as maritime (m) or continental (c), depending upon whether they form over water or land. This classification is an indication of the relative moisture content of the air mass. Tropical air might be designated maritime tropical (mT) or continental tropical (cT). Similarly, polar air may be either maritime polar (mP) or continental polar (cP). Arctic/Antarctic air, due to the predominance of landmasses and ice fields in the high latitudes, is rarely maritime Arctic (mA). Equatorial air is found exclusively over the ocean surface and is designated neither (cE) nor (mE), but simply (E).

A third classification sometimes applied to tropical and polar air masses indicates whether the air mass is warm (w) or cold (k) relative to the underlying surface. Thus, the symbol mTw indicates maritime tropical air which is warmer than the underlying surface, and cPk indicates continental polar air which is colder than the underlying surface. The w and k classifications are primarily indications of stability (i.e., change of temperature with increasing height). If the air is cold relative to the surface, the lower portion of the air mass will be heated, resulting in instability (temperature markedly decreases with increasing height) as the warmer air tends to rise by convection. Conversely, if the air is warm relative to the surface, the lower portion of the air mass is cooled, tending to remain close to the surface. This is a stable condition (temperature increases with increasing height).

Two other types of air masses are sometimes recognized. These are monsoon (M), a transitional form between cP and E; and superior (S), a special type formed in the free atmosphere by the sinking and consequent warming of air aloft.

Atmospheric pressure is directly related to the density of the air mass above any given point on the Earth's surface. Temperature distribution is the most significant regulator or contributor to atmospheric density. Since temperature decreases considerably as you move higher in the troposphere, temperature (density) distribution in the lower troposphere contributes greatly to atmospheric pressure measured at sea-level. Air masses not only are characterized by temperature and moisture, but they also represent distributions of sea-level pressure. Examples of characteristic weather systems associated with air masses include the Arctic High, Bermuda High, Aleutian Low, Icelandic Low, Siberian High, and the Azores High.

3810. Isobars and Wind

Isobars are lines that connect points of equal sea-level pressure across the Earth's surface. Isobars can be thought of as lines of equal density and representative of the three dimensional density structure of the atmosphere. The distance between isobars changes depending on the density difference; the closer the isobars are together, the greater the pressure difference or pressure gradient. As mentioned earlier in this chapter, the pressure gradient or pressure gradient force at sea-level is the force that drives the wind over the ocean.

The graphic in Figure 3810a shows the relationships between the pressure gradient force (PGF), the true wind direction (V), friction (F), and the Coriolis Force (f). The surface winds (V) blow across the isobars at about a 25 to 35 degree angle from higher to lower pressure. Vg is the **geostrophic wind**, the wind in which the **Coriolis Force** (f) and PGF balance each other. At higher levels in the atmosphere the flow becomes more geostrophic due to the reduction in friction away from the surface.

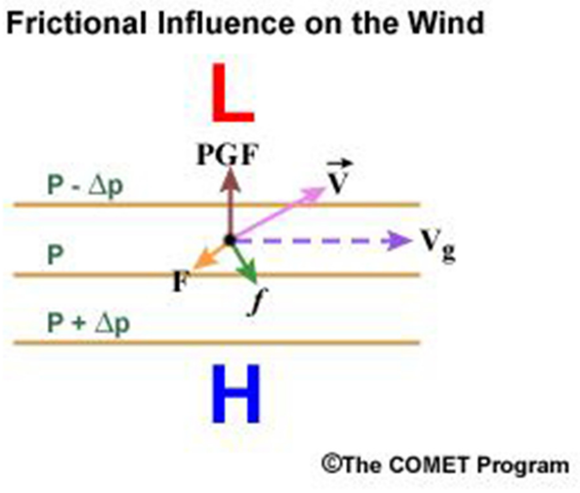

Figure 3810a. A simple pressure gradient of parallel isobars is used to demonstrate that the associated geostrophic wind (Vg) itself would be larger and oriented in a different direction than the real wind (V). The amount of slowing and turning that occurs is dependent on the surface friction (F). The Coriolis force (f) is always directed to the right of the real wind in the Northern Hemisphere and the pressure gradient force (PGF) is always pointed toward lower pressure. Used with permission of UCAR/COMET Program.

In Figure 3810b, isobars define where the pressure centers are located and their intensity is represented by a central pressure in hectopascals. Because average mean sea-level pressure (MSLP) across the globe is 1013.25 hPa, it can be used as a reference to compare any given high or low. The 1035 hPa high in the central Pacific is 22 hPa higher than average; it is a moderate strength high. The 971 hPa low over the western Bering Sea is 42 hPa lower than average and is a strong low. The fronts lie in pressure troughs, as they are concentrated zones of density difference. The closer the isobars are spaced, the higher the wind speed. In the troughs the isobars change direction or turn; therefore, the wind direction shifts due to the change in isobars.

3811. Cyclone and Anticyclone Air Flow

An area of relatively low pressure is called a **cyclone** and is typically depicted by an L as shown in Figure 3810b. Its counterpart for high pressure is called an **anticyclone** and is shown by an H. These terms are used particularly in connection with the winds associated with such centers. Wind tends to blow from an area of high pressure to one of low pressure, but due to the rotation of the Earth, wind is deflected toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere. Cyclones tend to occur along the boundaries between air masses or fronts.

Because of the rotation of the Earth, therefore, the circulation tends to be counterclockwise around areas of low pressure and clockwise around areas of high pressure in the Northern Hemisphere, and the speed is proportional to the spacing of isobars. In the Southern Hemisphere, the direction of circulation is reversed. Based upon this condition, a general rule, known as **Buys Ballot's Law**, or the **Baric Wind Law**, can be stated:

If an observer in the Northern Hemisphere faces away from the surface wind, the low pressure is toward his left; the high pressure is toward his right.

If an observer in the Southern Hemisphere faces away from the surface wind, the low pressure is toward his right; the high pressure is toward his left.

In a general way, these relationships apply in the case of the general distribution of pressure, as well as to temporary local pressure systems.

The reason for the wind shift along a front is that the isobars have a change of direction along these lines. Since the direction of the wind is directly related to the direction of isobars, any change in the latter results in a shift in the wind direction. The isobars change direction because the fronts lie in a trough of lower pressure. The trough is in response to a concentrated temperature (density) difference existing.

In the Northern Hemisphere, the wind shifts toward the right (clockwise) when either a warm or cold front passes. In the Southern Hemisphere, the shift is toward the left (counterclockwise). When an observer is on the poleward side of the path of a frontal wave, wind shifts are reversed (i.e., to the left in the Northern Hemisphere and to the right in the Southern Hemisphere).

In an anticyclone, successive isobars are relatively far apart, resulting in light winds. In a cyclone, the isobars are more closely spaced and as mentioned earlier, have a steeper pressure gradient and thus stronger winds. Anticyclones occur within air masses and are not associated with the boundaries between air masses.

Since an anticyclonic area is a region of outflowing winds, air is drawn into it from aloft. Descending air is warmed, and as air becomes warmer, its capacity for holding uncondensed moisture increases. Therefore, clouds tend to

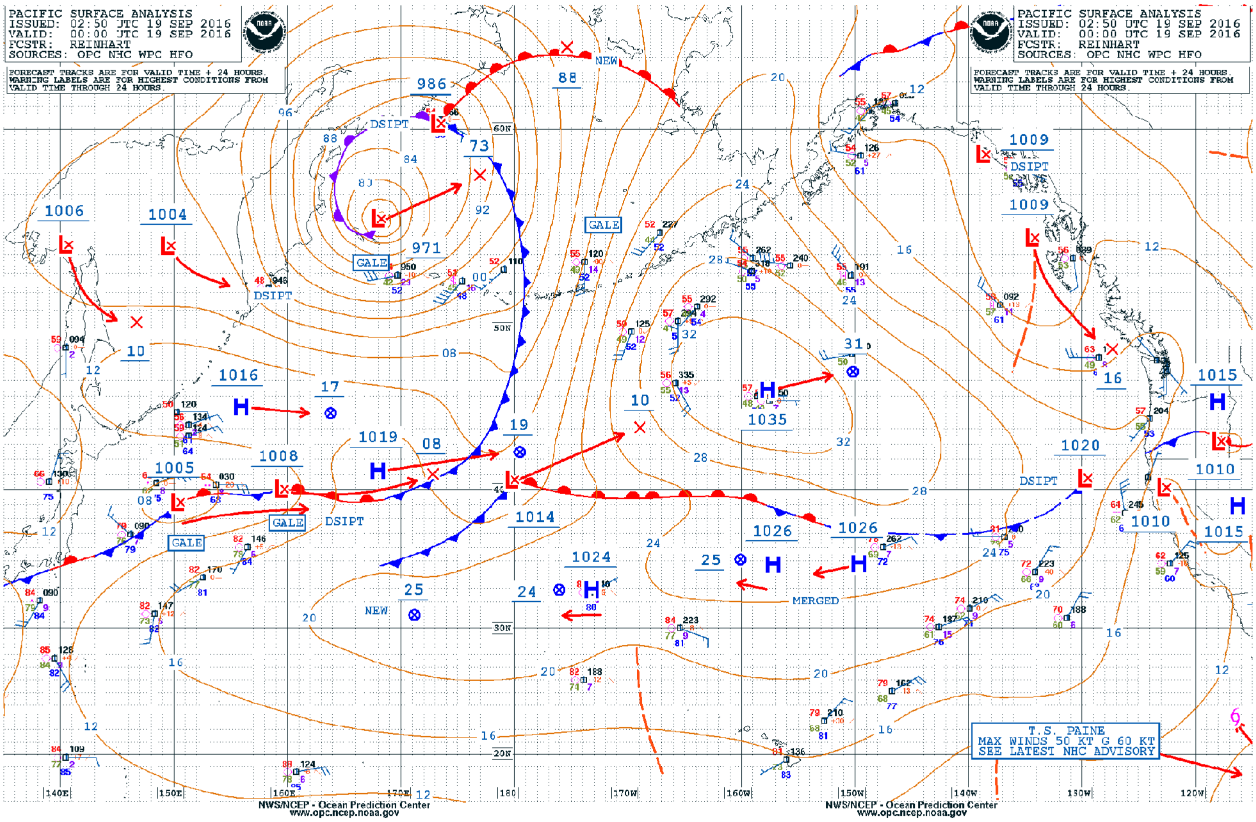

Figure 3810b. Sea-level pressure analysis showing isobars (thin brown solid lines) at 4 hPa intervals, fronts, cyclones (denoted by red L's) and anticyclones (blue H's) for the North Pacific from 0000 UTC 19 September 2016.

dissipate. Clear skies are characteristic of an anticyclone, although scattered clouds and showers are sometimes encountered.

In contrast, a cyclonic area is one of converging winds. The resulting upward movement of air results in cooling, a condition favorable to the formation of clouds and precipitation. More or less continuous rain and generally stormy weather are usually associated with a cyclone.

Between the two hemispheric belts of high pressure associated with the horse latitudes, cyclones form only occasionally over certain areas at sea, generally in summer and fall.

In the areas of the prevailing westerlies, migratory cyclones (lows) and anticyclones (highs) are a common occurrence. These are sometimes called **extra-tropical cyclones** and **extra-tropical anticyclones** to distinguish them from the more violent tropical cyclones. It should be noted that some extra-tropical cyclones do reach hurricane force intensity. Formation of extra-tropical cyclones occurs over sea and land, and the lows intensify as they move poleward. Cyclones begin elongated but as their life cycle proceeds, they become more circular.

3812. Cyclones and Fronts

As air masses move within the general circulation, they travel from their source regions to other areas dominated by air having different temperature and moisture characteristics. Between two air masses a transition of change in temperature, moisture, and wind speed and direction exists. This transition zone is called a **frontal zone** or **front**. Because the frontal zone is a zone of temperature difference in the horizontal and vertical, the density of the atmosphere changes and the isobars form a trough of lower pressure. The stronger the frontal zone, meaning the larger the temperature (density) difference, the lower the pressure in the trough and the stronger the associated winds.

Fronts are represented on weather maps by lines; a cold front is shown with pointed barbs, a warm front with rounded barbs, and an occluded front with both, alternating. The line of the front is placed on the warmest side of the frontal zone. A stationary front is shown with pointed and rounded barbs alternating and on opposite sides of the line with the pointed barbs away from the colder air. The front may take on a wave-like character, becoming a "frontal wave."

Before the formation of frontal waves, the isobars (lines of equal atmospheric pressure) tend to run parallel to the fronts. As a wave is formed, the pattern is distorted somewhat, as shown in Figure 3812a. In this illustration, colder air is north of warmer air. In Figure 3812b through Figure 3812d, isobars are drawn at 4-hectopascal intervals.

The wave tends to travel in the direction of the general circulation, which in the temperate latitudes is usually in an easterly and slightly poleward direction.

In the first stages, these effects are not marked, but as the wave continues to grow, they become more pronounced, as shown in Figure 3812b. As the amplitude of the wave increases, pressure near the center usually decreases, and the low is said to "deepen." As it deepens, its forward speed generally decreases.

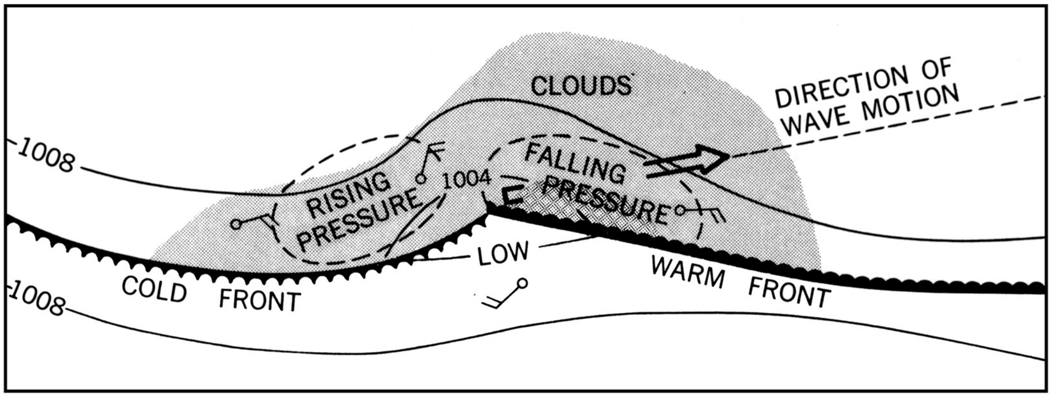

Figure 3812a. First stage in the development of a frontal wave (top view).

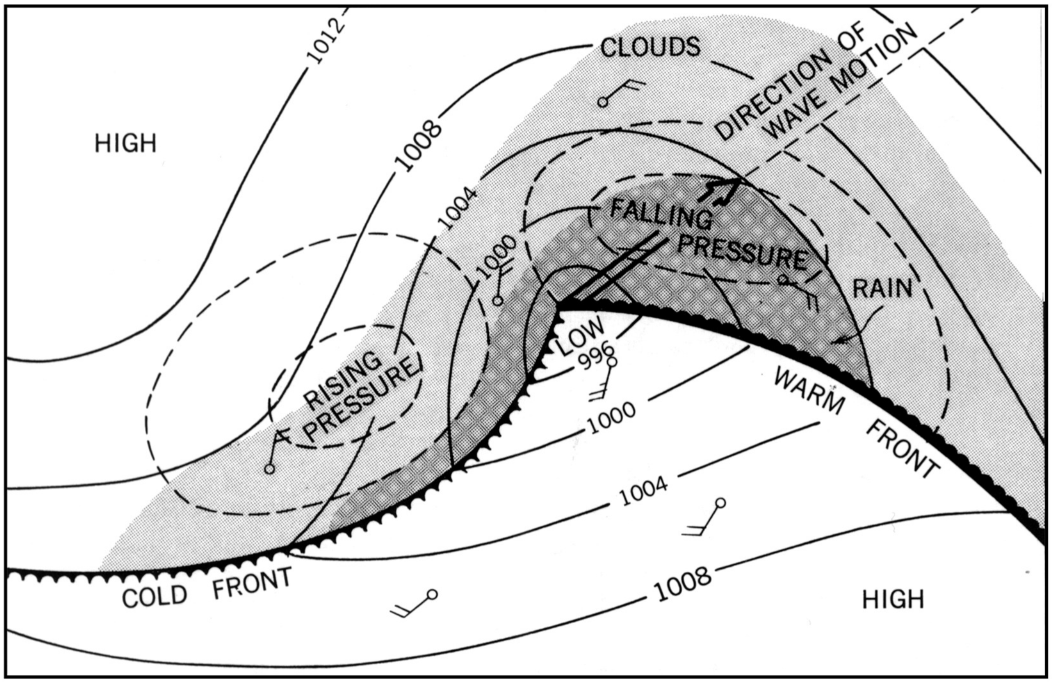

Figure 3812b. A fully developed frontal wave (top view).

Along the leading edge of the wave, warmer air is replacing colder air. This is called the **warm front**. The trailing edge is the **cold front**, where colder air is underrunning and displacing warmer air.

As the warm front passes, the temperature rises, the wind shifts clockwise (in the Northern Hemisphere), and the steady rain stops. Drizzle may fall from low-lying stratus clouds, or there may be fog for some time after the wind shift. During passage of the warm sector between the warm front

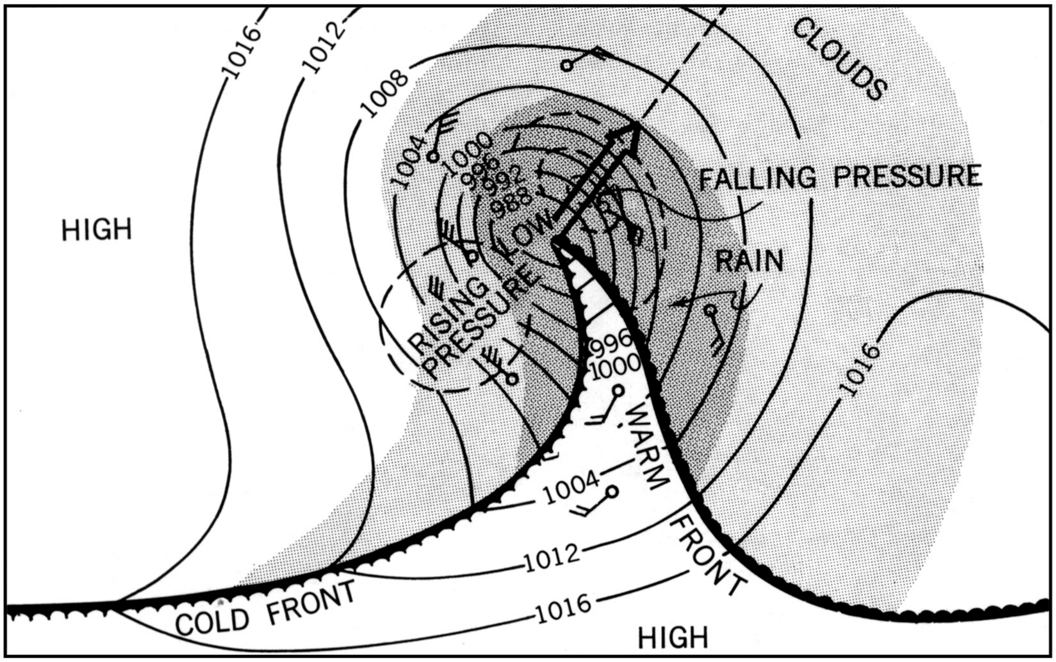

Figure 3812c. A frontal wave nearing occlusion (top view).

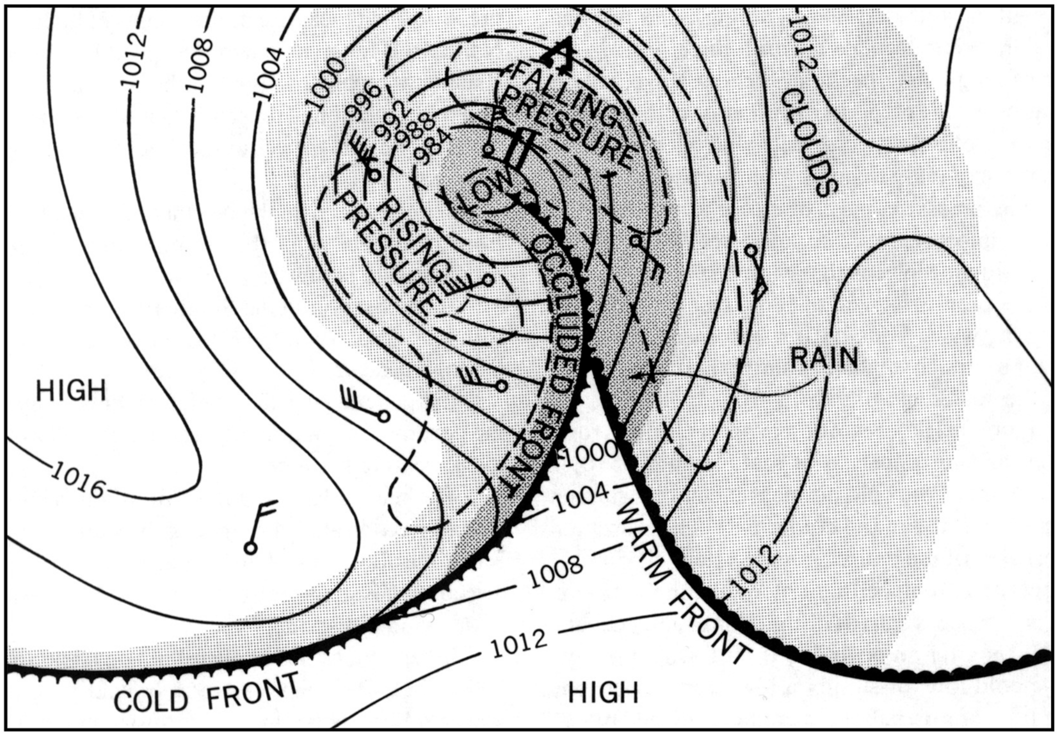

Figure 3812d. An occluded front (top view).

and the cold front, there is little change in temperature or pressure. However, if the wave is still growing and the low deepening, the pressure might slowly decrease. In the warm sector the skies are generally clear or partly cloudy, with cumulus or stratocumulus clouds most frequent. The warm air is usually moist, and haze or fog may often be present.

The warm air, being less dense, tends to ride up greatly over the colder air it is replacing. Partly because of the re-

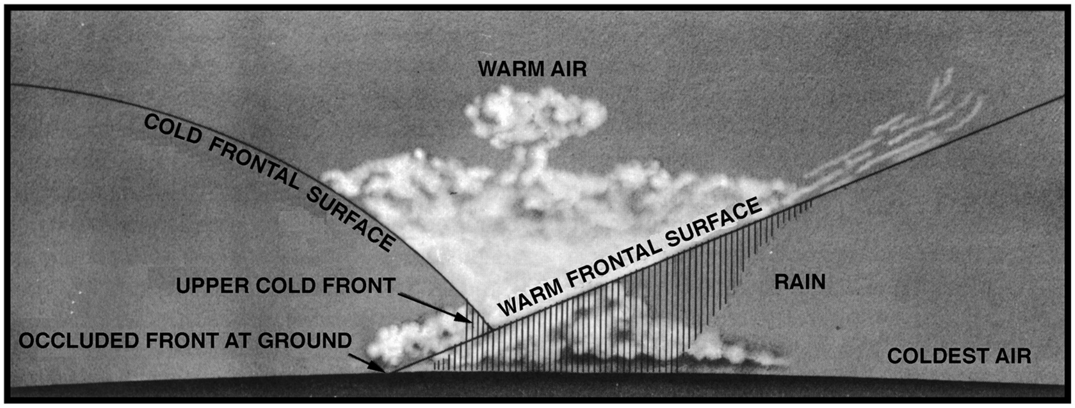

Figure 3812e. An occluded front (cross section).

placement of cold, dense air with warm, light air, the pressure decreases. Since the slope is gentle, the upper part of a warm frontal surface may be many hundreds of miles ahead of the surface portion. The decreasing pressure, indicated by a "falling barometer," is often an indication of the approach of such a wave. In a slow-moving, well-developed wave, the barometer may begin to fall several days before the wave arrives. Thus, the amount and nature of the change of atmospheric pressure between observations, called **pressure tendency**, is of assistance in predicting the approach of such a system.

The advancing cold air, being more dense, tends to ride under the warmer air at the cold front, lifting it to greater heights. The slope here is such that the upper-air portion of the cold front is behind the surface position relative to its motion. After a cold front has passed, the pressure increases, giving a rising barometer.

The approach of a well-developed warm front (i.e., when the warm air is mT) is usually heralded not only by falling pressure, but also by a more-or-less regular sequence of clouds. First, cirrus appear. These give way successively to cirrostratus, altostratus, altocumulus, and nimbostratus. Brief showers may precede the steady rain accompanying the nimbostratus.

As the faster moving, steeper cold front passes, the wind veers (shifts clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere), the temperature falls rapidly, and there are often brief and sometimes violent **squalls** with showers, frequently accompanied by thunder and lightning. Clouds are usually of the convective type. A cold front usually coincides with a well-defined wind-shift line (a line along which the wind shifts abruptly from southerly or southwesterly to northerly or northwesterly in the Northern Hemisphere, and from northerly or northwesterly to southerly or southwesterly in the Southern Hemisphere). At sea, a series of brief showers accompanied by strong, shifting winds may occur along or some distance (up to 200 miles) ahead of a cold front. These are called squalls (in common nautical use, the term **squall** may be additionally applied to any severe local storm accompanied by gusty winds, precipitation, thunder, and lightning), and the line along which they occur is called a **squall line**.

Because of its greater speed and steeper slope, which may approach or even exceed the vertical near the Earth's surface (due to friction), a cold front and its associated weather pass more quickly than a warm front. After a cold front passes, the pressure rises, often quite rapidly, the visibility usually improves, and the clouds tend to diminish. Clear, cool or cold air replaces the warm hazy air.

As the wave progresses and the cold front approaches the slower moving warm front, the low becomes deeper and the warm sector becomes smaller, as shown in Figure 3812c.

Finally, when the two parts of the cold air mass meet, the warmer portion tends to rise above the colder part as shown in Figure 3812e and Figure 3412e. The warm air continues to rise until the entire frontal system dissipates. The catch up mechanism of the cold front overtaking the warm front to form the occlusion is best described as a roll up of frontal zones (isotherms, lines of equal temperature) and not a catching up of fronts.

As the warmer air is replaced by colder air, the pressure gradually rises, a process called **filling**. This usually occurs within a few days after an occluded front forms. Finally, there results a cold low, or simply a low pressure system across which little or no gradient in temperature and moisture can be found.

The sequence of weather associated with a low depends greatly upon the observer's location with respect to the path of the center. That described previously assumes that the low center passes poleward of the observer. If the low center passes south of the observer, between the observer and the equator, the abrupt weather changes associated with the passage of fronts are not experienced. Instead, the change from the weather characteristically found ahead of a warm front, to that behind a cold front, takes place gradually. The exact sequence is dictated by the distance from the center, the severity and age of the low.

Although each low generally follows this pattern, no two are ever exactly alike. Other centers of low pressure and high pressure, and the air masses associated with them, even though they may be 1,000 miles or more away, influence the formation and motion of individual low centers and their accompanying weather. Particularly, a high stalls or diverts a low. This is true of temporary highs as well as semi-permanent highs, but not to as great a degree.

Studies of explosively intensifying maritime cyclones in the late 1980's and early 1990s revealed an alternative model to portray the evolution of frontal cyclones over the oceans. This model is shown in Figure 3812f and was developed after studying numerical model results and data acquired by research aircraft. It is commonly called the **Shapiro Keyser Model**. Four phases of development were identified: the incipient frontal wave (I), the frontal fracture (II), bent-back front and frontal T-bone (III), and warm core seclusion (IV). This model related the frontal evolution (top portion of Figure 3812f) with the amplification and roll up of the thermal wave by displaying the changes in the temperature structure and air flows over time (as shown in the bottom illustrations of Figure 3812f).

Similar to the earlier description, a frontal wave develops on a pre-existing frontal zone as a kink in the temperature gradient (phase I). The front separates the colder easterly flow from the warmer westerly flow to the south of the front. Clouds and precipitation mainly occur to the east of the developing low pressure and north of the developing warm front.

In the frontal fracture (phase II), the thermal wave has amplified with isotherms (lines of constant temperature) contracting as the temperature gradients along the fronts strengthen. The cold front has separated (fractured) from the warm front as can be seen below phase II in Figure 3812f. The warm front has extended to the west of the developing low center as the temperature gradient has strengthened to the west of the low pressure center. The temperature frontal wave has taken on more of a T shape with two distinct fronts and airflows. The cold front is fractured from the warm front because the temperature gradient immediately south of the low is weak but strengthens as one

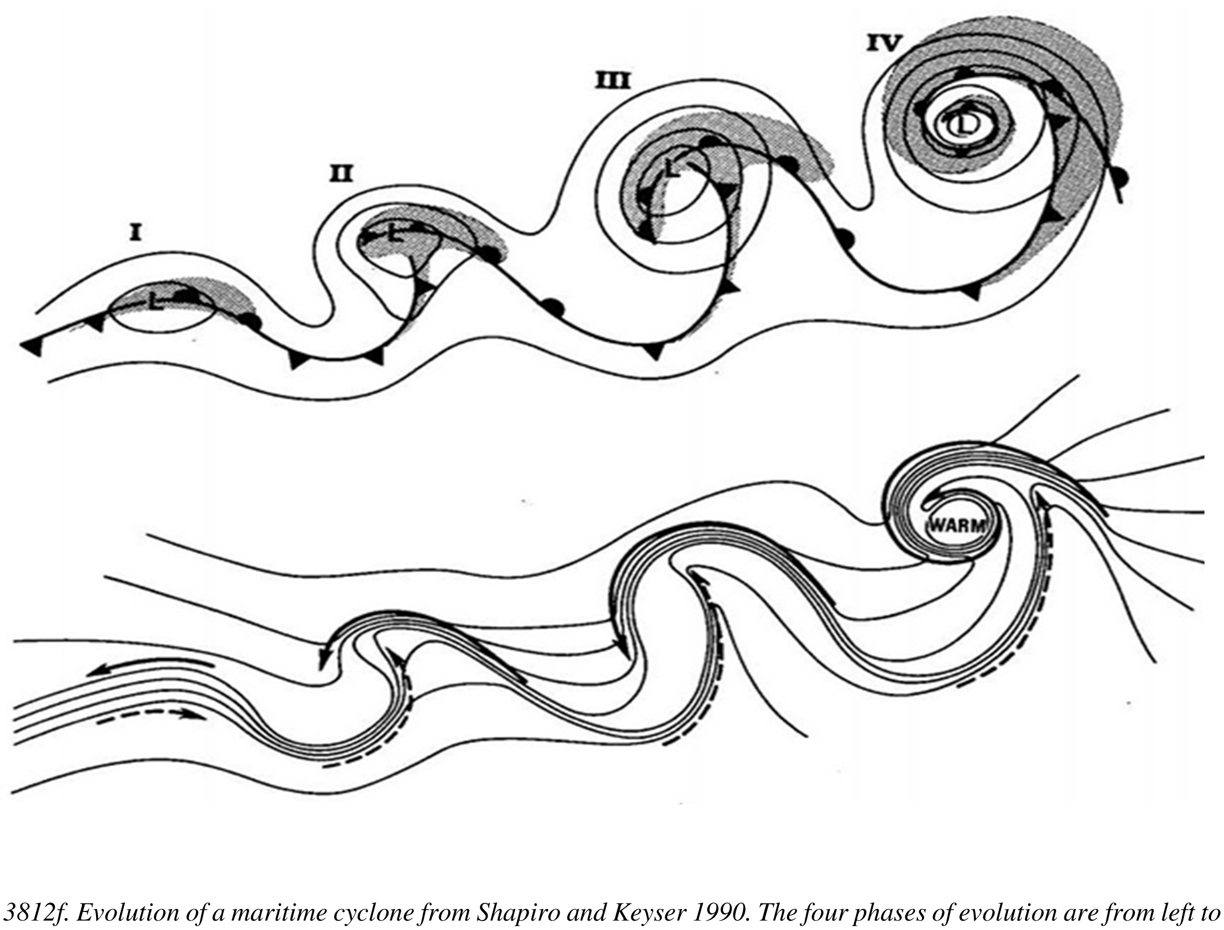

Figure 3812f. Evolution of a maritime cyclone from Shapiro and Keyser 1990. The four phases of evolution are from left to right: incipient frontal wave (I), frontal fracture (II), bent-back front and frontal T-bone (III), and warm core seclusion (IV). Top series showing evolution over time of isobars, fronts, and cloud pattern. Bottom series showing cold and warm airflows-solid and dashed arrows, and isotherms (lines of equal temperature)-solid thin lines.

moves farther south along the cold.

The process continues in phase III as the frontal wave continues to amplify. Temperature gradients continue to constrict as they intensify and thus the fronts strengthen. The warm front that extended further west of the low center in from phase II begins to wrap eastward under (equatorward of) the low center. At this point it is referred to as the bent-back front. Often the highest winds in this phase are on the cold side (west, in this case) of the bent-back front where the isobars have the tightest packing or gradient. This is in the vicinity of the arrow head in the bottom image of phase III.

Phase IV is the mature phase of the evolution. In this final phase, the bent-back front has encircled the low pressure center as the thermal wave rolls up like an ocean wave. In the lower troposphere, warm air has pooled over the vicinity of the low center and is surrounded by cooler air. This warm pool is called a **warm seclusion** and is a sign of the cyclone nearing or reaching its lowest pressure and strongest intensity. Highest winds often occur equatorward (south and southwest in the Northern Hemisphere) of the low center on the cold side of the bent-back front. Warm seclusions were once thought to be rare but are a frequent occurrence in strong ocean cyclones. Wind speed estimates from space-based radar instruments called **scatterometers** often show the highest winds in this region on the cold (equatorward) side of the encircling bent-back front.

3813. Ocean Storm Evolution Example

The following are examples of a North Atlantic storm from 2011 that reached hurricane force strength. The series of four graphics (as seen in Figures 3413a through d) includes infrared (thermal) satellite imagery of clouds, sea-level pressure, wind speed, and infrared satellite image for phases I, II, III, and IV of the cyclone. The graphics illustrate the relationship between the frontal evolution of the fronts and the wind field. Each cyclone is different due to the complexity of the atmosphere; however, the main frontal features and wind field are fairly typical of a winter maritime cyclone in either the North Atlantic or Pacific. Wind speeds are shown by the color bar in the center of the figure.

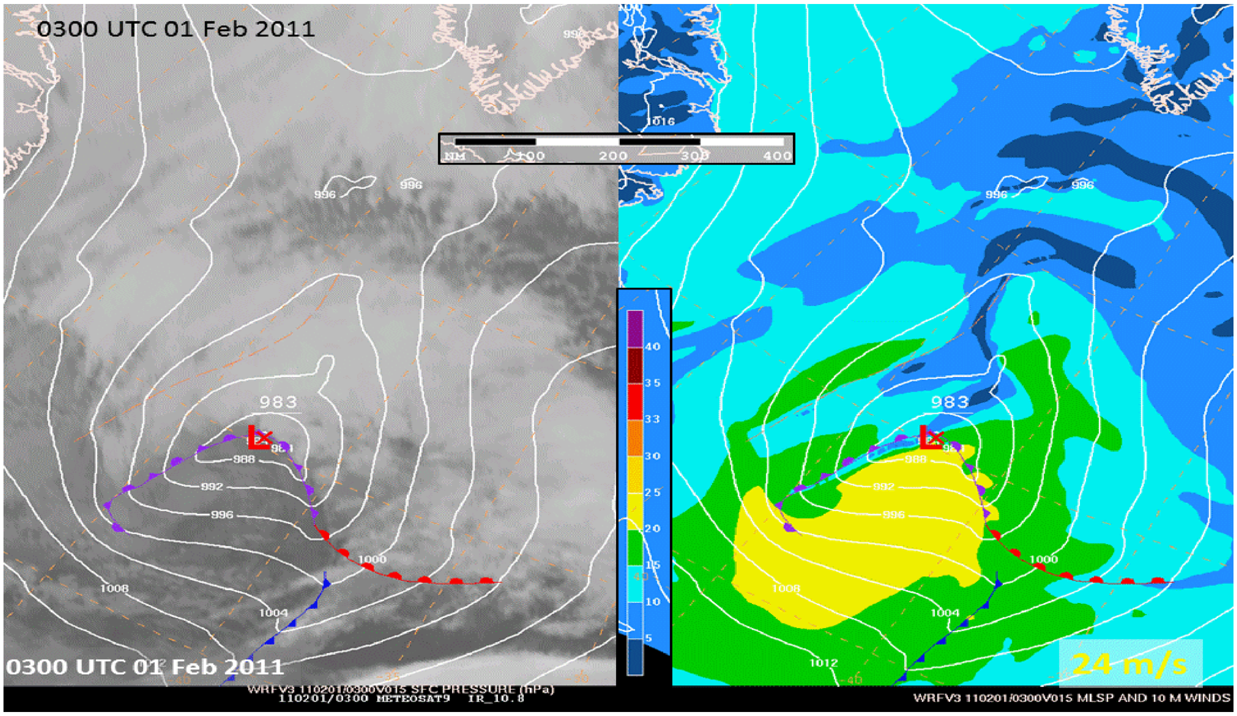

Figure 3813a. Two panel image of a North Atlantic cyclone from 0300 UTC 01 Feb 2011 showing isobars at 4 hPa intervals, infrared satellite image from Meteosat geostationary satellite, fronts, and central pressure (left). On the right panel, isobars and numerical model wind speeds from 10m above the ocean surface colored based on the color bar on the left of the panel. Maximum 10m wind speed is listed in the lower right in m/s showing 24 m/s.

There are three main fronts with this cyclone (Figure 3813a), the warm front (red) extending southeastward from the low center, the cold front (blue) extending south and southwest from the junction of the warm to occluded front, and the occluded front (purple) extending through the cyclone center and then to the southwest and south well west of the cyclone center. The portion of the occluded front west of the center is the bent-back front or bent-back occlusion. It is very similar to a warm front through the low center and then behaves much more like a cold front to the west. The highest winds in this example at this time were in the zone south of the low center in the colder air between the bent-back and cold front.

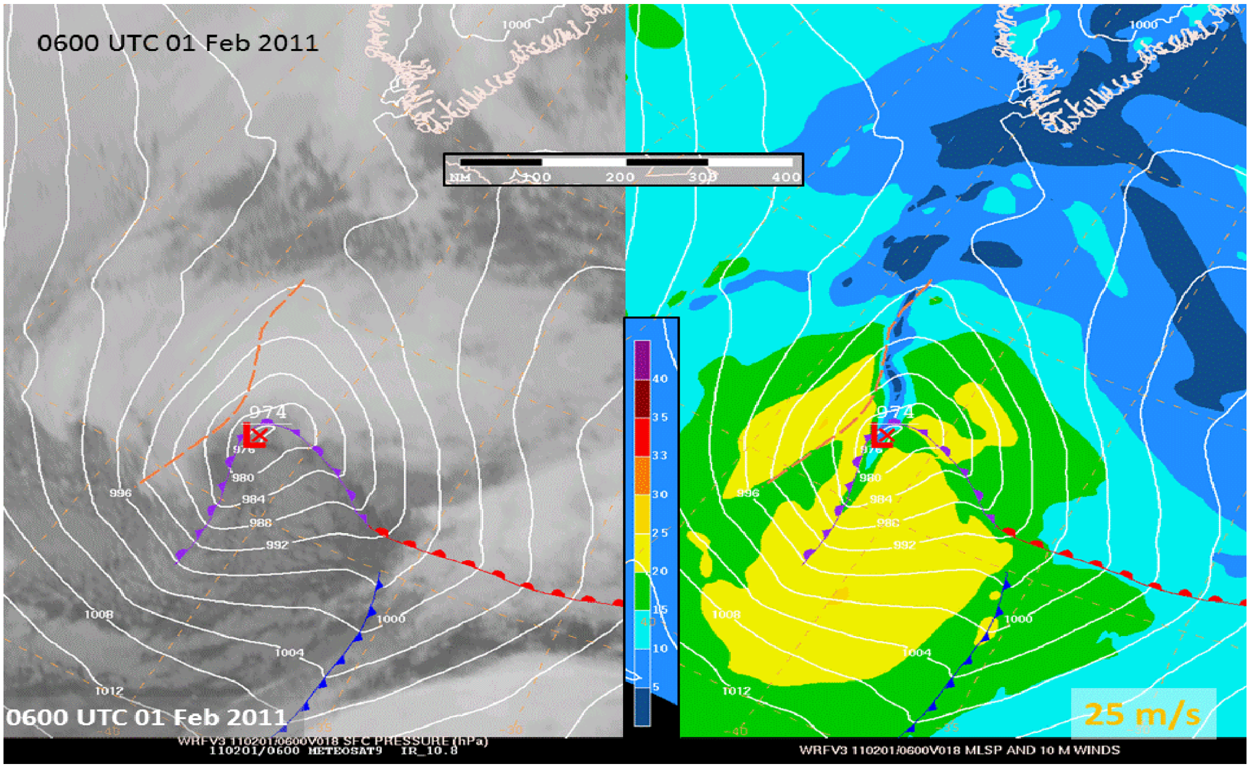

Figure 3813b. As in the previous figure but for 0600 UTC 01 Feb 2011.

Three hours later (Figure 3813b) the cyclone has deepened to 974 hPa and the wind field has expanded with a larger area of winds 20 to 25 m/s. Winds have increased to the east of the low center northeast of the occluded front, to the west of the bent-back, and also to the west of a developing trough of lower pressure to the west of the low center. The bent-back front is sweeping eastward to the south of the low center. Maximum wind speed is 25 m/s.

Another 3 hours have gone by (Figure 3813c) and at 0900 UTC the low center has further dropped in central pressure by 6 hPa in 3 hours. The wind field has further expanded and more importantly, the area of maximum wind speeds is concentrated to the southwest of the bent-back front. Comparing to the 0600 UTC, the bent-back front has continued to wrap eastward to the south of the low center and the wind speeds immediately southwest of the bent-back front have increased to 30 to 34 m/s or hurricane force. The highest wind speeds are often found in this region of intensifying ocean cyclones. The fronts continue to lie in pressure troughs delineating both wind shifts and wind maxima. To the north of the low the trough of lower pressure (dashed orange/brown line at 0300 and 0600 UTC) has strengthened into a frontal zone that behaves similarly to a warm front. In this case this northwestward pointing frontal zone separates modified cold air north of the warm and occluded fronts from colder and more dense Arctic air from northern Canada and the Labrador Sea.

In the final image (Figure 3813d) a narrow zone of very intense winds lies immediately to the south of the bent-back front with a core of winds well into hurricane force of 35 m/s. Maximum wind speed was 36 m/s per the numerical model used to represent this storm. Satellite radar-based wind speed estimates also showed winds to hurricane force. The cold frontal fracture has expanded and the isobars south of the warm to occluded juncture change direction only gradually. The gradual turning of the isobars means there is no longer a concentrated zone of temperature difference in this area. It does not mean there is no temperature difference, just that the difference occurs over a broad zone. The significant frontal zones are associated with the warm front, occluded front, the bent-back to the south of the low center and the stationary front extending northwest from the bent-back front. Notice that a wind maximum lies adjacent and on the cold side of each frontal zone. This illustrates that fronts and their evolution have a very important relationship to the wind field evolution. In this maturing phase of the cyclone, warm air has been advected or drawn into the region above the cyclone center and is surrounded by colder air. This zone of warmer air is called the warm seclusion, thus the warm seclusion phase of the cyclone evolution. On the south side of the warm seclusion is a very intense zone of temperature difference or gradient associat-

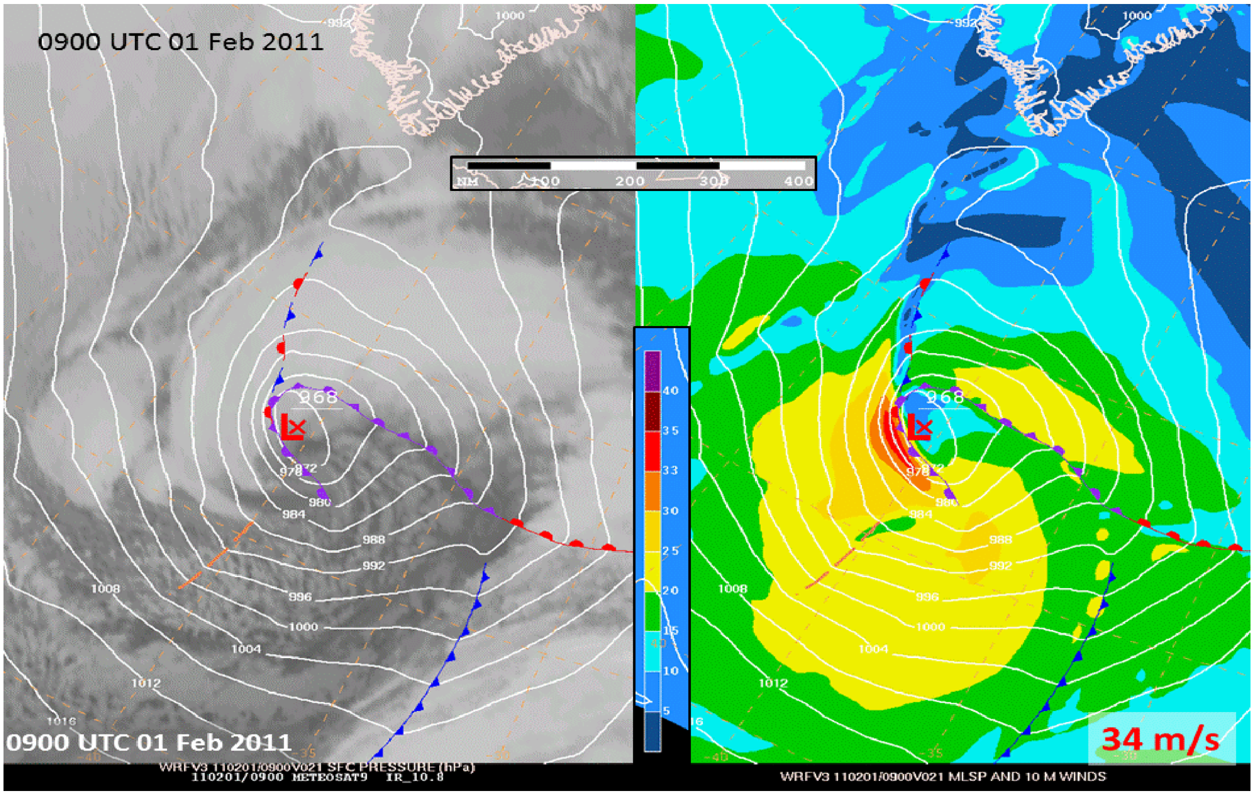

Figure 3813c. As in the previous figure but for 0900 UTC 01 Feb 2011.

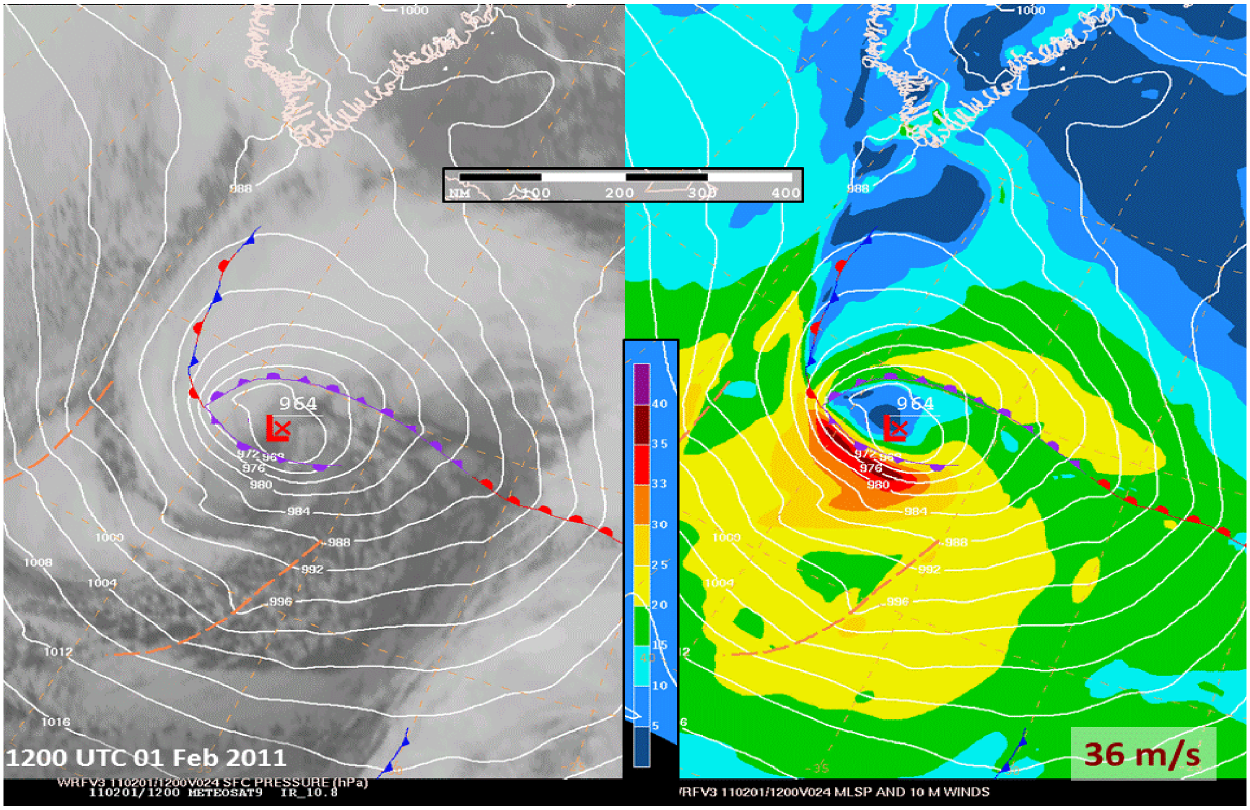

Figure 3813d. As in the previous figure but for 1200 UTC 01 Feb 2011.

ed with the bent-back front. Often this bent-back frontal zone is the strongest zone of temperature contrast during the life of the storm. The atmosphere compensates for this intense frontal zone by developing very high winds near the ocean surface. It is in this area that forecasters often observe violent storm or hurricane force winds. It is also a favored area for extreme waves to develop, occasionally in excess of 15 to 20 m.

By 1200 UTC the cyclone has reached a central pressure of 964 hPa, a drop of 19 hPa in 9 hours. A rough rule of thumb for a cyclone to explosively deepen is for the central pressure to drop at a rate of 1 hPa per hour. This cyclone has deepened over 2 hPa per hour. Rapidly intensifying ocean cyclones that deepened 24 hPa or greater in 24 hours are called "**bombs**" or **meteorological bombs**. Deepening rates that qualify as "bombs" vary with latitude with 1 hPa reduction in central pressure per hour (24 hPa in 24 hours) being valid at 60 degrees latitude. Poleward of 60 degrees, the rate required for a "bomb" is greater than 1 hPa per hour. Equatorward, the required rate for a "bomb" is less than 1 hPa/hour. The cyclone illustrated here qualifies as a strong bomb. Graphical weather analyses and forecasts issued by the U.S. National Weather Service use the phrase Rapidly Intensifying (RPDLY INTSFYG) to highlight potential explosive intensification.

Earlier depictions of cyclone evolution and the occlusion process have value such as where to expect pressure falls and rises, precipitation, wind shifts, and clouds. Utilizing satellite-sensed winds and waves and numerical forecast models, suggest that the Shapiro-Keyser Cyclone evolution from frontal wave to mature warm seclusion well represents the latest in understanding.

LOCAL WEATHER PHENOMENA

3814. Local Winds

In addition to the winds of the general circulation and those associated with migratory cyclones and anticyclones, there are numerous local winds which influence the weather in various places.

Varying conditions of topography produce a large variety of local winds throughout the world. Winds tend to follow valleys, and tend to deflect from high banks and shores. In mountain areas wind flows in response to temperature distribution and gravity. An **anabolic wind** is one that blows up an incline, usually as a result of surface heating. A **katabatic wind** is one which blows down an incline. There are two types, **foehn** and **fall wind**.

The **foehn** (fãn) is a warm, dry wind which initiates from horizontally moving air encountering a mountain barrier. As it blows upward to clear the mountains, it is cooled below the dew point, resulting in clouds and rain on the windward side. As the air continues to rise, its rate of cooling is reduced because the condensing water vapor gives off heat to the surrounding atmosphere. After crossing the mountain barrier, the air flows downward along the leeward slope, being warmed by compression as it descends to lower levels. Since it loses less heat on the ascent than it gains during descent, and since it has lost its moisture during ascent, it arrives at the bottom of the mountains as very warm, dry air. This accounts for the warm, arid regions along the eastern side of the Rocky Mountains and in similar areas. In the Rocky Mountain region this wind is known by the name **chinook**. It may occur at any season of the year, at any hour of the day or night, and have any speed from a gentle breeze to a gale. It may last for several days or for a very short period. Its effect is most marked in winter, when it may cause the temperature to rise as much as 20°F to 30°F within 15 minutes, and cause snow and ice to melt within a few hours. On the west coast of the United States, a foehn wind, given the name **Santa Ana**, blows through a pass and down a valley of that name in Southern California. This wind is frequently very strong and may endanger small craft immediately off the coast.

A cold wind blowing down an incline is called a **fall wind**. Although it is warmed somewhat during descent, as is the foehn, it remains cold relative to the surrounding air. It occurs when cold air is dammed up in great quantity on the windward side of a mountain and then spills over suddenly, usually as an overwhelming surge down the other side. It is usually quite violent, sometimes reaching hurricane force. A different name for this type wind is given at each place where it is common. The **tehuantepecer** of the Mexican and Central American coast, the **pampero** of the Argentine coast, the **mistral** of the western Mediterranean, and the **bora** of the eastern Mediterranean are examples of this wind.

Many other local winds common to certain areas have been given distinctive names. A **blizzard** is a violent, intensely cold wind laden with snow mostly or entirely picked up from the ground, although the term is often used popularly to refer to any heavy snowfall accompanied by strong wind. A **dust whirl** is a rotating column of air about 100 to 300 feet in height, carrying dust, leaves, and other light material. This wind, which is similar to a waterspout at sea, is given various local names such as dust devil in southwestern United States and desert devil in South Africa. A gust is a sudden, brief increase in wind speed, followed by a slackening, or the violent wind or squall that accompanies a thunderstorm. A puff of wind or a light breeze affecting a small area, such as would cause patches of ripples on the surface of water, is called a **cat's paw**.

The most common are the land and sea breezes, caused by alternate heating and cooling of land adjacent to water. The effect is similar to that which causes the monsoons, but on a much smaller scale, and over shorter periods. By day the land is warmer than the water, and by night it is cooler. This effect occurs along many coasts during the summer.

Between about 0900 and 1100 local time the temperature of the land becomes greater than that of the adjacent water. The lower levels of air over the land are warmed, and the air rises, drawing in cooler air from the sea. This is the **sea breeze** and is shown in Figure 3814a. Late in the afternoon, when the Sun is low in the sky, the temperature of the two surfaces equalizes and the breeze stops. After sunset, as the land cools below the sea temperature, the air above it is also cooled. The contracting cool air becomes more dense, increasing the pressure near the surface. This results in an outflow of winds to the sea. This is the **land breeze**, which blows during the night and dies away near sunrise. The land breeze is illustrated in Figure 3814b. Since the atmospheric pressure changes associated with this cycle are not great, the accompanying winds generally do not exceed gentle to moderate breezes. The circulation is usually of limited extent reaching a distance of perhaps 20 miles inland, not more than 5 or 6 miles offshore, and to a height of a few hundred feet. In the doldrums and subtropics, this process is repeated with great regularity throughout most of the year. As the latitude increases, it becomes less prominent, being masked by winds of migratory cyclones and anticyclones. However, the effect often may be present to reinforce, retard, or deflect stronger prevailing winds.

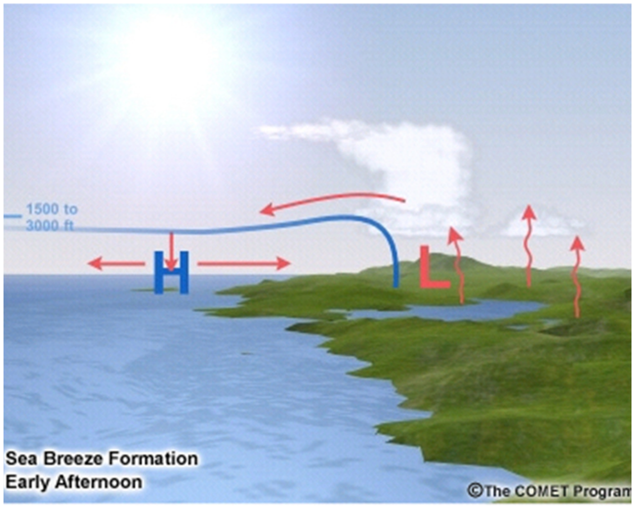

Figure 3814a. Sea breeze formation in the early afternoon.Used with permission of UCAR/COMET Program.

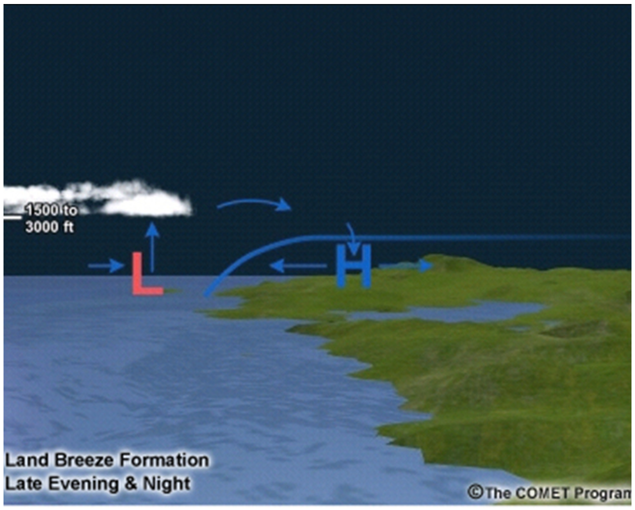

Figure 3814b. Land breeze formation in the late evening and at night.Used with permission of UCAR/COMET Program.

3815. Waterspouts

A **waterspout** is a small, whirling storm over ocean or inland waters. Its chief characteristic is a tall, funnel-shaped cloud; when fully developed it is usually attached to the base of a cumulus cloud. See Figure 3815. The water in a waterspout is mostly confined to its lower portion, and may be either salt spray drawn up by the sea surface, or freshwater resulting from condensation due to the lowered pressure in the center of the vortex creating the spout. The air in waterspouts may rotate clockwise or counterclockwise, depending on the manner of formation. They are found most frequently in tropical regions, but are not uncommon in higher latitudes.

There are two types of waterspouts: **tornadoes** which are those derived from violent convective storms over land moving seaward, and those formed over the sea and which are associated with fair or foul weather. The latter type is most common, lasts a maximum of 1 hour, and has variable strength. Many waterspouts are no stronger than dust whirlwinds, which they resemble; at other times they are strong enough to destroy small craft or to cause damage to larger vessels, although modern ocean-going vessels have little to fear.

Waterspouts vary in diameter from a few feet to several hundred feet, and in height from a few hundred feet to several thousand feet. Sometimes they assume fantastic shapes; in early stages of development an elongated hour glass shape between cloud and sea is common. Since a waterspout is often inclined to the vertical, its actual length may be much greater than indicated by its height.

3816. Deck Ice

Ships traveling through regions where the air temperature is below freezing may acquire thick deposits of ice as a result of salt spray freezing on the rigging, deckhouses, and deck areas. This accumulation of ice is called **ice accretion**. Also, precipitation may freeze to the superstructure and exposed areas of the vessel, increasing the load of ice. See Figure 3816.

On small vessels in heavy seas and freezing weather, deck ice may accumulate very rapidly and increase the topside weight enough to capsize the vessel. Accumulations of more than 2 cm per hour are classified as

Figure 3815. Waterspout. Image courtesy of NOAA.

heavy freezing spray. Fishing vessels with outriggers, A-frames, and other top hamper are particularly susceptible.

Figure 3816. Deck ice.

RESTRICTED VISIBILITY

3817. Fog

Fog is a cloud whose base is at the surface of the Earth, and is composed of droplets of water or ice crystals (ice fog) formed by condensation or crystallization of water vapor in the air.

Radiation fog forms over low-lying land on clear, calm nights. As the land radiates heat and becomes cooler, it cools the air immediately above the surface. This causes a temperature inversion to form, the temperature increasing with height. If the air is cooled to its dew point, fog forms. Often, cooler and more dense air drains down surrounding slopes to heighten the effect. Radiation fog is often quite shallow, and is usually densest at the surface. After sunrise the fog may "lift" and gradually dissipate, usually being entirely gone by noon. At sea the temperature of the water undergoes little change between day and night, and so radiation fog is seldom encountered more than 10 miles from shore.

Advection fog forms when warm, moist air blows over a colder surface and is cooled below its dew point. It is most commonly encountered at sea, may be quite dense, and often persists over relatively long periods. Advection fog is common over cold ocean currents. If the wind is strong enough to thoroughly mix the air, condensation may take place at some distance above the surface of the Earth, forming low stratus clouds rather than fog.

Off the coast of California, seasonal winds create an offshore current which displaces the warm surface water, causing an upwelling of colder water. Moist Pacific air is transported along the coast in the same wind system and is cooled by the relatively cold water. Advection fog results. In the coastal valleys, fog is sometimes formed when moist air blown inland during the afternoon is cooled by radiation during the night.

When very cold air moves over warmer water, wisps of visible water vapor may rise from the surface as the water "steams." In extreme cases this **frost smoke**, or **Arctic sea smoke**, may rise to a height of several hundred feet, the portion near the surface constituting a dense fog which obscures the horizon and surface objects, but usually leaves the sky relatively clear.

Haze consists of fine dust or salt particles in the air too small to be individually apparent, but in sufficient number might reduce horizontal visibility and cast a bluish or yellowish veil over the landscape, subduing its colors and making objects appear indistinct. This is sometimes called dry haze to distinguish it from damp haze, which consists of small water droplets or moist particles in the air, smaller and more scattered than light fog. In international meteorological practice, the term "haze" is used to refer to a condition of atmospheric obscurity caused by dust and smoke.

Mist is synonymous with drizzle in the United States but is often considered as intermediate between haze and fog in its properties. Heavy mist can reduce visibility to a mile or less.

A mixture of smoke and fog is called **smog**. Normally it is not a problem in navigation except in severe cases accompanied by an offshore wind from the source, when it may reduce visibility to 2-4 miles.

ATMOSPHERIC EFFECTS ON LIGHT RAYS

3818. Mirage

Light is refracted as it passes through the atmosphere. When refraction is normal, objects appear slightly elevated, and the visible horizon is farther from the observer than it otherwise would be. Since the effects are uniformly progressive, they are not apparent to the observer. When refraction is not normal, some form of mirage may occur. A **mirage** is an optical phenomenon in which objects appear distorted, displaced (raised or lowered), magnified, multiplied, or inverted due to varying atmospheric refraction which occurs when a layer of air near the Earth's surface differs greatly in density from surrounding air. This may occur when there is a rapid and sometimes irregular change of temperature or humidity with height. See Figure 3818a.

Figure 3818a. Distorted image of the moon rising.

If there is a temperature inversion (increase of temperature with height), particularly if accompanied by a rapid decrease in humidity, the refraction is greater than normal. Objects appear elevated, and the visible horizon is farther away. Objects which are normally below the horizon become visible. This is called **looming**. If the upper portion of an object is raised much more than the bottom part, the object appears taller than usual, an effect called **towering**. If the lower part of an object is raised more than the upper part, the object appears shorter, an effect called **stooping**. When the refraction is greater than normal, a superior mirage may occur. An inverted image is seen above the object, and sometimes an erect image appears over the inverted one, with the bases of the two images touching. Greater than normal refraction usually occurs when the water is much colder than the air above it.

If the temperature decrease with height is much greater than normal, refraction is less than normal, or may even cause bending in the opposite direction. Objects appear lower than normal, and the visible horizon is closer to the observer. This is called **sinking**. Towering or stooping may also occur if conditions are suitable. When the refraction is reversed, an inferior mirage may occur. A ship or an island appears to be floating in the air above a shimmering horizon, possibly with an inverted image beneath it. Conditions suitable to the formation of an inferior mirage occur when the surface is much warmer than the air above it. This usually requires a heated landmass, and therefore is more common near the coast than at sea.

When refraction is not uniformly progressive, objects may appear distorted, taking an almost endless variety of shapes. The Sun, when near the horizon, is one of the objects most noticeably affected. A **fata morgana** is a complex mirage characterized by marked distortion, generally in the vertical. It may cause objects to appear towering, magnified, and at times even multiplied. See Figure 3818b.

Figure 3818b. A fata morgana captured from South Pole Station, Antarctica.

3819. Sky Coloring

White light is composed of light of all colors. Color is related to wavelength, with the visible spectrum varying from about 400 to 700nanometers. The characteristics of each color are related to its wavelength (or frequency). The shorter the wavelength, the greater the amount of bending when light is refracted. It is this principle that permits the separation of light from celestial bodies into a spectrum ranging from red, through orange, yellow, green, and blue, to violet, with infrared being slightly outside the visible range at one end and ultraviolet being slightly outside the visible range at the other end. Light of shorter wavelengths is scattered and diffracted more than that of longer wavelengths.

Light from the Sun and Moon is white, containing all colors. As it enters the Earth's atmosphere, a certain amount of it is scattered. The blue and violet, being of shorter wavelength than other colors, are scattered most. Most of the violet light is absorbed in the atmosphere. Thus, the scattered blue light is most apparent, and the sky appears blue. At great heights, above most of the atmosphere, it appears black.

When the Sun is near the horizon, its light passes through more of the atmosphere than when higher in the sky, resulting in greater scattering and absorption of blue and green light, so that a larger percentage of the red and orange light penetrates to the observer. For this reason the Sun and Moon appear redder at this time, and when this light falls upon clouds, they appear colored. This accounts for the colors at sunset and sunrise. As the setting Sun approaches the horizon, the sunset colors first appear as faint tints of yellow and orange. As the Sun continues to set, the colors deepen. Contrasts occur, due principally to differences in heights of clouds. As the Sun sets, the clouds become a deeper red, first the lower clouds and then the higher ones, and finally they fade to a gray.

When there is a large quantity of smoke, dust, or other material in the sky, unusual effects may be observed. If the material in the atmosphere is of suitable substance and quantity to absorb the longer wavelength red, orange, and yellow light, the sky may have a greenish tint, and even the Sun or Moon may appear green. If the green light, too, is absorbed, the Sun or Moon may appear blue. A green Moon or blue Moon is most likely to occur when the Sun is slightly below the horizon and the longer wavelength light from the Sun is absorbed, resulting in green or blue light being cast upon the atmosphere in front of the Moon. The effect is most apparent if the Moon is on the same side of the sky as the Sun.

3820. Rainbows

The **rainbow**, that familiar arc of concentric colored bands seen when the Sun shines on rain, mist, spray, etc., is caused by refraction, internal reflection, and diffraction of sunlight by the drops of water. The center of the arc is a point 180° from the Sun, in the direction of a line from the Sun passing through the observer. The radius of the brightest rainbow is 42°. The colors are visible because of the difference in the amount of refraction of the different colors making up white light, the light being spread out to form a spectrum. Red is on the outer side and blue and violet on the inner side, with orange, yellow, and green between, in that order from red.

Sometimes a secondary rainbow is seen outside the primary one, at a radius of about 50°. The order of colors of this rainbow is reversed. Very rarely, a third can be seen. On rare occasions a faint rainbow is seen on the same side as the Sun. The radius of this rainbow and the order of colors are the same as those of the primary rainbow.

Figure 3820. A fogbow.

A similar arc formed by light from the Moon (a lunar rainbow) is called a **Moonbow**. The colors are usually very faint. A faint, white arc of about 39° radius is occasionally seen in fog opposite the Sun. This is called a **fogbow**. See Figure 3820.

3821. Halos

Refraction, or a combination of refraction and reflection, of light by ice crystals in the atmosphere may cause a **halo** to appear. The most common form is a ring of light of radius 22° or 46° with the Sun or Moon at the center. Cirrostratus clouds are a common source of atmospheric ice crystals. Occasionally a faint, white circle with a radius of 90° appears around the Sun. This is called a **Hevelian halo**. It is probably caused by refraction and internal reflection of the Sun's light by bipyramidal ice crystals. A halo formed by refraction is usually faintly colored like a rainbow, with red nearest the celestial body and blue farthest from it.

A brilliant rainbow-colored arc, of about a quarter of a circle with its center at the zenith and the bottom of the arc about 46° above the Sun, is called a **circumzenithal arc**. Red is on the outside of the arc, nearest the Sun. It is produced by the refraction and dispersion of the Sun's light striking the top of prismatic ice crystals in the atmosphere and may be so brilliant as to be mistaken for an unusually bright rainbow. A similar arc formed 46° below the Sun, with red on the upper side, is called a **circumhorizontal arc**. Any arc tangent to a **heliocentric halo** (one surrounding the Sun) is called a **tangent arc**. As the Sun increases in elevation, such arcs tangent to the halo of 22° gradually bend their ends toward each other. If they meet, the elongated curve enclosing the circular halo is called a **circumscribed halo**. The inner edge is red.

A halo consisting of a faint, white circle through the Sun and parallel to the horizon is called a **parhelic circle**. A similar one through the Moon is called a **paraselenic circle**. They are produced by reflection of Sunlight or Moonlight from vertical faces of ice crystals.

A **parhelion** (plural: parhelia) is a form of halo consisting of an image of the Sun at the same altitude and some distance from it, usually 22°, but occasionally 46°. A similar phenomenon occurring at an angular distance of 120° (sometimes 90° or 140°) from the Sun is called a **paranthelion**. One at an angular distance of 180°, a rare occurrence, is called an **anthelion**, although this term is also used to refer to a luminous, colored ring or glory sometimes seen around the shadow of one's head on a cloud or fog bank. A parhelion is popularly called a mock Sun or Sun dog. Similar phenomena in relation to the Moon are called **paraselene** (popularly a mock Moon or Moon dog), **parantiselene**, and **antiselene**. The term parhelion should not be confused with perihelion, the orbital point nearest the Sun when the Sun is the center of attraction.

A Sun pillar is a glittering shaft of white or reddish light occasionally seen extending above and below the Sun, usually when the Sun is near the horizon. A phenomenon similar to a **Sun pillar**, but observed in connection with the Moon, is called a **Moon pillar**. A rare form of halo in which horizontal and vertical shafts of light intersect at the Sun is called a **Sun cross**. It is probably due to the simultaneous occurrence of a Sun pillar and a parhelic circle. A similar phenomenon around the Moon is called a **Moon cross**.

See Figure 3821 for a depiction of many of these halo phenomenons.

3822. Corona

When the Sun or Moon is seen through altostratus clouds, its outline is indistinct, and it appears surrounded by a glow of light called a **corona**. This is somewhat similar in appearance to, but quite distinct in cause from, the corona seen around the Sun during a solar eclipse. When the effect is due to clouds, the glow may be accompanied by one or more rainbow-colored rings of small radii, with the celestial body at the center. These can be distinguished from a halo by their much smaller radii and also by the fact that the order of the colors is reversed, red being on the inside, nearest the body, in the case of the halo, and on the outside, away from the body, in the case of the corona.

A corona is caused by diffraction of light by tiny droplets of water. The radius of a corona is inversely proportional to the size of the water droplets. A large corona indicates small droplets. If a corona decreases in size, the water droplets are becoming larger and the air more humid. This may be an indication of an approaching rainstorm. The

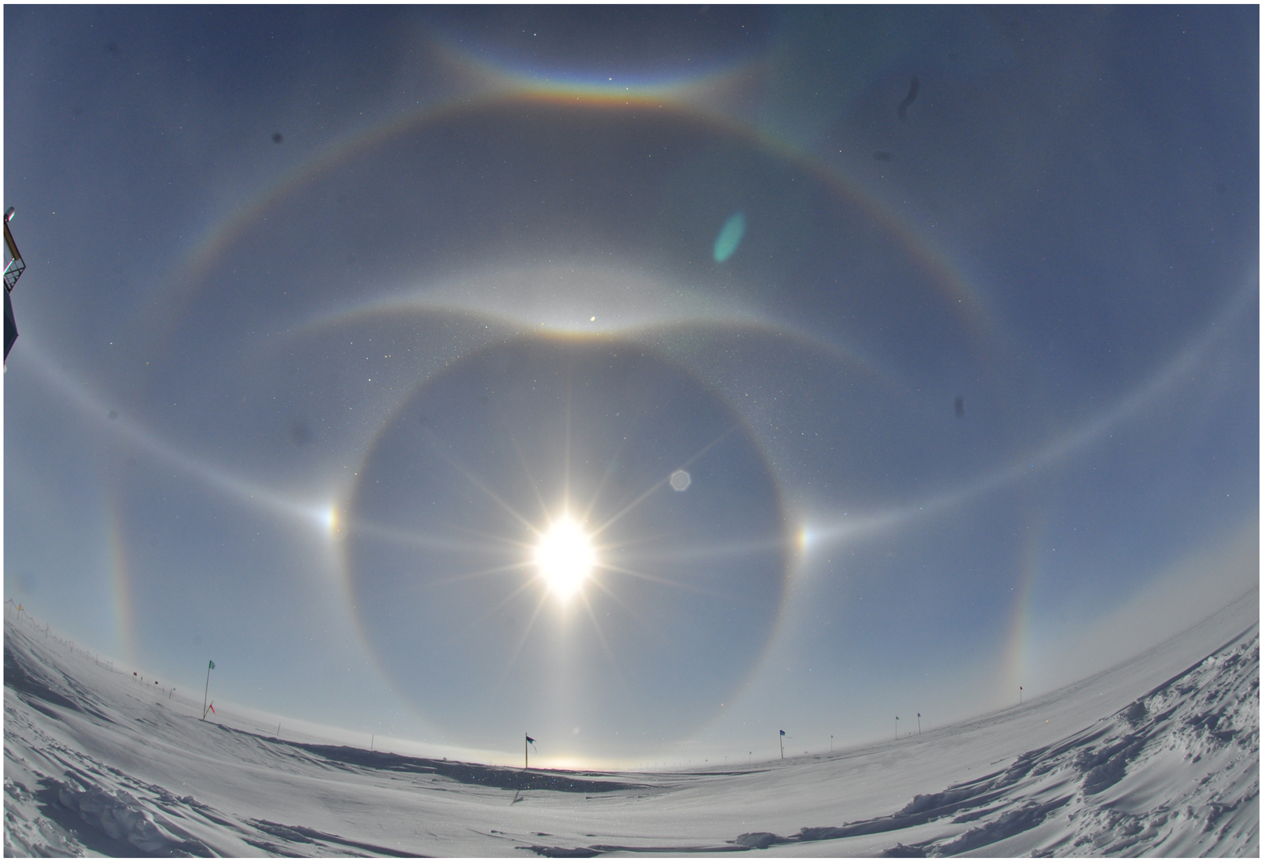

Figure 3821. From top to bottom: Circumzenithal arc, supralateral arc, Parry arc, tangential arc, 22 degree halo, parhelic circle, and sun dogs on right and left intersection of 22 degree halo and parhelic circle. Image courtesy of NOAA.

glow portion of a corona is called an **aureole**.

3823. The Green Flash

As light from the Sun passes through the atmosphere, it is refracted. Since the amount of bending is slightly different for each color, separate images of the Sun are formed in each color of the spectrum. The effect is similar to that of imperfect color printing, in which the various colors are slightly out of register. However, the difference is so slight that the effect is not usually noticeable. At the horizon, where refraction is at its maximum, the greatest difference, which occurs between violet at one end of the spectrum and red at the other, is about 10 seconds of arc. At latitudes of the United States, about 0.7 seconds of time is needed for the Sun to change altitude by this amount when it is near the horizon. The red image, being bent least by refraction, is first to set and last to rise. The shorter wave colors blue and violet are scattered most by the atmosphere, giving it its characteristic blue color. Thus, as the Sun sets, the green image may be the last of the colored images to drop out of sight. If the red, orange, and yellow images are below the horizon, and the blue and violet light is scattered and absorbed, the upper rim of the green image is the only part seen, and the Sun appears green. This is the **green flash**. The shade of green varies, and occasionally the blue image is seen, either separately or following the green flash (at sunset). On rare occasions the violet image is also seen. These colors may also be seen at sunrise, but in reverse order. They are occasionally seen when the Sun disappears behind a cloud or other obstruction. See Figure 3823.

The phenomenon is not observed at each sunrise or sunset, but under suitable conditions is far more common than generally supposed. Conditions favorable to observation of the green flash are a sharp horizon, clear atmosphere, a temperature inversion, and a very attentive observer. Since these conditions are more frequently met when the horizon is formed by the sea than by land, the phenomenon is more common at sea. With a sharp sea horizon and clear atmosphere, an attentive observer may see the green flash at as many as 50 percent of sunsets and sunrises, although a telescope may be needed for some of the observations.

Durations of the green flash (including the time of blue and violet flashes) of as long as 10 seconds have been reported; such lengths are rare and most commonly occur at higher latitudes. Usually a green flash lasts for a period of about 1/2 to 21/2 seconds, with about 11/4 seconds being average. This variability is probably due primarily to changes in the index of refraction of the air near the horizon.

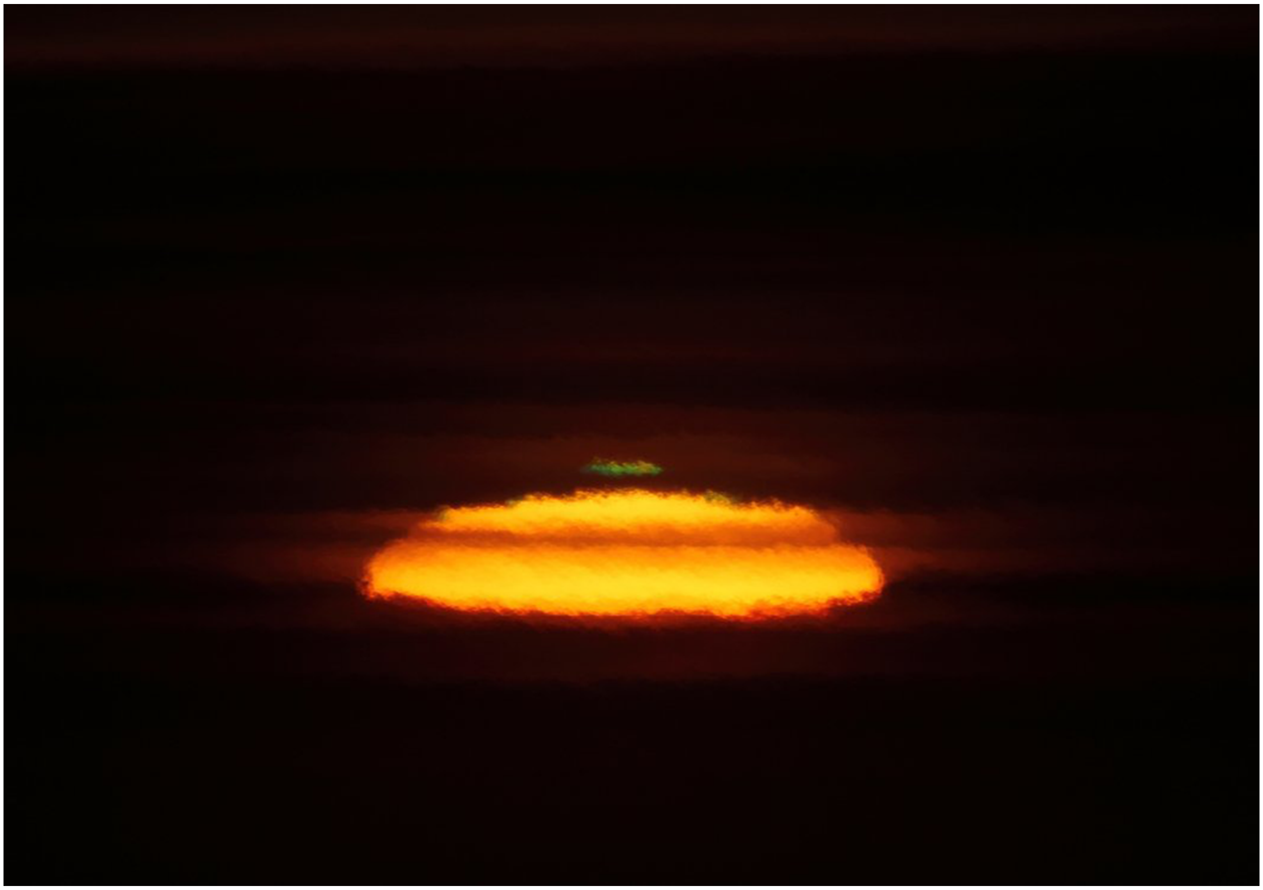

Figure 3823. Green Flash.

Under favorable conditions, a momentary green flash has been observed at the setting of Venus and Jupiter. A telescope improves the chances of seeing such a flash from a planet, but is not a necessity.

3824. Crepuscular Rays

Crepuscular rays are beams of light from the Sun passing through openings in the clouds, and made visible by illumination of dust in the atmosphere along their paths. Actually, the rays are virtually parallel, but because of perspective, they appear to diverge. Those appearing to extend downward are popularly called **backstays of the Sun**, or the **Sun drawing water**. Those extending upward and across the sky, appearing to converge toward a point 180° from the Sun, are called **anticrepuscular rays**.

THE ATMOSPHERE AND RADIO WAVES

3825. Atmospheric Electricity

Radio waves traveling through the atmosphere exhibit many of the properties of light, being refracted, reflected, diffracted, and scattered. These effects are discussed in greater detail in Chapter 21, Radio Waves.

Various conditions induce the formation of electrical charges in the atmosphere, the most common of which involves atmospheric convection. Thunderstorms contain updrafts where ice particles of various size and shape collide in the presence of supercooled water. This process typically results in the stratification of layers of negative and positive charge within the cloud, producing large electric fields. As enormous electrical stresses build up within thunderclouds, they induce a region of opposing charge on the Earth's surface. These electric fields grow until they surpass a certain minimum threshold, resulting in a phenomenon termed lightning.

Lightning is the discharge of electricity from one part of a thundercloud to another, between different clouds, or between a cloud and the Earth or a terrestrial object. Over a billion lightning flashes occur each year globally (~40 flashes every second). Most lightning is **intra-cloud** (IC; ~90%), and most **cloud-to-ground** (CG) **lightning** lowers negative charge from within the cloud to the ground (~90%). Positive CG lightning lowers positive charge from within the cloud to the ground, and objects taller than their surroundings also can trigger upward lightning flashes of positive or negative polarity.

Lightning generates **electromagnetic pulses** that propagate as radio waves in all directions. CG lightning generally exhibits strong current in long vertical channels, emitting most efficiently in the low-frequency (LF) to very-low frequency (VLF) range. IC lightning channels typically are more horizontal with weaker current, emitting most efficiently in the high-frequency (HF) to very-high frequency (VHF) range. Ground-based lightning detection networks geolocate lightning using the signal arrival angle and/or arrival times at multiple sensors. Satellite sensors also detect lightning, but they observe the optical lightning emissions at cloud top.

Strong VLF signals propagate long distances (1000's of km), so long-range VLF networks (3-30 kHz) can detect high-current lightning globally with fewer than 100 sensors (mostly CG detection). Alternatively, local VHF networks (50-200 MHz) detect emissions associated with electrical breakdown during lightning channel formation and re-illumination. The VHF networks provide detailed 3-D lightning mapping, but are spatially limited by the line-of-site propagation of VHF radio waves. Some networks employ a blended approach (e.g., 1 Hz to 12 MHz) to provide a degree of global CG lightning detection with better performance (i.e., IC detection) in regions with more sensors. Since higher frequency signals attenuate more quickly than lower frequency signals, regardless of the technology, IC lightning observations are limited in regions lacking sensors (e.g., the deep ocean).

Thunder, the noise that accompanies lightning, is caused by the heating, ionizing, and rapid expansion of the air by lightning, sending out a compression wave along the lightning channel. Thunder audibility is influenced by the temperature, humidity, wind velocity, wind shear, temperature inversions, terrain features, and clouds. When thunder is heard, lightning is present, whether or not visible to the observer. Thunder is seldom heard beyond 10 miles (16 km), so if thunder is audible, lightning is close enough to strike.

The sound of distant thunder has a characteristic low-pitched rumbling sound. **Pitch**, the degree of highness or lowness of a sound, is due to strong absorption and scattering of high-frequency components of the original sound waves. The rumbling results from the fact that sound waves are emitted from different locations along the lightning channel, which lie at varying distances from the observer. The longer the lightning channels, the longer the thunder. The elapsed time between the lightning and thunder is due to the difference in travel time of light and sound. Since the former is comparatively instantaneous, and the speed of sound is about 1,117 feet per second, the approximate distance in nautical miles is equal to the elapsed time in seconds, divided by 5.5.

Lightning occurs in fairly well-documented regions and seasons, so knowledge of local weather patterns can help mitigate its threat to humans. Nearly 70 percent of all lightning occurs in the tropical latitude band between 35° N and 35° S. Globally, 85 to 90 percent of lightning occurs over land because solar radiation heats land quicker, causing convection (thunderstorms) to be taller and stronger. The signs of lightning almost always are present before it strikes, whether it is as direct as thunder or as obscure as a growing cumulus cloud on the horizon. Lightning trends are indicative of thunderstorm intensity, so rapidly updating lightning observations provides valuable insights into thunderstorm evolution. IC lightning better indicates thunderstorm intensity since it relates more closely to updraft evolution than does CG lightning. Other manifestations of atmospheric electricity also are known to occur. For example, **St. Elmo's fire** is a luminous discharge of electricity from pointed objects such as the masts and antennas of ships, lightning rods, steeples, mountain tops, blades of grass, , etc., when there is a considerable difference in the electrical charge between the object and the air. It appears most frequently during thunderstorms. An object from which St. Elmo's fire emanates is in danger of being struck by lightning because this discharge may be the initial phase of a CG lightning flash. Throughout history those who have not understood St. Elmo's fire have regarded it with superstitious awe, considering it a supernatural manifestation. This view is reflected in the name corposant (from “corpo santo,” meaning “body of a saint”) sometimes given this phenomenon.

See Figure 3825a for a depiction of flash density across the planet over an 18 year period of time.

The **Aurora (Northern Lights)** and **Aurora Australis (Southern Lights)** are the result of electrically charged particles colliding with the upper reaches of Earth's atmosphere. Electrons, primarily responsible for the visible aurora, are energized through acceleration processes in the magnetosphere. They follow the magnetic field of Earth down to the Polar Regions where they collide with oxygen and nitrogen atoms and molecules in Earth's upper atmosphere. In these collisions, the electrons transfer their energy to the atmosphere thus exciting the atoms and molecules to higher energy states. When they relax down to lower energy states, they release their energy in the form of light. This is similar to how a neon light works. The aurora typically forms 80 to 500 km above Earth's surface.

Earth's magnetic field guides the electrons such that the aurora forms two ovals approximately centered at the magnetic poles. During major geomagnetic storms these ovals expand away from the poles such that aurora can be seen over much of the northern United States. Often the auroral forms consist of tall rays that look much like a curtain or folds of cloth. During the evening, these rays can form arcs that stretch from horizon to horizon. Late in the evening, near midnight, the arcs often begin to twist and sway, just as if a wind were blowing on the curtains of light. At some point, the arcs may expand to fill the whole sky, moving rapidly and becoming very bright. Then in the early morning the auroral forms can take on a more cloud-like

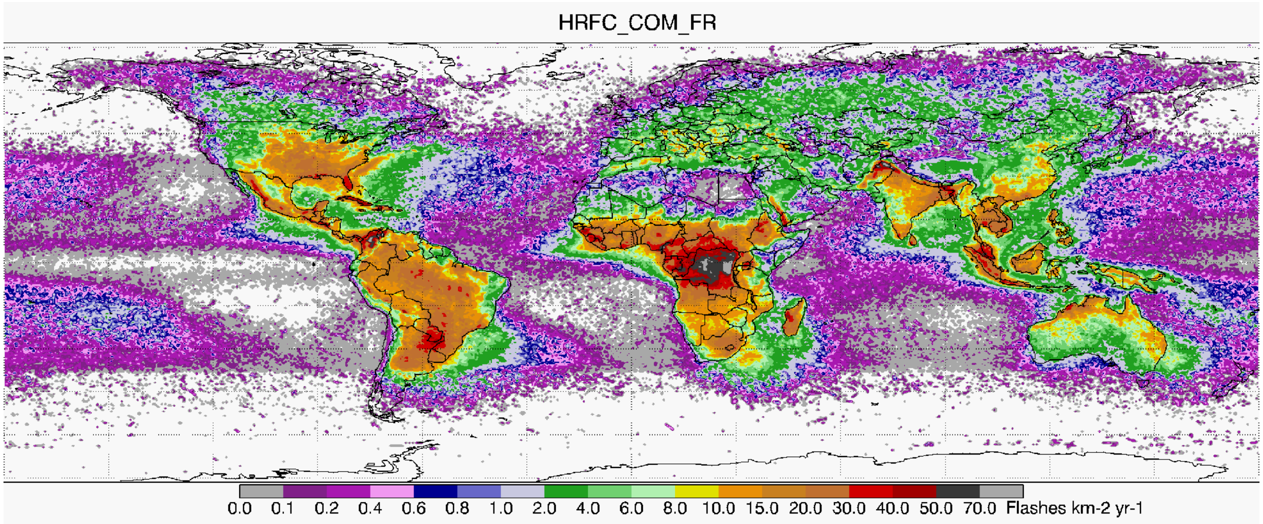

Figure 3825a. LIS/OTD 0.5 Degree High Resolution Full Climatology (HRFC) Annual Flash Density Map (1995-05-04 to 2013-12-31) available at https://dx.doi.org/10.5067/LIS/LIS-OTD/DATA302

appearance. These diffuse patches often blink on and off repeatedly for hours, then they disappear as the sun rises in the east.

When space weather activity increases and more frequent and larger storms and substorms occur, the aurora extends equator-ward. During large events, the aurora can be observed as far south as the U.S., Europe, and Asia. During very large events, the aurora can be observed even farther from the poles. Of course, to observe the aurora, the skies must be clear and free of clouds. It must also be dark so during the summer months at auroral latitudes, the midnight sun prevents auroral observations. See Figure 3825b.

Figure 3825b. Aurora (Northern Lights) video capture. Image courtesy of NOAA.

The best place to observe the aurora is under an oval-shaped region between the north and south latitudes of about 60 and 75 degrees. At these polar latitudes, the aurora can be observed more than half of the nights of a given year as long as its dark.

More information, including a 30-minute aurora forecast for both the northern and southern hemispheres and tips for viewing the aurora can be found at the Space Weather Prediction Center's website.

WEATHER ANALYSIS AND FORECASTING

3826. Forecasting Weather

The prediction of weather at some time in the future is based upon an understanding of weather processes and observations of present conditions. Thus, when there is a certain sequence of cloud types, rain usually can be expected to follow. If the sky is cloudless, more heat will be received from the Sun by day, and more heat will be radiated outward from the warm Earth by night than if the sky is overcast. If the wind is from a direction that transports warm, moist air over a colder surface, fog can be expected. A falling barometer indicates the approach of a "low," probably accompanied by stormy weather. Thus, before meteorology passed from an "art" to "science," many individuals learned to interpret certain atmospheric phenomena in terms of future weather, and to make reasonably accurate forecasts for short periods into the future.

With the establishment of weather observation stations, continuous and accurate weather information became available. As observations expanded and communication techniques improved, knowledge of simultaneous conditions over wider areas became available. This made possible the collection of "synoptic" reports at civilian and military forecast centers.

Individual observations are made at stations on shore and aboard vessels at sea. Observations aboard merchant ships at sea are made and transmitted on a voluntary and cooperative basis. The various national meteorological services supply shipmasters with blank forms, printed instructions, reporting software, and other materials essential to the making, recording, and interpreting of observations. Any shipmaster can render an extremely valuable service by reporting weather conditions for all usual and unusual or non-normal weather occurrences.

Symbols and numbers are used to indicate on a synoptic chart, popularly called a weather map, the conditions at each observation station. **Isobars** are drawn through lines of equal atmospheric pressure, fronts are located and symbolically marked, areas of precipitation and fog are indicated, etc. For examples of how fronts and other symbols are used on weather charts, see the National Weather Service link in Figure 3826.

Ordinarily, weather maps for surface observations are prepared every 6 (sometimes 3) hours. In addition, synoptic charts for selected heights are prepared every 12 (sometimes 6) hours. Knowledge of conditions aloft is of value in establishing the three-dimensional structure and motion of the atmosphere as input to the forecast.


National Weather Service
Ocean Prediction Center

Figure 3826. Ocean Prediction Center terminology and weather symbols:
http://www.opc.ncep.noaa.gov/product_description/keyterm.shtml

With the advent of the computer, highly sophisticated numerical models have been developed to analyze and forecast weather patterns. The civil and military weather centers prepare and disseminate vast numbers of weather charts (analyses and prognoses) daily to assist local forecasters in their efforts to provide users with accurate weather forecasts. The accuracy of the forecast decreases with the length of the forecast period. A 12-hour forecast is likely to be more reliable than a 24-hour forecast. Long-term forecasts for 2 weeks or a month in advance are limited to general statements. For example, a prediction may be made about which areas will have temperatures above or below normal and how precipitation will compare with normal, but no attempt is made to state that rainfall will occur at a certain time and place.

Forecasts are issued for various areas. The national meteorological services of most maritime nations, including the United States, issue forecasts for ocean areas and warnings of approaching storms. The forecasting efforts of all nations are coordinated by the **World Meteorological Organization**.

3827. Weather Dissemination

Timely access to weather information is important to ensure the safety and efficiency of activities at sea. Weather forecasting agencies, both public and private, use the latest technology to deliver a broad range of climate, water, and weather information in graphical and text form.

The **Global Maritime Distress and Safety System (GMDSS)** was established to provide more effective and efficient emergency and safety communications, and to disseminate Maritime Safety Information (MSI) to all ships on the world's oceans regardless of location or atmospheric conditions. MSI includes navigational warnings, meteorological warnings and forecasts, and other urgent safety-related information. GMDSS goals are defined in the International Convention for the **Safety Of Life At Sea (SOLAS)**, and affect vessels over 300 gross tons and passenger vessels of any size. The U.S. National Weather Service participates directly in the GMDSS by preparing meteorological forecasts and warnings for broadcast via NAVTEX and SafetyNET.

Disseminating weather information is carried out in a number of ways; some are part of GMDSS and others are not. Weather forecasts and warnings are available by various means including TV, radio (AM/FM and specifically FM 162.400MHz to 164.550MHz), and satellite broadcasts (SBN/NOAAPORT, NWWS and EMWIN), telephone (Weather Apps or call-in to local Weather Forecast Offices), and the Internet (Figure 3827a and other commercial weather providers and software programs).

Figure 3827a. National Weather Service website: http://www.weather.gov

Visual storm warnings are displayed in various ports, and storm warnings are broadcast by radio. Worldwide marine meteorological and oceanographic forecasting and dissemination responsibilities via Inmarsat-C SafetyNET have been divided into MetAreas by the World Meteorological Organization (WMO)- Intergovernmental Oceanographic Commission (IOC) Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM). The forecasting responsibilities for each MetArea are handled by the National Meteorological Services appointed as Issuing Services within the framework of the WMO Marine Broadcast System for the GMDSS. More information about which forecasting agency has forecasting responsibilities for each Metarea can be found in Figure 3827b.

NAVTEX Broadcasts

NAVTEX is an international automated medium frequency (518 kHz) direct-printing service for delivery of navigational and meteorological warnings and forecasts, as well as urgent marine safety information to ships. It was developed as an automated means of receiving this information aboard ships at sea within approximately 200 nautical miles of shore. NAVTEX stations in the U.S. are operated by the U.S. Coast Guard. There are no user fees associated with receiving NAVTEX broadcasts. Information about marine weather forecasts broadcast through NAVTEX can be found at the link provided in Figure 3827c. Additional information is also available on individual Met Area webpages.

Figure 3827b. WMO Marine broadcast system for GMDSS website: http://weather.gmdss.org/metareas.html

NOAA's National Weather Service
Marine Forecasts

Figure 3827c. National Weather Service NAVTEX marine weather forecast broadcasts: http://www.nws.noaa.gov/om/marine/navtex.htm

Inmarsat Broadcasts

Inmarsat-C SafetyNET is an internationally adopted, automated satellite system for promulgating weather forecasts and warnings, marine navigational warnings, and other safety-related information to all types of vessels. There are no user fees associated with receiving SafetyNET broadcasts. The National Weather Service prepares high-seas forecasts and warnings for broadcast via SafetyNET for each of the three ocean areas they are responsible for covering four times daily. Information about marine weather forecasts broadcast through Inmarsat-C SafetyNET can be found at the link in Figure 3827d.

Radiofax Broadcasts

Radiofax, also known as HF FAX, radiofacsimile or weatherfax, is a means of broadcasting graphic weather maps and other graphic images via HF radio. HF radiofax

NOAA's National Weather Service
Marine Forecasts

Figure 3827d. Inmarsat marine weather forecast broadcasts:
http://www.nws.noaa.gov/om/marine/inmarsat.htm

is also known as WEFAX, although this term is generally used to refer to the reception of weather charts and imagery via satellite. Maps are received using a dedicated radiofax receiver or a single sideband shortwave receiver connected to an external facsimile recorder or PC equipped with a radiofax interface and application software.

The earliest broadcasts of weather maps via radiofacsimile appear to have been made in 1926 by American inventor Charles Francis Jenkins in a demonstration to the Navy. The U.S. Weather Bureau conducted further tests of its applicability in 1930. While radiofacsimile has been used for everything from transmitting newspapers to wanted posters in the past, the broadcasting of marine charts is today the primary application.

The National Weather Service radiofax program prepares high seas weather maps for broadcast via four U.S. Coast Guard stations (Boston, New Orleans, Pt. Reyes, and Kodia) and one Department of Defense transmitter site (Honolulu). These broadcasts are prepared by the **Ocean Prediction Center**, **National Hurricane Center**, **Honolulu Forecast Office**, and **Anchorage Forecast Office**. Limited satellite imagery, sea surface temperature maps, and text forecasts are also available at their individual websites.

All National Weather Service radiofax products are available via the Internet (HTTP, FTP or Email). Although available, internet access is not feasible for most vessels. Broadcasts of graphic marine forecasts via HF radiofax remains among the most valued of NWS marine services. An example of radiofax surface analysis chart is shown in Figure 3827e.

More information about marine weather radiofax broadcasts can be found at the link in Figure 3427f.

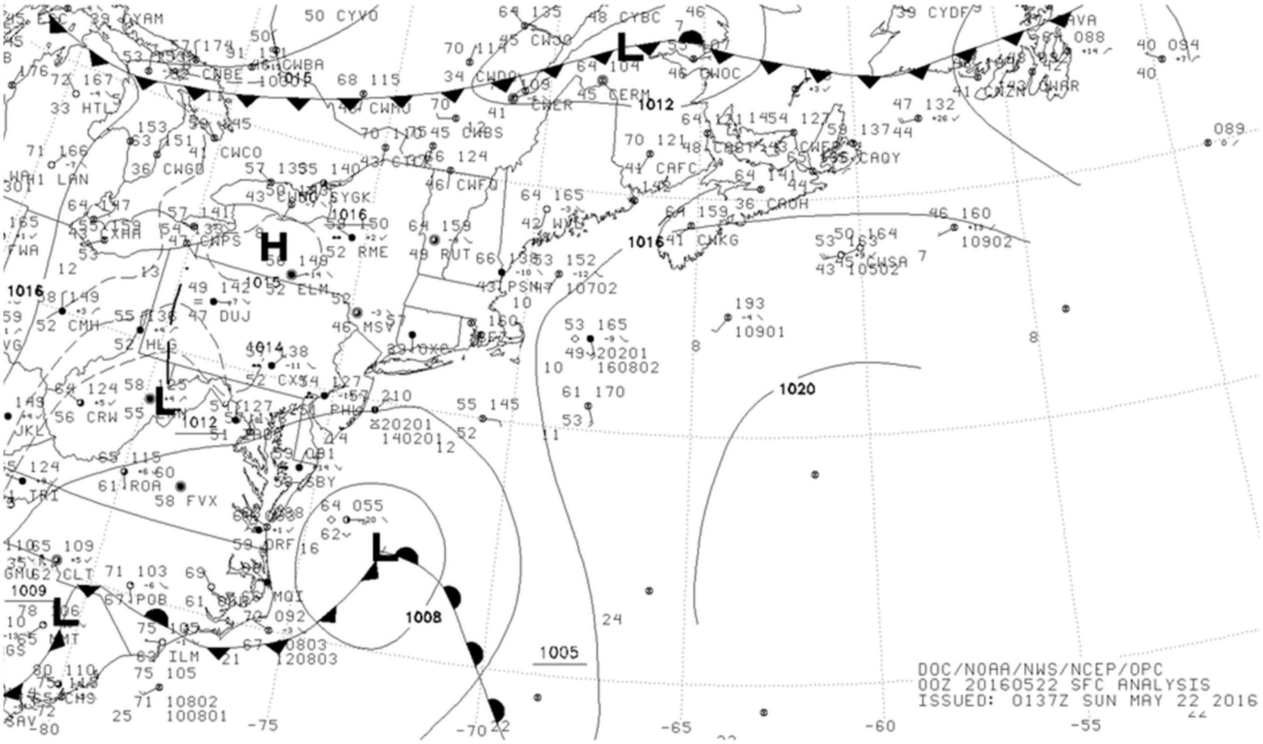

Figure 3827e. National Weather Service radiofax surface analysis example.

Weather Products via the Internet

With the advent of wireless technologies, information updates are almost seamless to keep mariners current on changing environmental conditions. These technologies include the dissemination and receipt of nautical charts,

NOAA's National Weather Service
Marine Forecasts

Figure 3827f. Information on marine weather radiofax broadcasts:
http://www.nws.noaa.gov/om/marine/radiofax.htm

ocean and weather information using satellite telephones, the Internet and various computer or commercial applications. The reduction in the price for satellite-based internet access have enabled vessels to access large graphic files produced by various weather forecasting agencies, including the National Weather Service, online. Additional websites to the ones already presented in this chapter that a mariner may find useful are listed below.

Information on dissemination of marine weather information may be found in *NGA Pub. 117*, *Radio Navigational Aids* and the *International Maritime Organization* publication, *Master Plan of Shore Based Facilities for the GMDSS*;

Information on day and night visual storm warnings is given in the various volumes of *Sailing Directions*, both *En-routes* and *Planning Guides*.

Then National Weather Service - Worldwide Marine Radiofacsimile Broadcast Schedule (dated September 9, 2016) can be accessed via the link in Figure 3827g.

NOAA's National Weather Service
Marine Forecasts

Figure 3827g. Worldwide Marine Radiofacsimile Broadcast Schedule:
http://www.nws.noaa.gov/os/marine/rfax.pdf

Meteorological and oceanographic information, including weather forecasts produced by the United States can be found in the links contained in Figure 3827h, Figure 3827i and Figure 3827j.

NOAA's National Weather Service
Marine Forecasts

Figure 3827h. Information on weather forecasts produced by the United States:
http://www.nws.noaa.gov/om/marine/home.htm

NOAA's National Weather Service
Marine Forecasts

Figure 3827i. Coastal and Great Lakes forecast:
http://www.nws.noaa.gov/om/marine/zone/usamz.htm

Naval Oceanography Portal

Figure 3827j. Fleet Numerical Meteorology and Oceanography Center:
http://www.usno.navy.mil/FNMOC

For additional port-area tides and currents information see the link in Figure 3827k.

For additional meteorological information derived from data buoy collectors see Figure 3827l.

Figure 3827k. NOAA port information:
https://tidesandcurrents.noaa.gov/ports.html

3828. Interpreting Weather

The factors which determine weather are numerous and varied. Ever-increasing knowledge regarding them makes possible a continually improving weather service. However, the ability to forecast is acquired through study and long practice, and therefore the services of a trained meteorologist should be utilized whenever available.

The value of a forecast is increased if one has access to the information upon which it is based, and understands the principles and processes involved. It is sometimes as important to know the various types of weather which may be experienced as it is to know which of several possibilities is most likely to occur.


National Oceanic and Atmospheric Administration's
National Data Buoy Center
Center of Excellence in Marine Technology

Figure 3827l. National Data Buoy Center:
http://www.ndbc.noaa.gov/

At sea, reporting stations are unevenly distributed, sometimes leaving relatively large areas with incomplete reports, or none at all. Under these conditions, the locations of highs, lows, fronts, etc., are imperfectly known, and their very existence may even be in doubt. At such times mariners who can interpret the observations made from their own vessel may be able to predict weather for the next several hours more reliably than a trained meteorologist ashore.

3829. References

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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 (including 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.

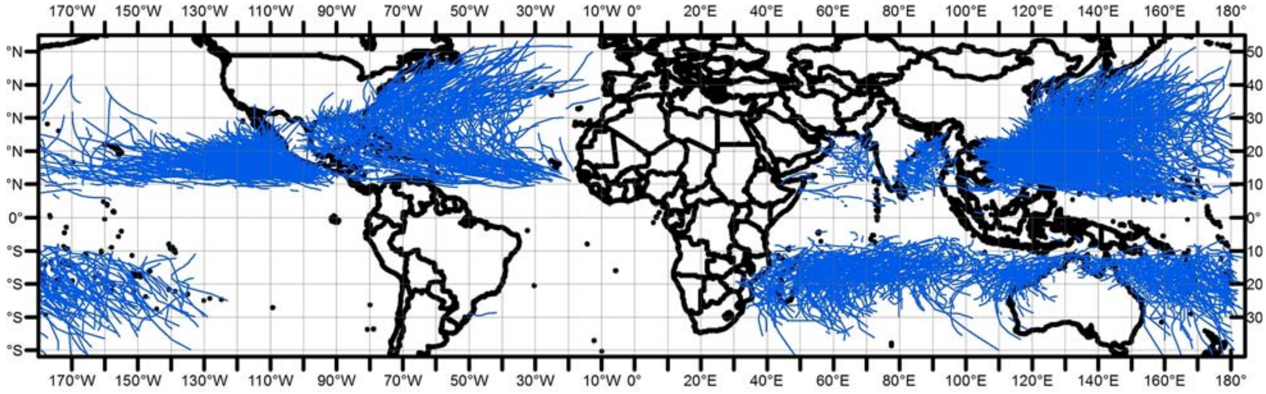


Figure 3902a. Tracks of all tropical cyclones with maximum 1-minute mean wind speed of 34 kts or greater during the period 1981-2010 (data sources National Hurricane Center, Central Pacific Hurricane Center, Joint Typhoon Warning Center; image credit Colorado State University).

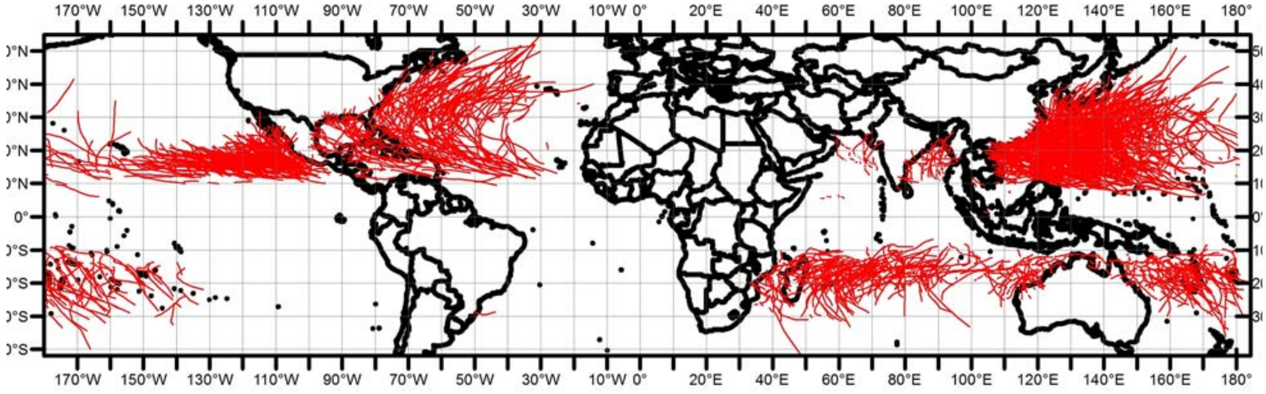


Figure 3902b. Tracks of all tropical cyclones with maximum 1-minute mean wind speed of 64 kts or greater during the period 1981-2010 (sources National Hurricane Center, Joint Typhoon Warning Center and Colorado State University).

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).

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).

Western North Pacific: More tropical cyclones form 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 reintensify 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-curvature 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-

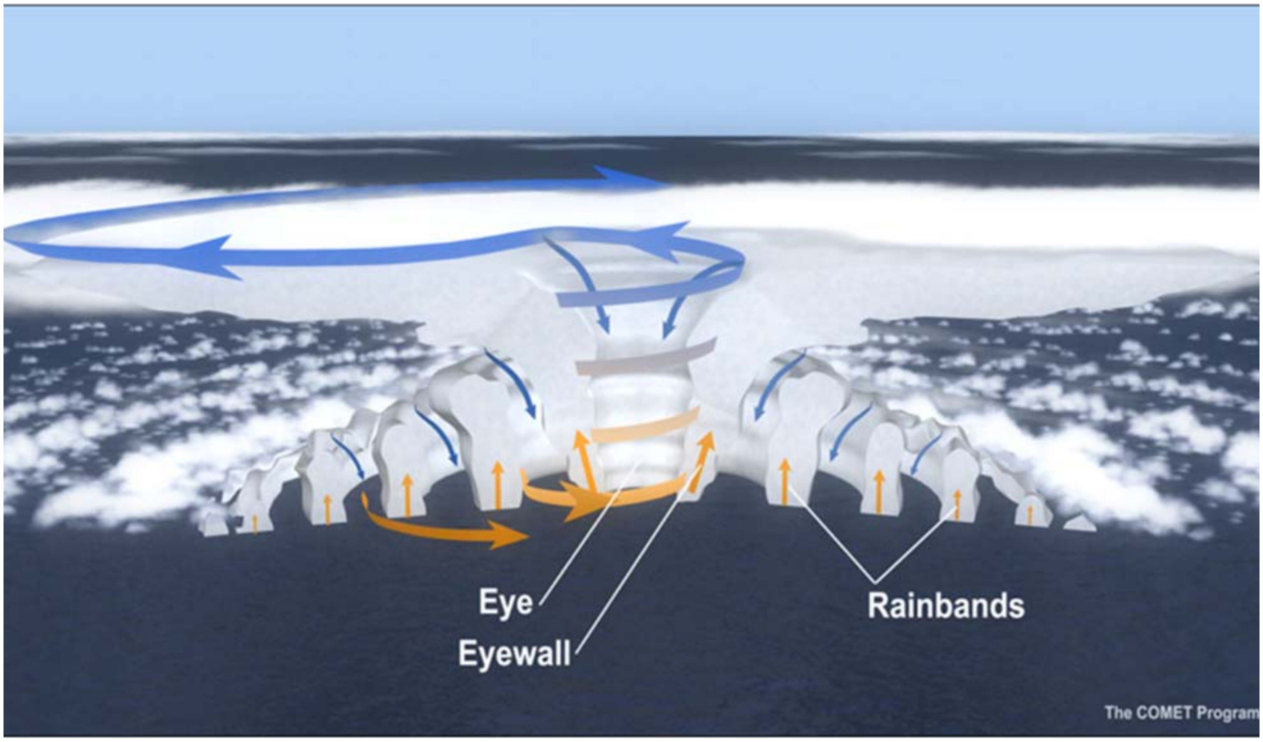


Figure 3904. Schematic cross-section of a mature hurricane. Used with permission of © UCAR/COMET Program.

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

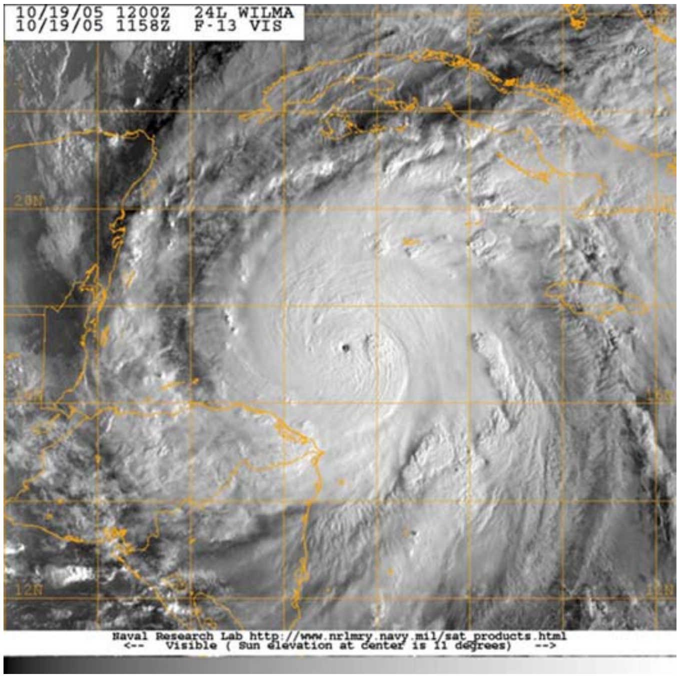


Figure 3905. Visible satellite image of 2005 Atlantic Hurricane Wilma (image courtesy Naval Research Laboratory)

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 though 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

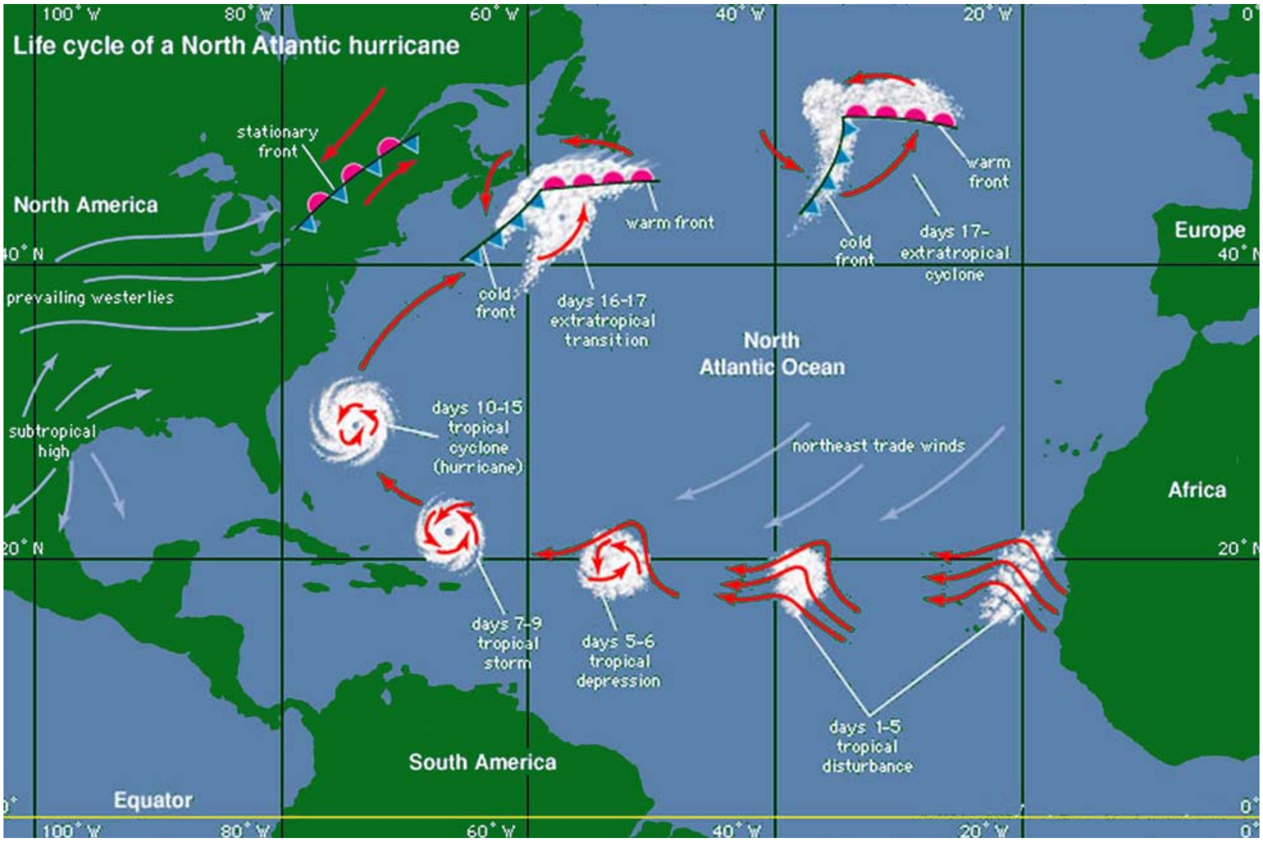


Figure 3906. Hurricane life cycle for the North Atlantic.

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 landlocked 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 fast 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

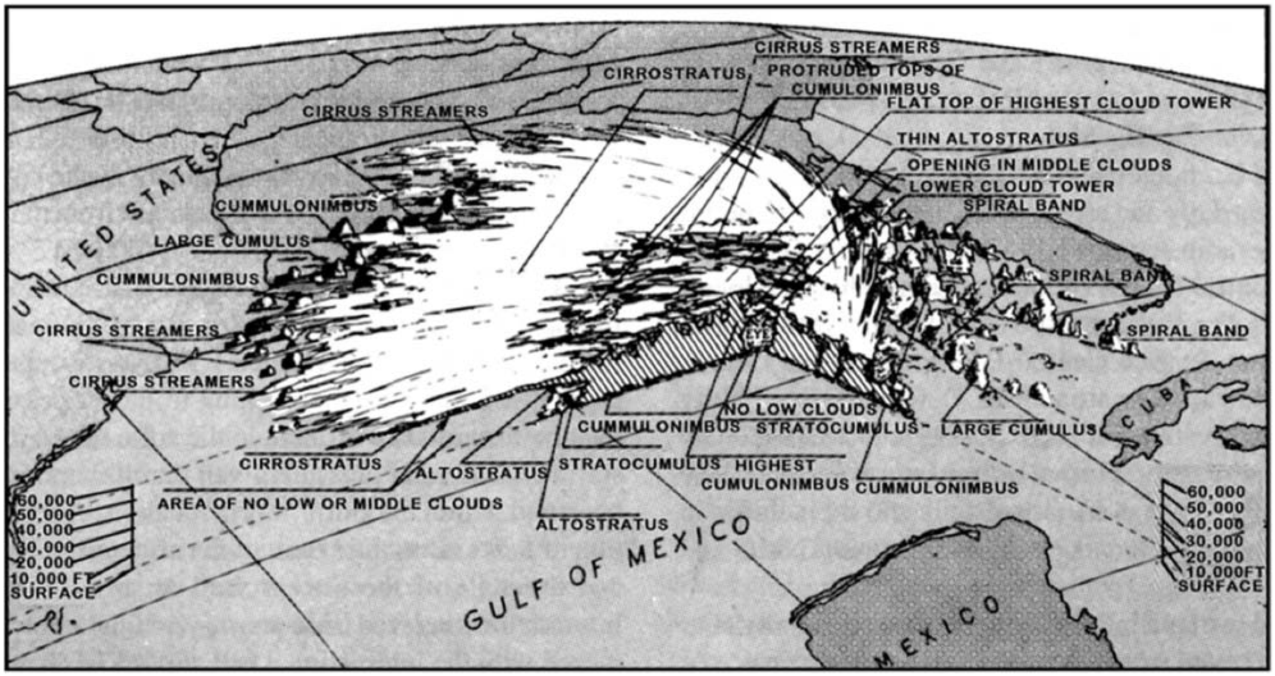


Figure 3909. Typical cloud structures associated with a tropical cyclone.

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 Carpenteria: **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).

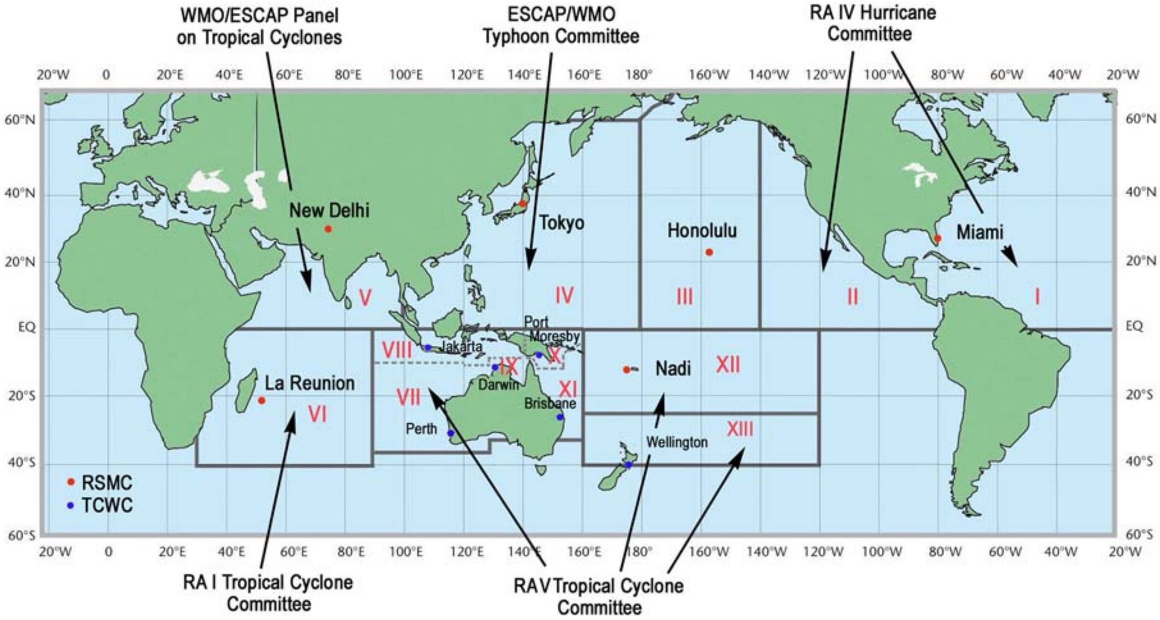


Figure 3910a. Location and area of responsibility for the WMO-recognized tropical cyclone Regional Specialized Meteorological Centers and Tropical Cyclone Warning Centers (WMO).

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

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

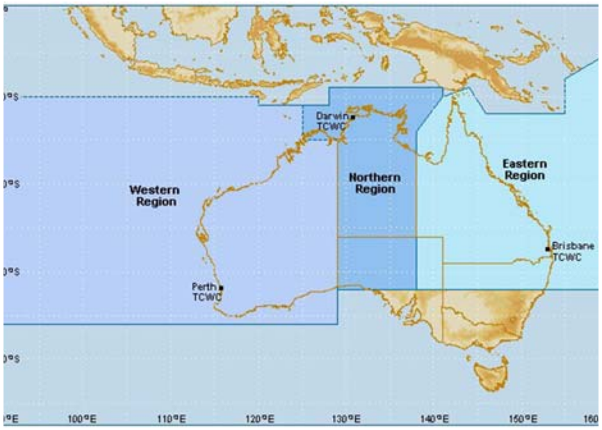


Figure 3910g. Australian Bureau of Meteorology regions.

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

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

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

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.

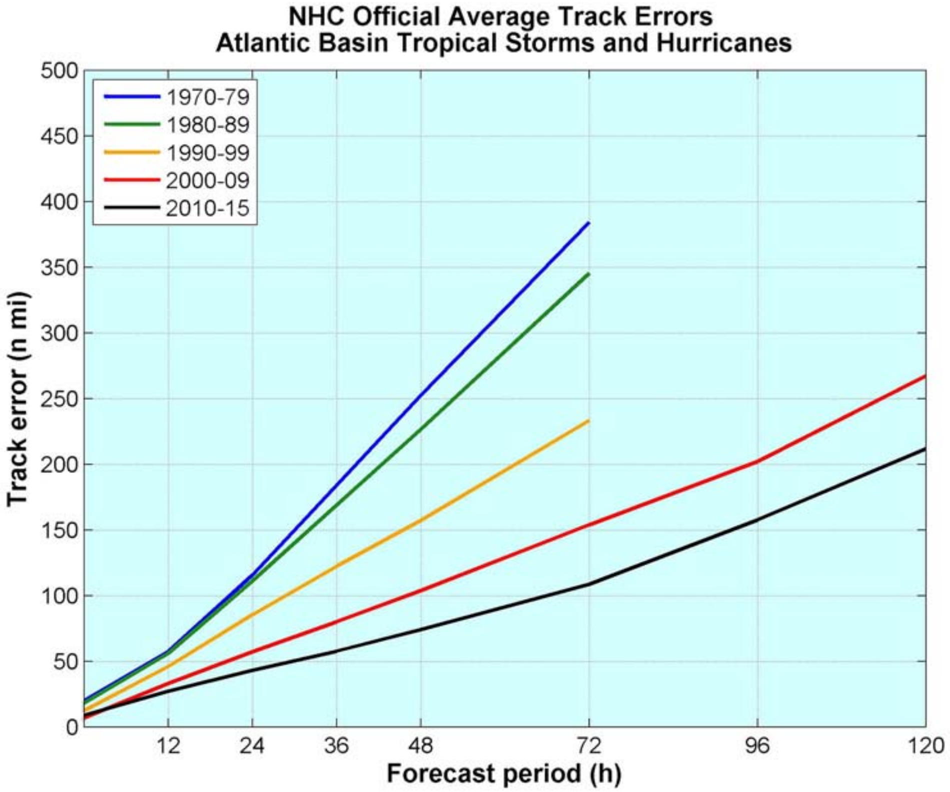


Figure 3910m. National Hurricane Center official track forecast accuracy for Atlantic basin tropical storms and hurricanes by decade.

3911. Tropical Cyclone Forecast Products

Each RSMC has its own collection of forecast and 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).

Figure 3911a. Link to the NHC User's Guide for their tropical cyclone products.
http://www.nhc.noaa.gov/pdf/NHC_Product_Description.pdf

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

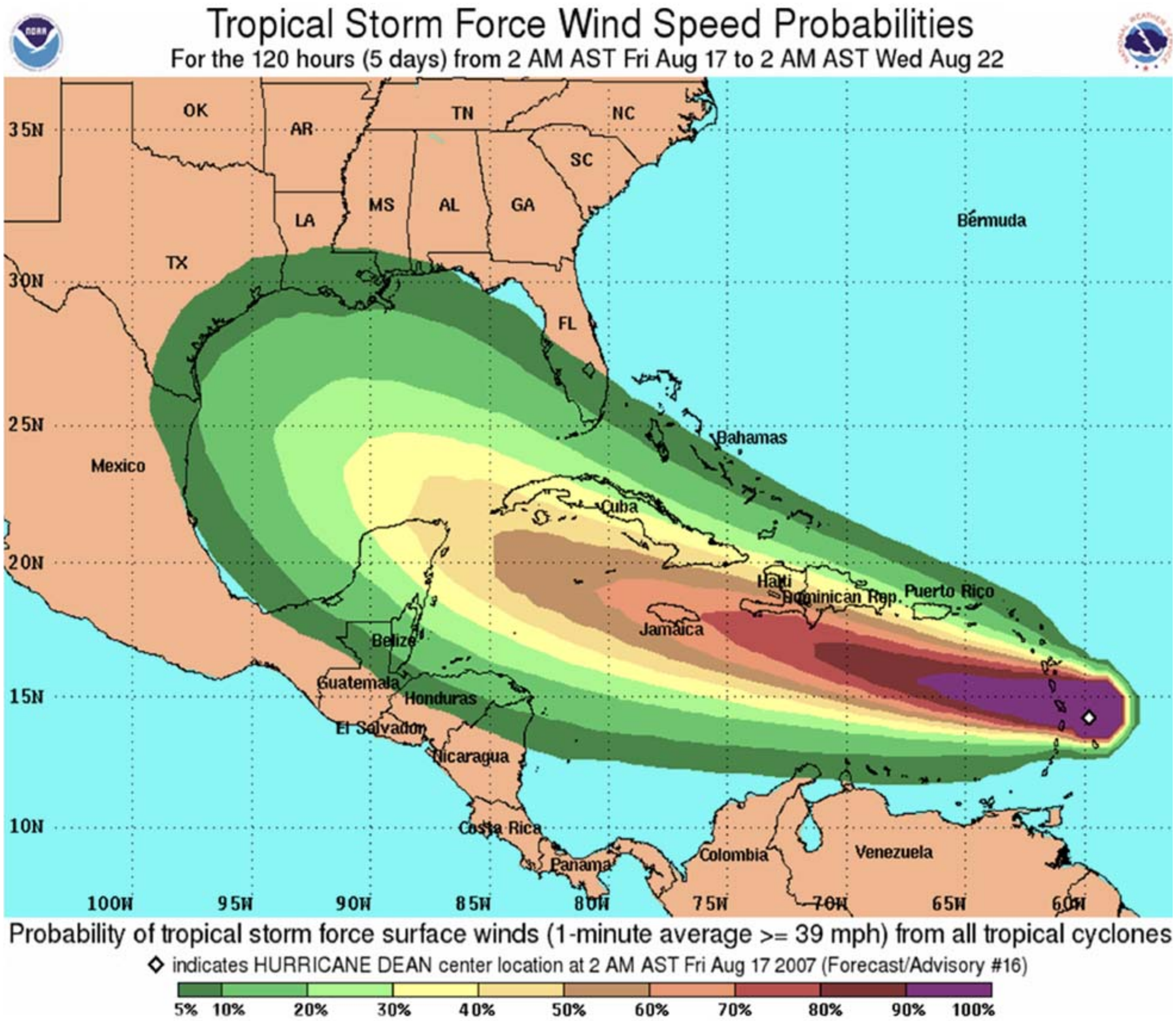


Figure 3911b. Tropical cyclone surface wind speed probability graphic.

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-

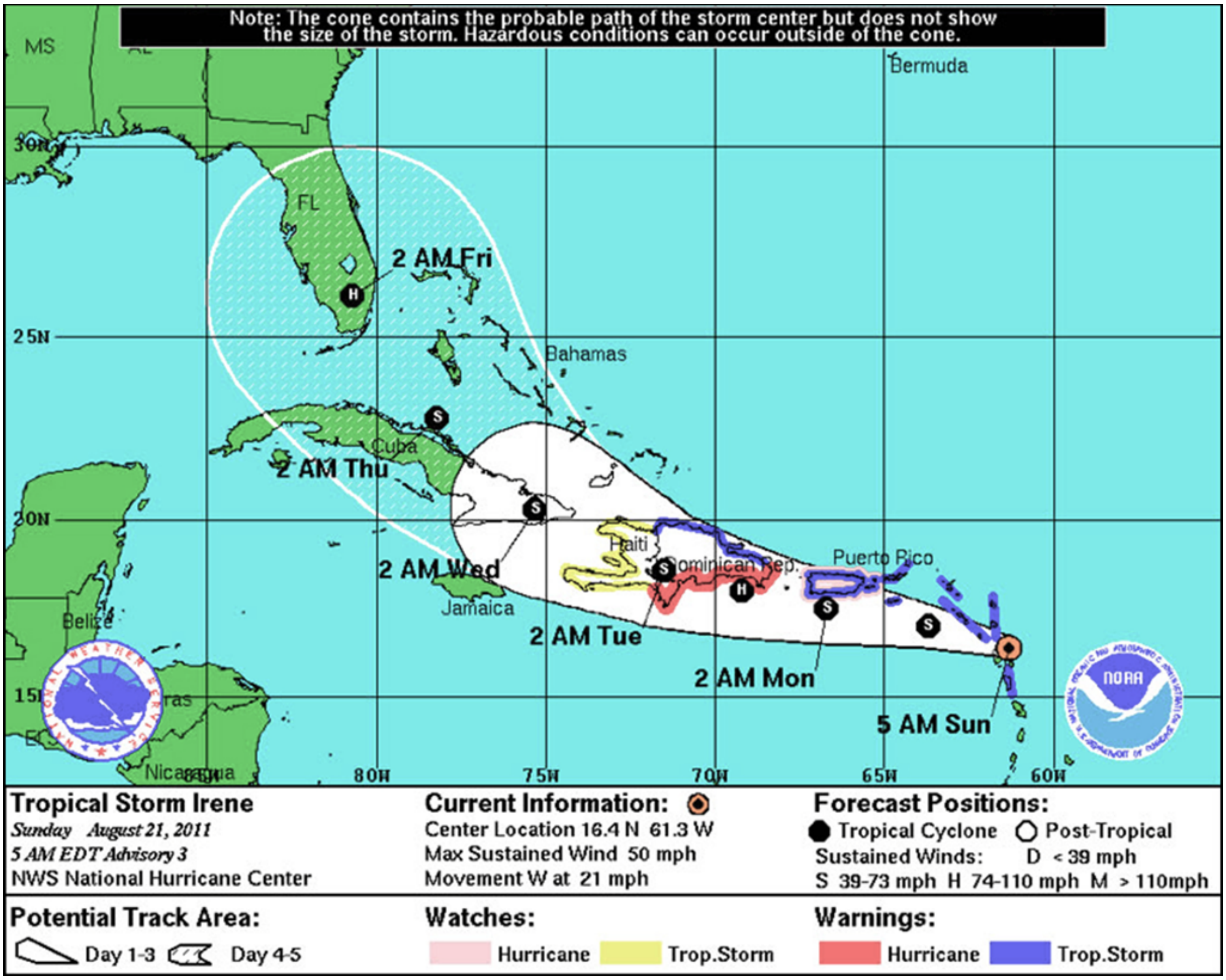


Figure 3911d. Tropical cyclone track forecast cone and watch/warning graphic.

pict 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.

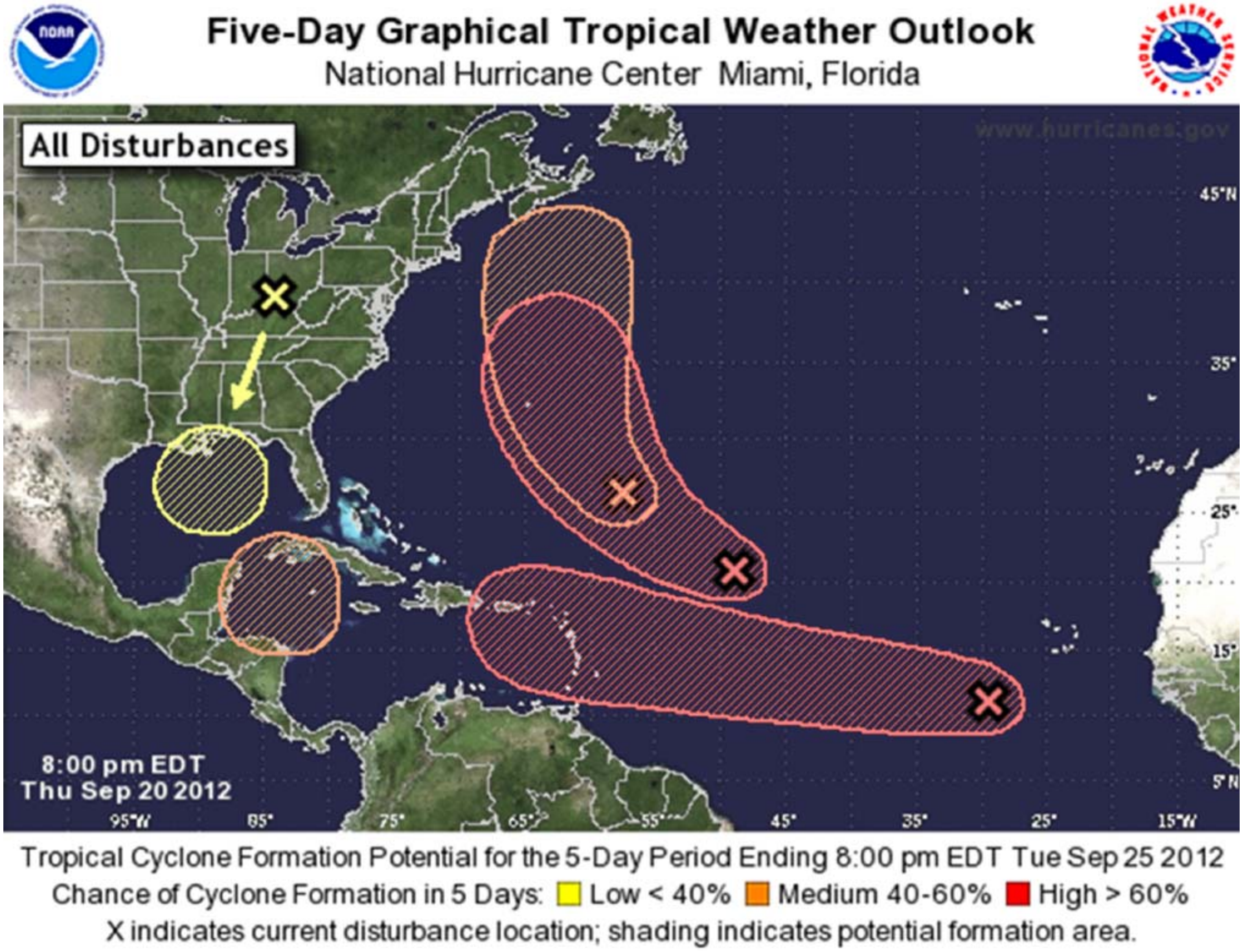


Figure 3911e. Five-day graphical tropical weather outlook.

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-

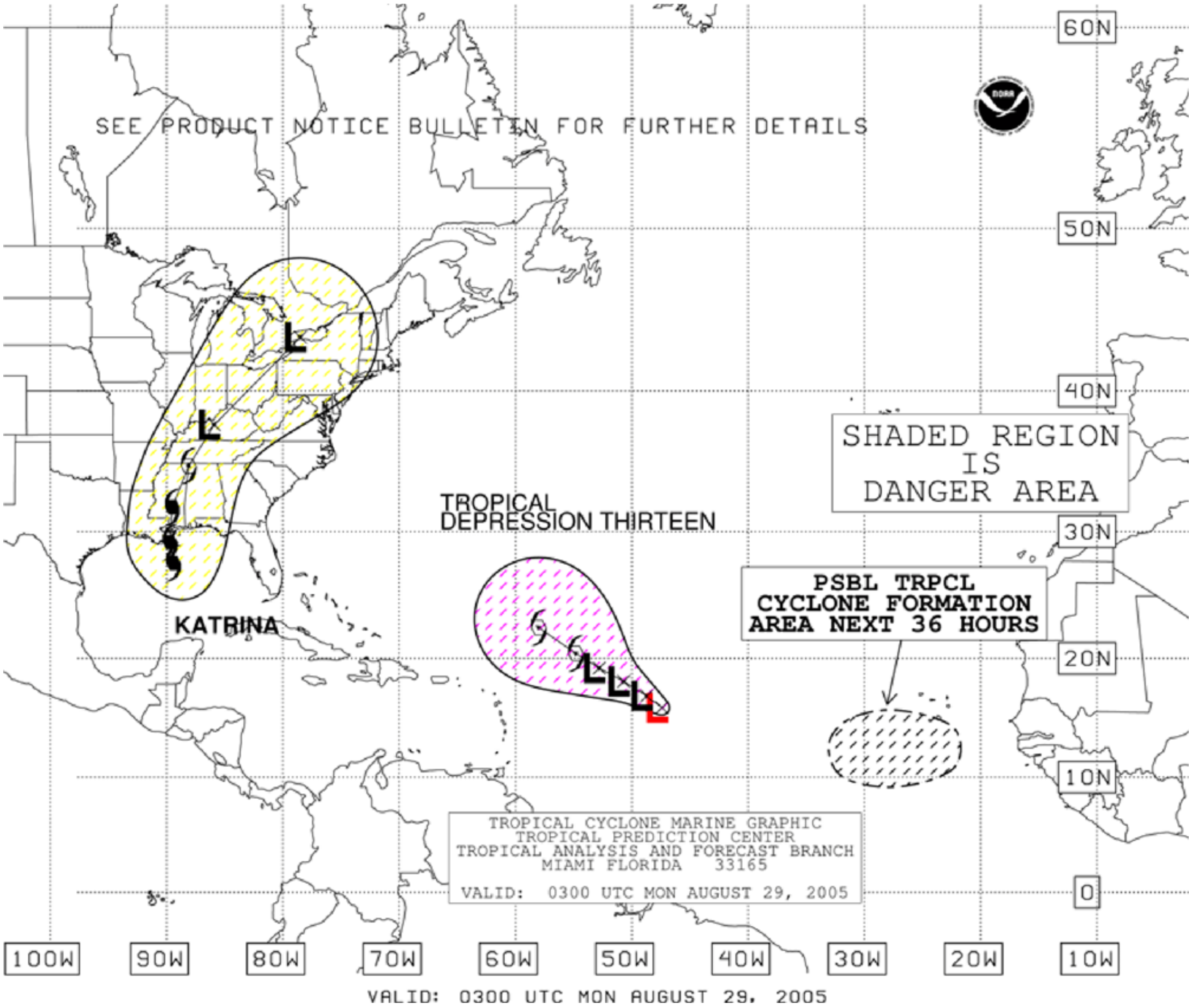


Figure 3912a. Former Tropical Cyclone Danger Graphic based on the Mariner's 1-2-3 rule.

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 usually 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

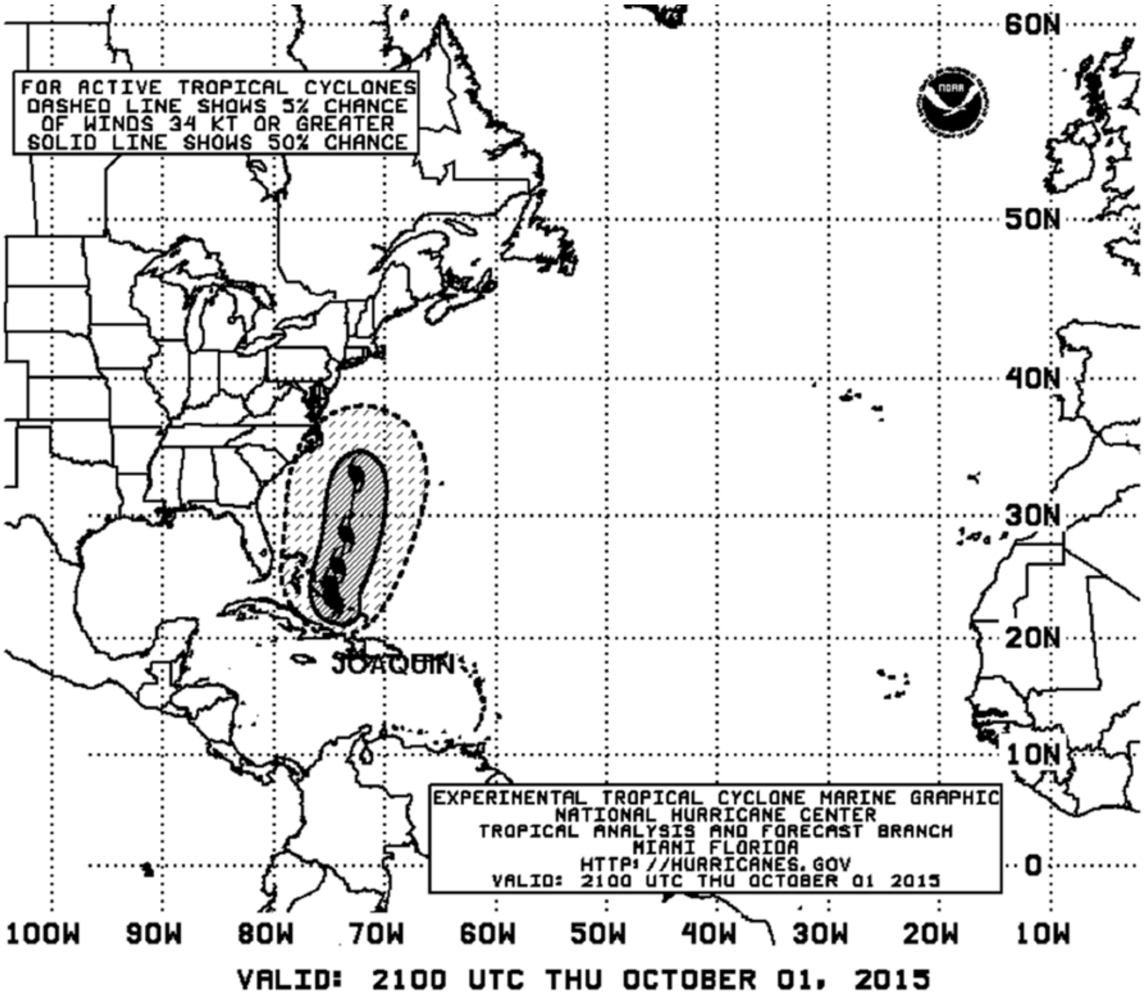


Figure 3912b. Probability-based Tropical Cyclone Danger Graphic.

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

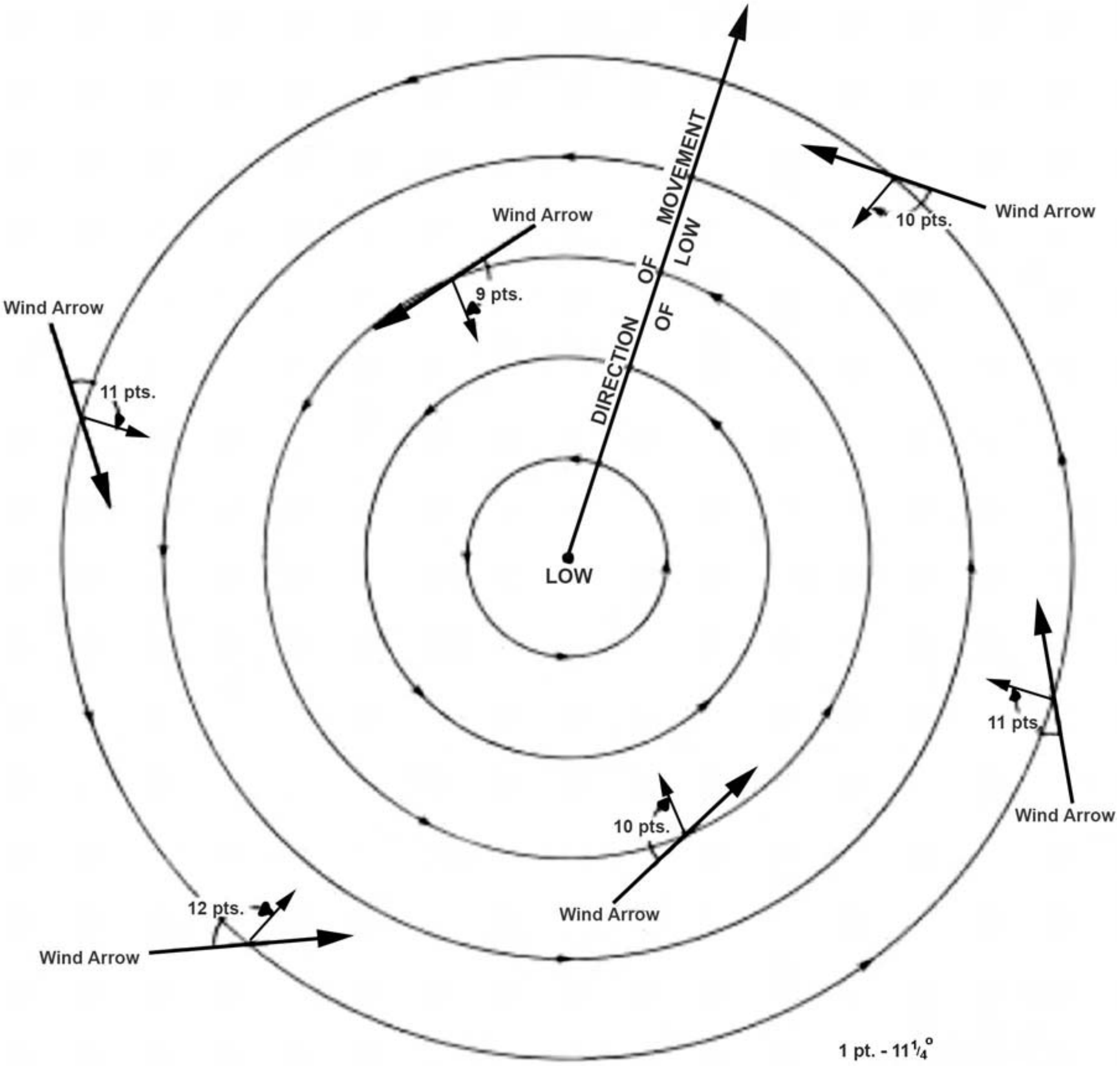


Figure 3913a. Approximate relationship of wind to isobars and storm center in the Northern Hemisphere.

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

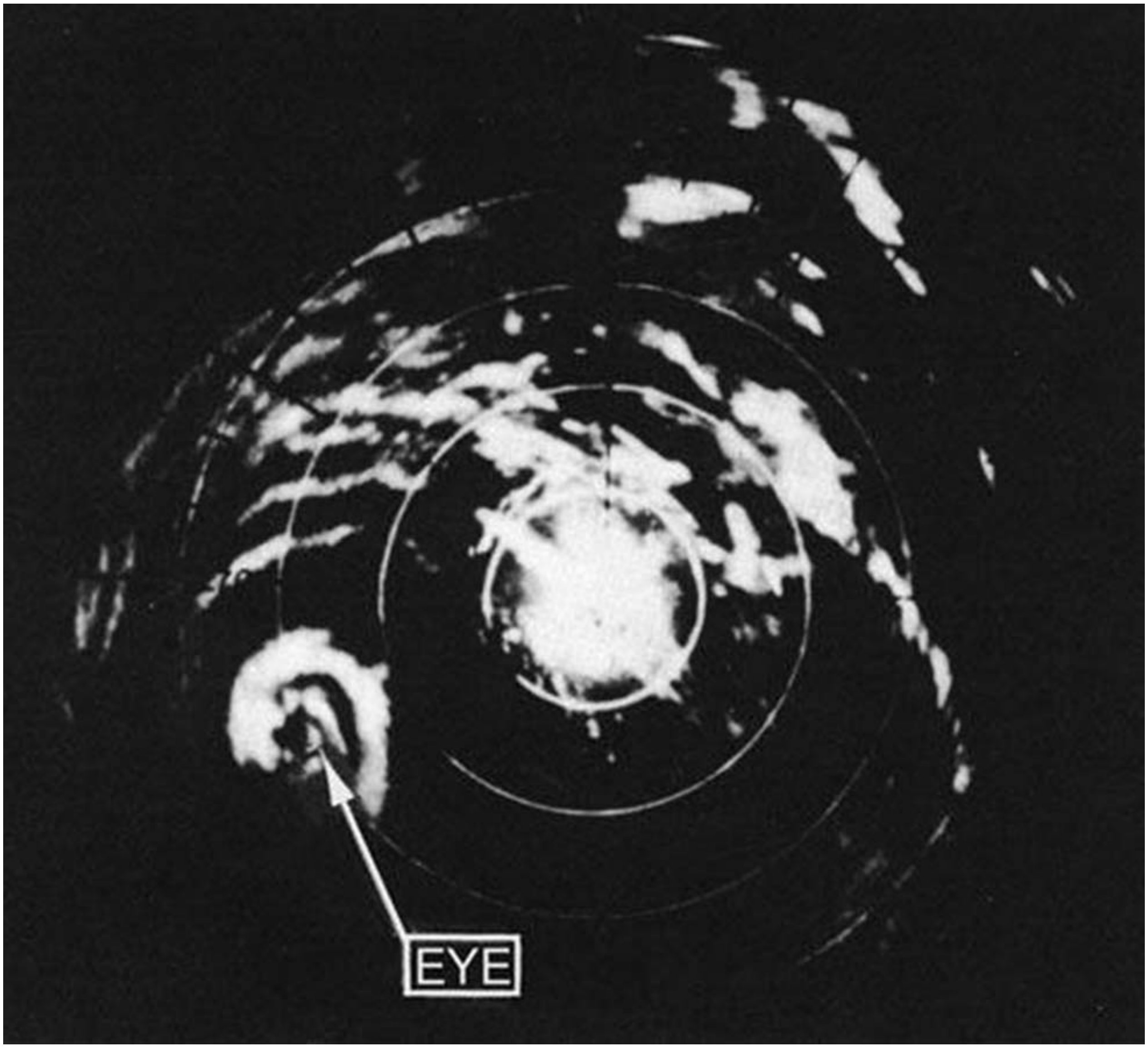


Figure 3913b. Radar PPI presentation of a tropical cyclone.

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 observations 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

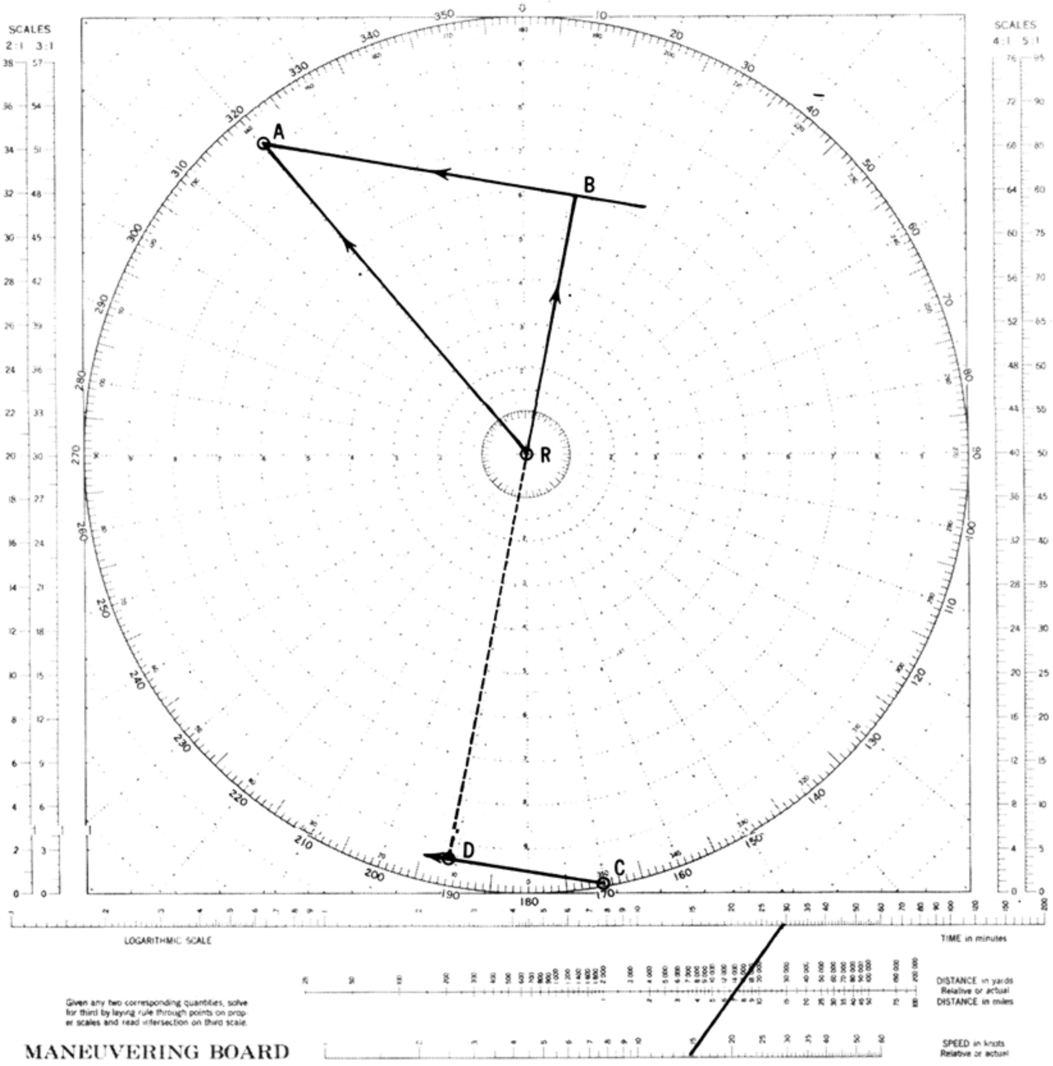


Figure 3915a. Determining the course to avoid the storm center.

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

© Figure 3904 provided courtesy of University Corporation for Atmospheric Research (UCAR), COMINT Program, Boulder, CO 80301.

CHAPTER 40

WEATHER OBSERVATIONS

BASIC WEATHER OBSERVATIONS

4000. Introduction

Weather forecasts are based upon information acquired by observations made at a large number of stations. Ashore, these stations are located so as to provide adequate coverage of the area of interest. Observations at sea are made by mariners, buoys, and satellites. Since the number of observations at sea is small compared to the number ashore, marine observations are of great importance. Data recorded by designated vessels are sent by radio or satellite to national meteorological centers ashore, where they are calculated into computer forecast models for the development of synoptic charts. These models are then used to prepare local and global forecasts. The complete set of weather data gathered at sea is then sent to the appropriate meteorological services for use in the preparation of weather atlases and in marine climatological studies.

Weather observations are normally taken on the major synoptic hours (0000, 0600, 1200, and 1800 UTC). However, three-hourly intermediate observations are necessary on the Great Lakes, within 200 nautical miles from the United States or Canadian coastline, or within 300 nautical miles of a named tropical cyclone. Even with satellite imagery, actual reports are needed to confirm developing patterns and provide accurate temperature, pressure, and other measurements. Forecasts can be no better than the data received.

4001. Atmospheric Pressure

The sea of air surrounding the Earth exerts a pressure of about 14.7 pounds per square inch on the surface of the Earth. This **atmospheric pressure**, sometimes called **barometric pressure**, varies from place to place, and at the same place it varies over time.

Atmospheric pressure is one of the most basic elements of a meteorological observation. When the pressure at each station is plotted on a synoptic chart, lines of equal atmospheric pressure, called **isobars**, indicate the areas of high and low pressure. These are useful in making weather predictions because certain types of weather are characteristic of each type of area, and wind patterns over large areas can be deduced from the isobars.

Atmospheric pressure is measured with a **barometer**. The earliest known barometer was the **mercurial barometer,** invented by Evangelista Torricelli in 1643. In its simplest form, it consists of a glass tube a little more than 30 inches in length and of uniform internal diameter. With one end closed, the tube is filled with mercury, and inverted into a cup of mercury. The mercury in the tube falls until the column is just supported by the pressure of the atmosphere on the open cup, leaving a vacuum at the upper end of the tube. The height of the column indicates atmospheric pressure, with greater pressures supporting higher columns of mercury.

The **aneroid barometer** has a partly evacuated, thin metal cell which is compressed by atmospheric pressure. Slight changes in air pressure cause the cell to expand or contract, while a system of levers magnifies and converts this motion to a reading on a gauge or recorder.

Early mercurial barometers were calibrated to indicate the height, usually in inches or millimeters, of the column of mercury needed to balance the column of air above the point of measurement. While units of inches and millimeters are still widely used, many modern barometers are calibrated to indicate the centimeter-gram-second unit of pressure, the **hectopascal (hPa)**, formerly known as the millibar. The hectopascal is equal to 1,000 dynes per square centimeter. A **dyne** is the force required to accelerate a mass of one gram at the rate of one centimeter per second per second. 1,000 hPa = 100,000 Pascal = 14.50 pounds per square inch = 750.0 mm Hg = 0.9869 atmosphere. A reading in any of the three units of measurement can be converted to the equivalent reading in any of the other units by using the Conversion Table for hecto-Pascals (millibars), Inches of Mercury, and Millimeters of Mercury (Table 34) or the conversion factors. However, the pressure reading should always be reported in hPa.

4002. The Aneroid Barometer

The **aneroid barometer** (Figure 4002a) measures the force exerted by atmospheric pressure on a partly evacuated, thin metal element called a **sylphon cell** or aneroid capsule. A small spring is used, either internally or externally, to partly counteract the tendency of the atmospheric pressure to crush the cell. Atmospheric pressure is indicated directly by a scale and a pointer connected to the cell by a combination of levers. The linkage provides considerable magnification of the slight motion of the cell, to permit

Figure 4002a. An aneroid barometer.

readings to higher precision than could be obtained without it. An aneroid barometer should be mounted permanently. Prior to installation, the barometer should be carefully set. U.S. ships of the **Voluntary Observation Ship (VOS)** program are set to sea level pressure. Other vessels may be set to station pressure and corrected for height as necessary. An adjustment screw is provided for this purpose. The error of this instrument is determined by comparison with a mercurial barometer, Digiquartz barometer, or a standard precision aneroid barometer. If a qualified meteorologist is not available to make this adjustment, adjust by first removing only one half the apparent error. Then tap the case gently to assist the linkage to adjust itself, and repeat the adjustment. If the remaining error is not more than half a hPa (0.015 inch), no attempt should be made to remove it by further adjustment. Instead, a correction should be applied to the readings. The accuracy of this correction should be checked from time to time.

More information regarding the Voluntary Observation Ship (VOS) program can be accessed via the link provided in Figure 4002b.

Figure 4002b. Voluntary Observation Ship (VOS) Program. http://www.vos.noaa.gov/

4003. The Barograph

The **barograph** (Figure 4003) is a recording barometer. In principle it is the same as a non-recording aneroid barometer except that the pointer carries a pen at its outer end, and a slowly rotating cylinder around which a chart is wrapped replaces the scale. A clock mechanism inside the cylinder rotates it so that a continuous line is traced on the chart to indicate the pressure at any time. The barograph is usually mounted on a shelf or desk in a room open to the atmosphere and in a location which minimizes the effect of the ship's vibration. Shock absorbing material such as sponge rubber may be placed under the instrument to minimize vibration. The pen should be checked each time the chart is changed.

A **marine microbarograph** is a precision barograph using greater magnification and an expanded chart. It is designed to maintain its precision through the conditions encountered aboard ship. Two sylphon cells are used, one

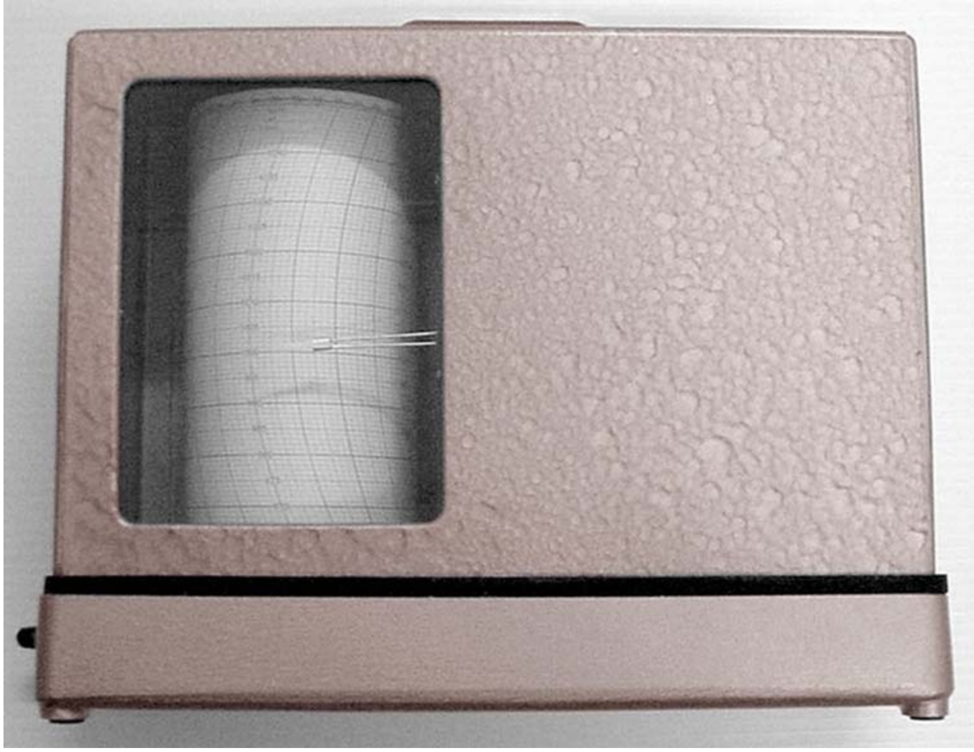


Figure 4003. A marine barograph.

mounted over the other, in tandem. Minor fluctuations due to shocks or vibrations are eliminated by damping. Since oil filled dashpots are used for this purpose, the instrument should never be inverted. The dashpots of the marine microbarograph should be kept filled with dashpot oil to within three-eighths inch of the top. The marine microbarograph is fitted with a valve so it can be vented to the outside for more accurate pressure readings.

Ship motions are compensated by damping and spring loading which make it possible for the microbarograph to be tilted up to 22° without varying more than 0.3 hPa from the true reading. Microbarographs have been almost entirely replaced by standard barographs.

Both instruments require checking from time to time to insure correct indication of pressure. The position of the pen is adjusted by a small knob provided for this purpose. The adjustment should be made in stages, eliminating half the apparent error, tapping the case to insure linkage adjustment to the new setting, and then repeating the process.

4004. Adjusting Barometer Readings

Atmospheric pressure as indicated by a barometer or barograph may be subject to several errors.

Instrument error: Inaccuracy due to imperfection or incorrect adjustment can be determined by comparison with a standard precision instrument. The National Weather Service provides a comparison service. In major U.S. ports, a **Port Meteorological Officer (PMO)** carries a portable precision aneroid barometer or a digital barometer for barometer comparisons on board ships which participate in the VOS program. The portable barometer is compared with station barometers before and after a ship visit. If a barometer is taken to a National Weather Service shore station, the comparison can be made there. The correct sea level pressure can also be obtained by telephone. The shipboard barometer should be corrected for height, as explained below, before comparison with this value. If there is reason to believe that the barometer is in error, it should be compared with a standard, and if an error is found, the barometer should be adjusted to the correct reading, or a correction applied to all readings. More information regarding PMOs is available via the link provided in Figure 4004.

Figure 4004. *Link to Port Meteorological Officers website.*
http://www.vos.noaa.gov/met_officers.shtml

Height error: The atmospheric pressure reading at the height of the barometer is called the **station pressure** and is subject to a height correction in order to correct it to sea level. Isobars adequately reflect wind conditions and geographic distribution of pressure only when they are drawn for pressure at constant height (or the varying height at which a constant pressure exists). On synoptic charts it is customary to show the equivalent pressure at sea level, called **sea level pressure**. This is found by applying a correction to station pressure. The correction depends upon the height of the barometer and the average temperature of the air between this height and the surface. The outside air temperature taken aboard ship is sufficiently accurate for this purpose and is an important correction that should be applied to all readings of any type of barometer. See the Correction of Barometer Reading for Height Above Sea Level table (Table 31) for this correction. Of special note on the Great Lakes, each Lake is at a different height above sea level, so an additional correction is needed.

Temperature error: Barometers are calibrated at a standard temperature of 32°F. Modern aneroid barometers compensate for temperature changes by using different metals having unequal coefficients of linear expansion.

4005. Temperature

Temperature is a measure of heat energy, measured in degrees. Several different temperature scales are in use.

On the **Fahrenheit (F)** scale, pure water freezes at 32° and boils at 212°.

On the **Celsius (C)** scale, commonly used with the metric system, the freezing point of pure water is 0° and the boiling point is 100°. This scale has been known by various names in different countries. In the United States it was formerly called the centigrade scale. The Ninth General Conference of Weights and Measures, held in France in 1948, adopted the name Celsius to be consistent with the naming of other temperature scales after their inventors, and to avoid the use of different names in different countries. On the original Celsius scale, invented in 1742 by a Swedish astronomer named Anders Celsius, numbering was the reverse of the modern scale, 0° representing the boiling point of water, and 100° its freezing point.

Temperature of one scale can be easily converted to another because of the linear mathematical relationship between them. Note that the sequence of calculation is slightly different; algebraic rules must be followed.

$$C = \frac{5}{9}(F - 32), \text{ or } \qquad C = \frac{F - 32}{1.8}$$

$$F = \frac{9}{5}C + 32, \text{ or } \qquad F = 1.8C + 32$$

$$K \text{ (Kelvin)} = C + 273.15$$

$$R \text{ (Rankine)} = F + 459.69$$

A temperature of –40° is the same by either the Celsius or Fahrenheit scale. Similar formulas can be made for conversion of other temperature scale readings. The Conversion Table for Thermometer Scales (Table 29) gives the equivalent values of Fahrenheit, Celsius, and Kelvin temperatures.

The intensity or degree of heat (temperature) should not be confused with the amount of heat. If the temperature of air or some other substance is to be increased by a given number of degrees, the amount of heat that must be added depends on the mass of the substance. Also, because of differences in their specific heat, equal amounts of different substances require the addition of unequal amounts of heat to raise their temperatures by equal amounts. The units used for measurement of heat are the **British thermal unit (BTU),** the amount of heat needed to raise the temperature of 1 pound of water 1° Fahrenheit, and the **calorie**, the amount of heat needed to raise the temperature of 1 gram of water 1° Celsius.

4006. Temperature Measurement

Temperature is measured with a **thermometer**. Most thermometers are based upon the principle that materials expand with an increase of temperature, and contract as temperature decreases. In its most common form, a thermometer consists of a bulb filled with mercury or a glycol based fluid, which is connected to a tube of very small cross sectional area. The fluid only partly fills the tube. In the remainder is a vacuum. Air is driven out by boiling the fluid, and the top of the tube is then sealed. As the fluid expands or contracts with changing temperature, the length of the fluid column in the tube changes.

Sea surface temperature observations are used in the forecasting of fog and furnish important information about the development and movement of tropical cyclones. Commercial fishermen are interested in the sea surface temperature as an aid in locating certain species of fish. There are several methods of determining seawater temperature. These include engine room intake readings, condenser intake readings, thermistor probes attached to the hull, and readings from buckets recovered from over the side. Although the condenser intake method is not a true measure of surface water temperature, the error is generally small.

If the surface temperature is desired, a sample should be obtained by bucket, preferably made of canvas, from a forward position well clear of any discharge lines. The sample should be taken immediately to a place where it is sheltered from wind and Sun. The water should then be stirred with the thermometer, keeping the bulb submerged, until a constant reading is obtained.

A considerable variation in sea surface temperature can be experienced in a relatively short distance of travel. This is especially true when crossing major ocean currents such as the Gulf Stream and the Kuroshio Current. Significant variations also occur where large quantities of fresh water are discharged from rivers or bays. A clever navigator will note these changes as an indication of when to allow for set and drift in dead reckoning.

4007. Humidity

Humidity is a measure of the atmosphere's water vapor content. **Relative humidity** is the ratio, stated as a percentage, of the pressure of water vapor present in the atmosphere to the saturation vapor pressure at the same temperature.

As air temperature decreases, the relative humidity increases, as long as the wet-bulb temperature remains the same or decreases at a slower rate than air temperature. At some point, saturation takes place, and any further cooling results in condensation of some of the moisture. The temperature at which this occurs is called the dew point, and the moisture deposited upon objects is called dew if it forms in the liquid state, or frost if it forms as ice crystals.

The same process causes moisture to form on the outside of a container of cold liquid, the liquid cooling the air in the immediate vicinity of the container until it reaches the dew point. When moisture is deposited on man-made objects, it is sometimes called **sweat**. It occurs whenever the temperature of a surface is lower than the dew point of air in contact with it. It is of particular concern to the mariner because of its effect upon instruments, and possible damage to ship or cargo. Lenses of optical instruments may sweat, usually with such small droplets that the surface has a "frosted" appearance. When this occurs, the instrument is said to "fog" or "fog up," and is useless until the moisture is removed. Damage is often caused by corrosion or direct water damage when pipes or inner shell plates of a vessel sweat and drip. Cargo may also sweat if it is cooler than the dew point of the air.

Clouds and fog form from the condensation of water on minute particles of dust, salt, and other material in the air. Each particle forms a nucleus around which a droplet of water forms. If air is completely free from solid particles on which water vapor may condense, the extra moisture remains vaporized, and the air is said to be **supersaturated**.

Relative humidity and dew point are measured with a **hygrometer**. The most common type, called a **psychrometer**, consists of two thermometers mounted together on a single strip of material. One of the thermometers is mounted a little lower than the other, and has its bulb covered with muslin. When the muslin covering is thoroughly moistened and the thermometer well ventilated, evaporation cools the bulb of the thermometer, causing it to indicate a lower reading than the other. A **sling psychrometer** is ventilated by whirling the thermometers. The difference between the dry-bulb and wet-bulb temperatures is used to enter **psychrometric tables** (Relative Humidity and Dew Point Tables) (Table 35 and Table 36) to find the relative humidity and dew point. If the wet-bulb temperature is above freezing, reasonably accurate results can be obtained by a psychrometer consisting of dry- and wet-bulb thermometers mounted so that air can circulate freely around them without special ventilation. This type of installation is common aboard ship.

Example: *The dry-bulb temperature is 65°F, and the wet-bulb temperature is 61°F.*

Required: *(1) Relative humidity, (2) dew point.*

Solution: *The difference between readings is 4°. Entering the Relative Humidity Table (Table 35) with this value, and a dry-bulb temperature of 65°, the relative humidity is found to be 80%. From the Dew Point Table (Table 36) the dew point is 58°.*

Answers: *(1) Relative humidity 80 percent, (2) dew point 58°.*

Also in use aboard many ships is the **electric psychrometer**. This is a hand held, battery operated instrument with two mercury thermometers for obtaining dry- and wet-bulb temperature readings. It consists of a plastic housing that holds the thermometers, batteries, motor, and fan.

4008. Wind Measurement

Wind measurement consists of determination of the direction and speed of the wind. Direction is measured by a **wind vane**, and speed by an **anemometer**. Several types of wind speed and direction sensors are available, using vanes to indicate wind direction (where the wind is coming from) and rotating cups or propellers for speed sensing. Many ships have reliable wind instruments installed, and inexpensive wind instruments are available for even the smallest yacht. If no anemometer is available, wind speed can be estimated by its effect upon the sea and nearby objects. The direction can be computed accurately, even on a fast moving vessel, by maneuvering board or using the Direction and Speed of True Wind in Units of Ship's Speed Table (Table 30).

4009. True and Apparent Wind

An observer aboard a vessel proceeding through still air experiences an apparent wind which is from dead ahead and has an apparent speed equal to the speed of the vessel. Thus, if the actual or true wind is zero and the speed of the vessel is 10 knots, the apparent wind is from dead ahead at 10 knots. If the true wind is from dead ahead at 15 knots, and the speed of the vessel is 10 knots, the apparent wind is 15 + 10 = 25 knots from dead ahead. If the vessel reverses course, the apparent wind is 15 – 10 = 5 knots, from dead astern.

The **apparent wind** is the vector sum of the true wind and the *reciprocal* of the vessel's course and speed vector. Since wind vanes and anemometers measure apparent wind, the usual problem aboard a vessel equipped with an anemometer is to convert apparent wind to true wind. There are several ways of doing this. Perhaps the simplest is by the graphical solution illustrated in the following example:

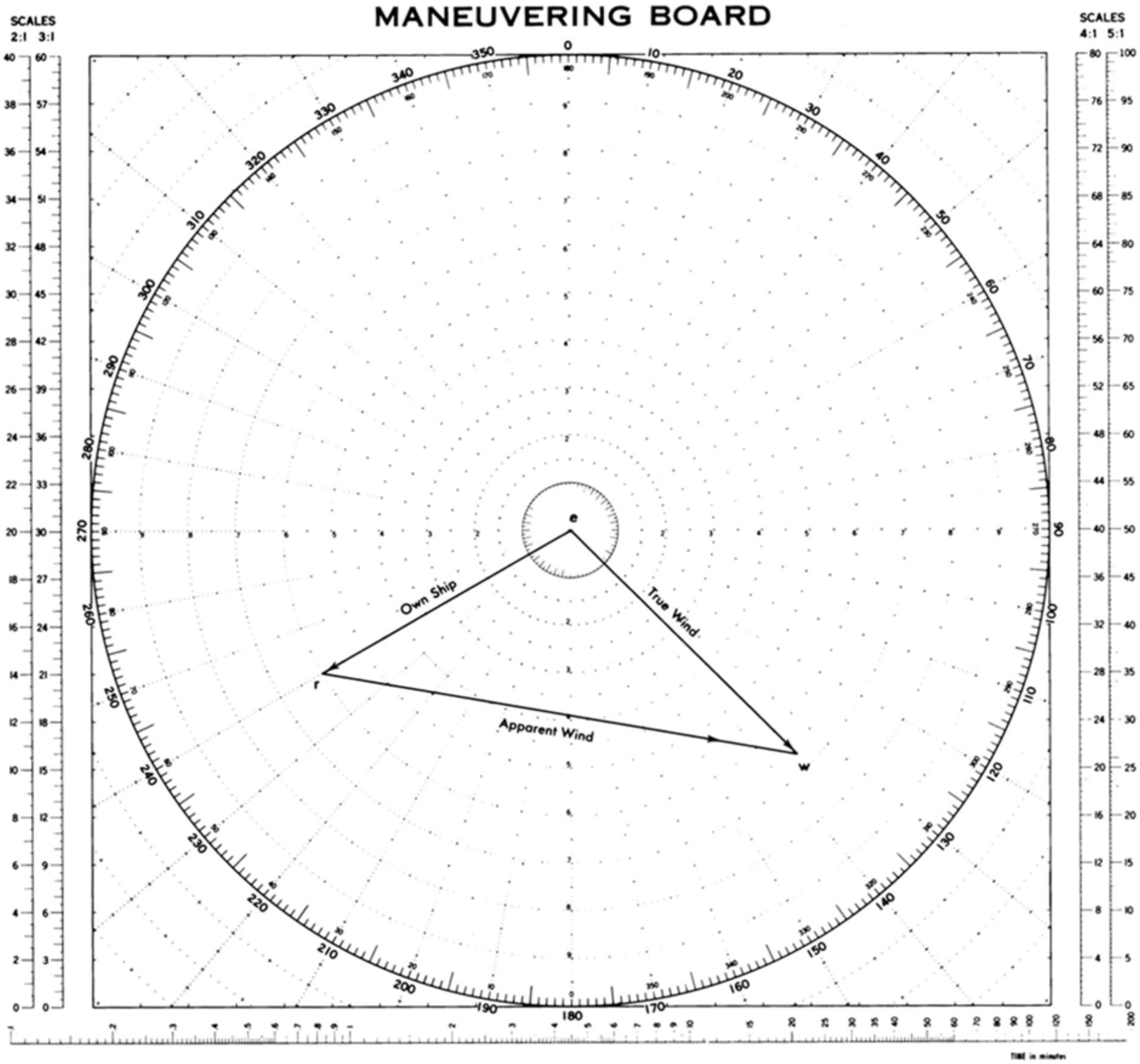


Figure 4009a. Finding true wind by Maneuvering Board.

Example 1: *A ship is proceeding on course 240° at a speed of 18 knots. The apparent wind is from 040° relative at 30 knots.*

Required: *The direction and speed of the true wind.*

Solution: *(Figure 4009a) First starting from the center of a maneuvering board, plot the ship's vector "er," at 240°, length 18 knots (using the 3–1 scale). Next plot the relative wind's vector from r, in a direction of 100° (the reciprocal of 280°) length 30 knots. The true wind is from the center to the end of this vector or line "ew."*

Alternatively, you can plot the ship's vector from the center, then plot the relative wind's vector toward the center, and see the true wind's vector from the end of this line to the end of the ship's vector. Use parallel rulers to transfer the wind vector to the center for an accurate reading.

Answer: *True wind is from 315° at 20 knots.*

On a moving ship, the direction of the true wind is always on the same side and aft of the direction of the apparent wind. The faster the ship moves, the more the apparent wind draws ahead of the true wind.

A solution can also be made in the following manner without plotting: On a maneuvering board, label the circles 5, 10, 15, 20, etc., from the center, and draw vertical lines tangent to these circles. Cut out the 5:1 scale and discard that part having graduations greater than the maximum speed of the vessel. Keep this sheet for all solutions. (For durability, the two parts can be mounted on cardboard or other suitable material.) To find true wind, spot in point 1 by eye. Place the zero of the 5:1 scale on this point and align the scale (inverted) using the vertical lines. Locate point 2 at the speed of the vessel as indicated on the 5:1 scale. It is always vertically below point 1. Read the relative direction and the speed of the true wind, using eye interpolation if needed.

A tabular solution can be made using the Direction and Speed of True Wind in Units of Ship's Speed table (Table 30). The entering values for this table are the apparent wind speed in units of ship's speed, and the difference between the heading and the apparent wind direction. The values taken from the table are the relative direction (right or left) of the true wind, and the speed of the true wind in units of ship's speed. If a vessel is proceeding at 12 knots, 6 knots constitutes one-half (0.5) unit, 12 knots one unit, 18 knots 1.5 units, 24 knots two units, etc.

Example 2: *A ship is proceeding on course 270° at a speed of 10 knots. The apparent wind is from 10° off the port bow, speed 30 knots.*

Required: *The relative direction, true direction, and speed of the true wind by table.*

Solution: *The apparent wind speed is*

$$\frac{30}{10} = 3.0\ ships\ speed\ units$$

Enter the Direction and Speed of True Wind in Units of Ship's Speed table (Table 30) with 3.0 and 10° and find the relative direction of the true wind to be 15° off the port bow (345° relative), and the speed to be 2.02 times the ship's speed, or 20 knots, approximately. The true direction is 345° + 270° (-360) = 255°.

Answers: *True wind from 345° relative = 255° true, at 20 knots.*

One can also find apparent wind from the true wind, course or speed required to produce an apparent wind from a given direction or speed, or course and speed to produce an apparent wind of a given speed from a given direction. Such problems often arise in aircraft carrier operations and in some rescue situations. Printable maneuvering board files are available through the link provided in Figure 4009b.

Figure 4009b. Link to Pub 1310, The Radar Navigation and Maneuvering Board Manual.
https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_st=&_pageLabel=msi_portal_page_62&pubCode=0008

When wind speed and direction are determined by the appearance of the sea, the result is true speed and direction. Waves move in the same direction as the generating wind, and are not deflected by Earth's rotation. If a wind vane is used, the direction of the apparent wind thus determined can be used with the speed of the true wind to determine the direction of the true wind by vector diagram.

WIND AND WAVES

4010. Effects of Wind on the Sea

There is a direct relationship between the speed of the wind and the state of the sea. This is useful in predicting the sea conditions to be anticipated when future wind speed forecasts are available. It can also be used to estimate the speed of the wind, which may be necessary when an anemometer is not available.

Wind speeds are usually grouped in accordance with the ***Beaufort Scale of Wind Force***, devised in 1806 by English Admiral Sir Francis Beaufort (1774-1857). As adopted in 1838, Beaufort numbers ranged from 0 (calm) to 12 (hurricane). The Beaufort wind scale and sea state photographs at the end of this chapter can be used to estimate wind speed (also see Table 4012). With the exception of Force 12, contributed by John Thomson of Ponteland, Northumberland, England, these pictures (courtesy of the Meteorological Service of Canada) represent the results of a project carried out on board the Canadian Ocean Weather Ships VANCOUVER and QUADRA at Ocean Weather Station PAPA (50°N, 145°W), between April 1976 and May 1981. The aim of the project was to collect color photographs of the sea surface as it appears under the influence of the various ranges of wind speed, as defined by The Beaufort Scale. The photographs represent as closely as possible steady state sea conditions over many hours for each Beaufort wind force. They were taken from heights ranging from 12-17 meters above the sea surface; anemometer height was 28 meters.

4011. Estimating the Wind at Sea

When there is not a functioning anemometer, observers on board ships will usually determine the speed of the wind by estimating Beaufort force. Through experience, ships' officers have developed various methods of estimating this force. The effect of the wind on the observer, the ship's rigging, flags, etc., is used as a guide, but estimates based on these indications give the relative wind which must be corrected for the motion of the ship before an estimate of the true wind speed can be obtained.

The most common method involves the appearance of the sea surface. The state of the sea disturbance, i.e. the dimensions of the waves, the presence of white caps, foam, or spray, depends principally on three factors:

1. **The wind speed**. The higher the speed of the wind, the greater is the sea disturbance.
2. **The wind's duration**. At any point on the sea, the disturbance will increase the longer the wind blows at a given speed, until a maximum state of disturbance is reached.
3. **The fetch**. This is the length of the stretch of water over which the wind acts on the sea surface from the same direction.

For a given wind speed and duration, the longer the fetch, the greater is the sea disturbance. If the fetch is short, such as a few miles, the disturbance will be relatively small no matter how great the wind speed is or how long it has been blowing.

Swell waves are not considered when estimating wind speed and direction. Only those waves raised by the wind blowing at the time are of any significance.

A wind of a given Beaufort force will, therefore, produce a characteristic appearance of the sea surface provided that it has been blowing for a sufficient length of time, and over a sufficiently long fetch.

In practice, the mariner observes the sea surface, noting the size of the waves, the white caps, spindrift, etc., and then finds the criterion which best describes the sea surface as observed. This criterion is associated with a Beaufort number, for which a corresponding mean wind speed and range in knots are given. Since meteorological reports require that wind speeds be reported in knots, the mean speed for the Beaufort number may be reported, or an experienced observer may judge that the sea disturbance is such that a higher or lower speed within the range for the force is more accurate.

This method should be used with caution. The sea conditions described for each Beaufort force are "steady-state" conditions; i.e. the conditions which result when the wind has been blowing for a relatively long time, and over a great stretch of water. However, at any particular time at sea the duration of the wind or the fetch, or both, may not have been great enough to produce these "steady-state" conditions. When a high wind springs up suddenly after previously calm or near calm conditions, it will require some hours, depending on the strength of the wind, to generate waves of maximum height. The height of the waves increases rapidly in the first few hours after the commencement of the blow, but increases at a much slower rate later on.

Beaufort force of wind.	Theoretical maximum wave height (ft) unlimited duration and fetch.	Duration of winds (hours), with unlimited fetch, to produce percent of maximum wave height indicated.			Fetch (nautical miles), with unlimited duration of blow, to produce percent of maximum wave height indicated.		
		50%	75%	90%	50%	75%	90%
3	2	1.5	5	8	3	13	25
5	8	3.5	8	12	10	30	60
7	20	5.5	12	21	22	75	150
9	40	7	16	25	55	150	280
11	70	9	19	32	85	200	450

Table 4011. Duration of winds and length of fetches required for various wind forces.

At the beginning of the fetch (such as at a coastline when the wind is offshore) after the wind has been blowing for a long time, the waves are quite small near shore, and increase in height rapidly over the first 50 miles or so of the fetch. Farther offshore, the rate of increase in height with distance slows down, and after 500 miles or so from the beginning of the fetch, there is little or no increase in height.

Table 4011 illustrates the duration of winds and the length of fetches required for various wind forces to build seas to 50 percent, 75 percent, and 90 percent of their theoretical maximum heights.

The theoretical maximum wave heights represent the average heights of the highest third of the waves, as these waves are most significant.

It is clear that winds of force 5 or less can build seas to 90 percent of their maximum height in less than 12 hours, provided the fetch is long enough. Higher winds require a much greater time, force 11 winds requiring 32 hours to build waves to 90 percent of their maximum height. The times given in Table 4011 represent those required to build waves starting from initially calm sea conditions. If waves are already present at the onset of the blow, the times would be somewhat less, depending on the initial wave heights and their direction relative to the direction of the wind which has sprung up.

The first consideration when using the sea criterion to estimate wind speed, therefore, is to decide whether the wind has been blowing long enough from the same direction to produce a steady state sea condition. If not, then it is possible that the wind speed may be underestimated.

Experience has shown that the appearance of white-caps, foam, spindrift, etc. reaches a steady state condition before the height of the waves attain their maximum value. It is a safe assumption that the appearance of the sea (such as white-caps, etc.) will reach a steady state in the time required to build the waves to 50-75 percent of their maximum height. Thus, from Table 4011 it is seen that a force 5 wind could require 8 hours at most to produce a characteristic appearance of the sea surface.

A second consideration when using the sea criteria is the amount of the fetch over which the wind has been blowing to produce the present state of the sea. On the open sea, unless the mariner has the latest synoptic weather map available, the length of the fetch will not be known. It will be seen from Table 4011 though, that only relatively short fetches are required for the lower wind forces to generate their characteristic seas. On the open sea, the fetches associated with most storms and other weather systems are usually long enough so that even winds up to force 9 can build seas up to 90 percent or more of their maximum height, providing the wind blows from the same direction long enough.

When navigating close to a coast or in restricted waters, however, it may be necessary to make allowances for the shorter stretches of water over which the wind blows. For example, referring to Table 4011, if the ship is 22 miles from a coast, and an offshore wind with an actual speed of force 7 is blowing, the waves at the ship will never attain more than 50 percent of their maximum height for this speed no matter how long the wind blows. Hence, if the sea criteria were used under these conditions without consideration of the short fetch, the wind speed would be underestimated. With an offshore wind, the sea criteria may be used with confidence if the distance to the coast is greater than the values given in the extreme right-hand column of Table 4011, provided that the wind has been blowing offshore for a sufficient length of time.

4012. Wind Speed Calculating Factors

Tidal and Other Currents: A wind blowing against the tide or a strong non-tidal current causes higher, steeper waves having a shorter period than normal, which may result in an overestimate of the wind speed if the estimation is made by wave height alone. On the other hand, a wind blowing in the same direction as a tide or strong current causes less sea disturbance than normal, with longer period waves, which may result in underestimating the wind speed.

Shallow Water: Waves running from deep water into shallow water increase in steepness, hence their tendency to break. Therefore, with an onshore wind there will naturally be more whitecaps over shallow waters than over the deeper water farther offshore. It is only over relatively deep water that the sea criteria can be used with confidence.

Swell: Swell is the name given to waves, generally of considerable length, which were raised in some distant area and which have moved into the vicinity of the ship, or to waves raised nearby that continue after the wind has abated or changed direction. The direction of swell waves is usually different from the direction of the wind and the sea waves. Swell waves are not considered when estimating wind speed and direction. Only those waves raised by the wind blowing at the time are used for estimation. The wind-driven waves show a greater tendency to break when superimposed on the crests of swell, and hence, more whitecaps may be formed than if the swell were absent. Under these conditions, the use of the sea criteria may result in a slight overestimate of the wind speed.

Precipitation: Heavy rain has a damping or smoothing effect on the sea surface that is mechanical in character. Since the sea surface will therefore appear less disturbed than would be the case without the rain, the wind speed may be underestimated unless the smoothing effect is taken into account.

Ice: Even small concentrations of ice floating on the sea surface will dampen waves considerably, and concentrations averaging greater than about seven-tenths will eliminate waves altogether. Young sea ice, which in the early stages of formation has a thick soupy consistency and later takes on a rubbery appearance, is very effective in dampening waves. Consequently, the sea criteria cannot be used with any degree of confidence when sea ice is present. In higher latitudes, the presence of an ice field some distance to windward of the ship may be suspected if, when the ship is not close to any coast, the wind is relatively strong but the seas abnormally underdeveloped. The edge of the ice field acts like a coastline, and the short fetch between the ice and the ship is not sufficient for the wind to fully develop the seas.

Wind Shifts: Following a rapid change in the direction of the wind, as occurs at the passage of a cold front, the new wind will flatten out to a great extent the waves which were present before the wind shift. This happens because the direction of the wind after the shift may differ by 90° or more from the direction of the waves, which does not change. Hence, the wind may oppose the progress of the waves and quickly dampen them out. At the same time, the new wind begins to generate its own waves on top of this dissipating swell, and it is not long before the cross pattern of waves gives the sea a “choppy” or confused appearance. It is during the first few hours following the wind shift that the appearance of the sea surface may not provide a reliable indication of wind speed. The wind is normally stronger than the sea would indicate, as old waves are being flattened out, and the new wave pattern develops.

Night Observations: On a dark night, when it is impossible to see the sea clearly, the observer may estimate the apparent wind from its effect on the ship's rigging, flags, etc., or simply the "feel" of the wind.

Wind Scales and Sea Codes: Table 4012 contains descriptions for the Beaufort wind scale and corresponding sea state codes.

Beaufort Wind Scale with Corresponding Sea Codes

Beaufort Number	Wind Velocity (knots)	Wind Velocity (mph)	Wind Description	Sea State Description	Sea State	
					Term and Height of Waves (feet)	Condition Number
0	< 1	< 1	Calm	Sea surface smooth and mirror-like	Calm, glassy 0	0
1	1-3	1-3	Light Air	Scaly ripples, no foam crests		
2	4-6	4-7	Light Breeze	Small wavelets, crests glassy, no breaking	Calm, rippled 0 - 0.3	1
3	7-10	8-12	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Smooth, wavelets 0.3 - 1	2
4	11-16	13-18	Moderate Breeze	Small waves, becoming longer, numerous whitecaps	Slight 1- 4	3
5	17-21	19-24	Fresh Breeze	Moderate waves, taking longer form, many whitecaps, some spray	Moderate 4 - 8	4
6	22-27	25-31	Strong Breeze	Larger waves, whitecaps common, more spray	Rough 8 - 13	5
7	28-33	32-38	Near Gale	Sea heaps up, white foam steaks off breakers	Very rough 13 - 20	6
8	34-40	39-46	Gale	Moderately high, waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks		
9	41-47	47-54	Strong Gale	High waves, sea begins to roll, dense streaks of foam, spray may reduce visibility		
10	48-55	55-63	Storm	Very high waves, with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	High 20 - 30	7
11	59-63	64-72	Violent Storm	Exceptionally high waves, foam patches cover sea, visibility more reduced	Very high 30 - 45	8
12	64 and over	73 and over	Hurricane	Air filled with foam, sea completely white with driving spray, visibility greatly reduced	Phenomenal 45 and over	9

Table 4012. Beaufort wind scale with corresponding sea codes.

CLOUDS

4013. Cloud Formation

Clouds consist of innumerable tiny droplets of water, or ice crystals, formed by condensation of water vapor around microscopic particles in the air. **Fog** is a cloud in contact with the surface of the Earth.

The shape, size, height, thickness, and nature of a cloud all depend upon the conditions under which it is formed. Therefore, clouds are indicators of various processes occurring in the atmosphere. The ability to recognize different types, and a knowledge of the conditions associated with them, are useful in predicting future weather (see Figure 4013b).

Although the variety of clouds is virtually endless, they may be classified by type. Clouds are grouped into three families according to common characteristics and the altitude of their bases. The families are High, Middle, and Low clouds. As shown in Table 4013a, the altitudes of the cloud bases vary depending on the latitude in which they are located. Large temperature changes cause most of this latitudinal variation.

Cloud Group	Tropical Regions	Temperate Regions	Polar Regions
High	6,000 to 18,000m (20,000 to 60,000ft)	5,000 to 13,000m (16,000 to 43,000ft)	3,000 to 8,000m (10,000 to 26,000ft)
Middle	2,000 to 8,000m (6,500 to 26,000ft)	2,000 to 7,000m (6,500 to 23,000ft)	2,000 to 4,000m (6,500 to 13,000ft)
Low	surface to 2,000m (0 to 6,500ft)	surface to 2,000m (0 to 6,500ft)	surface to 2,000m (0 to 6,500ft)

Table 4013a. Approximate height of cloud bases above the surface for various locations

High clouds are composed principally of ice crystals. As shown in Table 4013a, the air temperatures in the tropic regions that are low enough to freeze all liquid water usually occur above 6000 meters, but in the polar regions these temperatures are found at altitudes as low as 3000 meters. **Middle clouds** are composed largely of water droplets, although higher ones have a tendency toward ice particles. **Low clouds** are composed entirely of water droplets. Clouds types cannot be sufficiently distinguished just by their base altitudes, so within these 3 families are 10 principal cloud types. The names of these are composed of various combinations and forms of the following basic words, all from Latin:

Cirrus, meaning “curl, lock, or tuft of hair.”
Alto, meaning “high, upper air.”
Stratus, meaning “spread out, flatten, cover with a layer.”
Cumulus, meaning “heap, a pile, an accumulation.”
Nimbus, meaning “rainy cloud.”

Individual cloud types recognize certain characteristics, variations, or combinations of these. The following are images and definitions of the 10 principal cloud types and their commonly used symbols.

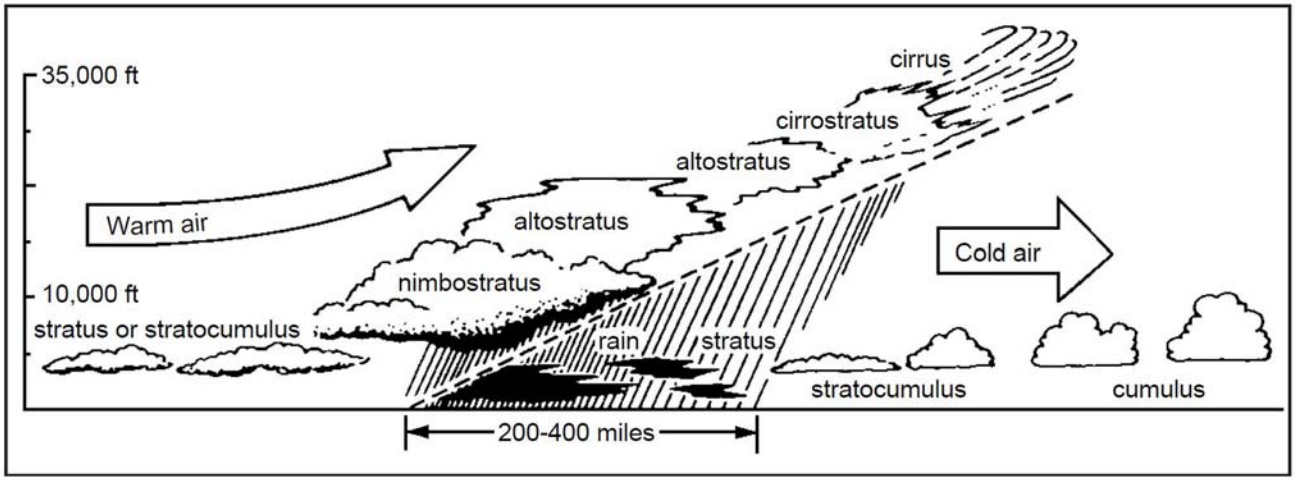


Figure 4013b. Vertical section of clouds ahead of a low. If a warm front is present, it will lie along the dashed lines.

4014. High Clouds

Cirrus (Ci) (Figure 4014a through Figure 4014f) are detached high clouds of delicate and fibrous appearance, without shading, generally white in color, often of a silky appearance. Their fibrous and feathery appearance is caused by their composition of ice crystals. Cirrus appear in varied forms, such as isolated tufts; long, thin lines across the sky; branching, feather-like plumes; curved wisps which may end in tufts, and other shapes. These clouds may be arranged in parallel bands which cross the sky in great circles, and appear to converge toward a point on the horizon. This may indicate the general direction of a low pressure area. Cirrus may be brilliantly colored at sunrise and sunset. Because of their height, they become illuminated before other clouds in the morning, and remain lighted after others at sunset. Cirrus are generally associated with fair weather, but if they are followed by lower and thicker clouds, they are often the forerunner of rain or snow.

Figure 4014a. Dense Cirrus in patches or sheaves, not increasing, or Cirrus like cumuliform tufts.

Figure 4014b. Cirrus filaments, strands, hooks, not expanding.

Cirrostratus (Cs) (Figure 4014g through Figure 4014p) are thin, whitish, high clouds sometimes covering the sky completely and giving it a milky appearance and at other times presenting, more or less distinctly, a formation like a tangled web. The thin veil is not sufficiently dense to blur the outline of the Sun or Moon. However, the ice crystals of which the cloud is composed refract the light passing through to form halos with the Sun or Moon at the center. As cirrus begins to thicken, it will change into cirrostratus. In this form it is popularly known as “mares’ tails.” If it continues to thicken and lower, with the ice crystals melting to form water droplets, the cloud formation is known as altostratus. When this occurs, rain may normally be expected within 24 hours. The more brush-like the cirrus when the sky appears, the stronger the wind at the level of the cloud.

Figure 4014c. Cirrus filaments, strands, hooks, not expanding.

Figure 4014d. Dense Cirrus in patches or sheaves, not increasing, or Cirrus like cumuliform tufts.

Figure 4014e. Dense Cirrus, often the anvil remaining from Cumulonimbus.

Cirrocumulus (Cc) (Figure 4014q and Figure 4014r) are high clouds composed of small white flakes or scales, or

Figure 4014f. Dense Cirrus, often the anvil remaining from Cumulonimbus.

Figure 4014g. Cirrus hooks or filaments, increasing and becoming denser.

Figure 4014h. Cirrus hooks or filaments, increasing and becoming denser.

Figure 4014i. Cirrus bands and/or Cirrostratus, increasing, growing denser, veil below 45.

Figure 4014j. Cirrus bands and/or Cirrostratus, increasing, growing denser, veil below 45.

Figure 4014k. Cirrus bands and/or Cirrostratus, increasing, growing denser, veil below 45.

of very small globular masses, usually without shadows and arranged in groups of lines, or more often in ripples resembling sand on the seashore. One form of cirrocumulus is popularly known as "mackerel sky" because the pattern resembles the scales on the back of a mackerel. Like cirrus, cirrocumulus are composed of ice crystals and are generally associated with fair weather, but may precede a storm if they thicken and lower. They may turn gray and appear hard before thickening.

Figure 4014l. Cirrus bands and/or Cirrostratus, increasing, growing denser, veil below 45.

Figure 4014m. Cirrostratus covering the whole sky.

4015. Middle Level Clouds

Altostratus (As) (Figure 4015a through Figure 4015d) are middle level clouds having the appearance of a grayish or bluish, fibrous veil or sheet. The Sun or Moon, when seen through these clouds, appears as if it were shining through ground glass with a corona around it. Halos are not formed. If these clouds thicken and lower, or if low, ragged "scud" or rain clouds (nimbostratus) form below them, continuous rain or snow may be expected within a few hours.

Altocumulus (Ac) (Figure 4015e through Figure 4015r) are middle level clouds consisting of a layer of large, ball-like masses that tend to merge together. The balls or patches may vary in thickness and color from dazzling white to dark gray, but they are more or less regularly arranged. They may appear as distinct patches similar to cirrocumulus, but can be distinguished by hav-

Figure 4014n. Cirrostratus covering the whole sky.

Figure 4014o. Cirrostratus, not increasing, not covering the whole sky.

Figure 4014p. Cirrostratus, not increasing, not covering the whole sky.

Figure 4014q. Cirrocumulus alone, and/or Cirrus and Cirrostratus.

Figure 4014r. Cirrocumulus alone, and/or Cirrus and Cirrostratus.

ing individual patches which are generally larger, showing distinct shadows in some places. They are often mistaken for stratocumulus. If altocumulus thickens and lowers it may produce thundery weather and showers, but it does not bring prolonged bad weather. Sometimes the patches merge to form a series of big rolls resembling ocean waves, with streaks of blue sky between. Because of perspective, the rolls appear to run together near the horizon. These regular parallel bands differ from cirrocumulus because they occur in larger masses with shadows. Altocumulus move in the direction of the short dimension of the rolls, like ocean waves. Sometimes altocumulus appear briefly in the form shown in Figure 4015o and Figure 4015p, sometimes before a thunderstorm. They are generally arranged in a line with a flat horizontal base, giving the impression of turrets on a cas-

Figure 4015a. Altostratus, semitransparent, Sun or Moon dimly visible.

Figure 4015b. Altostratus, semitransparent, Sun or Moon dimly visible.

Figure 4015c. Altostratus, dense enough to hide Sun or Moon, or nimbostratus.

Figure 4015d. Altostratus, dense enough to hide Sun or Moon, or nimbostratus

tle. The turreted tops may look like miniature cumulus and possess considerable depth and great length. These clouds usually indicate a change to chaotic, thundery skies.

Figure 4015e. Altocumulus, semitransparent, cloud elements change slowly, one level.

Figure 4015f. Altocumulus, semitransparent, cloud elements change slowly, one level.

Figure 4015g. Altocumulus patches, semitransparent, multilevel, cloud elements changing, also Altocumulus Lenticular

Figure 4015h. Altocumulus patches, semitransparent, multilevel, cloud elements changing, also Altocumulus Lenticular

4016. Low Clouds

Cumulus (Cu) (Figure 4016a through Figure 4016d) are dense clouds with vertical development formed by rising air which is cooled as it reaches greater heights. They have a horizontal base and dome-shaped upper surfaces, with protuberances extending above the dome. Cumulus appear in patches, never covering the entire sky. When vertical development is not great, the clouds resemble tufts of cotton or wool, being popularly

Figure 4015i. Altocumulus, one or more bands or layers, expanding, thickening.

Figure 4015j. Altocumulus, one or more bands or layers, expanding, thickening.

called "woolpack" clouds. The horizontal bases of such clouds may not be noticeable. These are called "fair weather" cumulus because they commonly accompany stable air and good weather. However, they may merge with altocumulus, or may grow to cumulonimbus before a thunderstorm. Since cumulus are formed by updrafts, they are accompanied by turbulence, causing "bumpiness" in the air. The extent of turbulence is proportional to the vertical extent of the clouds. Cumulus are marked by strong contrasts of light and dark.

Figure 4015k. Altocumulus from the spreading of Cumulus or Cumulonimbus.

Figure 4015l. Altocumulus from the spreading of Cumulus or Cumulonimbus.

Figure 4015m. Altocumulus, one or more layers, mainly opaque, not expanding, or Altocumulus with Altostratus or Nimbostratus.

Stratocumulus (Sc) (Figure 4016e through Figure 4016h) are low level clouds appearing as soft, gray, roll-shaped masses. They may be shaped in long, parallel rolls similar to altocumulus moving forward with the wind. The

Figure 4015n. Altocumulus, one or more layers, mainly opaque, not expanding, or Altocumulus with Altostratus or Nimbostratus.

Figure 4015o. Altocumulus with tower or turret like sproutings.

Figure 4015p. Altocumulus with tower or turret-like sproutings.

Figure 4015q. Altocumulus of a chaotic sky, usually with heavy broken cloud sheets at different levels.

Figure 4015r. Altocumulus of a chaotic sky, usually with heavy broken cloud sheets at different levels.

Figure 4016a. Cumulus with very little vertical extent.

motion is in the direction of their short dimension, like ocean waves. These clouds, which vary greatly in altitude, are the final product of the characteristic daily change taking place in cumulus clouds. They are usually followed by clear skies during the night.

Stratus (St) (Figure 4016i through Figure 4016l) is a low cloud in a uniform layer resembling fog. Often the base is not more than 1,000 feet high. A veil of thin stratus gives the sky a hazy appearance. Stratus is often quite thick, permitting so little sunlight to penetrate that it appears dark to an observer below. From above it is white. Light mist may descend from stratus. Strong wind sometimes breaks stratus into shreds called “fractostratus.”

Nimbostratus (Ns) (Figure 4016m and Figure 4016n) is a low, dark, shapeless cloud layer, usually nearly uniform, but sometimes with ragged, wet-looking bases.

Figure 4016b. Cumulus with very little vertical extent.

Figure 4016c. Cumulus with moderate or greater vertical extent.

Figure 4016d. Cumulus with moderate or greater vertical extent.

Nimbostratus is the typical rain cloud. The precipitation which falls from this cloud is steady or intermittent, but not showery.

Cumulonimbus (Cb) (Figure 4016o through Figure 4016r) is a massive cloud with great vertical development, rising in mountainous towers to great heights. The upper part consists of ice crystals, and often spreads out in the shape of an anvil which may be seen at such distances that the base may be below the horizon. Cumulonimbus often produces showers of rain, snow, or hail, frequently accompanied by lightning and thunder. Because of this, the cloud is often popularly called a "thundercloud" or "thunderhead." The base is horizontal, but as showers occur it lowers and becomes ragged.

Figure 4016e. Stratocumulus from the spreading out of Cumulus.

Figure 4016f. Stratocumulus from the spreading out of Cumulus.

Figure 4016g. Stratocumulus not formed from the spreading out of Cumulus.

Figure 4016h. Stratocumulus not formed from the spreading out of Cumulus.

Figure 4016i. Stratus in a sheet or layer.

Figure 4016j. Stratus in a sheet or layer.

Figure 4016k. Stratus fractus and/or Cumulus fractus of bad weather.

Figure 4016l. Stratus fractus and/or Cumulus fractus of bad weather.

Figure 4016m. Nimbostratus formed from lowering Altostratus.

4017. Cloud Height Measurement

At sea, cloud heights are often determined by estimation. This is a difficult task, particularly at night.

The height of the base of clouds formed by vertical development (any form of cumulus), if formed in air that has risen from the surface of the Earth, can be determined by psychrometer. This is because the height to which the air must rise before condensation takes place is proportional to the difference between surface air temperature and the dew point. At sea, this difference multiplied by 126.3 gives the height in meters. That is, for every degree difference between surface air temperature and the dew point, the air must rise 126.3 meters before condensation will take place. Thus, if the dry-bulb temperature is 26.8°C, and the wet-bulb temperature is 25.0°C, the dew point is 24°C, or 2.8°C

Figure 4016n. Nimbostratus formed from lowering Altostratus.

Figure 4016o. Cumulonimbus, tops not fibrous, outline not completely sharp, no anvil.

lower than the surface air temperature. The height of the cloud base is 2.8   126.3 = 354 meters.

Figure 4016p. Cumulonimbus, tops not fibrous, outline not completely sharp, no anvil.

Figure 4016q. Cumulonimbus with fibrous top, often with an anvil.

Figure 4016r. Cumulonimbus with fibrous top, often with an anvil.

OTHER OBSERVATIONS

4018. Visibility Measurement

Visibility is the horizontal distance at which prominent objects can be seen and identified by the unaided eye. It is usually measured directly by the human eye. Ashore the distances of various buildings, trees, lights, and other objects can be used as a guide in estimating the visibility. At sea, however, such an estimate is difficult to make with accuracy. Other ships and the horizon may be of some assistance. See the Distance of the Horizon (Table 12).

Ashore, visibility is sometimes measured by a **transmissometer**, a device which measures the transparency of the atmosphere by passing a beam of light over a known short distance, and comparing it with a reference light.

4019. Upper Air Observations

Upper air information provides the third dimension to the weather map. Unfortunately, the equipment necessary to obtain such information is quite expensive, and the observations are time consuming. Consequently, the network of observing stations is quite sparse compared to that for surface observations, particularly over the oceans and in isolated land areas. Where facilities exist, upper air observations are made by means of unmanned balloons, in conjunction with theodolites, radiosondes, and radar.

4020. New Technologies in Weather Observing

Shipboard, upper air, buoy, radar, and satellite observations are the foundation for the development of accurate forecast computer models, both in the short and long term. New techniques such as Doppler radar, satellite analysis, and the integration of data from many different sites into complex computer algorithms provide a method of predicting storm tracks with a high degree of accuracy. Tornadoes, line squalls, individual thunderstorms, and entire storm systems can be continuously tracked and their paths predicted with unprecedented accuracy. At sea, the mariner has immediate access to this data through facsimile transmission of synoptic charts, satellite photographs, communications satellite contact with weather routing services, or through internet providers.

Automated weather stations and buoy systems provide regular transmissions of meteorological and oceanographic information by radio. Some of these buoys or stations can be accessed via the telephone. For further information, visit the National Data Buoy Center's web site at http://www.ndbc.noaa.gov. These buoys and sta-tions are generally located at isolated and relatively inaccessible locations from which weather and ocean data are of great importance. Depending on the type of system used, the elements usually measured include wind direc-tion and speed, atmospheric pressure, air and sea surface temperature, spectral wave data, and a temperature profile from the sea surface to a predetermined depth.

Regardless of advances in the technology of observing and forecasting, the shipboard weather report remains the cornerstone upon which the accuracy of many forecasts are based.

4021. Recording Observations

Instructions for recording weather observations aboard U.S. Navy vessels are given in NAVMETOCCOMINST 3144.1 (series).

Instructions for recording observations aboard merchant vessels are given in the National Weather Service *Observing Handbook No. 1, Marine Surface Observations*. The handbook is available online via the link provided in Figure 4021.

Figure 4021. Link to Weather Observing Handbook No. 1, Marine Surface Observations.
http://www.vos.noaa.gov/ObsHB-508/ObservingHandbook1_2010_508_compliant.pdf

Force 0: Wind Speed less than 1 knot.
Sea: Sea like a mirror.

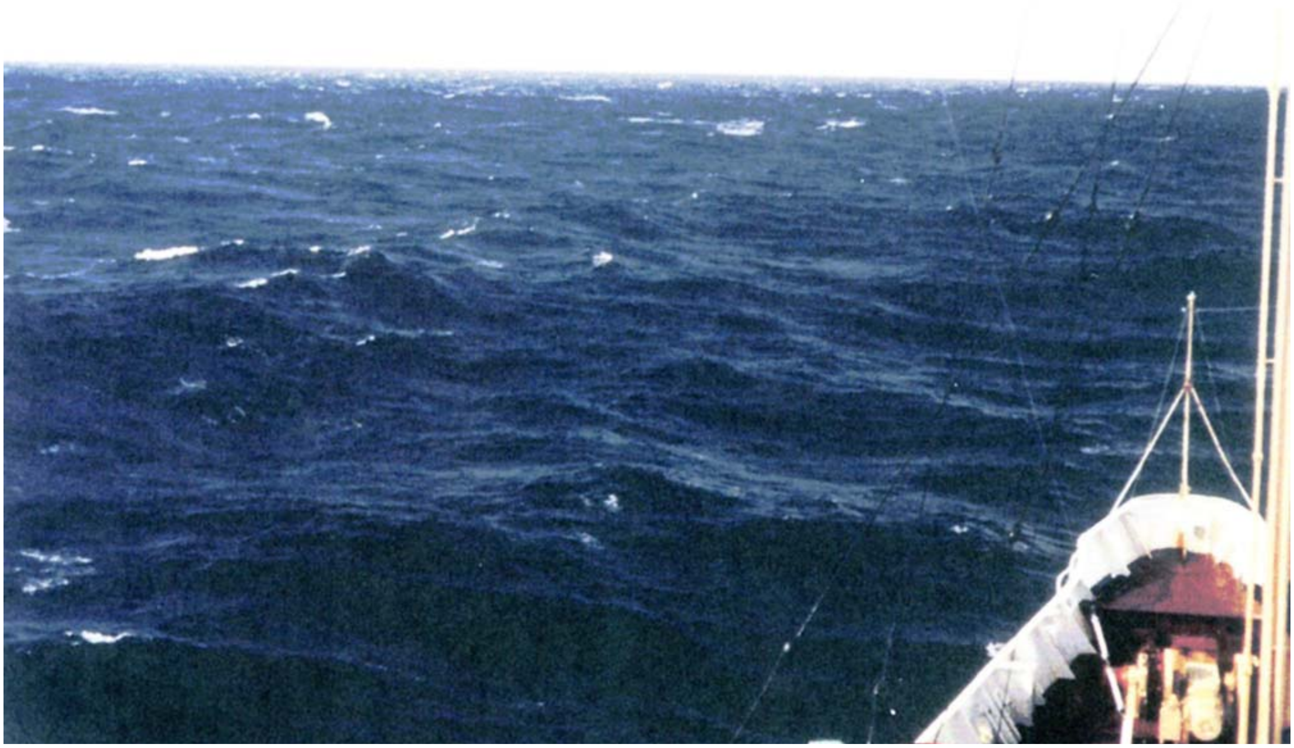
Force 1: Wind Speed 1-3 knots.
Sea: Wave height 0.1m (.25ft); Ripples with appearance of scales, no foam crests.

Force 2: Wind Speed 4-6 knots.
Sea: Wave height 0.2-0.3 m (0.5-1 ft); Small wavelets, crests of glassy appearance, not breaking.

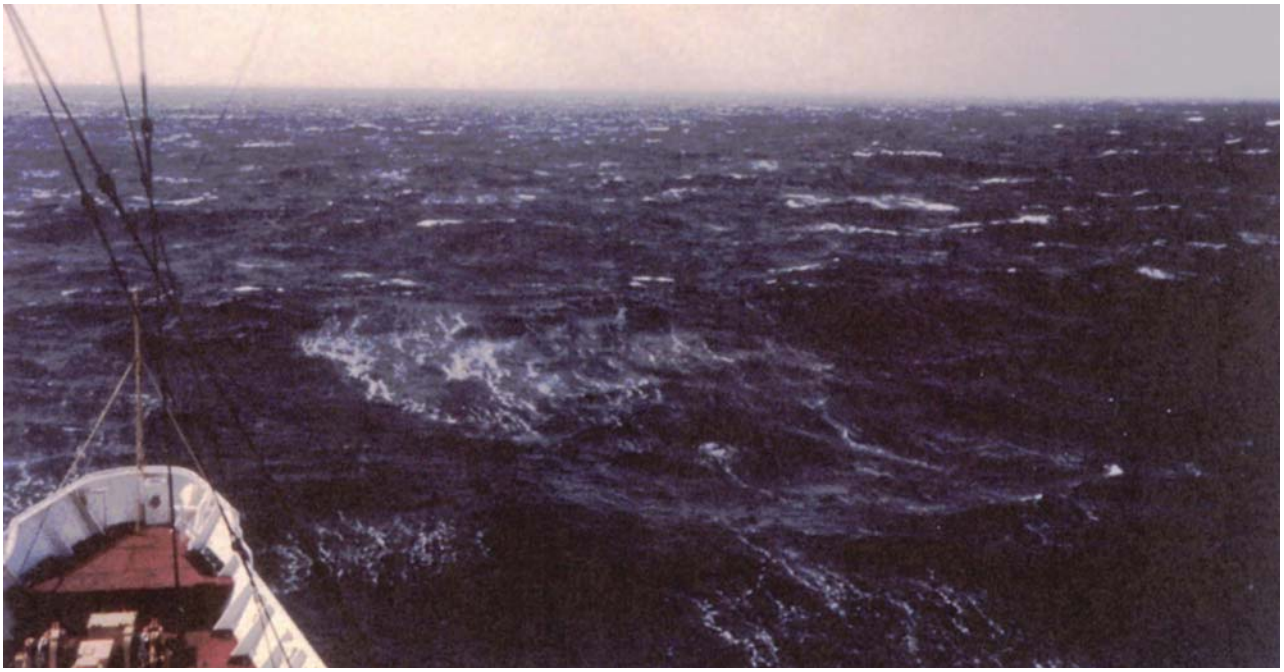
Force 3: Wind Speed 7-10 knots.
Sea: Wave height 0.6-1m (2-3 ft); Large wavelets, crests begin to break, scattered whitecaps.

Force 4: Wind Speed 11-16 knots.
Sea: Wave height 1-1.5 m (3.5-5 ft); Small waves becoming longer, numerous whitecaps.

Force 5: Wind Speed 17-21 knots.
Sea: Wave height 2-2.5 m (6-8 ft); Moderate waves, taking longer form, many whitecaps, some spray.

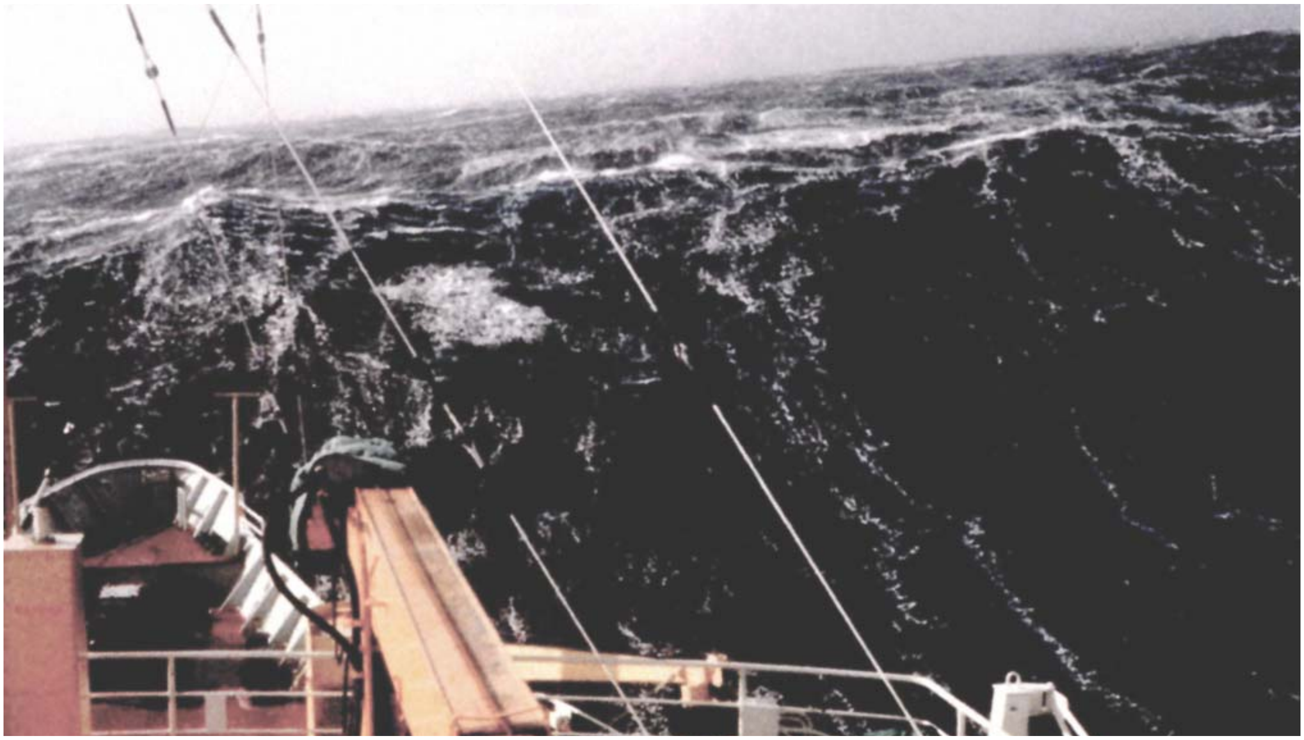


Force 6: Wind Speed 22-27 knots.
Sea: Wave height 3-4 m (9.5-13 ft); Larger waves forming, whitecaps everywhere, more spray.



Force 7: Wind Speed 28-33 knots.
Sea: Wave height 4-5.5 m (13.5-19 ft); Sea heaps up, white foam from breaking waves begins to be blown in streaks along direction of wind.

Force 8: Wind Speed 34-40 knots.
Sea: Wave height 5.5-7.5 m (18-25 ft); Moderately high waves of greater length, edges of crests begin to break into spindrift, foam is blown in well marked streaks.



Force 9: Wind Speed 41-47 knots.
Sea: Wave height 7-10 m (23-32 ft); High waves, sea begins to roll, dense streaks of foam along wind direction, spray may reduce visibility.

Force 10: Wind Speed 48-55 knots (storm).
Sea: Wave height 9-12.5 m (29-41 ft); Very high waves with overhanging crests, sea takes white appearance as foam is blown in very dense streaks, rolling is heavy and shocklike, visibility is reduced.

Force 11: Wind Speed 56-63 knots.
Sea: Wave height 11.5-16 m (37-52 ft); Exceptionally high waves, sea covered with white foam patches, visibility still more reduced.

Force 12: Wind Speed 64-71 knots.
Sea: Wave height more than 16 m (52 ft); Air filled with foam, sea completely white with driving spray, visibility greatly reduced.

CHAPTER 41

WEATHER ROUTING

PRINCIPLES OF WEATHER ROUTING

4100. Introduction

Ship weather routing develops an optimum track for ocean voyages based on forecasts of weather, sea conditions, and a ship's individual characteristics for a particular transit. Within specified limits of weather and sea conditions, the term optimum is used to mean maximum safety and crew comfort, minimum fuel consumption, minimum time underway, or any desired combination of these factors. The purpose of this chapter is to acquaint the mariner with the basic philosophy and procedures of ship weather routing as an aid to understanding the routing agency's recommendations.

The mariner's first resources for route planning in relation to weather are the *Pilot Chart Atlases* (Figure 4100a), the *Sailing Directions (Planning Guides)* (Figure 4100b), and other climatological sources such as historical weather data tables. These publications give climatic data, such as wind speed and direction, wave height frequencies and ice limits, for the major ocean basins of the world. They may recommend specific routes based on probabilities, but not on specific conditions.

Figure 4100a. Pilot Chart Atlases
https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0003.

The ship routing agency, acting as an advisory service, attempts to avoid or reduce the effects of specific adverse weather and sea conditions by issuing initial route recommendations prior to sailing. It recommends track changes while underway (diversions), and weather advisories to alert the commanding officer or master about approaching unfavorable weather and sea conditions which cannot be effectively avoided by a diversion. Adverse weather and sea conditions are defined as those conditions which will cause damage, significant speed reduction, or time loss.

Figure 4100b. Sailing Directions (Planning Guides)
https://msi.nga.mil/NGAPortal/MSI.portal?_nfpb=true&_pageLabel=msi_portal_page_62&pubCode=0011.

The initial route recommendation is based on a survey of weather and sea forecasts between the point of departure and the destination. It takes into account the type of vessel, hull type, speed capability, safety considerations, cargo, and loading conditions. The vessel's progress is continually monitored, and if adverse weather and sea conditions are forecast along the vessel's current track, a recommendation for a diversion or a weather advisory is transmitted. By this process of initial route selection and continued monitoring of progress for possible changes in the forecast weather and sea conditions along a route, it is possible to maximize both speed and safety.

In providing for optimum sailing conditions, the advisory service also attempts to reduce transit time by avoiding the adverse conditions which may be encountered on a shorter route, or if the forecasts permit, diverting to a shorter track to take advantage of favorable weather and sea conditions. A significant advantage of weather routing accrues when: (1) the passage is relatively long, about 1,500 miles or more; (2) the waters are navigationally unrestricted, so that there is a choice of routes; and (3) weather is a factor in determining the route to be followed.

Use of this advisory service in no way relieves the commanding officer or master of responsibility for prudent seamanship and safe navigation. There is no intent by the routing agency to inhibit the exercise of professional judgment and prerogatives of commanding officers and masters.

The techniques of ship routing and access to the advice are increasingly less expensive, and are thus being made available to coastal vessels, smaller commercial craft, and even yachts.

4101. Historical Perspective

The advent of extended range forecasting and the development of selective climatology, along with powerful computer modeling techniques, have made ship routing systems possible. The ability to effectively advise ships to take advantage of favorable weather was hampered previously by forecast limitations and the lack of an effective communications system.

Development work in the area of data accumulation and climatology has a long history. Benjamin Franklin, as deputy postmaster general of the British Colonies in North America, produced a chart of the Gulf Stream from information supplied by masters of New England whaling ships. This first mapping of the Gulf Stream helped improve the mail packet service between the British Colonies and England. In some passages the sailing time was reduced by as much as 14 days over routes previously sailed.

In the mid-19th century, Matthew Fontaine Maury compiled large amounts of atmospheric and oceanographic data from ships' log books. For the first time, a climatology of ocean weather and currents of the world was available to the mariner. This information was used by Maury to develop seasonally recommended routes for sailing ships and early steam powered vessels in the latter half of the 19th century. In many cases, Maury's charts were proved correct by the savings in transit time. Average transit time on the New York to California via Cape Horn route was reduced from 183 days to 139 days with the use of his recommended seasonal routes.

In the 1950's the concept of ship weather routing was put into operation by several private meteorological groups and by the U.S. Navy. By applying the available surface and upper air forecasts to transoceanic shipping, it was possible to effectively avoid much heavy weather while generally sailing shorter routes than previously. The development of computers, the Internet and communications technology has made weather routing available to nearly everyone afloat.

4102. System Types

Optimum Track Ship Routing (OTSR), the ship routing service of the U.S. Navy, utilizes short to medium range forecasting techniques in route selection and surveillance procedures. The short to medium range dynamic forecasts of 3 to 10 days are derived from meteorological equations processed by high-speed super computers. These forecasts are computed at least twice daily from a data base of global surface and upper air observations, and include surface pressure, upper air constant pressure heights and spectral wave values. A significant increase in data acquisition, particularly from satellite imagery over oceans and data sparse areas have extended the time period for which these forecasts are useful.

Selective climatology has been effective in predicting average conditions months in advance during such events as the El Nino Southern Oscillation (ENSO) which encompasses both the El Nino and La Nina. Such predictions do not represent forecasting, but can indicate the likelihood of certain atmospheric weather patterns appearing or prevailing.

For extended range forecasting, generally beyond ten days, computer models use a combination of analogs, climatology and ensemble techniques to find the logical sequence of events following the dynamic forecasts of 3 to 10 days. Beyond ten days, climatology is used to determine the optimum track.

Aviation was first in applying the principle of minimum time tracks (MTT) to a changing wind field. But the problem of finding an MTT for a specific flight is much simpler than for a transoceanic ship passage because an aircraft's transit time is much shorter than a ship's. Thus, marine minimum time tracks require significantly longer range forecasts to develop an optimum route.

Automation has enabled ship routing agencies to develop realistic minimum time tracks. Computation of minimum time tracks makes use of:

1. A navigation system to compute route distance, time enroute, estimated times of arrival (ETA's), and to provide 6 hourly DR synoptic positions for the range of the dynamic forecasts for the ship's current track.
2. A surveillance system to survey wind, seas, fog, and ocean currents obtained from the dynamic and climatological fields.
3. An environmental constraint system imposed as part of the route selection and surveillance process. Constraints are the upper limits of wind and seas desired for the transit. They are determined by the ship's loading, speed capability, and vulnerability. The constraint system is an important part of the route selection process and acts as a warning system when the weather and sea forecast along the present track exceeds predetermined limits.
4. Ship speed characteristics used to approximate ship's speed of advance (SOA) while transiting the forecast sea states.

Criteria for route selection reflect a balance between the captain's desired levels of speed, safety, comfort, and consideration of operations such as fleet maneuvers, fishing, towing, etc.

Ship weather routing services are being offered by many nations. These include Japan, United Kingdom, Russia, Netherlands, Germany, and the United States. Also, several private firms provide routing services to shipping industry clients. Several personal computer-based software applications have become available, making weather routing available to virtually everyone at sea.

There are two general types of routing services available. The first uses techniques similar to the Navy's Optimum Track Ship Routing (OTSR) system to forecast conditions and compute routing recommendations, which are then broadcast to the vessel. Because this service is per-formed ashore, it allows for greater computer power to be applied to the routing task. The second assembles and processes weather and sea condition data and transmits this to ships at sea for on-board processing and generation of route recommendations. This system allows the ship's master to have greater flexibility in changing parameters, evaluating various scenarios, selecting routes, and displaying data.

4103. Ship and Cargo Considerations

Ship and cargo characteristics have a significant influence on the application of ship weather routing. Ship size, speed capability, and type of cargo are important considerations in the route selection process prior to sailing and the surveillance procedure while underway. A ship's characteristics identify its vulnerability to adverse conditions and its ability to avoid them.

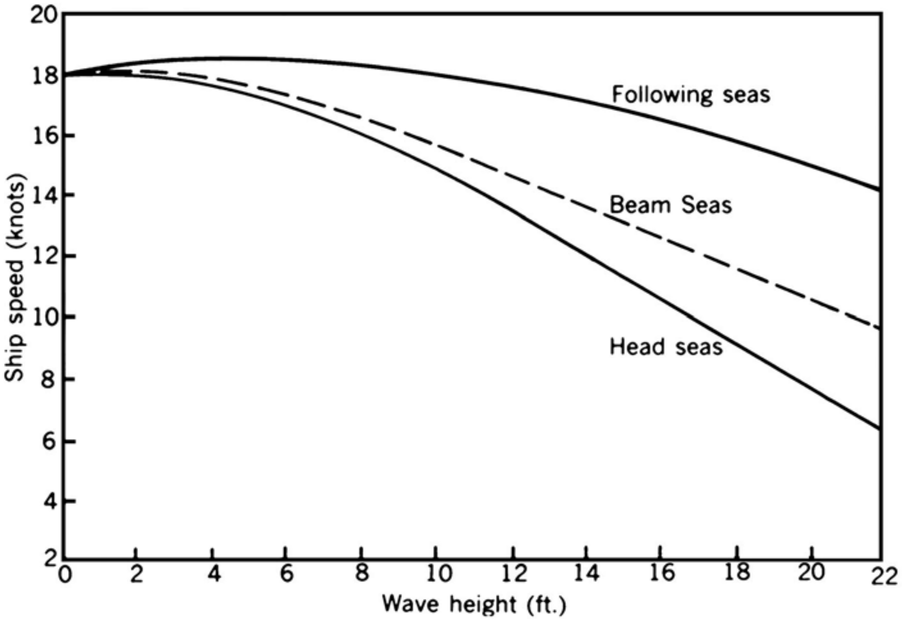


Figure 4103. Performance curves for head, beam, and following seas.

Generally, ships with higher speed capability and lighter loads will have shorter optimum routes and be better able to maintain near normal SOA's than ships with lower speed capability or heavy cargoes. Some routes are unique because of the type of ship or cargo. Avoiding one element of weather to reduce pounding or rolling may be of prime importance. For example, a 20 knot ship with a heavy deck cargo may be severely hampered in its ability to maintain a 20 knot SOA in any seas exceeding moderate head or beam seas because of the possibility of damage resulting from the deck load's characteristics. A similar ship with a stable cargo under the deck is not as vulnerable and may be able to maintain the 20 knot SOA in conditions which would drastically slow the deck-loaded vessel. In towing operations, a tug is more vulnerable to adverse weather and sea conditions, not only in consideration of the tow, but also because of its already limited speed capability. Its slow speed adds to the difficulty of avoiding adverse weather and sea conditions.

Ship performance curves (speed curves) are used to estimate the ship's SOA while transiting the forecast sea states. The curves indicate the effect of head, beam, and following seas of various significant wave heights on the ship's speed. Figure 4103 is a performance curve prepared for a commercial 18-knot vessel. Each vessel will have its own performance curves, which vary widely according to hull type, length, beam, shape, power, and tonnage. Recommendations for sailing vessels must account for wind speed, wind angle, and vessel speed.

With the speed curves it is possible to determine just how costly a diversion will be in terms of the required distance and time. A diversion may not be necessary where the duration of the adverse conditions is limited. In this case, it may be better to ride out the weather and seas knowing that a diversion, even if able to maintain the normal SOA, will not overcome the increased distance and time required.

At other times, the diversion track is less costly because it avoids an area of adverse weather and sea conditions, while being able to maintain normal SOA even though the distance to destination is increased. Based on input data for environmental conditions and ship's behavior, route selection and surveillance techniques seek to achieve the optimum balance between time, distance, and acceptable environmental and seakeeping conditions. Although speed performance curves are an aid to the ship routing agency, the response by mariners to deteriorating weather and sea conditions is not uniform. Some reduce speed voluntarily or change heading sooner than others when unfavorable conditions are encountered. Certain waves with characteristics such that the ship's bow and stern are in successive crests and troughs present special problems for the mariner. Being nearly equal to the ship's length, such wavelengths may induce very dangerous stresses. The degree of hogging and sagging and the associated danger may be more apparent to the mariner than to the ship routing agency. Therefore, adjustment in course and speed for a more favorable ride must be initiated by the commanding officer or master when this situation is encountered.

4104. Environmental Factors

Environmental factors of importance to ship weather routing are those elements of the atmosphere and ocean that may produce a change in the status of a ship transit. In ship routing, consideration is given to wind, seas, fog, ice, and ocean currents. While all of the environmental factors are important for route selection and surveillance, optimum routing is normally considered attained if the effects of wind and seas can be optimized.

Wind: The effect of wind speed on ship performance is difficult to determine. In light winds (less than 20-knots), ships lose speed in headwinds and gain speed slightly in following winds. For higher wind speeds, ship speed is reduced in both head and following winds. This is due to the increased wave action, which even in following seas results in increased drag from steering corrections, and indicates the importance of sea conditions in determining ship performance. In dealing with wind, it is also necessary to know the ship's sail area. High winds will have a greater adverse effect on a large, fully loaded container ship or car carrier than a fully loaded tanker of similar length. This effect is most noticeable when docking or when navigating in restricted waters, but the effect of beam winds over several days at sea can also be considerable. For sailing vessels, the wind is critical and accurate forecasts are vital to a successful voyage.

Wave Height: Wave height is the major factor affecting ship performance. Wave action is responsible for ship motions which reduce propeller thrust and cause increased drag from steering corrections. The relationship of ship speed to wave direction and height is similar to that of wind. Head seas reduce ship speed, while following seas increase ship speed slightly to a certain point, beyond which they retard it. In heavy seas, exact performance may be difficult to predict because of the adjustments to course and speed for shiphandling and comfort. Although the effect of sea and swell is much greater for large commercial vessels than is wind speed and direction, it is difficult to separate the two in ship routing.

In an effort to provide a more detailed description of the actual and forecast sea state, several countries and private companies have developed global and regional wave forecasting computer programs. These wave forecasts are based on the analyzed and forecast planetary boundary wind fields and are produced for both the Northern and Southern Hemispheres out to 144 hours or more. Most of these forecasts produce values for significant wave height, primary wave height and secondary wave height, as well as direction and period of these waves.

Fog: Fog, while not directly affecting ship performance, should be avoided as much as feasible, in order to maintain normal speed in safe conditions. Extensive areas of fog during summertime can be avoided by selecting a lower latitude route than one based solely upon wind and seas. Although the route may be longer, transit time may be less due to not having to reduce speed in reduced visibility. In addition, crew fatigue due to increased watchkeeping vigilance can be reduced.

North Wall Effect: During the Northern Hemisphere fall and winter, the waters to the north of the Gulf Stream in the North Atlantic are at their coldest, while the Gulf Stream itself remains at a constant relatively warm temperature. After passage of a strong cold front or behind a developing coastal low pressure system, Arctic air is sometimes drawn off the Mid-Atlantic coast of the United States and out over the warm waters of the Gulf Stream by northerly winds. This cold air is warmed as it passes over the Gulf Stream, resulting in rapid and intense deepening of the low pressure system and higher than normal surface winds. Higher waves and confused seas result from these winds. When these winds oppose the northeast set of the current, the result is increased wave heights and a shortening of the wave period. If the opposing current is sufficiently strong, the waves will break. These phenomena are collectively called the "North Wall Effect," referring to the region of most dramatic temperature change between the cold water to the north and the warm Gulf Stream water to the south. The most dangerous aspect of this phenomenon is that the strong winds and extremely high, steep waves occur in a limited area and may develop without warning. Thus, a ship that is laboring in near-gale force northerly winds and rough seas, proceeding on a northerly course, can suddenly encounter storm force winds and dangerously high breaking seas. Numerous ships have foundered off the North American coast in the approximate position of the Gulf Stream's North Wall. A similar phenomenon occurs in the North Pacific near the Kuroshio Current and off the Southeast African coast near the Agulhas Current.

Ocean Currents: Ocean currents do not present a significant routing problem, but they can be a determining factor in route selection and diversion. This is especially true when the points of departure and destination are at relatively low latitudes. The important considerations to be evaluated are the difference in distance between a great-circle route and a route selected for optimum current, with the expected increase in SOA from the following current, and the decreased probability of a diversion for weather and seas at the lower latitude. For example, it has proven beneficial to remain equatorward of approximately 22°N for westbound passages between the Canal Zone and southwest Pacific ports. For eastbound passages, if the maximum latitude on a great-circle track from the southwest Pacific to the Canal Zone is below 24°N, a route passing near the axis of the Equatorial Countercurrent is practical because the increased distance is offset by favorable current. Direction and speed of ocean currents are more predictable than wind and seas, but some variability can be expected. Major ocean currents can be disrupted for several days by very intense weather systems such as hurricanes and by global phenomena such as El Nino.

Figure 4104a. Ice accumulation on deck can cause significant problems with stability of small ships. Freezing spray conditions should be avoided when possible. Image courtesy of Lars Anderson, SMHI.

Ice: The problem of ice includes pack ice, floating ice of land origin (icebergs) and deck ice. Areas of icebergs or pack ice should be avoided because of the difficulty of detection and the potential for collision. Icebergs are a hazard in the North Atlantic from late February through July, and occasionally later. The hazard of floating ice is frequently combined with restricted visibility in fog. International Ice Patrol warnings are incorporated into the planning of routes to safely avoid dangerous iceberg areas. The International Convention for the Safety of Life At Sea (SOLAS) Chapter V, Regulation 6 requires ships transiting the region of icebergs guarded by the Ice Patrol during the ice season to make use of the services provided by the Ice Patrol. The Ice Patrol sets an Iceberg Limit to delineate this region of icebergs. Vessels are recommended to transit to the east and south of this region at all times. The Ice Patrol's iceberg warning products are updated daily in textual, graphical, and electronic format and can be accessed through the USCG NAVCEN web portal (see Figure 4104b). The U.S. Navy ship routing office at Fleet Weather Center Norfolk maintains a safety margin of 100 nautical miles from icebergs reported by the Ice Patrol. In a severe winter, the Denmark Strait may be closed due to the presence of icebergs.

Figure 4104b. North American Ice Service Products
https://www.navcen.uscg.gov/?pageName=iipProducts.

Deck ice may be more difficult to contend with from a ship routing point of view because it is caused by freezing weather associated with a large weather system. While mostly a nuisance factor on large ships, it causes significant problems with the stability of small ships (Figure 4104a).

Latitude: Generally, the higher the latitude of a route, even in the summer, the greater are the problems with the environment. Certain operations should benefit from seasonal planning as well as optimum routing. For example, towing operations north of about 40° latitude should be avoided in non-summer months if possible.

4105. Synoptic Weather Considerations

A ship routing agency should direct its forecasting skills to avoiding or limiting the effect of weather and seas associated with extratropical low pressure systems in the mid and higher latitudes and the tropical systems in low latitude. Seasonal or monsoon weather is also a factor in route selection and diversion in certain areas.

Despite the amount of attention and publicity given to tropical cyclones, mid-latitude low pressure systems generally present more difficult problems to a ship routing agency. This is primarily due to the fact that major ship traffic is sailing in the latitudes of the migrating low pressure systems, and the amount of potential exposure to intense weather systems, especially in winter, is much greater.

Low pressure systems weaker than gale intensity (winds less than 34 knots) are not a severe problem for most ships. However, a relatively weak system may generate prolonged periods of rough seas which may hamper normal work aboard ship. Ship weather routing can frequently limit rough conditions to short periods of time and provide more favorable conditions for most of the transit. Relatively small vessels, tugs with tows, low powered ships, yachts, and

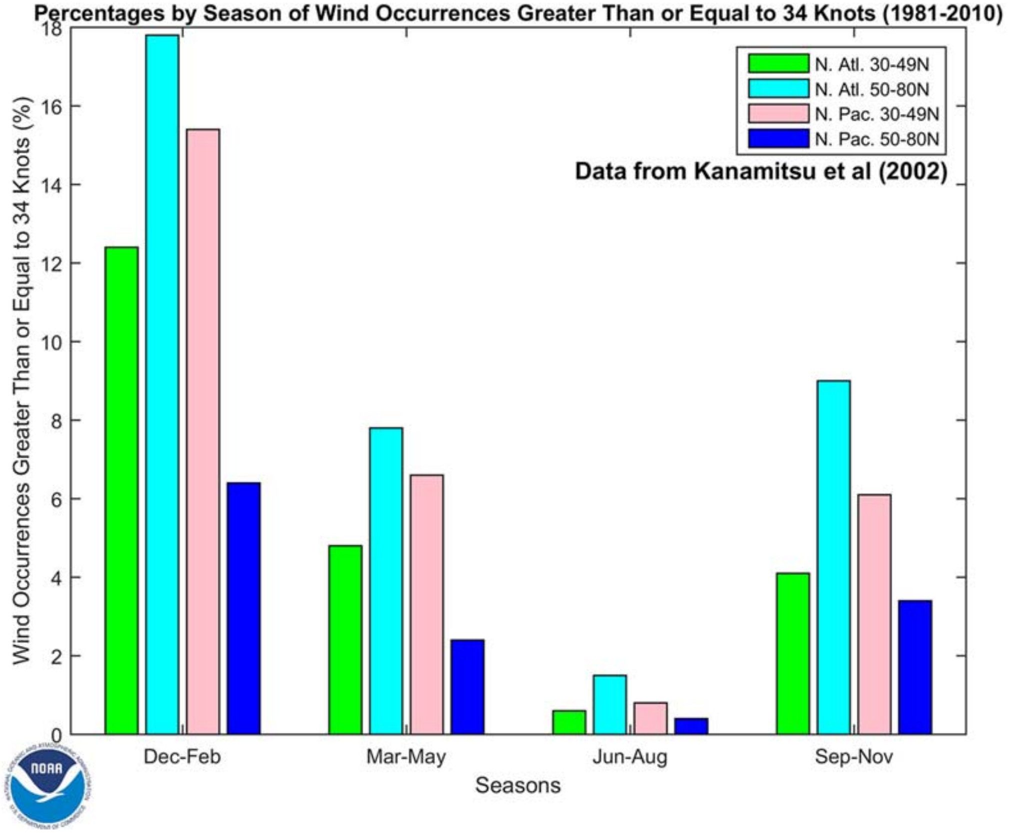


Figure 4105a. Percentages by season of wind occurrences greater than or equal to 34 knots, separated by geographic area. The percentages represent areas over the high seas only and do not include values over ice.

ships with sensitive cargoes can be significantly affected by weather systems weaker than gale intensity. Using a routing agency can enhance both safety and efficiency.

Gales (winds 34 to 47 knots) and storms (winds greater than 48 knots) in the open sea can generate very rough or high seas, particularly when an adverse current such as the Gulf Stream is involved. This can force a reduction in speed in order to gain a more comfortable and safe ride. Because of the extensive geographic area covered by a well developed low pressure system, once ship’s speed is reduced the ability to improve the ship’s situation is severely hampered. Thus, exposure to potential damage and danger is greatly increased. The vessel in such conditions may be forced to slow down just when it is necessary to speed up to avoid even worse conditions.

A recommendation for a diversion by a routing agency well in advance of the intense weather and associated seas will limit the duration of exposure of the vessel. If effective, ship speed will not be reduced and satisfactory progress will be maintained even though the remaining distance to destination is increased. Overall transit time is usually shorter than if no track change had been made and the ship had remained in heavy weather. In some cases diversions are made to avoid adverse weather conditions and shorten the track at the same time. Significant savings in time and costs can result.

In very intense low pressure systems, with high winds and long duration over a long fetch, seas will be generated and propagated as swell over considerable distances. Even on a diversion, it is difficult to effectively avoid all unfavorable conditions. Generally, original routes for transoceanic passages, issued by the U.S. Navy's ship routing service, are within areas that experience gale force winds or higher often. Figure 4105a shows the frequency of gale force winds or higher by latitude in the North Atlantic and North Pacific. To avoid the area of significant gale activity in the Atlantic from October to April, the latitude of transit is generally in the lower thirties.

The areas, seasons, and the probability of development of tropical cyclones are fairly well defined in climatological publications. In long range planning, considerable benefit can be gained by limiting the exposure to the potential hazards of tropical systems.

It is advisable to avoid tropical cyclones. In the eastern North Pacific, the climatological distribution of tropical cyclones is relatively compact (See Figure 4105b). The climatological distribution of tropical cyclones for the western North Pacific is shown in Figure 4105c. The climatological distribution of tropical cyclones in the North Atlantic is shown in Figure 4105d.

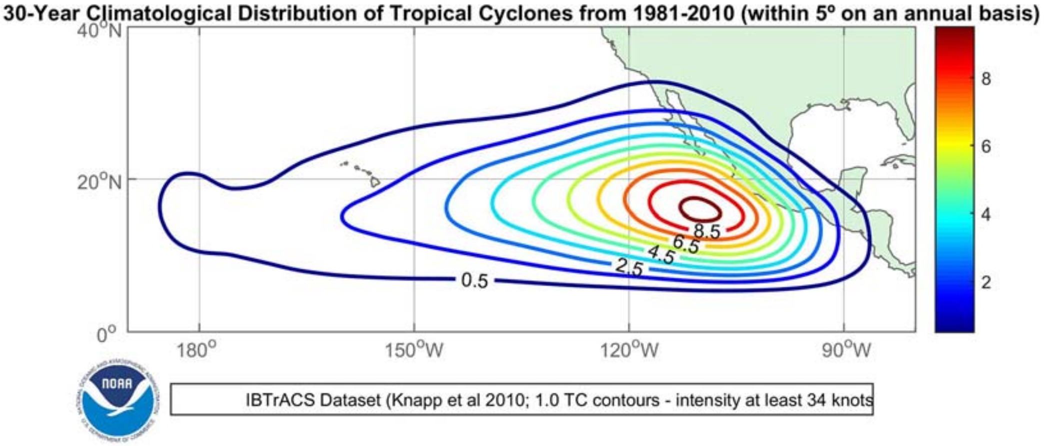


Figure 4105b. Average number of tropical cyclones that come within 5 degrees of a point in the Eastern Pacific Ocean.

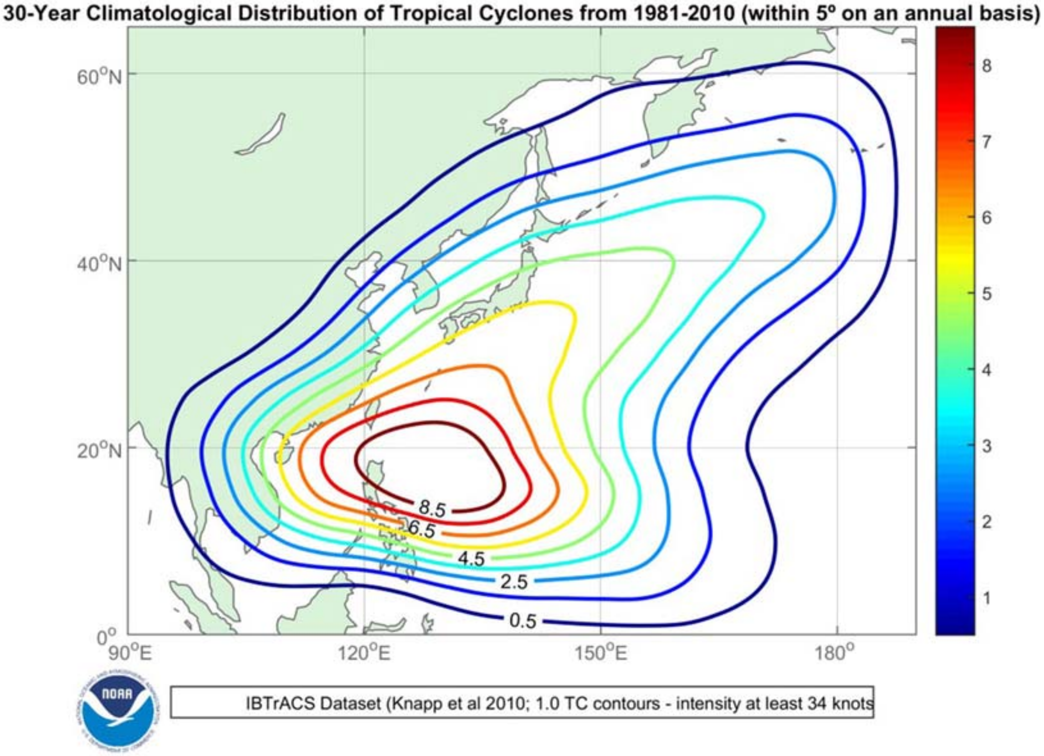


Figure 4105c. Average number of tropical cyclones that come within 5 degrees of a point in the Western Pacific Ocean.

It has proven equally beneficial to employ similar avoidance considerations for routing in the monsoon areas of the Indian Ocean and the South China Sea. This is accomplished by providing routes and diversions that generally avoid the areas of high frequency of tropical cyclones (Figure 4105e, Figure 4105f and Figure 4105g), gale force winds and associated heavy seas, as much as feasible. Ships can then remain in satisfactory conditions with limited increases in route distance.

Depending upon the points of departure and destination, there are many combinations of routes that can be used when transiting the northern Indian Ocean (Arabian Sea, Bay of

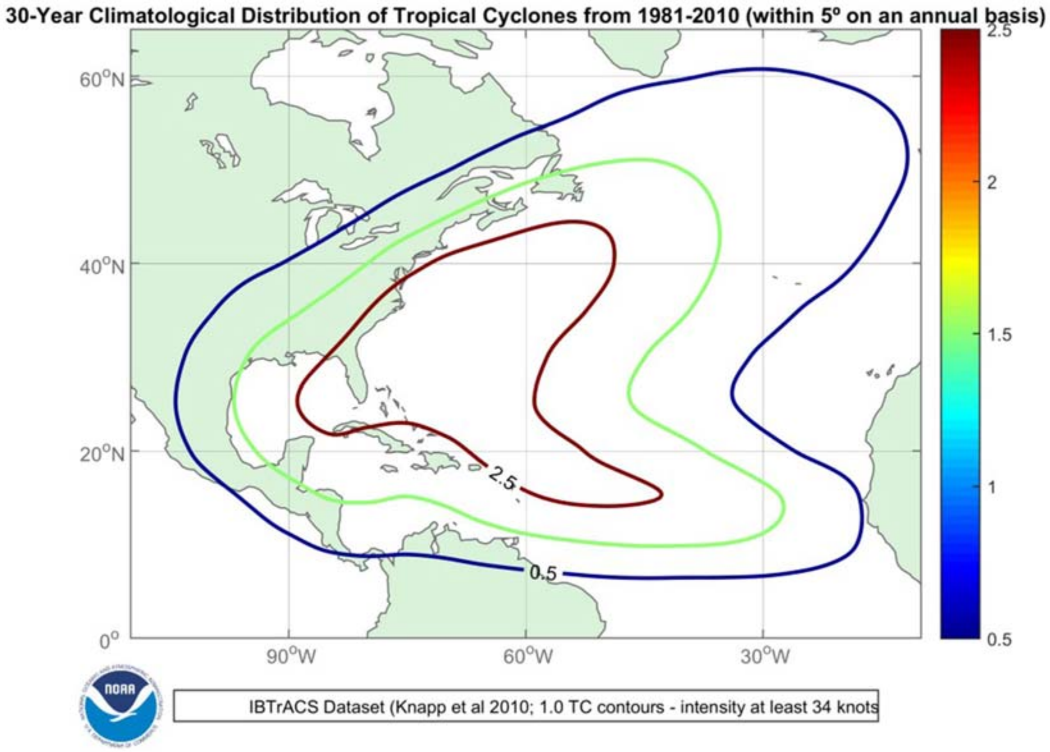


Figure 4105d. Average number of tropical cyclones that come within 5 degrees of a point in the North Atlantic Ocean.

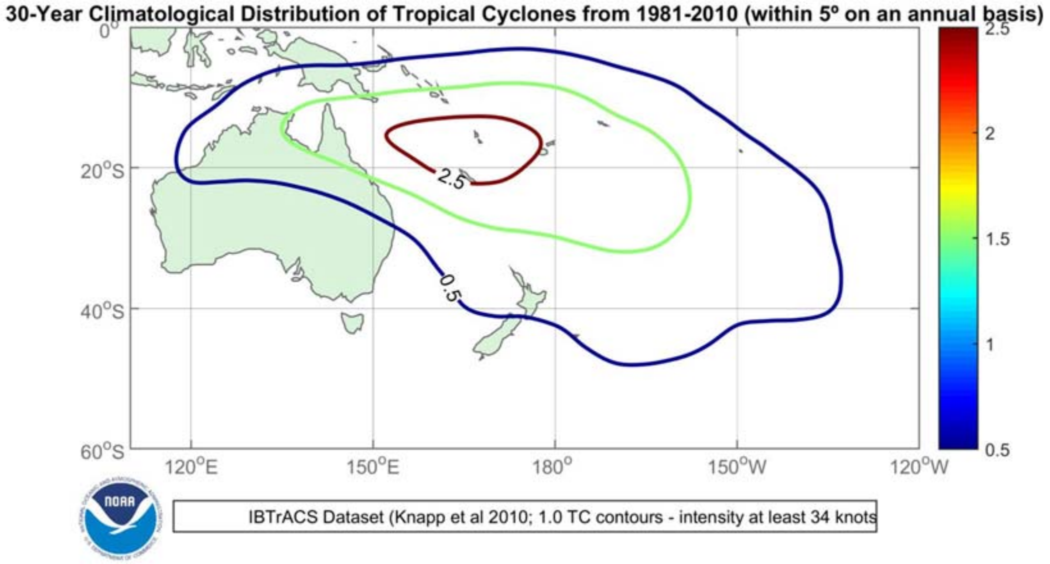


Figure 4105e. Average number of tropical cyclones that come within 5 degrees of a point in the South Pacific Ocean.

Bengal) and the South China Sea. For example, in the Arabian Sea during the summer monsoon, routes to and from the Red Sea, the western Pacific, and the eastern Indian Ocean should hold equatorward. Ships proceeding to the Persian Gulf during this period are held farther south and west to put the heaviest seas on the quarter or stern when transiting the Arabian Sea. Eastbound ships departing the Persian Gulf may proceed generally east southeast toward the Indian sub-continent, then south, to pass north and east of the highest southwesterly seas in the Arabian Sea.

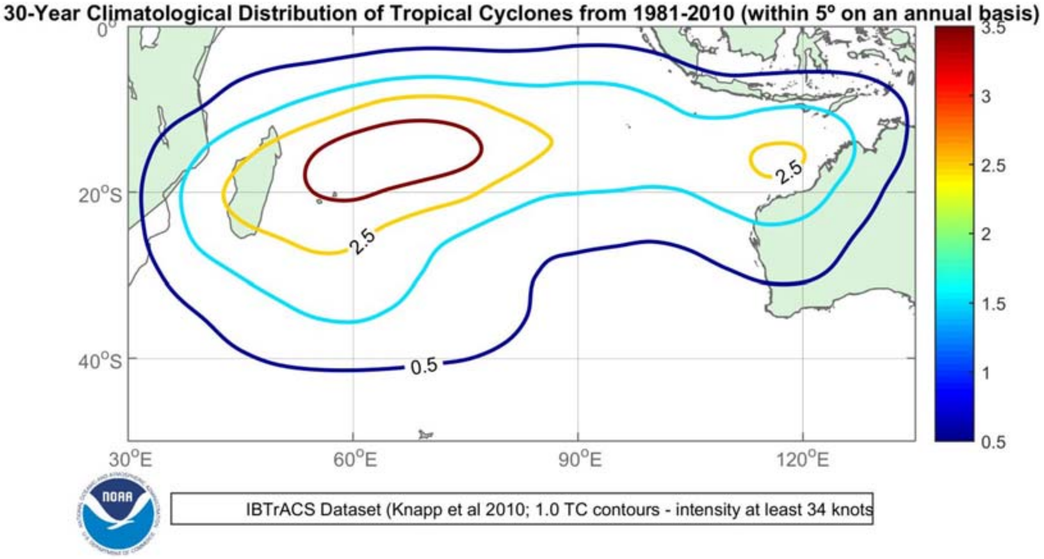


Figure 4105f. Average number of tropical cyclones that come within 5 degrees of a point in the South Indian Ocean.

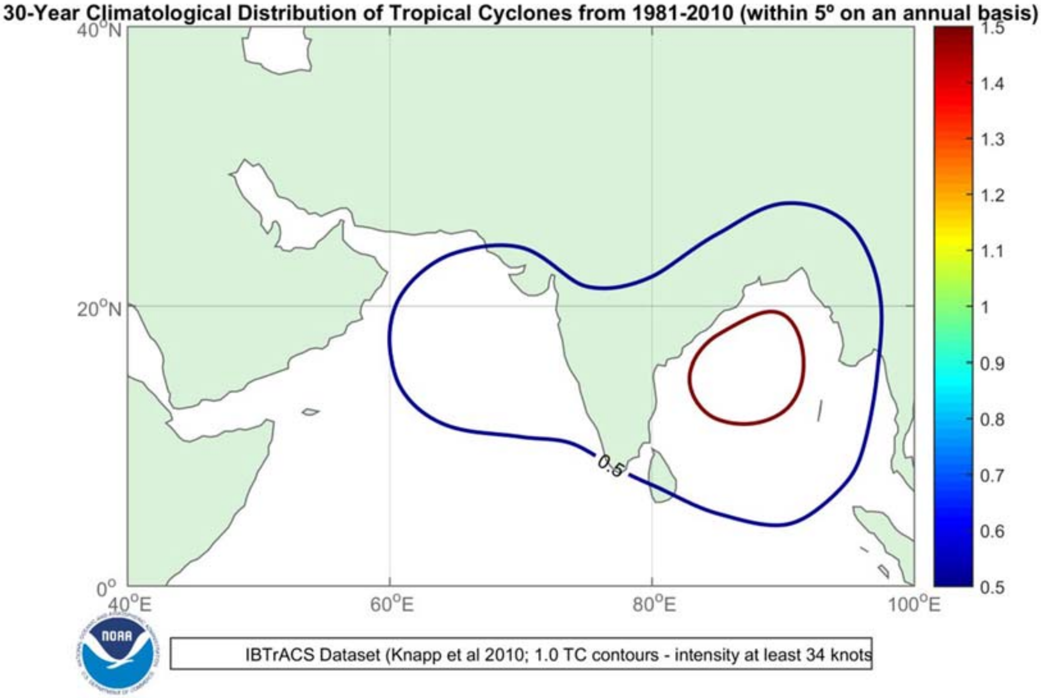


Figure 4105g. Average number of tropical cyclones (at least 34 knots) that come within 5 degrees of a point in the Bay of Bengal and Arabian Sea.

Westbound ships out of the Persian Gulf for the Cape of Good Hope appear to have little choice in routes unless considerable distance is added to the transit by passing east of the highest seas. In the winter monsoon, routes to or from the Red Sea for the western Pacific and the Indian Ocean are held farther north in the Arabian Sea to avoid the highest seas. Ships proceeding to the Persian Gulf from the western Pacific and eastern Indian Ocean may hold more eastward when proceeding north in the Arabian Sea. Ships departing the Persian Gulf area will have considerably less difficulty than during the summer monsoon. Similar considerations can be given when routing ships proceeding to and from the Bay of Bengal.

In the South China Sea, transits via the Palawan Passage are recommended when strong, opposing wind and seas are forecast. This is especially true during the winter monsoon. During periods when the major monsoon flow is slack, ships can use the shortest track as conditions permit.

4106. Special Weather and Environmental Considerations

In addition to the synoptic weather considerations in ship weather routing, there are special environmental problems that can be avoided by following recommendations and advisories of ship routing agencies. These problems generally cover a smaller geographic area and are seasonal in nature, but are still important to ship routing.

In the North Atlantic, because of heavy shipping traffic, frequent poor visibility in rain or fog, and restricted navigation, particularly east of Dover Strait, some mariners prefer to transit to or from the North Sea via Pentland Firth, passing north of the British Isles rather than via the English Channel.

Weather routed ships generally avoid the area of dense fog with low visibility in the vicinity of the Grand Banks off Newfoundland and the area east of Japan north of 35°N. Fishing vessels in these two areas provide an added hazard to safe navigation. This condition exists primarily from May through September. During summer, Arctic-bound shipping, transiting between the U.S. East Coast and the Davis Strait-Baffin Bay area, frequently use the Cabot Strait and the Strait of Belle Isle, where navigation aids are available and icebergs are typically present in large numbers following the melt of pack ice along the Labrador Coast in the spring.

In the northern hemisphere winter, a strong high pressure system moving southeast out of the Rocky Mountains brings cold air down across Central America and the western Gulf of Mexico producing gale force winds in the Gulf of Tehuantepec. This fall wind is similar to the pampero, mistral, and bora of other areas of the world. An adjustment to ship's track can successfully avoid the highest seas associated with the "Tehuantepecer." For transits between the Canal Zone and northwest Pacific ports, little additional distance is required to avoid this area (in winter) by remaining south of at least 12°N when crossing 97°W. While avoiding the highest seas, some unfavorable swell conditions may be encountered south of this line. Ships transiting between the Panama Canal and North American west coast ports can stay close along the coast of the Gulf of Tehuantepec to avoid heavy seas during gale conditions, but may still encounter high offshore winds.

In the summer, the semi-permanent high pressure systems over the world's oceans produce strong equatorward flow along the west coasts of continents. This feature is most pronounced off the coast of California and Portugal in the Northern Hemisphere and along Chile, western Australia, and southwest Africa in the Southern Hemisphere. Very rough seas are generated and are considered a definite factor in route selection or diversion when transiting these areas.

4107. Types of Recommendations and Advisories

A **preliminary route recommendation** is issued to a ship more than ten days prior to sailing, then updated two days prior to sailing based on short to medium range dynamic forecasts. Preliminary route recommendations are a composite representation of experience, climatology, weather and sea state forecasts, the vessel's mission and operational concerns, and the vessel's seagoing characteristics. The U.S. Navy normally requires its units to provide a transit proposal 30 to 45 days prior to sailing, which is vetted through the OTSR program. These transit proposals are based on smart climatology, ship type, mission and environmental limits. All long range planning routes are based more on seasonal and climatological expectations than the current weather situation. Surveillance is a continuous process and these routes are subject to revision prior to sailing if weather and sea conditions dictate

Adjustment of departure time is a recommendation for delay in departure, or early departure if feasible, and is intended to avoid or significantly reduce the adverse weather and seas forecast on the first portion of the route, if sailing on the original EDD. The initial route is not revised, only the timing of the ship's transit through an area with currently unfavorable weather conditions. Adjusting the departure time is an effective method of avoiding a potentially hazardous situation where there is no optimum route for sailing at the originally scheduled time. A go/no go recommendation may be made to vessels engaged in special missions such as speed record attempts or heavy-lift voyages.

A **diversion** is an underway adjustment in track and is intended to avoid or limit the effect of adverse weather conditions forecast to be encountered along the ship's current track, or to take advantage of favorable conditions along another route. Ship's speed is expected to be reduced by the encounter with the heavy weather. In most cases the distance to destination is increased in attempting to avoid the adverse weather, but this is partially overcome by being able to maintain a nearly normal SOA.

Adjustment of SOA is a recommendation for slowing or increasing the ship's speed as much as practicable, in an attempt to avoid an adverse weather situation by adjusting the timing of the encounter. This is also an effective means of maintaining maximum ship operating efficiency, while not diverting from the present ship's track. By adjusting the SOA, a major weather system can sometimes be avoided with no increase in distance. The development of fast ships (SOA greater than 30 knots) gives the ship routing agency the potential to "make the ship's weather" by adjusting the ship's speed and track for encounter with favorable weather conditions..

Evasion is a recommendation to the vessel to take independent action to avoid, as much as possible, a potentially dangerous weather system. The ship routing meteorologist may recommend a general direction for safe evasion but does not specify an exact track. The recommendation for evasion is an indication that the weather and sea conditions have deteriorated to a point where shiphandling and safety are the primary considerations and progress toward destination has been temporarily suspended, or is at least of secondary consideration.

A **weather advisory** is a transmission sent to the ship advising the commanding officer or master of expected adverse conditions, their duration, and geographic extent. It is initiated by the ship routing agency as a service and an aid to the ship. The best example of a situation for which a forecast is helpful is when the ship is currently in good weather but adverse weather is expected within 48 hours for which a diversion has not been recommended, or a diversion where adverse weather conditions are still expected. This type of advisory may include a synoptic weather discussion and a wind, seas or fog forecast.

The ability of the routing agency to achieve optimum conditions for the ship is aided by the commanding officer or master adjusting course and speed where necessary for an efficient and safe ride. At times, the local sea conditions may dictate that the commanding officer or master take independent action.

4108. Southern Hemisphere Routing

Available data on which to base analyses and forecasts is generally very limited in the Southern Hemisphere, although this situation is improving with the increasing availability of remotely sensed data. Weather and other environmental information obtained from satellites is contributing greatly to an improvement in southern hemisphere forecast products.

Passages south of the Cape of Good Hope and Cape Horn should be timed to avoid heavy weather as much as possible, since intense and frequent low pressure systems are common in these areas. In particular, near the southeast coasts of Africa and South America, intense low pressure systems form in the lee of relatively high terrain near the coasts of both continents. Winter transits south of Cape Horn are difficult, since the time required for transit is longer than the typical interval between storms. Remaining equatorward of about 35°S as much as practicable will limit exposure to adverse conditions. If the frequency of lows passing these areas is once every three or four days, the probability of encountering heavy weather is high.

Tropical cyclones in the Southern Hemisphere present a significant problem because of the sparse surface and upper air observations from which forecasts can be made. Satellites provide the most reliable means by which to obtain accurate positions of tropical systems, and also give the first indication of tropical cyclone formation.

In the Southern Hemisphere, OTSR and other ship weather routing services are available, but are hampered by sparse data reports from which reliable short and extended range forecasts can be produced. Strong climatological consideration is usually given to any proposed southern hemisphere transit, but satellite data is increasingly available to enhance short and extended range forecasts. OTSR procedures for the Northern Hemisphere can be instituted in the Southern Hemisphere whenever justified by basic data input and available forecast models.

4109. Communications

A vital part of a ship routing service is communication between the ship and the routing agency. Reports from the ship show the progress and ability to proceed in existing conditions. Weather reports from the ship enrich the basic data on which analyses are based and forecasts derived, assisting both the reporting ship and others in the vicinity.

Despite all efforts to achieve the best forecasts possible, the quality of forecasts does not always warrant maintaining the route selected. In the U.S. Navy's ship routing program, experience shows that one-third of the ships using OTSR receive some operational or weather-dependent change while underway.

The routing agency needs reports of the ship's position and the ability to transmit recommendations for track change or weather advisories to the ship. The ship needs both send and receive capability for the required information. Information on seakeeping changes initiated by the ship is desirable in a coordinated effort to provide optimum transit conditions. New satellite communications services are making possible the transmission of larger amounts of data than possible through traditional radio messages, a development which supports systems using on-board analysis to generate routes.

4110. Benefits

The benefits of ship weather routing services are primarily in time and cost reductions and increased safety. The savings in operating costs are derived from reductions in transit time, heavy weather encounters, fuel consumption, cargo and hull damage, and more efficient scheduling of dockside activities. The savings are further increased by fewer emergency repairs, more efficient use of personnel, improved topside working conditions, lower insurance rates because of reduced risks under weather routing, and ultimately, extended ship operating life.

An effective routing service maximizes safety by greatly reducing the probability of severe or catastrophic damage to the ship, and injury of crew members. The efficiency and health of the crew is also enhanced by avoiding heavy weather. This is especially important on modern, automated ships with reduced crews and smaller craft such as fishing vessels and yachts.

4111. Conclusion

The success of ship weather routing depends upon the validity of forecasts and the routing agency's ability to make appropriate route recommendations and diversions. Anticipated improvements in a routing agency's recommendations will come from advancements in meteorology, technology, and the application of ocean wave forecast models. Advancements in mathematical meteorology, coupled with the continued application of forecast computer models, will extend the time range and accuracy of the dynamic and statistical forecasts. Additionally, a better understanding of the problems encountered by the mariner and their implications while offshore will assist the routing agency in making appropriate recommendations.

Technological advancements in the areas of satellite and automated communications and onboard ship response systems will increase the amount and type of information to and from the ship with fewer delays. Mariners will have a better quality of meteorological information, and the meteorologists will have a better understanding of the problems, constraints, and priorities of the vessel's masters. Ship response and performance data included with the ship's weather report will provide the routing agency with real-time information with which to ascertain the actual state of the ship. Being able to predict a ship's response in most weather and sea conditions will result in improved routing procedures.

Shipboard and anchored wave measuring devices contribute to the development of ocean wave analysis and forecast models. Shipboard seakeeping instrumentation, with input of measured wave conditions and predetermined ship response data for the particular hull, enables a master or commanding officer to adjust course and speed for actual conditions.

Modern ship designs, exotic cargoes, and sophisticated transport methods require individual attention to each ship's areas of vulnerability. Any improvement in the description of sea conditions by ocean wave models will improve the output from ship routing and seakeeping systems.

Advanced planning of a proposed transit, combined with the study of expected weather conditions, both before and during the voyage, as is done by ship routing agencies, and careful on board attention to seakeeping (with instrumentation if available) provide the greatest opportunity to achieve the goal of optimum environmental conditions for ocean transit.

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