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.

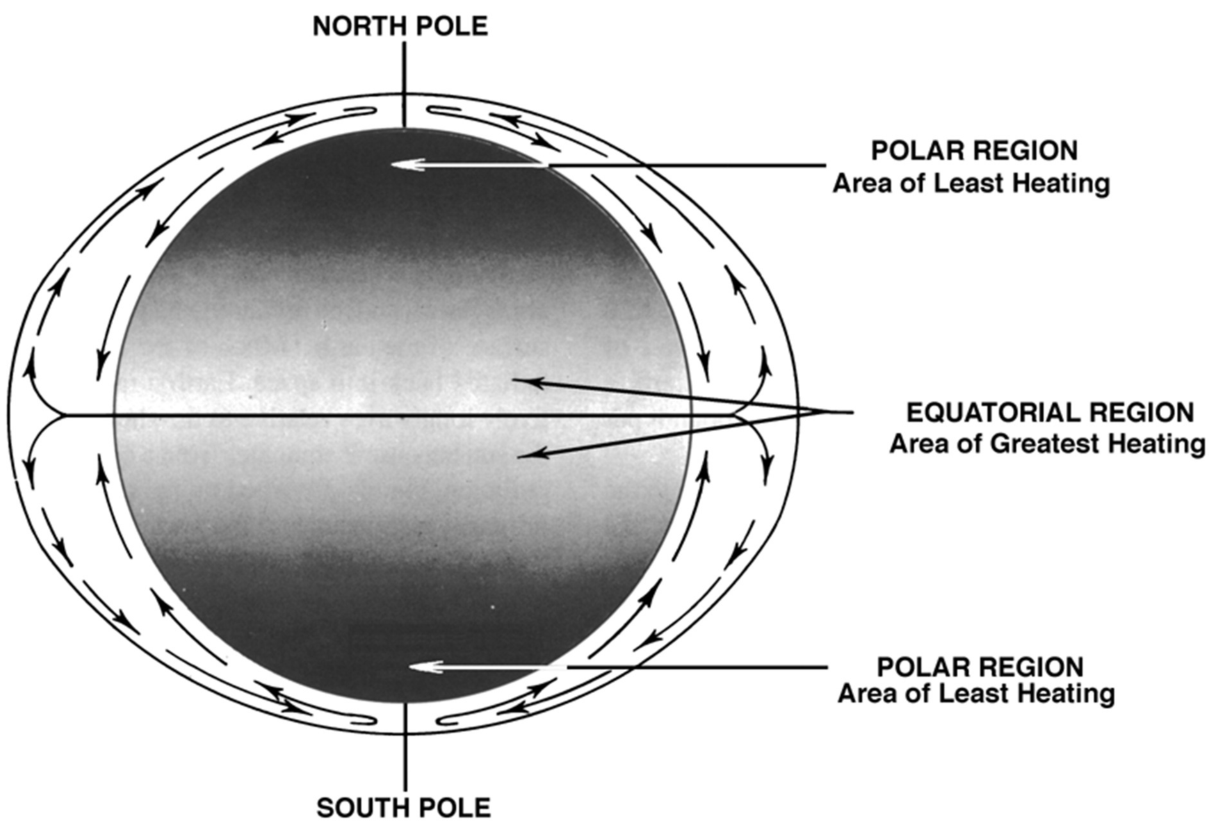

Figure 3802a. Ideal atmospheric circulation for a uniform and non-rotating Earth.

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-

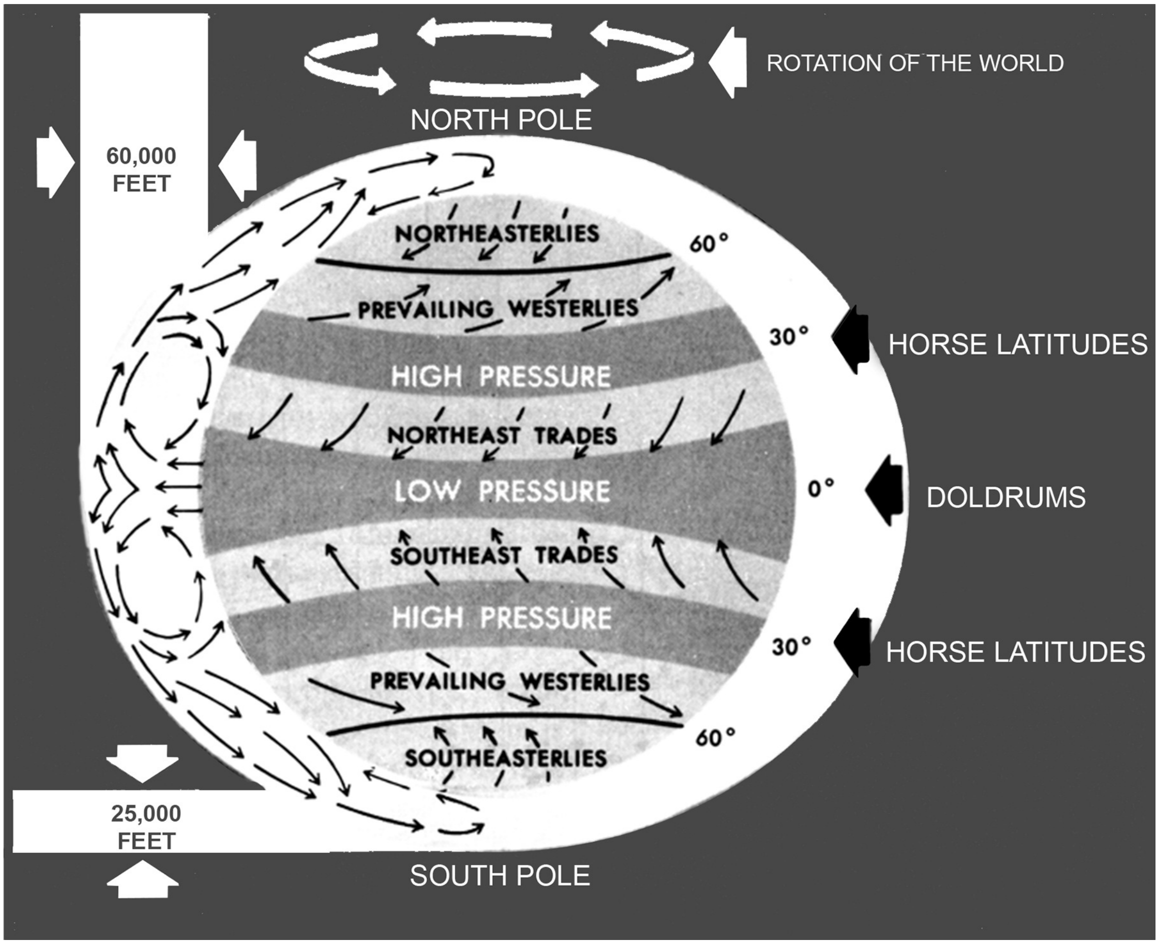

Figure 3802b. Simplified diagram of the general circulation of the atmosphere.

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

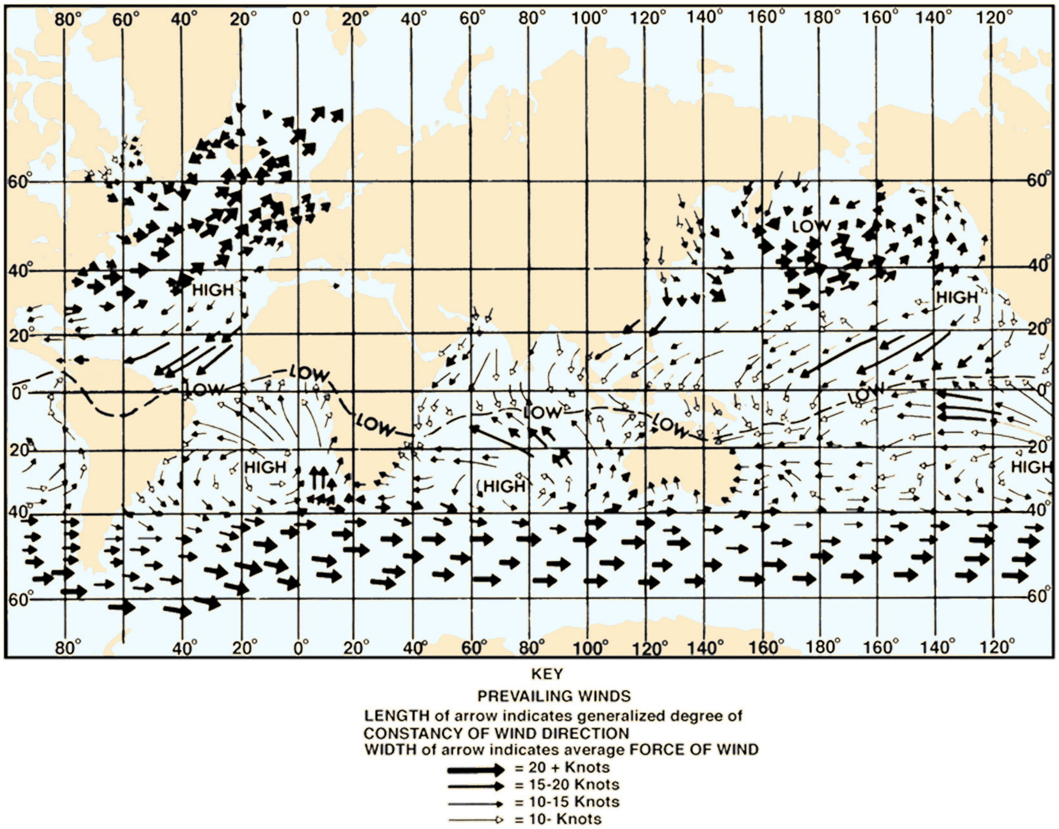

Figure 3802c. Generalized pattern of actual surface winds in January and February.

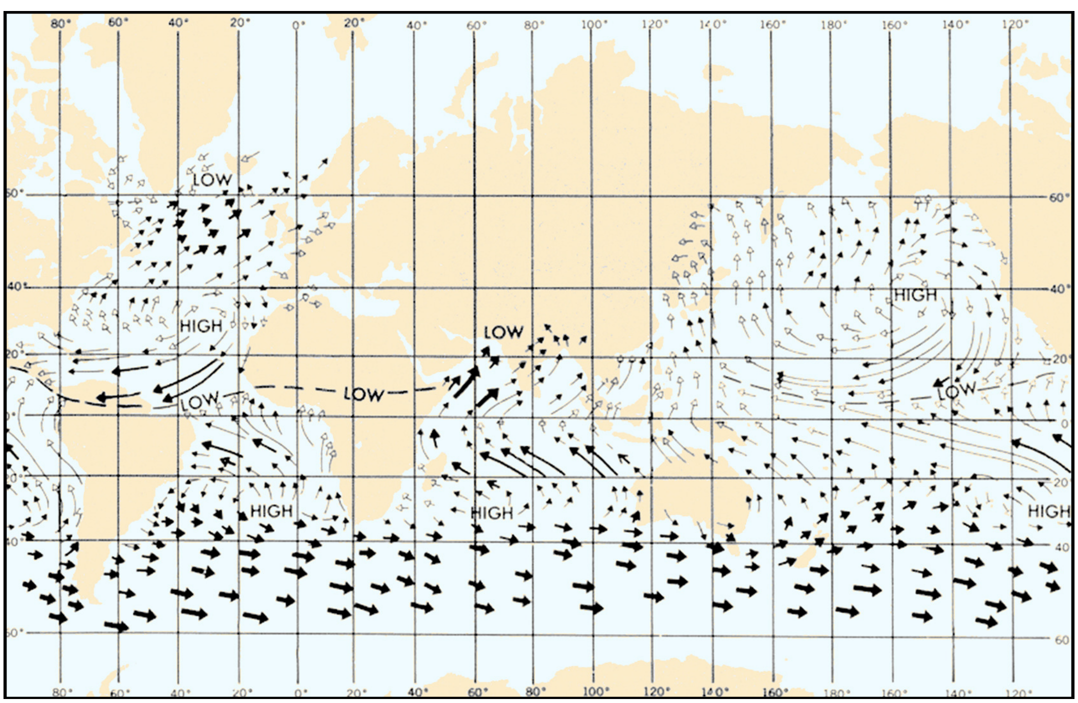

Figure 3802d. Generalized pattern of actual surface winds in July and August. (See key with Figure 3402c).

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

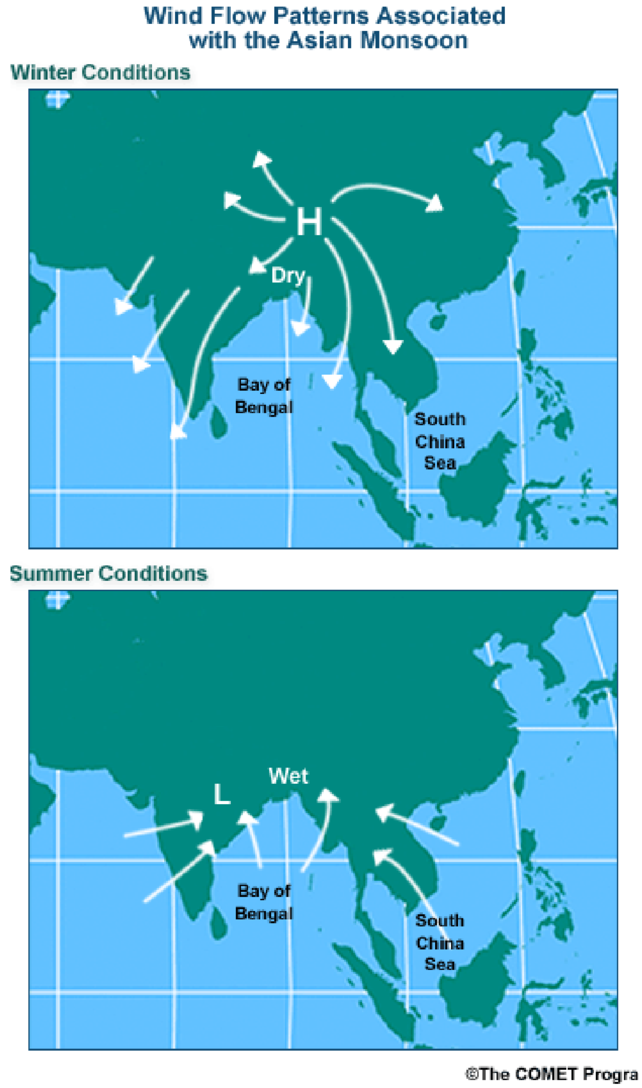

Figure 3808. The winter and summer monsoon. Used with permission of UCAR/COMET Program.

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.

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.

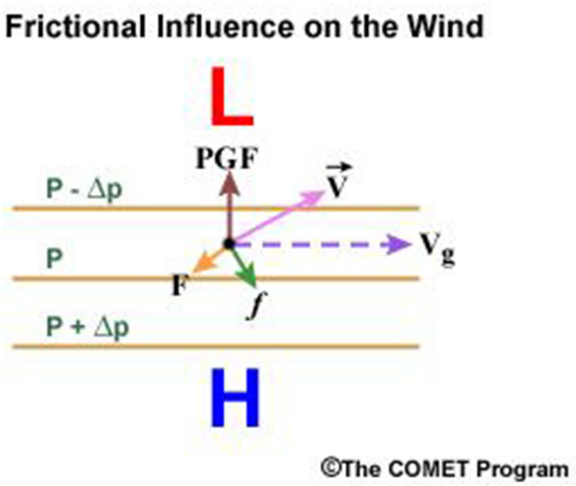

Figure 3810a. A simple pressure gradient of parallel isobars is used to demonstrate that the associated geostrophic wind (Vg) itself would be larger and oriented in a different direction than the real wind (V). The amount of slowing and turning that occurs is dependent on the surface friction (F). The 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

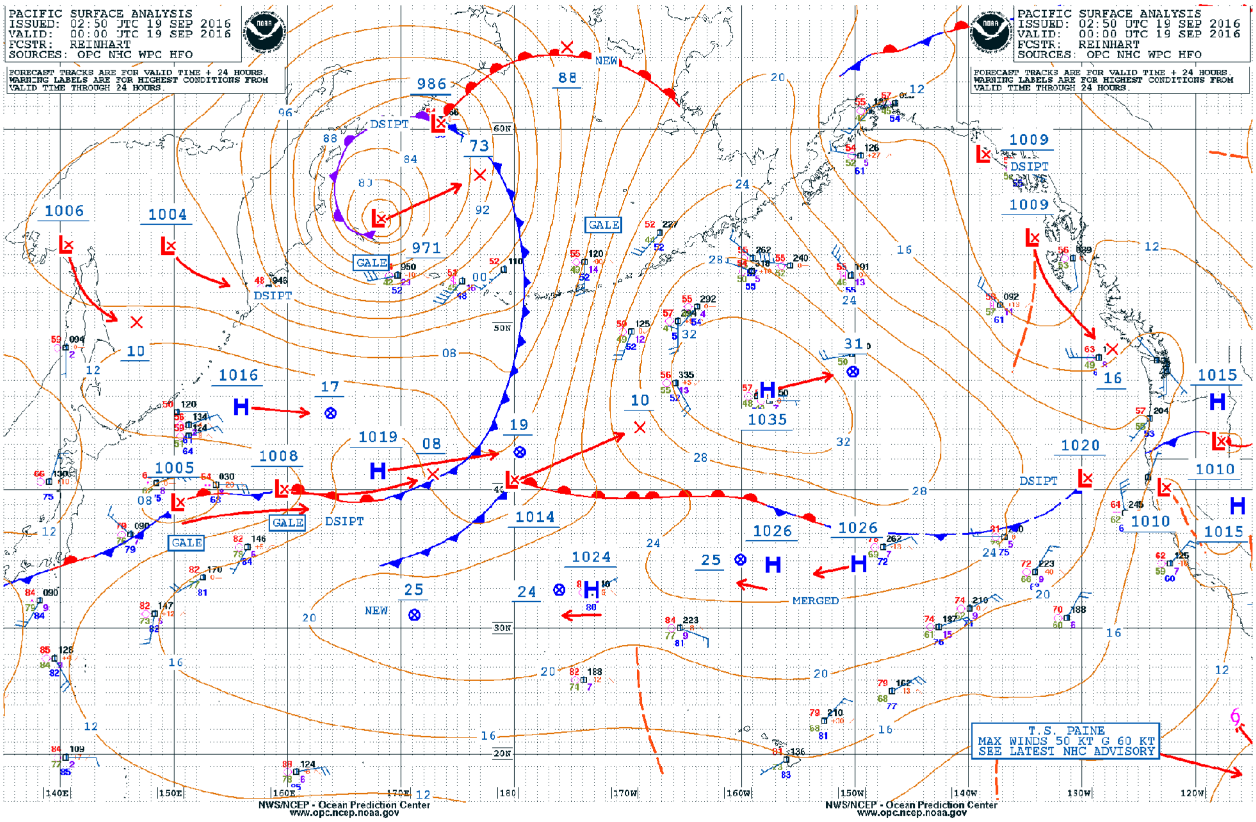

Figure 3810b. Sea-level pressure analysis showing isobars (thin brown solid lines) at 4 hPa intervals, fronts, cyclones (denoted by red L's) and anticyclones (blue H's) for the North Pacific from 0000 UTC 19 September 2016.

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

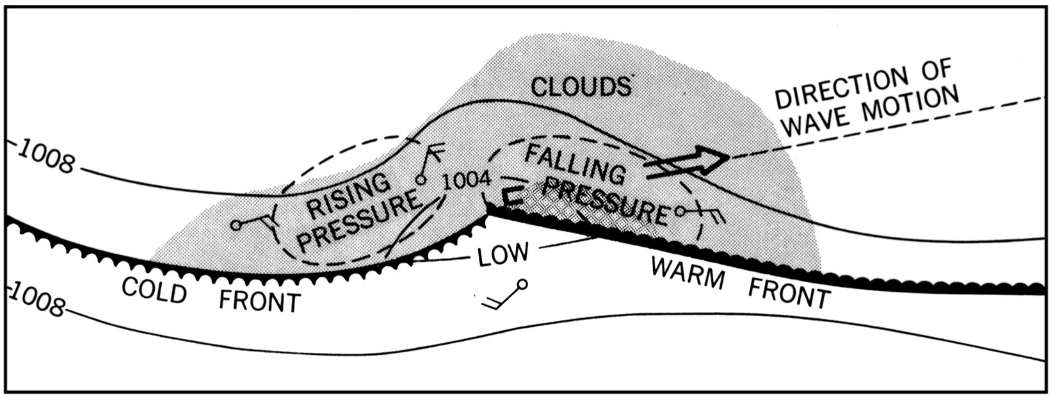

Figure 3812a. First stage in the development of a frontal wave (top view).

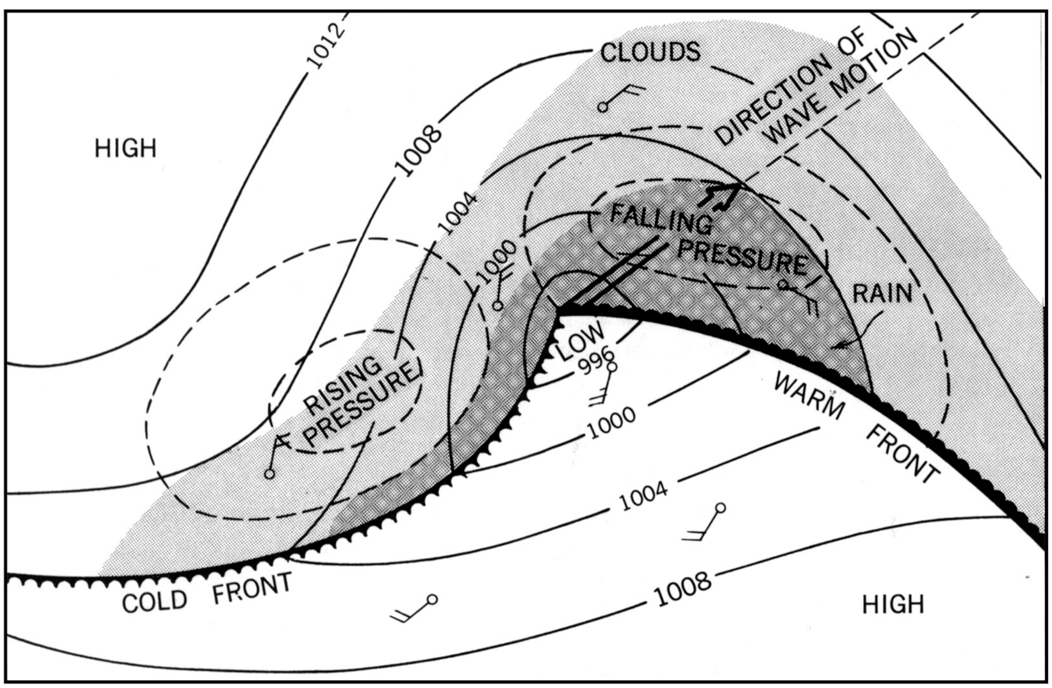

Figure 3812b. A fully developed frontal wave (top view).

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.

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 under-running 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

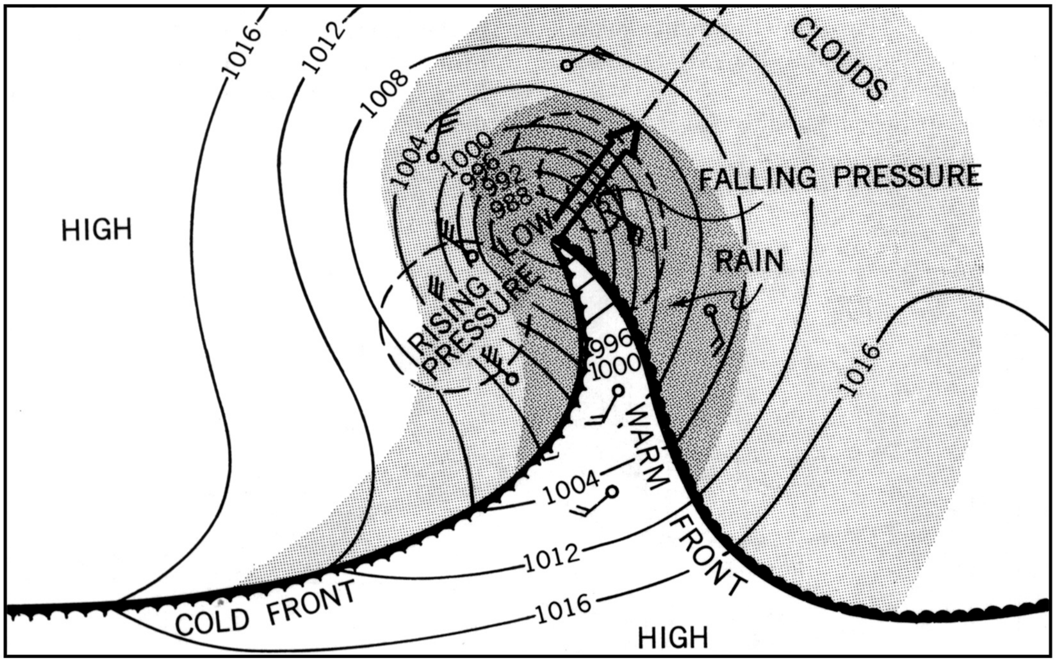

Figure 3812c. A frontal wave nearing occlusion (top view).

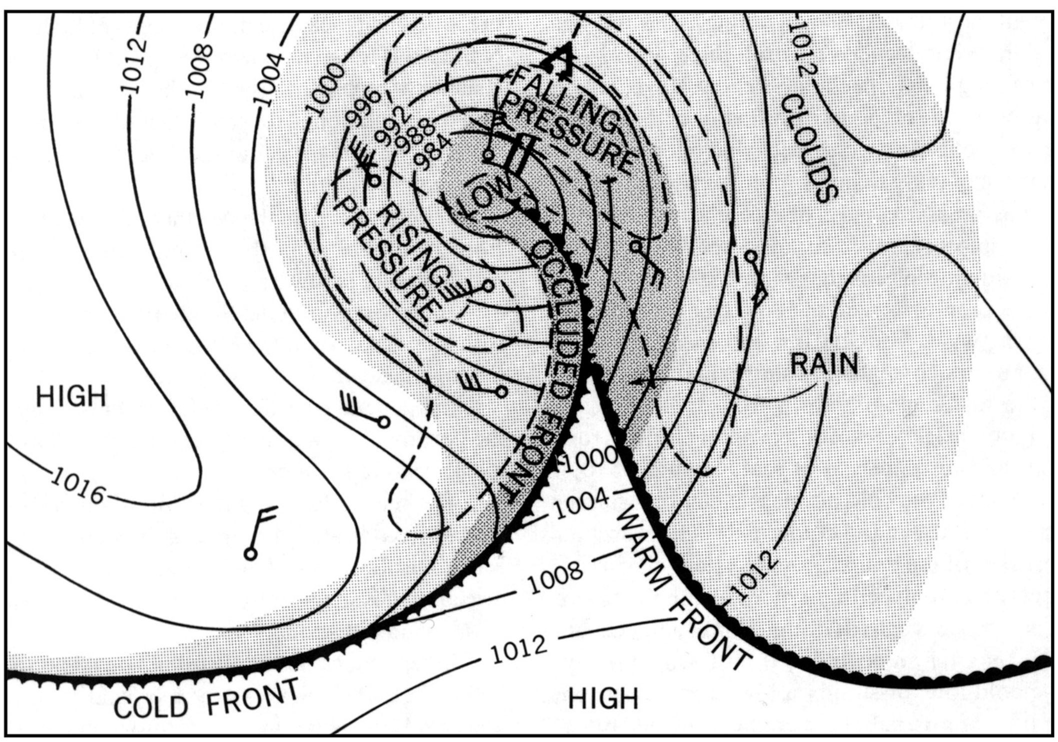

Figure 3812d. An occluded front (top view).

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-

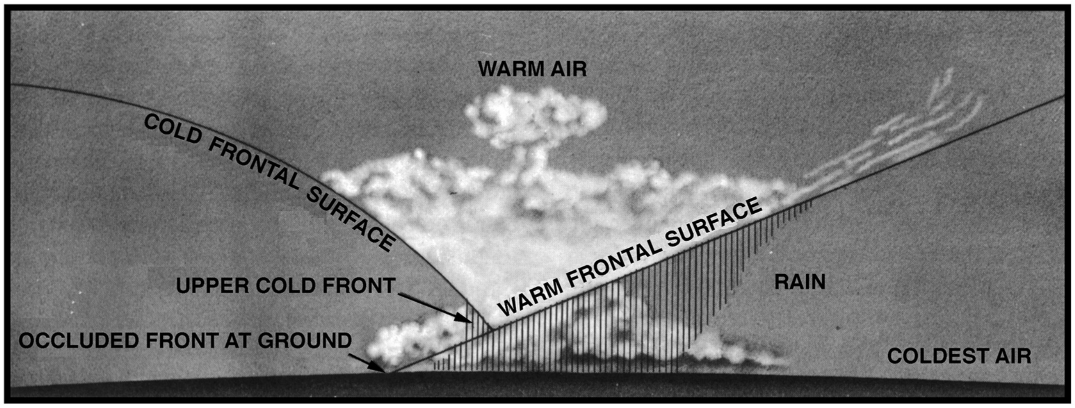

Figure 3812e. An occluded front (cross section).

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 devel-

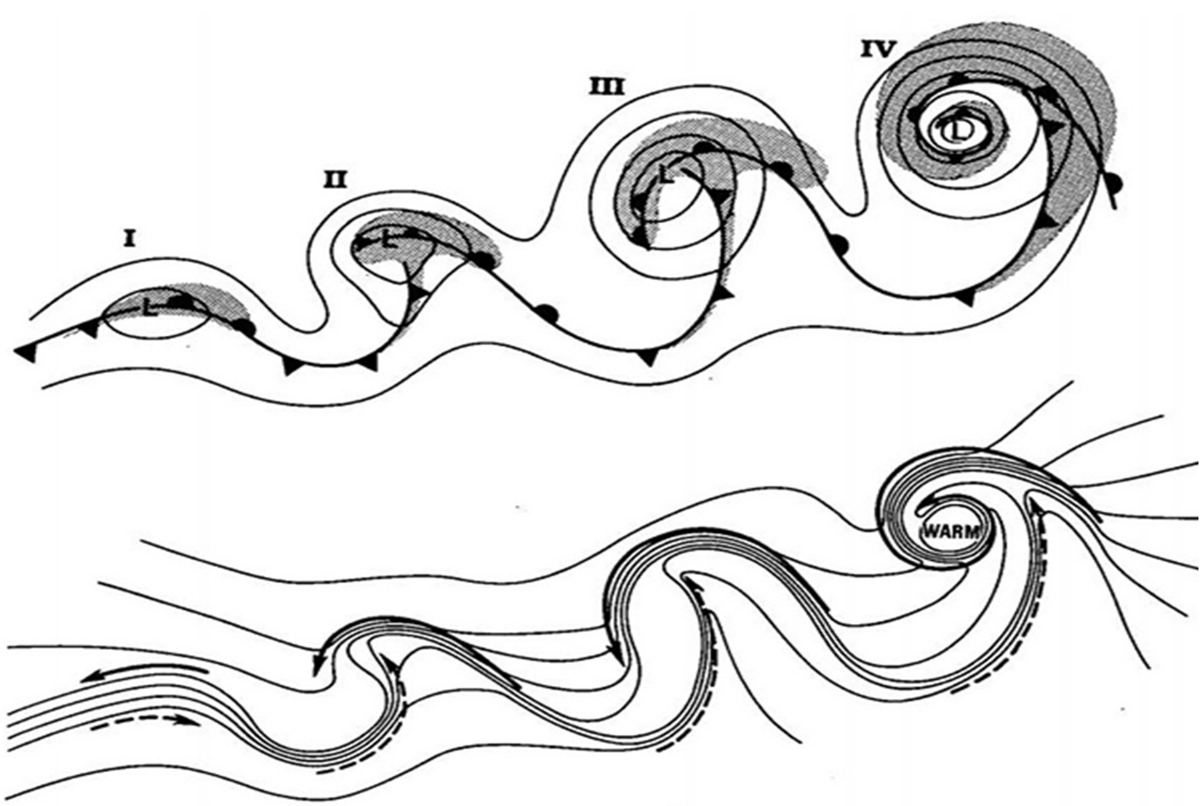

Figure 3812f. Evolution of a maritime cyclone from Shapiro and Keyser 1990. The four phases of evolution are from left to right: incipient frontal wave (I), frontal fracture (II), bent-back front and frontal T-bone (III), and warm core seclusion (IV). Top series showing evolution over time of isobars,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

ops 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 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.

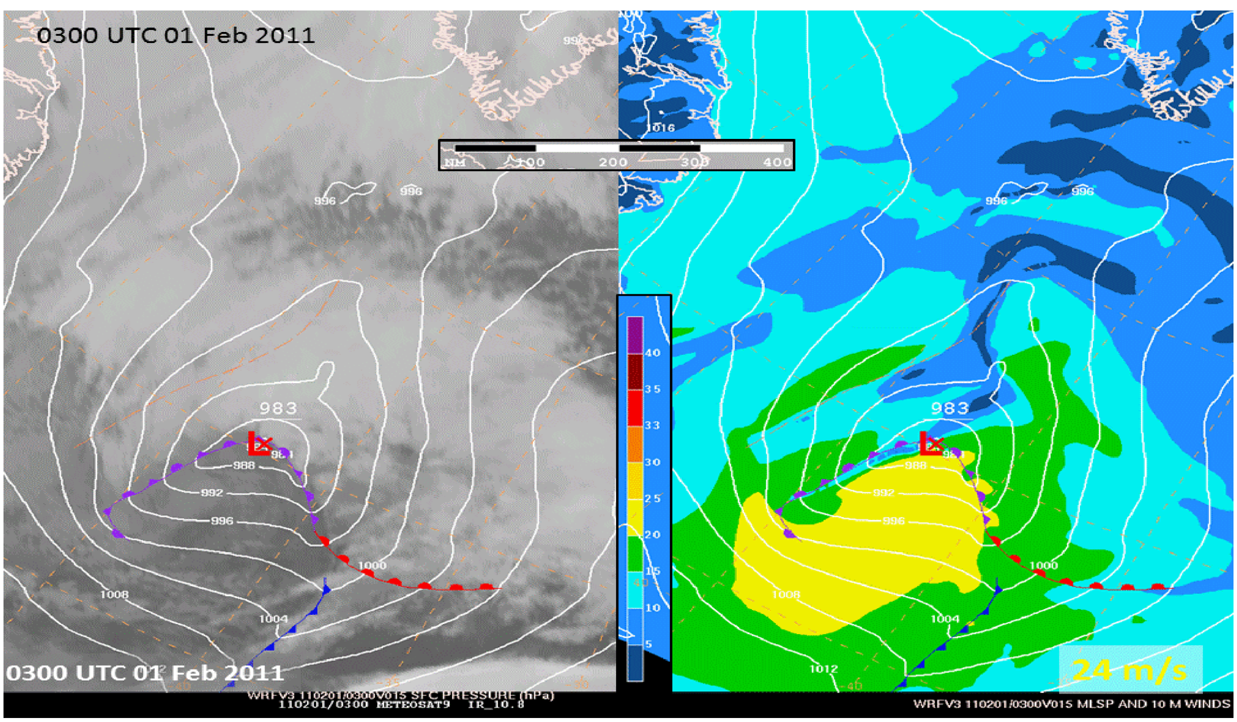

Figure 3813a. Two panel image of a North Atlantic cyclone from 0300 UTC 01 Feb 2011 showing isobars at 4 hPa intervals, infrared satellite image from Meteosat geostationary satellite, fronts, and central pressure (left). On the right panel, isobars and numerical model wind speeds from 10m above the ocean 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.

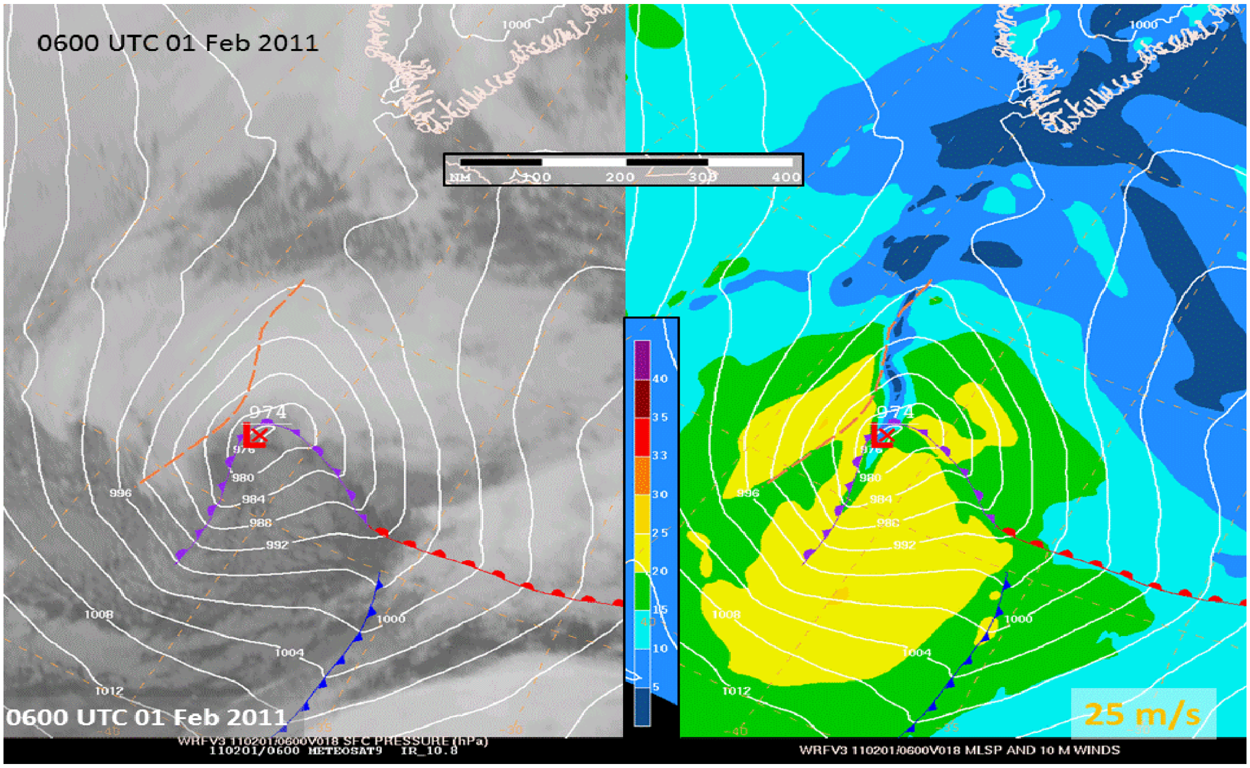

Figure 3813b. As in the previous figure but for 0600 UTC 01 Feb 2011.

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-

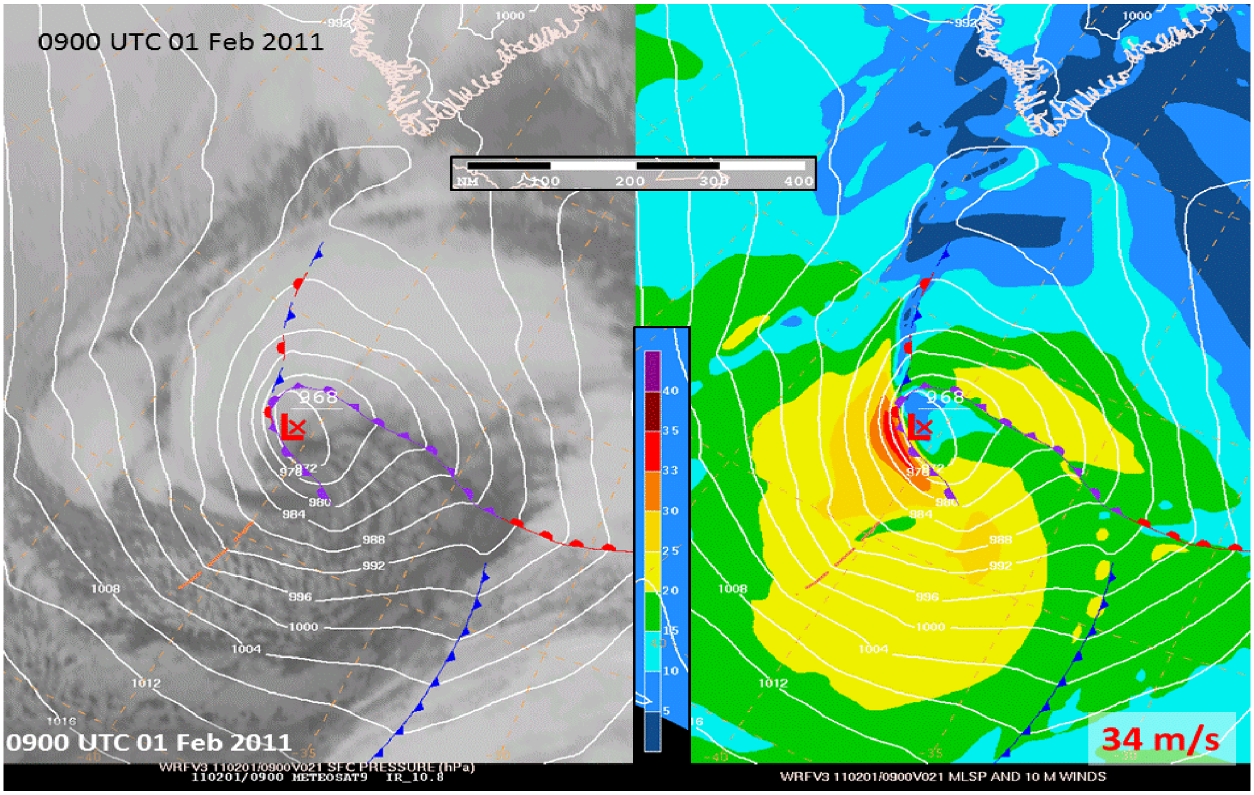

Figure 3813c. As in the previous figure but for 0900 UTC 01 Feb 2011.

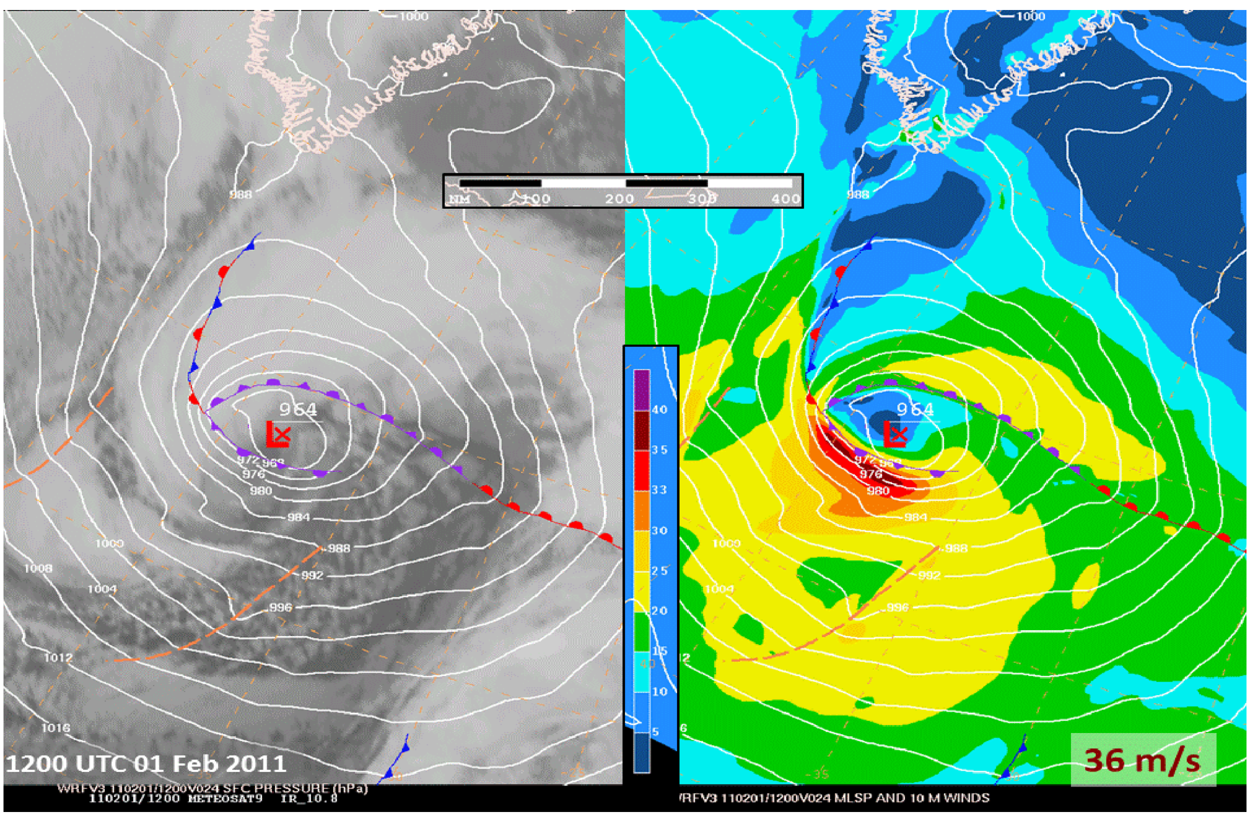

Figure 3813d. As in the previous figure but for 1200 UTC 01 Feb 2011.

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.

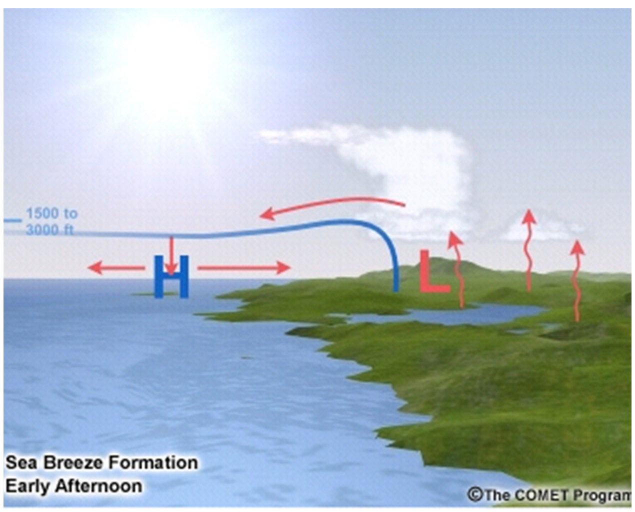

Figure 3814a. Sea breeze formation in the early afternoon.Used with permission of UCAR/COMET Program.

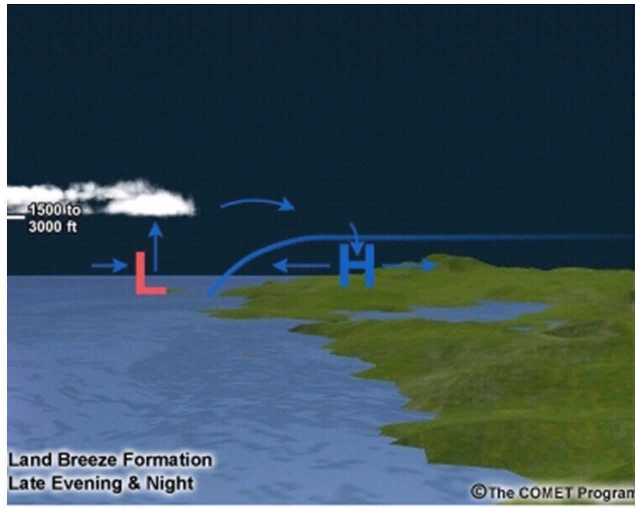

Figure 3814b. Land breeze formation in the late evening and at night.Used with permission of UCAR/COMET Program.

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

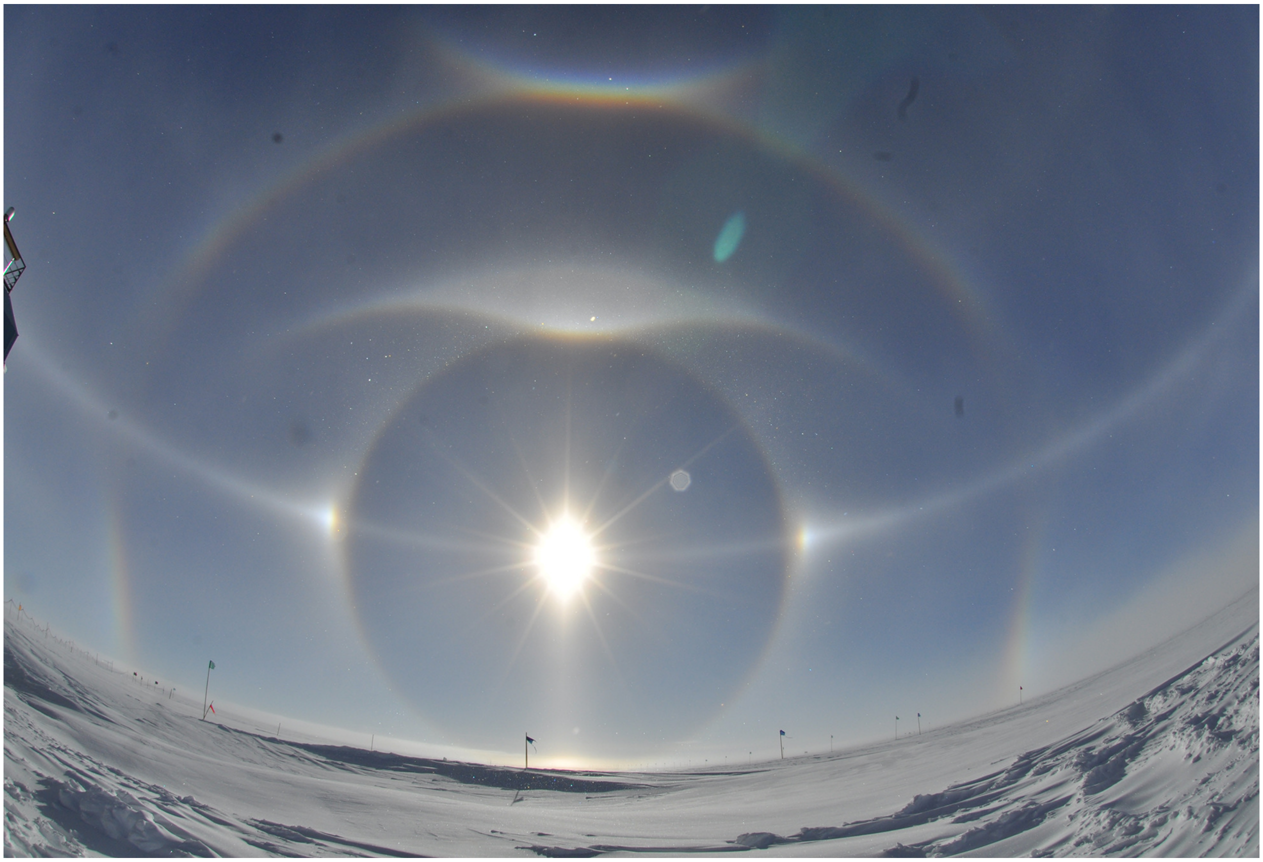

Figure 3821. From top to bottom: Circumzenithal arc, supralateral arc, Parry arc, tangential arc, 22 degree halo, parhelic circle, and sun dogs on right and left intersection of 22 degree halo and parhelic circle. Image courtesy of NOAA.

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.

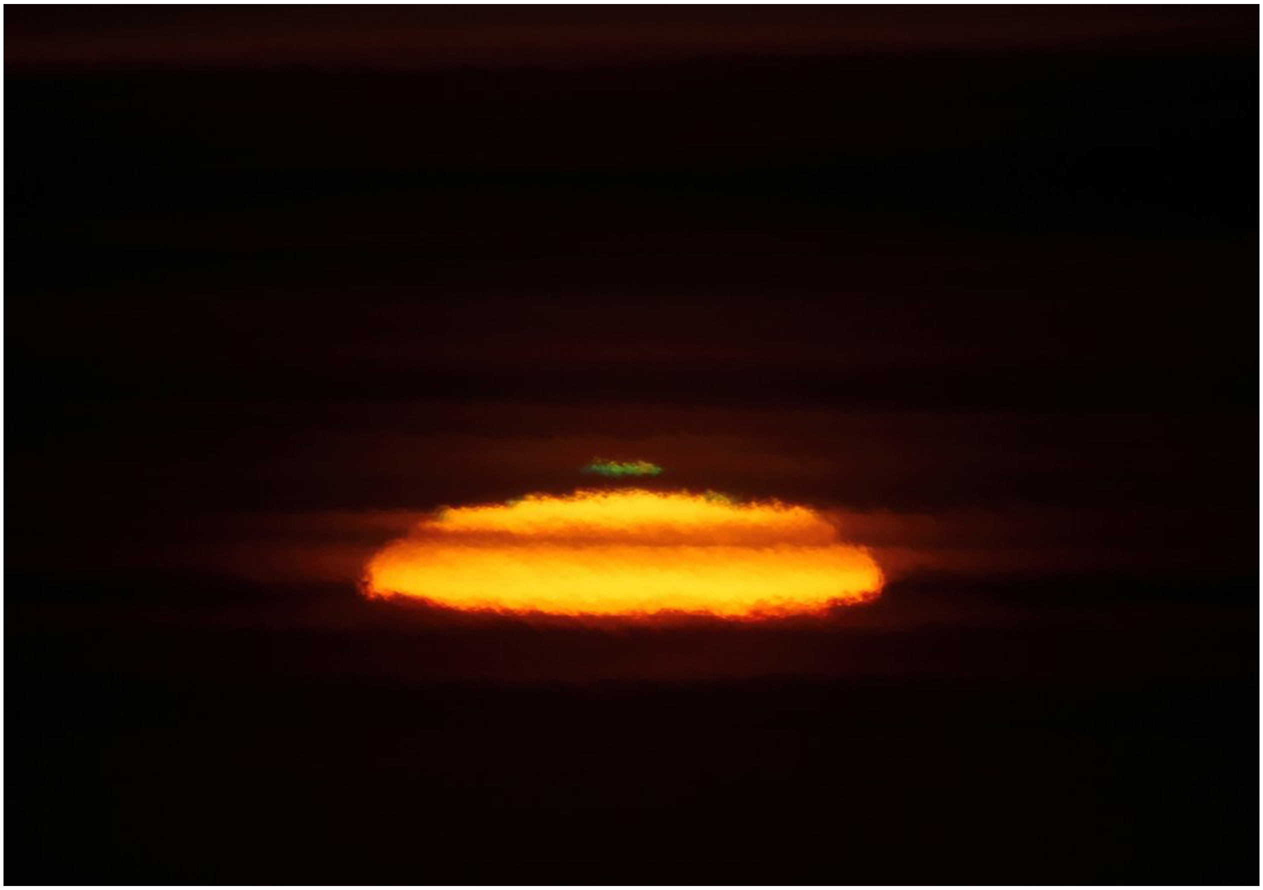

Figure 3823. Green Flash.

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

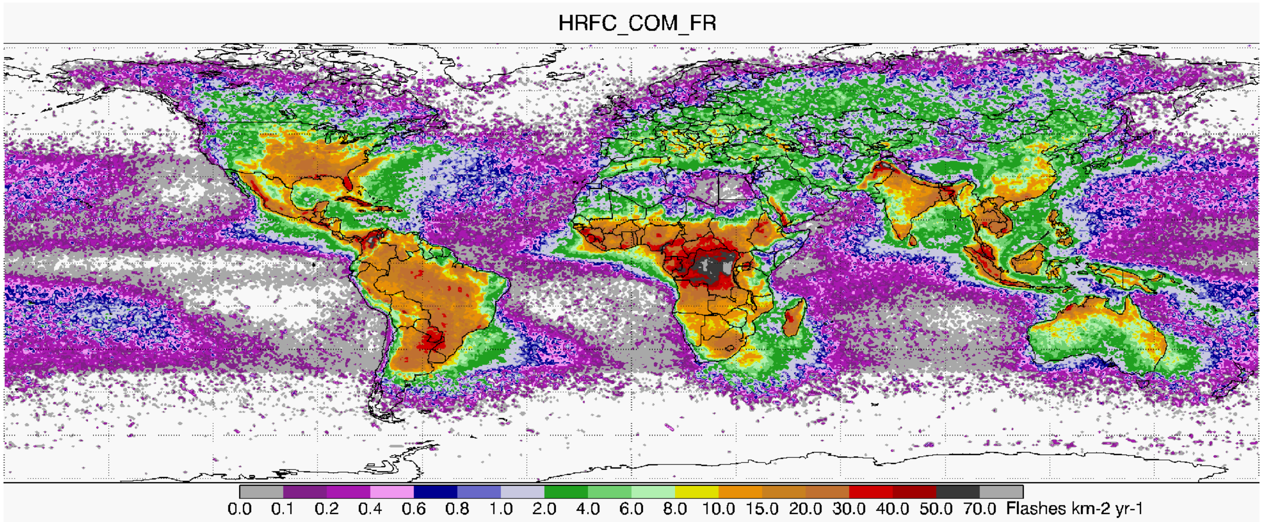

Figure 3825a. LIS/OTD 0.5 Degree High Resolution Full Climatology (HRFC) Annual Flash Density Map (1995-05-04 to 2013-12-31) available at https://dx.doi.org/10.5067/LIS/LIS-OTD/DATA302

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.

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.

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

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 as-

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

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

sociated 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.

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

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.

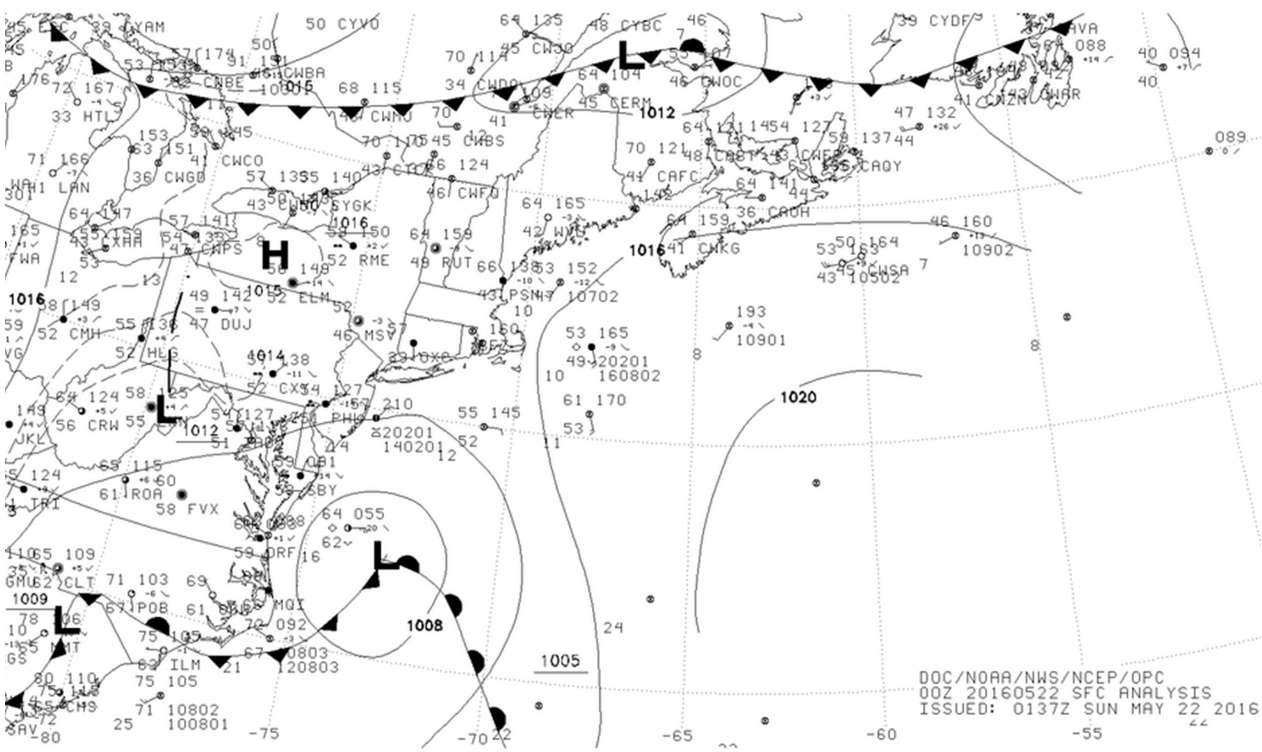

Figure 3827e. National Weather Service radiofax surface analysis example.

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,

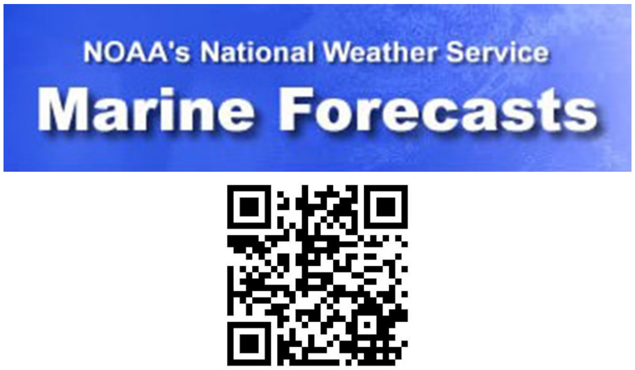

Figure 3827f. Information on marine weather radiofax broadcasts:
http://www.nws.noaa.gov/om/marine/radiofax.htm

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.

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.

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

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

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

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

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.

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

© Figures 3808, 3810a, 3814a & 3814b are provided courtesy of University Corporation for Atmospheric Research (UCAR), COMINT Program, Boulder, CO 80301.