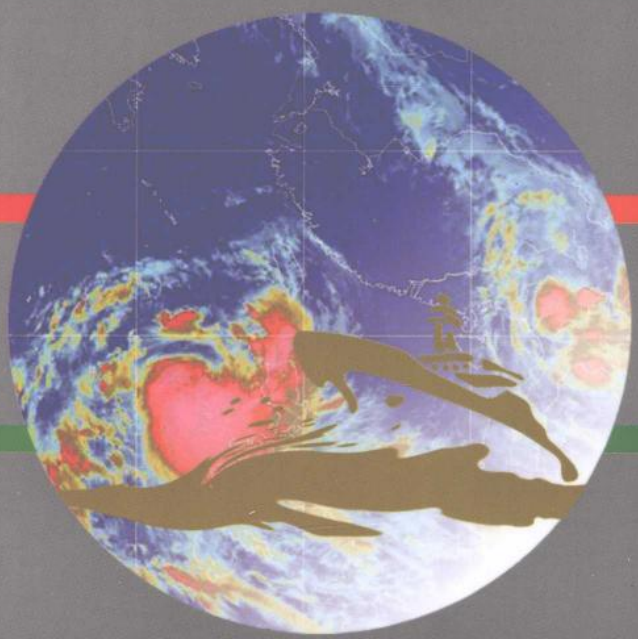
航海气象学与海洋学

Meteorology and Oceanography for Mariners

（英文版）

刘大刚　冷　梅　主编
张永宁　主审



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Abstract

This book is applicable to the deck mates aiming at observing and recording weather conditions and in interpreting prevailing conditions to predict future weather patterns and also to professionally study weather forecasts. This book is organized into five sections. Starting with the basic knowledge of the meteorological elements, temperature, pressure, humidity, wind, cloud, visibility and weather phenomena are briefed. An emphasis on Buys – Ballot Law explains the formation of the wind and the relationship between the wind and air pressure field. Then weather systems often encountered at sea, such as fronts, cyclones and anticyclones, are covered. Tropical cyclones produce the most severe weather so we have much discussion on the topic. The following section is the summary of the ocean climatology. The fourth section is the introduction of ocean current, waves, and sea ice. The last section of the book recites the weather information and services available at sea. Fax charts are by far the most valuable forecasting tool at our disposal. We cannot emphasize too strongly the importance of understanding these charts, and having a reliable means to receive them.

This book is to be used as a textbook for the course of *Meteorology and Oceanography for Mariners* in Dalian Maritime University. This book may also be used by mariners as general reference.

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Contents

CHAPTER 1 BASIC KNOWLEDGE OF THE ATMOSPHERE AND METEOROLOGICAL ELEMENTS

1.1 The Atmosphere

1.1.1 Introduction

The atmosphere is the envelope of gases surrounding the Earth.

Weather is a set of all the phenomena occurring in a given atmosphere at a given time. Weather refers, generally, to day-to-day temperature and precipitation activity, whereas climate is the term for the average atmospheric conditions over a much longer period of time.

Meteorology is the scientific study of the atmosphere. Maritime meteorology mainly deals with air and wave forecasts for ships operating at sea.

Commercial and recreational use of waterways can be limited significantly by wind direction and speed, wave periodicity and heights, tides, and precipitation. These factors can each influence the safety of marine transit. Consequently, a variety of codes have been established to efficiently transmit detailed marine weather forecasts to vessel pilots via radio, for example the MAFOR (marine forecast). Typical weather forecasts can be received at sea through the use of RTTY, Navtex and Radiofax.

Organizations such as the Ocean Prediction Center, Honolulu National Weather Service Forecast Office, United Kingdom Met Office, and JMA prepare high seas forecasts for the world's oceans.

1.1.2 Vertical Structure of the Atmosphere

The Earth's atmosphere contains several different layers that can be defined according to air temperature.

The troposphere is the lowest portion of the Earth's atmosphere. It contains approximately 75% of the atmosphere's mass and 99% of its water vapor and aerosols.

In the middle latitudes the average depth of the troposphere is approximately 12 km. It is deeper in the tropical regions, up to 20 km, and shallower near the poles, at 7 km in summer, and indistinct in winter.

The lowest part of the troposphere, where friction with the Earth's surface influences air flow, is the **planetary boundary layer.** This layer is typically a few hundred meters to 2 km deep depending on the landforms under neath and time of day.

The word troposphere derives from the Greek: tropos for "turning" or "mixing", reflecting the fact that turbulent mixing plays an important role in the troposphere's structure and behavior.

Weather elements (temp, humidity, stability) distribute unevenly in this layer.

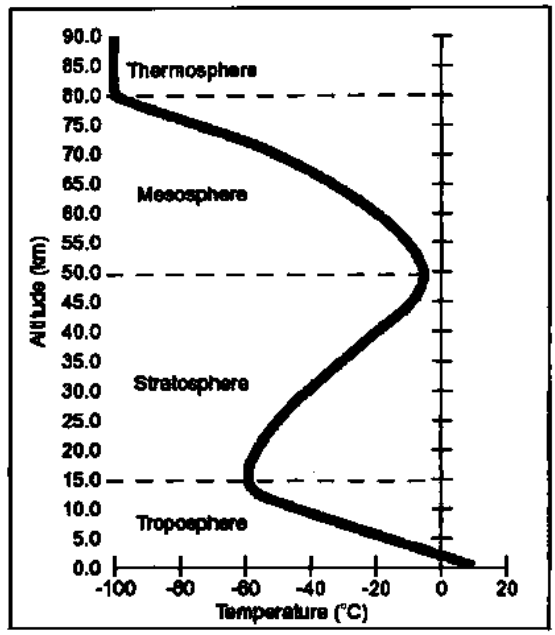


Figure 1.1 Structure of the Atmosphere

Most of the phenomena we associate with day-to-day weather occur in the troposphere.

In the troposphere, the average environmental lapse rate is a drop of about 6.5 °C for every 1 km increase in height.

The border between the troposphere and stratosphere is called the tropopause.

The region of the atmosphere where the lapse rate changes from positive (in the troposphere) to negative (in the stratosphere), is defined as the tropopause. Thus, the tropopause is an inversion layer, and there is little mixing between the two layers of the atmosphere.

The **stratosphere** is located at about 20 to 55 km above the Earth's surface.

In the **stratosphere**, the temperature remains constant for a while and then increases with altitude because a localized concentration of ozone gas molecules absorbs ultraviolet sunlight creating heat energy.

The **mesosphere** is located at about 55 to 85 km above the Earth's surface and contains little in the way of trace gases so there is little to absorb heat from the sun. The lowest temp is about −90 °C.

The thermosphere is at a height of above 85 km. The temperatures there can be higher than 1000 °C.

The ionosphere extends from 80 to 400 km above the Earth's surface.

1.1.3 Composition of the Atmosphere

The chemical composition of the troposphere is essentially uniform, with the notable exception of water vapor.

Table 1.1 **Constituents of the Atmosphere**

Gas Name	Chemical Formula	Percent Volume
Nitrogen	N_2	78.09
Oxygen	O_2	20.95
Argon	Ar	0.93
Water Vapor	H_2O	0~4
Carbon Dioxide	CO_2	0.03
Ozone	O_3	0.00006

The table shows that nitrogen and oxygen are the main components of the atmosphere by volume. Together these two gases make up approximately 99% of the dry atmosphere. Both of these gases have very important associations with life.

Another most abundant gas on the table is **water vapor.**

Water vapor varies in concentration in the atmosphere both spatially and temporally. The highest concentrations of water vapor are found near the equator over the oceans and tropical rain forests. Cold polar areas and subtropical continental deserts are locations where the volume of water vapor can approach zero percent. Water vapor has several very important functional roles on our planet.

It redistributes heat energy on the Earth through latent heat energy exchange. The condensation of water vapor creates precipitation that falls to the Earth's surface providing needed fresh water for plants and animals. It helps warm the Earth's atmosphere through the Greenhouse Effect.

Carbon dioxide in the Earth's atmosphere is considered a trace gas currently occurring at an average concentration of about 383 parts per million by volume or 582 parts per million by mass.

Atmospheric concentrations of carbon dioxide fluctuate slightly with the change of the seasons, driven primarily by seasonal plant growth in the Northern Hemisphere.

Concentrations of carbon dioxide fall during the northern spring and summer as plants consume the gas, and rise during the northern autumn and winter as plants go dormant, die and decay. Carbon dioxide is a greenhouse because it transmits visible light but strongly absorbs infrared and near-infrared energy.

Ozone in the lower atmosphere is an air pollutant with harmful effects on the respiratory systems of animals and will burn sensitive plants. However, the ozone layer in the upper atmosphere is beneficial, preventing potentially damaging ultraviolet light from reaching the Earth's surface. Ozone is present in low concentrations throughout the Earth's atmosphere.

The highest levels of ozone in the atmosphere are in the stratosphere, in a region also known as the ozone layer between about 10 km and 50 km above the surface.

In recent decades the amount of ozone in the stratosphere has been declining mainly because of emissions of CFCs (chlorofluorocarbons), and similar chlorinated and brominated organic molecules, which have increased the concentration of ozone-depleting catalysts above the natural background. Ozone only makes up 0.00006% of the atmosphere.

Technically, an **aerosol** is a suspension of fine solid particles or liquid droplets in a gas, such as smoke, oceanic haze, air pollution, smog and CS gas ("tear gas").

The word aerosol derives from the fact that matter "floating" in air is a suspension (a mixture

in which solid or liquid or combined solid-liquid particles are suspended in a fluid). To differentiate suspensions from true solutions, the term sol evolved-originally meant to cover dispersions of tiny (sub-microscopic) particles in a liquid.

With studies of dispersions in air, the term "aerosol" evolved and now embraces liquid droplets, solid particles, and combinations of these.

1.2 Solar Radiation and Air Temperature

1.2.1 Solar Radiation

Electromagnetic radiation (often abbreviated **E-M radiation** or **EMR**) is a phenomenon that takes the form of self-propagating waves in a vacuum or in matter.

Electromagnetic radiation is classified into several types according to the frequency of its wave; these types include (in order of increasing frequency and decreasing wavelength): radio waves, microwaves, terahertz radiation, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. A small and somewhat variable window of frequencies is sensed by the eyes of various organisms; this is what is called the visible spectrum, or light.

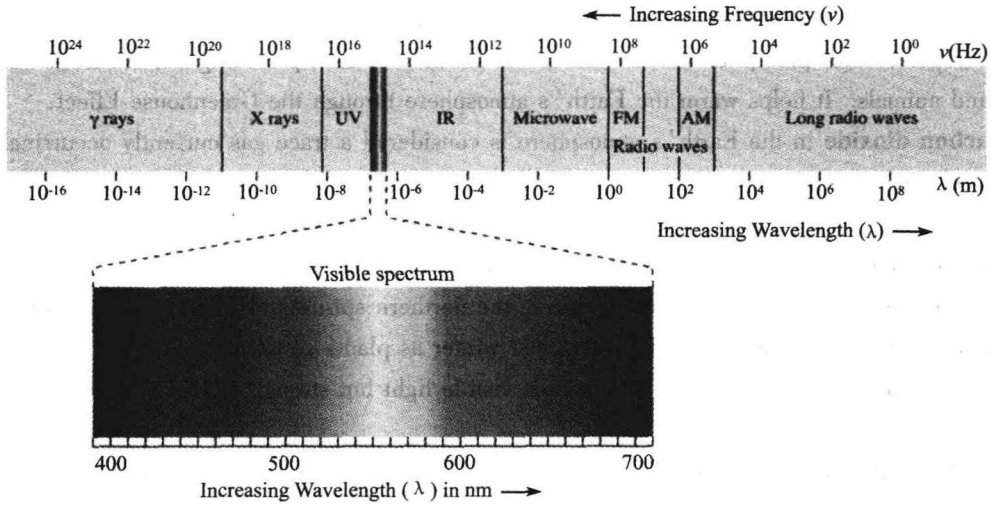


Figure 1.2 Electromagnetic Radiation

The behavior of E-M radiation depends on its wavelength. Higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths.

Thermal radiation is electromagnetic radiation emitted from the surface of an object which is due to the object's temperature.

Outgoing Long-wave Radiation (OLR) is the energy leaving the Earth as infrared radiation at low energy.

The Earth's radiation balance is very closely achieved since the OLR very nearly equals the **Shortwave Absorbed Radiation (SAR)** received as high energy from the sun. Thus, the first law of thermodynamics (energy conservation) is satisfied and the Earth's average temperature is very nearly stable. See Figure 1.3.

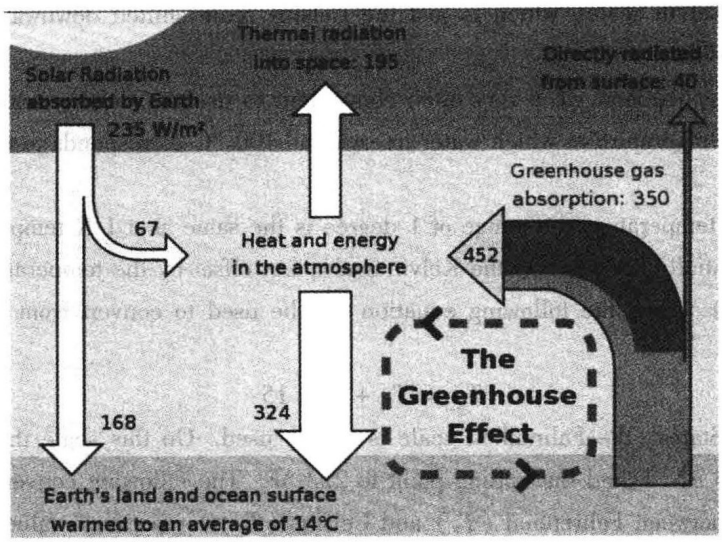


Figure 1.3 Exchanges of Energy Between outer Space, the Earth's Atmosphere, and the Earth's Surface

The OLR is affected by clouds and dust in the atmosphere, which tend to reduce it below clear sky values.

The OLR is dependent on the temperature of the radiating body.

The ability of the atmosphere to capture and recycle energy emitted by the Earth surface is the defining characteristic of the **Greenhouse Effect.**

The Greenhouse Effect is caused by an atmosphere containing gases such as water vapor and CO_2 that absorb and emit infrared radiation.

Greenhouse gases, such as methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O) and carbon dioxide (CO_2), absorb certain wavelengths of OLR adding heat to the atmosphere, which in turn causes the atmosphere to emit more radiation. Greenhouse gases trap heat within the surface-troposphere system, causing heating at the surface of the planet. Some of this radiation is directed back towards the Earth, increasing the average temperature of the Earth's surface.

Therefore, an increase in the concentration of a greenhouse gas would contribute to global warming by increasing the amount of radiation that is absorbed and emitted by these atmospheric constituents.

1.2.2 Air Temperature and Temperature Scales

Air temperature is a measure of the average energy of motion, or kinetic energy, of particles in the air.

Temperature is measured with thermometers that may be calibrated to a variety of temperature scales.

Temperature measurement using modern scientific thermometers and temperature scales goes back at least as far as the early 18th century, when Gabriel Fahrenheit adapted a thermometer (switching to mercury) and a scale.

The scientific world measures air temperature using the Celsius scale and thermodynamic tem-

perature using the Kelvin scale, which is just the Celsius scale shifted downwards so that 0 K = −273.15 °C, or absolute zero.

For everyday applications, it's very often convenient to use the Celsius scale, in which 0 °C corresponds to the temperature at which water freezes and 100 °C corresponds to the boiling point of water at sea level.

In this scale a temperature difference of 1 degree is the same as a 1 K temperature difference, so the scale is essentially the same as the Kelvin scale, but offset by the temperature at which water freezes (273.15 K). Thus the following equation can be used to convert from degrees Celsius to Kelvin:

$$T_K = T_C + 273.15 \tag{1.2.1}$$

In the United States, the Fahrenheit scale is widely used. On this scale the freezing point of water corresponds to 32 °F and the boiling point to 212 °F. The following conversion formulas may be used to convert between Fahrenheit (T_F) and Celsius (T_C) temperature values:

$$T_C = \frac{5}{9}(T_F - 32) \tag{1.2.2}$$

$$T_F = \frac{9}{5}T_C + 32 \tag{1.2.3}$$

1.2.3 Diurnal and Annual Variations of Air Temperature

Diurnal variation of air temperature means the systematic change of the temperature of the atmosphere during an average of 24-hour period. Usually, the minimum and maximum air temperatures are attained at about 1 hour after sunrise and 1500LMT, and in winter days the maximum air temperature occurs at 1400LMT.

The annual variation of air temperature is linked to the annual cycle of net radiation. Near the equator, there are no temperature seasons, net radiation is positive and shows only two minor peaks (equinoxes). In higher northern, the peak occurs in July on land and August at sea, and in January and February. The temperatures are the accordingly lowest. The annual range increases with latitude, especially over Northern Hemisphere continents. Continental locations have a larger range of daily and annual temperature than coastal locations, even if they are located at the same latitude.

1.3 Atmospheric Pressure

1.3.1 Air Pressure and Its Units

The atmospheric pressure or air pressure refers to the force which a column at air exerts on unit area of a given point.

Mean sea level pressure (MSLP) is the pressure at sea level or (when measured at a given elevation on land) the station pressure reduced to sea level assuming an isothermal layer at the station temperature.

This is the pressure normally given in weather reports on radio, television, and newspapers or on the Internet. When barometers at home are set to match the local weather reports, they measure pressure reduced to sea level, not the actual local atmospheric pressure.

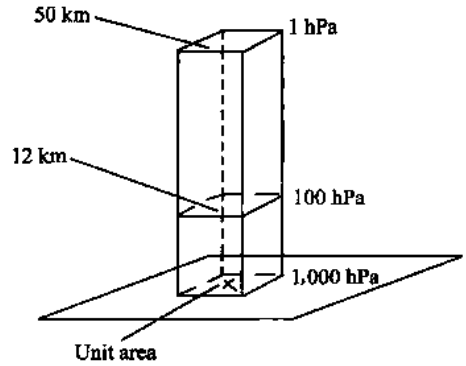


Figure 1.4 Definition of Air Pressure

Atmospheric air pressure is often given in millibars (mbar). Despite millibars not being an **SI unit**, meteorologists and weather reporters worldwide have long measured air pressure in millibars. After the advent of SI units, some meteorologists began using hectopascals (symbol **hPa**) which are numerically equivalent to millibars.

The exchange relations are as follows:

$$1\ \text{hPa} = 1\text{mbar} \tag{1.3.1}$$

$$1\ \text{hPa} = \frac{3}{4}\text{mmHg} \tag{1.3.2}$$

The **standard atmosphere** is an international reference pressure defined as **101,325 Pa** and formerly used as unit of pressure (symbol: atm). For practical purposes it has been replaced by the bar which is 100,000 Pa (**1,000 hPa**).

Atmospheric pressure varies widely on the Earth. The highest MSL pressure ever recorded on Earth was 1,084 hPa, measured in Agata, U. S. S. R., on December 31, 1968. Agata is located in northern Siberia. The weather was clear and very cold at the time, with temperatures between −40°C and −58°C.

The lowest MSL pressure ever measured was 870 hPa, set on October. 12, 1979, during Typhoon Tip in the western Pacific Ocean. The measurement was based on an instrumental observation made from a reconnaissance aircraft.

1.3.2 Variation of Pressure with Height

From the definition of air pressure we can see that low pressure areas have less atmospheric mass above their location, whereas high pressure areas have more atmospheric mass above their location.

Table1.2 Air Pressures with the Corresponding Average Altitudes

Air Pressures	Average Altitudes
850 hPa	1,500 m
700 hPa	3,000 m
500 hPa	5,500 m
300 hPa	9,000 m

Similarly, as elevation increases there is less overlying atmospheric mass, so that pressure de-

creases with increasing elevation. Table 1.2 gives a rough idea of air pressure at various altitudes.

The rate at which the pressure decreases with altitude is not a constant. A good approximation of this is that for every 100 m higher you go in the atmosphere, pressure will decrease by about 10 hPa. This works well up to about 3,000 m above sea level, but the actual rate at any given time is governed by temperature.

Cold air is denser and heavier per unit volume than the warm air, and pressure difference in the cold air column is larger than in the warm air column. Thus pressure falls with height must be greater in the cold column.

In the altitudes close to sea level, it can be considered as a decrease of 1 hPa per 8 m.

1.3.3 Diurnal and Annual Variations of Air Pressure

Atmospheric pressure shows a diurnal (twice-daily) cycle caused by global atmospheric tides. This effect is strongest in tropical zones, with amplitude of a few hectopascal, and almost zero in polar areas.

Except when weather systems are present, there are two maximum and two minimum pressures per day, and they occur at a constant local time every day. From a maximum at 1000, the pressure falls to a minimum at 1600, rises to another maximum at 2200, and falls again to a second minimum at 0400 local time.

Annual variation of air pressure refers to the periodic variation of the monthly mean pressure during a year. There is one maximum and one minimum pressure every year. The difference of the two values is called annual range. For continental areas the pressure rises to a maximum in the winter and falls to a minimum in the summer, for oceanic areas the pressure rises to a maximum in the summer, and falls to a minimum in the winter. The annual range on land is greater than that at sea.

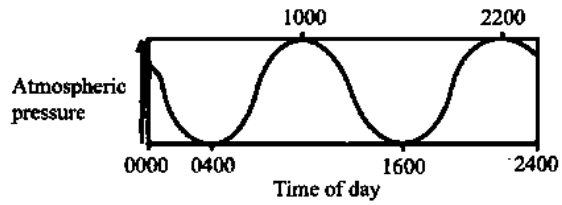


Figure 1.5 Variation of Pressure During One 24 h Period

1.3.4 Isobar

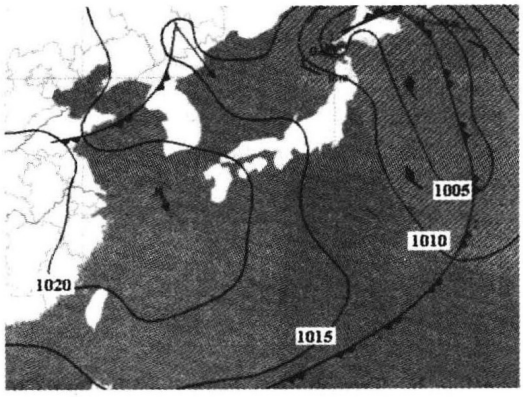
Isobars are lines connecting points of equal atmospheric pressure. On a surface chart, the interval between isobars is always constant, usually being 2.5 or 5 hPa in China, and 2 or 4 or 5 hPa in other countries.

1.3.5 Pressure Gradient

The pressure gradient is a physical quantity that describes in which direction and at what rate the pressure changes the most rapidly around a particular location. The pressure gradient is a dimensional quantity expressed in units of pressure per unit length.

The pressure gradient is the vector quantity defined as:

$$-\nabla p = -\left(\frac{\partial p}{\partial x}, \frac{\partial p}{\partial y}, \frac{\partial p}{\partial z}\right) \tag{1.3.3}$$



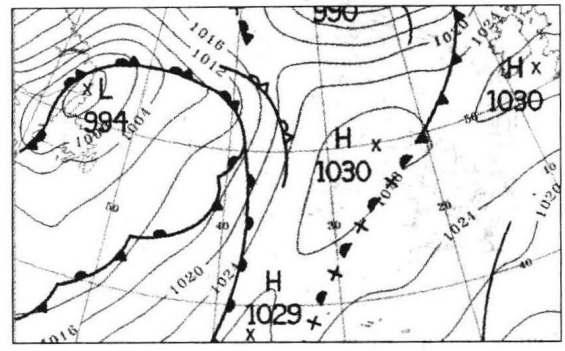


Figure 1.6.a Isobars on a Chinese Weather Chart **Figure 1.6.b Isobars on a British Weather Chart**

The horizontal pressure gradient is a 2 – dimensional vector resulting from the projection of the pressure gradient onto a local horizontal plane.

Near the Earth's surface, this horizontal pressure gradient is typically pointing towards low pressure, and noted as $-\frac{\Delta p}{\Delta n}\vec{n}$.

Its particular orientation at any one time and place depends strongly on the weather situation.

The magnitude of the pressure gradient can be assessed by noting the spacing of the isobars. If the isobars are close together, the pressure gradient is large; if the isobars are far apart, the pressure gradient is small.

1.3.6 Common Types of Pressure Fields

Centers of surface **high** and **low** pressure areas are found within closed isobars on a surface weather chart where there is absolute maxima and minima in the pressure field, and can show a user in a glance what the general weather is in their vicinity.

Weather charts in English-speaking countries will depict their highs as Hs and lows as Ls, while Spanish-speaking countries will depict their highs as As and lows as Bs, and in China sometimes as Gs and Ds.

A **ridge** is an elongated region of relatively high atmospheric pressure, the opposite of a **trough**. The area of almost constant pressure (and therefore few isobars) between two highs and two lows is known as a **col**. Between two highs is a **low belt**, and between two lows is a **high belt**.

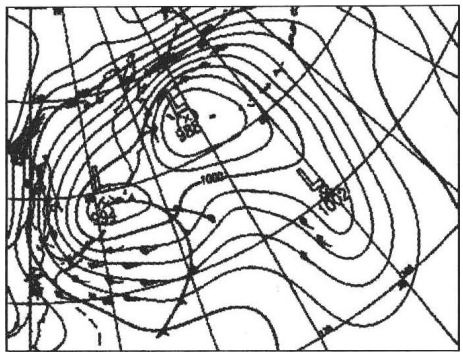


Figure 1.7.a Ridge on a Chinese Weather Chart

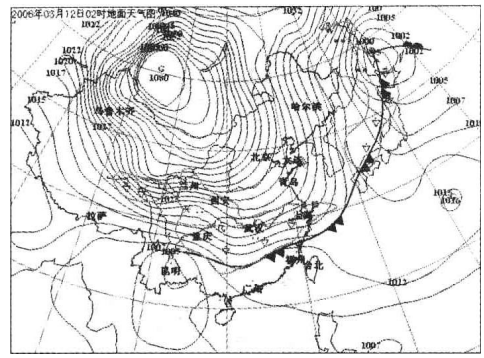


Figure 1.7.b Trough on a Japanese Weather Chart

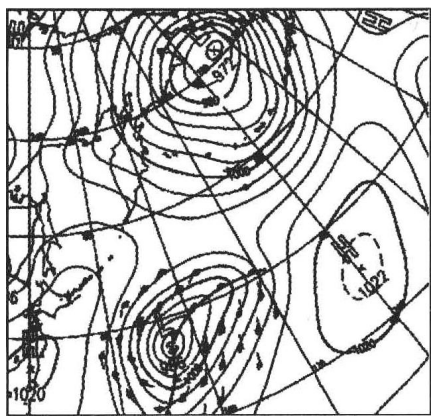


Figure 1.7.c Col on a Chinese Weather Chart

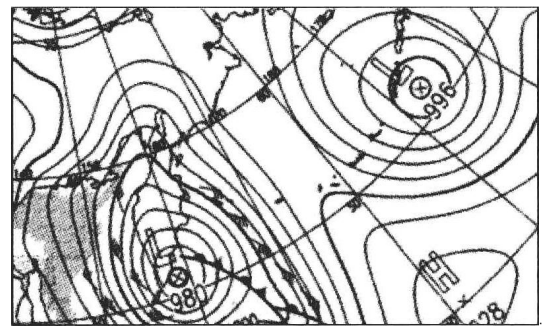


Figure 1.7.d High Belt on a Japanese Weather Chart

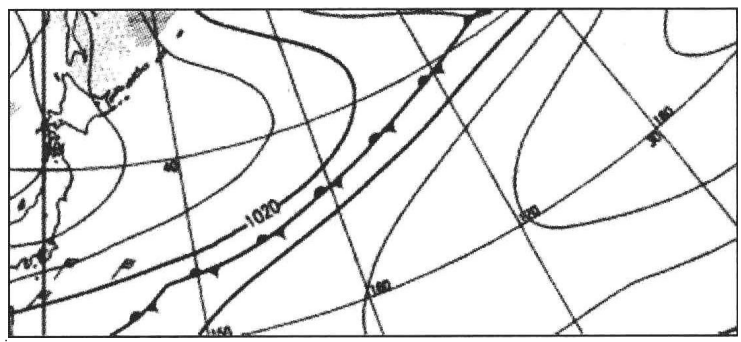


Figure 1.7.e Low Belt on a Korean Weather Chart

1.4 Stability of the Atmosphere

1.4.1 Concept of Stability

When someone pushes you on a swing, do you keep going in the same direction or do you swing back the other way? If it wasn't a really strong push, you come back. That's because a swing set is a stable system. That means if you don't do anything after you get pushed then you will return to

where you started. If the swing set was unstable then you would keep going with just a little push and not end up where you started.

One of the processes that are connected to vertical motions in the atmosphere is **stability.** It describes the tendency for the atmosphere to either resist or enhance vertical motions.

The stability of air in the atmosphere depends on the temperature of rising air relative to the temperature of the stationary surrounding air that it passes through, which varies from place to place and with changing atmospheric conditions.

The **environmental lapse rate** (the actual rate at which temperature drops with height), is not usually equal to the **adiabatic lapse rate** (or correspondingly). If the upper air is warmer than predicted by the adiabatic lapse rate, then when a parcel of air rises and expands, it will arrive at the new height at a lower temperature than its surroundings. In this case, the air parcel is denser than its surroundings, so it sinks back to its original height, and the air is stable against being lifted. If, on the contrary, the upper air is cooler than predicted by the adiabatic lapse rate, then when the air parcel rises to its new height it will have a higher temperature and a lower density than its surroundings, and will continue to accelerate upward.

1.4.2 Adiabatic Lapse Rate

The rate at which rising air cools can be determined from a scientific term called the 1st Law of Thermodynamics, which describes the relationship between temperature and pressure changes.

When a parcel of air rises, it expands, because the pressure is lower at higher altitudes. As the air parcel expands, it pushes on the air around it, doing work; but generally it does not gain heat in exchange from its environment, because its thermal conductivity is low. Such a process is called **adiabatic**, though the actual process of air parcel is not exactly an adiabatic rising.

Since the parcel does work and gains no heat, it loses energy, and so its temperature decreases. The reverse, of course, will be true for a sinking parcel of air.

The temperature of the troposphere generally decreases as altitude increases. The rate, at which the temperature decreases, $\gamma = -\frac{dT}{dZ}$ is called the lapse rate.

For dry air, which is approximately an ideal gas, the rate at which temperature decreases with height under such conditions is called the Adiabatic Lapse Rate. The word "dry" means the air is unsaturated. The dry adiabatic lapse rate γ_d is about 10 ℃/km.

As condensation causes a release of latent heat, the expansion of the air will induce a cooling effect, but this will be partially offset by heat release from the condensation of water. As a result, the rate of temperature change of rising air that is saturated is smaller than for dry air. This is called the Moist Adiabatic Lapse Rate, and it is not a constant value. This is because the rate of condensation changes with height. The moist rate varies between 4 and 9 ℃/km. It is reasonable for us to assume an "average" value of about 5 or 6 ℃/km.

1.4.3 Equilibrium of Stability

For a given air parcel, to determine the environmental stability, one must calculate the lapse rate for a sounding (γ).

The stability criteria:

$$\begin{aligned} &\gamma < \gamma_m \quad \text{absolute stable} \\ &\gamma_m < \gamma < \gamma_d \quad \text{conditional unstable} \\ &\gamma > \gamma_d \quad \text{absolute unstable} \end{aligned} \tag{1.4.1}$$

Under normal atmospheric conditions natural air is unsaturated to begin with, but becomes saturated if lifted high enough. If the lapse rate for a column of natural air lies between the dry adiabatic lapse rate and the saturation adiabatic lapse rate, the air may be stable or unstable, depending upon the distribution of moisture.

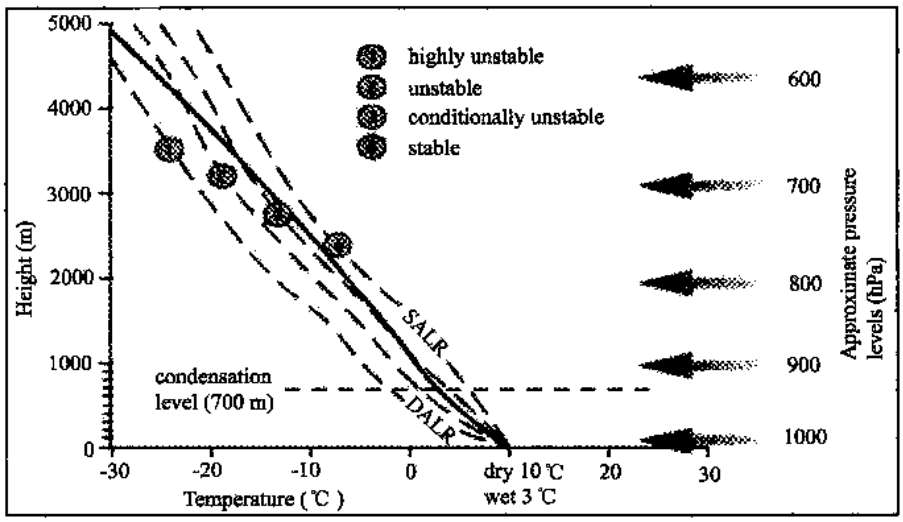


Figure 1.8 Air Stability

Note: ELR (Environmental Lapse Rate); DALR (Dry Adiabatic Lapse Rate); SALR (Saturated Adiabatic Lapse Rate)

1.4.4 Stability and Weather

The atmosphere can be either stable or unstable. If it's unstable then clouds can form. If it's really unstable then a lot of clouds can form and turn into a storm and then begin to rain.

Air stability determines whether clouds form when air is uplifted, and the types of cloud and weather.

As uplifted air cools, it condenses excess vapor out as cloud. The more unstable the atmosphere, the more prolonged the uplift. Small cumulus clouds are evidence of a fairly stable atmosphere. Large cumulonimbus clouds are evidence of a highly unstable atmosphere, conducive to the formation of thunderstorms.

Within depressions, atmospheric pressure is low and there is considerable atmospheric uplift and cooling at altitude, increasing atmospheric instability. Low-pressure systems are usually associated with an abundance of cloud and precipitation.

In high-pressure systems or anticyclones, air may be descending, compressing and gaining energy, such that temperature at altitude rises, thereby increasing atmospheric stability. Anticyclones are often associated with cloudless skies.

1.5 Air Humidity

1.5.1 Characteristics of Vapor in the Atmosphere

Water vapor (also *aqueous vapor*) is the gas phase of water. Water vapor is one state of water within the hydrosphere. Water vapor can be produced from the evaporation or boiling of liquid water or from the sublimation of ice. Under typical atmospheric conditions, water vapor is continuously generated by evaporation and removed by condensation.

Water vapor is a greenhouse gas along with other gases such as carbon dioxide and methane.

Water vapor is constantly cycling through the atmosphere, evaporating from the surface, condensing to form clouds blown by the winds, and subsequently returning to the Earth as precipitation. Heat from the Sun is used to evaporate water, and this heat is put into the air when the water condenses into clouds and precipitates. This evaporation-condensation cycle is an important mechanism for transferring heat energy from the Earth's surface to its atmosphere and in moving heat around the Earth.

Whenever a water molecule leaves a surface, it is said to have evaporated.

Another form of evaporation is sublimation, by which water molecules become gaseous directly from ice without first becoming liquid water. Sublimation accounts for the slow mid-winter disappearance of ice and snow at temperatures too low to cause melting.

Water vapor will only condense onto another surface when that surface is cooler than the dew point temperature, or when the water vapor equilibrium in air has been exceeded.

In the atmosphere, condensation produces clouds, fog and precipitation.

Deposition, the direct formation of ice from water vapor, is a type of condensation. Frost and snow are examples of deposition.

At the same temperature, a column of dry air will be denser or heavier than a column of air containing any water vapor. Thus, any volume of dry air will sink if placed in a larger volume of moist air.

Also, a volume of moist air will rise or be buoyant if placed in a larger region of dry air. As the temperature rises, the proportion water vapor in the air will increase, its buoyancy will become larger.

This increase in buoyancy can have a significant atmospheric impact, giving rise to powerful, moisture rich, upward air currents when the air temperature and sea temperature reaches 25 °C or above. This phenomenon provides a significant motivating force for cyclonic and anticyclonic weather systems (tornadoes and hurricanes).

1.5.2 Description of Air Humidity

Humidity is the amount of water vapor in the air, and it can be expressed by several different methods.

Absolute Humidity (a): The mass of water vapor present per unit volume of space, usually expressed in grams per cubic meter, is known as absolute humidity. It may be thought of as the density of the water vapor.

Vapor Pressure (e): The partial pressure of a given sample of moist air that is attributable to the water vapor is called the vapor pressure.

The vapor pressure necessary to saturate the air is the **saturation vapor pressure** (E). Its value depends mainly on the temperature of the air. Saturation vapor pressure increases rapidly with temperature: the value at 90 °F (32 °C) is about double the value at 70 °F (21 °C).

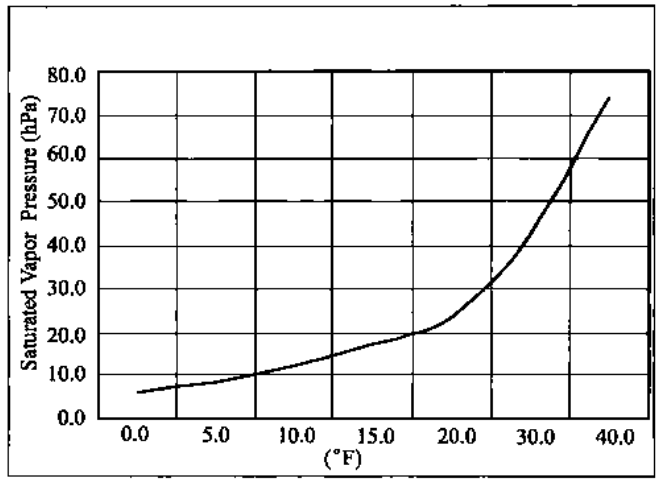


Figure 1.9 Saturation Vapor Pressure Increases Rapidly with Temperature

Relative Humidity (f): The ratio (in percent) between the observed vapor pressure to that required for saturation at the same temperature and pressure, expressed as:

$$f = \frac{e}{E} \times 100\% \qquad (1.5.1)$$

Although the major portion of the atmosphere is not saturated, for weather analysis it is desirable to be able to say how near it is to being saturated. This relationship is expressed as relative humidity.

When the air contains all of the water vapor possible for it to hold at its temperature, the relative humidity is 100 percent.

Relative humidity shows the degree of saturation, but it gives no clue to the actual amount of water vapor in the air.

Dew Point Temperature (T_d): The temperature the air would have if it was cooled, at constant pressure and water vapor content, until saturation (or condensation) occurred.

Because of the temperature dependence of the saturation vapor pressure, for a given value of relative humidity, warmer air has more water vapor than cooler air. The warmer the air is, the more water vapor it can "hold". Dew point is a measure of how much water vapor there is actually in the air.

The difference between the actual temperature and the dew point is called the **dew point depression.**

The dew point is associated with relative humidity. A high relative humidity indicates that the dew point is close to the current air temperature. Relative humidity of 100% indicates the dew point

is equal to the current temperature and the air is saturated with water. When the dew point remains constant and temperature increases, relative humidity will decrease.

1.5.3 Variations of Absolute Humidity

The actual amount of moisture in air will vary from one air mass to another. Even within an air mass there will be continuing variations in time and space.

The moisture contents of air masses are related to their regions of origin. Air masses originating in continental areas are relatively dry and those coming from large bodies of water, such as the Atlantic or the Gulf of Mexico are moist. Those from the Pacific are moist or moderately moist. When these maritime air masses enter continents, land stations will observe abrupt rises in absolute humidity. When any air mass traverses areas different from its source region, gradual changes take place as evaporation, transpiration, condensation, and precipitation add or subtract moisture.

If we consider only a very shallow layer of air near the surface, we find that the vertical variation of absolute humidity with height will change during each 24-hour period as conditions favoring evaporation alternate with conditions favoring condensation. During clear days, moisture is usually added to the air by evaporation from warm surfaces; therefore, the absolute humidity decreases upwards.

At night, moisture is usually taken from the air near the surface by condensation on cold surfaces and absorption by cold soil and other substances; thus, the absolute humidity may increase upward through a very shallow layer.

1.5.4 Variations of Relative Humidity

A typical fair-weather pattern of relative humidity is nearly a mirror image of the temperature pattern. Maximum humidity generally occurs about daybreak, at the time of minimum temperature. After sunrise, humidity drops rapidly and reaches a minimum at about the time of maximum temperature. It rises more gradually from late afternoon through the night. The daily range of humidity is usually greatest when the daily range of temperature is greatest. Variations in the humidity within an air mass from one day to the next are usually small, reflecting mostly differences in temperatures. But over several days, there may be noticeable cumulative differences in humidity as the air mass gradually picks up or loses moisture.

Seasonal changes in relative humidity patterns are also apparent. In monsoon areas, there is a moist summer and a dry winter, and the seasonal change is particularly noticeable. In the inland dry areas, the relative humidity reaches a maximum in the winter and falls to a minimum in the summer.

1.6 Wind

1.6.1 Definition and Description of Wind

Wind is the flow of gases on a large scale, and **wind direction** is reported by the direction from which it originates.

Sustained wind speeds are reported globally at a 10 metres (33 ft) height and are averaged over a 10-minute time frame.

The United States reports winds over a 1-minute average, while China typically reports winds

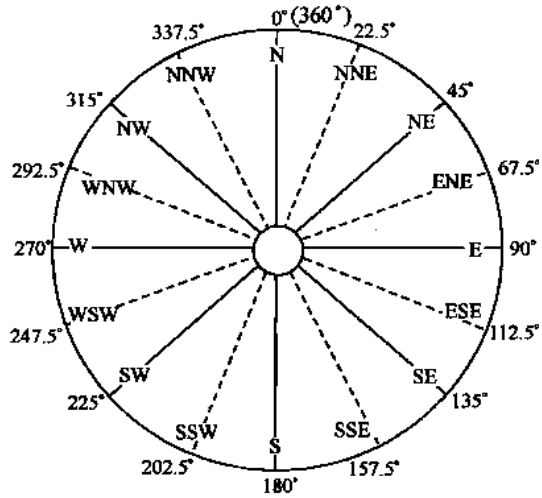


Figure 1.10 Wind Directions

over a 2-minute average, and India uses a 3-minute average.

Knowing the wind sampling average is important, as the value of a one-minute sustained wind is typically 14 percent greater than a ten-minute sustained wind.

A short burst of high-speed wind is termed a wind gust.

Strong winds of intermediate duration (around one minute) are termed squalls. Long-duration winds have various names associated with their average strength, such as breeze, gale, storm, hurricane, and typhoon.

Wind occurs on a range of scales, from thunderstorm flows lasting tens of minutes, to local breezes generated by heating of land surfaces and lasting a few hours, to global winds resulting from the difference in absorption of solar energy between the climate zones on Earth.

The two main causes of large scale atmospheric circulation are the differential heating between the equator and the poles, and the rotation of the planet (Coriolis Effect).

Within the tropics, thermal low circulations over terrain and high plateaus can drive monsoon circulations. In coastal areas the sea breeze / land breeze cycle can define local winds; in areas that have variable terrain, mountain and valley breezes can dominate local winds.

The exchanges between different units are as follows:

1 m/s = 3.6 km/h 1 kn = 1.852 km/h 1 km/h = 0.28 m/s 1 kn ≈ 0.5 m/s (1.6.1)

1.6.2 The Beaufort Scale of Wind Force

Historically, the **Beaufort wind force scale** provides an empirical description of wind speed based on observed sea conditions.

Originally it was a 13-level scale, but during the 1940s, the scale was expanded to 17 levels.

There are general terms that differentiate winds of different average speeds such as a breeze, a gale, a storm, tornado, or a hurricane.

Within the Beaufort scale, gale-force winds lie between 28 knots (52 km/h) and 47 knots (88 km/h) with adjectives such as moderate, fresh, strong, and whole used to differentiate the wind's

strength within the gale category.

A storm has winds of 48 knots (89 km/h) to 63 knots (117 km/h).

Globally terminology for tropical cyclones differs from one region to another globally. Most ocean basins use the average wind speed to determine the tropical cyclone's category.

Below is a summary of the classifications used by regional specialized meteorological centers worldwide:

Table 1.3 The Beaufort Scale

Beaufort scale		Average wind speed (knots)	Average wind speed (km/h)	Estimating speed over land	Estimating speed over water
0	Calm	Less than 1	Less than 1	Calm, smoke rises vertically	Sea is as flat as a mirror
1	Light Air	1 – 3	1 – 5	Direction of wind shown by smoke drift, but not by wind vanes	Ripples with the appearance of scales are formed, but without foam crests
2	Light Breeze	4 – 6	6 – 11	Wind felt on face; leaves rustle; ordinary wind vane moved by wind	Small wavelets, still short, but more pronounced; crests have a glassy appearance and do not break
3	Gentle Breeze	7 – 10	12 – 19	Leaves and small twigs in constant motion; wind extends light flag	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses
4	Moderate Breeze	11 – 16	20 – 28	Raises dust and loose paper; small branches moved	Small waves, becoming longer; fairly frequent white horses
5	Fresh Breeze	17 – 21	29 – 38	Small trees in leaf begin to sway; crested wavelets form on inland waters	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray)
6	Strong Breeze	22 – 27	39 – 49	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray)
7	Near Gale	28 – 33	50 – 61	Whole trees in motion; inconvenience felt when walking against the wind.	Sea heaps up and white foam from breaking waves begins to be blown in streaks in the direction of the wind
8	Gale	34 – 40	62 – 74	Breaks twigs off trees; generally impedes progress	Moderately high waves of greater length; edges of crests begin to break into the spindrift; the foam is blown in well-marked streaks in the direction of the wind
9	Strong Gale	41 – 47	75 – 88	Slight structural damage occurs (chimney pots and slates removed)	High waves; dense streaks of foam in the direction of the wind; crests of waves begin to topple, tumble and roll over; spray may affect visibility

Beaufort scale		Average wind speed (knots)	Average wind speed (km/h)	Estimating speed over land	Estimating speed over water
10	Storm	48 – 55	89 – 102	Seldom experienced inland; trees uprooted; considerable structural damage occurs	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of the sea takes a white appearance; the tumbling of the sea becomes heavy and shock-like; visibility is affected
11	Violent Storm	56 – 63	103 – 117	Very rarely experienced; accompanied by widespread damage	Exceptionally high waves (small and medium sized ships might be for a time lost to view behind the waves); the sea is completely covered with long white patches of foam lying in the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility is affected
12	Hurricane	64 and over	118 and over	Severe and extensive damage.	The air is filled with foam and spray; the sea is completely white with driving spray; visibility is very seriously affected

1.6.3 Geostrophic Wind and Gradient Wind

Wind is caused by differences in air pressure. When a difference in pressure exists, the air is accelerated from a higher to a lower pressure. The stronger the pressure difference, or pressure gradient, between a high-pressure system and a low-pressure system is, the stronger the wind is. This is expressed as:

$$| \vec{G}_n | = -\frac{1}{\rho} \cdot \frac{\Delta p}{\Delta n} \qquad (1.6.2)$$

On a rotating planet the air will be deflected by the **Coriolis Effect**, except exactly on the equator.

The Coriolis Effect is caused by the Earth's rotation. The deflection is to the right in the northern hemisphere and to the left in the Southern Hemisphere. This is expressed as:

$$| \vec{A}_n | = 2v\omega\sin\varphi \qquad (1.6.3)$$

The **Geostrophic wind** is the theoretical wind that would result from an exact balance between the Coriolis Effect and the pressure gradient force. It flows parallel to isobars and approximates the flow above the atmospheric boundary layer in the mid-latitudes.

Air naturally moves from areas of high pressure to areas of low pressure, due to the pressure gradient force. However, as soon as the air starts to move, the Coriolis "force" deflects it.

When the air moves from the high pressure area, its speed increases, and so does its Coriolis deflection. The deflection increases until the Coriolis and pressure gradient forces are in **geostrophic balance**: this point, the air flow is no longer moving from high to low pressure, but instead moves along an isobar.

This balance seldom holds exactly in nature. The true wind almost always differs from the geostrophic wind due to other forces such as friction from the ground or the centrifugal force from curved fluid flow. Thus, the actual wind would equal the geostrophic wind only if there was no friction and the isobars were perfectly straight. Despite this, much of the atmosphere outside the tropics and aloft from frictional effects of the surface, the large-scale winds tend to approach geostrophic balance and is close to geostrophic flow much of the time.

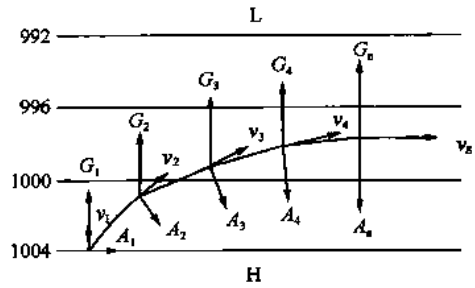


Figure 1.11 The Formation of Geostrophic Wind in the Northern Hemisphere

Assuming geostrophic balance, the geostrophic wind components on a constant-pressure surface can be derived as $\vec{v}_g$

From:

$$| \vec{G}_n | = | \vec{A}_n | \tag{1.6.4}$$

we can get:

$$-\frac{1}{\rho} \cdot \frac{\Delta p}{\Delta n} = 2 v_g \omega \sin\varphi \tag{1.6.5}$$

consequently:

$$v_g = -\frac{1}{2\rho\omega\sin\varphi} \cdot \frac{\Delta p}{\Delta n} \tag{1.6.6}$$

This formula is invalid at the equator, because $\sin\varphi$ is equal to zero there and therefore generally not used in the tropics.

Therefore, the speed of a geostrophic wind can be calculated from the pressure gradient, air density, rotational velocity of the earth, and latitude. The calculation ignores the curvature of the wind's path. A geostrophic wind is proportional to the pressure gradient or inversely proportional to the distance between the isobars. It is also inversely proportional to the density of the air and the $\sin\varphi$.

The **gradient wind** is not only similar to the geostrophic wind, but also includes centrifugal force.

Gradient flow is an extension of geostrophic flow as it accounts for curvature too, making this a more accurate approximation for the flow in the upper atmosphere.

Gradient flow is useful in studying atmospheric flow rotating around high and low pressures centers. This is the case where the radius of curvature of the flow about the pressure centers is small, and geostrophic flow no longer applies with a useful degree of accuracy.

However, mathematically gradient flow is slightly more complex, and geostrophic flow may be fairly accurate, so the gradient approximation is not as frequently used.

The gradient flow helps to explain why, in the Northern Hemisphere, low pressure systems spin counterclockwise and high pressure systems spin clockwise, and is opposite in the Southern Hemisphere.

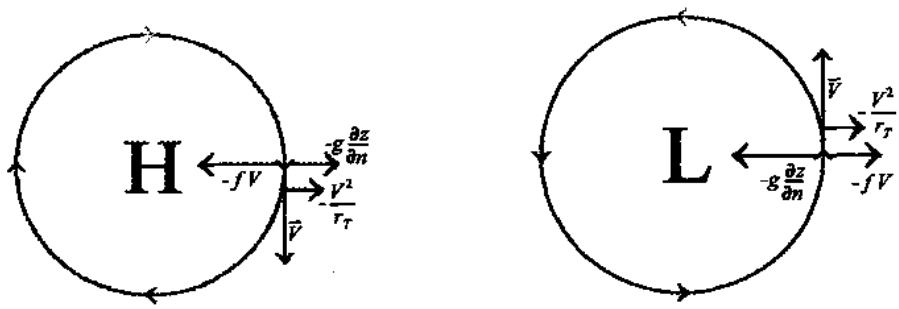


Figure 1.12(a) Gradient Wind in the Northern Hemisphere

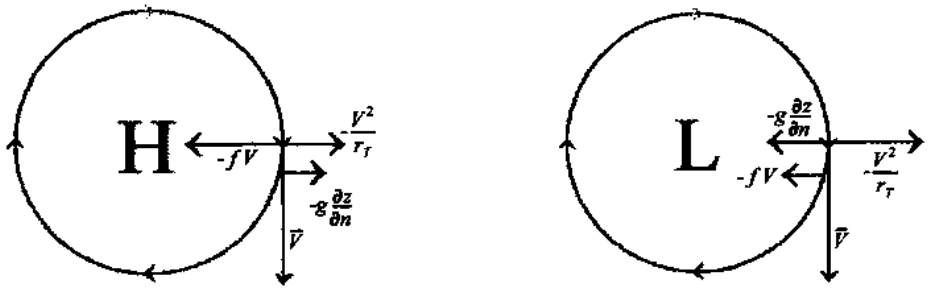


Figure 1.12(b) Gradient Wind in the Southern Hemisphere

1.6.4 Buys Ballot's Law

In meteorology, **Buys Ballot's Law** may be expressed as follows: In the Northern Hemisphere, stand with your back to the wind; the low pressure area will be on your left. This is because wind travels counterclockwise around low pressure zones in the Northern Hemisphere. It is reverse in the Southern Hemisphere.

1.6.5 The Effect of Friction

Surface winds on a weather map do not blow exactly parallel to the isobars as in geostrophic and gradient winds. Instead, surface winds tend to cross the isobars at an angle varying from 10° to 45°. At sea the angle is 10° to 20° and on land the angle is 35° to 45°. Close to the Earth's surface, friction reduces the wind speed, which in turn reduces the Coriolis Effect. As a result, the reduced Coriolis effect no longer balances the pressure gradient force, and the wind blows across the isobars toward or away from the pressure center. The pressure gradient force is now balanced by the sum of the frictional force and the Coriolis Effect. Thus in the Northern Hemisphere, we find surface winds blowing counterclockwise and inward into a surface low, and clockwise and out of a surface high. In the Southern Hemisphere, the Coriolis Effect acts to the left rather than the right. This causes the winds of the Southern Hemisphere to blow clockwise and inward around surface lows, and counterclockwise and outward around surface highs.

Surface wind speed is lower than that of the geostrophic wind due to the friction. Generally wind above the land (at the level of 10 – 12 m) is regarded as 1/3 ~ 1/2 of the corresponding geostrophic wind speed, and the ratio is 3/5 ~ 2/3 at sea. We can estimate the surface wind speed at sea with the following formula:

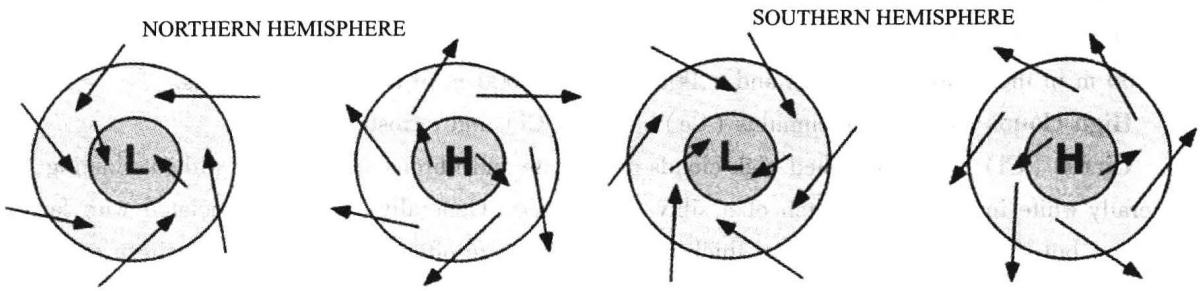


Figure 1.13 Circulation Patterns of High and Low Pressure Systems in the Northern and Southern Hemisphere

$$v_0 = v_g \times 65\% \tag{1.6.7}$$

An observer aboard a vessel proceeding through still air experiences an apparent wind which is from dead ahead and has an apparent speed equal to the speed of the vessel.

Thus, if the actual or true wind is zero and the speed of the vessel is 10 knots, the apparent wind is from dead ahead at 10 knots. If the true wind is from dead ahead at 15 knots, and the speed of the vessel is 10 knots, the apparent wind is 15 + 10 = 25 knots from dead ahead. If the vessel reverses course, the apparent wind is 15 − 10 = 5 knots, from dead astern.

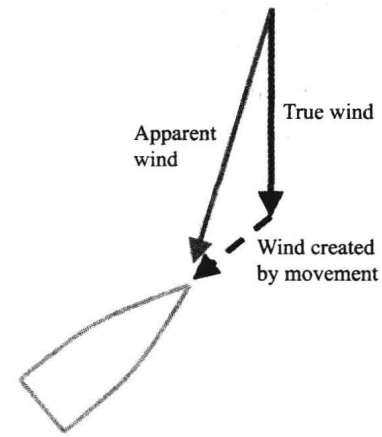


Figure1.14 True Wind and Apparent Wind

The apparent wind $\vec{v}_A$ is the vector sum of the true wind $\vec{v}_T$ and the vessel's course and speed vector $\vec{v}_S$. This is expressed as:

$$\vec{v}_A = \vec{v}_T + \vec{v}_S \tag{1.6.8}$$

Since wind vanes and anemometers measure apparent wind, the usual problem aboard a vessel equipped with an anemometer is to convert apparent wind to true wind.

1.7 Clouds and Precipitation

1.7.1 The Formation of Clouds

A cloud is a visible mass of little drops of water or frozen crystals suspended in the atmosphere above the surface of the Earth.

On Earth the condensing substance is typically water vapor, which forms small droplets or ice crystals, typically 0.01 mm in diameter. When surrounded by billions of other droplets or crystals they become visible as clouds.

1.7.2 The International Classification of Clouds

Cloud types are divided into two general categories: layered and convective. These names distinguish a cloud's altitude. Clouds are classified by the base height, not the cloud top, and bases

may differ depending upon the geographical zone.

High clouds will form between 3,000 m and 8,000 m in the polar regions, 5,000 m and 12,000 m in the temperate regions and 6,000 m and 18,000 m in the tropical regions.

High clouds include cirrocumulus (Cc), cirrus (Ci) and cirrostratus (Cs).

Cirrus (Ci) – are detached high clouds of delicate and fibrous appearance, without shading, generally white in color, and often of a silky appearance. Generally they are associated with fair weather, but if followed by lower and thicker clouds, they are often the forerunner of rain or snow.

Cirrocumulus (Cc) – are high clouds composed of small white flakes or scales, or of very small globular masses; usually without shadows and arranged in groups of lines, or more often in ripples resembling sand on the seashore. Generally they are associated with fair weather, but may precede a storm if they become thicken and lower.

Cirrostratus (Cs) – thin, whitish, high clouds sometimes covering the sky completely and giving it a milky appearance, and at other times presenting a formation like a tangled web.

The ice crystals of which the cloud is composed **refract** the light passing through to form **halos** with the sun or moon at the center.

If it continues to thicken and lower, the ice crystals melt to form water droplets, the cloud formation is known as ***altostratus***. When this occurs, rain may normally be expected within 24 hours.

Middle clouds tend to form at 2,000 m, but may form at heights up to 4,000 m, 7,000 m or 8,000 m depending on the region.

Middle clouds include altostratus (As) and altocumulus (Ac).

Nimbostratus clouds are sometimes included with the middle clouds.

Altostratus (As) – middle clouds have the appearance of a grayish or bluish. fibrous veil or sheet. The sun or moon, when seen through these clouds, appears as if it were shining through ground glass, with a *corona* around it. Halos are not formed.

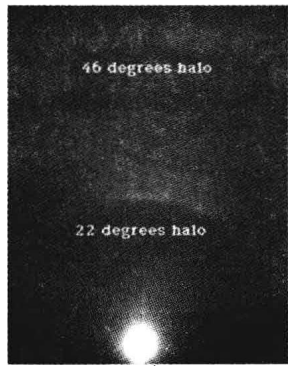


Figure 1.15.a Halo

Figure 1.15.b Corona

Altocumulus (Ac) – middle level clouds consisting of a layer of large, ball-like masses that tend to merge. They together may appear as distinct patches similar to Cc, but can be distinguished by having *individual* patches which are generally larger, showing distinct shadows in some places.

If Ac thickens and lowers, it may produce thundery weather and showers; but it does not bring

prolonged bad weather.

Low clouds are found up to 2,000 m and include the stratus (dense and grey). When stratus clouds contact the ground, they are called fog.

Vertical clouds can have strong up-currents, rise far above their bases, and form at many heights.

Vertical clouds are also refer red to as low clouds. Low clouds include Stratocumulus (Sc), nimbostratus (Ns), stratus (St), cumulonimbus (associated with heavy precipitation and thunderstorms) (Cb) and cumulus (Cu).

Stratocumulus (Sc) – low clouds appearing as soft, gray, roll-shaped masses. They may be shaped in long, parallel rolls similar to altocumulus, moving forward with the wind.

Stratus (St) – a low cloud in a uniform layer resembling fog.

Nimbostratus (Ns) – a low, dark, shapeless cloud layer, usually nearly uniform, but sometimes with ragged, wet-looking bases.

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

Figure 1.16 Cumulus and Cumulonimbus

Cumulus (Cu) – dense clouds with **vertical development have** a horizontal base and a dome-shaped upper surface, with protuberances extending above the dome. They appear in small patches, and never cover the entire sky.

It is called "fair weather" cumulus because they commonly accompany good weather. However, they may merge with Ac, or may grow to Cb before a thunderstorm.

Cumulonimbus (Cb) – a massive cloud with great vertical development. The upper part spreads out in the shape of an anvil which may be seen at such distances that the base may be below the horizon.

It often produces showers of rain, snow, or hail, frequently accompanied by lightning and thunder. The cloud is often popularly called a "thundercloud" or "thunderhead".

Table 1.4 International Cloud Classification

Clouds	Base Height (m)	Genera			Species	
		Chinese	International	Abbrev.	Chinese terms	Abbrev.
High Clouds	>5000	卷云	Cirrus	Ci	毛卷云	Ci fil
					密卷云	Ci dens
					伪卷云	Ci not
					钩卷云	Ci unc
		卷层云	Cirrostratus	Cs	薄幕卷层云	Cs nebu
					毛卷层云	Cs fil
		卷积云	Cirrocumulus	Cc	卷积云	Cc
Middle Clouds	2500~5000	高层云	Altostratus	As	透光高层云	As tra
					蔽光高层云	As op
		高积云	Altocumulus	Ac	透光高积云	Ac tra
					蔽光高积云	Ac op
					荚状高积云	Ac lent
					积云性高积云	Ac cug
					絮状高积云	Ac flo
					堡状高积云	Ac cast
Low Clouds	<2500	层积云	Stratocumulus	Sc	透光层积云	Sc tra
					蔽光层积云	Sc op
					积云性层积云	Sc cug
					堡状层积云	Sc cast
					荚状层积云	Sc lent
		层云	Stratus	St	层云	St
					碎层云	Fs
		雨层云	Nimbostratus	Ns	雨层云	Ns
					碎雨云	Fn
		积云	Cumulus	Cu	淡积云	Cu hum
					碎积云	Fc
					浓积云	Cu cong
		积雨云	Cumulonimbus	Cb	秃积雨云	Cb calv
					鬃积雨云	Cb cap

1.7.3 Cloud Cover

Cloud cover (also known as cloudiness, cloudage or cloud amount) refers to the fraction of the sky obscured by clouds when observed from a particular location.

Clear: blue sky to 3/10 of the sky.

Cloudy: 4/10 to 7/10 of the sky.

Overcast: more than 8/10 of the sky.

1.7.4 Types of Precipitation

In meteorology, **precipitation** is any product of the condensation of atmospheric water vapor that is pulled down by gravity and deposited on the Earth's surface.

Precipitation that reaches the surface of the Earth can occur in many different forms, including **Rain, freezing rain, drizzle, ice needles, snow, ice pellets or sleet, graupel, and hail.**

Precipitation can be divided into three categories, based on whether it falls as **liquid water**, liquid water that **freezes** on contact with the surface, or **ice.**

Mixtures of different types of precipitation, including types in different categories, can fall simultaneously.

Liquid forms of precipitation include rain and drizzle.

Rain or drizzle that freezes on contact within a subfreezing air mass is called "freezing rain" or "freezing drizzle".

Frozen forms of precipitation include snow, ice needles, ice pellets, hail, and graupel.

Rain is liquid precipitation, as opposed to other kinds of precipitation such as snow, hail and sleet.

Rain requires the presence of a thick layer of the atmosphere to have temperatures above the melting point of water near and above the Earth's surface.

Hail is formed within cumulonimbus clouds when strong updrafts of air cause the stones to cycle back and forth through the cloud, causing the hailstone to form in layers, until it becomes heavy enough to fall from the cloud.

Hail can occur during much warmer temperature region due to the process of its formation.

Drizzle (also called mizzle) is a light rain precipitation consisting of liquid water drops smaller than those of rain, and generally smaller than 0.5 mm in diameter. Drizzle is normally produced by low stratiform clouds and stratocumulus clouds. Owing to the small size of drizzle drops, under many circumstances drizzle largely evaporates before reaching the surface, and so may be undetected by observers on the ground.

Freezing rain is the name given to rain that falls when surface temperatures are below freezing. The raindrops become super cooled while passing through a sub-freezing layer of air, many hundred meters, just above the surface, and then freeze upon impact with any object they encounter. The resulting ice, called glaze, can accumulate to a thickness of several centimeters.

Snow is a type of precipitation within the Earth's atmosphere in the form of crystalline water ice, consisting of a multitude of snowflakes that fall from clouds. Since snow is composed of small ice particles, it is a granular material. It has an open and therefore soft structure, unless packed by external pressure.

Snowflakes come in a variety of sizes and shapes. Types which fall in the form of a ball due to melting and refreezing, rather than a flake, are known as graupel. Ice pellets and snow grains are examples of graupel.

Snowfall amount and its related liquid equivalent precipitation amount are determined using a variety of different rain gauges.

In China, precipitation can also be divided into steady, intermittent, and showery types according to the manner of their occurrence.

1.7.5 Intensity of Precipitation

Rainfall is measured through the use of rain gauges.

Rainfall intensity is classified according to the rate of precipitation.

Table 1.5 International Intensity Classes of Rainfall

Rainfall Intensity	Light Rain	Moderate Rain	Heavy Rain	Violent Rain
Precipitation Rate per Hour (mm/hr)	< 2.5	2.5 ~ 10	10 ~ 50	> 50

In China, the intensity of precipitation is classified according to the amount of precipitation of each day (00UTC-00UTC).

Table 1.6.1 Chinese Intensity Classes of Rainfall

Class	Occasional Drizzles	Little Rain	Moderate Rain	Heavy Rain	Rainstorm	Heavy Rainstorm	Very Heavy Rainstorm	Rain Shower
中文名称	零星小雨	小雨	中雨	大雨	暴雨	大暴雨	特大暴雨	阵雨
Precipitation of 24 h (mm)	<0.1	0.1 ~9.9	10.0 ~24.9	25.0 ~49.9	50.0 ~99.9	100.0 ~199.9	≥200.0	Accumulating rain duration less than 5 h in 12 h; Precipitation amount ≤15 mm

Table 1.6.2 Chinese Intensity Classes of Snowfall

Class	Occasional Snow	Little Snow	Middle Snow	Heavy Snow	Snow Storm	Snow Shower
中文名称	零星小雪	小雪	中雪	大雪	暴雪	阵雪
Precipitation of 24 h (mm)	<0.1	0.1 ~2.4	2.5 ~4.9	5.0 ~9.9	≥10.0	Accumulating snow duration less than 5 h in 12 h; Precipitation amount ≤3 mm

The relation between snow depth and amount of snowfall in China is about 8 – 10 mm to 1 mm in Northern China and 6 – 8 mm to 1 mm in Southern China.

The globally-averaged annual precipitation is 990 millimeters.

1.8 Visibility and Fog

1.8.1 Definition and Classification of Visibility

In meteorology, **visibility** is a measure of the distance at which an object or light can be clearly discerned.

It is reported within surface weather observations either in kilometers or miles, depending upon the country, and nautical miles for on board observation. Visibility affects all forms of traffic: roads, sailing, and aviation.

Meteorological visibility refers to transparency of air: in dark, meteorological visibility is still the same as in daylight for the same air.

In extremely clean air in Arctic or mountainous areas, the visibility can be up to 70 kilometers to 100 kilometers. However, visibility is often reduced somewhat by air pollution and high humidity. Various weather stations report this as haze (dry) or mist (moist).

Fog and smoke can reduce visibility to near zero, making driving extremely dangerous. The same can happen in a sandstorm in and near desert areas, or with forest fires. Heavy rain (such as from a thunderstorm), blizzards and ground blizzards (blowing snow) are also defined in part by low visibility.

Table 1.7 Classes of Visibility

Class	Visible Distance		Visibility	Possible Weather Phenomenon
	n mile	km		
0	<0.03	<0.05	Bad	Strong dense fog
1	0.03 ~ 0.10	0.05 ~ 0.2		Dense fog or snow storm
2	0.10 ~ 0.25	0.2 ~ 0.5		Heavy fog or heavy snow
3	0.25 ~ 0.50	0.5 ~ 1	Poor	Fog or moderate snow
4	0.50 ~ 1.00	1 ~ 2		Mist or rain storm
5	1 ~ 2	2 ~ 4	Moderate	Light snow, heavy rain, mist
6	2 ~ 5	4 ~ 10		Moderate rain, light snow, mist
7	5 ~ 11	10 ~ 20	Good	Light rain, drizzle
8	11 ~ 27	20 ~ 50	Very good	No precipitation
9	≥27	≥50	Excellent	Clear air

1.8.2 Definition and Classification of Fog

Fog is a cloud that is in contact with the ground.

A cloud may be considered partly fog; for example, the part of a cloud that is suspended in the air above the ground is not considered fog, whereas the part of the cloud that comes in contact with higher ground is considered fog.

Fog is distinguished from **mist** only by its density, as expressed in the resulting decrease in visibility. Fog reduces visibility to less than 1 km; whereas mist reduces visibility to no less than 1 km but less than 2 km.

The international definition of fog is a visibility of less than 1 kilometer; mist is a visibility of between 1 kilometer and 2 kilometers; and **haze** from 2 kilometers to 5 kilometers.

For aviation purposes in the UK, a visibility of less than 2 km but greater than 999 m is considered to be mist if the relative humidity is 95% or greater. Below 95% haze is reported.

Below is the definition published by the China Meteorological Center.

Table 1.8 Definition of Fog by China Meteorological Center

Name	Light Fog	Fog	Dense Fog	Very Dense Fog
中文名称	轻雾	雾	浓雾	强浓雾
Visible Distance (m)	10,000 ~ 1,000	1,000 ~ 500	500 ~ 50	<50

The foggiest place in the world is the Grand Banks off the island of Newfoundland, the meeting place of the cold Labrador Current from the north and the much warmer Gulf Stream from the south.

Fog forms when the difference between temperature and dew point is generally less than 2.5 °C.

Fog begins to form when water vapor condenses into tiny liquid water droplets in the air. Conversely, water vapor is formed by the evaporation of liquid water or by the sublimation of ice.

Since water vapor is colorless, it is actually the small liquid water droplets that are condensed from it that make water suspended in the atmosphere, visible in the form of fog or any other type of cloud.

Fog normally occurs at a relative humidity near 100%. This can be achieved by either adding

moisture to the air or dropping the ambient air temperature. Fog can form at lower humidities, and fog can sometimes not form with relative humidity at 100%.

Another common type of fog formation is sea fog (also known as hoar or fret). This is due to the peculiar effect of salt. Clouds of all types require minute hygroscopic particles upon which water vapor can condense. Over the ocean surface, the most common particles are salt from salt spray produced by breaking waves.

Except in areas of storminess, the most common areas of breaking waves are located near coastlines; hence the greatest densities of airborne salt particles are there. Condensation on salt particles has been observed to occur at humidities as low as 70%, thus fog can occur even in relatively dry air in suitable locations such as the California coast. Typically, such lower humidity fog is preceded by a transparent mistiness along the coastline as condensation competes with evaporation, a phenomenon that is typically noticeable by beachgoers in the afternoon.

Occasionally fog produces precipitation in the form of drizzle or very light snow. Drizzle occurs when the humidity of fog attains 100% and the minute cloud droplets begin to coalesce into larger droplets. This can occur when the fog layer is lifted and cooled sufficiently, or when it is forcibly compressed from above. Drizzle becomes freezing drizzle when the temperature at the surface drops below the freezing point.

Fog reduces visibility and thus contributes to accidents, particularly is transportation. Ships, trains, cars and planes cannot see each other and collide. Notable examples of accidents due to fog include the 25 July 1956 collision of the ocean liners the SS Andrea Doria and MS Stockholm, and more recently when the MV COSCO Busan struck the San Francisco-Oakland Bay Bridge (Nov. 7, 2007).

1.8.3 Main Types of Fog

Fog can form in a number of ways, depending on how the cooling that caused the condensation occurred.

Radiation fog is formed by the cooling of land after sunset by thermal radiation in calm conditions with a clear sky. The cool ground produces condensation in the nearby air by heat conduction. In perfect calm the fog layer can be less than a meter deep, but turbulence can promote a thicker layer. Radiation fogs occur at night, and usually does not last long after sunrise. Radiation fog is common in autumn and early winter.

Advection fog forms in the lower part of a warm moist air mass moving over a colder surface (land or water) by advection (wind) and is cooled. It is most common at sea when tropical air encounters cooler waters.

Precipitation fog (or ***frontal fog***) forms when precipitation falls into drier air below the cloud, the liquid droplets evaporate into water vapor. The water vapor cools and at the dew point it condenses and fog forms.

Steam fog, also called **sea smoke** or **evaporation fog**, is the most localized form and is created by cold air passing over much warmer water or moist land. It often causes freezing fog, or sometimes hoar frost.

1.9 Shipborne Observation and Shipborne Meteorological Instruments

1.9.1 Shipborne Observations

Surface weather observations are the fundamental data used for safety as well as climatological reasons to forecast weather and issue warnings worldwide. They can be taken manually, by a weather observer, by computer through the use of automated weather stations, or in a hybrid scheme using weather observers to augment the otherwise automated weather station.

For over a century. Reports from the world's oceans have been received real-time for safety reasons and to help with general weather forecasting. The reports are coded using the synoptic code, and relayed via radio or satellite to weather organizations worldwide.

Due to the importance of reports from the surface of the ocean, the Voluntary Observing Ship program, known as **VOS**, was set up to train crews in how to take weather observations while at sea and also to calibrate weather sensors used aboard ships when they arrive in port, such as barometers and thermometers.

All meteorological observations made at sea are recorded permanently in special logbooks for future use. Entries should be made in the logbooks neatly and legibly, preferably in black ball point pen.

Weather observations should be made anywhere on the oceans and seas of the world, even when within site of a coast, providing navigational duties will permit.

Weather observations at sea should be made four times a day as close as practicable to the standard synoptic hours of 0000, 0600, 1200, and 1800 UTC. Because the observations require some time to complete, they should be commenced a few minutes before these standard hours. The length of time required to make the observation will depend on the experience of the observer, but it should be arranged that all work is completed as close to the standard hour as possible, especially air pressure observation.

1.9.2 Code Used for the Transmission of Ships, Weather Messages

In order to reduce transmission time and costs, weather reports are coded in the World Meteorological Organization (WMO) FM 13 – X Ship Report of surface observations from a sea station. This code is made up of groups of five figures each. The position of numbers in a given group determines the element of weather which these numbers represent.

1.9.3 Non-Routine Reports

Special Weather Report (SPREP)

It is important that observed, significant changes in weather conditions be entered into the forecast system as soon as possible. Significant weather developments frequently occur between the standard times of observation, therefore it is important to identify those changes and relay special weather reports to the forecast office without delay. A special weather report is identified by the code word SPREP. The observation and message format is the same as for a standard observation, except the word SPREP and one space will immediately precede the ships call sign to assure the immediate attention of the forecaster. Example:SPREP D...D, YYGGiw etc.

A special weather report (SPREP) should be sent whenever one or more of the following criteria are met.

Wind

1. Mean wind speed doubles to 25 knots or more since the previous main or intermediate synoptic hour.

2. Mean wind speed increases to 34 knots (gale force) or more and gale warnings are not in effect.

3. Visibility Prevailing visibility decreases to 1/2 nautical miles or less from 2 nautical miles or more.

4. Waves Combined seas (wind, waves, and swell) become hazardous or increase to 2 ~ 3 meters (7 ~ 10 feet) or more in excess of those forecast.

5. Ice forms on the ship's superstructure.

Storm Reports

When storm (wind) conditions are encountered at sea, whether forecast or not, a storm report should be issued. The observation and the message format is the same as for a standard observation, except the word STORM and one space will immediately precede the ship's call sign. A storm report should be sent hourly if the storm has not been forecast, or at least every 3 hours if in storm conditions which have been forecast.

Example: STORM D...D YYGGiw etc.

Criteria: A storm report (STORM) should be sent whenever the mean wind speed increases to 48 knots or more.

Ship's observing officers are encouraged to send SPREPs and STORM reports even if the above conditions were forecast. These reports will aid marine forecasters in verifying their forecasts.

1.9.4 Visibility Measurement

Visibility is defined as the greatest distance at which a dark object of suitably large dimension can be seen and identified when observed against a background of sky or fog, or in the case of night observations, could be seen and identified if the general illumination were raised to the normal daylight level. It should be emphasized that the criterion of identifying an object should be used, and not merely seeing the object without recognizing what it is.

At land stations where there are almost always a number of objects or landscape features at known distances from the station can be used as visibility markers. On the high seas such markers are usually absent, making the estimation of visibility more difficult.

When the visibility is very low as in dense fog, it may not be possible to distinguish one end of the ship when standing at the other end. In this case objects on the ship itself can be used as markers. For the higher ranges the appearance of nearby ships if present, and a sufficient portion of their superstructures appear above the horizon, can be a useful guide.

When out of sight of land and other ships, the only visibility marker available is the horizon. The distance of the horizon can be found easily, Because under normal atmospheric conditions it depends only on the height above the sea surface from which it is observed.

Atmospheric conditions may be such that the visibility differs in various directions. Under such non-uniform conditions the maximum visibility common to one half or more of the horizon circle is reported. This is called prevailing visibility.

1.9.5 Wind Measurement

Wind measurement consists of determination of the direction and speed of the wind. Direction is measured by a wind vane, and speed by an anemometer. Several types of wind speed and direction sensors are available, using vanes to indicate wind direction and rotating cups or propellers for speed sensing. The mean direction and speed of the wind over the ten-minute period immediately preceding the observation is reported. If no anemometer is available, wind speed can be estimated by its effect upon the sea and nearby objects.

It is necessary to determine the true wind knowing the apparent wind and the ship's course and speed.

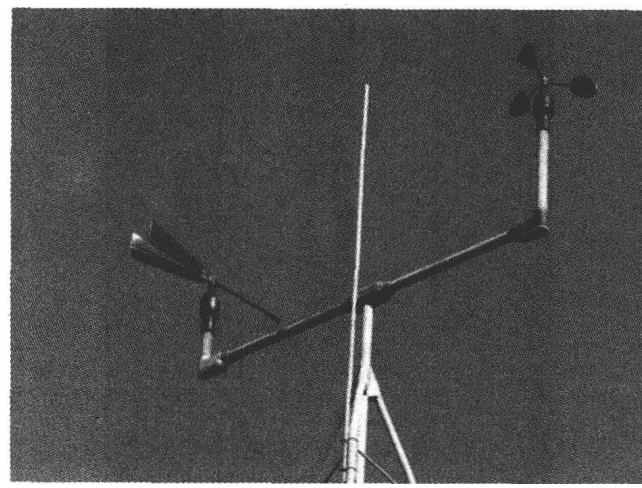


Figure 1.17 Wind Vane and Anemometer

1.9.6 Temperature Measurement

Many types of temperature measurement instruments are found in the science of meteorology, but only three kinds of measurements are involved in ships: the dry bulb temperature and the wet bulb temperature and the sea surface temperature.

The dry bulb temperature is a measure of the amount of heat in the air. The wet bulb temperature is a measure of the amount of moisture, in the form of invisible water vapor contained in the air. Air temperature is measured at a standard level of 1.5 m above the ground.

The wet bulb thermometer indicates a lower temperature than that of the dry bulb thermometer. The difference between the readings of the dry and the wet thermometers is called the depression of the wet bulb.

The dry bulb and wet bulb thermometers are mounted side by side in a specially designed marine screen, which should always be on the windward side of the ship so that the flow of air reaches it before passing over any other part of the ship. It should be located as far as possible from all sources of local heating that will tend to cause false air temperatures, particularly on days when the

relative wind is light. A position close to the bridge will avoid some of these heat sources.

Sea surface temperature observations are used in the forecasting of fog, and furnish important information about the development and movement of tropical cyclones.

There are several methods of determining seawater temperature. These include: engine room intake readings, condenser intake readings, thermistor probes attached to the hull, and readings from buckets recovered from over the side. Although the condenser intake method is not a true measure of surface water temperature, the error is generally small.

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

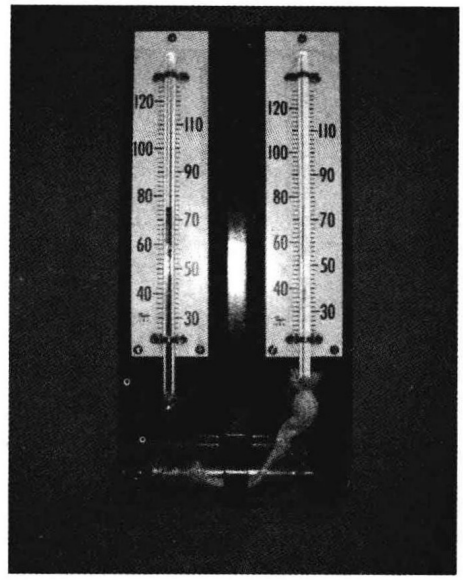


Figure 1.18 Dry Bulb and Wet Bulb Thermometers

1.9.7 Air Pressure Measurement

Mercury barometers are usually used by stations on land, while aneroid barometers are widely used on board. The principle by which the aneroid barometer functions is the balancing of atmospheric pressure by the elasticity of metal. The fundamental part of the instrument consists of a small circular capsule or bellows which has been partially exhausted of air and hermetically sealed. When the atmospheric pressure rises, the ends of the bellows are squeezed inwards under the increased pressure.

The standard pressure measuring instrument is the Belfort aneroid. It should always be mounted in a vertical position by screwing it to a bulkhead, through an anti-vibration mounting ring, if necessary.

Before taking a reading, tap the face of the barometer gently with the finger to release any static friction in the bearings.

In general, however, the aneroid does not retain its accuracy over as long a period as the mer-

cury barometer. It is therefore necessary to compare its readings with a standard barometer at fairly frequent intervals (at least once every three months is recommended), to ensure that changes in the elasticity of the metal has not altered its readings. This is the **Instrument Correction**. It is entered on the Barometer Tag which is then affixed to the aneroid for future reference.

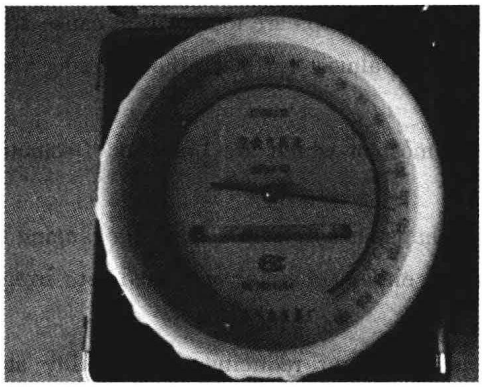


Figure 1.19(a) Anerold Barometer

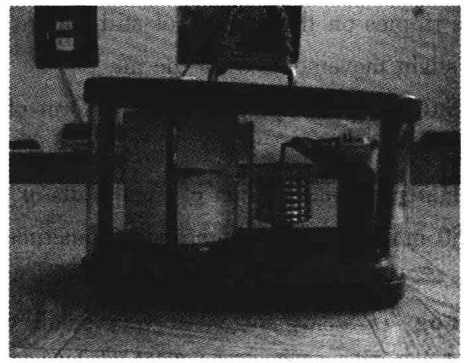


Figure 1.19(b) Barograph

The atmospheric pressure reading at the height of the barometer is called the station pressure, and is subject to a height correction in order to make it a sea level pressure reading. This correction is called the sea level correction, whose value depends of course on the altitude of the barometer above sea level. Generally the reading is added 1 millibar per 8 meters.

A marine microbarograph is a precision barograph using greater magnification and an expanded chart. It is designed to maintain its precision through all the conditions encountered aboard ship.

1.9.8 Weather Phenomena

There are three basic types of reportable weather phenomena, meteors-hydro-meteors (any kind of liquid or solid precipitation, fog or mist), lithometeors (haze, smoke, dust, etc.), and electrometeors (lightning, thunder).

The terms are listed below.

Precipitation: is any product of the condensation of atmospheric water vapor that is deposited on the Earth's surface. The most common types of precipitation are liquid (rain and drizzle) and frozen (snow, hail, ice pellets, snow pellets, snow grains, and diamond dust).

Intermittent: is applied to precipitation other than showers, and means that the precipitation must have stopped and recommenced at least once during the 60 minutes preceding the scheduled time of observation.

Continuous: is applied to the precipitation other than showers, and means that the precipitation that is occurring at the time of observation, has continued without a break through the past hour, or has commenced during the past hour and continued without a break.

Showers: Precipitation in the form of showers that begins and ends abruptly, and lasts for short periods ranging from less than a minute up to a half hour or more. Usually there are rapid fluctuations in the intensity of the precipitation, and there is a noticeable brightening of the sky after or between showers. Snow pellets and hail always occur in the form of showers, but rain, snow, and

ice pellets can occur with either showery or non-showery characteristics.

Rain: is defined as precipitation of liquid droplets. Rain drops are normally larger than drops of drizzle.

Drizzle: is defined as fairly uniform precipitation composed exclusively of fine drops of water of diameter less than 0.5 mm and very close to one another. Drizzle drops are too small to cause appreciable ripples on the surface of still water. The drops appear almost to float, thus making visible even slight movements of in the air.

Snow: is precipitation, in the form of ice crystals, most of which are branched (sometimes star-shaped).

Hail: is precipitation of small balls or pieces of ice (hailstones), with a diameter ranging from 5 to 50 mm (1/5 to 2 inches) or sometimes more, falling either separately or fused into irregular lumps.

Fog: is a suspension of very small water droplets in the air reducing the visibility at the Earth's surface. The term "fog" is restricted to cases in which the horizontal visibility at the Earth's surface is less than 1/2 nautical mile.

Mist: is a suspension in the air of microscopic water droplets or wet hygroscopic particles, reducing the visibility at the Earth's surface. The term "mist" is used when the visibility is reduced to not less than 1/2 nautical mile.

Haze: is a suspension in the air of extremely small dry particles invisible to the naked eye and sufficiently numerous to give the air an opalescent (milky or pearly) appearance. The visibility may be reduced but is always better than 1/2 nautical mile. Haze is sometimes confused with mist. If the relative humidity of the air is very high (90% ~100%), the phenomenon is mist; but if the relative humidity is lower (60% ~80%), the phenomenon may be classified as haze.

Thunderstorm: is considered to be occurring when thunder is heard. A thunderstorm is regarded as being heavy when sharp and pronounced thunder and lightning occur almost continuously, accompanied by heavy rain or snow, and often by hail. The peak wind preceding or accompanying the storm is usually in excess of 40 knots.

1.9.9 Cloud Types and Amounts

In making the cloud observation, it is necessary to stand in a location which affords an uninterrupted view of the whole sky.

The identification of the types is based primarily on their appearance as viewed from the Earth's surface.

If the cloud has a uniform featureless, sheet-like appearance, it is probably Cirrostratus, Altostratus, Stratus or Nimbostratus.

If the cloud layer consists of elements either detached or merged together, it is probably Cirrocumulus, Altocumulus, Stratocumulus or Cumulus of small or moderate vertical extent. The size of the elements determine whether it is Cc, Ac, or Sc.

If the cloud layer is in the form of more or less parallel rolls, it is either Altocumulus or Stratocumulus. The width of the rolls determining which type.

Ragged, tattered shreds of low cloud occurring alone are Cumulus or ragged Stratus, but if these tattered clouds are seen below a higher diffuse layer when precipitation is occurring or imminent, they are called Stratus of bad weather or Cumulus of bad weather, or more familiarly "scud".

Cumulus of moderate or great vertical extent is unmistakable due to its boiling, cauliflower-like appearance. Cirrus is also unmistakable because of a feathery, thread-like appearance.

If thunder, lightning, hail, or heavy showers are occurring, the cloud is almost certainly Cumulonimbus.

All cloud amounts are determined by estimation. To make an estimate for the whole sky at once requires practice and is rather difficult at first. It may be more convenient to imagine the sky divided into quadrants by two arcs drawn at right angles through the zenith. Each quadrant represents two-eighths of the sky. By estimating the number of eighths of cloud in each quadrant then the amount of cloud for the whole sky is obtained simply by adding the amounts estimated for the separate quadrants.

1.9.10 Observing Ocean Waves

The wave characteristics that are reported in the weather message are wave period, wave height, and the direction from which the waves are coming from (for swell only).

Wave direction, like wind direction is the direction from which the waves are coming. The wave direction is determined with reference to true north (not magnetic), and is recorded to the nearest 10° (e.g., 010°, 020°, 030°, etc. right around to 360°). Only the direction of the swell waves is required. The direction is most easily found by sighting along the wave crests. Then turn through 90°to face the advancing waves. The direction you are then facing will be the direction from which the waves are coming.

For measurements of period a stop watch is invaluable. If available, an ordinary watch with a second hand may be used, or a practiced observer may count seconds. The average value of the periods of the larger well-formed waves near the center of the wave groups is reported. To measure the period, an object floating on the water at some distance from the ship must be available. This can be a piece of wood thrown overboard from the bow by a crew member while you observe from the bridge.

When estimating wave height, consider only the larger well-formed waves near the center of the wave group. Estimate the average height of these larger waves, and disregard the lesser waves between the groups.

It is of the utmost importance that meteorological forecast centers receive ships' weather messages as soon as possible after the scheduled times of observation. On a ship equipped with Inmarsat communication system, weather observation reports originating within specified areas may be transmitted using this system.

CHAPTER 2 WEATHER SYSTEMS

2.1 Weather Charts

2.1.1 Outline of Weather Charts

Weather charts are created by plotting or tracing the values of relevant quantities such as sea level pressure, air temperature, and cloud cover onto a geographical map to help find synoptic scale weather systems such as weather fronts.

A synoptic scale feature is one whose dimensions are large in scale, more than several hundred kilometers in length. Migratory pressure systems and frontal zones exist on this scale.

Mesoscale features are smaller than synoptic scale systems like fronts, but larger than storm-scale systems like thunderstorms. Horizontal dimensions generally range at less then 200 km.

There are many types of charts of meteorological and hydrological information available by relevant organizations, such as surface chart, upper-air chart, wave chart, and other auxiliary charts. For mariners, the most commonly used charts are surface analysis and forecast charts, wave analysis and forecast charts, typhoon/hurricane/cyclone warning charts, etc.

2.1.2 Weather Chart Projections

A map projection is any method of representing the surface of a sphere or other shape on a plane. Map projections are necessary for creating maps. All map projections distort the surface in some fashion. Depending on the purpose of the map, some distortions are acceptable and others are not; therefore different map projections exist in order to preserve some properties of the sphere-like body at the expense of other properties. There is no limit to the number of possible map projections.

A **Lambert conformal conic projection** (LCC) is a conic map projection, which is often used for the mid-latitudes charts. In essence, the projection superimposes a cone over the sphere of the Earth, with two reference parallels (generally 30° and 60°) secant to the globe and intersecting it. The area between the two standard parallels is compressed, and that beyond is expanded. There is no distortion along the standard parallels, but distortion increases further from the chosen parallels.

Polar stereographic projection is a particular mapping that projects a sphere onto a plane. In the polar stereographic projection, the observer's perspective comes from looking down at the Pole. In all polar stereographic projections, meridians are straight lines and latitudes are arcs of great circles that intersect at right angles. It is often used for polar areas or the entire Northern or Southern Hemisphere charts.

The **Mercator projection** is a cylindrical map projection and used as the standard map projec-

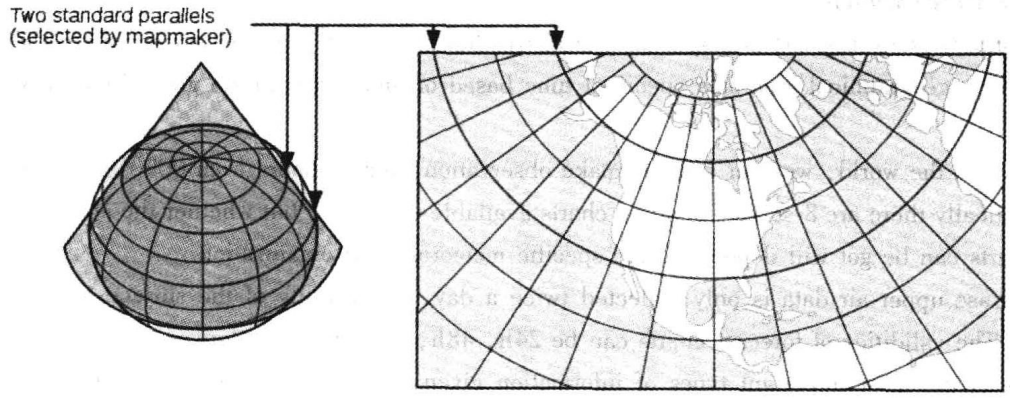


Figure 2.1 Lambert Conformal Conic Projection

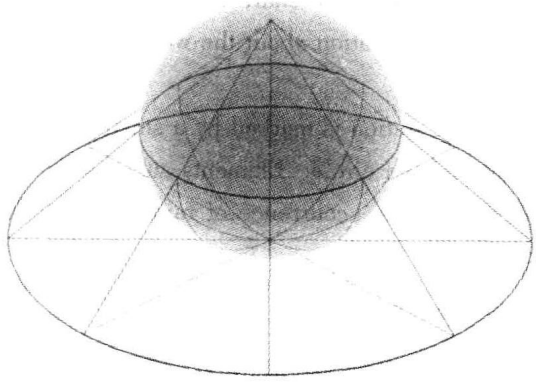


Figure 2.2 Polar Stereographic Projection

tion for nautical purposes because of its ability to represent lines of constant course, known as rhumb lines or loxodromes. While the linear scale is constant in all directions around any point, thus preserving the angles and the shapes of small objects (which makes the projection conformal), the Mercator projection distorts the sizes and shapes of large objects, as the scale increases from the equator to the poles, where it becomes infinite.

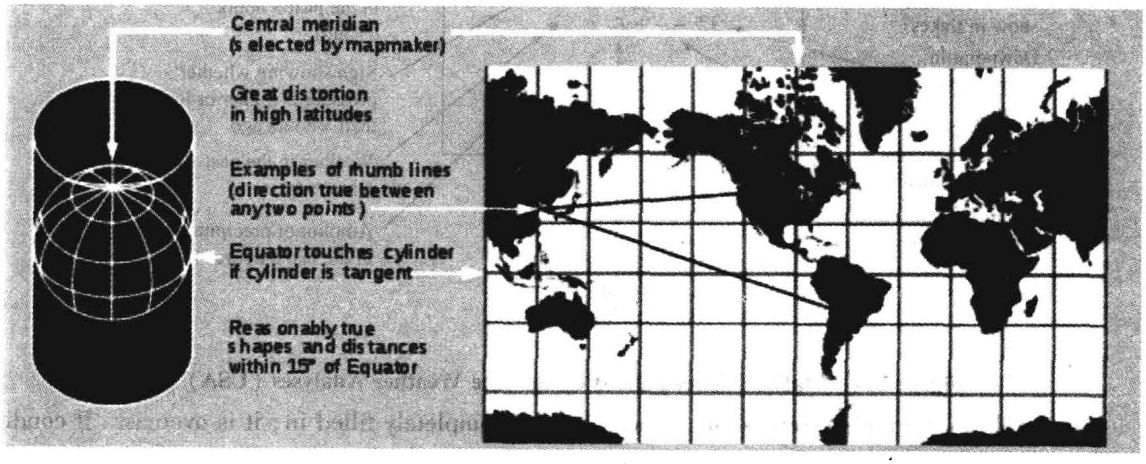


Figure 2.3 Mercator Projection

2.1.3 Surface Charts

A surface analysis chart is a special type of weather chart that provides a view of weather elements over a geographical area at a specified time based on information from ground-based weather stations.

Through the world, weather stations make observation every 3 hours from 0000UTC each day, so theoretically there are 8 surface analysis charts available each day, but whether the actual times of these charts can be got will depend on the specific meteorological organization.

Because upper-air data is only collected twice a day, the validity of the surface chart can be slightly. The validities of forecast charts can be 24h, 48h, 72h, 96h, or longer.

One of the most important types of information given on a surface analysis chart are weather symbol.

Weather symbols are plotted on a synoptic chart used for weather forecasting, and show the position of weather stations collecting information about the weather, and details of the various weather elements.

The position of a meteorological station is marked by a small circle. The weather report for each station is then plotted in and around the circle. Elements such as temperature and air pressure are entered as plain figures. Others, like the occurrence of rain, snow, cloud and fog are plotted with internationally agreed symbols.

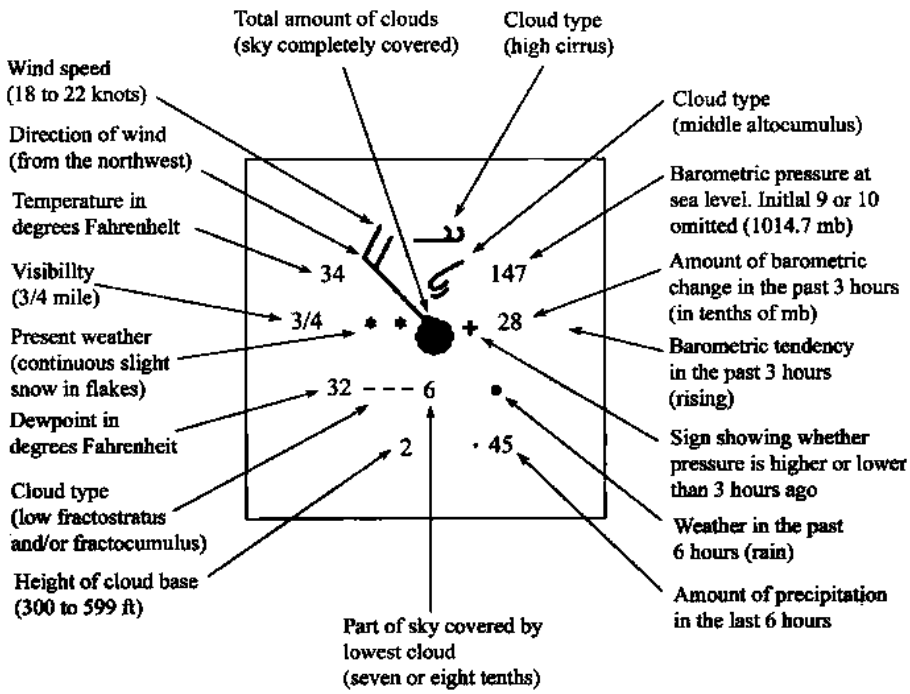


Figure 2.4 Station Model Plotted on Surface Weather Analyses (USA)

The circle in the middle represents cloud cover. If completely filled in, it is overcast. If conditions are completely clear, the circle is empty. Outside the United States, temperature and dew

point are plotted in degrees Celsius.

Wind direction is represented by an arrow pointing in the direction from which the wind is coming. The wind speed is denoted by "feathers" on the wind arrow; a short feather indicating 5 knots, a larger one 10 knots, a long and short one 15 knots and so on. When winds reach 50 knots, a filled in triangle is used for each 50 knots of wind.

Table 2.1 Wind Barb Interpretations

Speed (knots)	Symbol	Speed (knots)	Symbol
Less than 1		33–37	
1–2		38–42	
3–7		43–47	
8–12		48–52	
13–17		53–57	
18–22		58–62	
23–27		98–102	
28–32		103–107	

The weather symbols used on surface weather analyses were devised to take up the least room possible on weather maps.

The other important information given in surface charts is weather systems.

Surface analyses charts have special symbols to show frontal systems and other weather systems.

Fronts in meteorology are the leading edges of air masses with different density (e.g., air temperature and/or humidity). In surface weather analyses, fronts are depicted using various colored lines and symbols, depending on the type of front.

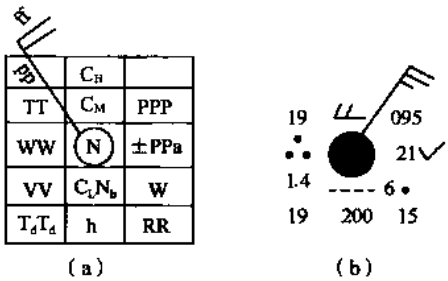


Figure 2.5 Station Model Plotted on Surface Weather Analyses (China)

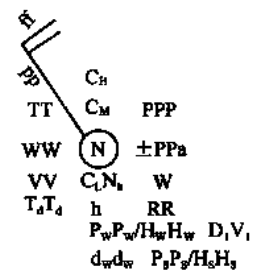


Figure 2.6 Station Model Plotted on Surface Weather Analyses (Maritime)

Table 2.2 A Guide to the Symbols for Weather Fronts that May be Found on a Weather Map

Names	Symbols
1. cold front	
2. warm front	
3. stationary front	
4. occluded front	
5. surface trough	
6. squall line	

Mean sea level air pressure field is described by isobars on surface charts.

Isobars are lines connecting points of equal atmospheric pressure.

On a surface chart, the interval between isobars is always constant, usually being 2.5 or 5 hPa in China, and 2 or 4 or 5 hPa in other countries.

Weather charts in English-speaking countries will depict their highs as Hs and lows as Ls, while Spanish-speaking countries will depict their highs as As and lows as Bs.

Internationally, the standard rainfall measurement unit is the millimeter.

Important weather areas such as fog areas, strong wind areas, precipitation areas are shown on some charts.

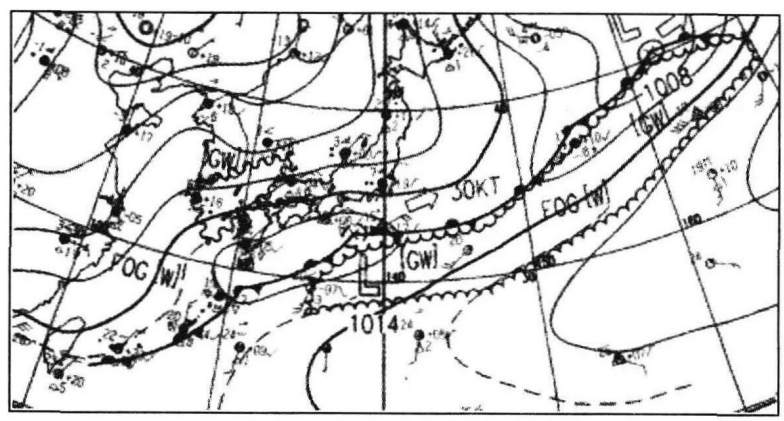


Figure 2.7.a Gale and Fog Warnings on a Japanese Surface Chart

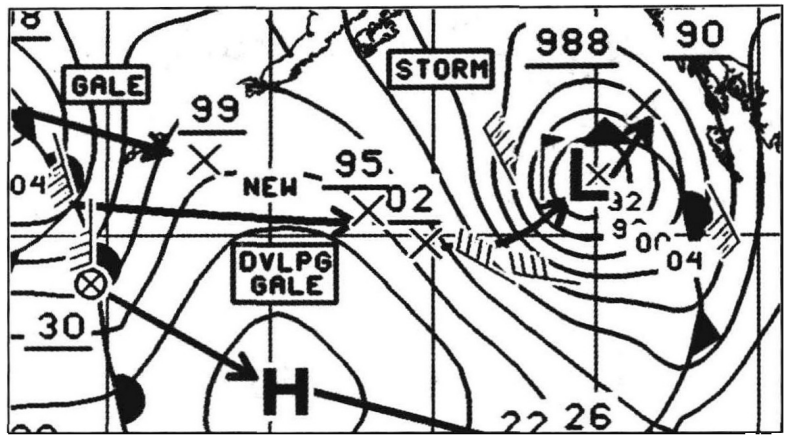


Figure 2.7.b Wind Warnings on a USA Surface Chart

2.2 Air Masses and Fronts

2.2.1 Air Mass

In meteorology, an air mass is a large volume of air defined by its temperature and water vapor content.

Air masses cover many hundreds or thousands of square kilometers, and adopt the characteristics of the surface below them.

They are classified according to latitude and their continental or maritime source regions. Colder air masses are termed polar or arctic, while warmer air masses are deemed tropical. Continental and superior air masses are dry, while maritime and monsoon air masses are moist.

Weather fronts separate air masses with different density (temperature and/or moisture) characteristics.

Once an air mass moves away from its source region, underlying vegetation and water bodies can quickly modify its character.

Classification schemes indicate an air mass' characteristics, as well as modification.

The Bergeron classification is the most widely accepted form of air mass classification, though others countries have produced more refined versions of this scheme over different regions of the globe.

Air mass classification involves three letters.

The first letter describes its **moisture** properties, with "c" used for continental air masses (dry) and "m" for maritime air masses (moist).

The second letter describes the thermal characteristic of its **source region**: "T" for tropical, "P" for polar, "A" for Arctic or antarctic, "M" for monsoon, "E" for equatorial, and "S" for superior air (dry air formed by significant downward motion in the atmosphere). For instance, an air mass originating over the desert southwest of the United States in summer may be designated "cT". An air mass originating over northern Siberia in winter may be indicated as "cA".

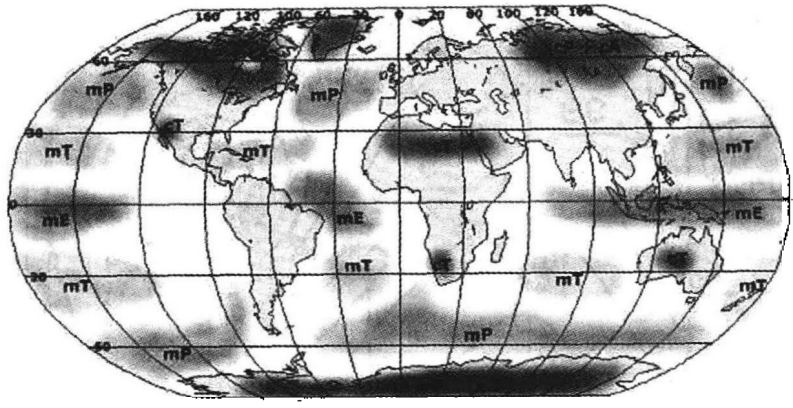


Figure 2.8 Source Regions of Global Air Masses

The third letter is used to designate the **stability** of the atmosphere. If the air mass is colder than the ground below it, it is labeled "k". If the air mass is warmer than the ground below it, it is labeled "w". An example of this might be a polar air mass blowing over the Gulf Stream, denoted as "cPk".

Arctic, **antarctic**, and **polar air masses** are cold. The qualities of Arctic air are developed over ice and snow-covered ground. Arctic air is very cold, colder than polar air masses. Arctic air can be shallow in the summer, and rapidly modify as it moves equatorward. Polar air masses that develop over higher latitudes over the land or ocean, are very stable, and are generally shallower than Arctic air. Polar air over the ocean (maritime) loses its stability as it gains moisture over warmer ocean waters.

Tropical and **equatorial air masses** are hot as they develop over lower latitudes. Those that develop over land (continental) are drier and hotter than those that develop over oceans, and travel northward on the western periphery of the subtropical high. Maritime tropical air masses are sometimes referred to as trade wind air masses. Monsoon air masses are moist and unstable. Superior air masses are dry, and rarely reach the ground. They normally resides over maritime tropical air masses, forming a warmer and drier layer over the more moderate moist air mass below, forming what is known as a Trade Wind inversion over the maritime tropical air mass.

When an air mass moves out of its source region, a number of factors act upon the air mass to change its properties. These modifying influences do not occur separately. For instance, in the passage of cold air over warmer water surfaces, there is not only a release of heat into the air, but also a release of some moisture. As an air mass expands and slowly moves out of its source region, it travels along a certain path. As an air mass leaves its source region, the first modifying factor is the type and condition of the surface over which the air travels. Here, the factors of surface temperature, moisture, and topography must be considered. The type of trajectory, whether cyclonic or anticyclonic, also has a bearing on its modification. The time interval since the air mass has been out of its source region determines to a great extent the characteristics of the air mass.

For example, if the air mass moves over a surface that is warmer (such as continental polar air

moving out from the continent in winter over warmer water), the warm water heats the lower layers of the air mass, increasing instability (decreasing in stability), and consequently spreading to higher layers. The changes in stability of the air mass give valuable indications of the cloud types that will form, as well as the type of precipitation to be expected. Also, the increase or decrease in stability gives further indication of the lower layer turbulence and visibility.

2.2.2 Front Classification

A **weather front** is a boundary separating two masses of air of different densities, and is the principal cause of meteorological phenomena. The air masses separated by a front usually differ in temperature and humidity.

Cold fronts may feature narrow bands of thunderstorms and severe weather, and may on occasion be preceded by squall lines.

Warm fronts are usually preceded by stratiform precipitation and fog. The weather usually clears quickly after a front's passage. Some fronts produce no precipitation and little cloudiness, althoughthere is invariably a wind shift.

An **occluded front** is formed when a cold front overtakes a warm front.

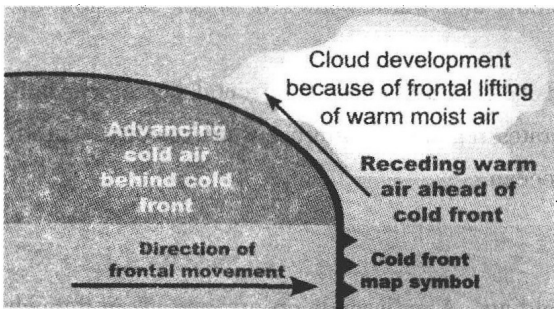


Figure 2.9.a Illustration of a Cold Front

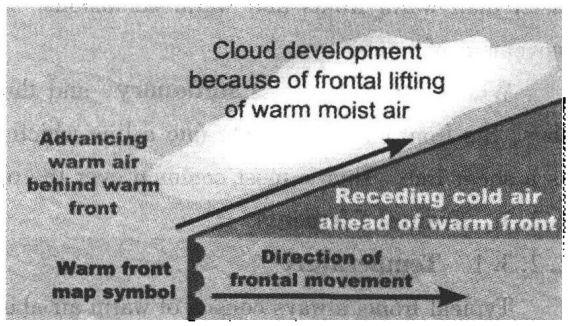


Figure 2.9.b Illustration of a Warm Front

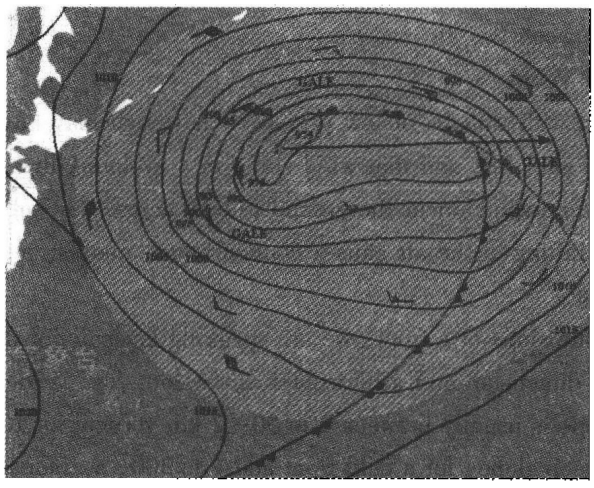


Figure 2.9.c Occluded Cyclone Front

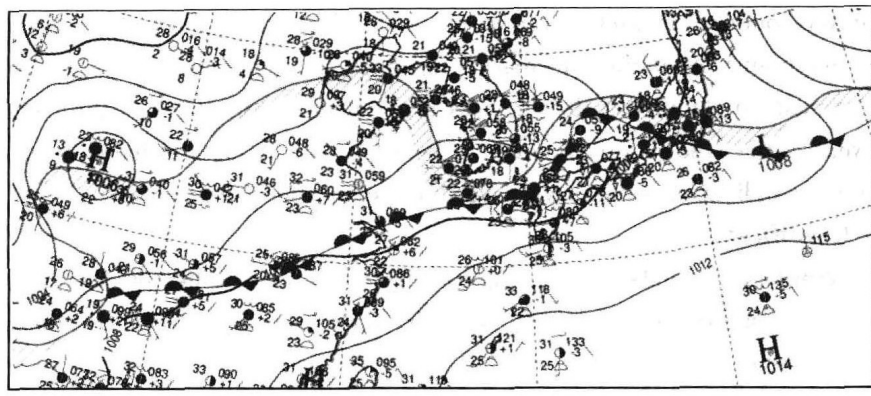


Figure 2.9.d Stationary Front Depiction

The occluded front lies within a sharp trough, but the air mass behind the boundary can be either warm or cold.

Cold fronts and **occluded fronts** generally move from west to east, while warm fronts move poleward. Because of the greater density of air in their wake, cold fronts and cold occlusions move faster than warm fronts and warm occlusions. Mountains and warm bodies of water can slow the movement of fronts.

When a front becomes **stationary**, and the density contrast across the frontal boundary vanishes, the front can degenerate into a line which separates regions of differing wind velocity, known as a shear line. This is most common over the open ocean.

2.2.3 Frontal Elements

2.2.3.1 Temperature

Typical fronts always consist of warm air above cold air. A radiosonde observation taken through a frontal surface often indicates a relatively narrow layer where the normal decrease of temperature with height is reversed. The degree to which a frontal zone appears pronounced is proportional to the temperature difference between two air masses.

2.2.3.2 Pressure and Wind

Fronts are associated with troughs of low pressure. A trough may have U-shaped or V-shaped isobars. A front is a wind shift line and that wind shifts in a cyclonic direction.

Friction causes the air (wind) near the ground to drift across the isobars toward lower pressure and then move upward. Lifting of the air causes condensation, clouds, and weather.

2.2.3.3 Frontal Slope

When we speak of the slope of a front, we are speaking basically of the steepness of the frontal surface, using a vertical dimension and a horizontal dimension. The vertical dimension used is normally 1 – 2 km. This slope is usually between 1 to 50 (2 km vertical for 100 km horizontal), which would be considered a steep slope, for a cold front and 1 to 300, a gradual slope, for a warm front. Factors favoring a steep slope are a large wind velocity between difference between air masses, small temperature difference, and high latitude. The frontal slope therefore depends on the latitude of the front, the wind speed, and the temperature difference between the air masses. Because cold air

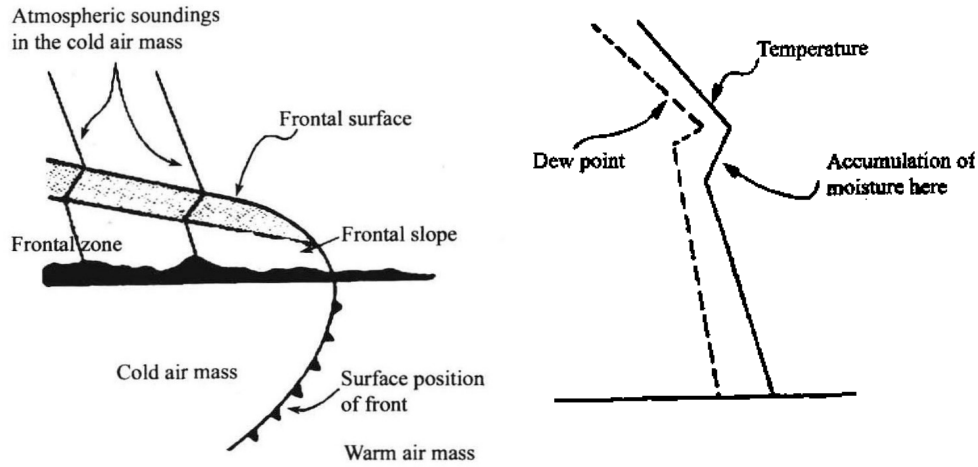


Figure 2.10 Frontal Inversions

tends to under run warm air, the steeper the slope is, the more intense the lifting and vertical motion of the warm air is and, therefore, the more intense the weather is.

2.2.3.4 Clouds and Weather

Cloud decks are usually in the warm air mass because of the upward vertical movement of the warm air. Clouds forming in a cold air mass are caused by the evaporation of moisture from precipitation from the overlying warm air mass and/or by vertical lifting. Convergence at the front results in a lifting of both types of air. The stability of air masses determines the cloud and weather structure at the fronts as well.

2.2.3.5 Movement

The speed of the movement of frontal systems is an important determining factor of weather conditions. Rapidly moving fronts usually cause more severe weather than slower moving fronts. The fast-moving front does have the advantage of moving across the area rapidly, permitting the particular locality to enjoy a quick return of good weather. Slow-moving fronts, on the other hand, may cause extended periods of unfavorable weather. A stationary front may bring bad weather for several days in succession.

2.2.4 Weather and Fronts

2.2.4.1 Slow-Moving Cold Fronts (Active Cold Front)

With the slow-moving cold front, there is a general upward motion of warm air along the entire frontal surface and pronounced lifting along the lower portion of the front. The average slope of the front is approximately 1:100. Near the ground, the slope is often much steeper because of surface friction.

Figure 2.11 illustrates the typical characteristics in the vertical structure of a slow-moving cold front. The lower half shows the typical upper airflow behind the front, and the upper half shows the accompanying surface weather. This is only one typical case. Many variations of this model can and do occur in nature. The slow-moving cold front is an active front because it has widespread frontal cloudiness, and precipitation at and behind the front caused by actual frontal lifting.

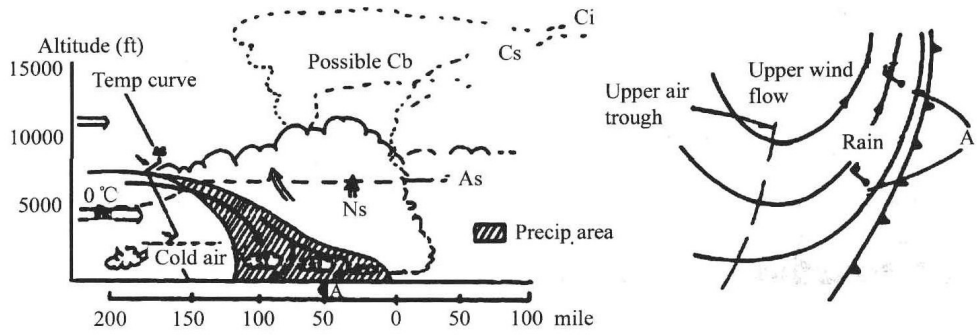


Figure 2.11 Typical Vertical Structure of a Slow-Moving Cold Front with Upper Wind Flow at the Back of the Front

The pressure tendency associated with this type of frontal passage is indicated by either an unsteady, or steady fall prior to frontal passage and then weak rises behind. Temperature and dew point drop sharply with the passage of a slow-moving cold front. The wind veers with the cold frontal passage and reaches its highest speed at the time of frontal passage. Isobars are usually curved anticyclonically in the cold air. This type of front usually moves at an average speed between 10 and 15 knots. Slow-moving cold fronts move with 100% of the wind component normal to the front.

The type of weather experienced with a slow-moving cold front is dependent upon the stability of the warm air mass. When the warm air mass is stable, a rather broad zone of altostratus and nimbostratus clouds accompany the front and extend several hundred kilometers behind the front. If the warm air is unstable (or conditionally unstable), thunderstorms and cumulonimbus clouds may develop within the cloud bank and may stretch for some 100 kilometers behind the surface front. Thus cumulonimbus clouds form within the warm air mass. In the cold air there may be some stratus or nimbostratus clouds formed by the evaporation of falling rain; but, generally, outside of the rain areas, there are relatively few low clouds. This is because of the descending motion of the cold air that sometimes produces a subsidence inversion some distance behind the front.

The ceiling is generally low with the frontal passage, and gradual lifting is observed after passage. Visibility is poor in precipitation and may continue to be reduced for many hours after frontal passage as long as the precipitation occurs. When the cold air behind the front is moist and stable, a deck of stratus clouds and/or fog may persist for a number of hours after frontal passage. The type of precipitation observed is also dependent upon the stability and moisture conditions of the air masses.

2.2.4.2 Fast-Moving Cold Fronts (Inactive Cold Front)

The fast-moving cold front is a very steep front that has warm air near the surface being forced vigorously upward. At high levels, the warm air is descending downward along the frontal surface. This front has a slope of 1:40 to 1:80 and usually moves rapidly; 25 to 30 knots may be considered an average speed of movement, they move with 80 to 90 percent of the wind component normal to the front. As a result of these factors, there is a relatively narrow but often violent band of weather.

Figure 2.12 shows a vertical cross section of a fast-moving cold front with resultant weather.

Also indicated in the lower half of the diagram is the surface weather in advance of the front and the upper airflow above the front.

If the warm air is moist and unstable, a line of thunderstorms frequently develops along this front. Sometimes, under these conditions, a line of strong convective activity is projected 100 to 400 kilometers ahead of the front and parallel to it. This may develop into a line of thunderstorms called a squall line. On the other hand, when the warm air is stable, an overcast layer of altostratus clouds and rain may extend over a large area ahead of the front. If the warm air is very dry, little or no cloudiness is associated with the front. The front depicted is a typical front with typical characteristics.

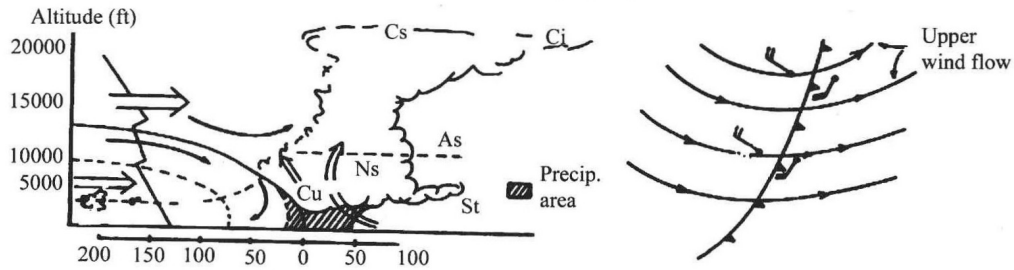


Figure 2.12 Typical Vertical Structure of a Fast-Moving Cold Front with Upper Wind Flow Across the Front

The fast-moving cold front is considered an inactive front because lifting occurs only at and ahead of the front.

Pressure tendencies fall ahead of the front with sudden and strong rises after the front passes.

Organized areas of thunderstorm activity not only reinforce pre-existing frontal zones, but can outrun cold fronts in a pattern where the upper level jet splits apart into two streams, with the resultant Mesoscale Convective System (MCS) forming at the point of the upper level split in the wind pattern running southeast into the warm sector parallel to low-level thickness lines. When the convection is strong and linear or curved, the MCS is called a squall line, with the feature placed at the leading edge of the significant wind shift and pressure rise. Even weaker and less organized areas of thunderstorms lead to locally cooler air and higher pressures, and outflow boundaries exist ahead of this type of activity, which can act as foci for additional thunderstorm activity later in the day.

These features are often depicted in the warm season across the United States on surface analyses and lie within surface troughs. If outflow boundaries or squall lines form over arid regions, a haboob may result. Squall lines are depicted on NWS surface analyses as an alternating pattern of two red dots and a dash labelled SQLN or SQUALL LINE, while outflow boundaries are depicted as troughs with a label of OUTFLOW BNDRY.

If a squall line lies some distance ahead of the front, there may be a strong rise associated with its passage and a shift in the wind. However, after the influence of the squall line has passed, winds back to southerly and pressures levels off. The temperature falls in the warm air just ahead of the front. This is caused by the evaporation of falling precipitation. Rapid clearing and adiabatic war-

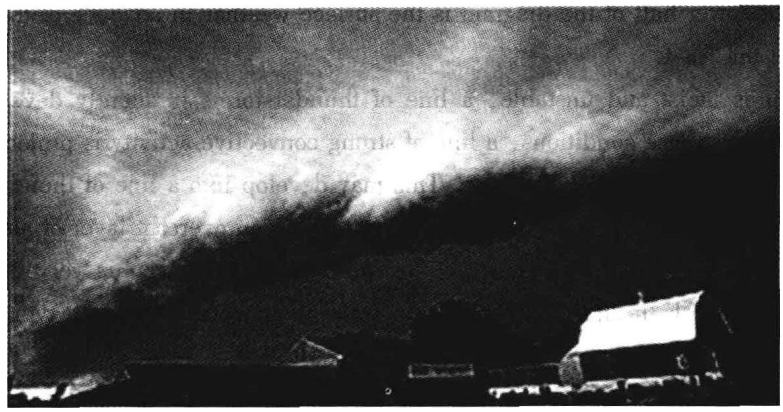


Figure 2.13 Squall—A Shelf Cloud such as this one can be a Sign that a Squall is Imminent

ming just behind the front tend to keep the cold air temperature near that of the warm air. An abrupt temperature change usually occurs far behind the front near the center of the high-pressure center associated with the cold air mass. The dew point and wind direction are a good indication of the passage of a fast-moving cold front. The wind veers with frontal passage and is strong, gusty, and turbulent for a considerable period of time after passage. The dew point decreases sharply after the front passes.

Cumulonimbus clouds are observed along and just ahead of the surface front. Stratus, nimbostratus, and altostratus may extend ahead of the front in advance of the cumulonimbus and may extendas much as 150 miles ahead of the front. These clouds are all found in the warm air. Generally, unless the cold air is unstable and descending currents are weak, and there are few clouds in the cold air behind the front. Showers and thunderstorms occur along, and just ahead of the front. The ceiling is low only in the vicinity of the front. Visibility is poor during precipitation, but improves rapidly after the front passes.

2.2.4.3 Warm Front

Warm fronts move more slowly than cold fronts. Their average speed is usually between 10 and 20 knots. They move with a speed of 60 to 80 percent of the component of the wind normal to the front in the warm air mass.

The troughs associated with warm fronts are not as pronounced as those with cold fronts, and sometimes make location difficult on the surface chart. The pressure tendency ahead of the front is usually a rapid or unsteady fall with a leveling off after the front passes. A marked decrease in isobaric gradient is noticed in the warm sector, except when rapid deepening is taking place. The wind increases in velocity in advance of warm fronts because of an increase in pressure gradient, and reaches a maximum just prior to frontal passage. The wind veers with frontal passage, usually from a south-easterly direction to a south-westerly direction behind the front. This shift is not as pronounced as with the cold front.

Temperature generally is constant or slowly rising in advance of the front until the surface front passes, at which time there is a marked rise. This rise is dependent upon the contrast between the

air masses. Dew point usually increases slowly with the approach of the front, with a rapid increase in precipitation and fog areas. If the warm sector air is maritime tropical, the dew point shows a further increase.

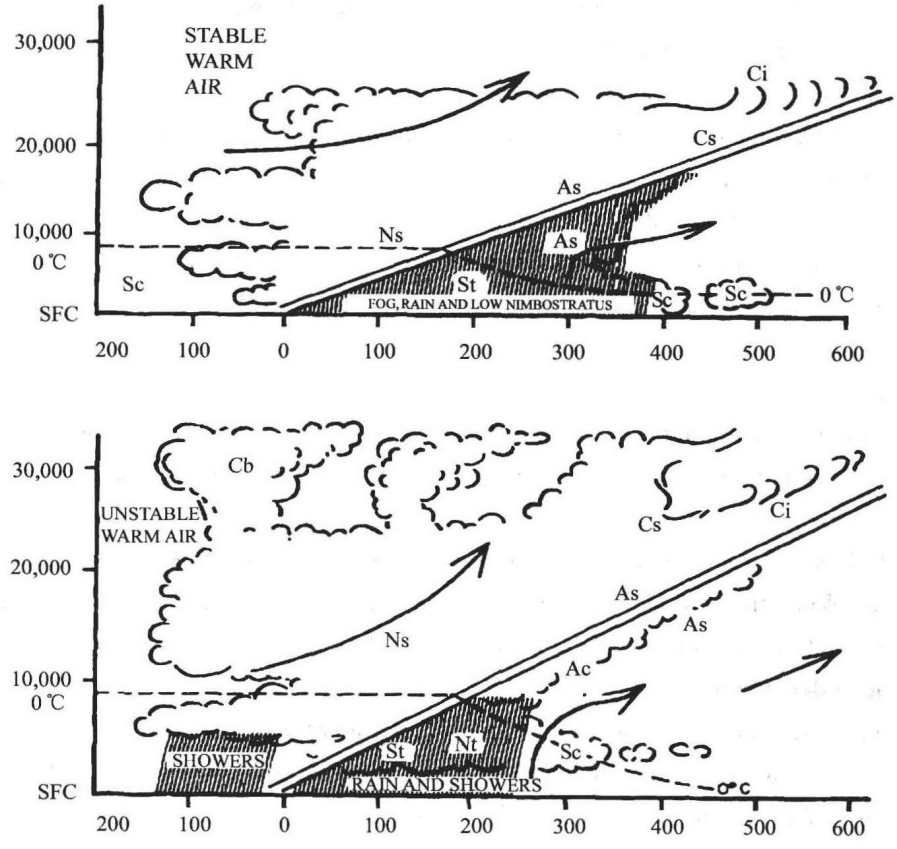


Figure 2.14 Vertical Cross Section of a Warm Front with Stable and Unstable Air

A characteristic phenomenon of a typical warm front is the sequence of cloud formations (Figure 2.14). They are noticeable in the following order: cirrus, cirrostratus, altostratus, nimbostratus, and stratus. The cirrus clouds may appear 1,400 to 2,000 kilometers or more ahead of the surface front, followed by cirrostratus clouds about 600 miles ahead of the surface front and altostratus about 500 miles ahead of the surface front.

Precipitation in the form of continuous or intermittent rain, snow, or drizzle is frequent as far as 300 miles in advance of the surface front. Surface, precipitation is associated with the nimbostratus in the warm air above the frontal surface and with stratus in the cold air. However, when the warm air is connectedly unstable, showers and thunderstorms may occur in addition to the steady precipitation. This is especially true with a cyclonic flow aloft over the warm front. Fog is common in the cold air ahead of a warm front.

Clearing usually occurs after the passage of a warm front, but under some conditions drizzle and fog may occur within the warm sector. Warm fronts usually move in the direction of the isobars of the warm sector; in the Northern Hemisphere this is usually from east to northeast.

The amount and type of clouds and precipitation vary with the characteristics of the air masses involved and depend on whether the front is active or inactive.

Generally, with warm fronts, an increase of the wind component with height perpendicular to the front gives an active front. This produces strong overrunning and pronounced prefrontal clouds and precipitation. Inactive fronts, characterized by broken cirrus and altocumulus, are produced by a decrease with height of the wind component perpendicular to the front.

When the overrunning warm air is moist and stable, nimbostratus clouds with continuous light to moderate precipitation are found approximately 300 miles ahead of the front. The base of the clouds lower rapidly as additional clouds form in the cold air under the frontal surface. These clouds are caused by evaporation of the falling rain. These clouds are stratiform when the cold mass is stable and stratocumulus when the cold air is unstable.

When the overrunning air is moist and unstable, cumulus and cumulonimbus clouds are frequently imbedded in the nimbostratus and altostratus clouds. In such cases, thunderstorms occur along with continuous precipitation. When the overrunning warm air is dry, it must ascend to relatively high altitudes before condensation can occur. In these cases only high and middle clouds are observed.

Visibility is usually good under the cirrus and altostratus clouds. It decreases rapidly in the precipitation area. When the cold air is stable and extensive, fog areas may develop ahead of the front, and visibility is extremely reduced in this area.

2.2.4.4 Occluded Fronts

An occluded front is a composite of two fronts. It forms when a cold front overtakes a warm front and one of these two fronts is lifted aloft. As a result, the warm air between the cold and warm front is shut off. An occluded front is often referred to simply as an occlusion. Occlusions may be either of the cold type or warm type.

A cold occlusion forms when the cold air in advance of a warm front is warmer than the cold air to the rear of the cold front. The over-taking cold air undercuts the cool air in advance of the warm front. This results in a section of the warm front being forced aloft.

A warm occlusion forms when the air in advance of the warm front is colder than the air to the rear of the cold front. When the cold air of the cold front overtakes the warm front, it moves up over this colder air in the form of an upper cold front.

Since the occluded front is a combination of a cold front and a warm front, the resulting weather is that of the cold front's narrow band of violent weather and the warm front's widespread area of cloudiness and precipitation occurring in combination along the occluded front. The most violent weather occurs at the apex or tip of the occlusion. The apex is the point on the wave where the cold front and warm front meet to start the occlusion process.

Cold occlusions are more frequent than warm occlusions. The lifting of the warm front by the cold front implies existence of an upper warm front to the rear of the cold occlusion; actually such a warm front aloft is rarely discernible and is seldom delineated on a surface chart.

The occlusion lies in a low-pressure area; and in the latter stages, a separate low center may

form at the tip of the occlusion, leaving another low-pressure cell near the end of the occlusion. The pressure tendency across the cold occluded front follows closely with those outlined for cold fronts; that is, they level off, or more often, rapid rises occur after the passage of the occluded front.

In the occlusion's initial stages of development, the weather and cloud sequence ahead of the occlusion is quite similar to that associated with warm fronts; however, the cloud and weather sequence near the surface position of the front is similar to that associated with cold fronts. As the occlusion develops and the warm air is lifted to higher and higher altitudes, the warm front and prefrontal cloud systems disappear. The weather and cloud systems are similar to those of a cold front. View A of figure 2. 15 shows the typical cloud and weather pattern associated with the cold occlusion. Most of the precipitation occurs just ahead of the occlusion. Clearing behind the occlusion is usually rapid, especially if the occlusion is in the advanced stage. Otherwise, clearing may not occur until after the passage of the warm front aloft.

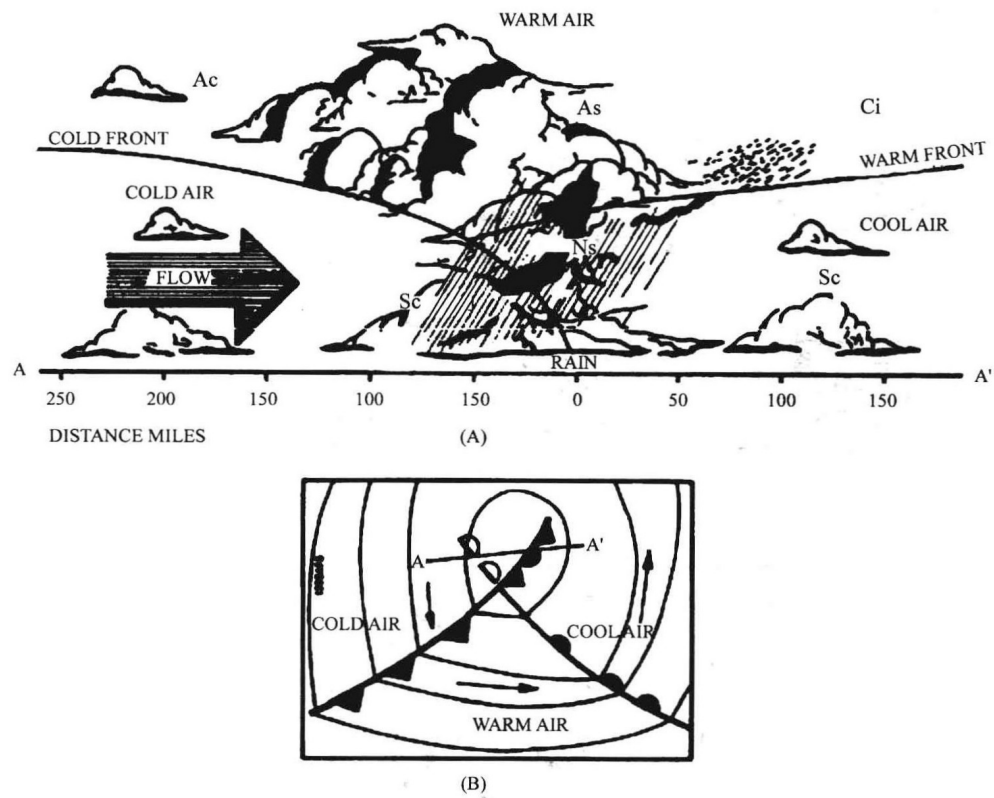


Figure 2. 15 Cold Type of Occlusion

(A) Vertical Structure Through Points A and A'; (B) Horizontal Structure

The warm occlusion usually develops in the Northern Hemisphere when conditions north and aheadof the warm front are such that low temperatures exist north of the warm front. This usually occurs along the west coast of continents when a relatively cool maritime cold front overtakes a warm front associated with a very cold continental air mass of high pressure situated over the western portion of the continent. The cold front then continues as an upper cold front above the warm front

surface. The occlusion is represented as a continuation of the warm front. The cold front aloft is usually represented on all surface charts.

The weather associated with warm front occlusions has the characteristics of both warm and cold fronts. The sequence of clouds ahead of the occlusion is similar to the sequence of clouds ahead of a warm front; the cold front weather occurs near the upper cold front. If either the warm or cool air that is lifted is moist and unstable, showers and sometimes thunderstorms may develop. The intensity of the weather along the upper front decreases with distance from the apex. Weather conditions change rapidly in occlusions and are usually most severe during the initial stages. However, when the warm air is lifted to higher and higher altitudes, the severe weather activity diminishes. When showers and thunderstorms occur, they are found just ahead and with the upper cold front. Normally, there is clearing weather after the passage of the upper front, but this is not always the case.

Those taken that intersect both fronts show two inversions. The warm type of occlusion (like the cold type) appears on upper air charts at approximately the same pressure level. However, one distinct difference does appear in the location of the warm isotherm ridge associated with occlusions. The warm isotherm ridge lies just to the rear of the occlusion at the peak of its development.

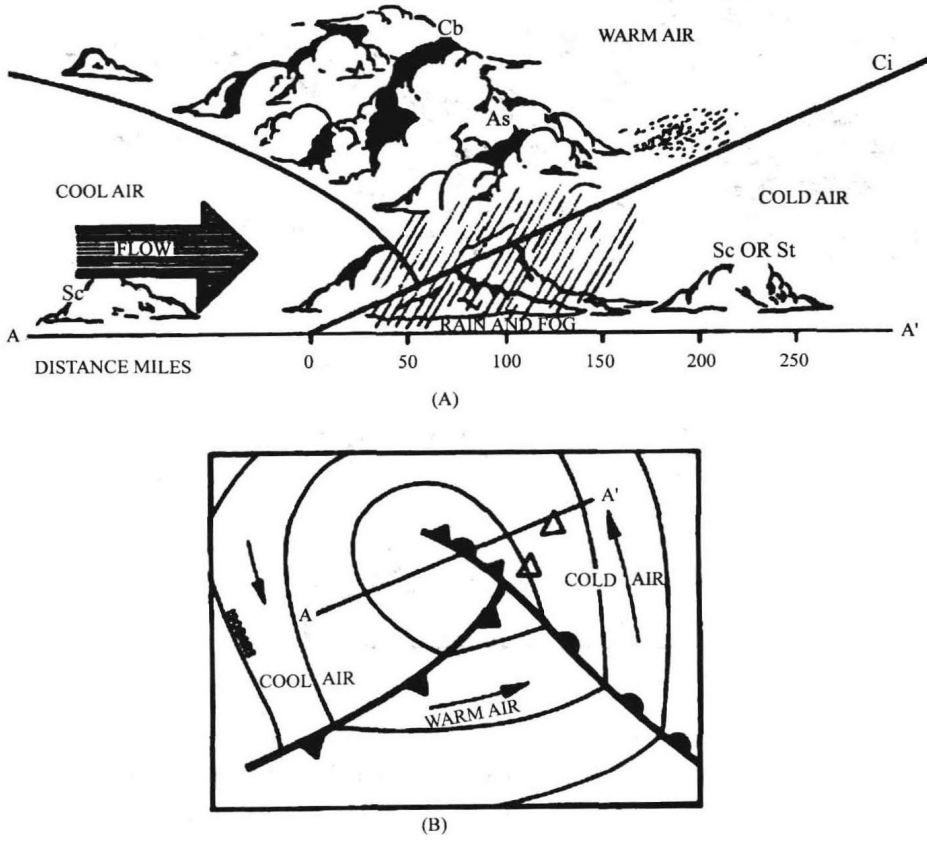


Figure 2.16 Warm Type of Occlusion(A) Vertical Structure through Points A and A'; (B) Horizontal Structure

2.2.4.5 Quasi-Stationary Fronts

A quasi-stationary front, or stationary front as it is often called, is a front along which one air mass is not appreciably replacing another air mass. A stationary front may develop from the slowing down or stopping of a warm or a cold front. When this front forms, the slope of the warm or cold front is initially very shallow. The dense cold air stays on the ground, and the warm air is displaced slowly upward. The front slows or stops moving because the winds behind and ahead of the front become parallel to the stationary front. The front is not making any appreciable head-way in any direction. A front moving less than 5 knots is usually classified as a stationary front.

2.3 Extra-tropical Anticyclone

2.3.1 Outline of Anticyclone

The letter H is used to represent a high pressure area.

A high-pressure area (also called a high or a high-pressure) is a region where the atmospheric pressure at the surface of the planet is greater than its surrounding environment.

Due to the Coriolis Effect, winds flow clockwise around high-pressure systems in the Northern Hemisphere and Counter clockwise in the Southern Hemisphere.

Regions of high-pressure are alternatively referred to as anticyclones. High-pressure areas are generally associated with cooler, drier air as well as clearing skies due to their formation within areas of atmospheric subsidence, or areas of large scale air descent.

Strong, vertically shallow high-pressure systems moving from higher latitudes to lower latitudes in the Northern Hemisphere are associated with continental Arctic air masses.

Once Arctic air moves over an unfrozen ocean, the air mass modifies greatly over the warmer water and takes on the character of a maritime air mass, which reduces the strength of the high-pressure system.

The area of high pressure associated with the descending branch of the Hadley cell, known as the **subtropical high**, sends tropical waves and tropical cyclones across the ocean and is strongest during the summer. The subtropical high also helps form most of the world's deserts. The subtropical high is a warm core high-pressure system, meaning it strengthens with height.

Some climatological high-pressure areas acquire regionally based names. The land-based **Siberian High** often remains quasi-stationary for more than a month during the most frigid time of the year, making it unique in that regard. It is also a bit larger and more persistent than its counterpart in North America.

Surface winds accelerates down valleys down the western Pacific Ocean coastline, causing the winter monsoon. Arctic high-pressure systems such as the Siberian High are cold core, meaning that they weaken with height.

The influence of the **Azores High**, also known as the Bermuda High, brings fair weather over much of the North Atlantic Ocean and mid to late summer heat waves in Western Europe. Along its southerly periphery, the clockwise circulation often impels easterly waves, and tropical cyclones which develop from them, across the ocean towards landmasses in the western portion of ocean

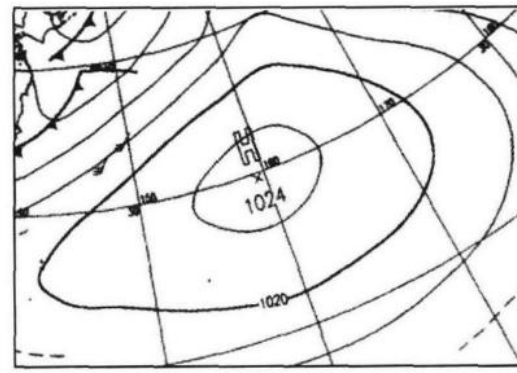


Figure 2.17 Subtropical High

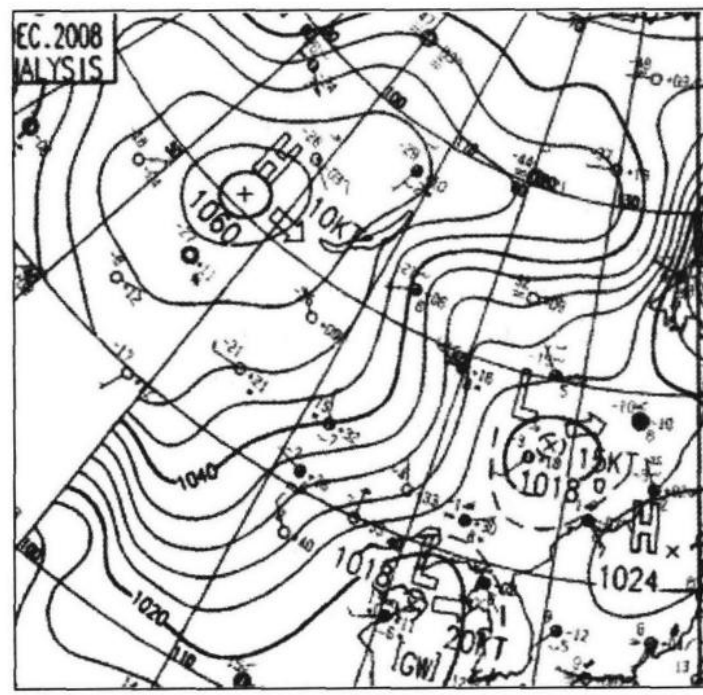


Figure 2.18 Siberian High

basins during the hurricane season.

2.3.2 Siberian High

The Siberian High (also Ruso-Siberian High/Anticyclone) is a massive collection of cold or very cold dry air that forms on the Eurasian terrain for much of the year. It reaches its greatest size and strength in the winter, when the air temperature near the center of the high-pressure cell or anticyclone is often lower than −40 °C. The sea-level pressure (atmospheric pressure) is often above 1,040 hPa.

The Siberian High is the strongest semi-permanent high in the northern hemisphere and is responsible for both the lowest temperature in the Northern Hemisphere, such as −67.8 °C on January15, 1885 at Verkhoyansk and the highest pressure, such as 1,083.8 hPa at Agata, Siberia

on December 31, 1968.

The Siberian High affects the weather patterns in the higher latitudes of the Northern Hemisphere. It may block or reduce the size of low-pressure cells or cyclones and generate dry weather across much of the Eurasian and Canadian landscape.

The Siberian High is responsible both for severe winter cold and attendant dry conditions across most of Siberia.

During the summer, the Siberian High is largely replaced by a low-pressure system, resulting in a summer precipitation maximum across almost all of Siberia.

In general, the Siberian High pressure system begins to build up at the end of August, reaches its peak in the winter, and remains strong until the end of April.

2.3.3 Weather Associated with the Extra-tropical Anticyclone

Based on the different weather characteristics in a cold high, we can divide the high into 3 sections: the leading edge, the center and the rear.

2.3.3.1 The Leading Edge of the Cold High (Eastern Part)

When the cold air surges, the adverse weather occurs near and after the cold front in the leading edge of the cold high where cold advection is strong and the isobars are close. Temperature drops rapidly, strong wind blows (N'ly in the Northern Hemisphere and S'ly in the Southern Hemisphere), and rain or storms frequently occur. The range of the temperature drop and strength of the wind vary with the season, intensity and path of the cold air. The most severe weather occurs in the winter half year. When navigating in high latitudes waters, mariners may encounter ship icing due to the temperature drop.

2.3.3.2 The Center of the Cold High (Middle Part)

In the center of the cold high, the isobars are sparse and the wind is gentle. It is clear, cold due to the cold subsidence air. Sometimes, subsidence of the air can produce a temperature inversion therefore radiation fog, smoke, and haze occur near the harbor and coastal waters. St and Sc cloud may appear in winter and Cu hum cloud may appear in summer. Generally the center weather is sustained for 2 ~ 3 days then the temperature picks up slightly due to the modification of the air mass.

2.3.3.3 The Rear of the Cold Air (Western Part)

Warm, moist air blows (S'ly in Northern Hemisphere and N'ly in Southern Hemisphere) and the weather resembles that of the warm air mass.

In the spring, Chinese coastal areas are under the influence of the rear part of the cold air centering at sea. Advection fog, drizzle and St cloud often occur.

On the average, a cold air activity last 7 days or so. Therefore, there is the proverb "three cold days and four warm days" in the Chinese coastal areas.

2.3.4 Movement of Extra-tropical Anticyclones

The movement of the cold air is under the control of the leading upper air. In general, in the Northern Hemisphere, the cold air moves towards the east or southeast. and in the Southern Hemisphere the cold air moves towards the east or northeast. In practice, there are some different patterns

of the movement: the cold air may move as a unity; or the center keeps stationary but one or two ridges extend; or the extended ridge eventually develops into an independent high center. The cold air center can split during the movement towards the east and south due to the modification of the air. Generally the cold air moves over the sea after passing China and modifies into warm air, and eventually merges into the subtropical high or weakens and dissipates at sea.

2.3.5 Cold Air Grades

During the northeast monsoon, it is of vital importance to forecast cold air surges into the Chinese coastal region and the formation of mid-latitude systems in the East China Sea and the Philippine Sea. During the winter season, cold air from the vicinity of Lake Baikal surges south-southeastward into China and the adjacent waters every 4 ~ 6 days. Based on the rate of temperature fall and the minimum to which it falls, Chinese National Weather Service criteria grades 5 levels of cold air activities.

Grade 1 —weak cold air. The drop of local daily minimum temperature in 48 hours <6 ℃.

Grade 2 —moderate cold air. The drop of local daily minimum temperature in 48 hours $\geqslant 6$ ℃ but < 8 ℃.

Grade 3 —strong cold air. The drop of local daily minimum temperature in 48 hours $\geqslant 8$ ℃, but the daily minimum temperature > 8 ℃.

Grade 4 —stronger cold air. The drop of local daily minimum temperature in 48 hours $\geqslant 8$ ℃, and the daily minimum temperature $\leqslant 8$ ℃.

Grade 5—**cold wave.** The drop of local daily minimum temperature in 24 hours $\geqslant 8$ ℃, or the drop of local daily minimum temperature in 48 hours $\geqslant 10$ ℃, or the drop of local daily minimum temperature in 72 hours $\geqslant 12$ ℃, and the daily minimum temperature $\leqslant 4$ ℃.

Cold wave surges in occur China, Western Europe, Australia and USA.

2.4 Subtropical High

2.4.1 Formation and Distribution

The **subtropical high** is a significant belt of high pressure situated around the latitudes of 30°N in the Northern Hemisphere and 30°S in the Southern Hemisphere. It is characterized by mostly calm winds, which act to reduce air quality under its axis by causing fog overnight, and haze during daylight hours caused by the stable atmosphere found near its location. Air flows out from its center toward the upper and lower latitudes of each hemisphere, creating both the Trade Winds and the Westerlies. It moves pole-ward during the summer, reaching its most northern latitude in early fall, before moving equator-ward during the cold season.

Heating of the Earth near the equator leads to large amounts of upward motion and convection along the monsoon trough or Intertropical Convergence Zone. The divergence over the near-equatorial trough leads to air rising and moving away from the equator. As it moves towards the Mid-Latitudes, the air cools and sinks, which leads to subsidence near the 30th parallel of both hemispheres. This circulation is known as the Hadley cell and leads to the formation of the subtropical high. Many of the world's deserts are caused by these climatological high-pressure areas.

2.4.2 Monitoring of the Northwest Pacific Subtropical High

Area index: sum of the grids of geopotential height ≥ 5,880 gpm in 500 hPa geoptential height field, within the area north of 10°N, and between 110°E and 180°E.

Intensity index: sum of the differences of grid geopotential height value minus 5,870 at those grids whose geopotential height ≥ 5,880 gpm, within the area north of 10°N, and between 110°E and 180°E.

Ridge line index: the mean of latitudes at the grids with the maximum geopotential height value, for those grids whose geopotential height ≥ 5,880 gpm on the specified longitudes on the east-west ridge line.

Northern margin index: the mean of the northernmost latitude grids in the 5,880 gpm contour line on the specified longitudes, within the area north of 10°N, and between 110°E and 180°E.

Western ridge point index: the longitude value of the westernmost grid in the 5,880 gpm contour line between 110°E and 180°E. If the grid lies west of 90°E, the value is recorded as 90°E.

Generally, the clear area in the satellite chart coincides with the area rounded by the 5,880 gpm contour line on a 500 hPa chart.

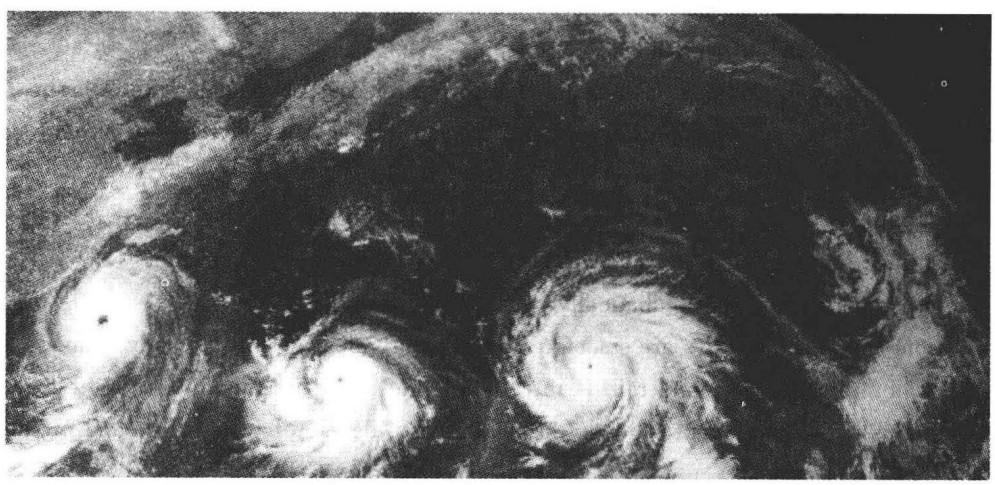


Figure 2.19 The Subtropical High Shows up as a Large Area of Dryness on a Satellite Image

2.4.3 Migration of Subtropical High

The subtropical high starts migrating pole-ward in late spring reaching its zenith in early autumn, before retreating equator-ward during the late fall, winter, and early spring. The equator-ward migration of the subtropical high during the cold season is due to increasing north-south temperature differences between the poles and tropics. The latitudinal movement of the subtropical high is strongly correlated to the progression of the monsoon trough or Intertropical Convergence Zone.

Most tropical cyclones form on the side of the subtropical high closer to the equator, then move pole ward past the ridge axis before recurving into the main belt of the Westerlies. During the Northern Hemisphere hurricane season (June 1 to November 30), tropical systems must move west under the Atlantic or Pacific high pressure before they can recurve to the north. Knowing where the high sits is critical in avoiding a hurricane in your travels.

2.4.4 Subtropical High Weather

When the subtropical high in the northwest Pacific is stronger than normal, it leads to a wet monsoon season for Asia. The subtropical high position is linked to how far northward monsoon moisture and thunderstorms extend into the United States.

When surface winds become light, the subsidence produced directly under the subtropical high can lead to a build up of particulates in urban areas under the ridge, leading to widespread haze. If the low level relative humidity rises towards 100 percent overnight, fog can form.

Typical weather conditions one may encounter in air masses around the subtropical highs are as follows:

1. North of a subtropical high. Any mT air that moves northward becomes cooled over the cool ocean surface. A stratus overcast may form, and drizzle may fall. Farther north, low ceilings (usually below 300 m) may reach the surface, producing fog. The mT air surges farthest north in summer because subtropical highs are best developed and polar fronts lie farthest north. This mT air brings most of the summer fogginess to northern seas and coasts. It brings the greatest fogginess to the Atlantic where it blows from the warm Gulf Stream over the cold Labrador current (near Newfoundland), and in the Pacific where it blows from the warm Kuroshio current over the cold Oyashio current (near the Kamchatka peninsula).

2. East of a subtropical high. Along the California a coast, and along the Atlantic coast of North Africa, the mT air blows from the west and the northwest. This air tends to remain stable for the following reasons:

a. It is coming from the northern, cooler portion of the source region;

b. Its surface layers remain cool because it moves over cold ocean currents;

c. Its upper portions warm adiabatically because of subsidence.

Throughout the year, airways are smooth. The skies are clear to partly cloudy. Clouds are generally patches of stratocumulus, and rain is rare. The chief hazard in this air is coastal fog. Stratus and stratocumulus clouds may cause the sky to be overcast, develop low ceilings, and produce drizzle that reduces visibility.

3. South of a subtropical high. Where the mT air moves southward or southwestward (as Trade Winds), its lower layers are warmed by the tropical ocean surface. This produces scattered cumulus. Near the equator, after absorbing much moisture and being heated, this air may develop cumulonimbus.

4. West of a subtropical high. This mT air blows from the east and the southeast. Since it flows over warm water all of the way, the air neither cools nor warms. Over the ocean near the Philippines (and near Florida and the West Indies), this Trade Wind brings good weather-clear or scattered cumulus clouds. When it is moving over land, this warm, moist air becomes unstable and turbulent and is a source of thunderstorms. When it moves over cold land (for example, southeastern United States in the winter), it becomes stable and produces stratus clouds or fog. Over cold ocean surfaces, such as the Sea of Japan, and the Kamchatka and Labrador currents, it develops the persistent low stratus and fogs characteristic of these areas.

2.5 Extratropical Cyclone

2.5.1 Outline of Extratropical Cyclone

Extratropical cyclones, sometimes called mid-latitude cyclones or wave cyclones, are a group of cyclones defined as synoptic scale low pressure weather systems that occur in the middle latitudes of the Earth (outside the tropics) having neither tropical nor polar characteristics, and are connected with fronts and horizontal gradients in temperature and dew point.

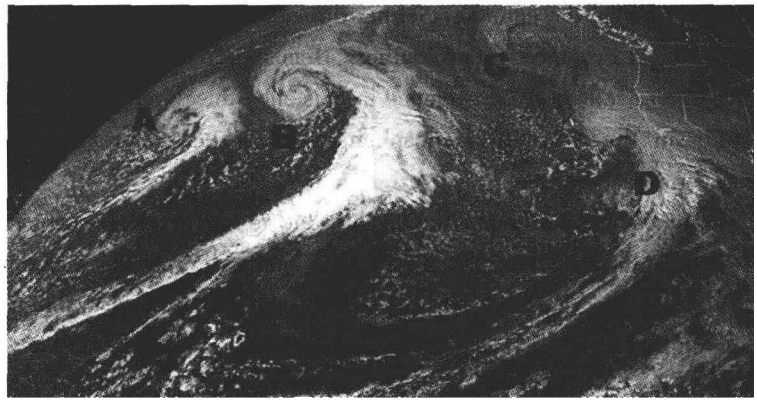


Figure 2.20 Frontal Cyclones Sample

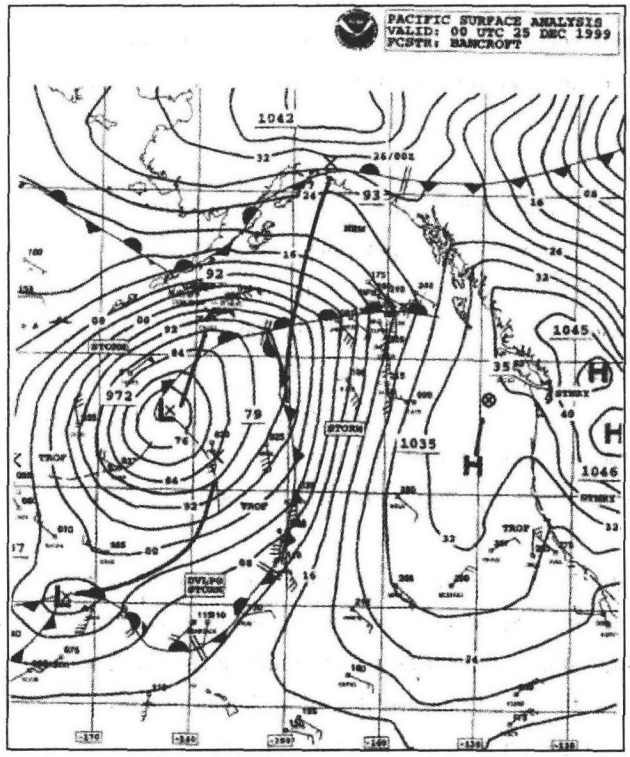


Figure 2.21 Frontal Cyclone Sample

Weather forecasters and the general public often describe them as "depressions" or "lows". Terms like frontal cyclone, frontal depression, frontal low, extratropical low, and non-tropical low are often used as well.

Extratropical cyclones are the everyday phenomena which, along with anticyclones, drive the weather over much of the Earth, producing anything from cloudiness and mild showers to heavy gales and thunderstorms.

Extratropical cyclones form anywhere within the extratropical regions of the Earth (usually between 30° and 60° latitude from the equator), either through cyclogenesis or extratropical transition.

A study of extratropical cyclones in the Southern Hemisphere shows that between the 30th and 70th parallels, there is an average of 37 cyclones in existence during any 6-hour period.

A separate study in the Northern Hemisphere suggests that approximately 234 significant extratropicalcyclones form each winter.

A rapidly falling atmospheric pressure is possible due to strong upper level forces on the system, and when pressures fall more than 1 hPa per hour, such a cyclone is sometimes referred to as a **bomb.** These bombs rapidly drop in pressure to below 980 hPa under favorable conditions such as near a natural temperature gradient like the Gulf Stream and Kuroshio.

The stronger the upper level divergence over the cyclone, the deeper the cyclone can become. Hurricane-force extratropical cyclones are most likely to form in the North Atlantic and northern Pacific oceans in the months of December and January. On 14 and 15 December 1986, an extratropical cyclone near Iceland deepened to below 920 hPa, which is a pressure equivalent to a category 5 hurricane. In the Arctic, the average pressure for cyclones is 988 hPa during the winter and 1,000 hPa during the summer.

2.5.2 Cyclogenesis

Cyclogenesis is a term that refers to the development of a particular a weather system. Mid-latitude cyclogenesis often occurs when an upper trough of intermediate wavelength interacts with a surface frontal zone. The low pressure system grows in the presence of vertical wind shear (winds increasing with height) and thermal instability (convection). The factors that lead to a lowering of the pressure at the surface are:

Diverging airflow at high altitudes that reduces the mass of the air over the surface low;

Inflow of warm, moist air at low and mid levels;

Latent heat release caused by convection in the warm air mass sector of the growing storm system.

When these conditions exist together, a storm system is most likely to develop. The most common type of cyclogenesis is referred to as leaf-to-comma cyclogenesis. This type of storm development begins with a cloud system known as a leaf cloud, and concludes with a comma-shaped cloud system. An illustration of the cloud patterns that form during this type of cyclogenesis can be seen in the following diagrams. It should be noted that there are many types of cyclogenesis, and each storm is unique when studied in detail.

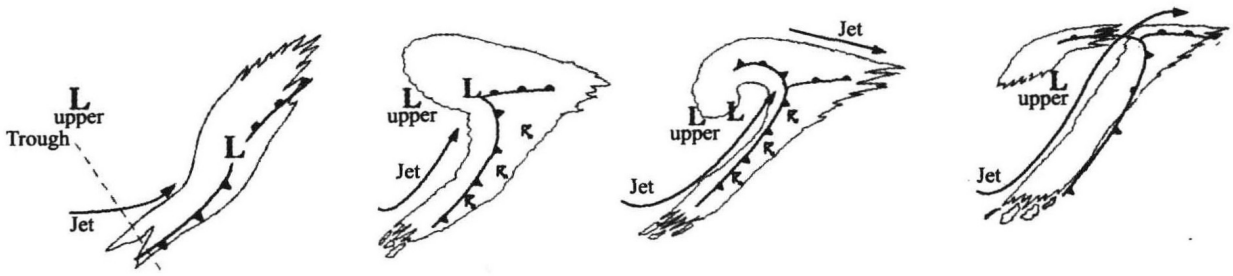


Figure 2.22 Norwegian Cyclogenesis Model

2.5.3 Weather Associated with Extratropical Cyclones

Figure 2.23(a) describes the patterns of wind flow, surface pressure, fronts, and zones of precipitation associated with a mid-latitude cyclone in the Northern Hemisphere. Around the low, winds blow counterclockwise and inwards (clockwise and inward in the Southern Hemisphere). West of the low, cold air traveling from the north and northwest creates a cold front extending from the cyclone's center to the southwest. Southeast of the low, northward moving warm air from the subtropics produces a warm front. Precipitation is located at the center of the low and along the fronts where air is being uplifted.

Mid-latitude cyclones can produce a wide variety of precipitation types. Precipitation types include: rain, freezing rain, hail, sleet, snow pellets, and snow. Frozen forms of precipitation (except hail) are common with storms that occur in the winter months. Hail is associated with severe thunderstorms that form along or in front of cold fronts during spring and summer months.

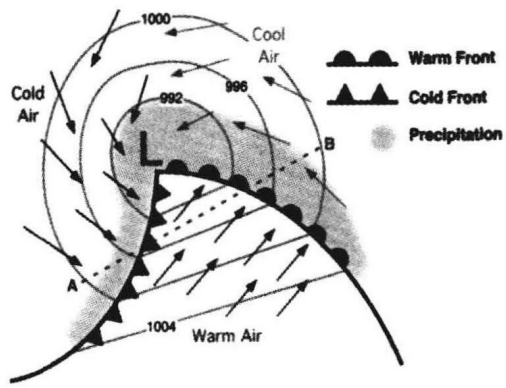


Figure 2.23(a) Fronts, Winds Patterns, Pressure Patterns

Figure 2.23(b) describes a vertical cross-section through a mature mid-latitude cyclone. In this cross-section, we can see how air temperature changes as we move from behind the cold front to a position ahead of the warm front. Behind the surface position of the cold front, forward moving cold dense air causes the uplift of the warm lighter air in advance of the front. Because this uplift is relatively rapid along a steep frontal gradient, the condensed water vapor quickly forms into cumulus and then cumulonimbus clouds. Cumulonimbus clouds produce heavy precipitation and can develop into severe thunderstorms if conditions are right. Along the gently sloping warm front, the lifting of moist air produces, first nimbostratus clouds followed by altostratus and cirrostratus. Precipitation is

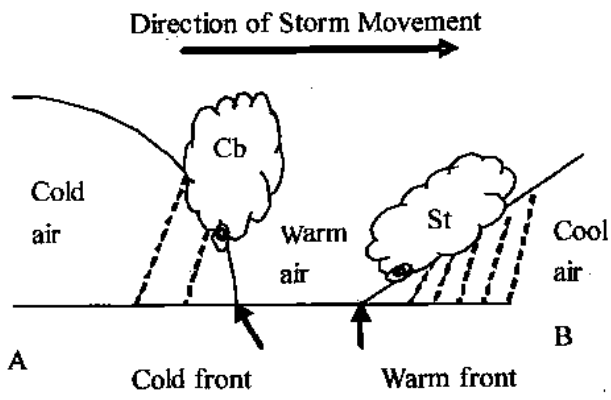


Figure2.23(b) Vertical Cross-section of the Line and Precipitation Distribution Found in an Idealized A-B in Figure 2.23(a) Mature Mid-latitude Cyclone

less intense along this front, varying from moderate to light showers some distance ahead of the surface location of the warm front.

2.5.4 Cyclone Tracking

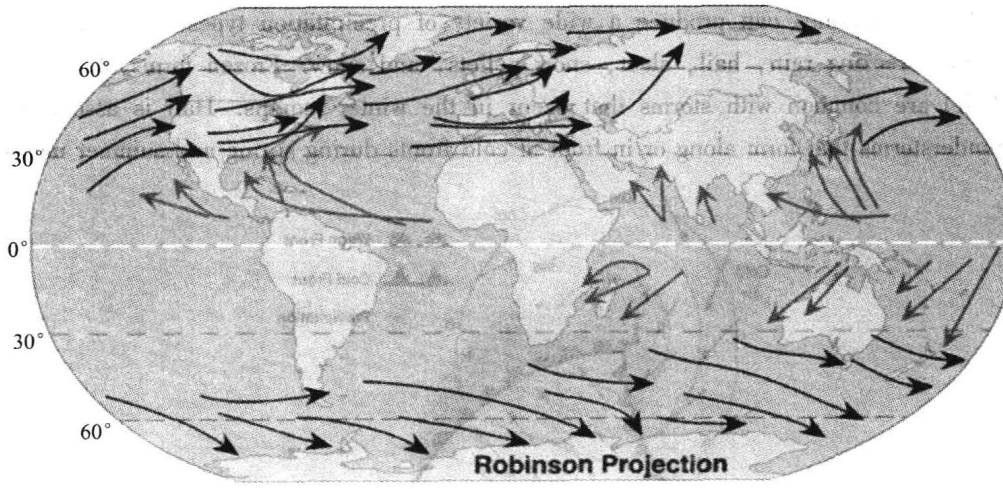


Figure 2.24 Typical Paths of Mid-latitude Cyclones are Represented Black Arrows. This Image also Shows the Typical Paths Traveled by Subtropical Hurricanes.

2.6 Tropical Cyclones

2.6.1 Outline of Tropical Cyclone

A tropical cyclone is a storm system characterized by a large low-pressure center and numerous thunderstorms that produce strong winds and heavy rain. Tropical cyclones feed on heat released when moist air rises, resulting in condensation of water vapor contained in the moist air. They are fueled by a different heat mechanism from other cyclonic windstorms such as European windstorms, and polar lows, leading to their classification as "warm core" storm systems. Tropical cyclones originate in the doldrums near the equator, and 10° north or south.

All tropical cyclones are areas of low atmospheric pressure near the Earth's surface. The pressures recorded at the centers of tropical cyclones are among the lowest that occur on the Earth's surface at sea level. Tropical cyclones are characterized and driven by the release of large amounts of latent heat of condensation, which occurs when moist air is carried upwards and its water vapor condenses. This heat is distributed vertically around the center of the storm. Thus, at any given altitude (except close to the surface, where water temperature dictates air temperature) the environment inside the cyclone is warmer than its outer surroundings.

The term "tropical" refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their formation in maritime tropical air masses. The term "cyclone" refers to such storms' cyclonic nature, with counterclockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere.

Depending on its location and strength, a tropical cyclone is referred to by names such as **hurricane**, **typhoon**, **tropical storm**, **cyclonic storm**, **tropical depression**, and simply **cyclone.**

While tropical cyclones can produce extremely powerful winds and torrential rain, they are also able to produce high waves and damaging storm surges as well as spawning tornadoes. They develop over large bodies of warm water, and lose their strength if they move over land. This is why coastal regions can receive significant damage from a tropical cyclone, while inland regions are relatively safe from receiving strong winds.

Tropical cyclones out at sea cause large waves, heavy rain, and high winds, disrupting international shipping and, at times, causing shipwrecks. Tropical cyclones stir up water, leaving a cool wake behind them, which causes the region to be less favorable for subsequent tropical cyclones.

On land, strong winds can damage or destroy vehicles, buildings, bridges, and other outside objects, turning loose debris into deadly flying projectiles. The storm surge, or the increase in sea level due to the cyclone, is typically the worst effect from landfalling tropical cyclones, historically resulting in 90% of tropical cyclone deaths. The broad rotation of a landfalling tropical cyclone, and vertical wind shear at its periphery, creates tornadoes. Tornadoes can also be created as a result of eyewall mesovortices, which persist until landfall.

Over the past two centuries, tropical cyclones have been responsible for the deaths of about 1.9 million people worldwide. Large areas of standing water caused by flooding lead to infection, as well as contributing to mosquito-borne illnesses. Crowded evacuees in shelters increase the risk of disease propagation. Tropical cyclones significantly interrupt infrastructure, leading to power outages, bridge destruction, and the hampering of reconstruction efforts.

Although cyclones take an enormous toll in lives and personal property, they may be important factors in the precipitation regimes of places they impact, as they may bring much-needed precipitation to otherwise dry regions. Tropical cyclones also help maintain the global heat balance by moving warm, moist tropical air to the middle latitudes and polar regions. The storm surge and winds of hurricanes may be destructive to human-made structures, but they also stir up the waters of coastal estuaries, which are typically important fish breeding locales. Tropical cyclone destruction spurs redevelopment, greatly increasing local property values.

2.6.2 Locations and Seasons

Most tropical cyclones form in a worldwide band of thunderstorm activity called by several names: the **Intertropical Front** (ITF), the **Intertropical Convergence Zone** (ITCZ), or the monsoon trough. Another important source of atmospheric instability is found in tropical waves, which cause about 85% of intense tropical cyclones in the Atlantic Ocean, and cause most of the tropical cyclones in the eastern Pacific basin.

Tropical cyclones move westward when equatorward of the subtropical ridge, intensifying as they move. Most of these systems form between 10 and 30 degrees away from the equator, and 87% form no farther away than 20 degrees of latitude, north or south. Because the Coriolis Effect initiates and maintains tropical cyclone rotation, tropical cyclones rarely form or move within about 5 degrees of the equator, where the Coriolis effect is weakest. However, it is possible for tropical cyclones to form within this boundary as Tropical Storm Vamei did in 2001 and Cyclone Agni in 2004.

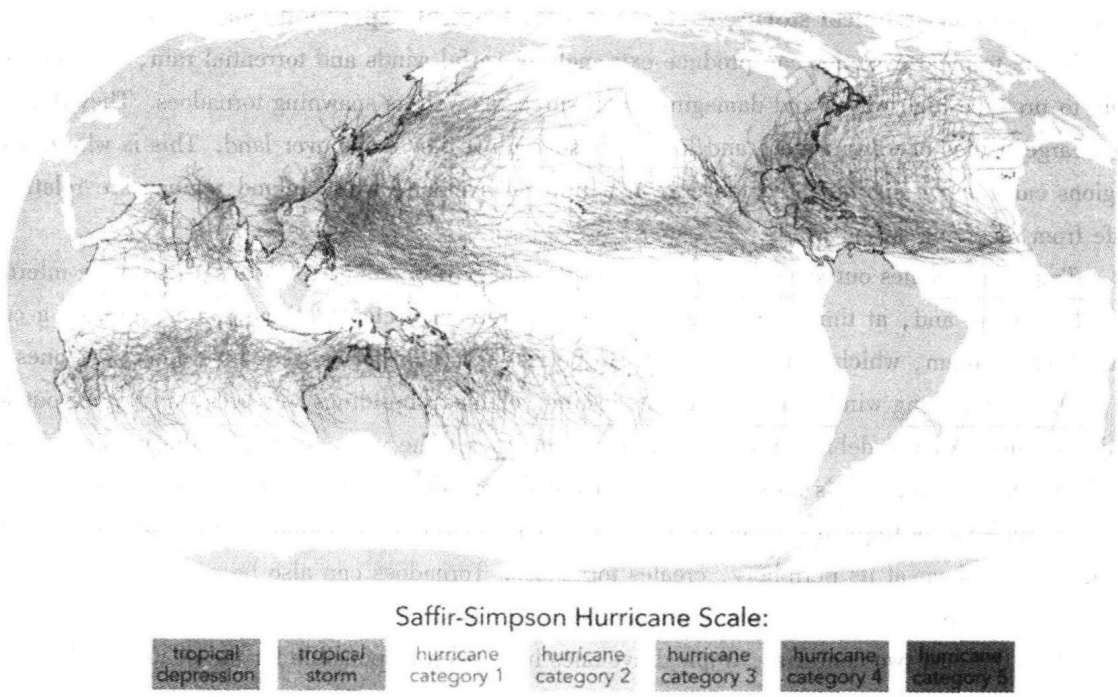


Figure 2.25 All Tropical Cyclone Tracks from 1945 to 2006

There are six Regional Specialized Meteorological Centers (RSMCs) worldwide. These organizations are designated by the World Meteorological Organization (WMO) and are responsible for tracking and issuing bulletins, warnings, and advisories about tropical cyclones in their designated areas of responsibility. Additionally, there are six Tropical Cyclone Warning Centers (TCWCs) that provide information to smaller regions. The RSMCs and TCWCs are not the only organizations that provide information about tropical cyclones to the public. The Joint Typhoon Warning Center (JTWC) issues advisories in all basins except the Northern Atlantic for the purposes of the United States Government. The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) issues advisories and names for tropical cyclones that approach the Philippines in the

northwestern Pacific to protect the lives and property of its citizens. The Canadian Hurricane Center (CHC) issues advisories on hurricanes and their remnants for Canadian citizens when they affect Canada.

On 26 March 2004, Cyclone Catarina became the first recorded South Atlantic cyclone and subsequently struck southern Brazil with winds equivalent to Category 2 on the Saffir-Simpson Hurricane Scale. Because the cyclone formed outside the authority of another warning center, Brazilian meteorologists initially treated the system as an extratropical cyclone, although subsequently classified it as tropical.

Worldwide, tropical cyclone activity peaks in late summer, when the difference between temperatures aloft and sea surface temperatures is the greatest. However, each particular basin has its own seasonal patterns. On a worldwide scale, May is the least active month, while September is the most active whilst November is the only month when all the tropical cyclone basins are active.

Table 2.3 Basins and WMO Monitoring Institutions

Basin	Responsible RSMCs and TCWCs
North Atlantic	National Hurricane Center (United States)
North-East Pacific	National Hurricane Center (United States)
North-Central Pacific	Central Pacific Hurricane Center (United States)
North-West Pacific	Japan Meteorological Agency
North Indian Ocean	India Meteorological Department
South-West Indian Ocean	Météo-France
Australian region	Bureau of Meteorology* (Australia) Meteorological and Geophysical Agency (Indonesia) Papua New Guinea National Weather Service
Southern Pacific	Fiji Meteorological Service Meteorological Service of New Zealand?
* : ***Indicates a Tropical Cyclone Warning Center***	

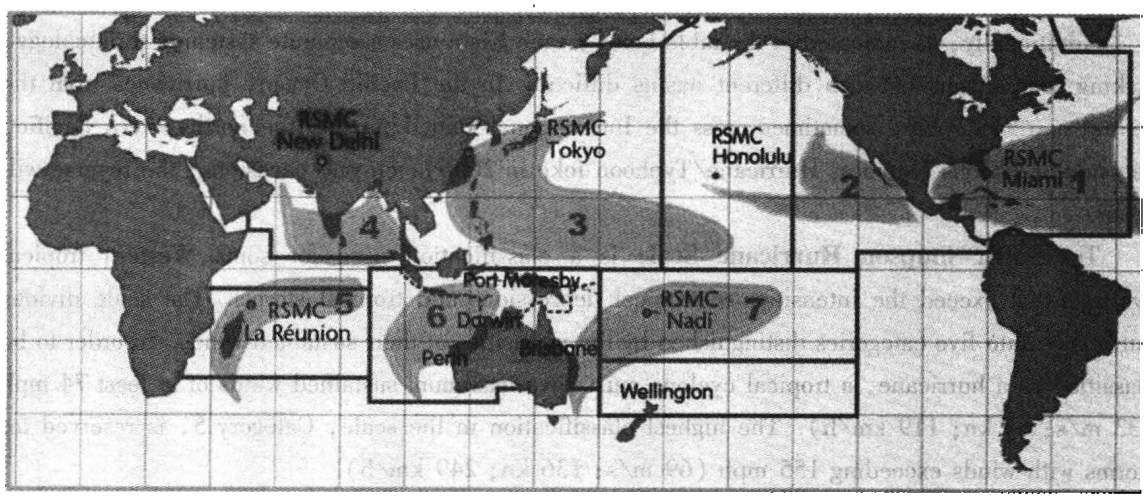


Figure 2.26 Six Regional Specialized Meteorological Centers

In the North Atlantic Ocean, a distinct hurricane season occurs from June 1 to November 30, sharply peaking from late August through to September. The statistical peak of the Atlantic hurricane

season is the 10th of September. The northeastern Pacific Ocean has a broader period of activity, but in a similar time frame to the Atlantic. The northwestern Pacific sees tropical cyclones year-round, with a minimum in February and March, and a peak in early September. In the northern Indian basin, storms are most common from April to December, with peaks in May and November. In the Southern Hemisphere, the tropical cyclone year begins on July 1 and runs all year round and encompasses the tropical cyclone seasons which run from November 1st until the end of April, with peaks in mid-February to early March.

Table 2.4 Season Lengths and Seasonal Averages

Basin	Season start	Season end	Tropical Storms (>34 knots)	Tropical Cyclones (>63 knots)	Category 3 + TCs (>95 knots)
Northwest Pacific	Apr.	Jan.	26.7	16.9	8.5
South Indian	Nov.	Apr.	20.6	10.3	4.3
Northeast Pacific	May	Nov.	16.3	9.0	4.1
North Atlantic	Jun.	Nov.	10.6	5.9	2.0
Australia Southwest Pacific	Nov.	Apr.	9	4.8	1.9
North Indian	Apr.	Dec.	5.4	2.2	0.4

2.6.3 Classifications, Terminology and Naming

Tropical cyclones are classified into three main groups, based on intensity: tropical depressions, tropical storms, and a third group of more intense storms, whose name depends on the region. For example, if a tropical storm in the northwestern Pacific reaches hurricane-strength winds on the Beaufort Scale, it is referred to as a typhoon; if a tropical storm passes the same benchmark in the northeastern Pacific Basin, or in the Atlantic, it is called a hurricane. Neither "hurricane" nor "typhoon" is used in either the Southern Hemisphere or the Indian Ocean. In these basins, storms of tropical nature are referred to as simply "cyclones".

Additionally, as indicated in the table below, each basin uses a separate system of terminology, making comparisons between different basins difficult. In the Pacific Ocean, hurricanes from the central northern Pacific sometimes cross the International Date Line into the northwestern Pacific, becoming typhoons (such as Hurricane/Typhoon Ioke in 2006); on rare occasions, the reverse will occur.

The **Saffir-Simpson Hurricane Scale** is a classification used for some Western tropical cyclones that exceed the intensities of tropical depressions and tropical storms. The scale divides hurricanes into five categories distinguished by the intensities of their sustained winds. In order to be classified as a hurricane, a tropical cyclone must have maximum sustained winds of at least 74 mph (33 m/s; 64 kn; 119 km/h). The highest classification in the scale, Category 5, is reserved for storms with winds exceeding 155 mph (69 m/s; 136 kn; 249 km/h).

Table 2.5 Saffir-Simpson Hurricane Scale

Category	Wind speed	Storm surge
	mph (km/h)	ft(m)
5	≥156 (≥250)	>18 (>5.5)
4	131 – 155 (210 – 249)	13 – 18 (4.0 – 5.5)
3	111 – 130 (178 – 209)	9 – 12 (2.7 – 3.7)
2	96 – 110 (154 – 177)	6 – 8 (1.8 – 2.4)
1	74 – 95 (119 – 153)	4 – 5 (1.2 – 1.5)
Additional classifications		
Tropical storm	39 – 73 (63 – 117)	0 – 3 (0 – 0.9)
Tropical depression	0 – 38 (0 – 62)	0 (0)

A tropical depression is an organized system of clouds and thunderstorms with a defined, closed surface circulation and maximum sustained winds of less than 17 m/s (33 kn) or 39 miles per hour (63 km/h). It has no eye and does not typically have the organization or the spiral shape of more powerful storms. However, it is already a low-pressure system, hence the name "depression".

The practice of the Philippines is to name tropical depressions from their own naming convention when the depressions are within the Philippines' area of responsibility.

A tropical storm is an organized system of strong thunderstorms with a defined surface circulation and maximum sustained winds between 17 metres per second (33 kn) (39 miles per hour (63 km/h)) and 32 m/s (62 kn) (73 miles per hour (117 km/h)). At this point, the distinctive cyclonic shape starts to develop, although an eye is not usually present.

Government weather services, other than the Philippines, first assign names to systems that reach this intensity.

A hurricane or typhoon (sometimes simply referred to as a tropical cyclone, as opposed to a depression or storm) is a system with sustained winds of at least 33 m/s (64 kn) or 74 miles per hour (119 km/h).

A cyclone of this intensity tends to develop an eye, an area of relative calm (and lowest atmospheric pressure) at the center of circulation. The eye is often visible in satellite images as a small, circular, cloud-free spot. Surrounding the eye is the eyewall, an area about 16 kilometres to 80 kilometres wide in which the strongest thunderstorms and winds circulate around the storm's center.

Maximum sustained winds in the strongest tropical cyclones have been estimated at about 85 m/s (165 kn) or 195 miles per hour (314 km/h).

Table 2.6 Tropical Cyclone Classifications (All Winds are 10 – minute Averages)

<table>
<tr><th>Beau-fort scale</th><th>10-minute sustained winds (knots)</th><th>N Indian Ocean IMD</th><th>SW Indian Ocean MF</th><th>Australia BOM</th><th>SW Pacific FMS</th><th>NW Pacific JMA</th><th>NW Pacific JTWC</th><th>NE Pacific & N Atlantic NHC, CHC & CPHC</th></tr>
<tr><td>0-6</td><td><28 knots</td><td>Depression</td><td>Trop. Disturbance</td><td rowspan="3">Tropical Low</td><td rowspan="3">Tropical Depression</td><td rowspan="3">Tropical Depression</td><td rowspan="2">Tropical Depression</td><td rowspan="2">Tropical Depression</td></tr>
<tr><td rowspan="2">7</td><td>28-29 knots</td><td rowspan="2">Deep Depression</td><td rowspan="2">Depression</td></tr>
<tr><td>30-33 knots</td><td rowspan="3">Tropical Storm</td><td rowspan="3">Tropical Storm</td></tr>
<tr><td>8-9</td><td>34-47 knots</td><td>Cyclonic Storm</td><td>Moderate Tropical Storm</td><td>Tropical Cyclone (1)</td><td rowspan="8">Tropical Cyclone</td><td>Tropical Storm</td></tr>
<tr><td>10</td><td>48-55 knots</td><td rowspan="2">Severe Cyclonic Storm</td><td rowspan="2">Severe Tropical Storm</td><td rowspan="2">Tropical Cyclone (2)</td><td rowspan="2">Severe Tropical Storm</td><td rowspan="5">Typhoon</td></tr>
<tr><td>11</td><td>56-63 knots</td><td>Hurricane (1)</td></tr>
<tr><td rowspan="7">12</td><td>64-72 knots</td><td rowspan="7">Very Severe Cyclonic Storm</td><td rowspan="3">Tropical Cyclone</td><td rowspan="2">Severe Tropical Cyclone (3)</td><td rowspan="6">Typhoon</td><td>Hurricane (2)</td></tr>
<tr><td>73-85 knots</td><td rowspan="3">Major Hurricane (3)</td></tr>
<tr><td>86-89 knots</td><td rowspan="3">Severe Tropical Cyclone (4)</td></tr>
<tr><td>90-99 knots</td><td rowspan="3">Intense Tropical Cyclone</td></tr>
<tr><td>100-106 knots</td><td rowspan="4">Major Hurricane (4)</td></tr>
<tr><td>107-114 knots</td><td rowspan="3">Severe Tropical Cyclone (5)</td></tr>
<tr><td>115-119 knots</td><td rowspan="2">Very Intense Tropical Cyclone</td><td rowspan="2">Super Typhoon</td></tr>
<tr><td>>120 knots</td><td>Super Cyclonic Storm</td><td>Major Hurricane (5)</td></tr>
</table>

WMO divides the naming system into 9 areas: NW Pacific, Central North Pacific, NE Pacific, North Atlantic, North Indian Ocean, SW Indian Ocean, the NW, N and NE of Australia. In each area, there is a naming list.

The lists are decided on, depending on the regions, either by committees of the World Meteorological Organization, or by national weather offices involved in the forecasting of the storms. Each year, the names of particularly destructive storms (if there are any) are "retired" and new names are chosen to take their place.

Table 2.7 Tropical Cyclone Naming Lists in NW Pacific

List 1	List 2	List 3	List 4	List 5	Note
English/Chinese	English/Chinese	English/Chinese	English/Chinese	English/Chinese	Source
Damrey/达维	Kong－rey/康妮	Nakri/娜基莉	Krovanh/科罗旺	Sarika/莎莉嘉	Cambodia
Haikui/海葵	Yutu/玉兔	Fengshen/风神	Dujuan/杜鹃	Haima/海马	China
Kirogi/鸿雁	Toraji/桃芝	Kalmaegi/海鸥	Mujigae 彩虹	Meari/米雷	Korea DPR
Kai-tak/启德	Man-yi/万宜	Fung-wong/凤凰	Choi-wan/彩云	Ma-on/马鞍	Hong Kong
Tembin/天秤	Usagi/天兔	Kammuri/北冕	Koppu/巨爵	Tokage/蝎虎	Japan
Bolaven/布拉万	Pabuk/帕布	Phanfone/巴蓬	Ketsana/凯萨娜	Nock-ten/洛坦	Laos
Chanchu/珍珠	Wutip/蝴蝶	Vongfong/黄蜂	Parma/芭玛	Muifa/梅花	Macau
Jelawat/杰拉华	Sepat/圣帕	Nuri/鹦鹉	Melor/茉莉	Merbok/苗柏	Malaysia
Ewiniar/艾云尼	Fitow/菲特	Sinlaku/森拉克	Nepartak/尼伯特	Nanmadol/南玛都	Micronesia FM
Bilis/碧利斯	Danas/丹娜丝	Hagupit/黑格比	Lupit/卢碧	Talas/塔拉斯	Phillipine
Kaemi/格美	Nari/百合	Changmi/蔷薇	Mirinae/银河	Noru/奥鹿	Korea
Prapiroon/派比安	Wipha/韦帕	Mekkhala/米克拉	Nida/妮妲	Kulap/玫瑰	Thailand
Maria/玛莉亚	Francisco/范斯高	Higos/海高斯	Omais/奥麦斯	Roke/洛克	USA
Saomai/桑美	Lekima/利奇马	Bavi/巴威	Conson/康森	Sonca/桑卡	Vietnam
Bopha/宝霞	Krosa/罗莎	Maysak/美莎克	Chanthu/灿都	Nesat/纳沙	Cambodia
Wukong/悟空	Haiyan/海燕	Haishen/海神	Dianmu/电母	Haitang/海棠	China
Sonamu/清松	Podul/杨柳	Noul/红霞	Mindulle/蒲公英	Nalgae/尼格	Korea DPR
Shanshan/珊珊	Lingling/玲玲	Dolphin/白海豚	Lionrock/狮子山	Banyan/榕树	Hong Kong
Yagi/摩羯	Kajiki/剑鱼	Kujira/鲸鱼	Kompasu/圆规	Washi/天鹰	Japan
Xangsane/象神	Faxai/法茜	Chan-hom/灿鸿	Namtheun/南川	Pakhar/帕卡	Laos
Bebinca/贝碧嘉	Peipah/琵琶	Linfa/莲花	Malou/玛瑙	Sanvu/珊瑚	Macau
Rumbia/温比亚	Tapah/塔巴	Nangka/浪卡	Meranti/莫兰蒂	Mawar/玛娃	Malaysia
Soulik/苏力	Mitag/米娜	Soudelor/苏迪罗	Fanapi/凡亚比	Guchol/古超	Micronesia FM
Cimaron/西马仑	Hagibis/海贝思	Molave/莫拉菲	Malakas/马勒卡	Talim/泰利	Phillipine
Chebi/飞燕	Noguri/浣熊	Koni/天鹅	Megi/鲇鱼	Doksuri/杜苏芮	Korea
Durian/榴莲	Ramasun/威马逊	Morakot/莫拉克	Chaba/暹芭	Khanun/卡努	Thailand
Utor/尤特	Matmo/麦德姆	Etau/艾涛	Aere/艾利	Vicente/韦森特	USA
Trami/潭美	Halong/夏浪	Vamco/环高	Songda/桑达	Saola/苏拉	Vietnam

Note: New names for the "retired" names

海葵——龙王 Longwang; 琵琶——画眉 Vamei; 麦德姆——查特安 Chataan
鹦鹉——鹿莎 Rusa; 红霞——凤仙 Pongsona; 白海豚——欣欣 Yanyan;
莫拉菲——伊布都 Imbudo; 莫拉克——翰文 Hanuman; 彩虹——鸣蝉 Maemi;
银河——苏特 Sudal; 狮子山——婷婷 Tingting; 凡亚比——云娜 Rananim;
艾利——库都 Kodo; 帕卡——麦莎 Matsa; 杜苏芮——彩蝶 Nabi.

2.6.4 Chinese Warning System

A two-stage warning system has been long-established in China for tropical cyclones of tropical storm intensity or above.

Warning: Winds may reach Beaufort Force 8 and rainstorms may occur in 48 hours.

Urgent Warning: Winds may reach Beaufort Force 8 and rainstorms may occur in 24 hours.

Nowadays, the use of this system is restricted to coastal waters only. Thus, similar to the US

system, warnings may be discontinued even if the cyclone is maintaining tropical storm intensity inland. However, color-coded alerts (mentioned below) may be in effect.

China Meteorological Administration standardized the system for national use. This set is part of a larger warning system that covers other forms of severe weather conditions, such as extreme temperature. torrential rainfall, drought, etc.

Figure 2.27 Color-coded Alerts of Tropical Cyclones

Blue alert: Winds may reach Beaufort Force 6 in 24 hours, or winds of Beaufort Force 6 ~ 7 are already blowing.

Yellow alert: Winds may reach Beaufort Force 8 in 24 hours, or winds of Beaufort Force 8 ~ 9 (gale force) are already blowing.

Orange alert: Winds may reach Beaufort Force 10 in 12 hours, or winds of Beaufort Force 10 ~ 11 (storm force) are already blowing.

Red alert: Winds may reach Beaufort Force 12 in 6 hours, or winds of Beaufort Force 12 (hurricane force) are already blowing.

Note that Guangdong has maintained a white alert as in the old system, which means a tropical cyclone may affect its area within 48 hours.

2.6.5 Conditions Necessary for the Formation of TCs

The formation of tropical cyclones is the topic of extensive ongoing research and is still not fully understood. While six factors appear to be generally necessary, tropical cyclones may occasionally form without meeting all of the following conditions.

In most situations, water temperatures of at least 26.5 °C (79.7 °F) are needed down to a depth of at least 50 m (160 ft); water at this temperature causes the overlying atmosphere to be unstable enough to sustain convection and thunderstorms.

Another factor is rapid cooling with height, which allows the release of the heat of condensation that powers a tropical cyclone.

High humidity is needed, especially in the low-to-mid troposphere; when there is a great deal of moisture in the atmosphere.

Low amounts of wind shear are needed, as high shear is disruptive to the storm's circulation.

Tropical cyclones generally need to form more than 555 km or 5 degrees of latitude away from the equator, allowing the Coriolis Effect to deflect winds blowing towards the low pressure center and creating a circulation.

Lastly, a formative tropical cyclone needs a pre-existing system of disturbed weather, although without a circulation no cyclonic development will take place.

2.6.6 Structure and Size

A strong tropical cyclone will harbor an area of sinking air at the center of circulation. If this

area is strong enough, it can develop into a large "eye". Weather in the eye is normally calm and free of clouds, although the sea may be extremely violent. The eye is normally circular in shape, and may range in size from 3 kilometres to 370 kilometres in diameter.

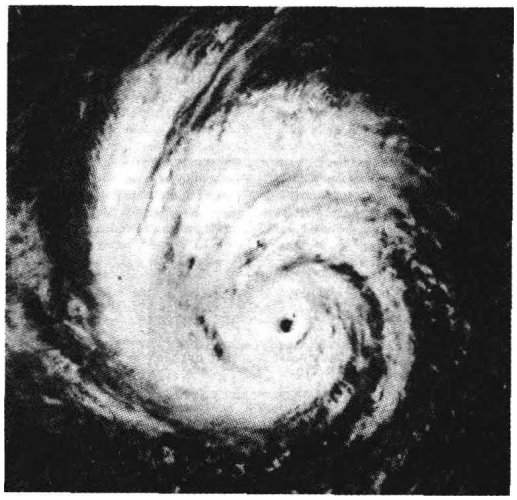


Figure 2.28 Satellite Photograph of a Hurricane

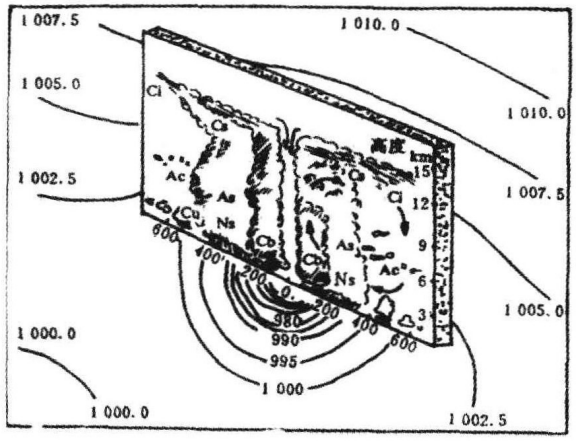


Figure 2.29 A Simplified Model Hurricane

Intense, mature tropical cyclones can sometimes exhibit an outward curving of the eyewall's top, making it resemble a football stadium; this phenomenon is thus sometimes referred to as the stadium effect.

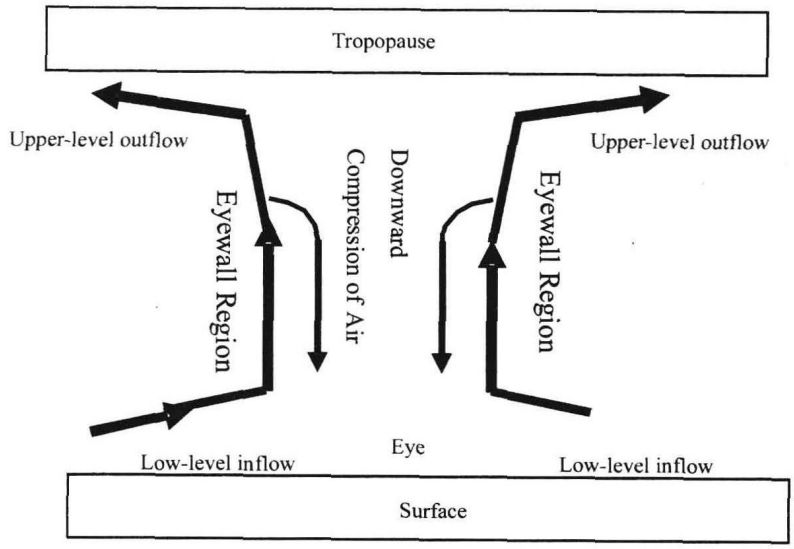


Figure 2.30 Side View of a Simplified Model Hurricane

There are other features that either surround the eye, or cover it. The central dense overcast (CDO) is the concentrated area of strong thunderstorm activity near the center of a tropical cyclone; in weaker tropical cyclones, the CDO may cover the center completely. The eyewall is a circle of strong thunderstorms that surrounds the eye; here is where the greatest wind speeds are found, where clouds reach the highest, and precipitation is the heaviest. The heaviest wind damage occurs

where a tropical cyclone's eyewall passes over land. Eyewall replacement cycles occur naturally in intense tropical cyclones.

When cyclones reach peak intensity they usually have an eyewall and radius of maximum winds that contract to a very small size, around 10 kilometres to 25 kilometres. Outer rainbands can form into an outer ring of thunderstorms that slowly move inward and robs the inner eyewall of its needed moisture and angular momentum.

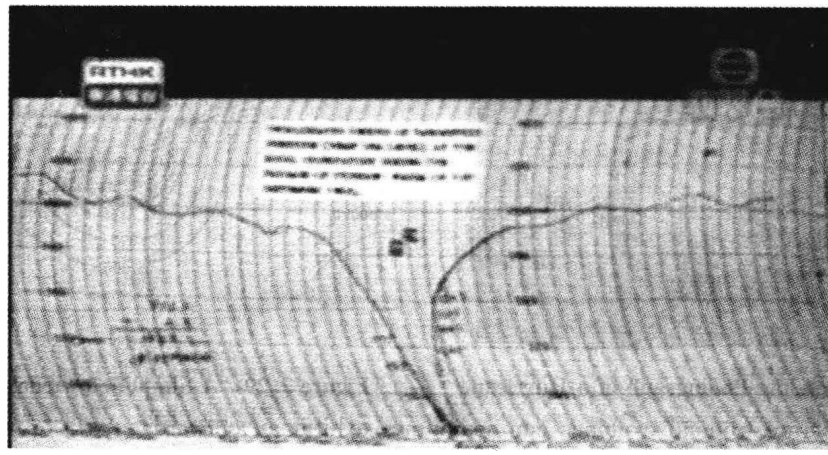


Figure 2.31 V-shaped Barograph Record of a Typhoon

When the inner eyewall weakens, the tropical cyclone weakens (In other words, the maximum sustained winds weaken and the central pressure rises). The outer eyewall completely replaces the inner one at the end of the cycle. The storm can be of the same intensity as it was previously or even stronger after the eyewall replacement cycle finishes. The storm may strengthen again as it builds a new outer ring for the next eyewall replacement.

One measure of the size of a tropical cyclone is determined by measuring the distance from its center of circulation to its **outermost closed isobar**, also known as its **ROCI.** If the radius is less than 2 degrees of latitude or 222 kilometres (138 mile), then the cyclone is "very small" or a "midget". A radius between 3 and 6 latitude degrees or 333 kilometres to 670 kilometres are considered "average-sized". "Very large" tropical cyclones have a radius of greater than 8 degrees or 888 kilometres.

Table 2.8 Size Descriptions of Tropical Cyclones

ROCI	Type
Less than 2 degrees latitude	Very small/midget
2 to 3 degrees of latitude	Small
3 to 6 degrees of latitude	Medium/Average
6 to 8 degrees of latitude	Large anti-dwarf
Over 8 degrees of latitude	Very large

Tropical cyclones in the northwestern Pacific Ocean are on average, the largest on Earth, with Atlantic tropical cyclones roughly half their size. Other methods of determining a tropical cyclone's size include measuring the radius of gale force winds.

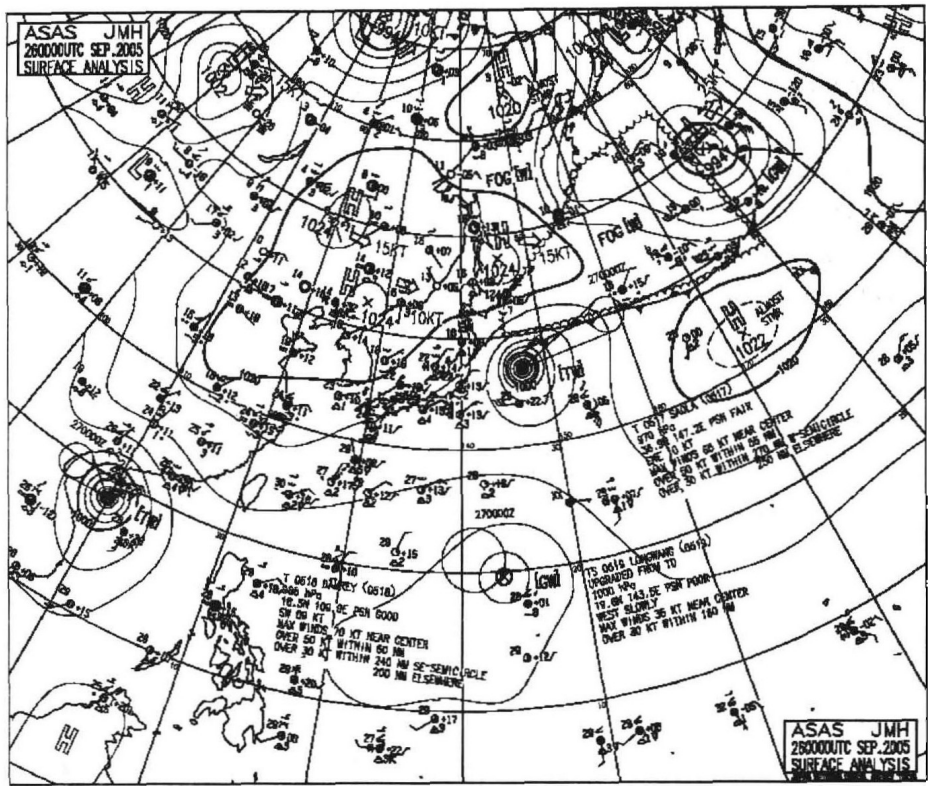


Figure 2.32 Tropical Cyclones on a Japanese Surface Chart

2.6.7 Dissipation of Tropical Cyclones

A tropical cyclone can cease to have tropical characteristics through several different ways. One such way is if it moves over land, thus depriving it of the warm water it needs to power itself, quickly losing strength. Most strong storms lose their strength very rapidly after landfall and become disorganized areas of low pressure within a day or two, or evolve into extratropical cyclones. While there is a chance a tropical cyclone could regenerate if it managed to get back over open warm water, if it remains over mountains for even a short time, weakening will accelerate.

Many storm fatalities occur in mountainous terrain, if the dying storm unleashes torrential rainfall, leading to deadly floods and mudslides. Additionally, dissipation can occur if a storm remains in the same area of ocean for too long, mixing the upper 60 meters of water, dropping sea surface temperatures more than 5 °C. Without warm surface water, the storm cannot survive.

A tropical cyclone can dissipate when it moves over waters significantly below 26.5 °C.. This will cause the storm to lose its tropical characteristics (i.e. thunderstorms near the center and warm core) and become a remnant low pressure area, which can persist for several days. This is the main dissipation mechanism in the northeastern Pacific Ocean. Weakening or dissipation can occur if it experiences vertical wind shear, causing the convection and heat engine to move away from the center.

Additionally, its interaction with the main belt of the Westerlies, by means of merging with a

nearby frontal zone, can cause tropical cyclones to evolve into extratropical cyclones. This transition can take 1 ~ 3 days. Even after a tropical cyclone is said to be extratropical or dissipated, it can still have tropical storm force (or occasionally hurricane/typhoon force) winds and drop several meters of rainfall. In the Pacific Ocean and Atlantic Ocean, such tropical-derived cyclones of higher latitudes can be violent and may occasionally remain at hurricane or typhoon-force wind speeds when they reach the west coast of North America. These phenomena can also affect Europe, where they are known as European windstorms.

Additionally, a cyclone can merge with another area of low pressure, becoming a larger area of low pressure. This can strengthen the resultant system, although it may no longer be a tropical cyclone.

2.6.8 Movement and Track

Although tropical cyclones are large systems generating enormous energy, their movements over the Earth's surface are controlled by large-scale winds-the streams in the Earth's atmosphere. The path of motion is referred to as a tropical cyclone's track and has been analogized by Dr. Neil Frank, former director of the National Hurricane Center, to "leaves carried along by a stream".

Tropical systems, while generally located equatorward of the 20th parallel, are steered primarily westward by the east-to-west winds on the equatorward side of the subtropical ridge-a persistent high pressure area over the world's oceans. In the tropical North Atlantic and northeastern Pacific Ocean, Trade Winds-another name for the westward-moving wind currents-steer tropical waves westward from the African coast and towards the Caribbean Sea, North America, and ultimately into the central Pacific ocean before the waves dampen out. These waves are the precursors to many tropical cyclones within this region. In the Indian Ocean and western Pacific (both north and south of the equator), tropical cyclogenesis is strongly influenced by the seasonal movement of the Intertropical Convergence Zone and the monsoon trough, rather than by easterly waves. Tropical cyclones can also be steered by other systems, such as other low pressure systems, high pressure systems, warm fronts, and cold fronts.

The Earth's rotation imparts an acceleration known as the Coriolis effect, Coriolis acceleration, or colloquially, Coriolis force. This acceleration causes cyclonic systems to turn towards the poles in the absence of strong steering currents. The poleward portion of a tropical cyclone contains easterly winds, and the Coriolis effect pulls them slightly more poleward. The westerly winds on the equatorward portion of the cyclone pull slightly towards the equator, but, because the Coriolis effect weakens toward the equator, the net drag on the cyclone is poleward. Thus, tropical cyclones in the Northern Hemisphere usually turn north (before being blown east), and tropical cyclones in the Southern Hemisphere usually turn south (before being blown east) when no other effects counteract the Coriolis effect.

The Coriolis effect also initiates cyclonic rotation, but it is not the driving force that brings this rotation to high speeds – that force is the heat of condensation.

When a tropical cyclone crosses the subtropical ridge axis, its general track around the high-pressure area is deflected significantly by winds moving towards the general low-pressure area to its

north. When the cyclone track becomes strongly poleward with an easterly component, the cyclone has begun recurvature. A typhoon moving through the Pacific Ocean towards Asia, for example, will recurve offshore of Japan to the north, and then to the northeast, if the typhoon encounters southwesterly winds (blowing northeastward) around a low-pressure system passing over China. Many tropical cyclones are eventually forced toward the northeast by extratropical cyclones in this manner, which move from west to east to the north of the subtropical ridge.

Officially, landfall occurs when a storm's center (the center of its circulation, not its edge) crosses the coastline. Storm conditions may be experienced on the coast and inland hours before landfall; in fact, a tropical cyclone can launch its strongest winds over land, yet not make landfall; if this occurs, then it is said that the storm made a direct hit on the coast. As a result of the narrowness of this definition, the landfall area experiences half of a land-bound storm by the time the actual landfall occurs. For emergency preparedness, actions should be timed when a certain wind speed or intensity of rainfall reaches land, not when landfall occurs.

When two cyclones approach one another, their centers will begin orbiting cyclonically about a point between the two systems. The two vortices will be attracted to each other, and eventually spiral into the center point and merge. When the two vortices are of unequal size, the larger vortex will tend to dominate the interaction, and the smaller vortex will orbit around it. This phenomenon is called the **Fujiwhara Effect**, after Sakuhei Fujiwhara.

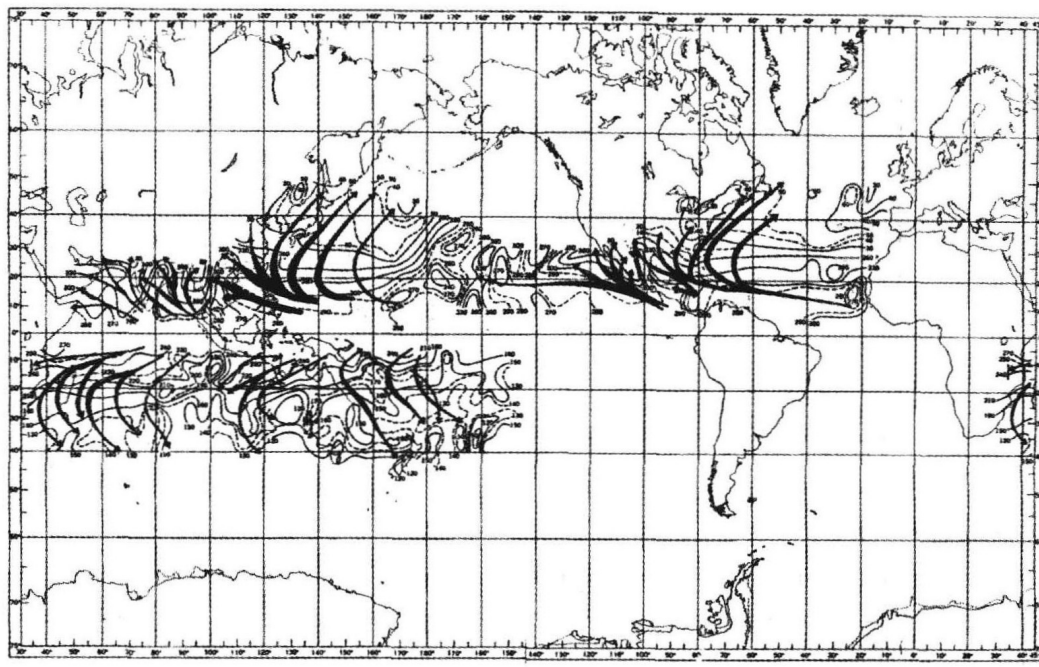


Figure 2.33 Tracks of Tropical Cyclones all Over the World

Note: The width of the arrow is, indicates the approximate frequency of storms; the wider the arrow the higher the frequency will be.

In the NW Pacific, there are four tropical cyclone track categories with various types and loca-

tions of synoptic features associated with each category of motion.

1. **Straight Runner** – TCs embedded in the deep easterly flow equatorward of a continuous mid-level subtropical ridge.

2. **Recurver** – TCs that move around the western edge of, or through breaks in, the mid-level subtropical ridge. The track changes orientation from westward and poleward to eastward and poleward.

3. **North Oriented** – TCs embedded in a reverse oriented trough. Low latitude TCs may move eastward before developing a slow, somewhat erratic northward track. Other storm TCs will slow their westward motion and assume a northward track.

4. **Other/Erratic Mover** – TCs embedded in weak or a climatological steering flow.

Examples include:

a. TUTT (Tropical Upper Tropospheric Trough) – induced TCs that form near the axis of the subtropical ridge or TCs in the summer that form along the monsoon trough and track to the north or northeast and don't recurve.

b. TCs in the South China Sea are often of this variety.

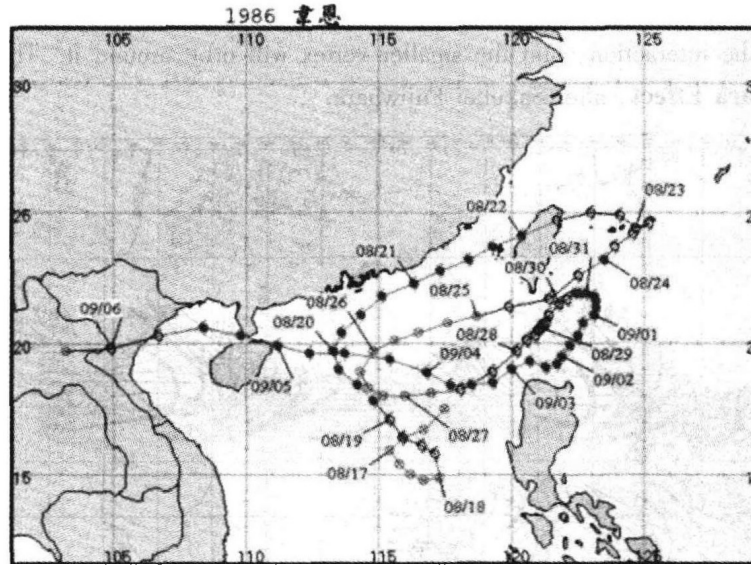


Figure 2.34 Abnormal Track of Typhoon Wayne

2.6.9 Observation and Forecasting

Intense tropical cyclones pose a particular observation challenge, as they are a dangerous oceanic phenomenon, and weather stations, being relatively sparse, are rarely available on the site of the storm itself. Surface observations are generally available only if the storm is passing over an island or a coastal area, or if there is a nearby ship. Usually, real-time measurements are taken on the periphery of the cyclone, where conditions are less catastrophic and its true strength cannot be evaluated. For this reason, there are teams of meteorologists that move into the path of tropical cyclones to help evaluate their strength at the point of landfall.

Tropical cyclones far from land are tracked by weather satellites capturing visible and infrared

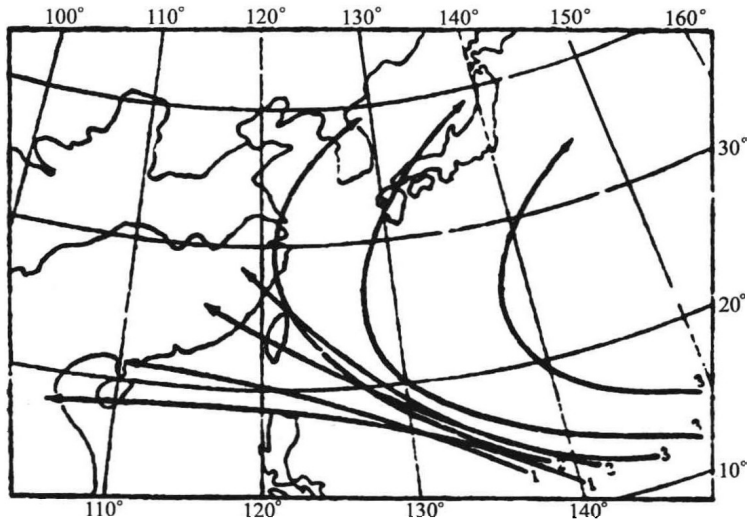


Figure 2.35 Tropical Cyclone Tracks in NW Pacific

images from space, usually at half-hour to quarter-hour intervals. As a storm approaches land, it can be observed by land-based Doppler radar. Radar plays a crucial role around landfall by showing a storm's location and intensity every few minutes.

In-situ measurements, in real-time, can be taken by sending specially equipped reconnaissance flights into the cyclone. In the Atlantic basin, these flights are regularly flown by United States government hurricane hunters. The aircraft used are WC-130 Hercules and WP-3D Orions, both four-engine turboprop cargo aircraft. These aircraft fly directly into the cyclone and take direct and remote-sensing measurements. The aircraft also launch GPS dropsondes inside the cyclone. These sondes measure temperature, humidity, pressure, and especially winds between flight level and the ocean's surface.

A new era in hurricane observation began when a remotely piloted Aerosonde, a small drone aircraft, was flown through Tropical Storm Ophelia as it passed Virginia's Eastern Shore during the 2005 hurricane season. A similar mission was also completed successfully in the western Pacific Ocean. This demonstrated a new way to probe the storms at low altitudes that human pilots seldom dare.

Because of the forces that affect tropical cyclone tracks, accurate track predictions depend on determining the position and strength of high and low-pressure areas, and predicting how those areas will change during the life of a tropical system.

High-speed computers and sophisticated simulation software allow forecasters to produce computer models that predict tropical cyclone tracks based on the future position and strength of high and low-pressure systems.

Combining forecast models with increased understanding of the forces that act on tropical cyclones, as well as with a wealth of data from Earth-orbiting satellites and other sensors, scientists have increased the accuracy of track forecasts over recent decades.

However, scientists are less skillful at predicting the intensity of tropical cyclones. The lack of

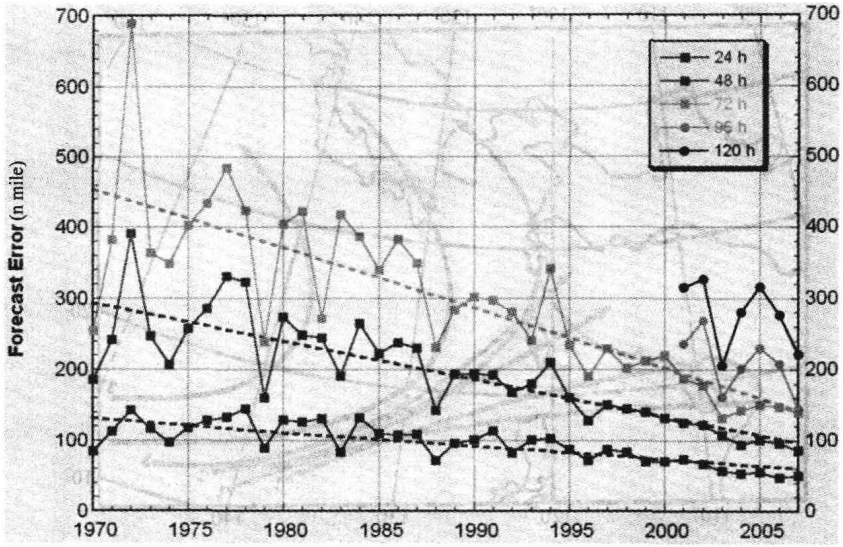


Figure 2.36 NHC Official Annual Average Track Errors (Atlantic Basin)

Note: A general decrease in error trends in tropical cyclone path prediction is evident since the 1970s.

improvement in intensity forecasting is attributed to the complexity of tropical systems, and an incomplete understanding of factors that affect their development.

2.6.10 Avoiding Tropical Cyclones

2.6.10.1 Approach and Passage of a Tropical Cyclone

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

When the storm center is 1,000 to 2,000 meters away, the barometer usually rises a little, and the skies are relatively clear. Cumulus clouds, if present at all, are few in number and their vertical development appears suppressed. The barometer usually appears restless, pumping up and down a few hundredths of an inch.

As the tropical cyclone comes nearer, a cloud sequence begins which resembles that associated with the approach of a warm front in middle latitudes. Snow-white, fibrous "mare's tails" (cirrus) appear when the storm is about 500 to 1,000 kilometers away. Usually these seem to converge, more or less, in the direction from which the storm is approaching. This convergence is particularly apparent at about the time of sunrise and sunset.

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

The cirrus becomes more confused and tangled, and then gradually gives way to a continuous veil of cirrostratus. Below this veil, altostratus forms, and then stratocumulus. These clouds gradu-

ally become more dense, and as they do so, the weather becomes unsettled. A fine, mist-like rain begins to fall, interrupted from time to time by rain showers. The barometer has fallen perhaps a tenth of an inch.

As the fall becomes more rapid, the wind increases in gustiness, and its speed becomes greater, reaching perhaps 22 to 40 knots (Beaufort 6 ~ 8). On the horizon appears a dark wall of heavy cumulonimbus, called the bar of the storm. This is the heavy bank of clouds comprising the main mass of the cyclone. Portions of this heavy cloud become detached from time to time, and drift across the sky, accompanied by rain squalls and wind of increasing speed. Between squalls, the cirrostratus can be seen through breaks in the stratocumulus. As the bar approaches, the barometer falls more rapidly and wind speed increases. The seas, which have been gradually mounting, become tempestuous. Squall lines, one after the other, sweep past in ever increasing number and intensity.

With the arrival of the bar, the day becomes very dark, squalls become virtually continuous, and the barometer falls precipitously, with a rapid increase in wind speed. The center may still be 200 to 400 kilometers away in a fully developed tropical cyclone. As the center of the storm comes closer, the ever-stronger wind shrieks through the rigging, and about the superstructure of the vessel. As the center approaches, rain falls in torrents. The wind fury increases. The seas become mountainous. The tops of huge waves are blown off to mingle with the rain and fill the air with water. Visibility is virtually zero in blinding rain and spray. Even the largest and most seaworthy vessels become virtually unmanageable, and may sustain heavy damage. Less sturdy vessels may not survive. Navigation virtually stops as safety of the vessel becomes the only consideration. The awesome fury of this condition can only be experienced. Words are inadequate to describe it.

If the eye of the storm passes over the vessel, the winds suddenly drop to a breeze as the wall of the eye passes. The rain stops, and the skies clear sufficiently to permit the sun or stars to shine through gaps in the comparatively thin cloud cover. Visibility improves. Mountainous seas approach from all sides in complete confusion. The barometer reaches its lowest point, which may be 1.5 or 2 inches below normal in fully developed tropical cyclones. As the wall on the opposite side of the eye arrives, the full fury of the wind strikes as suddenly as it ceased, but from the opposite direction. The sequence of conditions that occurred during approach of the storm is reversed, and passes more quickly, as the various parts of the storm are not as wide in the rear of a storm as on its forward side.

2.6.10.2 Locating the Center of a Tropical Cyclone

If intelligent action is to be taken to avoid the full fury of a tropical cyclone, early determination of its location and direction of travel relative to the vessel is essential. The bulletins and forecasts are excellent general guides, but they are not infallible, and may be sufficiently in error to induce a mariner in a critical position to alter course so as to unwittingly increase the danger to his vessel. Often it is possible, using only those observations made aboard ship, to obtain a sufficiently close approximation to enable the vessel to maneuver to the best advantage.

The presence of an exceptionally long swell is usually the first visible indication of the existence

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

When the cirrus clouds appear, their point of convergence provides an indication of the direction of the storm center. If the storm is to pass well to one side of the observer, the point of convergence shifts slowly in the direction of the storm movement. If the storm center will pass near the observer, this point remains steady. When the bar becomes visible, it appears to rest upon the horizon for several hours. The darkest part of this cloud is in the direction of the storm center. If the storm is to pass to one side, the bar appears to drift slowly along the horizon. If the storm is heading directly toward the observer, the position of the bar remains fixed. Once within the area of the dense, low clouds, one should observe their direction of movement, which is almost exactly along the isobars, with the center of the storm being 90° from the direction of cloud movement (left of direction of movement in the Northern Hemisphere, and right in the Southern Hemisphere).

The winds are probably the best guide to the direction of the center of a tropical cyclone. The circulation is cyclonic, but because of the steep pressure gradient near the center, the winds there blow with greater violence and are more nearly circular than in extratropical cyclones.

According to Buys Ballot's law, an observer whose back is to the wind has the low pressure on his left in the Northern Hemisphere, and on his right in the Southern Hemisphere. If the wind follows circular isobars exactly, the center would be exactly 90° from behind when facing away from the wind. However, the track of the wind is usually inclined somewhat toward the center, so that the angle from dead astern varies between perhaps 90° to 135°. The inclination varies in different parts of the same storm. It is least in front of the storm, and greatest in the rear, since the actual wind is the vector sum of the pressure gradient and the motion of the storm along the track. A good average is perhaps 110° in front, and 120° ~ 135° in the rear. These values apply when the storm center is still several hundred kilometers away. Closer to the center, the wind blows more nearly along the isobars, the inclination being reduced by one or two points at the wall of the eye. Since wind direction usually shifts temporarily during a squall, its direction at this time should not be used for determining the position of the center.

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

2.6.10.3 Maneuvering to Avoid the Storm Center

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

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

In the Northern Hemisphere, that part to the right of the storm track (facing in the direction toward which the storm is moving) is called the dangerous semicircle. It is considered dangerous because, (1) the actual wind speed is greater than that due to the pressure gradient alone, since it is augmented by the forward motion of the storm, and (2) the direction of the wind and sea is such as to carry a vessel into the path of the storm (in the forward part of the semicircle).

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

A plot of successive positions of the storm center should indicate the semicircle in which a vessel is located. However, if this is based upon weather bulletins, it may not be a reliable guide because of the lag between the observations upon which the bulletin is based and the time of reception of the bulletin, with the ever-present possibility of a change in the direction of the storm. The use of radar eliminates this lag at short range, but the return may not be a true indication of the center. Perhaps the most reliable guide is the wind. Within the cyclonic circulation, a wind shifting to the right in the Northern Hemisphere and to the left in the Southern Hemisphere indicates the vessel is probably in the dangerous semicircle. A steady wind shift opposite to this indicates the vessel is probably in the less dangerous semicircle.

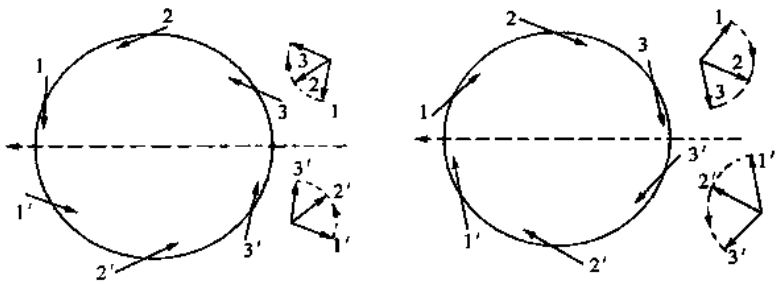


Figure 2.37 Winds Veering and Backing in the Dangerous Semicircle and Navigable Semicircle

However, if a vessel is underway, its own motion should be considered. If it is outrunning the storm or pulling rapidly toward one side (which is not difficult during the early stages of a storm, when its speed is low), the opposite effect occurs. This should usually be accompanied by a rise in atmospheric pressure, but if motion of the vessel is nearly along an isobar, this may not be a reliable indication. If in doubt, the safest action is usually to stop long enough to define the proper semicircle. The loss in time may be more than offset by the minimizing of the possibility of taking the wrong action, increasing the danger to the vessel. If the wind direction remains steady (for a vessel which is stopped), with increasing speed and falling barometer, the vessel is in or near the path of the storm. If it remains steady with decreasing speed and rising barometer, the vessel is near the storm track, behind the center.

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

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

If the vessel is faster than the storm, it is possible to overtake it. In this case, the only action usually needed is to slow enough to let the storm pull ahead. In all cases, one should be alert to changes in the direction of movement of the storm center, particularly in the area where the track normally curves toward the pole. If the storm maintains its direction and speed, the ship's course should be maintained as the wind shifts.

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

In a sailing vessel attempting to avoid a storm center, one should steer courses as near as possible to those prescribed above for power vessels. However, if it becomes necessary for such a vessel to heave to, the wind is of greater concern than the sea. A good general rule always is to heave to on whichever tack permits the shifting wind to draw aft. In the Northern Hemisphere, this is the starboard tack in the dangerous semicircle, and the port tack in the less dangerous semicircle. In the Southern Hemisphere these are reversed.

While each storm requires its own analysis, and frequent or continual resurvey of the situation,

the general rules for a steamer may be summarized as follows:

Northern Hemisphere

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

Left or less dangerous semicircle: Bring the wind on the starboard quarter (135° relative), hold course and make as much way as possible. If necessary, heave to with stern to the sea.

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

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

Southern Hemisphere

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

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

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

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

CHAPTER 3 BASIC KNOWLEDGE OF CLIMATOLOGY

3.1 Wind and Pressure Systems

3.1.1 Three-cell Circulation Model

Atmospheric circulation is the large-scale movement of air, and the means (together with the smaller ocean circulation) by which thermal energy is distributed on the surface of the Earth.

The large-scale structure of the atmospheric circulation varies from year to year, but the basic climatological structure remains fairly constant. However, individual weather systems-mid-latitude depressions, or tropical convective cells occur "randomly", and it is accepted that weather cannot be predicted beyond a fairly short limit: perhaps a month in theory, or (currently) about ten days in practice. Nonetheless, as the climate is the average of these systems and patterns—where and when they tend to occur again and again, it is stable over longer periods of time.

The wind belts girding of the planet are organized into three cells: the Hadley cell, the Ferrel cell, and the Polar cell.

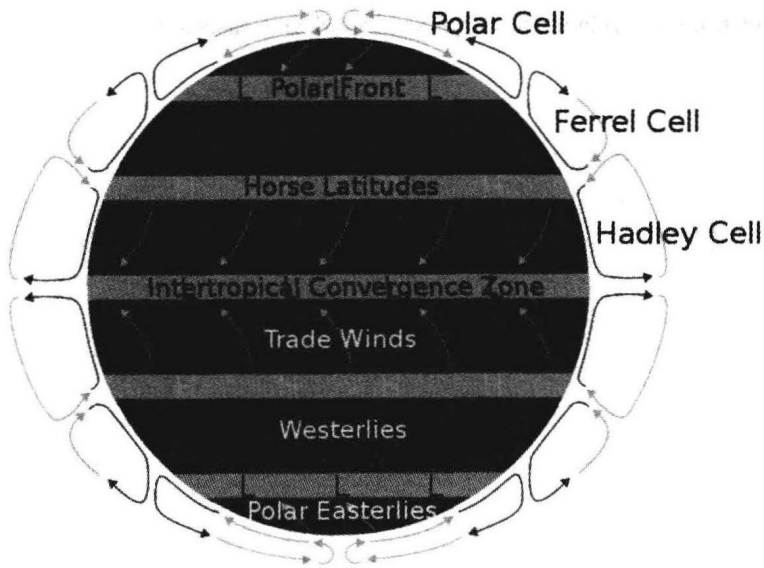


Figure 3.1 Global Circulation of Earth's Atmosphere

The **Hadley cell** mechanism is well understood. The atmospheric circulation pattern that George Hadley described to provide an explanation for the trade winds matches observations very well. It is a closed circulation loop, which begins at the equator with warm, moist air lifted aloft in equatorial low pressure areas (the Intertropical Convergence Zone, ITCZ) to the tropopause and carried pole-

ward. At about 30°N/S latitude, it descends in a high pressure area. Some of the descending air travels equatorially along the surface, closing the loop of the Hadley cell and creating the trade winds.

Though the Hadley cell is described as lying on the equator, it is more accurate to describe it as following the sun's zenith point, or what is termed the "thermal equator", which undergoes a semi-annual north-south migration.

The **Polar cell** is likewise a simple system. Though cool and dry relative to equatorial air, air masses at the 60th parallel are still sufficiently warm and moist to undergo convection and drive a thermal loop. Air circulates within the troposphere limited vertically by the tropopause at about 8 km. Warm air rises at lower latitudes and moves poleward through the upper troposphere at both the north and south poles. When the air reaches the polar areas, it has cooled considerably, and descends as a cold, dry high pressure area, moving away from the pole along the surface but twisting westward as a result of the Coriolis Effect to produce the Polar easterlies.

The **Ferrel cell**, theorized by William Ferrel, is a secondary circulation feature, dependent for its existence upon the Hadley cell and the Polar cell. It behaves much as an atmospheric ball bearing between the Hadley cell and the Polar cell, and comes about as a result of the eddy circulations (the high and low pressure areas) of the mid-latitudes.

For this reason it is sometimes known as the "zone of mixing". At its southern extent (in the Northern Hemisphere), it overrides the Hadley cell, and at its northern extent, it overrides the Polar cell. Just as the Trade Winds can be found below the Hadley cell, the westerlies can be found beneath the Ferrel cell. Thus, strong high pressure areas which divert the prevailing westerlies, such as a Siberian high (which could be considered an extension of the Arctic high), could be said to override the Ferrel cell, making it discontinuous.

While the Hadley, Ferrel and Polar cells are major factors in global heat transport, they do not act alone. Disparities in temperature also drive a set of longitudinal circulation cells, and the overall atmospheric motion is known as the **zonal overturning circulation.**

Latitudinal circulation is the consequence of the fact that incident solar radiation per unit area is highest at the heat equator, and decreases as the latitude increases, reaching its minimum at the poles. Longitudinal circulation, on the other hand, comes about because water has a higher specific heat capacity than land and thereby absorbs and releases more heat, but the temperature changes are less than on land. Even at mesoscales (a horizontal range of 5 to several hundred kilometres), this effect is noticeable; it is what brings the sea breeze, air cooled by the water, ashore in the day, and carries the land breeze, air cooled by contact with the ground, out to sea during the night.

On a larger scale, this effect ceases to be diurnal (daily), and instead is seasonal or even decadal in its effects. Warm air rises over the equatorial, continental, and western Pacific Ocean regions, flows eastward or westward, depending on its location, when it reaches the tropopause, and subsides in the Atlantic and Indian Oceans, and in the eastern Pacific.

The Pacific Ocean cell (also named Walker Circulation) plays a particularly important role in the Earth's weather. This entirely ocean-based cell comes about as the result of a marked difference

in the surface temperatures of the western and eastern Pacific. Under ordinary circumstances, the western Pacific waters are warm and the eastern waters are cool. The process begins when strong convective activity over equatorial East Asia and subsiding cool air off South America's west coast creates a wind pattern which pushes Pacific water westward and piles it up in the western Pacific. (Water levels in the western Pacific are about 60 cm higher than in the eastern Pacific, a difference due entirely to the force of moving air.)

3.1.2 Major Wind Patterns

3.1.2.1 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 Doldrums at longitudes with considerable landmass. On the average, the position is at 5°N, frequently called the meteorological equator.

3.1.2.2 The Trade Winds

The Trade Winds at the surface blow from the belts of high pressure toward the equatorial belts of low pressure. 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 strongest over eastern ocean areas.

The Trade Winds are generally considered among the most constant of winds, blowing for days or even weeks with little change of direction or speed. Cyclones from the middle latitudes rarely enter the regions of the Trade Winds, although tropical cyclones originate within these areas.

3.1.2.3 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 carry 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.

Figure 3.2 The ITCZ's Band of Clouds over the Eastern Pacific and the America as Seen from Space

3.1.2.4 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 (or 55°S) where these boisterous winds occur, are called the Roaring Forties. These winds are strongest at about latitude 50°S.

3.1.2.5 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 encoun-

tered. 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. The 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.

3.1.3 Observed Wind and Pressure Fields

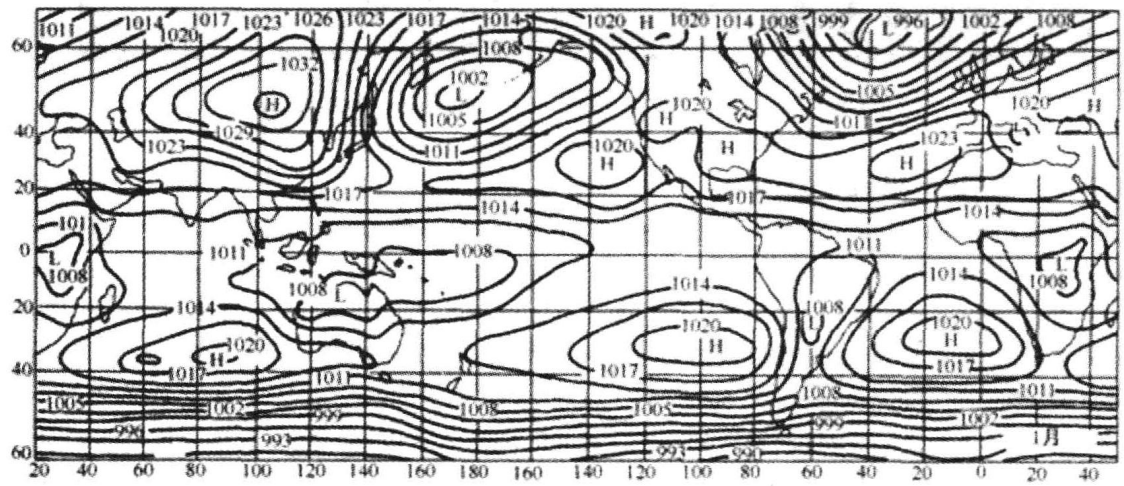


Figure 3.3 Mean Sea Level Pressure in January

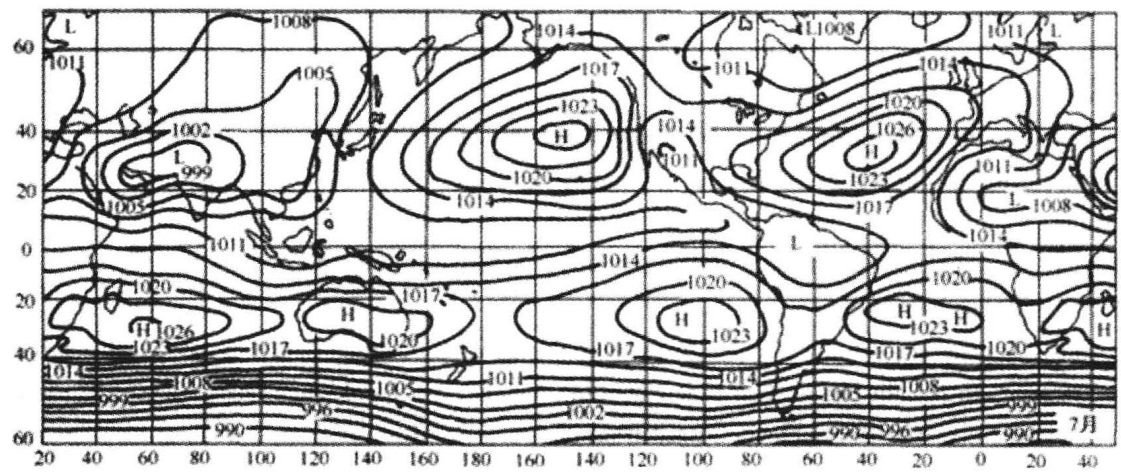


Figure 3.4 Mean Sea Level Pressure in July

The pressure belts of the general circulation are rarely continuous. They are broken up into detached areas of high and low pressure cells by the secondary circulation. The breaks correspond with regions showing differences in temperature from land to water surfaces.

During the winter months (December to February), areas of high pressure develop over central

Asia (**Siberian High**), off the coast of California (**Hawaiian High**), central North America (**Canadian High**), over Spain and northwest Africa extending into the subtropical North Atlantic (**Azores High**), and over the oceans in the Southern Hemisphere at the subtropics. Areas of low pressure occur just south of the Aleutian Islands (**Aleutian Low**), at the southern tip of Greenland (**Iceland Low**) and latitudes 50°S to 80°S.

During the summer months (June to August), a number of dominant winter pressure systems disappear. Gone are the Siberian High over central Asia and the North America. The Hawaiian and Azores High intensify and expand northward into their relative ocean basins. New areas of dominant high pressure develop over Australia and Antarctica (**South Polar High**). Regions of low pressure form over central Asia and southwest Asia (**Asiatic Low**).

There is a permanent belt of relatively low pressure along the equator and another deeper belt of low pressure paralleling the coast of the Antarctic continent. Permanent belts of high pressure largely encircle the Earth, generally over the oceans in both the Northern and Southern Hemispheres.

The largest individual circulation cells in the Northern Hemisphere are the Asiatic high in winter and the Asiatic low in summer. This seasonal change in pressure cells gives rise to the monsoonal flow over India and Southeast Asia.

3.1.4 Monsoon

3.1.4.1 Outline of Monsoon

A monsoon is traditionally defined as a seasonal reversing wind accompanied by seasonal changes in precipitation, but is now used to describe seasonal changes in atmospheric circulation and precipitation. The major monsoon systems of the world consist of the West African and Asia-Australian monsoons. The inclusion of the North and South American monsoons with incomplete wind reversal may be debated.

The term was first used in English in British India (now India, Bangladesh and Pakistan) and neighbouring countries to refer to the big seasonal winds blowing from the Bay of Bengal and the Arabian Sea in the southwest bringing heavy rainfall to the area. In hydrology, monsoon rainfall is considered to be that which occurs in any region that receives the majority of its rain during a particular season. This allows other regions of the world to qualify as monsoon regions.

Most summer monsoons have a dominant westerly component and a strong tendency to ascend and produce copious amounts of rain (because of the condensation of water vapor in the rising air). The intensity and duration, however, are not uniform from year to year. Winter monsoons, by contrast, have a dominant easterly component and a strong tendency to diverge, subside and cause drought.

Monsoons may be considered as large-scale sea breezes, due to seasonal heating and the resulting development of a thermal low over a continental landmass. They are caused by the larger amplitude of the seasonal cycle of land temperature compared to that of nearby oceans. This differential warming happens because heat in the ocean is mixed vertically through a "mixed layer" that may be fifty meters deep, through the action of wind and buoyancy-generated turbulence, whereas the land surface conducts heat slowly, with the seasonal signal penetrating perhaps meters or so. Additional-

ly, the specific heat capacity of liquid water is significantly higher than that of surfaces land.

Together, these factors mean that the heat capacity of the layer participating in the seasonal cycle is much larger over the oceans than over land, with the consequence that the air over the land warms faster and reaches a higher temperature than the air over the ocean. The hot air over the land tends to rise, creating an area of low pressure. This creates a steady wind blowing toward the land, bringing the moist near-surface air over the oceans with it. Similar rainfall is caused by the moist ocean air being lifted upwards by mountains, surface heating, convergence at the surface, divergence aloft, or from storm-produced outflows at the surface. However, as the lifting occurs, the air cools due to expansion in lower pressure, which in turn produces condensation.

In winter, the land cools off quickly, but the ocean retains heat for much longer. The cold air over the land creates a high pressure area which produces a breeze moving from land to ocean. Monsoons are similar to sea and land breezes, a term usually referring to the localized, diurnal (daily) cycle of circulation near coastlines, but they are much larger in scale, stronger and seasonal.

As monsoons have become better understood, the term monsoon has been broadened to include almost all of the phenomena associated with the annual weather cycle within the tropical and subtropical land regions of the Earth.

Even more broadly, it is now understood that in the geological past, monsoon systems must have always accompanied the formation of supercontinents such as Pangaea, with their extreme continental climates.

3.1.4.2 Global Monsoons

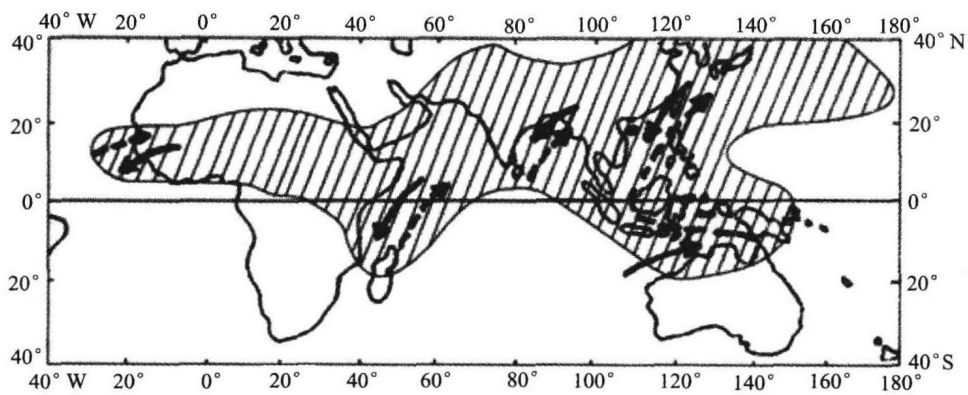


Figure 3.5 Global Monsoons

Africa

The monsoon of western Sub-Saharan Africa has traditionally been thought to be the result of the seasonal shifts of the Intertropical Convergence Zone and the great seasonal temperature and humidity differences between the Sahara and the equatorial Atlantic Ocean. It migrates northward from the equatorialAtlantic in February, reaches western Africa on June 22, then moves back to the south by October. The dry, northeasterly Trade Winds, and their more extreme form, the harmattan, are interrupted by the northern shift in the ITCZ and resultant southerly, rain-bearing winds during the summer. The semiarid Sahel and Sudan depend upon this pattern as most of their precipitation area

is desert.

North America

The North American Monsoon (also abbreviated as NAM) occurs from late June or early July into September, originating over Mexico and spreading into the southwest United States by mid-July. It affects Mexico along the Sierra Madre Occidental as well as Arizona, New Mexico, Nevada, Utah, Colorado, West Texas and California. It pushes as far west as the Peninsular Ranges and Transverse Ranges of Southern California, but rarely reaches the coastal strip (a wall of desert thunderstorms only a half-hour's drive away is a common summer sight from the sunny skies along the coast during the monsoon). The North American monsoon is known to many as the Summer, Southwest, Mexican or Arizona monsoon. It is also sometimes called the Desert Monsoon as large parts of the affected area are the Mojave and Sonoran Deserts.

Asia

The Asian monsoons may be classified into a few sub-systems, such as the South Asian Monsoon which affects the Indian subcontinent and surrounding regions, and the East Asian Monsoon which affects southern China, Korea and parts of Japan.

South Asian Monsoon

Southwest Monsoon

The southwestern summer monsoons occur from June through September. The Thar Desert and adjoining areas of the northern and central Indian subcontinent heat up considerably during the hot summers. This causes a low pressure area over the northern and central Indian subcontinent. To fill this void, the moisture-laden winds from the Indian Ocean rush in to the subcontinent. These winds, rich in moisture, are drawn towards the Himalayas, creating winds blowing storm clouds towards the subcontinent. The Himalayas act like a high wall, blocking the winds from passing into Central Asia, thus forcing them to rise. With the gain in altitude of the clouds, the temperature drops and precipitation occurs. Some areas of the subcontinent receive up to 10,000 mm (390 in) of rain.

The southwest monsoon is generally expected to begin around the start of June and finish down by the end of September. Due to its topology, the moisture-laden winds on reaching the southernmost point of the Indian Peninsula, become divided into two parts: the Arabian Sea Branch and the Bay of Bengal Branch.

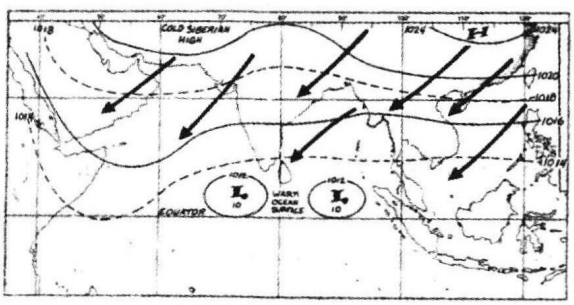


Figure 3.6.a Northeast Monsoon

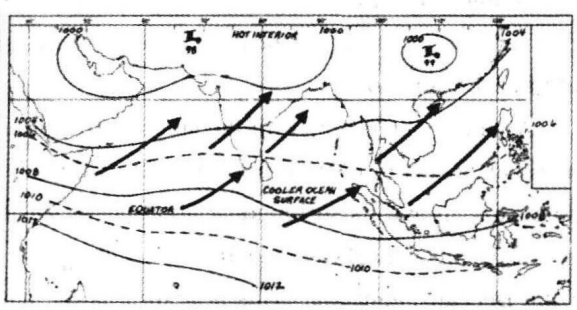


Figure 3.6.b Southwest Monsoon

The Arabian Sea Branch of the Southwest Monsoon first hits the Western Ghats of the coastal state of Kerala, India, thus making the area the first state in India to receive rain from the southwest monsoon. This branch of the monsoon moves northwards along the Western Ghats with precipitation on coastal areas, west of the Western Ghats. The eastern areas of the Western Ghats do not receive much rain from this monsoon as the wind does not cross the Western Ghats.

The Bay of Bengal branch of the Southwest Monsoon flows over the Bay of Bengal heading towards North-East India and Bengal, picking up more moisture from the Bay of Bengal. The winds arrive at the Eastern Himalayas with large amounts of rain. Mawsynram, situated on the southern slopes of the Eastern Himalayas in Shillong, India, is one of the wettest places on Earth. After the arrival at the Eastern Himalayas, the winds turns towards the west, travelling over the Indo-Gangetic Plain at a rate of roughly 1 ~ 2 weeks per state, pouring rain all along its way. June 1st is regarded as the date of onset of the monsoon in India, as indicated by the arrival of the monsoon in the southern most state of Kerala.

The monsoon accounts for 80% of the rainfall in India. Indian agriculture (which accounts for 25% of the GDP and employs 70% of the population) is heavily dependent on the rains, for growing crops especially cotton, rice, oilseeds and coarse grains. A delay of a few days in the arrival of the monsoon can badly affect the economy, as evidenced in the numerous droughts in India in the 1990s.

The monsoon is widely welcomed and appreciated by city-dwellers as well, for it provides relief from the climax of summer heat in June. However, the condition of the roads takes a battering each year. Often houses and streets are waterlogged and the slums are flooded in spite of having a drainage system. This lack of city infrastructure coupled with changing climate patterns causes severe economical loss including damage to property and loss of lives, as evidenced in the Bombay floods of 2005. Bangladesh and certain regions of India like Assam and West Bengal, also frequently experience heavy floods during this season. In the recent past, areas in India that used to receive scanty rainfall throughout the year, like the Thar Desert, have surprisingly ended up receiving floods due to the prolonged monsoon season.

The influence of the southwest monsoon is felt as far north as China's Xinjiang. It is estimated that about 70% of all precipitation in the central part of the Tianshan Mountains falls during the three summer months, when the region is under the monsoon influence; about 70% of that is directly of "cyclonic" (i. e., monsoon-driven) origin (as opposed to "local convection").

Northeast Monsoon

Around September, with the sun fast retreating south, the northern land mass of the Indian subcontinent begins to cool off rapidly. When this air pressure begins to build over northern India, the Indian Ocean and its surrounding atmosphere still holds its heat. This causes the cold wind to sweep down from the Himalayas and Indo-Gangetic Plain towards the vast spans of the Indian Ocean south of the Deccan Peninsula. This is known as the northeast monsoon or retreating monsoon.

While travelling towards the Indian Ocean, the dry cold wind picks up some moisture from the Bay of Bengal and pours it over peninsular India and parts of Sri Lanka. Cities like Madras, which

get less rain from the southwest monsoon, receive rain from this monsoon. About 50% to 60% of the rain received by the state of Tamil Nadu is from the northeast monsoon. In Southern Asia, the north-eastern monsoons take place from December to early March when the surface high-pressure system is strongest. The jet stream in this region splits into the southern subtropical jet and the polar jet. The subtropical flow directs northeasterly winds to blow across Southern Asia, creating dry air streams which produce clear skies over India. Meanwhile, a low pressure system develops over South-east Asia and Australasia and winds are directed toward Australia known as a monsoon trough.

East Asian Monsoon

The East Asian monsoon affects large parts of Indo-China, Philippines, China, Korea and Japan. It is characterised by a warm, rainy summer monsoon and a cold, dry winter monsoon. The rain occurs in a concentrated belt that stretches east-west except in East China where it is tilted east-northeast over Korea and Japan. The seasonal rain is known as Meiyu in China, Changma in Korea, and Bai-u in Japan, with the latter two resembling frontal rain.

The onset of the summer monsoon is marked by a period of premonsoonal rain over South China and Taiwan in early May. From May to August, the summer monsoon shifts through a series of dry and rainy phases as the rain belt moves northward, beginning over Indo-china and the South China Sea (May), to the Yangtze River Basin and Japan (June) and finally to North China and Korea (July). When the monsoon ends in August, the rain belt moves back to South China.

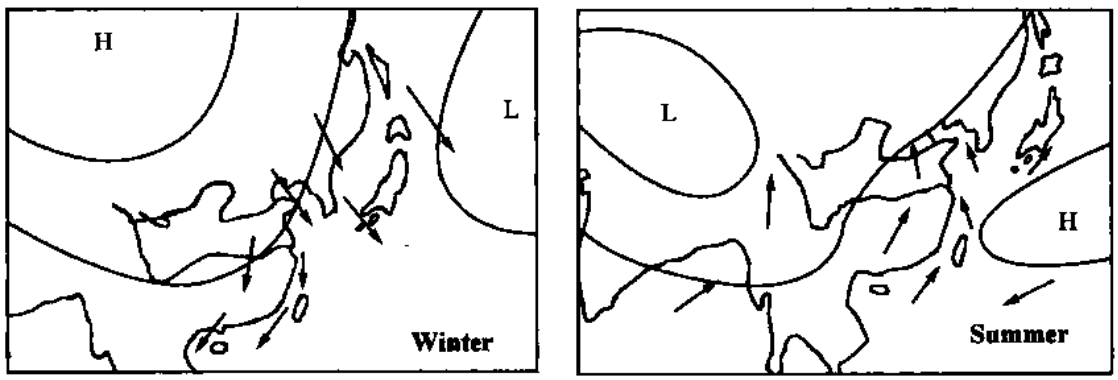


Figure 3.7 East Asian Monsoons

Australia

The rainy season occurs from September to February and it is a major source of energy for the Hadley circulation during boreal winter. The Maritime Continent Monsoon and the Australian Monsoon may be considered to be the same system, the Indo-Australian Monsoon.

It is associated with the development of the Siberian High and the movement of the heating maxima from the Northern Hemisphere to the Southern Hemisphere. North-easterly winds flow down Southeast Asia, and are turned north-westerly/westerly by Borneo topography towards Australia. This forms a cyclonic circulation vortex over Borneo, which together with descending cold surges of winter air from higher latitudes, cause significant weather phenomena in the region. Examples are the formation of a rare low-latitude tropical storm in 2001, Tropical Storm Vamei, and the devasta-

ting flood of Jakarta in 2007.

The onset of the monsoon over the maritime continent tends to follow the heating maxima down Vietnam and the Malay Peninsula (September), to Sumatra, Borneo and the Philippines (October), to Java, Sulawesi (November), Irian Jaya and northern Australia (December; January). However, the monsoon is not a simple response to heating but a more complex interaction topography, wind and sea, as demonstrated by its abrupt rather than gradual withdrawal from the region. The Australian monsoon or rainy season occurs in the Australia summer when the monsoon trough develops over Northern Australia. Over-three quarters of annual rainfall in northern Australia falls during this time.

Europe

The European Monsoon (more commonly known as the return of the westerlies) is the result of a resurgence of westerly winds from the Atlantic, where they become loaded with wind and rain. These westerly winds are a common phenomenon during the European winter, but they ease as spring approaches in late March and through April and May. The winds pick up again in June, which is why this phenomenon is also referred to as "the return of the westerlies".

The rain usually arrives in two waves, at the beginning of June and again in mid to late June. The European Monsoon is not a monsoon in the traditional sense in that it doesn't meet all the requirements to be classified as such. Instead the return of the westerlies is more regarded as a conveyor belt that delivers a series of low pressure centres to Western Europe where they create unseasonable weather. These storms generally feature significantly lower than average temperatures, fierce rain or hail, thunder and strong winds.

The return of the westerlies affects Europe's northern Atlantic coastline, more precisely Ireland, United Kingdom the Benelux countries, western Germany, northern France and parts of Scandinavia.

3.1.5 Sea and Land Breezes

In coastal regions, **sea breezes** and **land breezes** can be important factors in a location's prevailing winds. The sea is warmed by the sun more slowly because of water's greater specific heat compared to land. As the temperature of the surface of the land rises, the land heats the air above it by conduction. The warm air is less dense than the surrounding environment and so it rises. This causes a pressure gradient of about 2 millibars from the ocean to the land. The cooler air above the sea, now with higher sea level pressure, flows inland into the lower pressure, creating a cooler breeze near the coast. When large-scale winds are calm, the strength of the sea breeze is directly proportional to the temperature difference between the land mass and the sea. If an offshore wind of 8 knots (15 km/h) exists, the sea breeze is not likely to develop.

At night, the land cools off more quickly than the ocean because of differences in their specific heat values. This temperature change causes the daytime sea breeze to dissipate. When the temperature onshore cools below the temperature offshore, the pressure over the water will be lower than that of the land, establishing a land breeze, as long as an onshore wind is not strong enough to oppose it.

Sea breeze fronts occur mainly on sunny days when the landmass warms up above the water

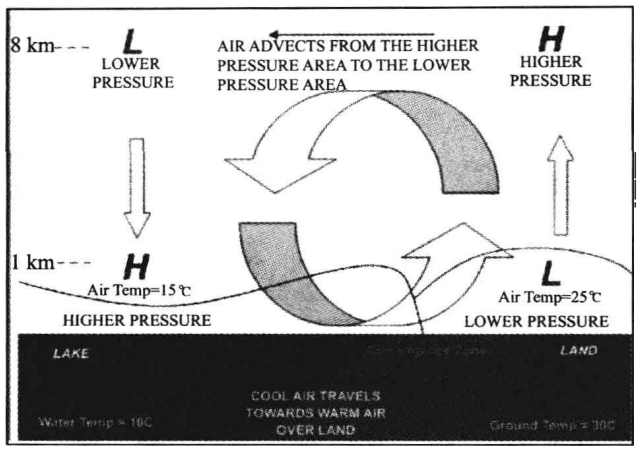


Figure 3.8 Idealized Circulation Pattern Associated with a Sea Breeze

temperature. Similar boundaries form downwind on lakes and rivers during the day, as well as offshore landmasses at night. Since the specific heat of water is so high, there is little diurnal change in the temperature of bodies of water, even on the sunniest days. The water temperature varies less than 1 °C (1 to 2 °F). By contrast, the land, with a lower specific heat, can vary several degrees in a matter of hours.

During the afternoon, air pressure decreases over the land as temperature rises. The relatively cooler air over the sea rushes in to fill the gap. The result is a relatively cool onshore wind. This process usually reverses at night where the water temperature is higher relative to the landmass, leading to an offshore land breeze. However, if water temperatures are colder than the land at night, the sea breeze may continue, only somewhat abated. This is typically the case along the California coast.

If enough moisture exists, thunderstorms can form along sea breeze fronts which then can send out outflow boundaries. This causes chaotic wind/pressure regimes if the steering flow is light. Like all other surface features, sea breeze fronts lie inside troughs of low pressure.

3.2 Areas and Seasons of Strong Winds at Sea

In the winter, the Aleutian Low and the Icelandic Low develop in the North Pacific Ocean and North Atlantic Ocean and the most favorable conditions for vigorous frontal activity are concentrated along the east coasts of North America and Asia. Therefore, gale wind frequency is high and it is widely distributed in the ocean. In the waters north of 30°N, the frequency of winds force ≥7 scale is 10% ~ 20%. The gale wind frequency is higher in the North Atlantic than that of the north Pacific.

In the summer, The south-west Monsoon is so strong that the wind frequently reaches 8 to 9 on the Beaufort scale in the north Indian Ocean.

In the Southern Hemisphere oceans, for waters south of 30°S, gale winds may be encountered through the year. The scope of high frequency of gale wind is larger in winter. For waters around Cape of Good Hope, the winds are even stronger due to the effect of the terrain.

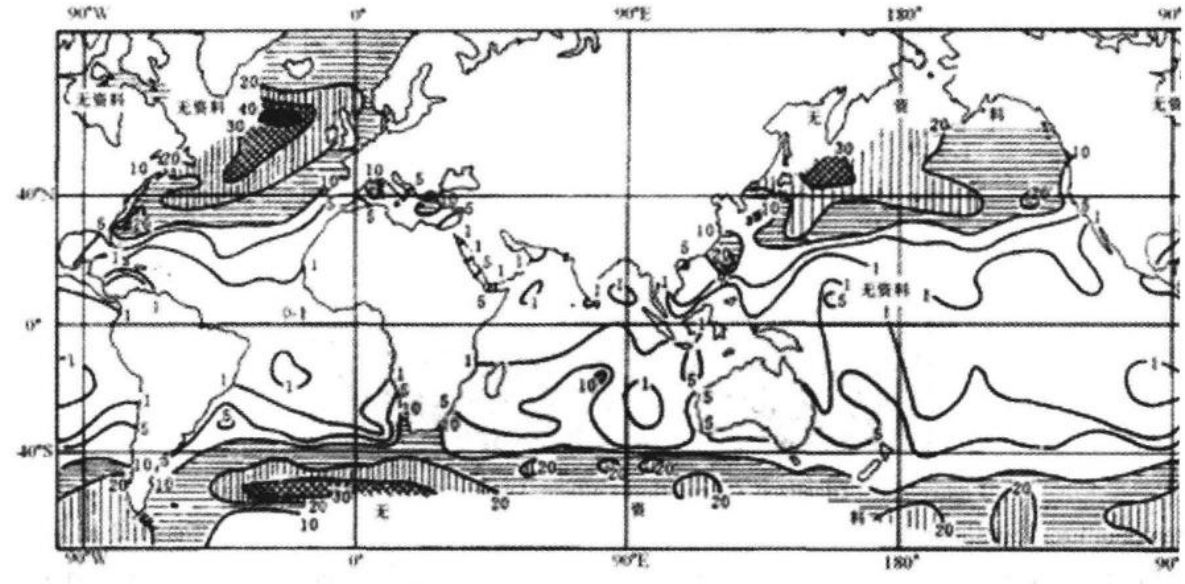


Figure 3.9 Frequency of Gale Wind (≥7 scale) in January

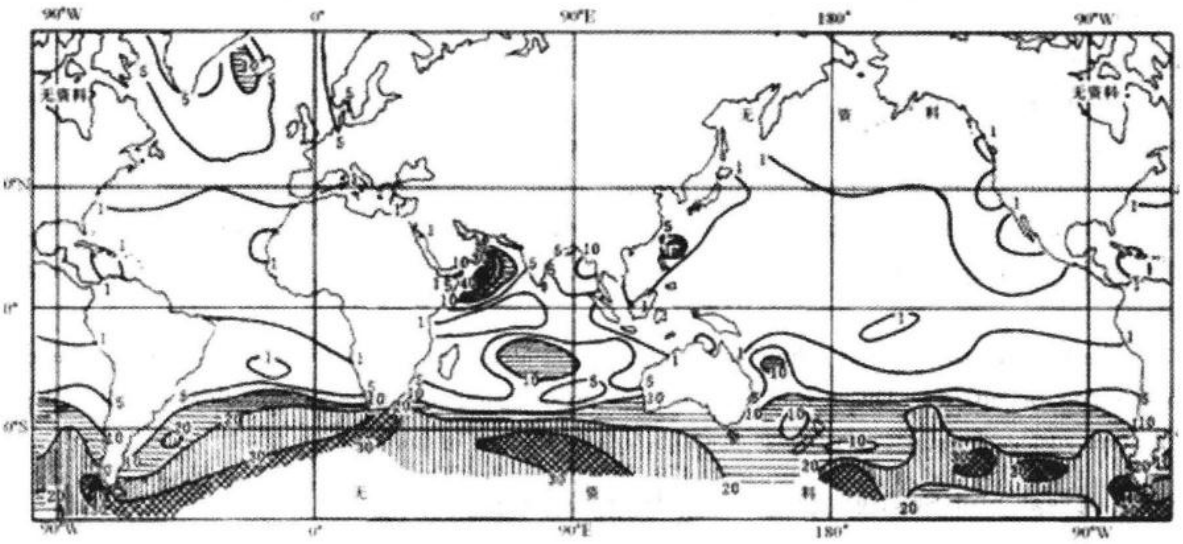


Figure 3.10 Frequency of Gale Wind (≥7 scale) in July

3.3 Distribution of Sea Fog

3.3.1 General Distribution of Sea Fog

Based on their formation characteristics, fog occurs in the following areas:

Advection fog mainly occurs in the cold water areas where the warm current meets the cold current in the temperate ocean, and it is the most common fog at sea.

Radiation fog is seldom found over 10 n mile away from the coasts.

Frontal fog mainly occurs in the middle latitudes and moves with the front.

Steam fog mainly occurs in the high latitudes cold waters.

Sea fog distribution is thus observed having the following characteristics:

More in spring and summer and less in autumn and winter;

More in the middle and high latitudes and less in the low latitudes;

More in the west coast of the ocean and less in the east coast;

Almost nil fog in the ocean center and near the equator;

More in the Northern Ocean and less in the Southern Ocean;

More in the Pacific Ocean and less in the Atlantic Ocean.

3.3.2 Foggy Locations in the Ocean

3.3.2.1 East of Hokkaido Japan to the Aleutian Islands

This is the foggiest place in the Pacific Ocean, the meeting place of the cold Oyashio Current from the north and the much warmer Kuroshio Current from the south. Warm, moist air blowing from south over the waters east of Japan and dense advection fog occurs frequently. Advection fog is more active from June to August and is most active in July. Frontal fogs are active in the winter due to frontal activities. The foggiest waters, however, are in the passage between Far East and North America, and the climate is adverse for navigation especially in the stormy winter.

3.3.2.2 The Grand Banks off Newfoundland

This is the foggiest place in the world, the meeting place of the cold Labrador Current from the north and the much warmer Gulf Stream from the south. The advection fog prevails in spring and summer. The foggy area can extend eastward near Iceland, and cover over 20 latitudes in the longitudinal direction. The passages between North America and Europe in the northern part of Atlantic are under the influence of fogs. Frontal fogs are active in winter due to frontal activities. Steam fog can also be encountered in winter due to the strong cold air blowing from the higher latitudes.

3.3.2.3 Waters Between Norway, Western Europe and Iceland

As the meeting place of the cold Iceland Current from the north and the much warmer North Atlantic current from the south, fog is common in all seasons. Advection fog is active in summer and frontal fog is active in winter. In autumn and winter, radiation fog and steam fog are active in the valleys and harbors along the Norwegian coastline. Even though it covers less area and is also less frequent than that east of Hokkaido Japan and Grand Banks, it affects the passages between Europe and North America and also West Europe and North Europe adversely. Statistically, cases of collision accidents due to fog in English Channel and Northern Sea waters are the most in navigation.

3.3.2.4 Waters East of Argentina, Between Tasmania and New Zealand and South of Madagascar

These are the three advection fog areas, the meeting places of the cold West Wind Drift and the warmer Brazil Current and East Australian Current, Agulhas Current respectively. The foggy areas are relative narrow and most fog occurs in the Southern Hemisphere's Summer.

3.3.2.5 East Coast of the Trades Belt, e.g., California, Peru, Chile, Canary Islands and West Coast of South Africa

The advection fog forms over upwelling waters due to the offshore winds all around the year. Occasionally advection fog may form when warm and moist air is blowing over the cold water. Fog is

more active in spring and summer, but it covers less areas and is less dense.

3.3.2.6 Arctic Ocean, Antarctica Ice Edge, Waters Between Ice, and East Coasts of Middle and High Latitudes of Continents

Steam fog forms when cold air blows from the higher latitudes of continents.

CHAPTER 4 BASIC KNOWLEDGE OF OCEANOGRAPHY

4.1 Ocean Currents

4.1.1 Outline of Ocean Currents

An ocean current is a continuous, directed movement of ocean water generated by the forces acting upon the water, such as the wind, Coriolis force, temperature and salinity differences, and tides caused by the gravitational pull of the Moon and the Sun. Depth contours, shoreline configurations and interaction with other currents influence a current's direction and strength.

Ocean currents can flow for great distances, and together they create the great flow of the global conveyor belt which plays a dominant part in determining the climate of many of the Earth's regions. Perhaps the most striking example is the Gulf Stream, which makes Northwest Europe much more temperate than any other region at the same latitude. Another example is the Hawaiian Islands, where the climate is cooler (sub-tropical) than the tropical latitudes in which they are located, due to the effect of the California Current.

Surface ocean currents are generally wind driven and develop their typical clockwise spirals in the Northern Hemisphere and counter clockwise rotation in the Southern Hemisphere because of the imposed wind stresses. In wind driven currents, the Ekman spiral effect results in the currents flowing at an angle to the driving winds. The areas of surface ocean currents move somewhat with the seasons; this is most notable in equatorial currents.

Ocean basins generally have a non-symmetric surface current, in that the eastern equatorward-flowing branch is broad and diffuse, whereas the western poleward-flowing branch is very narrow. These western boundary currents (of which the Gulf Stream is an example) are a consequence of basic fluid dynamics.

Deep ocean currents are driven by density and temperature gradients. Thermohaline circulation, also known as the ocean's conveyor belt, refers to the deep ocean density-driven ocean basin currents. Deep waters sink into the deep ocean basins at high latitudes where the temperatures are cold enough to cause the density to increase. These currents, which flow under the surface of the ocean and are thus hidden from immediate detection, are called submarine rivers. Upwelling and downwelling areas in the oceans are areas where significant vertical movement of ocean water is observed.

Surface currents make up about 10% of all the water in the ocean. Surface currents are generally restricted to the upper 400 m of the ocean.

Knowledge of surface ocean currents is essential in reducing costs of shipping, since they can

reduce fuel costs. In the sail-ship era knowledge was even more essential. A good example of this is the Agulhas Current, which long prevented Portuguese sailors from reaching India. Even today, the round-the-world sailing competitors employ surface currents to their benefit. Ocean currents are also very important in the dispersal of many life forms. An example is the life cycle of the eel.

4.1.2 The Formation of Currents

The primary generating forces are wind, and differences in density of the water caused by variations in heat and salt. Currents generated by these forces are modified by such factors as depth of water, underwater topography including shape of the basin in which the current is running, extent and location of land, and deflection by the rotation of the earth.

The force of wind blowing across the sea causes a surface layer of water to move. Due to the low viscosity of water, this force is not directly communicated to the ocean interior, but is balanced by the Coriolis force within a relatively thin surface layer, 10 ~ 200 m thick. This layer is called the Ekman Layer and the motion of this layer is called the Ekman Transport. Because of the deflection by the Coriolis force, the Ekman Transport is not in the direction of the wind, but is 90° to the right in the Northern Hemisphere and 90° toward the left in the Southern Hemisphere. The amount of water flowing in this Layer depends only upon the wind and the Coriolis force and is independent of the depth of the Ekman Layer and the viscosity of the water.

The large scale convergence or divergence of Ekman Transport serves to drive the general ocean circulation. Consider the case of the Northern Hemisphere subtropics. To the south lie easterly winds with associated northward Ekman Transport. To the north lie westerly winds with southward Ekman Transport. The convergence of these Ekman Transports is called Ekman pumping, and results in a thickening of the upper ocean and a increase in the depth of the thermocline. The resulting subsurface pressure gradients, balanced by the Coriolis force, give rise to the anticyclonic subtropical gyres found at mid-latitudes in each ocean basin. In subpolar regions, Ekman suction produces cyclonic gyres.

These wind driven gyres are not symmetrical. Along the **western boundary** of the oceans, currents are narrower, stronger, and deeper, often following a meandering course. These currents are sometimes called a **stream.** In contrast, currents in mid-ocean and at the **eastern boundary** are often broad, shallow and slow-moving. Sometimes these are called drift currents.

Within the Ekman Layer, the currents actually form a spiral. At the surface, the difference between wind direction and surface wind-current direction varies from about 15° along shallow coastal areas to a maximum of 45° in the deep oceans. As the motion is transmitted to successively deep layers, the Coriolis force continues to deflect the current. At the bottom of the Ekman layer, the current flows in the opposite direction to the surface current. This shift of current directions with depth, combined with the decrease in velocity with depth, is called the Ekman Spiral.

The velocity of the surface current is the sum of the velocities of the Ekman, geostrophic, tidal, and other currents. The Ekman surface current or wind drift current depends upon the speed of the wind, its constancy, the length of time it has blown, and other factors. In general, however, wind drift current is about 2 percent of the wind speed, or a little less, in deep water where the wind has

been blowing steadily for at least 12 hours.

The density of water varies with salinity, temperature and pressure. At any given depth, the differences in density are due only to differences in temperature and salinity. With sufficient data, maps showing geographical density distribution at a certain depth can be drawn, with lines connecting points of equal density. These lines are be similar to isobars on a weather map and serve an analogous purpose, showing areas of high density and those of low density. In an area of high density, the water surface is lower than in an area of low density, the maximum difference in height being about 1 meter in 100 km.

Because of this difference, water tends to flow from an area of higher water (low density) to one of lower water (high density). But due to the rotation of the Earth, it is deflected by the Coriolis force towards the right in the Northern Hemisphere, and towards the left in the Southern Hemisphere. This balance, between subsurface pressure fields and the Coriolis force, is called geostrophic equilibrium. At a given latitude, the greater the density gradient (rate of change with distance), the faster the geostrophic current.

4.1.3 Main Ocean Currents

A number of ocean currents flow with great persistence, setting up a circulation that continues with relatively little change throughout the year. Because of the influence of wind in creating current, there is a relationship between this oceanic circulation and the general circulation of the atmosphere. The oceanic circulation is shown on the Figure 4.1, with the names of the major ocean currents. Some differences in opinion exist regarding the names and limits of some of the currents, but those shown are generally. Speed may vary somewhat with the season. This is particularly noticeable in the Indian Ocean and along the South China coast, where currents are influenced to a marked degree by the monsoons.

The Southern Ocean has no meridional boundaries and its waters are free to circulate around the world. It serves as a conveyor belt for the other oceans, exchanging waters between them. The northern boundary of the Southern Ocean is marked by the Subtropical Convergence Zone. This zone marks the transition from the temperate region of the ocean to the polar region and is associated with the surfacing of the main thermocline. This zone is typically found at 40°S but varies with longitude and season.

The Gulf Stream, together with its northern extension towards Europe, the **North Atlantic Drift**, is a powerful, warm, and swift Atlantic Ocean current that originates at the tip of Florida, and follows the eastern coastlines of the United States and Newfoundland before crossing the Atlantic Ocean. The process of western intensification causes the Gulf Stream to be a northward accelerating current off the east coast of North America. The Gulf Stream influences the climate of the east coast of North America from Florida to Newfoundland, and the west coast of Europe. The climate of Western Europe and Northern Europe is warmer than it would otherwise be due to the North Atlantic Drift, one of the branches from the tail of the Gulf Stream.

A tremendous volume of water flows northward in the Gulf Stream. It can be distinguished by its deep indigo-blue color, which contrasts sharply with the dull green of the surrounding water. It is

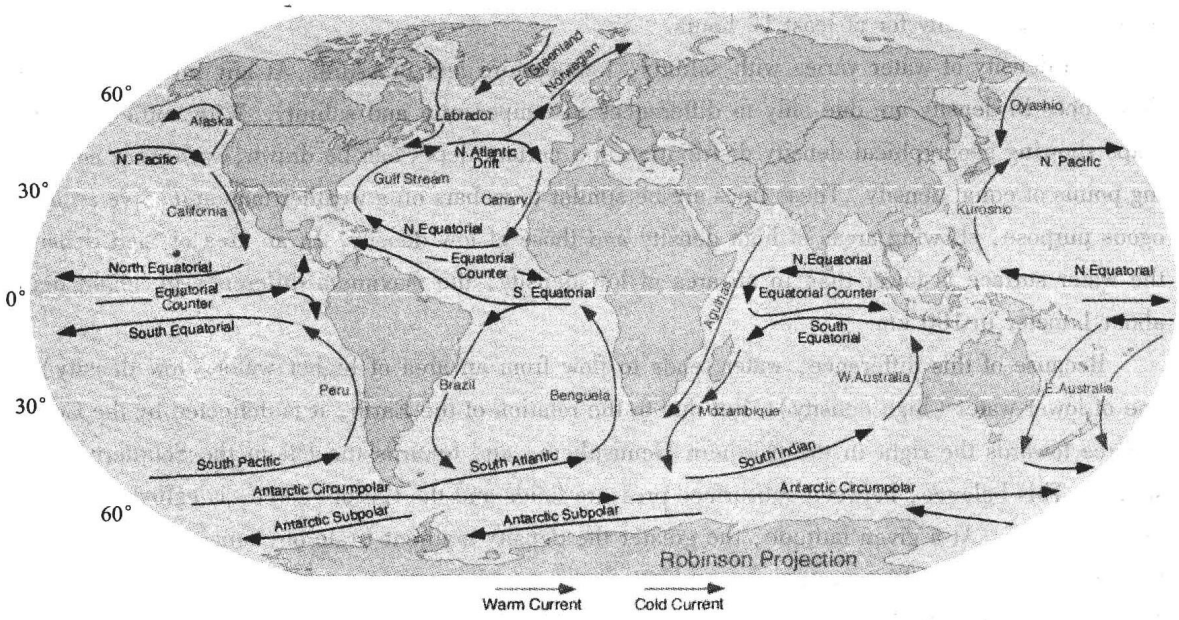


Figure 4.1 Ocean Surface Currents

accompanied by frequent squalls. When the Gulf Stream encounters the cold water of the **Labrador Current**, principally in the vicinity of the Grand Banks, there is little mixing of the waters. Instead, the junction is marked by a sharp change in temperature. The line or surface along which this occurs is called the cold wall. When the warm Gulf Stream water encounters cold air, evaporation is so rapid that the rising vapor may be visible as frost smoke. In spring and early summer, the Labrador Current transports icebergs from the glaciers of Greenland southwards into the trans-Atlantic shipping lanes.

Pacific Ocean currents follow the some general pattern of those in the Atlantic. The **Kuroshio** is a strong western boundary current in the western north Pacific Ocean. It begins off the east coast of Taiwan and flows northeastward past Japan, where it merges with the easterly drift of the North Pacific Current. The Kuroshio (Japanese for "Black Stream") is so named because of the dark color of its water. It is sometimes called the Japan Current. In many respects it is similar to the Gulf Stream of the Atlantic. Like that current, it carries large quantities of warm tropical water to higher latitudes, and then curves toward the east as a major part of the general clockwise circulation in the Northern Hemisphere. As it does so, it widens and slows, continuing on between the Aleutians and the Hawaiian Islands, where it becomes known as the **North Pacific Current.**

As in the Atlantic, there is in the Pacific a counterclockwise circulation to the north of the clockwise circulation. Cold water flowing southward through the western part of Bering Strait between Alaska and Siberia, is joined by water circulating counterclockwise in the Bering Sea to form the **Oyashio.** As the current leaves the strait, it curves toward the right and flows southwesterly along the coast of Siberia and the Kuril Islands. This current brings quantities of sea ice, but no icebergs. When it encounters the Kuroshio, the Oyashio curves southward and then eastward, the greater portion joining the Kuroshio and North Pacific Current.

The **Humboldt Current** (also known as **Peru Current**) is a cold, low-salinity ocean current that flows north-westward along the west coast of South America from the southern tip of Chile to northern Peru. It is an eastern boundary current flowing in the direction of the equator, and can extend 1,000 kilometers offshore. The Humboldt Current Large Marine Ecosystem (LME) is one of the major **upwelling** systems of the world, supporting an extraordinary abundance of marine life. The presence of the Humboldt Current and its associated wind shear prevents the formation of tropical cyclones in the area (The same effect occurs in the South Atlantic with the Benguela Current). Periodically, the upwelling that drives the system's productivity is disrupted by the El Niño-Southern Oscillation (**ENSO**) event.

Indian Ocean currents generally follow the same pattern of the Atlantic and Pacific but with differences caused principally by the monsoons, the more limited extent of water in the Northern Hemisphere, and by limited communication with the Pacific Ocean along the eastern boundary. During the Northern Hemisphere winter, the North Equatorial Current and South Equatorial Current flow toward the west, with the weaker, eastward Equatorial Countercurrent flowing between them, as in the Atlantic and Pacific (but somewhat south of the equator). But during the Northern Hemisphere summer, both the North Equatorial Current and the Equatorial Countercurrent are replaced by the Southwest Monsoon Current, which flows eastward and southeastward across the Arabian Sea and the Bay of Bengal. Near Sumatra, this current curves in a clockwise direction and flows westward, augmenting the South Equatorial Current, and setting up a clockwise circulation in the northern part of the Indian Ocean. Off the coast of Somalia, the Somali Current reverses direction during the Northern Hemisphere summer with northward currents reaching speeds of 5 knots or more.

4.1.4 El Niño-Southern Oscillation (ENSO)

El Niño/La Niña-Southern Oscillation, or **ENSO**, is a quasi-periodic climate pattern that occurs across the tropical Pacific Ocean. It is characterised by variations in the temperature of the surface of the tropical eastern Pacific Ocean – warming or cooling known as El Niño and La Niña respectively – and air surface pressure in the tropical western Pacific – the Southern Oscillation. The two variations are coupled: the warm oceanic phase, El Niño, accompanies high air surface pressure in the west Pacific, while the cold phase, La Niña, accompanies low air surface pressure in the west Pacific. Mechanisms that cause the oscillation remain under study.

ENSO causes extreme weather such as floods, droughts and other weather disturbances in many regions of the world.

In popular usage, the El Niño-Southern Oscillation is often called just "El Niño". El Niño is Spanish for "the boy" and refers to the Christ child, because periodic warming in the Pacific near South America is usually noticed around Christmas.

El Niño is defined by prolonged differences in Pacific Ocean surface temperatures when compared with the average value. The accepted definition is a warming or cooling of at least 0.5 °C (0.9 °F) averaged over the east-central tropical Pacific Ocean. Typically, this anomaly happens at irregular intervals of 2 ~ 7 years and lasts nine months to two years. The first signs of an El Niño are:

Rise in surface pressure over the Indian Ocean, Indonesia and Australia;

Fall in air pressure over Tahiti and the rest of the central and eastern Pacific Ocean;

Trade winds in the south Pacific weaken or head east;

Warm air rises near Peru, causing rain in the northern Peruvian deserts;

Warm water spreads from the west Pacific and the Indian Ocean to the east Pacific. It takes the rain with it, causing extensive drought in the western Pacific and rainfall in the normally dry eastern Pacific.

El Niño's warm rush of nutrient-poor tropical water, heated by its eastward passage in the Equatorial Current, replaces the cold, nutrient-rich surface water of the Humboldt Current. When El Niño conditions last for many months, extensive ocean warming and the reduction in easterly trade winds limits upwelling of cold nutrient-rich deep water, and its economic impact to local fishing for an international market can be serious.

The Southern Oscillation is the atmospheric component of El Niño. This component is an oscillation in surface air pressure between the tropical eastern and the western Pacific Ocean waters. The strength of the Southern Oscillation is measured by the Southern Oscillation Index (SOI). The SOI is computed from fluctuations in the surface air pressure difference between Tahiti and Darwin, Australia. El Niño episodes are associated with negative values of the SOI, meaning that the pressure at Tahiti is relatively low compared to Darwin.

Low atmospheric pressure tends to occur over warm water and high pressure occurs over cold water, in part because deep convection over the warm water acts to transport air. El Niño episodes are defined as sustained warming of the central and eastern tropical Pacific Ocean. This results in a decrease in the strength of the Pacific Trade Winds, and a reduction in rainfall over eastern and northern Australia.

La Niña is the name for the cold phase of ENSO, during which the cold pool in the eastern Pacific intensifies and the Trade Winds strengthen. The name La Niña originates from Spanish, meaning "the girl", analogous to El Niño meaning "the boy". It has also in the past been called anti-El Niño, and El Viejo (meaning "the old man").

4.2 Sea Waves

4.2.1 The Description of Sea Waves

In fluid dynamics, **wind waves** or, more precisely, **wind-generated waves** are surface waves that occur on the free surface of oceans, seas, lakes, rivers, and canals or even on small puddles and ponds. They usually result from the wind blowing over a vast stretch of fluid surface. Some waves in the oceans can travel thousands of kilometers before reaching land. Wind waves range in size from small ripples to huge rogue waves. There is little forward motion of individual water particles in a wave, despite the large amount of energy it may carry forward.

When directly being generated and affected by the local winds, a wind wave system is called a **wind sea.** After the wind ceases to blow, wind waves are called **swell.** Or, more generally, a swell consists of wind generated waves that are not-or hardly-affected by the local wind at the same

moment. They have been generated elsewhere, or some time ago. Wind waves in the ocean are called **ocean surface waves.**

Tsunamis are a specific type of wave not caused by wind but by geological effects such as earthquakes. In deep water, tsunamis are not visible because they are small in height and very long in wavelength. They may grow to devastating proportions at the coast due to reduced water depth.

Waves are characterized by:

Wave height (from trough to crest);

Wavelength (from crest to crest);

Period (time interval between the arrival of consecutive crests at a stationary point);

The direction of wave propagation.

Waves in a given area typically have a range of heights. For weather reporting and for scientific analysis of wind wave statistics, their characteristic height over a period of time is usually expressed as **significant wave height**. This figure represents an average height of the highest one-third of the waves in a given time period (usually chosen somewhere in the range from 20 minutes to 12 hours), or in a specific wave or storm system. Given the variability of wave height, the largest individual waves are likely to be about twice the reported significant wave height for a particular day or storm.

Average $\overline{H}$	0.64
Significant $H_{1/3}$	1.00
Highest 10 percent $H_{1/10}$	1.29
Highest H_{max}	1.87

4.2.2 The Formation of Waves

The great majority of large breakers one observes on a beach result from distant winds. Five factors influence the formation of wind waves:

Wind speed;

Distance of open water that the wind has blown over (called the fetch);

Width of area effected by fetch;

Time duration the wind has blown over a given area, and Water depth.

All of these factors work together to determine the size of wind waves. The greater each of the variables, the larger the waves.

4.2.3 Types of Wind Waves

Three different types of wind waves develop over time, capillary waves, or ripples, seas and swells.

Ripples appear on smooth water when the wind blows, but will die quickly if the wind stops. The restoring force that allows them to propagate is surface tension. Seas are the larger-scale, often irregular motions that form under sustained winds. They tend to last much longer, even after the wind has died, and the restoring force that allows them to persist is gravity. As seas propagate away from their area of origin, they naturally separate according to their direction and wavelength. The regular wave motions formed in this way are known as swells.

Individual "rogue waves" (also called "freak waves", "monster waves", "killer waves", and

"king waves") sometimes occur, up to heights near 30 meters, and are much higher than the other waves in the sea state. Such waves are distinct from tides, caused by the Moon and Sun's gravitational pull. Tsunamis that are caused by underwater earthquakes or landslides, and waves generated by underwater explosions or the fall of meteorites, all have far longer wavelengths than wind waves.

Some waves undergo a phenomenon called "breaking". A breaking wave is one whose base can no longer support its top, causing it to collapse. A wave breaks when it runs into shallow water, or when two wave systems oppose and combine forces. When the slope, or steepness ratio of a wave is too great, breaking is inevitable.

Individual waves in deep water break when the wave steepness – the ratio of the wave height H to the wavelength λ – exceeds about 0.17, so for $H > 0.17\ \lambda$. In shallow water, with the water depth small compared to the wavelength, the individual waves break when their wave height H is larger than 0.8 times the water depth h, that is $H > 0.8$ h. Waves can also break if the wind grows strong enough to blow the crest off the base of the wave.

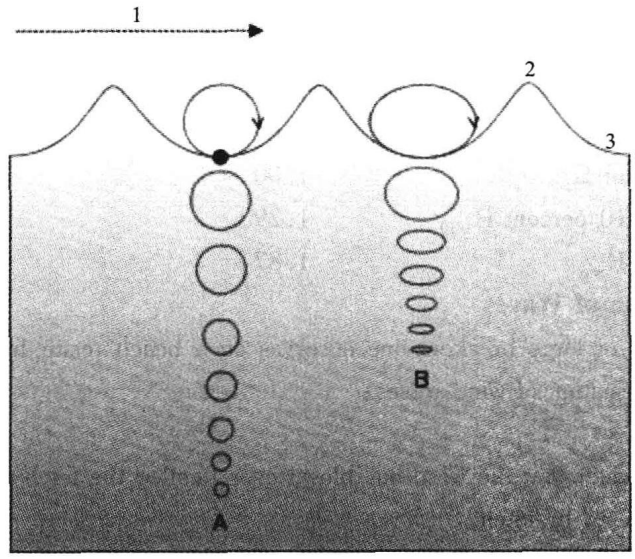


Figure 4.2 Motion of a Particle in a Wind Wave

A = At deep water. The orbital motion of fluid particles decreases rapidly with increasing depth below the surface.

B = At shallow water (sea floor is now at B). The elliptical movement of a fluid particle flattens with decreasing depth.

1 = Propagation direction.

2 = Wave crest.

3 = Wave trough.

When several wave trains are present, as is always the case in nature, the waves form groups. In deep water the groups travel at a group velocity which is half of the phase speed. Following a single wave in a group one can see the wave appearing at the back of the group, growing, and finally disappearing at the front of the group.

As the water depth h decreases towards the coast, this will have an effect: wave height changes due to wave shoaling and refraction. As the wave height increases, the wave may become unstable when the crest of the wave moves faster than the trough. This causes *surf*, a breaking of the waves.

4.2.4 Effects of Currents on Waves

A following current increases wavelengths and decreases wave heights. An opposing current has the opposite effect, decreasing the length and increasing the height. This effect can be dangerous in certain areas of the world where a stream current opposes waves generated by severe weather. An example of this effect is off the coast of South Africa, where the Agulhas Current is often opposed by westerly storms, creating steep, dangerous seas. A strong opposing current may cause the waves to break, as in the case of overfalls in tidal currents. The extent of wave alteration is dependent upon the ratio of the still-water wave speed to the speed of the current. Moderate ocean currents running at oblique angles to wave directions appear to have little effect, but strong tidal currents perpendicular to a system of waves have been observed to completely destroy them in a short period of time.

4.2.5 The Effect of Ice on Waves

When ice crystals form in seawater, internal friction is greatly increased. This results in smoothingof the sea surface. The effect of pack ice is even more pronounced. A vessel following a lead through such ice may be in smooth water even when a gale is blowing and heavy seas are beating against the outer edge of the pack. Hail or torrential rain is also effective in flattening the sea, even in a high wind.

4.2.6 Tsunamis

Tsunamis are ocean waves produced by sudden, large scale motion of a portion of the ocean floor or the shore, such as a volcanic eruption, earthquake (sometimes called seaquake if it occurs at sea), or a landslide. If they are caused by a submarine earthquake, they are usually called seismic sea waves. The point directly above the disturbance, at which the waves originate, is called the epicenter. often a tsunami or a storm tide that overflows the land is popularly called a tidal wave, although it bears no relation to the tide.

If a volcanic eruption occurs below the surface of the sea, the escaping gases cause a quantity of water to be pushed upward in the shape of a dome. As this water settles back, it creates a wave which travels at high speed across the surface of the ocean.

Tsunamis travel in a series of waves. Near the epicenter, the first wave may be the highest. At greater distances, the highest wave usually occurs later in the series, commonly between the third and the eighth wave. Following the maximum, they again become smaller, but the tsunami may be detectable for several days.

In deep water the wave height of a tsunami is probably never greater than 1 meter. Since the wavelength is usually considerably more than 200 kilometers, the wave is not conspicuous at sea. In the Pacific, where most tsunamis occur, the wave period varies between about 15 and 60 minutes, and the speed in deep water is more than 400 knots. The approximate speed can be computed by the formula: $S = 0.6(gd)^{1/2} = 3.4d^{1/2}$, where S is the speed in knots, g is the acceleration due to gravity (10 meters per second), and d is the depth of water in meter. This formula is applicable to any

wave in water having a depth of less than half the wavelength. For most ocean waves it applies only in shallow water, because of the relatively short wavelength.

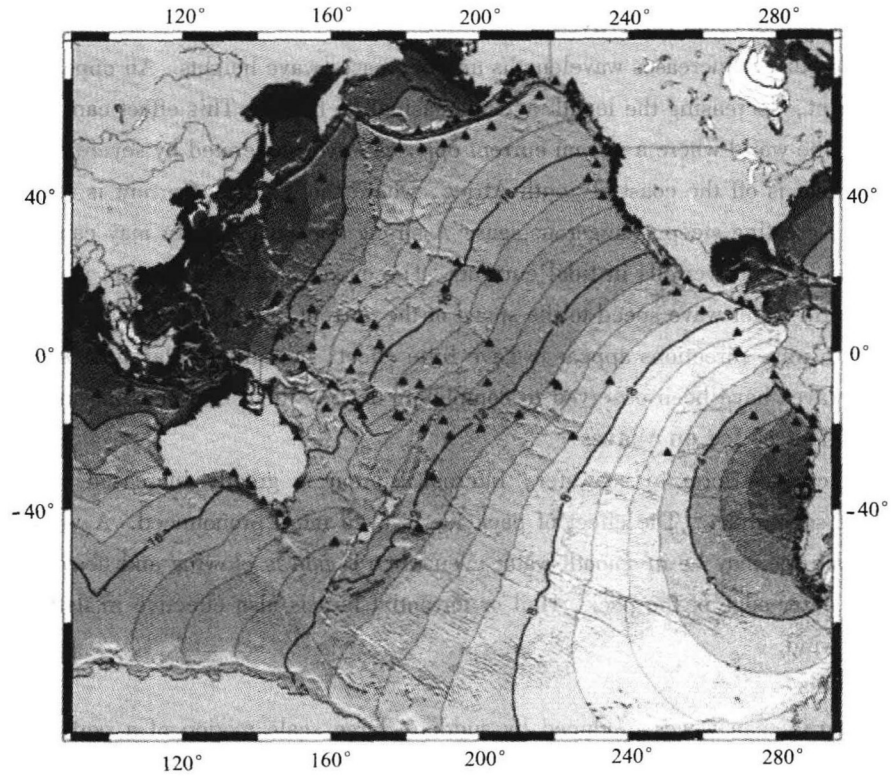


Figure 4.3 Tsunami Waves in Feb. 2010 After the Earthquake in Chile

When a tsunami enters shoal water, it undergoes the same changes as other waves. The formula indicates that speed is proportional to depth of water. Because of the great speed of a tsunami when it is in relatively deep water, the slowing is relatively much greater than that of an ordinary wave crested by wind. Therefore, the increase in height is also much greater. The size of the wave depends upon the nature and intensity of the disturbance. The height and destructiveness of the wave arriving at any place depends upon its distance from the epicenter, topography of the ocean floor and the coastline. The angle at which the wave arrives, the shape of the coastline, and the topography along the coast and offshore, all have an effect. The position of the shore is also a factor, as it may be sheltered by intervening land, or be in a position where waves have a tendency to converge, either because of refraction or reflection, or both.

Tsunamis 15 meters in height or higher have reached the shore, inflicting widespread damage. On April 1, 1946, seismic sea waves originating at an epicenter near the Aleutians, spread over the entire Pacific. Scotch Cap Light on Unimak Island, 20 meters above sea level, was completely destroyed. Traveling at an average speed of 1 km per hour, the waves reached the Hawaiian Islands in 4 hours and 34 minutes, where they arrived as waves 15 meters above the high water level, and floo-

ded a strip of coast more than 300 meters wide at some places. They left a death toll of 173 and property damage of $25 million. Less destructive waves reached the shores of North and South America, as well as Australia, 12,400 km from the epicenter.

After this disaster, for instance a tsunami warning system was set up in the Pacific, even though destructive waves are relatively rare (averaging about one in 20 years in the Hawaiian Islands). This system monitors seismic disturbances throughout the Pacific basin and predicts times and heights of tsunamis. Warnings are immediately sent out if a disturbance is detected.

In addition to seismic sea waves, earthquakes below the surface of the sea may produce a longitudinal wave that travels upward at the speed of sound. When a ship encounters such a wave, it is felt as a sudden shock which may be so severe that the crew thinks the vessel has struck bottom.

4.2.7 Storm Tides

In relatively tideless seas like the Baltic and Mediterranean, winds cause the chief fluctuations in sea level. Elsewhere, the lunar tide usually masks these variations. However, under exceptional conditions, either severe extra-tropical storms or tropical cyclones can produce changes in sea level that exceed the normal range of tide. Low sea level is of little concern except to shipping, but a rise above ordinary high-water mark, particularly when it is accompanied by high waves, can result in a catastrophe.

Although, like tsunamis, these storm tides or storm surges are popularly called tidal waves, they are not associated with the tide. They consist of a single wave crest and hence have no period or wavelength.

Three effects in a storm induce a rise in sea level. The first is wind force on the sea surface, which results in a piling-up of water (sometimes called "wind set-up"). The second effect is the convergence of wind-driven currents, which elevates the sea surface along the convergence line. In shallow water, bottom friction and the effects of local topography cause this elevation to persist and may even intensify it. The low atmospheric pressure that accompanies severe storms causes the third effect, which is sometimes referred to as the "inverted barometer". One cm of mercury is equivalent to about 13.6 cm of water, and the adjustment of the sea surface to the reduced pressure can amount to about one meter at equilibrium.

All three of these causes act independently, and if they happen to occur simultaneously, their effects are cumulative. In addition, the wave can be intensified or amplified by the effects of local topography. Storm tides may reach heights of 6 meters or more, and it is estimated that they cause three-fourths of the deaths attributed to hurricanes.

4.3 Sea Ice

4.3.1 Types of Sea Ice

Sea ice is largely formed from ocean water that freezes. At a salinity of 35 parts per thousand, the approximate average for the oceans, the freezing point is -1.88 ℃. As the density of surface seawater increases with decreasing temperature, convective density-driven currents are induced bringing warmer, less dense water to the surface.

Sea ice may be contrasted with **icebergs**, which are chunks of ice shelves or glaciers that calve into the ocean. Icebergs are compacted snow and hence made of fresh water.

Land-fast ice, or simply fast ice, is sea ice that has frozen along coasts ("fastened" to them) or to the sea floor over shallow parts of the continental shelf, and extends out from land into sea. Unlike drift ice, it does not move with currents and wind.

Drift ice consists of ice that floats on the surface of the water, as distinguished from fast ice, attached to coasts.

When packed together in large masses, drift ice is called **pack ice.** Pack ice may be either freely floating or blocked by fast ice while drifting past.

The most important areas of pack ice are the polar ice packs formed from seawater in the Earth's polar regions: the Arctic ice pack of the Arctic Ocean, and the Antarctic ice pack of the Southern Ocean. Polar packs significantly change their size during seasonal changes of the year. Because of vast amounts of water added to or removed from the oceans and atmosphere, the behavior of polar ice packs have a significant impact on the global changes in climate.

The mean areal density, or concentration, of pack ice in any given area is expressed in tenths. Concentrations range from: open water (total concentration of all ice is less than one tenth), very open pack (1 to 3 tenths concentration), open pack (4 to 6 tenths concentration), close pack (7 to 8 tenths concentration), very close pack (9 to 10 to less than 10 to 10 concentration), to compact or consolidated pack (10 to 10 or complete coverage). The extent to which an ice cover of varying concentrations can be penetrated by a vessel varies from place to place and with changing weather conditions. With a concentration of 1 to 3 tenths in a given area, an unreinforced vessel can generally navigate safely, but the danger of receiving heavy damage is always present. When the concentration increases to between 3 and 5 tenths, the area becomes only occasionally accessible to an unreinforced vessel, depending upon the wind and current. With concentrations of 5 to 7 tenths, the area becomes accessible only to ice strengthened vessels, which on occasion will require icebreaker assistance. Navigation in areas with concentrations of 7 tenths or more should only be attempted by icebreakers.

An **ice flow** is a floating chunk of ice that is less than 10 kilometers in its greatest dimension. Wider chunks of ice are called ice fields.

Pancake ice is sea ice that has been compressed by the action of waves on frazil ice. Plates are typically 1 ~3 meters across.

4.3.2 Iceberg Drift

Icebergs extend a considerable distance below the surface and have relatively small "sail areas" compared to their subsurface mass. Therefore, the near-surface current is thought to be primarily responsible for drift. However, observations have shown that wind can be the dominant force that governs iceberg drift at a particular location or time. Also, the current and wind may contribute nearly equally to the resultant drift.

Two other major forces which act on a drifting iceberg are the Coriolis force and, to a lesser extent, the pressure gradient force which is caused by gravity owing to a tilt of the sea surface, and

is important only for iceberg drift in a major current.

The relative influence of currents and winds on the drift of an iceberg varies according to the direction and magnitude of the forces acting on its sail area and subsurface cross-sectional area. Studies tend to show that, generally, where strong currents prevail, the current is dominant. In regions of weak currents, however, winds that blow for a number of hours in a steady direction materially affect the drift of icebergs. Generally, it can be stated that currents tend to have a greater effect on deep-draft icebergs, while winds tend to have a greater effect on shallow-draft icebergs.

4.3.3 Extent of Ice in the Sea

When an area of sea ice, no matter what form it takes or how it is disposed, is described, it is referred to as pack ice. In both polar regions the pack ice is a very dynamic feature, with wide deviations in its extent dependent upon changing oceanographic and meteorological phenomena.

In winter the Arctic pack extends over the entire Arctic Ocean, and for a varying distance outward from it; the limits recede considerably during the warmer summer months.

Each year a large portion of the ice from the Arctic Ocean moves outward between Greenland and Spitsbergen (Fram Strait) into the North Atlantic Ocean and is replaced by new ice. Because of this constant annual removal and replacement of sea ice, relatively little of the Arctic pack ice is more than 10 years old.

Ice covers a large portion of the Antarctic waters and is probably the greatest single factor contributing to the isolation of the Antarctic continent. During the Austral winter (June through September), ice completely surrounds the continent, forming an almost impassable barrier that extends northward on the average to about 54°S in the Atlantic and to about 62°S in the Pacific. Disintegration of the pack ice during the Austral summer months of December through March causes the limits of the ice edge to recede considerably, opening some coastal areas of the Antarctic to navigation.

Sea level glaciers exist on a number of landmasses bordering the northern seas, including Alaska, Greenland, Svalbard (Spitsbergen), Zemlya Frantsa-Iosifa (Franz Josef Land), Novaya Zemlya, and Severnaya Zemlya (Nicholas II Land). Except in Greenland and Franz Josef Land, the rate of calving is relatively slow, and the few icebergs produced melt near their points of formation. Many of those produced along the western coast of Greenland, however, are eventually carried into the shipping lanes of the North Atlantic, where they constitute a major menace to ships.

Those calved from Franz Josef Land glaciers drift southwest in the Barents Sea to the vicinity of Bear Island. Generally the majority of icebergs produced along the east coast of Greenland remain near their source. However, a small number of bergy bits, growlers, and small icebergs are transported south from this region by the East Greenland Current around Kap Farvel at the southern tip of Greenland and then northward by the West Greenland Current into Davis Strait to the vicinity of 67°N. Relatively few of these icebergs menace shipping, but some are carried to the south and southeast of Kap Farvel by a counterclockwise current gyre centered near 57°N and 43°W.

The main source of the icebergs encountered in the North Atlantic is the west coast of Greenland between 67°N and 76°N, where approximately 10,000 – 15,000 icebergs are calved each year. In this area there are about 100 lowlying coastal glaciers, 20 of them being the principal producers of

icebergs. Of these 20 major glaciers, 2 located in Disko Bugt between 69°N and 70°N are estimated to contribute 28 percent of all icebergs appearing in Baffin Bay and the Labrador Sea. The West Greenland Current carries icebergs from this area northward and then westward until they encounter the south flowing Labrador Current. West Greenland icebergs generally spend their first winter locked in the Baffin Bay pack ice; however, a large number can also be found within the sea ice extending along the entire Labrador coast by late winter. During the next spring and summer, when they are freed by the break up of the pack ice, they are transported farther southward by the Labrador Current.

CHAPTER 5 WEATHER INFORMATION AND SERVICES

5.1 Weather Information for Shipping

5.1.1 Introduction of WMO

The World Meteorological Organization (WMO) is a specialized agency of the United Nations. It has its headquarters in Geneva, Switzerland. It is the UN system's authoritative voice on the state and behaviour of the Earth's atmosphere, its interaction with the oceans, the climate it produces, and the resulting distribution of water resources.

WMO has a membership of 189 Member States and Territories (as at 4 December 2009). It originated from the International Meteorological Organization (IMO), which was founded in 1873. Established in 1950, WMO became the specialized agency of the United Nations in 1951 for meteorology (weather and climate), operational hydrology and related geophysical sciences.

As weather, climate and the water cycle know no national boundaries, international cooperation at a global scale is essential for the development of meteorology and operational hydrology, as well as reaping the benefits from their application. WMO provides the framework for such international cooperation.

Since its establishment, WMO has played a unique and powerful role in contributing to the safety and welfare of humanity. Under WMO leadership and within the framework of WMO programmes, National Meteorological and Hydrological Services contribute substantially to the protection of life and property against natural disasters, to safeguarding the environment, and to enhancing the economic and social well-being of all sectors of society in areas such as food security, water resources and transport.

WMO promotes cooperation in the establishment of networks for making meteorological, climatological, hydrological and geophysical observations, as well as the exchange, processing and standardization of related data, and assists technology transfer, training and research. It also fosters collaboration between the National Meteorological and Hydrological Services of its Members, and furthers the application of meteorology to public weather services, agriculture, aviation, shipping, the environment, water issues, and the mitigation of the impact of natural disasters.

WMO facilitates the free and unrestricted exchange of data and information, products and services in real or near-real time on matters relating to safety and security of society, economic welfare and the protection of the environment. It contributes to policy formulation in these areas at national and international levels.

In the specific case of weather-climate and water-related hazards, which account for nearly

90% of all natural disasters, WMO's programs provide vital information for the advance warnings that save lives and reduce damage to property and the environment. WMO also contributes to reducing the impacts of human-induced disasters, such as those associated with chemical and nuclear accidents, forest fire and volcanic ash. Studies have shown that, apart from the incalculable benefit to human well-being, every dollar invested in meteorological and hydrological services produces an economic return many times greater, often ten times or more.

WMO plays a leading role in international efforts to monitor and protect the environment through its programs. In collaboration with other UN agencies and the National Meteorological and Hydrological Services, WMO supports the implementation of a number of environmental conventions and is instrumental in providing advice and assessments to governments on related matters. These activities contribute towards ensuring the sustainable development and well-being of nations.

The vision of WMO is to provide world leadership in expertise and international cooperation in weather, climate, hydrology and water resources and related environmental issues and thereby contribute to the safety and well-being of people throughout the world and to the economic benefit of all nations.

The mission of WMO is to:

—Facilitate worldwide cooperation in the establishment of networks of stations for the making of meteorological observations as well as hydrological and other geophysical observations related to meteorology, and to promote the establishment and maintenance of centres charged with the provision of meteorological and related services;

—Promote the establishment and maintenance of systems for the rapid exchange of meteorological and related information;

—Promote standardization of meteorological and related observations, and to ensure the uniform publication of observations and statistics;

Further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;

—Promote activities in operational hydrology, and to further close cooperation between meteorological and hydrological services;

—Encourage research and training in meteorology and, as appropriate, in related fields, and to assist in coordinating the international aspects of such research and training.

5.1.2 Receiving Marine Weather Forecast Products Onboard

Since 1975, many methods have been developed to communicate marine warnings, statements, forecasts, and observations. In 1975, communications between ships or from ship-to-shore were carried out by either VHF radio or an MF radio telephone. Any marine warnings, statements, and forecasts were disseminated by the Coast Guard on VHF radio. Today, the VHF radio is still a major player in communicating marine products.

In recent years there has been a very welcome increase in the amount of data available that can be used by the seaman. There are the GMDSS services of NAVTEX and the INMARSAT SafetyNET. There are services, such as MetFAX and Marinecall, available over telephone links. There is a com-

prehensive cover of MRCC/MRSC VHF/MF stations around much of the world coastline. There are HF broadcasts (some using SSB). There are Radiofax and some radio teleprinter broadcasts. Finally, of course there is the Internet with its large, some would say confusingly large, amount of weather information in text and chart format.

Forecasts in text or broadcast by voice have necessarily to be brief and general contains three parts: **warnings, synoptic situation analysis and marine weather forecast.** Here is an example:

TURKISH STATE METEOROLOGICAL SERVICE

EXTENDED MARINE WEATHER FORECAST REPORT

16.01.2003

FZTU LTBG 160600

MARINE WEATHER BULLETIN FROM BANDIRMA MARINE METEOROLOGICAL STATION

FM LTBG TO AREAS 160600 GMT JANUARY B /CAST WX NR 161

Part 1 NO GALE

Part 2

AT 0000 GMT 1020 hPa RIDGE OF 1036 hPa HIGH PRESSURE CENTER OVER SPAIN EXTENDING FROM UKRAINA TO ISRAEL PASSING CRIMEA, CAUCASUS, EAST ANATOLIA AND SYRIA. THIS SYSTEM WEAKING AND GOING TO EAST...

Part 3 FORECAST

PERIOD FROM 160600 UTC TO 170600 UTC

Crusade WIND NORTH AND NORTHWEST 2 OR 4, SEAS 1,0 OR 1,5 m. PARTLY CLOUDY, VISIBILITY GOOD.

Delta WIND NORTH AND NORTHWEST 3 OR 5, SEAS 1,0 OR 2,0 m. PARTLY CLOUDY, VISIBILITY GOOD.

Taurus WIND WEST AND NORTHWEST 3 OR 5 IN WEST, NORTH AND NORTHEAST 2 OR 4 IN EAST, SEAS 1,0 OR 2,0 m. PARTLY CLOUDY VISIBILITY GOOD.

5.1.3 Radiofax Weather Charts

Radiofax, also known as **weatherfax** (portmanteau word from the words "weather facsimile") and **HF fax** (due to its common use in the short waves), is an analogue mode for transmitting images in grayscale. 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. Today, Radiofax is primarily used worldwide for the dissemination of weather charts, satellite weather images, and forecasts to ships at sea. The oceans are covered by coastal stations in various countries. Today Radiofax data is also available via FTP downloads from sites on the Internet.

Each station broadcasts tens of charts in a single day, thus mariners should understand the chart title first. Generally the title describes the type (analysis or forecast), level (surface or upper air), content (weather, wave, current, ice, streamline, satellite, or tropical cyclone), time (analysis) and valid time (forecast), coverage (Asia, North Pacific, Europe, Australia, and so

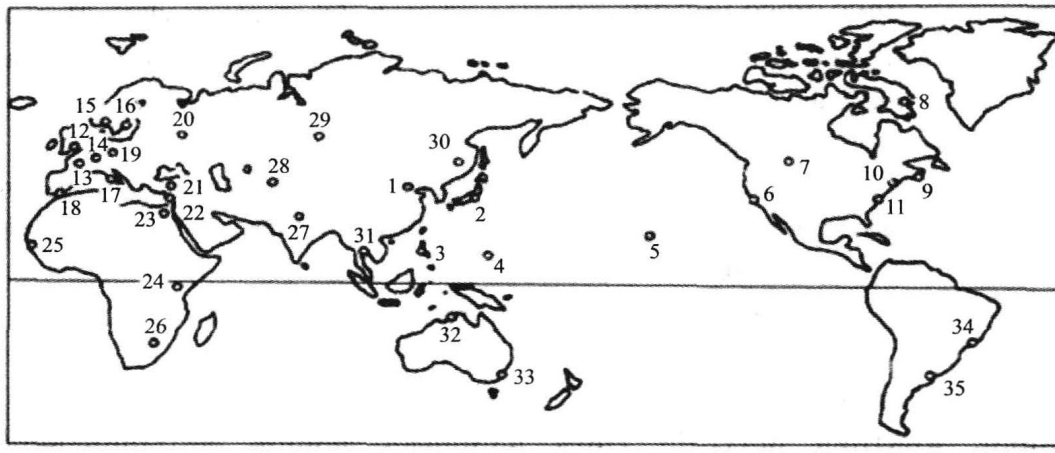


Figure 5.1 Main Coastal Stations Broadcasting Radiofax

on) and the station call sign (e.g. BMF for Beijing, JMH for Tokyo). For details, mariners should consult the relative schedule.

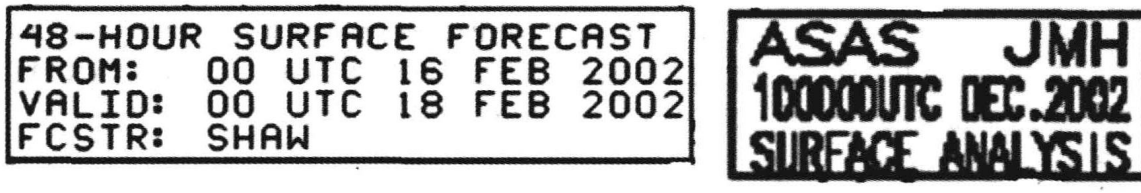


Figure 5.2 Radiofax Title Samples

5.2 Interpretation and Application of Weather Charts

5.2.1 Interpretation and Application of Surface Charts

In the example pictured here, the North Atlantic analysis is prepared for the area from 15°N to 65°N latitude and between 10°E and 100°W longitude. The boxes in the upper left and upper right show the chart's valid time and date: 1200 UTC (noon, Greenwich time) 22 August 2000. The forecaster's name is on the line below: George Bancroft. The chart below was chosen for its variety of symbols and combination of tropical and extratropical cyclone activity.

Analyses of surface isobars are shown in 4-millibar increments, with the isobars labeled every 8 mb (last two whole digits of pressure in millibars). Low and high pressure systems are depicted as "L" and "H" with an underlined pressure label nearby given in whole millibar units of 3 or 4 digits. The Marine Prediction Center also includes forecast tracks for pressure systems (denoted by arrows) and forecast positions valid 24 hours after the chart's valid time ("X" for lows and circled Xs for highs, and tropical cyclone symbols). The 24-hour forecast pressures are shown near the forecast positions as the last two whole digits of pressure, underlined, or undetermined pressure "XX" for tropical cyclones. The first two digits, the 9 or 10, of the forecast pressure are left out to distinguish forecast positions from actual (synoptic) positions. If there is a 24-hour forecast of a pressure system that was not present at analysis time, it would be labeled as "NEW".

Fronts and low-pressure troughs are also shown. If a front is dissipating, it is broken into alternating pips (filled triangles or half-circles) and line segments. Fronts that are forming are depicted as broken lines of pips, without the alternating line segments. A pair of parallel line segments (" = ") appears at a junction between one type of front and another. Troughs are shown as dashed lines labeled as "TROF". As an example, the North Atlantic surface analysis is shown here. Boxed numbers have been placed adjacent to various features, and are organized as increasing from west to east.

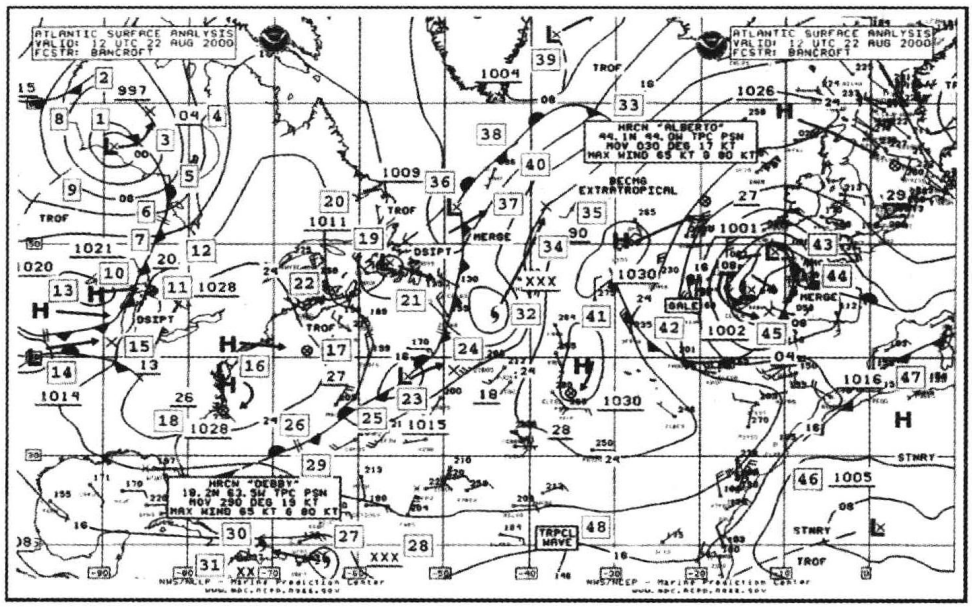


Figure 5.3 North Atlantic Analysis by NOAA

The same numbers appear below with accompanying explanations.

1. Inland low ("L") is over Hudson Bay near 57°N 89.5°W.

2. The central pressure is 997 mb.

3. The low has a forecast track (arrow) that takes it NE to a position near 59.5°N 85°W 24 hours later, marked by an "X".

4. The 24-hour forecast pressure is "04" (1,004 mb).

5. An occluded front extends SE from the low center.

6. The " = " marks the transition from an occluded front to a cold front.

7. The cold front extends SW to near 42°N 97°W.

8. Another cold front is shown entering the NW corner of the chart.

9. A low-pressure trough (labeled as "TROF") extends SW from the Hudson Bay low. This is an elongated area of relatively low pressure often accompanied by clouds, precipitation and shifting winds.

10. A high-pressure center appears farther to the south ("H") near 46°N 91°W and has a central pressure of 1,021 mb.

11. The high is forecast to be near 46°N 84°W 24 hours later, marked by a "circled X".

12. The 24-hour forecast of central pressure of the high is "20" (1,020 mb).

13. Another high to the west with central pressure 1,020 mb is forecast to move east and dissipate ("DSIPT") within 24 hours.

14. Another inland low is on the west edge of the chart near 40°N 98°W with a central pressure of 1,014 mb and a stationary front extending E from the center to 39°N 85°W.

15. The low is forecast to be near 41°N 89°W ("X") 24 hours later, with a forecast pressure of "13" (1,013 mb).

16. Near the coast, a complex area of high pressure has centers near 41°N 75°W and 38°N 76°W, both with pressures of 1,028 mb.

17. The northern high-pressure center is forecast to be near 40.5°N 67°W ("circled X") 24 hours later, with a forecast pressure of "27" (1,027 mb).

18. The southern high-pressure center is forecast to move SE initially, then curve SW, to a 24-hour forecast position near Cape Hatteras with a pressure of "26" (1,026 mb).

19. A low-pressure center is shown over the Island of Newfoundland.

20. Its central pressure is 1,011 mb.

21. The low is forecast to move ESE and dissipate ("DSIPT") within 24 hours.

22. A low-pressure trough ("TROF") extends SW from the low.

23. Another low to the south is near 38°N 54°W, with a central pressure of 1,015 mb.

24. The low is forecast to move ENE to near 39°N 49°W 24 hours later, with a forecast central pressure of "18" (1,018 mb).

25. A stationary front extends southwest from the low to 30.5°N 67°W and northeast from the low center to 42°N 50°W.

26. The symbol ("=") marks the transition from a stationary front to a dissipating stationary front, which extends southwest to near Florida.

27. Hurricane Debby is centered near 18.2°N 63.5°W.

28. The central pressure of Debby is shown as "XXX", which stands for the central pressure of any named tropical cyclone. These pressures are so low that drawing all the isobars Surface-Analysis Charts would make the chart illegible. Beginning in the 2001 Atlantic hurricane season, MPC will begin showing estimated central pressures of tropical cyclones instead of "XXX".

29. Information about Debby's synoptic position, motion and maximum winds is contained in the rectangle above Debby's hurricane symbol.

30. Debby is forecast to move WNW to a 24-hour forecast position near 20°N 71°W, and remain a hurricane.

31. The "XX" represents an undetermined 24-hour forecast of central pressure located near the forecast hurricane symbol.

32. Hurricane Alberto is centered near 44.1°N 44.0°W with central pressure "XXX".

33. Information about Alberto's synoptic position, motion and winds is in the rectangle above and to the right of Alberto's hurricane symbol.

34. Alberto is forecast to move NE and lose tropical characteristics, becoming an extratropical

low-pressure system (typically associated with fronts) near 53N 38W, marked by an "X", 24 hours later.

35. Since Alberto will be extratropical in 24 hours, its forecast central pressure is shown ("90") or 990 mb.

36. The low-pressure center north of Alberto near 53°N 49°W has a central pressure of 1,009 mb. A low-pressure trough ("TROF") extends SW from the center to the Island of Newfoundland.

37. The low is forecast to merge with Alberto within 24 hours.

38. A stationary front extends NE from the low center to 59°N 30°W. A cold front trails SW from the low to 42°N 50°W, where the " = " symbol marks the change to a stationary front.

39. A weak low centered near Greenland, with central pressure 1,004 mb, is forecast to move NE, to a 24-hour forecast position north of the chart area. A trough ("TROF") extends south from the center.

40. A ship, call sign "Y4HP", near 55°N 44°W, reports a pressure of 1,009.6 mb ("096") and a SSW wind of 5 kt (one half of a wind barb). Each full wind barb is 10 kt, and a pennant is 50 kt. A weather symbol appears to the left of the ship's location (dense fog).

41. An elongated area of high pressure dominates this portion of the Atlantic and contains 3 centers. The northern center, near 59.5°N 10°W with a 1,026 mb center, is forecast to move SE, to be near 56°N 3°E with a pressure of "29" (1,029 mb) 24 hours later. The central high pressure center at 50°N 30°W with pressure label 1030 mb is forecast to move NE to a 24-hour position near 53°N 19.5°W with pressure "27" (1,027 mb). The southern center near 39.5°N 34°W with pressure 1,030 mb is forecast to be near 36°N 35°W with a pressure of "28" (1,028 mb) 24 hours later.

42. The area near the European coast is dominated by a primary gale-force low near 46°N 14°W with pressure 1,002 mb, and a secondary center at 49°N 11°W with a central pressure of 1,001 mb. A dying occluded front surrounds the primary low center.

43. A short occluded front extends SE from the secondary low center.

44. From the frontal change symbol (" = ") near 47°N 9°W, a warm front extends E and a cold front curves SW and then NW.

45. The secondary low center is forecast to move SW and then SE to 44°N 12°W by 24 hours with the 24-hour forecast pressure label "04" (1,004 mb). The primary low is forecast to merge with it ("MERGE" label).

46. A cold front extends SW across the western Mediterranean Sea.

47. This part of North Africa is dominated by a 1,005 mb low centered at 21°N 1°E and a 1,016 mb high near 34°N 4°E. Both are stationary ("STNRY"). A low-pressure trough extends SW from the low.

48. A tropical wave, or trough embedded in the trade-wind easterlies, is depicted with a trough symbol and the label "TRPCL WAVE". A tropical wave is often accompanied by showers and a small wind shift.

In the example pictured here, the North Pacific analysis is prepared for the area from 10°N to

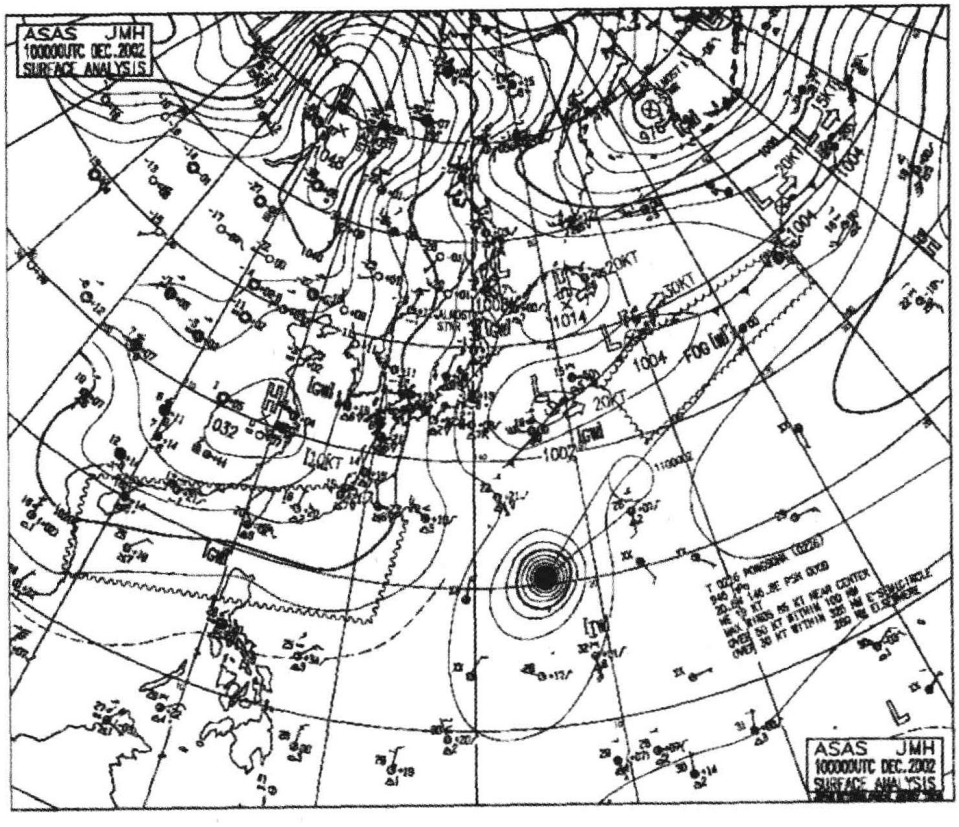


Figure 5.4 North Pacific Analysis by JMH

70°N latitude and between 110°E and 160°W longitude. It contains as much information as that of a MPC product. The isobars with values as 980, 1000, 1020 etc. are conspicuous since they are darkened.

The standard abbreviations used are:

STNRY: Stationary, the system moves at the speed less than 5 kn with uncertain direction;

SLW: Slowly, the system moves at the speed less than 5 kn with certain direction;

UKN: Unknown;

KT: knot, also abbreviated as "kn", the movement speed of a weather system.

For severe weather and tropical cyclone, the following abbreviations are used:

FOG[W]: fog warning, visibility less than 0.5 n mile;

[W]: warning, wind force ≥7;

[GW]: gale warning, wind force 8~9, for tropical cyclone, it means the wind force reaches or will reach 8~9 in 24 hours, and it corresponds to TS or TD;

[SW]: storm warning, for tropical cyclone, the wind force reaches or will reach 10~11 in 24 hours, and it corresponds to TS or STS; for other weather system, the wind force is ≥10;

[TW]: typhoon warning, the wind force is ≥12, in NE Pacific and Atlantic, the [HW] is used.

For tropical cyclone grades, the following abbreviations are used:

T: Typhoon, maximum wind force ≥12;

STS: Severe Tropical Storm, maximum wind force 10 ~ 11;

TS: Tropical Storm, maximum wind force 8 ~ 9;

TD: Tropical Depression, maximum wind force ≥8, the center of the cyclone is certain;

L: Tropical Low Area, maximum wind force ≥8, the center of the cyclone is uncertain.

PSN GOOD: the observation error of the cyclone center is less than 20 n miles.

PSN FAIR: the observation error of the cyclone center is 20 ~ 40 n miles.

PSN POOR: the observation error of the cyclone center is greater than 40 n miles.

For the forecast circle of the tropical cyclone, the center of the system will drop into it with the probability of 70%.

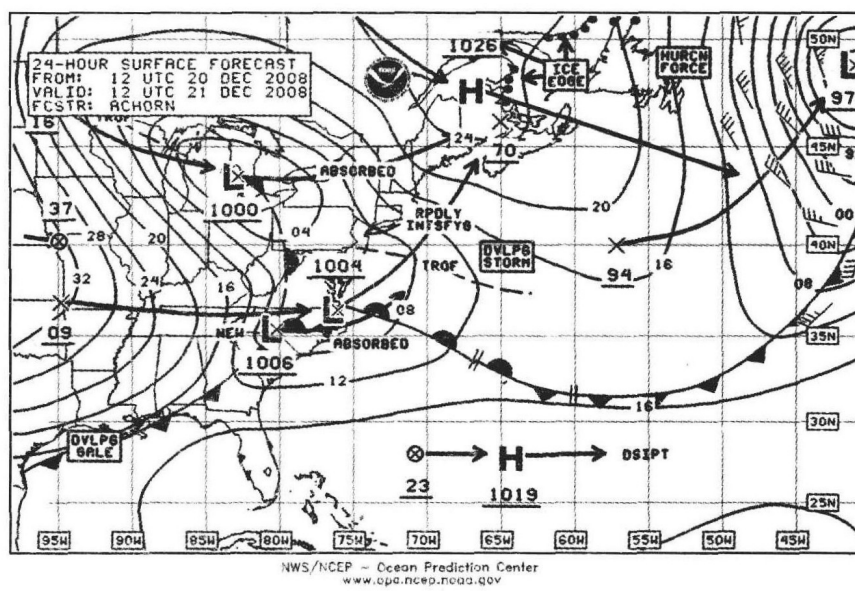


Figure 5.5 Atlantic Surface Forecast by NOAA

Surface forecast charts are issued in the same formats as their synoptic counterparts. The "from" time is when the forecast was issued. The "valid" time is when it is for. High and low pressure systems, frontal systems and gale areas are of vital importance for mariners to forecast the weather condition. The valid time can be from 12 hours to 192 hours.

5.2.2 Interpretation and Application of Wave Charts

In the wave analysis chart (AWPN) of JMH, the thick solid lines are the contour lines of observed waves (combining the wave heights in meters of seas and swells) higher than 2 meters with the increment of 1 meter. The symbol " = > " indicate the main direction of the waves, that is, the direction of the highest wave where several waves exist. The random waves area is also indicated. The station data includes the position and call sign of the station, wind direction and speed, sea wave direction, height and period, swell direction, height and period. The meteorological data includes the position and center pressure of the highs, the lows, the tropical cyclones, and the fronts.

In the wave analysis chart of NWS (USA), the wave height is a significant wave height.

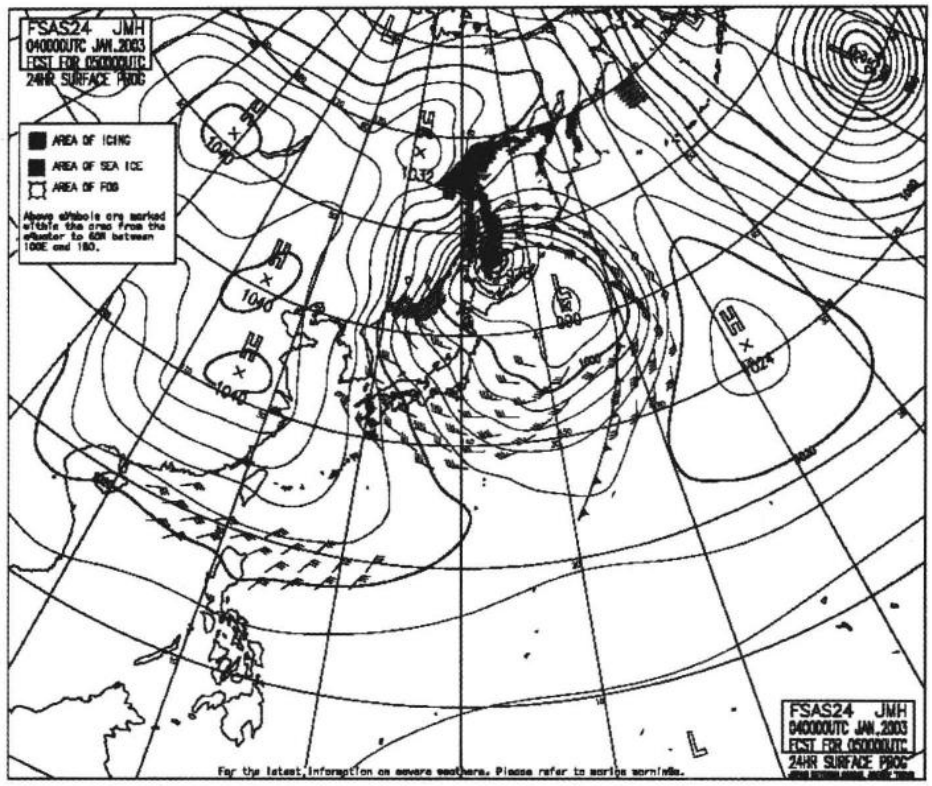


Figure 5.6 Asia Surface Forecast by JMH

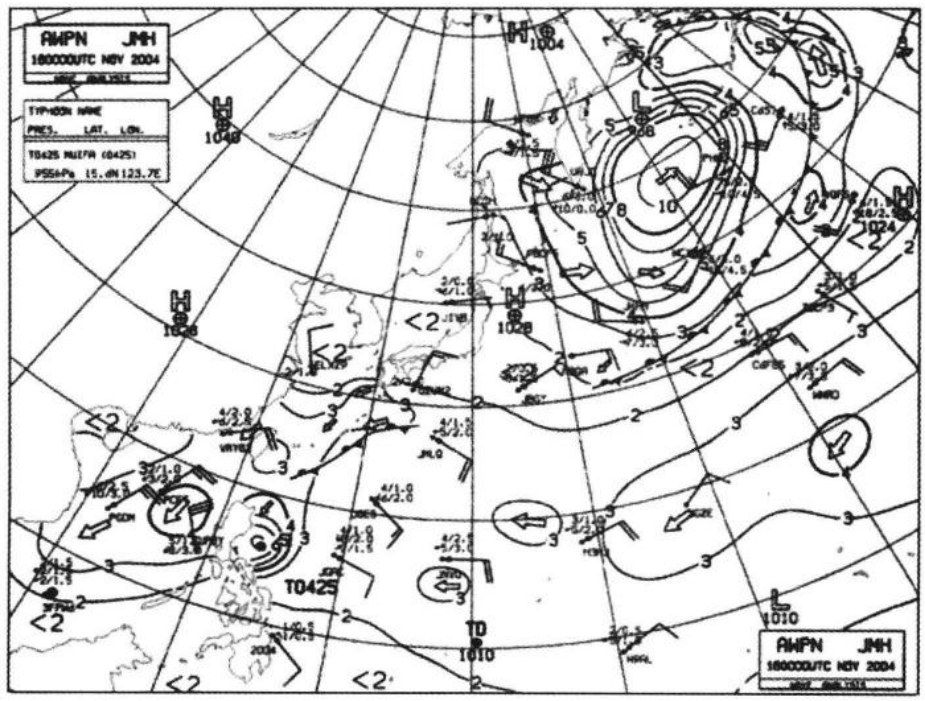


Figure 5.7 Wave Analysis of North Pacific by JMH

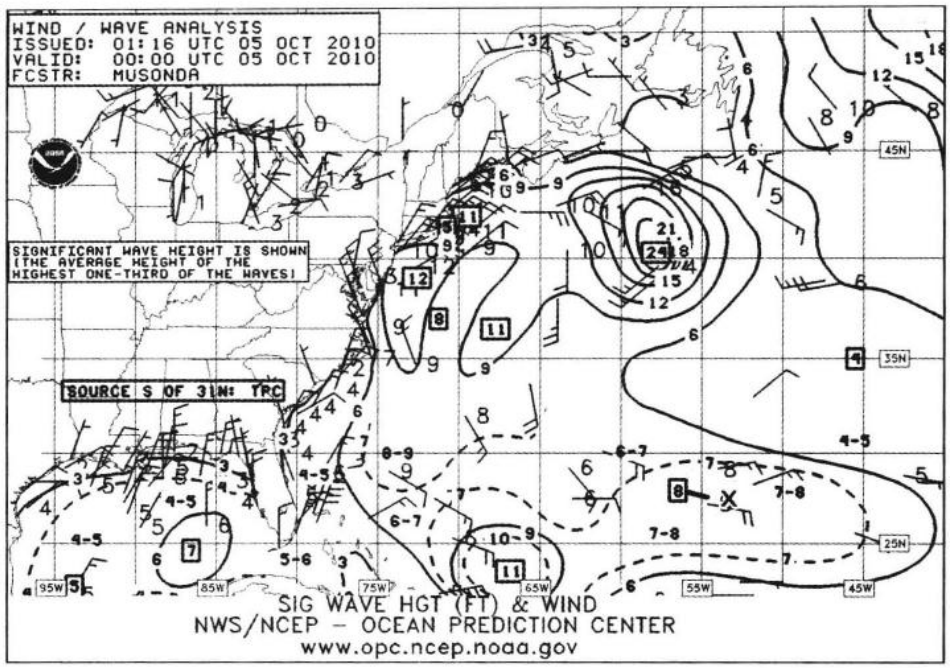


Figure 5.8 Wave Analysis of North Atlantic by NOAA

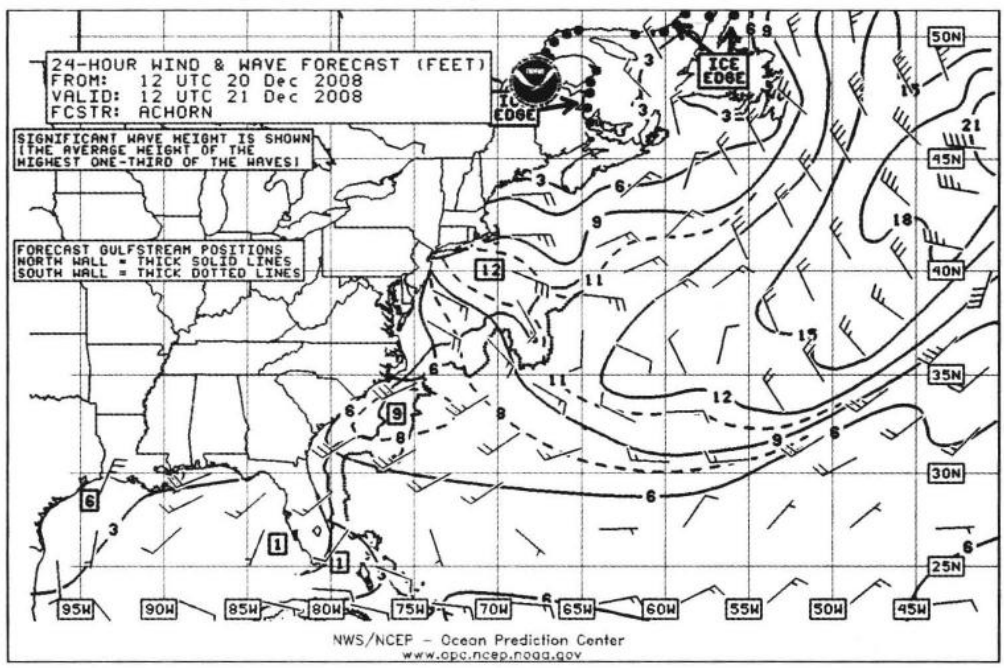


Figure 5.9 Wave Forecast of North Atlantic by NOAA

Wave heights in the forecast charts are significant wave heights, based on wave spectrum and other methods. There are also wave data and meteorological data.

The valid time of Radiofax wave forecast is usually 24 ~ 36 h. From the Internet, color charts are available and the valid time is 12 ~ 144 h.

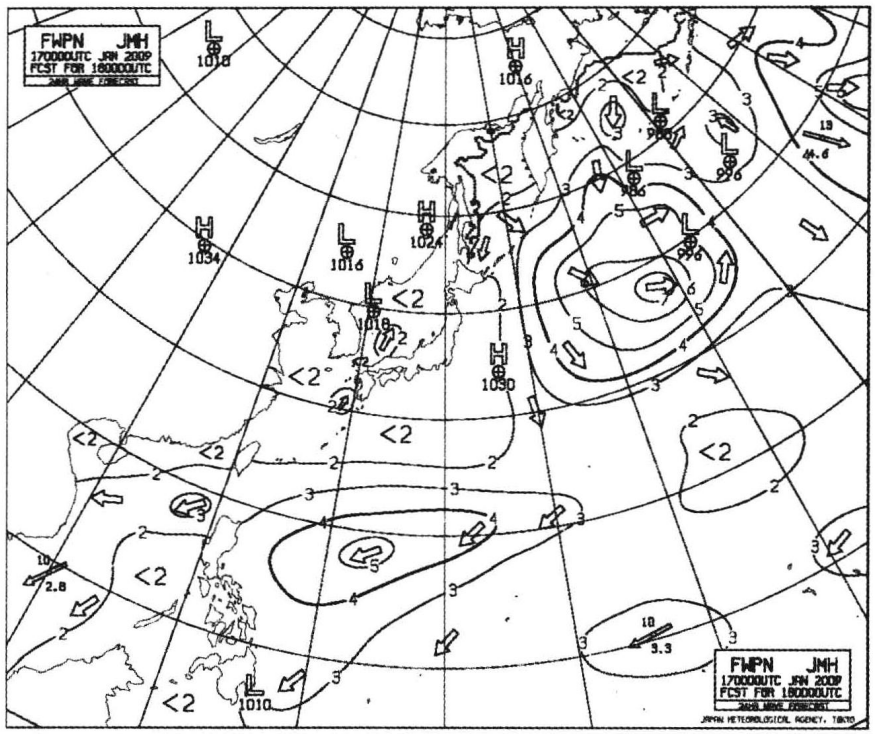


Figure 5.10 Wave Forecast of North Pacific by JMH

5.2.3 TC Warning Reports and TC Forecast Charts

Whenever a tropical cyclone warning signal is in effect, bulletins are issued. These warnings are broadcast via NAVTEX, an international broadcast system for disseminating navigational information for ships plying in the region. Here is an example:

WWJP71 RJTD 301800

IMPORTANT WARNING FOR NAHA NAVTEX AREA

301800 UTC ISSUED AT 302100UTC

SEVERE TROPICAL STORM 0911 KROVANH(0911) 980 HPA AT 32.7°N 140.0°E

MOVING NNW 09 KNOTS

POSITION FAIR

MAX WINDS 55 KNOTS NEAR CENTER

RADIUS OF OVER 50 KNOT WINDS 30 NM

RADIUS OF OVER 30 KNOT WINDS 180 NM NORTHEAST AND 120 NM ELSEWHERE

EXPECTED MAX WINDS 60 KNOTS FOR NEXT 12 HOURS

FORECAST POSITION FOR 310600 UTC AT 34.9°N 140.1°E WITH 50 MILES RADIUS OF 70 PERCENT PROBABILITY CIRCLE

MAX WINDS 60 KNOTS NEAR CENTER

FORECAST POSITION FOR 311800 UTC AT 37.9°N 141.8°E WITH 85 MILES RADIUS OF 70 PERCENT PROBABILITY CIRCLE

MAX WINDS 55 KNOTS NEAR CENTER

OUTLOOK POSITION FOR 011800 UTC AT 43.3°N 150.1°E WITH 180 MILES RADIUS

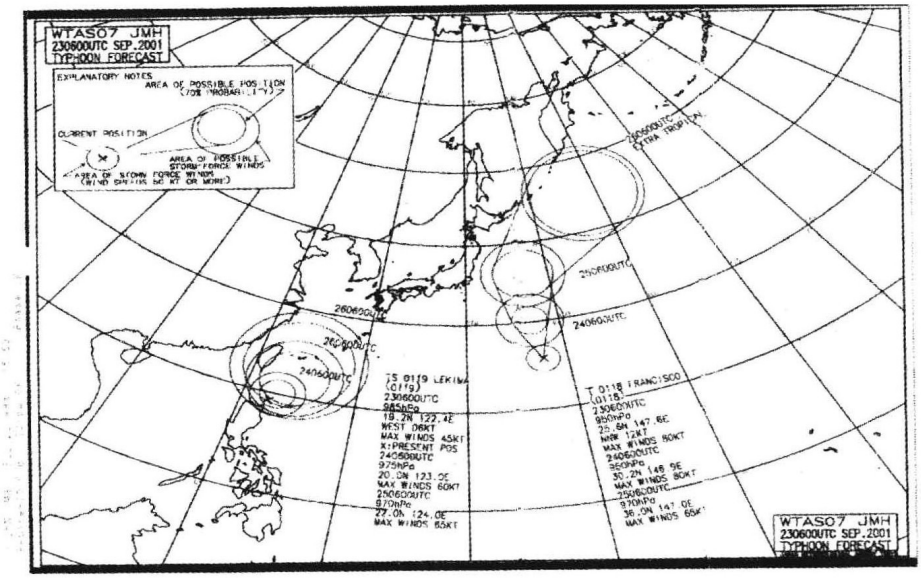


Figure 5.11 Typhoon Warning by JMH

OF 70 PERCENT PROBABILITY CIRCLE BECOMING EXTRATROPICAL LOW
MAX WINDS 35 KNOTS

In the Typhoon Warning Chart of JMH, the solid circles are the observed and forecast areas of stormy winds (wind force $\geqslant 10$); the broken circles are 70 percent probability circles of the cyclone center.

5.2.4 Interpretation and Application of Satellite Imagery

The various types of satellite images that are now widely available can significantly enhance the understanding of meteorological processes and weather forecasting, especially the movement of weather systems. The first weather satellite was launched on 1 April 1960, and the subsequent launch of other observing systems has resulted in the creation of an imaging network on a truly global scale. Information is now available for inhospitable land areas and the oceans, where weather data were previously unavailable. The advent of weather satellites has also provided a continuous, automatic feed of data, with a coverage and resolution (horizontal and vertical) not possible by any other means. Therefore, we can now "look down" and record what is happening, and make accurate predictions about what is likely to happen in the short term.

There are two types of satellite providing weather data.

Geostationary – these orbit at a height of 35,780 km above the equator, and "hang" over the same spot on the Earth's surface all the time. For example, Meteosat, the geostationary satellite operated by European countries, provides pictures of the North Atlantic and Europe every 30 minutes and images of the half globe every hour. The images do not show objects in great detail because the satellite is too far from the Earth.

Polar-orbiting – these pass over the Earth from pole to pole. The NOAA satellites, currently operated by the USA, orbit at a height of 830 km and take 1 hour and 42 minutes to complete each orbit. During this time, the Earth has turned by about 25 degrees, so the satellite views a different

part of the surface each time it passes. As the orbit is much lower than that of the geostationary satellites, the images provide detailed information about the cloud structure.

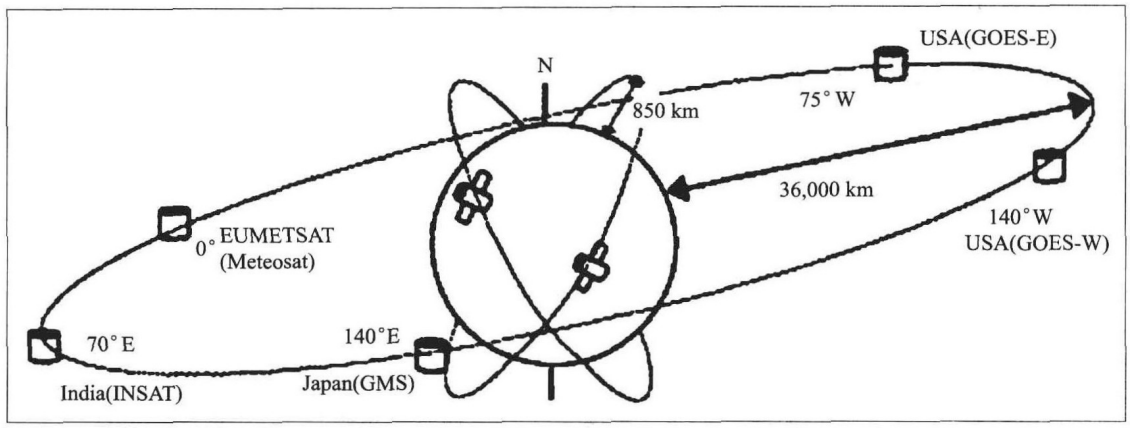


Figure 5.12 The Current Global Satellite Network Comprises Five Geostationary, High-altitude Satellites and Two Polar-orbiting Ones

There are several satellite images products available; the visible images and infrared images are the most widely used.

One type of radiometer measures visible light and provides visible images. What is being viewed is sunlight that has been reflected from the Earth or clouds. In general, the brighter the cloud appears, the thicker it is. The only disadvantage of visible images, as their name suggests, is that they are only available during daylight.

Unlike visible images, infrared images are available even when there is no daylight. These are useful in measuring the temperature of the cloud or the Earth's surface. The images are usually prepared in such a way that cold surfaces appear white, and warm ones darker. Because of the adiabatic lapse rate, temperatures in the lower part of the atmosphere normally decrease with height, so high cloud (with low temperatures) appears white, with low cloud or the Earth's surface appearing darker.

A combination of visible and infrared images is very useful and can help distinguish between high and low cloud. For example, if a bright area appears on both the infrared and visible images in the same place, it is likely to be thick, high cloud. However, if the area appears bright on the visible image but dark on the infrared one, it is probably low cloud or perhaps fog.

5.2.4.1 Analyzing Cloud Patterns

In general, the clouds shown in satellite pictures can be classified as layer clouds or convective clouds. Layer clouds tend to cover large areas and are indicated on a satellite picture by an area of uniform brightness. This type of cloud is formed by a large-scale rising motion in the atmosphere, often associated with depressions or fronts. Convective clouds are usually formed by air being heated from below. The rising air generates cloud with the surrounding descending air being cloud-free. The individual clouds can be identified on a satellite picture, and it is sometimes possible to look at the build-up of thunderstorm cells.

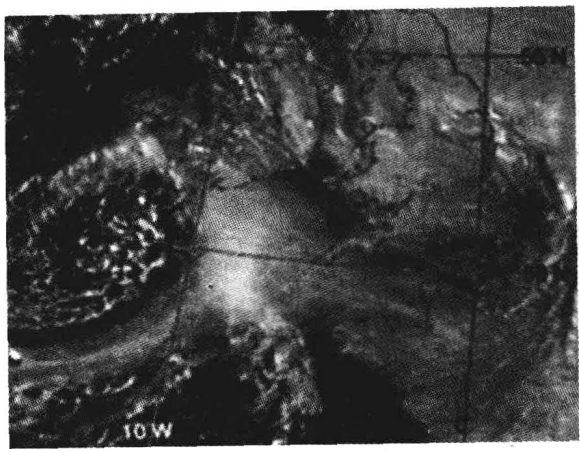


Figure 5.13(a) An Example of a Visible Image

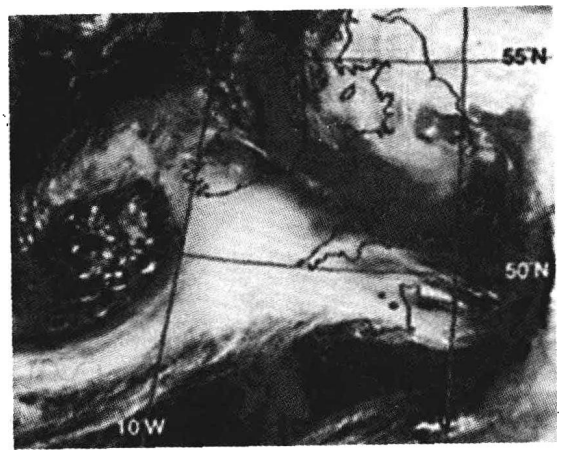


Figure 5.13(b) An Example of an Infrared Image

5.2.4.2 Identifying the Location of Depressions (Low Pressure)

Satellite pictures are particularly helpful in locating depressions and fronts. Depressions can be picked out by their distinctive swirl of cloud, and frontal systems can often be seen as a wishbone-shaped area of cloud radiating from a depression. A cold front is often clearly shown as a distinctive trailing edge of the left-hand prong of the wishbone pattern.

5.2.4.3 Inferring the Location of Anticyclones (High Pressure)

In anticyclones, the air is descending and warming – this means that thick cloud will not form, so areas of high pressure, especially blocking anticyclones, can be easily identified by the absence of any cloud and the ground and coastline can be clearly seen on the image.

5.2.4.4 Estimating Wind Speeds and the Movement of Frontal Systems

If a sequence of images can be obtained, it is possible to calculate how far clouds have moved in successive pictures and thus estimate the speed at which the cold and warm fronts are moving.

5.2.5 Interpretation and Application of Other Charts

5.2.5.1 Ocean Current Charts

Both analysis and forecast charts of ocean currents are available. Since the ocean currents are relatively steady, the interval between two charts is ten days or one month. The current drift, showing, the position of the main currents and surface sea temperature are available.

5.2.5.2 Ice Information Services

Advance knowledge of ice conditions to be encountered, and how these conditions will change over specified time periods are invaluable for both the planning and operational phases of a voyage to the polar regions.

The content of sea ice analyses is directly dependent upon the planned use of the product, the required level of detail, and the availability of on-site ice observations and/or remotely-sensed data. Ice analyses are produced by blending relatively small numbers of visual ice observations from ships, shore stations and fixed wing aircraft with increasing amounts of remotely sensed data. The efficient receipt and accurate interpretation of these data are critical to producing a near real-time (24 ~ 48 hour old) analysis or "picture" of the ice cover. In general, global and regional scale ice analyses

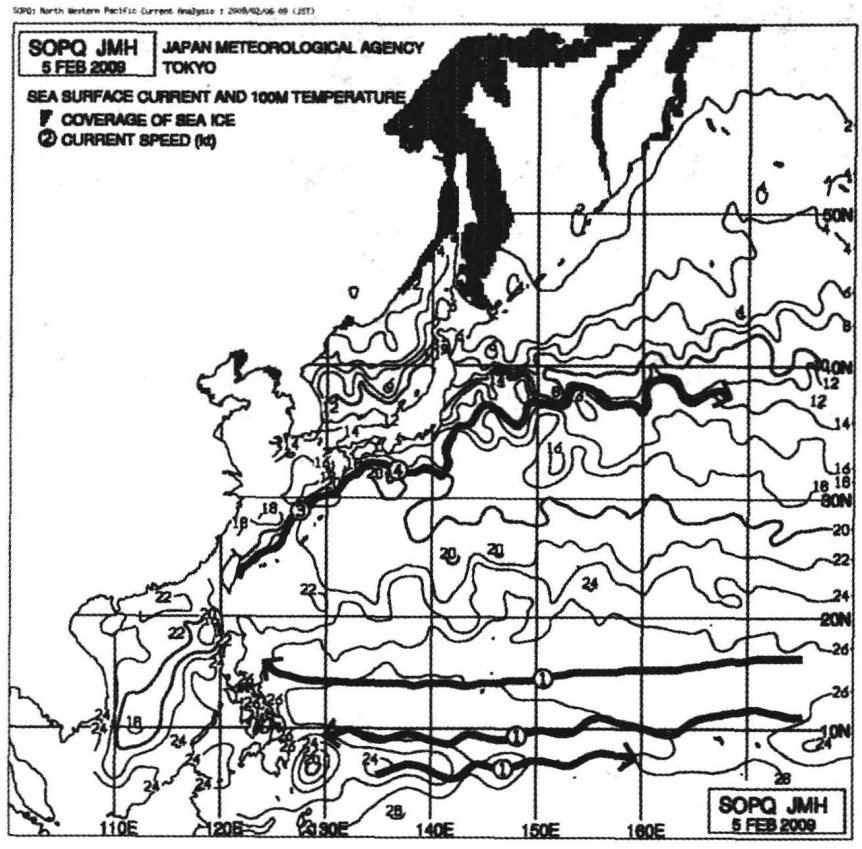


Figure 5.14 Ocean Current Analysis by JMH

depict ice edge location, ice concentrations within the pack, and the ice stages of development or thickness. Local scale ice analyses emphasize the location of thin ice covered or open water leads/polynyas, areas of heavy compression, frequency of ridging, and the presence or absence of dangerous multiyear ice and/or icebergs. The parameters defined in this tactical scale analysis are considered critical to both safety of navigation, and the efficient routing of ships through the sea ice cover.

Sea ice forecasts are routinely separated into four temporal classes: short-term (24 ~ 72 hour), weekly (5 ~ 7 days), monthly (15 ~ 30 days) and seasonal (60 ~ 90 days) forecasts.

Short-term forecasts are generally paired with local-scale ice analyses and focus on changes in the ice cover based on ice drift, ice formation and ablation, and divergent/convergent processes. Of particular importance are the predicted location of the ice edge and the presence or absence of open water polynyas and coastal/flaw leads. The accurate prediction of the location of these ice features is important for both ice avoidance and ice exploitation purposes.

Similar but with less detail, weekly ice forecasts also emphasize the change in ice edge location and concentration areas within the pack. The National Ice Center presently employs several prediction models to produce both short-term and weekly forecasts. These include empirical models which relate ice drift with geostrophic winds and a coupled dynamic/thermodynamic model called the Polar Ice Prediction System (PIPS). Unlike earlier models, the latter accounts for the effects of ice thick-

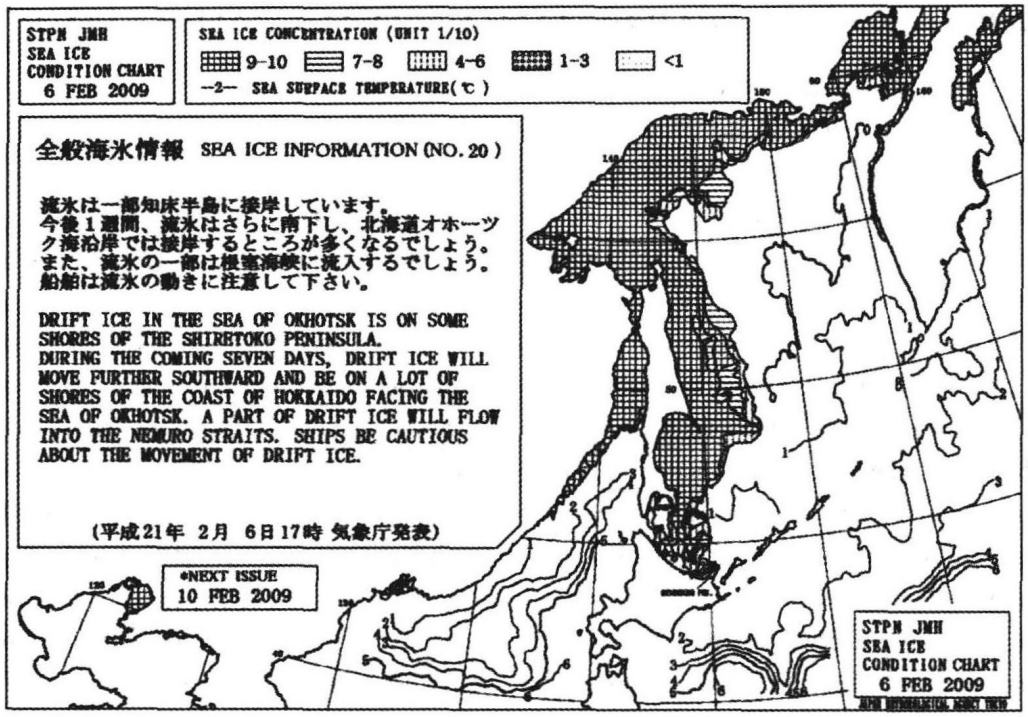


Figure 5.15 Sea Ice Condition Chart by JMH

ness, concentration, and growth on ice drift.

Monthly ice forecasts predict changes in overall ice extent and are based upon the predicted trends in air temperatures, projected paths of transiting low pressure systems, and continuity of ice conditions.

Seasonal or 90-day ice forecasts predict seasonal ice severity and the projected impact on annual shipping operations.

Of particular interest to the National Ice Center are seasonal forecasts for the Alaskan North Slope, Baffin Bay for the annual re-supply of Thule, Greenland, and Ross Sea / McMurdo Sound in Antarctica. Seasonal forecasts are also important to Great Lakes and St. Lawrence Seaway shipping interests.

Other countries which provide sea ice information services are as follows: Arctic-Canada, Denmark (Greenland), Japan (Seas of Okhotsk, Japan and Bo Hai), Iceland, Norway, Russia and the United Kingdom; Antarctic - Argentina, Australia, Chile, Germany, Japan and Russia; and Baltic-Finland, Germany, Sweden and Russia. Except for the United States, the ice information services of all countries place specific focus upon ice conditions in territorial seas or waters adjacent to claims on the Antarctic continent. The National Ice Center of the United States is the only organization which provides global ice products and services.

5.3 Introduction of Weather Routing

5.3.1 Outline of Weather Routing

Ship weather routing develops an optimum track for ocean voyages based on forecasts of weather, sea conditions, and a ship's individual characteristics for a particular transit. Within specified limits of weather and sea conditions, the term optimum is used to mean maximum safety and crew comfort, minimum fuel consumption, minimum time underway, or any desired combination of these factors.

The mariner's first resources for route planning in relation to weather are the Pilot Chart Atlases and the Sailing Directions (Planning Guides). These publications give climatic data, such as wave height frequencies and ice limits, for the major ocean basins of the world. They recommend specific routes based on probabilities, but not on specific conditions.

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

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

In providing optimum sailing conditions, the advisory service also attempts to reduce transit time by avoiding the adverse conditions which may be encountered on a shorter route, or if the forecasts permit, diverting to a shorter track to take advantage of favorable weather and sea conditions.

The greatest potential advantage for ship weather routing exists when:

(1) the passage is relatively long, about 2,700 kilometers or more;

(2) the waters are navigationally unrestricted, so that there is a choice of routes; and

(3) and weather is a factor in determining the route to be followed.

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

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

Ship weather routing services are being offered by many nations. These include China, Japan, United Kingdom, Russia, Netherlands, Germany, and the United States. Also, several private firms provide routing services to shipping industry clients.

There are two general types of commercial ship routing services. The first uses techniques to forecast conditions and compute routing recommendations ashore. The second assembles and processes weather and sea condition data, and transmits this to ships at sea for on-board processing and generation of route recommendations. The former system allows for greater computer power to be applied to the routing task because powerful computers are available ashore. The latter system allows greater flexibility to the ship's master in changing parameters, selecting routes, and displaying data.

5.3.2 Ship and Cargo Considerations

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

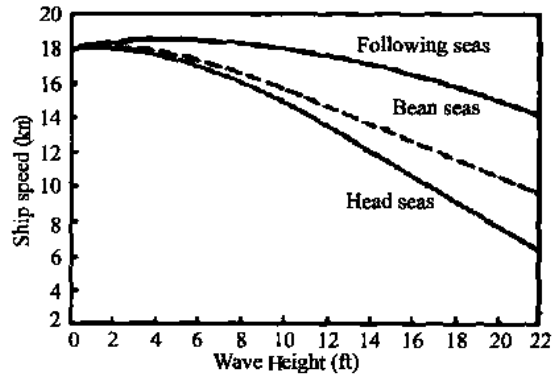


Figure 5.16 Ship Speed Characteristics

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

Ship performance curves (speed curves) are used to estimate the ship's SOA while transiting the forecast sea conditions. The curves indicate the effect of head, beam, and following seas of vari-

ous significant wave heights on the ship's speed. Figure 5.16 is a performance curve prepared for an 18 knot vessel.

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

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

5.3.3 Environmental Factors

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

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

Wave Height: Wave height is the major factor affecting ship performance. Wave action is responsible for ship motions which reduce propeller thrust and cause increased drag from steering corrections. The relationship of ship speed to wave direction and height is similar to that of wind. Head seas reduce ship speed, while following seas increase ship speed slightly to a certain point,

beyond which they retard it. In heavy seas, exact performance may be difficult to predict because of the adjustments to course and speed for ship-handling and comfort. Although the effect of sea and swell is much greater than wind, it is difficult to separate the two in ship routing.

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

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

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

such as hurricanes and by global phenomena such as El Nino.

Ice: The problem of ice is twofold: floating ice (icebergs) and deck ice. If possible, areas of icebergs or pack ice should be avoided because of the difficulty of detection and the potential for collision. Deck ice may be more difficult to contend with from a ship routing point of view because it is caused by freezing weather associated with a large weather system. While mostly a nuisance factor on large ships, it causes significant problems with the stability of small ships.

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

5.3.4 Synoptic Weather Considerations

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

Despite the amount of attention and publicity given to tropical cyclones, mid-latitude low pressure systems generally present the most difficult problems for a ship routing agency. This is primarily due to the fact that major ship traffic is sailing in the latitudes of the migrating low pressure systems, and the amount of potential exposure to intense weather systems, especially in winter, is much greater. Low pressure systems weaker than gale intensity (winds less than 34 knots) are not a severe problem for most ships.

However, a relatively weak system may generate prolonged periods of rough seas which may hamper normal work aboard ship. Ship weather routing can frequently limit rough conditions to short periods of time and provide the most favorable conditions for most of the transit. Relatively small ships, tugs with tows, low powered ships, and ships with sensitive cargoes can be significantly affected by weather systems weaker than gale intensity. Using a routing agency can be beneficial.

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

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

The areas, seasons, and the probability of development of tropical cyclones are fairly well

defined in climatological publications. In long range planning, considerable benefit can be gained by limiting the exposure to the potential hazards of tropical systems.

5.3.5 Types of Recommendations and Advisories

An **initial route recommendation** is issued to a ship or routing authority normally 48 to 72 hours prior to sailing, and the process of surveillance begins. Surveillance is a continuous process, maintained until the ship arrives at its destination. Initial route recommendations are a composite representation of experience, climatology, weather and sea state forecasts, operational concerns, and the ship's seagoing characteristics. A planning route provides a best estimate of a realistic route for a specific transit period. Such routes are provided when estimated dates of departure (EDDs) are given to the routing agency well in advance of departure, usually a week to several months.

Long range planning routes are based more on seasonal and climatological expectations than the current weather situation. While planning routes are an attempt to make extended range (more than a week) or long range (more than a month) forecasts, these recommendations are likely to be revised near the time of departure to reflect the current weather pattern. An initial route recommendation is more closely related to the current weather patterns by using the latest forecasts than the planning route recommendations. These, too, are subject to revision prior to sailing, if weather and sea conditions warrant.

Adjustment of departure time is a recommendation for delay in departure, or early departure if feasible, and is intended to avoid or significantly reduce the adverse weather and seas forecast on the first portion of the route, if sailing on the original EDD. The initial route is not revised, only the timing of the ship's transit through an area with currently unfavorable weather conditions. Adjusting the departure time is an effective method of avoiding a potentially hazardous situation where there is no optimum route for sailing at the originally scheduled time.

A diversion is an underway adjustment in track and is intended to avoid or limit the effect of adverse weather conditions forecast to be encountered along the ship's current track. Ship's speed is expected to be reduced by the encounter with heavy weather. In most cases the distance to destination is increased in attempting to avoid the adverse weather, but this is partially overcome by being able to maintain near normal SOA. Diversions are also recommended where satisfactory weather and sea conditions are forecast on a shorter track.

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

Evasion is a recommendation to the commanding officer or master to take independent action to avoid, as much as possible, a potentially dangerous weather system. The ship routing meteorologist may recommend a general direction for safe evasion but does not specify an exact track. The recom-

mendation for evasion is an indication that the weather and sea conditions have deteriorated to a point where shiphandling and safety are the primary considerations and progress toward destination has been temporarily suspended, or is at least of secondary consideration.

Weather advisory is a transmission sent to the ship advising the commanding officer or master of expected adverse conditions, their duration, and geographic extent. It is initiated by the ship routing agency as a service and an aid to the ship. The best example of a situation for which a forecast is helpful is when the ship is currently in good weather but adverse weather is expected within 24 hours for which a diversion has not been recommended, or a diversion where adverse weather conditions are still expected. This type of advisory may include a synoptic weather discussion, and a wind, seas, or fog forecast.

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

5.3.6 Communications

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

Despite all efforts to achieve the best forecasts possible, the quality of forecasts does not always warrant maintaining the route selected. The routing agency needs reports of the ship's position and the ability to transmit recommendations for track change or weather advisories to the ship. The ship needs both send and receive capability for the required information. Information on seakeeping changes initiated by the ship is desirable in a coordinated effort to provide optimum transit conditions.

New satellite communications services are making possible the transmission of larger amounts of data than previously possible through traditional radio messages, a development which supports systems using on-board analysis to generate routes.

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