

# Meteorology and Climatology

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## Introduction

All biological, physical and chemical processes on earth are influenced by the weather and climate. Radiation, air temperature and relative humidity, precipitation and wind are main characteristics of their influence.

- Weather comprises the short-term (some days) characteristic of atmospheric processes. It may change from hour to hour, from day to day.

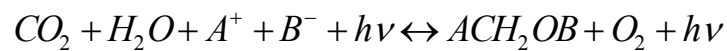
- „Witterung“ (special German word - there is no English analogue) characterise the atmospheric condition for period of some weeks within a season.

- Climate represents the long-term properties of the atmosphere at a given place that means averages, variations, extremes and their frequency distributions.

Climate is, therefore not only specified through an average atmospheric state but also by variations and changes of atmospheric conditions. The weather determines the tactical day to day decisions of farmers, whereas the climate influences the long term strategy for crop planting and management. Climatic factors describe atmospheric properties and processes like, i.e. radiation intensity, duration of radiation, air temperature and humidity, rain amount and intensity. The climate factors are influenced by the climate elements like latitude, exposition, altitude, land-sea distribution. Furthermore the local climate can be strongly influenced by local topography (e.g. valley, mountain, sea shore, city) so that macro-climate, meso-climate and micro-climate are the results of different scales in space and time. It means that climatic variables differ in their characteristics from place to place and determine soil types, vegetation zones, fauna distribution, land use, life styles, etc.

The physical characteristics of various materials specify their reaction on atmospheric impact so that, for example, with the same absorbed energy the soil can be heated up about 3 times as high as water. The integral effect of such interaction is that soil surfaces are warmer than water surfaces in summer and cooler in winter. Transferred from annual to diurnal variations during daytime soil surfaces are usually warmer and during night times cooler than water surfaces.

In forestry and agriculture the special attention is paid for an interaction between vegetation and atmosphere. An atmospheric effect on plant production can be rather well evaluated if one will try to quantify the atmospheric influence on the idealised processes of photosynthesis and respiration:



In the presence of chlorophyll, sufficient heat and radiation ( $h\nu$ ) abiotic (mineral) components can be bound together to form biological organic matter. In equilibrium the some amount of  $CO_2$  is fixed in photosynthesis (equation from left to right) as is liberated during respiration and mineralisation (equation right to left).

Water molecules are used for incorporation within the organic material and for evapotranspiration at the surface of the leaves to transport nutrient anions and cations to the point of their demand and to cool the leaves.

The energy and materials for such processes mostly come from the Sun and the atmosphere. They supply photosynthetic active radiation (PAR) for photosynthesis and global radiation for evapotranspiration and to maintain a temperature regime of the plant and its suspending. The atmosphere also supplies  $CO_2$  and water via the soil moisture and the roots for solution transport, evapotranspiration and cooling of the plants. Also oxygen comes from the atmosphere for respiration of the plant and the soil system. Where the turbulent and diffusive transport of oxygen is limited free oxygen respiration can not proceed and other oxygen carries or electron accelors have to substitute molecular oxygen. The situation that molecular oxygen is found in the atmosphere means that some reservoir of organic molecules has not been oxidised yet. The two reservoirs - molecular oxygen in the atmosphere and organic in the deep sea sediments - are separated from each other, so that they can not react with one another. The deep humus layer in boreal forests and the lack of a significant humus layer on tropical soils indicate the influence of temperature and moisture on the microbial decomposition processes of organic material.

The climatic features of different areas are therefore important factors for soil properties, microbial activities, plant productivity, fauna and flora distributions, water influence on soil and vegetation cover and finally for our living conditions.

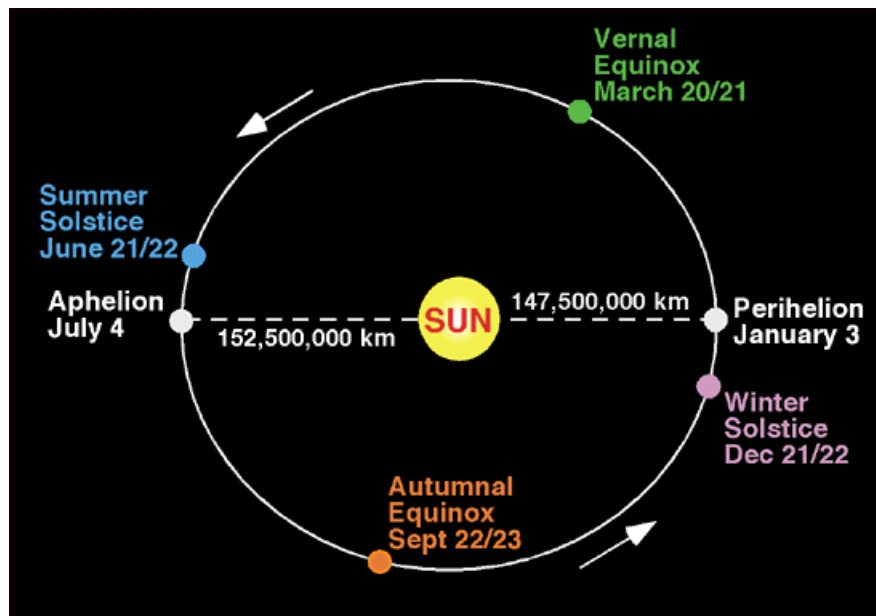
We will, therefore, try to understand the causes for different climatic conditions on earth especially in the tropics.

# 1. Earth-Sun Geometry

## Earth Rotation and Revolution

The term **Earth rotation** refers to the spinning of the Earth on its axis. One rotation takes exactly twenty-four hours and is called a mean solar day. If you could look down at the Earth's North Pole from space you would notice that the direction of rotation is counterclockwise. The opposite is true if you viewed the Earth from the South Pole.

The orbit of the Earth around the sun is called **Earth revolution**. This celestial motion takes  $365 \frac{1}{4}$  days to complete one cycle. Further, the Earth's orbit around the sun is not circular, but **elliptical** (see **Figure 1-1**). An elliptical orbit causes the Earth's distance from the sun to vary annually. However, this phenomenon does **not** cause the seasons! This annual variation in the distance from the sun does influence the amount of solar radiation intercepted by the Earth by approximately 6%. On January 3<sup>rd</sup>, **perihelion**, the Earth is closest to the sun (147.5 million kilometers). The Earth is farthest from the sun on July 4<sup>th</sup>, or **aphelion**. The average distance of the Earth from the sun over a one year period is 150 million kilometers.

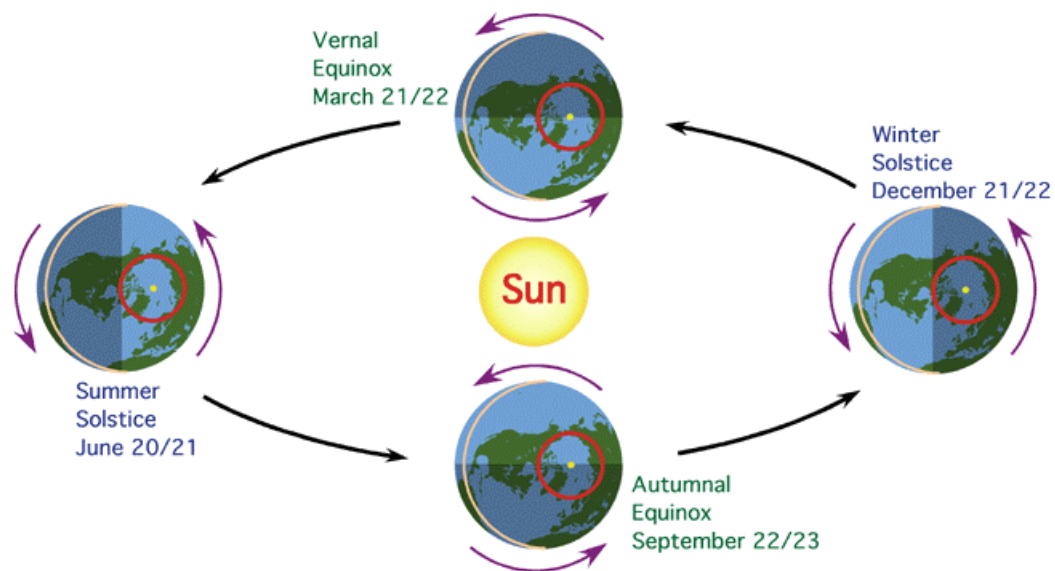


**Figure 1-1.** Position of the equinoxes, solstices, aphelion, and perihelion on the Earth's orbit.

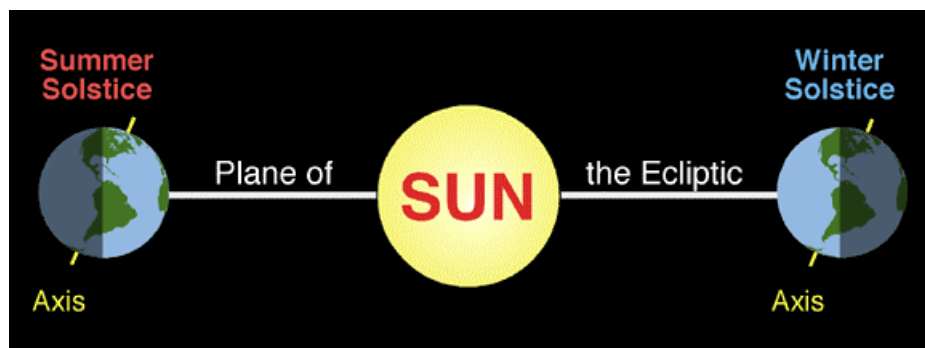
## Tilt of the Earth's Axis

The Earth's axis is not **perpendicular** to the plane of the **ecliptic (orbit plane)**, but inclined at a fixed angle of  $23.5^\circ$ . Moreover, the northern end of the Earth's axis always points to the same place in space (**North Star**). However, the relative position of the Earth's axis to the sun does change during this cycle (**Figure 1-2**). This circumstance is responsible for the annual changes in the height of the sun above the horizon. It also causes the **seasons** and climatic differences, by controlling the **intensity** and **duration** of sunlight received by locations on the Earth.

On June 21 or 22, the **summer solstice**, the Earth is positioned in its orbit so that the North Pole is leaning  $23.5^\circ$  toward the sun (**Figures 1-2, 1-3**). During the summer solstice, all locations North of the equator have day lengths greater than twelve hours, while all locations South of the equator have day lengths less than twelve hours. On December 21 or 22, the **winter solstice**, the Earth is positioned so that the South Pole is leaning  $23.5^\circ$  toward the sun (**Figures 1-2, 1-3**). During the winter solstice, all locations North of the equator have day lengths less than twelve hours, while all locations South of the equator have day lengths greater than twelve hours.

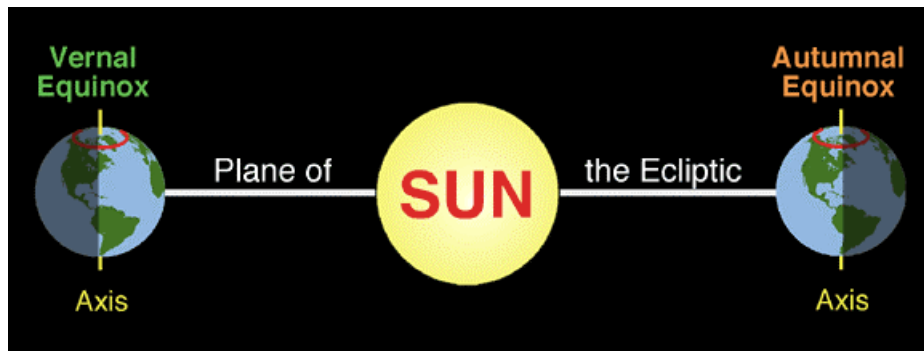


**Figure 1-2.** Annual change in the position of the Earth in its revolution around the sun. In this graphic, we are viewing the Earth from a position in space that is above the North Pole (yellow dot) at the summer solstice, the winter solstice, and the two equinoxes. Note how the position of the North Pole on the Earth's surface does not change. However, its position relative to the sun does change and this shift is responsible for the seasons. The red circle on each of the Earths represents the Arctic Circle (66.5° N). During the summer solstice, the area above the Arctic Circle is experiencing 24 hours of daylight because the North Pole is tilted 23.5° toward the sun. The Arctic Circle experiences 24 hours of night when the North Pole is tilted 23.5° away from the sun in the winter solstice. During the two equinoxes, the circle of illumination cuts through the polar axis and all locations on the Earth experience 12 hours of day and night.



**Figure 1-3.** During the summer solstice the Earth's North Pole is tilted 23.5° towards the sun relative to the circle of illumination. This phenomenon keeps all places above a latitude of 66.5° N in 24 hours of sunlight, while locations below a latitude of 66.5° S are in darkness. The North Pole is tilted 23.5° away from the sun relative to the circle of illumination during the winter solstice. On this date, all places above a latitude of 66.5° N are now in darkness, while locations below a latitude of 66.5° S receive 24 hours of daylight.

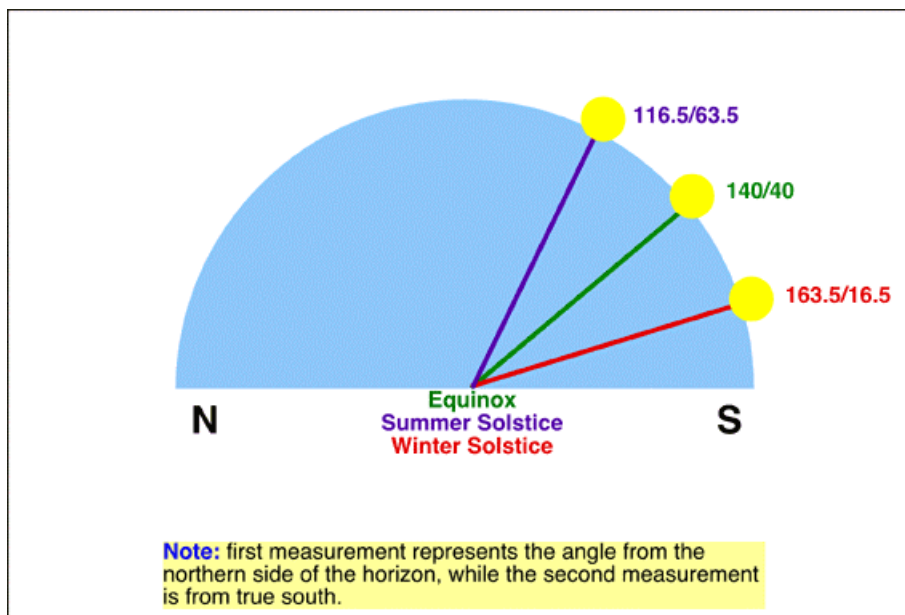
On September 22 or 23, the **autumnal equinox**, neither pole is tilted toward the sun (**Figures 1-2, 1-4**). March 20 or 21 marks the arrival of the **spring** or **vernal equinox** when once again the poles are not tilted toward the sun. Day lengths on both of these days, regardless of latitude, are exactly 12 hours.



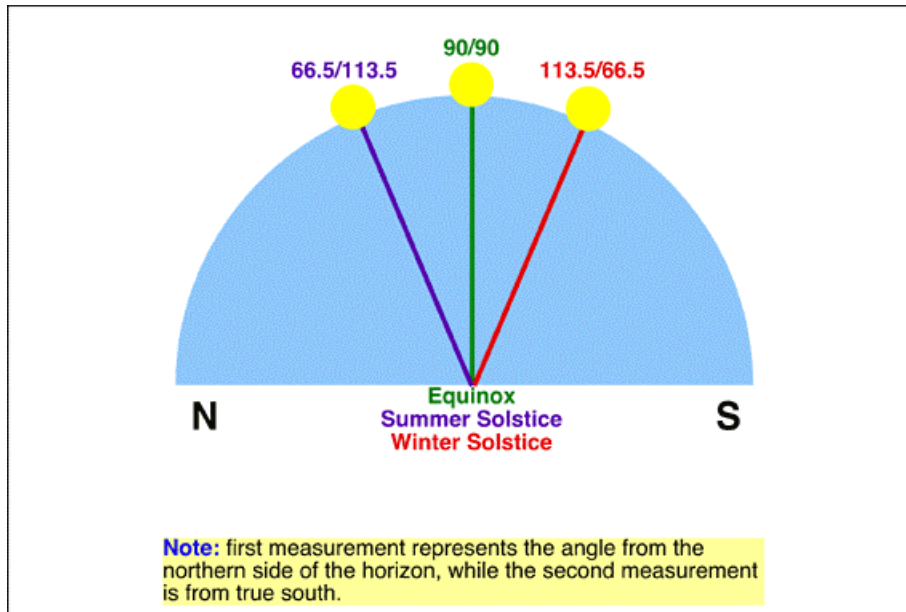
**Figure 1-4.** During the equinoxes, the axis of the Earth is not tilted toward or away from the sun and the circle of illumination cuts through the poles. This situation does not suggest that the 23.5° tilt of the Earth no longer exists. The vantage point of this graphic shows that the Earth's axis is inclined 23.5° toward the viewer for both dates (see **Figure 1-2**). The red circles shown in the graphic are the Arctic Circle.

#### Axis Tilt and Solar Altitude

The annual change in the relative position of the Earth's axis in relationship to the sun causes the height of the sun (solar altitude) to vary in our skies. The total variation in maximum solar altitude for any location on the Earth over a one year period is 47° ( $2 \times 23.5 = 47$ ). For example, at 50° North maximum solar altitude varies from 63.5° on the summer solstice to 16.5° on the winter solstice (**Figure 1-5**). Maximum solar height at the equator goes from 66.5° above the northern end of the horizon during the summer solstice, to directly overhead (90°) on the fall equinox, and then down to 66.5° above the southern end of the horizon during the summer solstice (**Figure 1-6**).

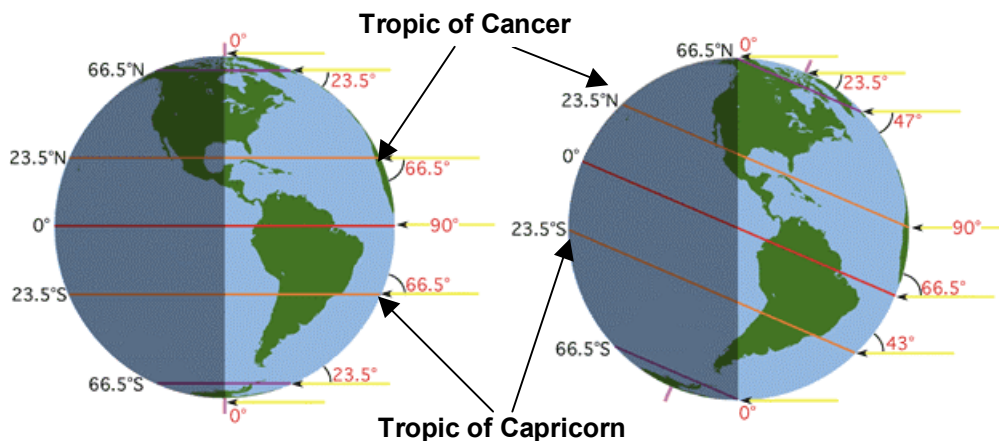


**Figure 1-5.** Variations in solar altitude at solar noon for 50° North during the summer solstice, equinox, and winter solstice.



**Figure 1-6.** Variations in solar altitude at solar noon for the equator during the summer solstice, equinox, and winter solstice.

The location on the Earth where the sun is directly overhead at solar noon is known as the **subsolar point**. The subsolar point occurs on the equator during the equinoxes (**Figure 1-7**). During the summer solstice, the subsolar point moves to the Tropic of Cancer because at this time the North Pole is tilted  $23.5^\circ$  toward the sun. The subsolar point is located at the Tropic of Capricorn on the winter solstice. On this date, the South Pole is now tilted toward the sun (**Figures 1-2 and 1-3**).



**Figure 1-7.** Relationship of maximum sun height to latitude for the equinox (left) and summer solstice (right). The red values on the right of the globes are maximum solar altitudes at solar noon. Black numbers on the left indicate the location of the Equator, Tropic of Cancer ( $23.5^\circ$  N), Tropic of Capricorn ( $23.5^\circ$  S), Arctic Circle ( $66.5^\circ$  N), and the Antarctic Circle ( $66.5^\circ$  S). The location of the North and South Poles are also identified. During the equinox, the equator is the location on the Earth with a sun angle of  $90^\circ$  for solar noon. Note how maximum sun height declines with latitude as you move away from the Equator. For each degree of latitude traveled maximum sun height decreases by the same amount. At equinox, you can also calculate the noon angle by subtracting the location's latitude from 90. During the summer solstice, the sun is now directly overhead at the Tropic of Cancer. All locations above this location have maximum sun heights that are  $23.5^\circ$  higher from the equinox situation. Places above the Arctic Circle are in 24 hours of daylight. Below the Tropic of Cancer the noon angle of the sun drops one degree in height for each degree of latitude traveled. At the Antarctic Circle, maximum sun height becomes  $0^\circ$  and locations south of this point on the Earth are in 24 hours of darkness.

The following **table** describes the changes in solar altitude at solar noon for the two solstices and equinoxes. All measurements are in degrees (horizon has 180 degrees from True North to True South) and are measured from either True North or True South (whatever is closer).

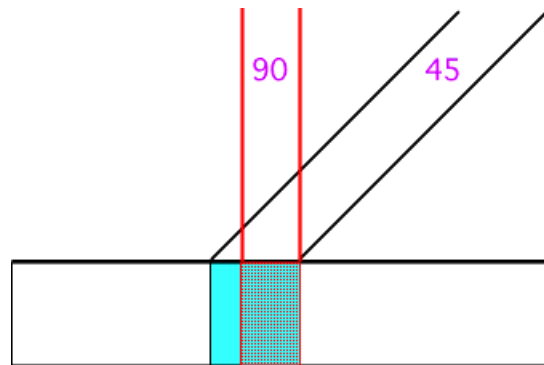
**Table 1-1.** Maximum sun altitudes for selected latitudes during the two solstices and equinoxes

Location's Latitude	Vernal Equinox March 21/22	Summer Solstice June 20/21	Autumnal Equinox September 22/23	Winter Solstice December 21/22
90° N	0°	23.5°	0°	- 23.5°
70° N	20°	43.5°	20°	-3.5°
66.5° N	23.5°	47°	23.5°	0°
60° N	30°	53.5°	30°	6.5°
50° N	40°	63.5°	40°	16.5°
23.5° N	66.5°	90°	66.5°	43°
0°	90°	66.5°	90°	66.5°
23.5° S	66.5°	43°	66.5°	90°
50° S	40°	16.5°	40°	63.5°
60° S	30°	6.5°	30°	53.5°
66.5° S	23.5°	0°	23.5°	47°
70° S	20°	-3.5°	20°	43.5°
90° S	0°	- 23.5°	0°	23.5°

## 2. Earth-Sun Relationships and Insolation

In the previous topic, we learned that the Earth's seasons are controlled by changes in the **duration** and **intensity** of solar radiation or **insolation**. Both of these factors are in turn governed by the annual change in the position of the Earth's axis relative to the sun (see Figure 1-4).

Yearly changes in the position of the Earth's axis cause the location of the sun to wander  $47^\circ$  across our skies. Changes in the location of the sun have a direct effect on the intensity of solar radiation. The intensity of solar radiation is largely a function of the angle of incidence, the angle at which the sun's rays strike the Earth's surface. If the sun is positioned directly overhead or  $90^\circ$  from the horizon, the incoming insolation strikes the surface of the Earth at right angles and is most intense. If the sun is  $45^\circ$  above the horizon, the incoming insolation strikes the Earth's surface at an angle. This causes the rays to be spread out over a larger surface area reducing the intensity of the radiation. **Figure 2-1** models the effect of changing the angle of incidence from  $90^\circ$  to  $45^\circ$ . As illustrated, the lower sun angle ( $45^\circ$ ) causes the radiation to be received over a much larger surface area. This surface area is approximately 40% greater than the area covered by an angle of  $90^\circ$ . The lower angle also reduces the intensity of the incoming rays by 30 %.



**Figure 2-1.** Effect of angle on the area that intercepts an incoming beam of radiation.

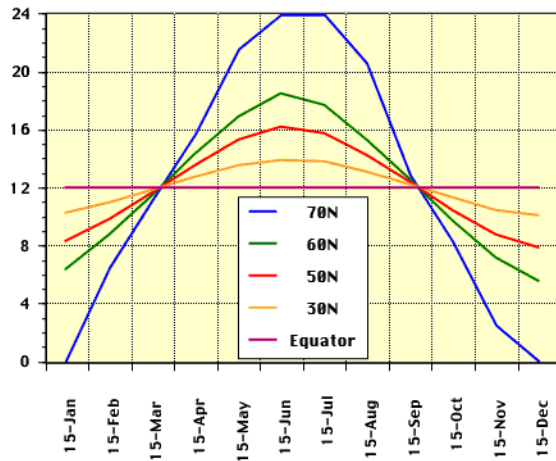
We can also model the effect the angle of incidence has on insolation intensity with the following simple equation:

$$\text{Intensity} = \text{SIN} (\text{A})$$

where, **A** is the angle of incidence and **SIN** is the sine function found on most calculators. Using this equation we can determine that an angle of  $90^\circ$  gives us a value of 1.00 or 100 % ( $1.00 \times 100$ ). Let us compare this maximum value with values determined for other angles of incidence. **Note** the answers are expressed as a percentage of the potential maximum value.

<b>SIN <math>80^\circ</math></b>	<b>= 0.98 or 98%</b>
<b>SIN <math>70^\circ</math></b>	<b>= 0.94 or 94%</b>
<b>SIN <math>60^\circ</math></b>	<b>= 0.87 or 87%</b>
<b>SIN <math>50^\circ</math></b>	<b>= 0.77 or 77%</b>
<b>SIN <math>40^\circ</math></b>	<b>= 0.64 or 64%</b>
<b>SIN <math>30^\circ</math></b>	<b>= 0.50 or 50%</b>
<b>SIN <math>20^\circ</math></b>	<b>= 0.34 or 34%</b>
<b>SIN <math>10^\circ</math></b>	<b>= 0.17 or 17%</b>
<b>SIN <math>0^\circ</math></b>	<b>= 0.00 or 0%</b>

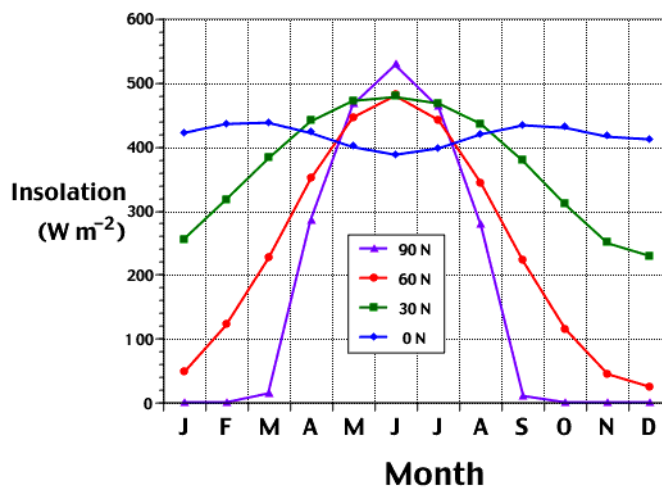
The yearly changes in the position of the Earth's axis relative to the plane of the ecliptic also causes seasonal variations in day length to all locations outside of the equator. Longest days occur during the summer solstice for locations north of the equator and on the winter solstice for locations in the Southern Hemisphere. The equator experiences equal day and night on every day of the year. Day and night is also of equal length for all Earth locations on the autumnal and vernal **equinoxes**. **Figure 2-2** describes the change in the length of day for locations at the equator,  $10^\circ$ ,  $30^\circ$ ,  $50^\circ$ ,  $60^\circ$ , and  $70^\circ$  North over a one-year period. The illustration suggests that days are longer than nights in the Northern Hemisphere from the March equinox to the September equinox. Between the September to March equinox days are shorter than nights in the Northern Hemisphere. The opposite is true in the Southern Hemisphere. The graph also shows that the seasonal (winter to summer) variation in day length increases with increasing latitude.



**Figure 2-2.** Annual variations in day length for locations at the equator, 30, 50, 60, and 70° North latitude.

**Figure 2-3** below describes the potential insolation available for the equator and several locations in the Northern Hemisphere over a one-year period. The values plotted on this **graph** take into account the combined effects of angle of incidence and day length duration. Locations at the equator show the least amount of variation in insolation over a one-year period. These slight changes in insolation result only from the annual changes in the altitude of the sun above the horizon, as the duration of daylight at the equator is always 12 hours. The peaks in insolation intensity correspond to the two equinoxes when the sun is directly overhead. The two annual minimums of insolation occur on the solstices when the maximum height of the sun above the horizon reaches an angle of 66.5°. The most extreme variations in insolation received in the Northern Hemisphere occur at 90° North. During the summer solstice this location receives more potential incoming solar radiation than any other location graphed. At this time the sun never sets. In fact, it remains at an altitude of 23.5° above the horizon for the whole day. From September 22 (autumnal equinox) to March 21, (vernal equinox) no insolation is received at 90° North. During this period the sun slips below the horizon as the northern axis of the Earth becomes tilted away from the sun.

The annual insolation curve for locations at 60° North best approximates the seasonal changes in solar radiation intensity perceived at our latitude. Maximum values of insolation are received at the summer solstice when day length and angle of incidence are at their maximum. During the summer solstice day length is 18 hours and 27 minutes and the angle of the sun reaches a maximum value of 53.5° above the horizon. Minimum values of insolation are received at the winter solstice when day length and angle of incidence are at their minimum. During the winter solstice day length is only 5 hours and 33 minutes and the angle of the sun reaches a lowest value of 6.5° above the horizon.



**Figure 2-3.** Monthly values of available insolation for the equator, 30, 60, and 90° North.

### 3. Atmospheric Composition

Table 3-1 lists the eleven most abundant gases found in the Earth's lower atmosphere by volume. Of the gases listed, nitrogen, oxygen, water vapour, carbon dioxide, methane, nitrous oxide, and ozone are extremely important to the health of the Earth's biosphere.

The table indicates 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. Nitrogen is removed from the atmosphere and deposited at the Earth's surface mainly by specialized nitrogen fixing bacteria, and by way of lightning through precipitation. The addition of this nitrogen to the Earth's surface soils and various water bodies supplies much needed nutrition for plant growth. Nitrogen returns to the atmosphere primarily through biomass combustion and denitrification.

Oxygen is exchanged between the atmosphere and life through the processes of photosynthesis and respiration. Photosynthesis produces oxygen when carbon dioxide and water are chemically converted into glucose with the help of sunlight. Respiration is a process whose reciprocal is photosynthesis. In respiration, oxygen is combined with glucose to chemically release energy for metabolism. The products of this reaction are water and carbon dioxide.

**Table 3-1:** Average composition of the atmosphere up to an altitude of 25 km.

Gas Name	Chemical Formula	Percent Volume
Nitrogen	N <sub>2</sub>	78.08%
Oxygen	O <sub>2</sub>	20.95%
*Water	H <sub>2</sub> O	0 to 4%
Argon	Ar	0.93%
*Carbon Dioxide	CO <sub>2</sub>	0.0360%
Neon	Ne	0.0018%
Helium	He	0.0005%
*Methane	CH <sub>4</sub>	0.00017%
Hydrogen	H <sub>2</sub>	0.00005%
*Nitrous Oxide	N <sub>2</sub> O	0.00003%
*Ozone	O <sub>3</sub>	0.000004%

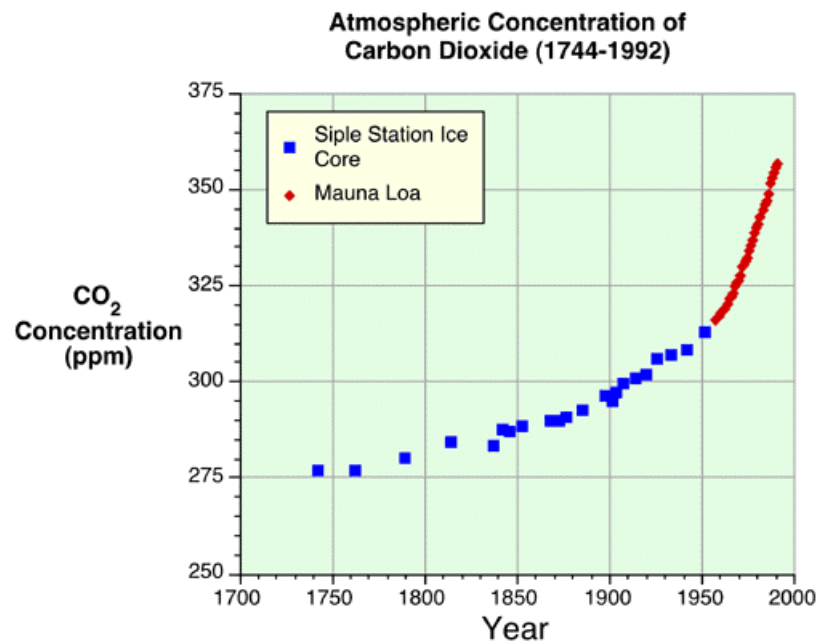
\* variable gases

The next most abundant gas on the table is water vapour. Water vapour varies in concentration in the atmosphere both spatially and temporally. The highest concentrations of water vapour 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 vapour can approach zero percent. Water vapour has several very important functional roles on our planet: 1) It redistributes heat energy on the Earth through latent heat energy exchange. 2) The condensation of water vapour creates precipitation that falls to the Earth's surface providing needed fresh water for plants and animals. 3) It helps warm the Earth's atmosphere through the greenhouse effect.

The fifth most abundant gas in the atmosphere is carbon dioxide. The volume of this gas has increased by over 25 % in the last three hundred years (see Figure 3-1). This increase is primarily due to human induced burning for fossil fuels, deforestation, and other forms of land-use change. Some scientists believe that this increase is causing global warming through an enhancement of the greenhouse effect. Carbon dioxide is also exchanged between the atmosphere and life through the processes of photosynthesis and respiration.

Methane is a very strong greenhouse gas. Since 1750, methane concentrations in the atmosphere have increased by more than 140 %. The primary sources for the additional methane added to the atmosphere (in order of importance) are: rice cultivation; domestic grazing animals; termites; landfills; coal mining; and, oil and gas extraction. Anaerobic conditions associated with rice paddy flooding results in the formation of methane gas. However, an accurate estimate of how much methane is being produced from rice paddies has been difficult to ascertain. More than 60 % of all rice paddies are found in India and China where scientific data concerning emission rates are unavailable. Nevertheless, scientists believe that the contribution of rice paddies is large because this form of crop production has more than doubled since 1950. Grazing animals release methane to the environment as a result of herbaceous digestion. Some researchers believe the addition of methane from this source has more than quadrupled over the last century. Termites also release methane through similar processes. Land-use change in the tropics, due to deforestation, ranching, and farming, may be causing termite numbers to expand. If this assumption is correct, the contribution from these insects may be important. Methane is also released from landfills, coal mines, and gas and oil drilling. Landfills produce methane as organic wastes

decompose over time. Coal, oil, and natural gas deposits release methane to the atmosphere when these deposits are excavated or drilled.



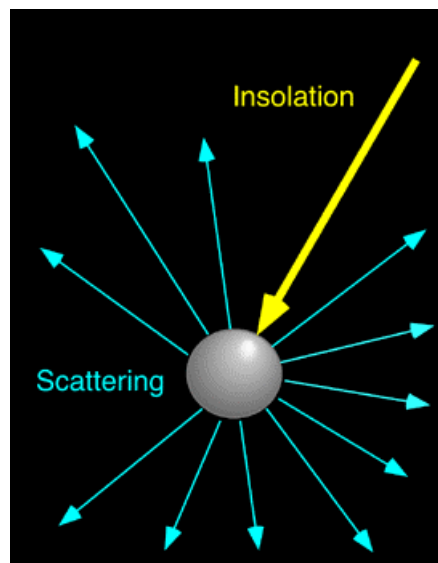
**Figure 3-1:** The following graph illustrates the rise in atmospheric carbon dioxide from 1744 to 1992. Note that the increase in carbon dioxide's concentration in the atmosphere has been **exponential** during the period examined. An extrapolation into the immediate future would suggest continued increases.

The average concentration of the greenhouse gas nitrous oxide is now increasing at a rate of 0.2 to 0.3 % per year. Its part in the enhancement of the greenhouse effect is minor relative to the other greenhouse gases already mentioned. However, it does have an important role in the artificial fertilization of ecosystems. In extreme cases, this fertilization can lead to the death of forests, eutrophication of aquatic habitats, and species exclusion. Sources for the increase of nitrous oxide in the atmosphere include: land-use conversion; fossil fuel combustion; biomass burning; and soil fertilization. Most of the nitrous oxide added to the atmosphere each year comes from deforestation and the conversion of forest, savannah and grassland ecosystems into agricultural fields and rangeland. Both of these processes reduce the amount of nitrogen stored in living vegetation and soil through the decomposition of organic matter. Nitrous oxide is also released into the atmosphere when fossil fuels and biomass are burned. However, the combined contribution to the increase of this gas in the atmosphere is thought to be minor. The use of nitrate and ammonium fertilizers to enhance plant growth is another source of nitrous oxide. How much is released from this process has been difficult to quantify. Estimates suggest that the contribution from this source represents from 50 % to 0.2 % of nitrous oxide added to the atmosphere annually. Ozone's role in the enhancement of the greenhouse effect has been difficult to determine. Accurate measurements of past long-term (more than 25 years in the past) levels of this gas in the atmosphere are currently unavailable. Moreover, concentrations of ozone gas are found in two different regions of the Earth's atmosphere. The majority of the ozone (about 97 %) found in the atmosphere is concentrated in the stratosphere at an altitude of 15 to 55 kilometers above the Earth's surface. This stratospheric ozone provides an important service to life on the Earth as it absorbs harmful ultraviolet radiation. In recent years, levels of stratospheric ozone have been decreasing due to the buildup of human created chlorofluorocarbons in the atmosphere. Since the late 1970s, scientists have noticed the development of severe holes in the ozone layer over Antarctica. Satellite measurements have indicated that the zone from 65°N to 65°S has had a 3 % decrease in stratospheric ozone since 1978.

Ozone is also highly concentrated at the Earth's surface in and around cities. Most of this ozone is created as a by product of human created photochemical smog. This buildup of ozone is toxic to organisms living at the Earth's surface.

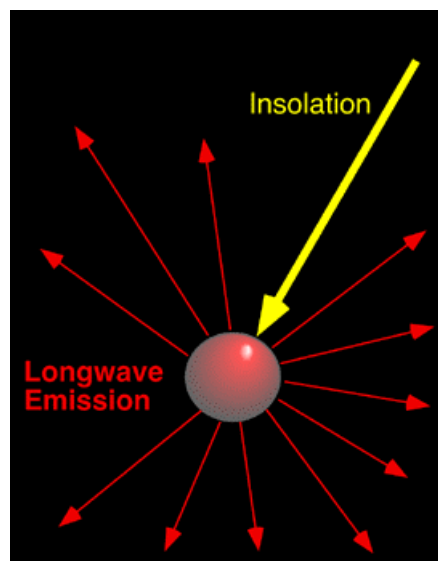
## 4. Atmospheric Effects on Incoming Solar Radiation

Three atmospheric processes modify the solar radiation passing through our atmosphere destined to the Earth's surface. These processes act on the radiation when it interacts with gases and suspended particles found in the atmosphere. The process of scattering occurs when small particles and gas molecules diffuse part of the incoming solar radiation in random directions without any alteration to the wavelength of the electromagnetic energy (**Figure 4-1**). Scattering does, however, reduce the amount of incoming radiation reaching the Earth's surface. A significant proportion of scattered shortwave solar radiation is redirected back to space. The amount of scattering that takes place is dependent on two factors: wavelength of the incoming radiation and the size of the scattering particle or gas molecule. In the Earth's atmosphere, the presence of a large number of particles with a size of about 0.5 microns results in shorter wavelengths being preferentially scattered. This factor also causes our sky to look blue because this colour corresponds to those wavelengths that are best diffused. If scattering did not occur in our atmosphere the daylight sky would be black.



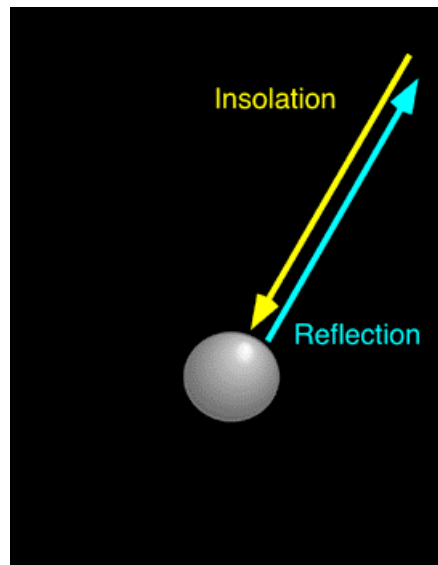
**Figure 4-1:** Atmospheric scattering.

If intercepted, some gases and particles in the atmosphere have the ability to **absorb** incoming insolation (**Figure 4-2**). Absorption is defined as a process in which solar radiation is retained by a substance and converted into heat energy. The creation of heat energy also causes the substance to emit its own radiation. In general, the absorption of solar radiation by substances in the Earth's atmosphere results in temperatures that get no higher than 1800 degrees Celsius. According to Wien's Law, bodies with temperatures at this level or lower would emit their radiation in the longwave band. Further, this emission of radiation is in all directions so a sizable proportion of this energy is lost to space.



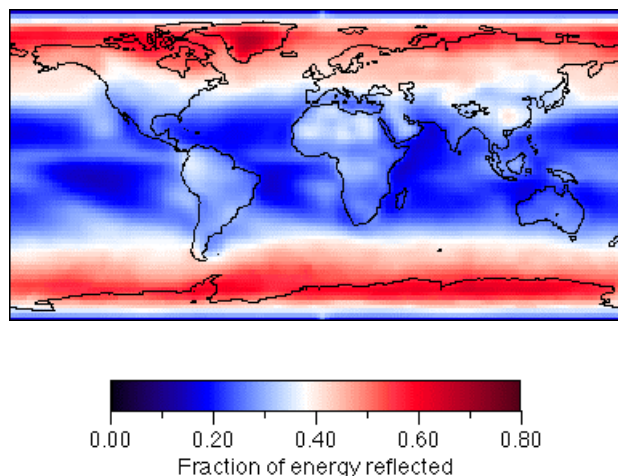
**Figure 4-2:** Atmospheric absorption.

The final process in the atmosphere that modifies incoming solar radiation is reflection (**Figure 4-3**). Reflection is a process where sunlight is redirect by 180 degrees after it strikes an atmospheric particle. This redirection causes a 100 % loss of the insolation. Most of the reflection in our atmosphere occurs in clouds when light is intercepted by particles of liquid and frozen water. The reflectivity of a cloud can range from 40 to 90 %.



**Figure 4-3:** Atmospheric reflection.

Sunlight reaching the Earth's surface unmodified by any of the above atmospheric processes is termed direct solar radiation. Solar radiation that reaches the Earth's surface after it was altered by the process of scattering is called diffused solar radiation. Not all of the direct and diffused radiation available at the Earth's surface is used to do **work** (photosynthesis, creation of sensible heat, evaporation, etc.). As in the atmosphere, some of the radiation received at the Earth's surface is redirected back to space by reflection. The following **image** describes the spatial pattern of surface reflectivity as measured for the year 1987.



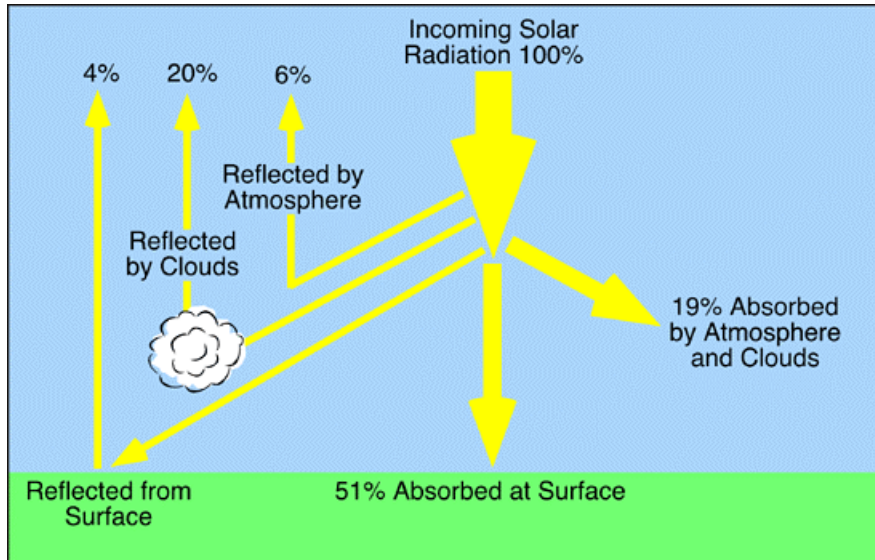
**Figure 4-4:** Annual (1987) reflectivity of the Earth's surface.

The reflectivity or albedo of the Earth's surface varies with the type of material that covers it. For example, fresh snow can reflect up to 95 % of the insolation that reaches it surface. Some other surface type reflectivities are:

- Dry sand 35 to 45 %
- Broadleaf deciduous forest 5 to 10 %
- Needle-leaf coniferous forest 10 to 20 %
- Grass type vegetation 15 to 25 %

Reflectivity of the surface is often described by the term **surface albedo**. The Earth's average **albedo**, reflectance from both the atmosphere and the surface, is about 30 %.

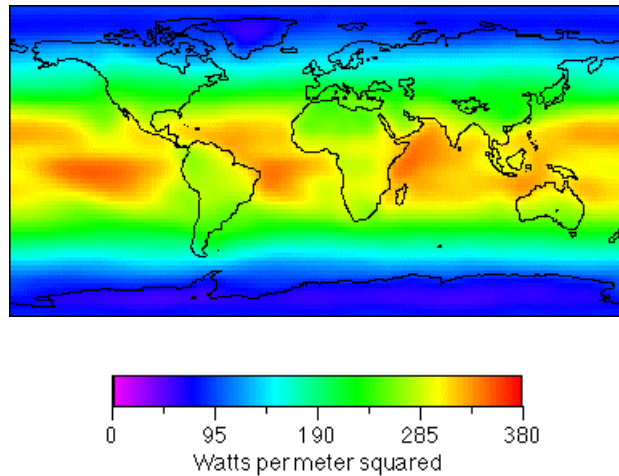
**Figure 4-5** describes the modification of solar radiation by atmospheric and surface processes for the whole Earth over a period of one year. Of all the sunlight that passes through the atmosphere annually, only 51 % is available at the Earth's surface to do work. This energy is used to heat the Earth's surface and lower atmosphere, **melt** and evaporate water, and run photosynthesis in plants. Of the other 49 %, 4 % is reflected back to space by the Earth's surface, 26 % is scattered or reflected to space by clouds and atmospheric particles, and 19 % is absorbed by atmospheric gases, particles, and clouds.



**Figure 4-5:** Global modification of incoming solar radiation by atmospheric and surface processes.

## 5. Global Patterns of Insolation Receipts

The following **image** describes the annual pattern of solar radiation absorption at the Earth's surface for the year 1987.



**Figure 5-1:** Annual (1987) pattern of solar radiation absorbed at the Earth's surface.

The combined effect of Earth-sun relationships (angle of incidence and day length variations) and the modification of the solar beam as it passes through the atmosphere produces specific global patterns of annual insolation receipt as seen on **Figure 5-1** above (and **figures** below). After examining these patterns, the following trends can be identified:

- Highest values of insolation received occur in tropical latitudes. Within this zone there are localised maximums over the tropical oceans and deserts where the atmosphere has virtually no cloud development for most of the year. Insolation quantities at the equator over land during the solstices are approximately the same as values found in the middle latitudes during their summer (see pictures below).
- Outside the tropics, annual receipts of solar radiation generally decrease with increasing latitude. Minimum values occur at the poles. This pattern is primarily the result of Earth-sun geometric relationships and its effect on the duration and intensity of solar radiation received.
- In middle and high latitudes, insolation values over the ocean, as compared to those at the same latitude over the land, are generally higher (see **NASA** images). Greater cloudiness over land surfaces accounts for this variation.

**NASA's Surface Radiation Budget Project** has used satellite data, computer models, and meteorological data to determine shortwave surface radiation fluxes for the period July 1983 to June 1991. The following pictures display these fluxes for January and July globally:

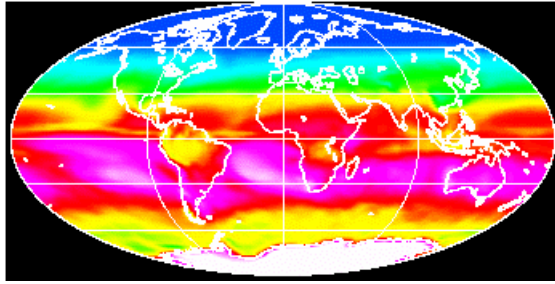
In the equations below, the mathematical terms have the following definitions

**K** = Shortwave Direct Radiation

**k** = Shortwave Indirect Radiation

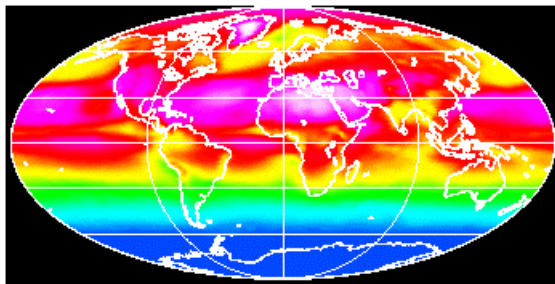
**a** = Reflectivity of the Surface or Surface Albedo

Average Available Solar Insolation at the Earth's Surface: January 1984-1991 (**K + k**)



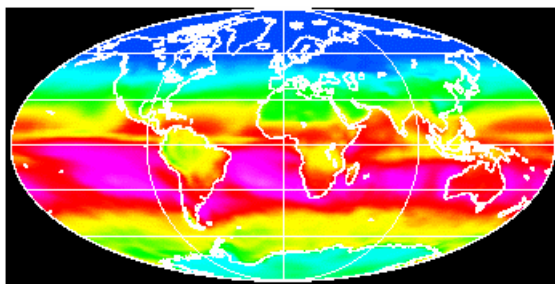
**Figure 5-2:** Average available solar insolation at the Earth's surface: January 1984-1991. Highest values of available solar insolation occur at the South Pole due to high solar input and little cloud cover. High values also occur along the subtropical oceans of the Southern Hemisphere. Color range: blue - red - white, Values: 0 - 350W/m<sup>2</sup>. Global mean = 187W/m<sup>2</sup>, Minimum = 0W/m<sup>2</sup>, Maximum = 426W/m<sup>2</sup>. (Source: NASA Surface Radiation Budget Project).

Average Available Solar Insolation at the Earth's Surface: July 1983-1990 (**K + k**)



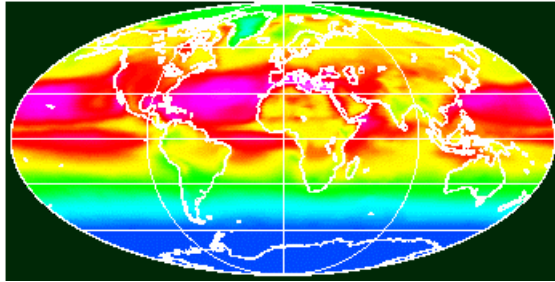
**Figure 5-3:** Average available solar insolation at the Earth's surface: July 1983-1990. Highest values of available solar insolation over Greenland due to high solar input and low cloud amounts. High values also occur along the subtropics of the Northern Hemisphere. Colour range: blue - red - white, Values: 0 - 350W/m<sup>2</sup>. Global mean = 180W/m<sup>2</sup>, Minimum = 0W/m<sup>2</sup>, Maximum = 351W/m<sup>2</sup>. (Source: NASA Surface Radiation Budget Project).

Average Absorbed Solar Insolation at the Earth's Surface: Jan. 1984-1991 [**(K + k)(1 - a)**]



**Figure 5-4:** Average absorbed solar insolation at the Earth's surface: January 1984-1991. Highest values occur along the subtropical oceans of the Southern Hemisphere. Lowest values occur over areas of high surface reflection such as the South Pole, cloudy regions, and areas of low solar input like the high latitudes of the Northern Hemisphere. Color range: blue - red - white, Values: 0 - 350W/m<sup>2</sup>. Global mean = 162W/m<sup>2</sup>, Minimum = 0W/m<sup>2</sup>, Maximum = 315W/m<sup>2</sup>. (Source: NASA Surface Radiation Budget Project).

Average Absorbed Solar Insolation at the Earth's Surface: July 1983-1990  $[(K + k)(1 - a)]$



**Figure 5-5:** Average absorbed solar insolation at the Earth's surface: July 1983-1990. Highest values occur over the subtropical oceans of the Northern Hemisphere due to high solar input and little cloud coverage. Lowest values occur in areas of high surface reflection such as snow/ice covered surfaces like Greenland, cloudy regions such as storm tracks, and areas of low solar input like the high latitudes of the Southern Hemisphere. Color range: blue - red - white, Values: 0 - 350W/m<sup>2</sup>. Global mean = 158/m<sup>2</sup>, Minimum = 0W/m<sup>2</sup>, Maximum = 323/m<sup>2</sup>. (**Source:** NASA Surface Radiation Budget Project).

## 6. Net Radiation and the Planetary Energy Balance

Shortwave radiation from the sun enters the surface-atmosphere system of the Earth and is ultimately returned to space as longwave radiation (because the Earth is cooler than the sun). A basic necessity of this energy interchange is that incoming solar insolation and outgoing radiation be equal in quantity. One way of modelling this balance in energy exchange is described graphically with the use of the following two **cascade** diagrams.

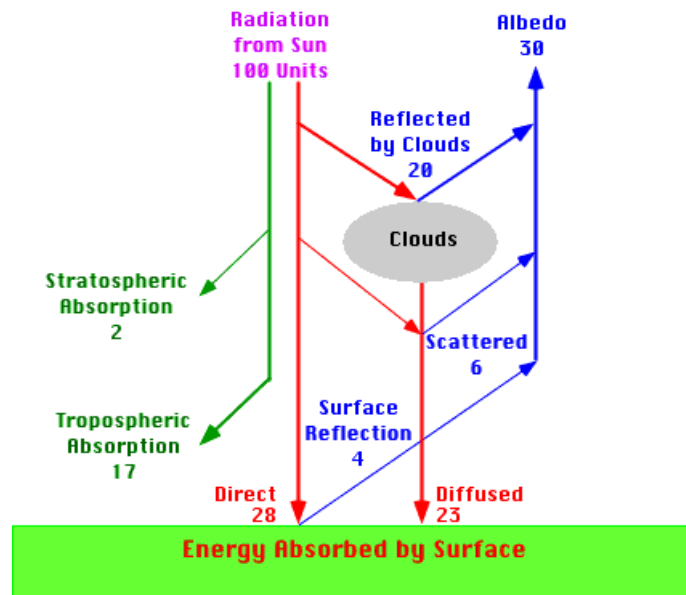


Figure 6-1: Global shortwave radiation cascade.

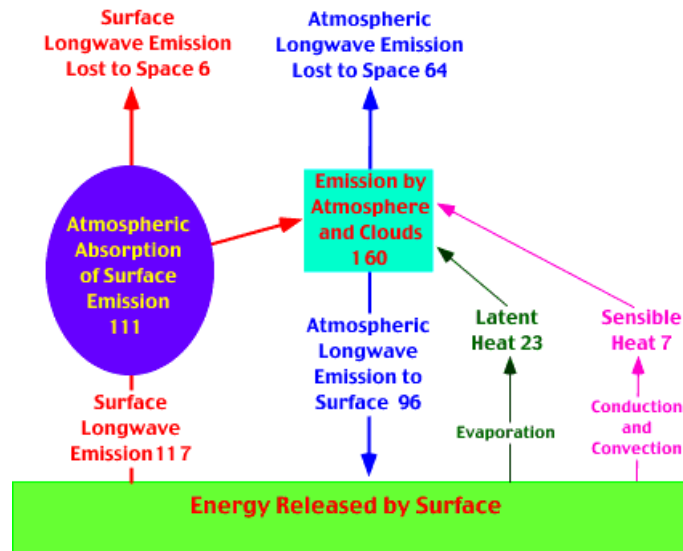
The **Global Shortwave Radiation Cascade** describes the relative amounts (based on **100 units** available at the top of the atmosphere) of shortwave radiation partitioned to various atmospheric processes as it passes through the atmosphere. The diagram indicates that **19 units** of insolation are absorbed (and therefore transferred into heat energy and longwave radiation) in the atmosphere by the following two processes:

**Stratospheric Absorption of the Ultraviolet Radiation by Ozone 2 units;** and

**Tropospheric Absorption of Insolation by Clouds and Aerosols 17 units.**

**23 units** of solar radiation are scattered in the atmosphere subsequently absorbed at the surface as diffused insolation. **28 units** of the incoming solar radiation are absorbed at the surface as direct insolation. Total amount of solar insolation absorbed at the surface equals **51 units**. The total amount of shortwave radiation absorbed at the surface and in the atmosphere is **70 units**.

Three main losses of solar radiation back to space occur in the Earth's shortwave radiation cascade. **4 units** of sunlight are returned to space from surface reflection. Cloud reflection returns another **20 units** of solar radiation. Back scattering of sunlight returns **6 units** to space. The total loss of shortwave radiation from these processes is **30 units**. The term used to describe the combined effect of all of these shortwave losses is Earth albedo.



**Figure 6-2:** Global longwave radiation cascade.

The **Global Longwave Radiation Cascade** indicates that energy leaves the Earth's surface through three different processes. **7 units** leave the surface as sensible heat. This heat is transferred into the atmosphere by conduction and convection. The melting and evaporation of water at the Earth's surface incorporates **23 units** energy into the atmosphere as latent heat. This latent heat is released into the atmosphere when the water condenses or becomes solid. Both of these processes become part of the emission of longwave radiation by the atmosphere and clouds.

The surface of the Earth emits **117 units** of longwave radiation. Of this emission only **6 units** are directly lost to space. The other **111 units** are absorbed by greenhouse gases in the atmosphere and converted into heat energy and then into atmospheric emissions of longwave radiation (the greenhouse effect).

The atmosphere emits **160 units** of longwave energy. Contributions to this **160 units** are from surface emissions of longwave radiation (**111 units**), latent heat transfer (**23 units**), sensible heat transfer (**7 units**), and the absorption of shortwave radiation by atmospheric gases and clouds (**19 units**, see **Figure 6-1**). Atmospheric emissions travel in two directions. **64 units** of atmospheric emission is lost directly to space. **96 units** travel to the Earth's surface where it is absorbed and transferred into heat energy.

The total amount of energy lost to space in the global longwave radiation cascade is **70 units** (surface emission **6 units** + atmospheric emission **64 units**.) This is the same amount of energy that was added to the Earth's atmosphere and surface by the **Global Shortwave Radiation Cascade**.

Finally, to balance the surface energy exchanges in this cascade we have to account for **51 units** of missing energy [atmosphere and cloud longwave emission (**96 units**) minus surface longwave emission (**117 units**) minus latent heat transfer (**23 units**) minus sensible heat transfer (**7 units**) = **-51 units**]. This missing component to the radiation balance is the **51 units** of energy absorbed at the Earth's surface as direct and diffused shortwave radiation (see **Figure 6-1**).

The following equations can be used to mathematically model **net shortwave radiation balance**, **net longwave radiation balance**, and **net radiation balance** for the Earth's surface at a single location or for the whole globe for any temporal period:

$$\begin{aligned}
 K^* &= (K + k)(1 - a) \\
 L^* &= (L_D - L_U) \\
 Q^* &= (K + k)(1 - a) - L_U + L_D
 \end{aligned}$$

where

$Q^*$  is surface **net radiation** (global annual values of  $Q^* = 0$ , because input equals output, local values can be positive or negative),

$K^*$  is surface **net shortwave radiation**,

**K** is surface direct shortwave radiation,

**k** is diffused shortwave radiation (scattered insolation) at the surface,

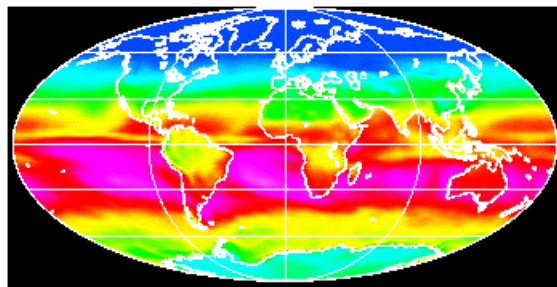
**a** is the albedo of surface,

**L\*** is **net longwave radiation** at the surface,

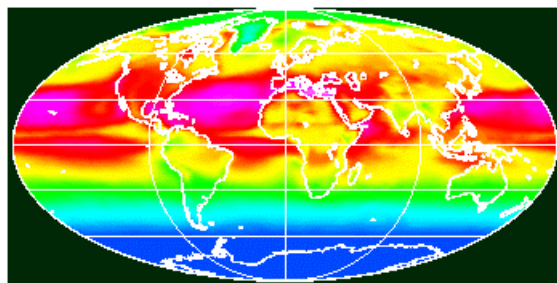
**L<sub>D</sub>** is atmospheric counter-radiation (see Greenhouse Effect) directed to the Earth's surface, and

**L<sub>U</sub>** is longwave radiation lost from the Earth's surface.

NASA's **Surface Radiation Budget Project** has used satellite data, computer models, and meteorological data to determine surface net shortwave radiation, net longwave radiation, and net radiation balances for the period July 1983 to June 1991. The following pictures display these balances for January and July globally:

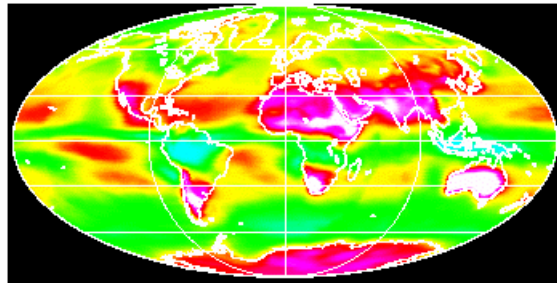


**Figure 6-3:** Average net shortwave radiation at the Earth's surface: January 1984-1991 ( $K^*$ ). Highest values occur along the subtropical oceans of the Southern Hemisphere. Lowest values occur over areas of high surface reflection such as the South Pole, cloudy regions, and areas of low solar input like the high latitudes of the Northern Hemisphere. Color range: blue - red - white, Values: 0 to  $350\text{W/m}^2$ . Global mean =  $162\text{W/m}^2$ , Minimum =  $0\text{W/m}^2$ , Maximum =  $315\text{W/m}^2$ .

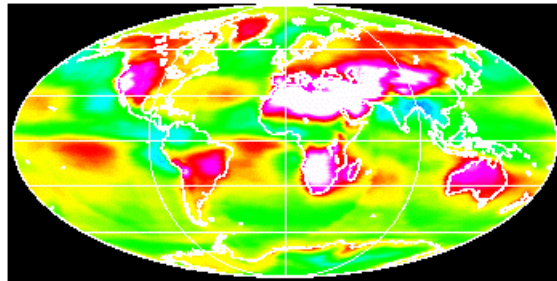


**Figure 6-4:** Average net shortwave radiation at the Earth's surface: July 1983-1990 ( $K^*$ ). Highest values occur over the subtropical oceans of the Northern Hemisphere due to high solar input and little cloud coverage. Lowest values occur in areas of high surface reflection such as snow/ice covered surfaces like Greenland, cloudy regions such as storm tracks, and areas of low solar input like the high latitudes of the

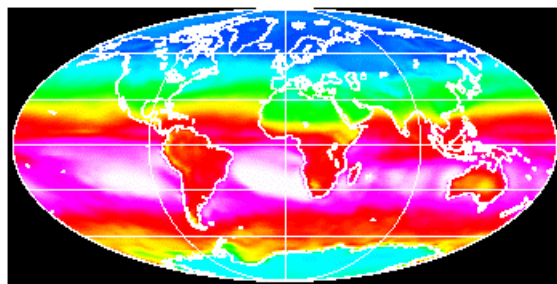
Southern Hemisphere. Color range: blue - red - white, Values: 0 to 350W/m<sup>2</sup>. Global mean = 158W/m<sup>2</sup>, Minimum = 0W/m<sup>2</sup>, Maximum = 323W/m<sup>2</sup>.



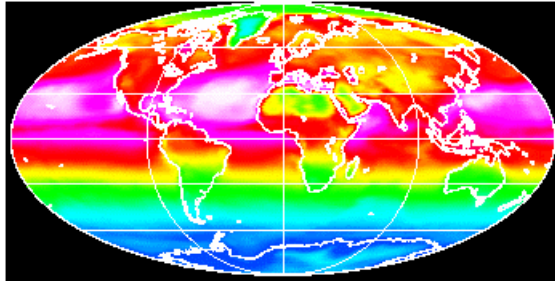
**Figure 6-5:** Average net longwave radiation at the Earth's surface: January 1984-1991, ( $L^*$ ). Net longwave loss is a negative quantity. Highest values of longwave loss occurs where surface temperatures are high and cloud cover is minimal, such as the subtropical deserts of the Northern and Southern Hemisphere. Cold surfaces have low values of loss. Color range: white - red - blue, Values: -100 to 0W/m<sup>2</sup>. Global mean = -48W/m<sup>2</sup>, Minimum = -125W/m<sup>2</sup>, Maximum = -11W/m<sup>2</sup>.



**Figure 6-6:** Average net longwave radiation at the Earth's surface: July 1983-1990 ( $L^*$ ). Net longwave loss is a negative quantity. Highest values of longwave loss occurs where surface temperatures are high and cloud cover is minimal, such as the subtropical deserts of the Northern and Southern Hemisphere. Cold surfaces have low values of loss. Color range: white - red - blue, Values: -100 to 0W/m<sup>2</sup>. Global mean = -47W/m<sup>2</sup>, Minimum = -144W/m<sup>2</sup>, Maximum = -4W/m<sup>2</sup>.



**Figure 6-7:** Average net radiation at the Earth's surface: January 1984-1991( $Q^*$ ). Total net radiation is the sum of shortwave and longwave net radiation. It is dominated by the shortwave portion. Highest values occur along the subtropical oceans of the Southern Hemisphere. Lowest values occur over areas of low solar input such as the North Pole, and areas of high surface reflection such as the South Pole. Color range: blue - red - white, light green = 0 W/m<sup>2</sup>, Values: -50 to 250W/m<sup>2</sup>. Global mean = 114W/m<sup>2</sup>, Minimum = -60W/m<sup>2</sup>, Maximum = 261W/m<sup>2</sup>.



**Figure 6-8:** Average net radiation at the Earth's surface: July 1983-1990 ( $Q^*$ ). Total net radiation is the sum of shortwave and longwave net radiation. It is dominated by the shortwave portion. Highest values occur along the subtropical oceans of the Northern Hemisphere. Lowest values occur over areas of low solar input such as the South Pole, and areas of high surface reflection such as the North Pole. Color range: blue - red - white, light green =  $0 \text{ W/m}^2$ , Values:  $-50$  to  $250 \text{ W/m}^2$ . Global mean =  $111 \text{ W/m}^2$ , Minimum =  $-65 \text{ W/m}^2$ , Maximum =  $249 \text{ W/m}^2$ .

## 7. Global Heat Balance: Introduction to Heat Fluxes

Figure 7-1 illustrates the annual values of net shortwave and net longwave radiation from the South Pole to the North Pole. On closer examination of this graph one notes that the lines representing **incoming** and **outgoing radiation** do not have the same values. From 0 - 30 degrees latitude North and South incoming solar radiation exceeds outgoing terrestrial radiation and a surplus of energy exists. The reverse holds true from 30 - 90 degrees latitude North and South and these regions have a deficit of energy. Surplus energy at low latitudes and a deficit at high latitudes results in energy transfer from the equator to the poles. It is this meridional transport of energy that causes atmospheric and oceanic circulation. If there were no energy transfer the poles would be 25 degrees Celsius cooler, and the equator 14 degrees Celsius warmer!

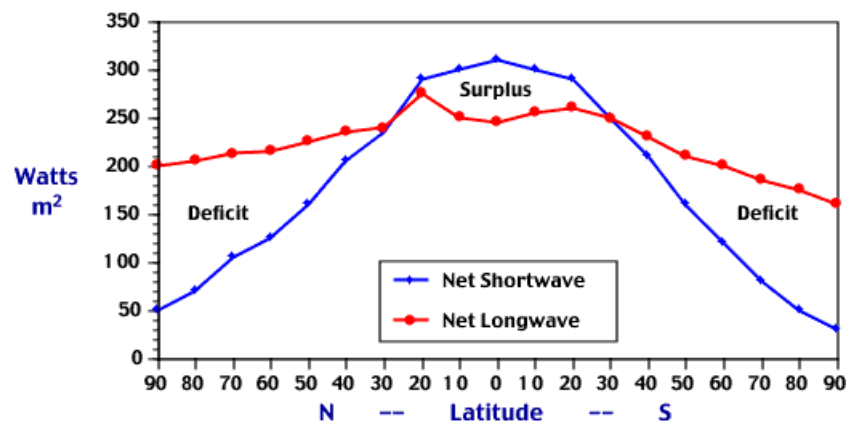


Figure 7-1: Balance between average net shortwave and longwave radiation from 90 degrees North to 90 degrees South

The redistribution of energy across the Earth's surface is accomplished primarily through three processes: sensible heat flux, latent heat flux, and surface heat flux into oceans. Sensible heat flux is the process where heat energy is transferred from the Earth's surface to the atmosphere by conduction and convection. This energy is then moved from the tropics to the poles by advection, creating atmospheric circulation. As a result, atmospheric circulation moves warm tropical air to the polar regions and cold air from the poles to the equator. Latent heat flux moves energy globally when solid and liquid water is converted into vapor. This vapor is often moved by atmospheric circulation vertically and horizontally to cooler locations where it is condensed as rain or is deposited as snow releasing the heat energy stored within it. Finally, large quantities of radiation energy are transferred into the Earth's tropical oceans. The energy enters these water bodies at the surface when absorbed radiation is converted into heat energy. The warmed surface water is then transferred downward into the water column by conduction and convection. Horizontal transfer of this heat energy from the equator to the poles is accomplished by ocean currents.

The following equation describes the partitioning of heat energy at the Earth's surface:

$$Q^* = H \text{ (Sensible heat)} + L \text{ (Latent heat)} + S \text{ (Surface heat flux into soil or water)}$$

The actual amount of net radiation being partitioned into each one of these components is a function of the following factors:

- Presence or absence of water in liquid and solid forms at the surface.
- Specific heat of the surface receiving the net radiation.
- Convective and conductive characteristics of the receiving surface.
- Diffusion characteristics of the surface's overlying atmosphere.

## 8. The Concept of Temperature

### Temperature and Heat

Temperature and heat are not the same phenomenon. Temperature is a measure of the intensity or degree of hotness in a body. Technically, it is determined by getting the average speed of a body's molecules. Heat is a measure of the quantity of heat energy present in a body. The spatial distribution of temperature in a body determines heat flow. Heat always flows from warmer to colder areas.

The heat held in an object depends not only on its temperature but also its mass. For example, let us compare the heating of two different masses of water (**Table 8-1**). In this example, one mass has a weight of 5 grams, while the other is 25 grams. If the temperature of both masses is raised from 20°C to 25°C, the larger mass of water will require five times more heat energy for this increase in temperature. This larger mass would also contain 5 times more stored heat energy.

**Table 8-1:** Heat energy required to raise two different quantities of water 5 degrees Celsius.

Mass of the Water	Starting Temperature	Ending Temperature	Heat Required
5 grams	20 degrees Celsius	25 degrees Celsius	25 Calories of Heat
25 grams	20 degrees Celsius	25 degrees Celsius	125 Calories of Heat

### Temperature Scales

A number of measurement scales have been invented to measure temperature. **Table 9-2** describes important temperatures for the three dominant scales in use today.

**Table 8-2:** Temperature of absolute zero, the ice point of water, and the steam point of water using various temperature measurement scales.

Measurement Scale	Steam Point of Water	Ice Point of Water	Absolute Zero
<b>Fahrenheit</b>	<b>212</b>	<b>32</b>	<b>-460</b>
<b>Celsius</b>	<b>100</b>	<b>0</b>	<b>-273</b>
<b>Kelvin</b>	<b>373</b>	<b>273</b>	<b>0</b>

The most commonly used scale for measuring temperature is the Celsius system. The Celsius scale was developed in 1742 by the Swedish astronomer Anders Celsius. In this system, the melting point of ice was given a value of 0, the boiling point of water is 100, and absolute zero is -273. The Fahrenheit system is a temperature scale that is used exclusively in the United States. This system was created by German physicist Gabriel Fahrenheit in 1714. In this scale, the melting point of ice has a value of 32, water boils at 212, and absolute zero has a temperature of -460. The Kelvin scale was proposed by British physicist Lord Kelvin in 1848. This system is often used by scientists because its temperature readings begin at absolute zero and due to the fact that this scale is proportional to the amount of heat energy found in an object. The Kelvin scale assigns a value of 273 for the melting temperature of ice, while the boiling point of water occurs at 373.

### Measurement of Air Temperature

A thermometer is a device that is used to measure temperature. Thermometers consist of a sealed hollow glass tube filled with some type of liquid. Thermometers measure temperature by the change in the volume of the liquid as it responds to the addition or loss of heat energy from the environment immediately outside its surface. When heat is added, the liquid inside the thermometer expands. Cooling causes the liquid to contract. Meteorological thermometers are often filled with either alcohol or mercury. Alcohol thermometers are favoured in very cold environments because of this liquid's low freezing point (-112 degrees Celsius).

By international agreement, the nations of the world have decided to measure temperature in a similar fashion. This standardisation is important for the accurate generation of weather maps and forecasts, both of which depend on having data determined in a uniform way. Weather stations worldwide try to determine minimum and maximum temperatures for each and every day. By averaging these two values, daily mean temperatures are also calculated. Many stations also take temperature readings on the hour. Temperature measurements are determined by thermometers designed and approved by the World Meteorological Organisation. These instruments are housed in specially designed instrument shelters that allow for the standardisation of measurements taken anywhere on the Earth (**Figure 8-1** and **Figure 8-2**).



**Figure 8-1:** Well ventilated instrument shelters are used to protect thermometers from precipitation, direct sun, and other physical elements. Construction standardisation of these shelters, by international agreement, guarantees that measurements are comparable in any of the over 15,000 weather stations found worldwide.

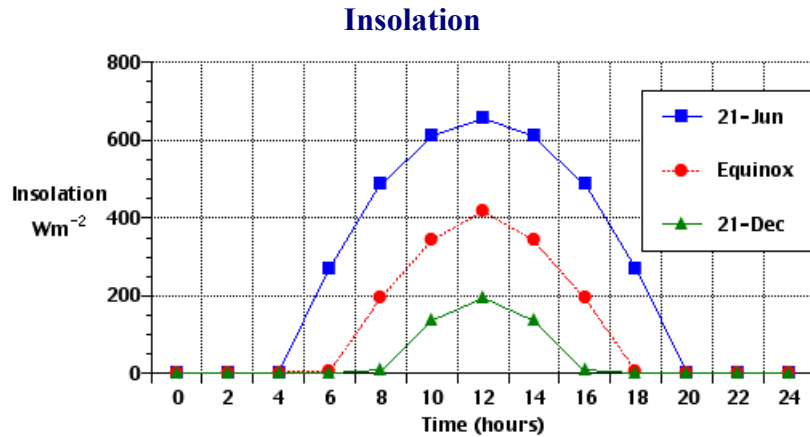


**Figure 8-2:** Thermometers found inside the instrument shelter are mounted approximate 1.5 meters above the ground surface. The top thermometer contains alcohol and is used to determine daily minimum temperatures. The lower thermometer uses mercury to determine the daily maximum temperature.

## 9. Daily and Annual Cycles of Temperature

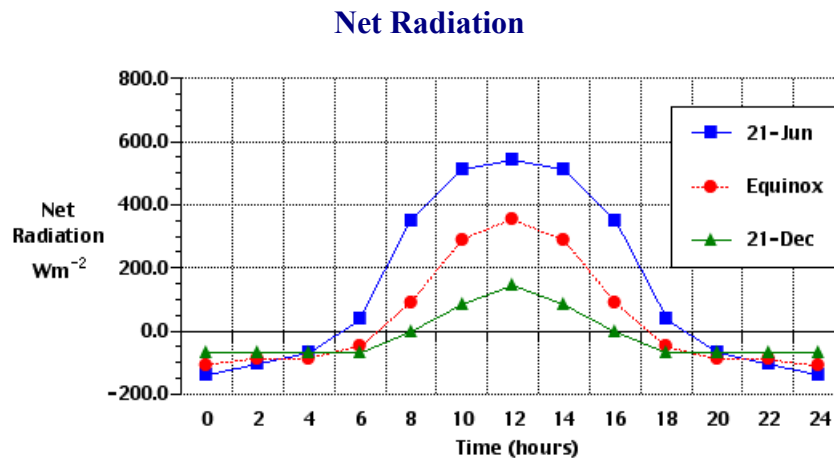
### Daily Cycles of Air Temperature

At the Earth's surface quantities of insolation and net radiation undergo daily cycles of change because the planet rotates on its polar axis once every 24 hours. Insolation is usually the main positive component making up net radiation. Variations in net radiation are primarily responsible for the particular patterns of rising and falling air temperature over a 24 hour period. The following three **graphs** show hypothetical average curves of **insolation**, **net radiation**, and **air temperature** for a typical land based location at 45 degrees of latitude on the equinoxes and solstices (**Figures 9-1, 9-2, and 9-3**).



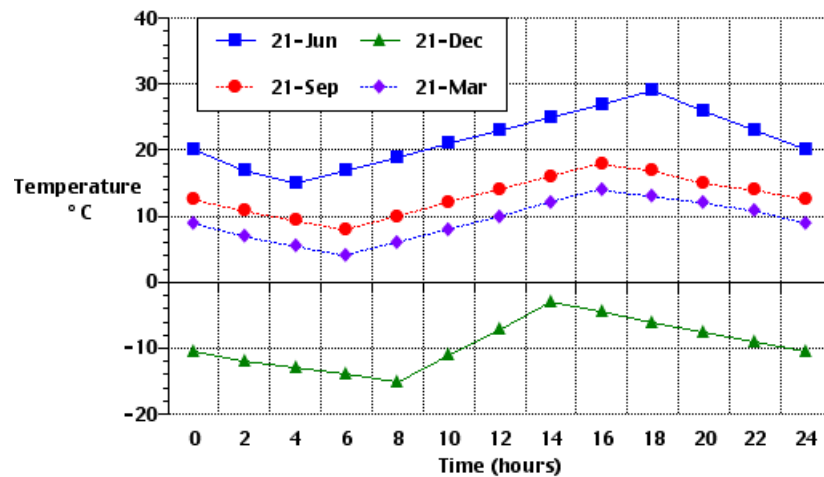
**Figure 9-1:** Hourly variations in insolation received for a location at 45 degrees North latitude over a 24 hour period.

In the above graph, shortwave radiation received from the sun is measured in Watts. For all dates, peak reception occurs at solar noon when the sun attains its greatest height above the horizon.



**Figure 9-2:** Hourly variations in net radiation for a location at 45 degrees North latitude over a 24 hour period.

## Temperature



**Figure 9-3:** Hourly variations in surface temperature for a location at 45 degrees North latitude over a 24 hour period.

Units in **Figure 9-2** are the same as the insolation graph above. The net radiation graph indicates that there is a surplus of radiation during most of the day and a deficit throughout the night. The deficit begins just before sunset when emitted longwave radiation from the Earth's surface exceeds solar insolation and longwave radiation from the atmosphere.

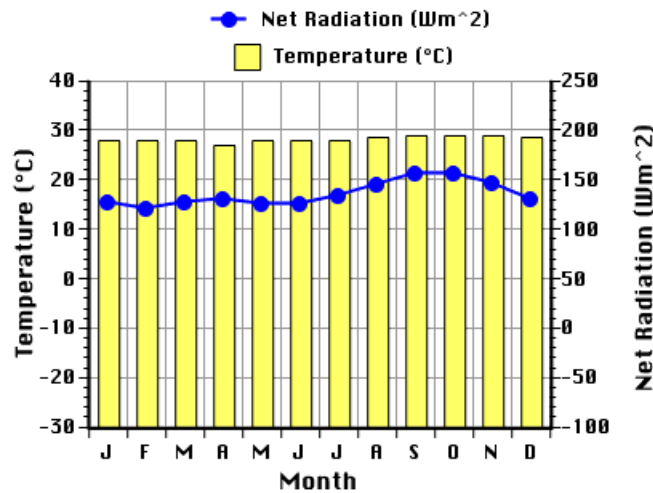
The relative placement of the temperature profiles for the various dates correlates to the amount of net radiation available for daily surface absorption and heat generation. The more energy available, the higher up the Y-axis the profile is on the **graph**. Autumnal equinox (September 21) is warmer than the vernal equinox (March 21) because of the heating that occurred in the previous summer months. For all dates, minimum temperature occurs at **sunrise**. Temperature drops throughout the night because of two processes. First, the Earth's radiation balance at the surface becomes negative after **sunset**. Thus, the surface of the Earth stops heating up as solar radiation is not being absorbed. Secondly, conduction and convection transport heat energy up into the atmosphere and the warm air that was at the surface is replaced by cooler air from above because of atmospheric mixing. Temperature begins rising as soon as the net radiation budget of the surface becomes positive. Temperature continues to rise from sunrise until sometime after solar noon. After this time, mixing of the Earth's surface by convection causes the surface to cool despite the positive addition of radiation and heat energy.

### Annual Cycle of Air Temperature

As the Earth revolves around the sun, locations on the surface may under go seasonal changes in air temperature because of annual variations in the intensity of net radiation. Variations in net radiation are primarily controlled by changes in the intensity and duration of received solar insolation which are driven by variations in daylength and angle of incidence. The discussion below examines how changes in net radiation can effect **mean monthly temperatures** for the following five locations:

- **Manaus**, Brazil, 3 degrees South latitude (**Figure 9-4**).
- **Bulawayo**, Zimbabwe, 20 degrees South latitude (**Figure 9-5**).
- **Albuquerque**, USA, 35 degrees North latitude (**Figure 9-6**).
- **London**, England, 52 degrees North latitude (**Figure 9-7**).
- **Fairbanks**, USA, 65 degrees North latitude (**Figure 9-8**).

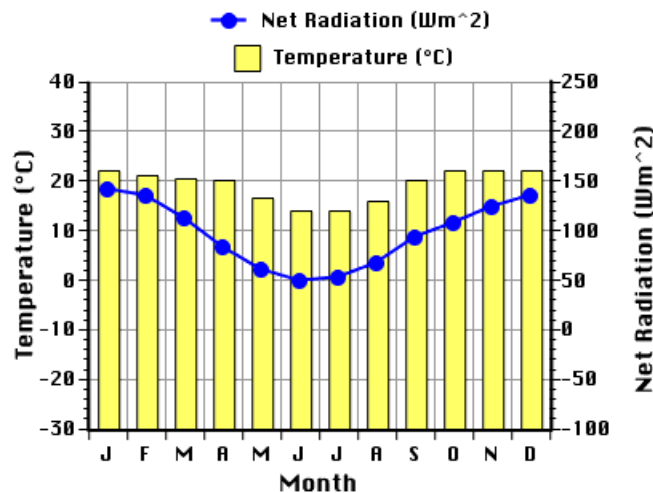
### Manaus, Brazil - 3°South, 60°West



**Figure 9-4:** Monthly variations in net radiation and average monthly temperature for Manaus, Brazil.

At **Manaus**, values of monthly net radiation average about 135 Watts per square meter. Monthly variation in net radiation is only about 35 Watts over the entire year (**Figure 9-4**). Two peaks in net radiation are visible on the graph. Both of these peaks occur during the equinoxes when the height of the sun above the horizon is at its maximum (90 degrees above the horizon). Minimum values of net radiation correspond to the time of the year when the sun reaches its minimum height of only 66.5 degrees above the horizon at solar noon. Because of the consistent nature of net radiation, mean monthly air temperature only varies by 2 degrees Celsius over the entire year.

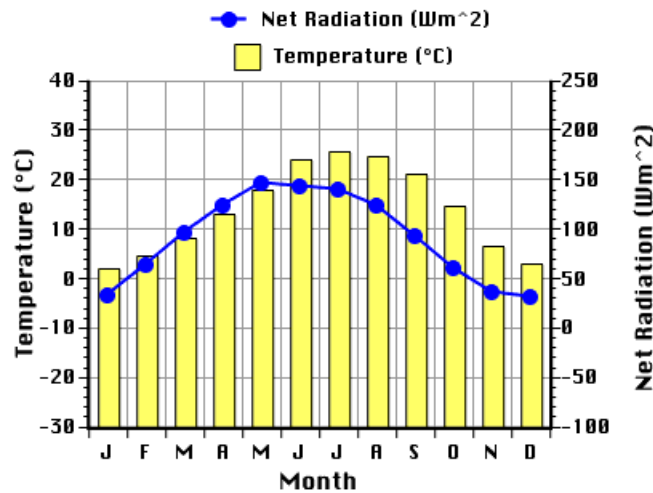
### Bulawayo, Zimbabwe - 20°South, 29°East



**Figure 9-5:** Monthly variations in net radiation and average monthly temperature for Bulawayo, Zimbabwe.

Net radiation at **Bulawayo** has a single peak and trough over the one year period graphed. This pattern is primarily controlled by variations in the intensity and duration of incoming solar insolation (**Figure 9-5**). During the winter solstice the sun reaches its highest altitude above the horizon and daylength is at a maximum (13 hours and 12 minutes). The lowest values of net radiation occur around the summer solstice when the sun reaches its lowest altitude above the horizon and daylength is at a minimum (10 hours and 48 minutes) in the Southern Hemisphere. Monthly temperature variations follow the monthly change in net radiation. Net radiation represents energy available to do work. When received at the Earth's surface much of this energy is used to create sensible heat.

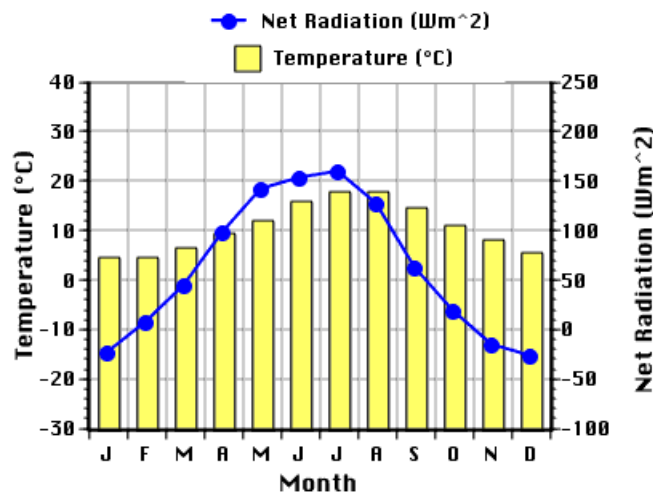
## Albuquerque, USA - 35°North, 107°West



**Figure 9-6:** Monthly variations in net radiation and average monthly temperature for Albuquerque, USA.

At **Albuquerque**, maximum net radiation occurs in May. The timing of this peak roughly coincides with the summer solstice when daylengths are at their longest and solar heights are their greatest (**Figure 9-6**). However, monthly temperature variations do not mirror the changes in net radiation exactly. Peak monthly temperatures occur about two months after the net radiation maximum. This lag is probably caused by the delayed movement of stored heat energy in the ground into the atmosphere. Minimum monthly temperatures do coincide with the lowest values of net radiation which occur during the winter solstice.

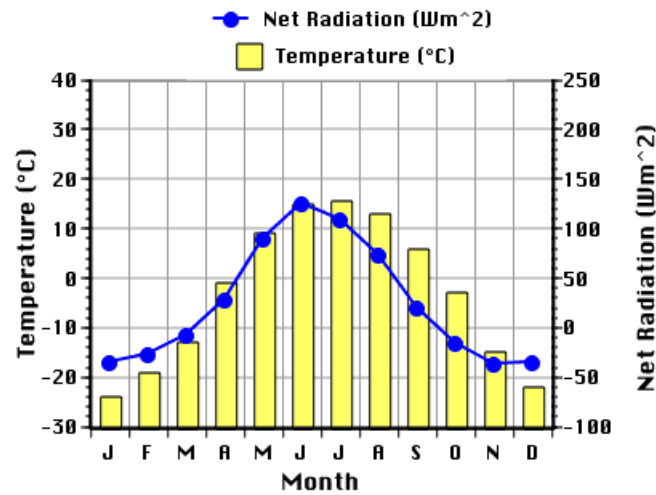
## London, England - 52°North, 1°East



**Figure 9-7:** Monthly variations in net radiation and average monthly temperature for London, England.

The annual patterns of net radiation and mean monthly temperature for **London** are quite similar to those already described for Albuquerque (**Figures 9-6 and 9-7**). London does, however, experience a greater annual variation in net radiation. This greater variation can be explained by the effect increasing latitude has on annual variations of insolation. During the winter months, outgoing longwave radiation actually exceeds incoming insolation producing negative net radiation values. This was not seen in Albuquerque. The variation in monthly mean temperature is also less extreme in London when compared to Albuquerque. Intuitively, one would expect London to have a greater annual change in temperature because of the greater variation in net radiation over the year. However, London's climate is moderated by the frequent addition of latent heat energy from seasonal precipitation.

## Fairbanks, USA - 65°North, 148°West

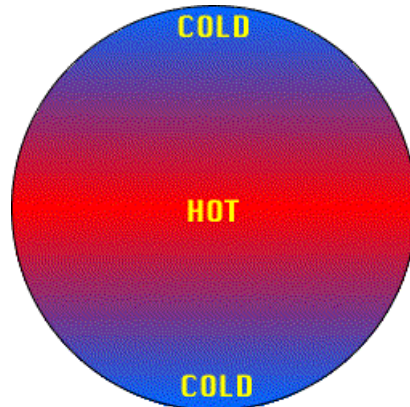


**Figure 9-8:** Monthly variations in net radiation and average monthly temperature for Fairbanks, USA.

Of the five locations examined, **Fairbanks** has the greatest variations in mean monthly temperature. Fairbanks is also the coldest of the climates examined (**Figure 9-8**). This is primarily due to the fact that during six months of the year net radiation is negative because outgoing longwave radiation exceeds incoming insolation. Fairbanks also receives the least cumulative amount of net radiation over the entire year. Mean month temperature is at its maximum in July which is one month ahead of the peak in net radiation.

## 10. Global Surface Temperature Distribution

If the Earth was a homogeneous body without the present land/ocean distribution, its temperature distribution would be strictly latitudinal (**Figure 10-1**). However, the Earth is more complex than this being composed of a mosaic of land and water. This mosaic causes latitudinal zonation of temperature to be disrupted spatially.



**Figure 10-1:** Simple latitudinal zonation of temperature.

The following two factors are important in influencing the distribution of temperature on the Earth's surface:

- The latitude of the location determines how much solar radiation is received. Latitude influences the angle of incidence and duration of daylength.
- Surface properties - surfaces with high albedo absorb less incident radiation. In general, land absorbs less insolation than water because of its lighter colour. Also, even if two surfaces have the same albedo, a surface's specific heat determines the amount of heat energy required for a specific rise in temperature per unit mass. The specific heat of water is some five times greater than that of rock and the land surface (see **Table 10-1** below). As a result, water requires the input of large amounts of energy to cause a rise in its temperature.

**Table 10-1:** Specific Heat of Various Substances.

Substance	Specific Heat
Water	1.00
Air	0.24
Granite	0.19
Sand	0.19
Iron	0.11

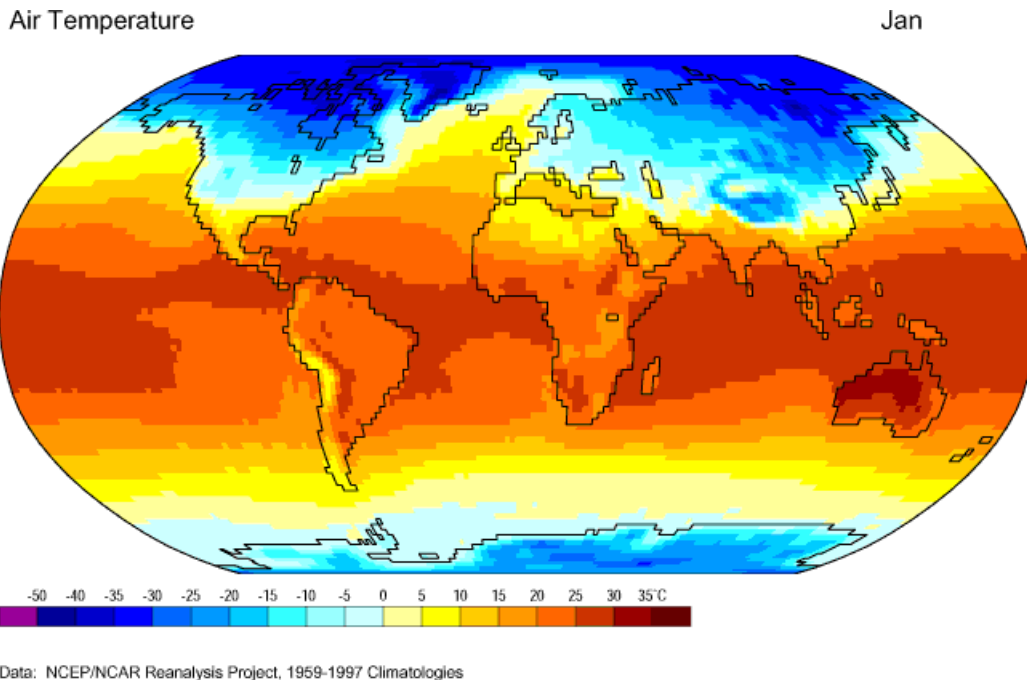
Mainly because of specific heat, land surfaces behave quite differently from water surfaces. In general, the surface of any extensive deep body of water heats more slowly and cools more slowly than the surface of a large land body. Other factors influencing the way land and water surfaces heat and cool include:

- Solar radiation warms an extensive layer in water, on land just the immediate surface is heated.
- Water is easily mixed by the process of convection.
- Evaporation of water removes energy from water's surface.

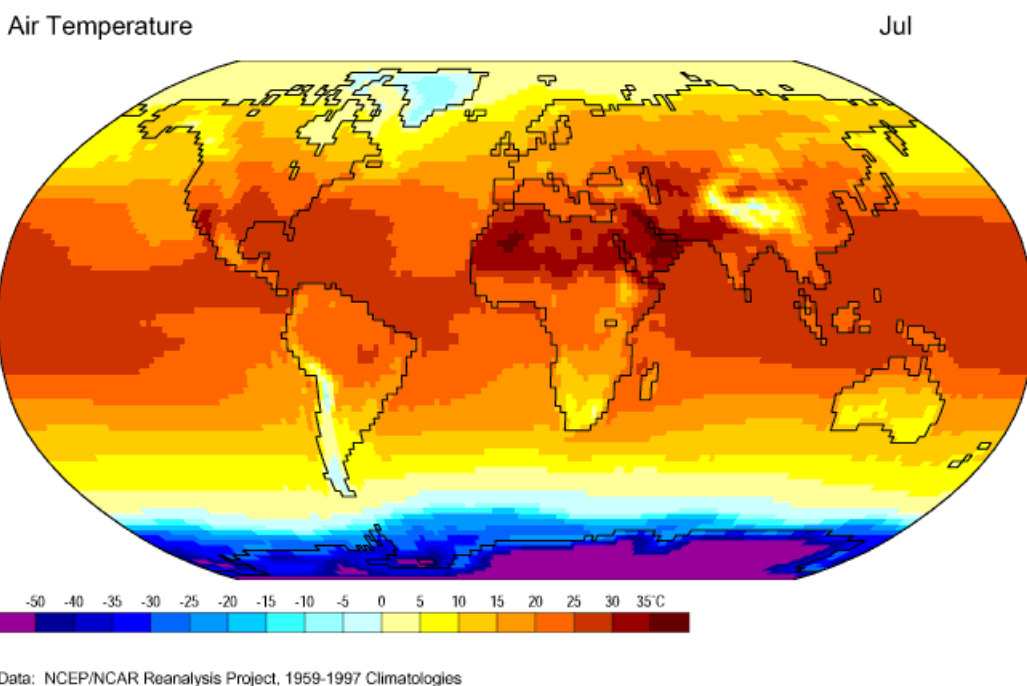
The following images illustrate the Earth's temperature distribution patterns for an average January and July based on 39 years of data (**Figures 10-2** and **10-3**). Note that the spatial variations of temperature on these figures is mostly latitudinal. However, the horizontal banding of isotherms is somewhat upset by the fact that water heats up more slowly in the summer and cools down more slowly in the winter when compared to land surfaces. During January, much of the terrestrial areas of the Northern Hemisphere are below freezing (**Figure 10-2**). Some notable Northern Hemisphere cold-spots include the area around Baffin Island Canada, Greenland, Siberia, and the Plateau of Tibet. Temperatures over oceans tend to be hotter because of the water's ability to hold heat energy.

In the Southern Hemisphere, temperatures over the major landmasses are generally greater than 20 degrees Celsius with localised hot-spots in west-central Australia, the Kalahari Desert in Africa, and the plains of

Bolivia, Paraguay, and Argentina (**Figure 10-2**). Subtropical oceans are often warmer than landmass areas near the equator. At this latitude, land areas receive less incoming solar radiation because of the daily convective development of cumulus and cumulonimbus clouds. In the mid-latitudes, oceans are often cooler than landmass areas at similar latitudes. Terrestrial areas are warmer because of the rapid heating of land surfaces under frequently clear skies. Antarctica remains cold and below zero degrees Celsius due to the presence of permanent glacial ice which reflects much of the solar radiation received back to space.



**Figure 10-2:** Mean January air temperature for the Earth's surface, 1959-1997. (Source of Original Modified Image: Climate Lab Section of the Environmental Change Research Group, University of Oregon).



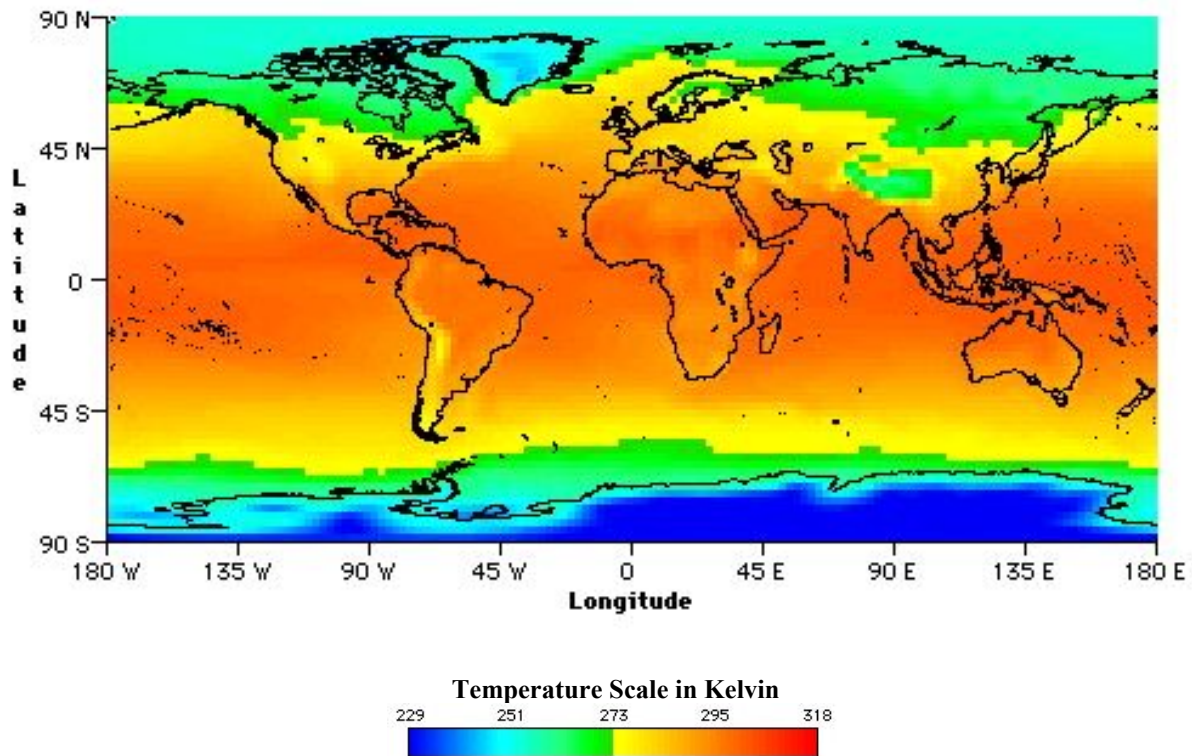
**Figure 10-3:** Mean July air temperature for the Earth's surface, 1959-1997. (Source of Original Modified Image: Climate Lab Section of the Environmental Change Research Group, University of Oregon).

In July, the Northern Hemisphere is experiencing its summer season because the North Pole is now tilted towards the sun (**Figure 10-3**). Some conspicuous hot-spots include the south-central United States, Arizona and northwest Mexico, northern Africa, the Middle East, India, Pakistan, and Afghanistan. Temperatures over oceans tend to be relatively cooler because of the land's ability to heat quickly. Two terrestrial areas of cooler temperatures include Greenland and the Plateau of Tibet. In these regions, most of the incoming solar radiation is sent back to space because of the presence of reflective ice and snow.

In the Southern Hemisphere, temperatures over the major landmasses are generally cooler than ocean surfaces at the same latitude (**Figure 10-3**). Antarctica is bitterly cold because it is experiencing total darkness. Note that Antarctica is much colder than the Arctic was during its winter season (**Figures 10-2 and 10-3**). The Arctic consists mainly of ocean. During the summer, this surface is able to absorb considerable quantities of sunlight which is then converted into heat energy. The heat stored in the ocean is carried over into the winter season. Antarctica has a surface composed primarily of snow and ice. This surface absorbs only a small amount of the solar radiation during the summer. So it never really heats up. As a result, the amount of heat energy stored into the winter season is minimal.

**Figure 10-4** describes average annual global temperature data for the Earth for the period 1982-1994. The patterns of temperature distribution on this figure are once again mostly latitudinal. However, the latitudinal banding is partially upset by the fact that water bodies are generally warmer than land surfaces. The image also shows the effect of altitude (e.g., Himalayas and Andes mountains) and albedo (Greenland and Antarctica) on surface air temperature.

**Average Annual Global Temperature 1982-1994**

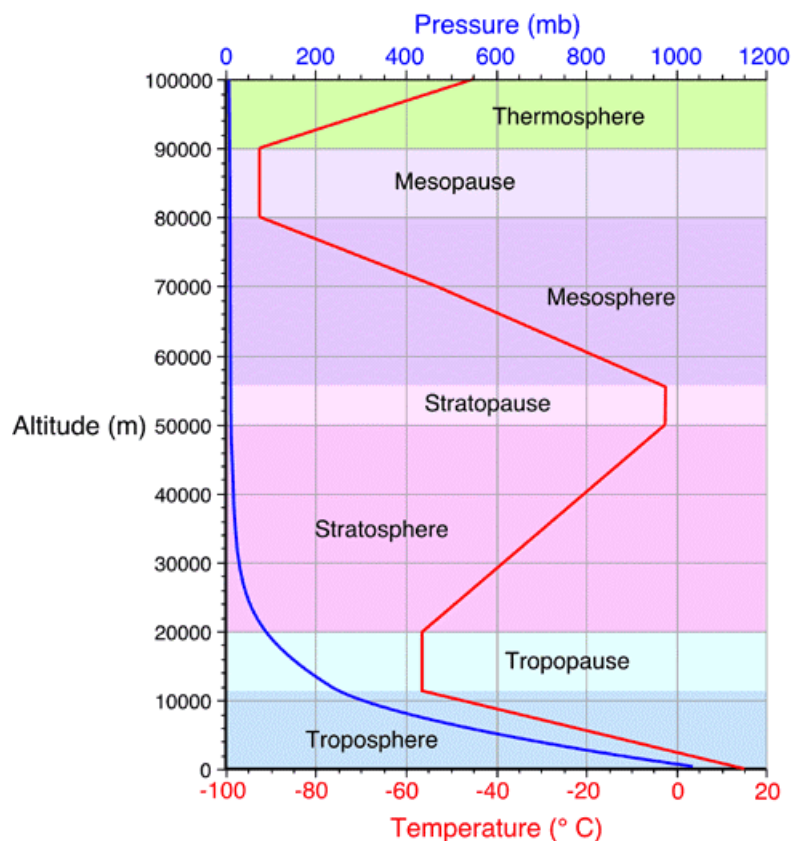


**Figure 10-4:** Average annual temperatures for the Earth's surface (1982-94).

## 11. The Layered Atmosphere

The Earth's atmosphere contains several different layers that can be defined according to air temperature or chemical composition. Figure 2-1 displays some of these layers in an average atmosphere. According to temperature, the atmosphere contains seven different layers (Figure 11-1). From the surface of the Earth to approximately 11 kilometers in altitude the layer called the troposphere exists. About 75 % of the total mass of the atmosphere is contained in this layer. It is also the layer where the majority of our weather occurs. Maximum air temperature also occurs near the Earth's surface in this layer. With increasing height, air temperature drops uniformly with altitude at a rate of approximately 6.5 degrees Celsius per 1000 meters. This phenomenon is commonly called the Environmental Lapse Rate. At an average temperature of -55 degrees Celsius, the top of the troposphere is reached.

The tropopause, extending from 11 to 20 km, is an isothermal layer in the atmosphere where temperature remains constant over a distance of about 9 km. It is also the layer in the atmosphere where the jet streams occur. Above the tropopause, is the stratosphere. This layer extends from an average altitude of 20 to 48 km above the Earth's surface. In the stratosphere, temperature increases with altitude because a localized concentration of ozone gas molecules absorbs ultraviolet sunlight creating heat energy. Ozone is primarily found in the atmosphere at varying concentrations between the altitudes of 10 to 50 km. This layer of ozone is also called the ozone layer. The ozone layer is important to organisms at the Earth's surface as it protects them from the harmful effects of the sun's ultraviolet radiation. Without the ozone layer life could not exist on the Earth's surface.



**Figure 11-1:** Vertical change in average global atmospheric temperature and pressure. Variations in the way temperature changes with height indicates the atmosphere is composed of a number of different layers (labeled above). These variations are due to alterations in the chemical and physical nature of the atmosphere with altitude.

Separating the mesosphere from the stratosphere is another isothermal layer called the stratopause. In the mesosphere, the atmosphere reaches its coldest temperatures (about  $-90^{\circ}\text{C}$ ) at a height of approximately 80 kilometers. Above the mesosphere is another isothermal layer called the mesopause.

The last atmospheric layer, as defined by vertical temperature change, has an altitude greater than 90 km and is called the thermosphere. The thermosphere is the hottest layer in the atmosphere. Heat is generated from the absorption of solar radiation by oxygen molecules. Temperatures in this layer can reach 1300 to  $1800^{\circ}\text{C}$ .

## 12. Physical Behaviour of the Atmosphere and the Gas Laws

In the 3<sup>rd</sup> chapter was said that the atmosphere is composed of a mixture of many different gases. This mixture behaves in many ways as if it were a single gas. As a result of this phenomenon, the following generalisations describe important relationships between temperature, pressure, density and volume, that relate to the Earth's atmosphere

1) When temperature is held constant, the density of a gas is proportional to pressure, and volume is inversely proportional to pressure. Accordingly, an increase in pressure will cause an increase in density of the gas and a decrease in its volume.

(2) If volume is kept constant, the pressure of a unit mass of gas is proportional to temperature. If temperature increase so will pressure, assuming no change in the volume of the gas.

(3) Holding pressure constant, causes the temperature of a gas to be proportional to volume, and inversely proportional to density. Thus, increasing temperature of a unit mass of gas causes its volume to expand and its density to decrease as long as there is no change in pressure.

These relationships can also be described mathematically by the Ideal Gas Law. Two equations that are commonly used to describe this law are:

$$\text{Pressure} \times \text{Volume} = \text{Constant} \times \text{Temperature}$$

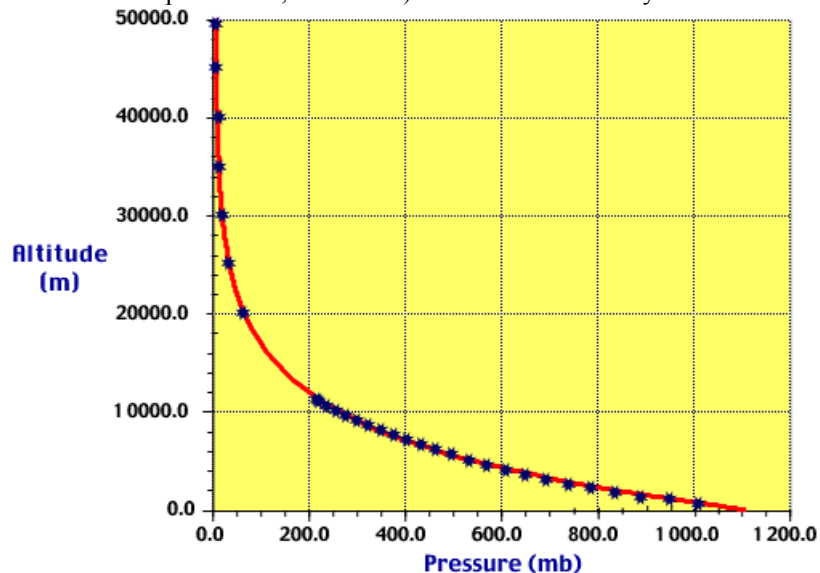
and

$$\text{Pressure} = \text{Density} \times \text{Constant} \times \text{Temperature}$$

## 13. Atmospheric Pressure

### Introduction

Air is a tangible material substance and as a result has mass. Any object with mass is influenced by the universal force known as gravity. Newton's **Law of Universal Gravitation** states: any two objects separated in space are attracted to each other by a force proportional to the product of their masses and inversely proportional to the square of the distance between them. On the Earth, gravity can also be expressed as a force of acceleration of about 9.8 meters per second per second. As a result of this force, any object falling towards the surface of the Earth accelerates at an accelerating rate (1st second - 9.8 meters per second, 2nd second - 19.6 meters per second, 3rd second - 29.4 meters per second, and so on.) until terminal velocity is attained.

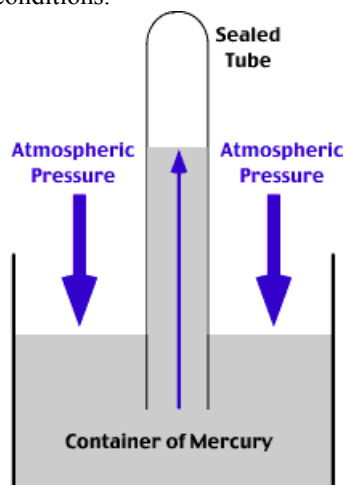


**Figure 13-1:** Change in average atmospheric pressure with altitude.

Gravity shapes and influences all atmospheric processes. It causes the density and pressure of air to decrease exponentially as one moves away from the surface of the Earth. **Figure 13-1** models the average change in air pressure with height above the Earth's surface. In this graph, air pressure at the surface is illustrated as being approximately 1013 millibars (**mb**) or 1 kilogram per square centimeter of surface area.

### Measuring Atmospheric Pressure

Any instrument that measures air pressure is called a **barometer**. The first measurement of atmospheric pressure began with a simple experiment performed by **Evangelista Torricelli** in 1643. In his experiment, Torricelli immersed a tube, sealed at one end, into a container of mercury (see **Figure 13-2** below). Atmospheric pressure then forced the mercury up into the tube to a level that was considerably higher than the mercury in the container. Torricelli determined from this experiment that the pressure of the atmosphere is approximately 30 inches or 76 centimeters (one **cm** of mercury is equal to 13.3 **mb**). He also noticed that height of the mercury varied with changes in outside weather conditions.

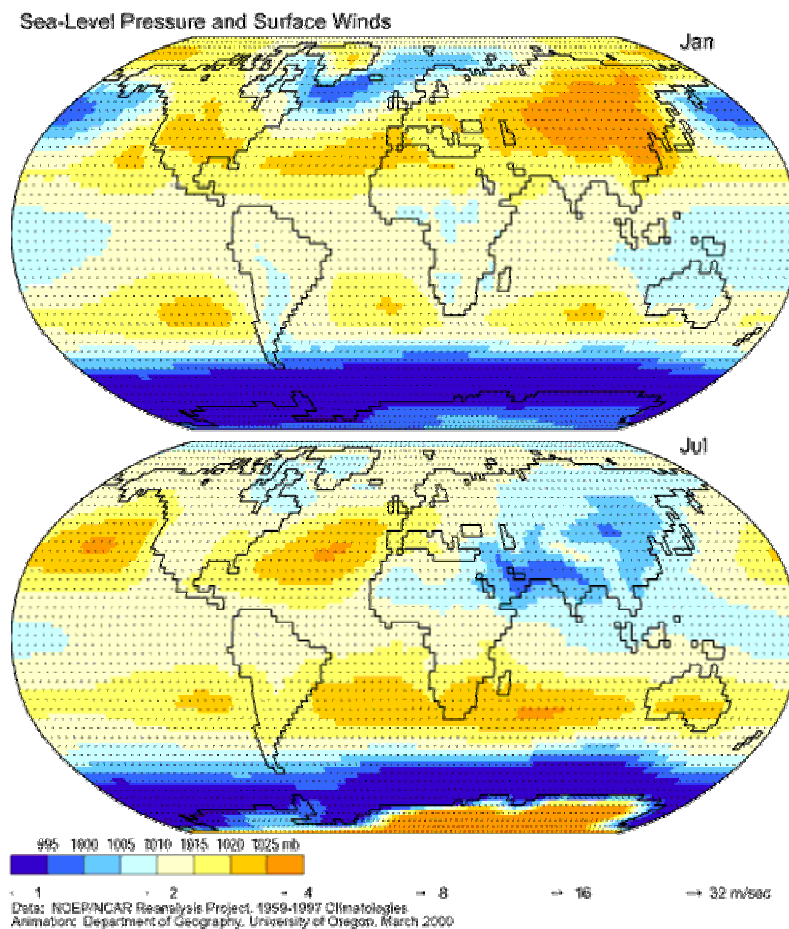


**Figure 13-2:** Diagram showing the construction of Torricelli's barometer.

The most common type barometer used in homes is the **aneroid barometer** (Figure 13-3). Inside this instrument is a small, flexible metal capsule called an aneroid cell. In the construction of the device, a vacuum is created inside the capsule so that small changes in outside air pressure cause the capsule to expand or contract. The size of the aneroid cell is then calibrated and any change in its volume is transmitted by springs and levers to an indicating arm that points to the corresponding atmospheric pressure.



**Figure 13-3:** Aneroid barometer.



**Figure 13-4:** Monthly average sea-level pressure and prevailing winds for the Earth's surface, 1959-1997

For climatological and meteorological purposes, standard sea-level pressure is said to be 76.0 cm or 29.92 inches or 1013.2 millibars. Scientists often use the kilopascal (**kPa**) as their preferred unit for measuring pressure. 1 kilopascal is equal to 10 millibars.

#### **Atmospheric Pressure at the Earth's Surface**

**Figure 13-4** describes average sea-level pressure for the Earth's surface. This animation indicates that surface air pressure varies both spatially and temporally. During the winter months (January), areas of high pressure develop over central Asia (**Siberian High**), off the coast 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 to 80 degrees South.

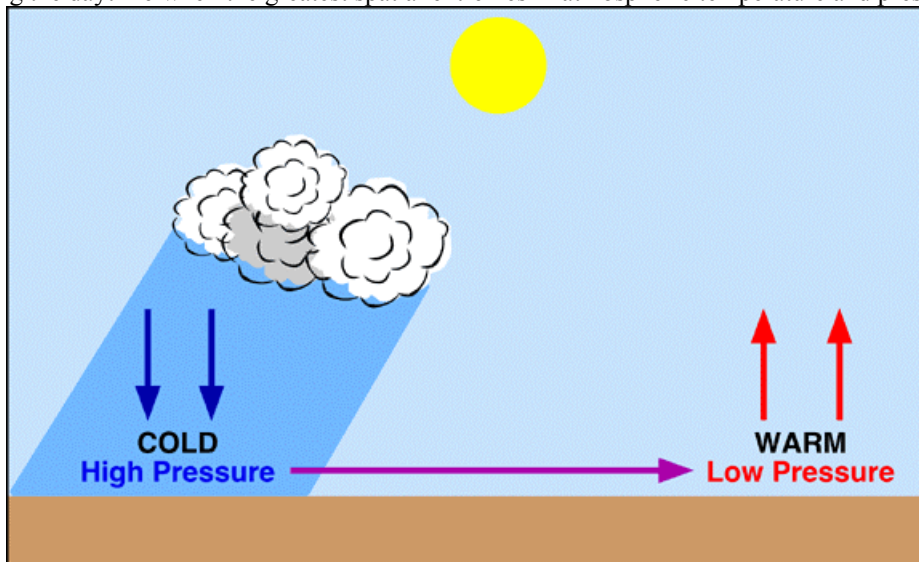
During the summer months (July), a number of dominant winter pressure systems disappear. Gone are the **Siberian High** over central Asia and the dominant low pressure systems near the Aleutian Islands and at the southern tip of Greenland. The **Hawaiian** and **Azores High** intensify and expand northward into their relative ocean basins. High pressure systems over the subtropical oceans in Southern Hemisphere also intensify and expand to the north. 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**). These pressure systems are responsible for the summer monsoon rains of Asia.

## 14. Forces Acting to Create Wind

### Introduction

Wind can be defined simply as air in motion. This motion can be in any direction, but in most cases the horizontal component of wind flow greatly exceeds the flow that occurs vertically. The speed of wind varies from absolute calm to speeds as high as 380 kilometers per hour (Mt. Washington, New Hampshire, April 12, 1934). In 1894, strong winds in Nebraska pushed six fully loaded coal cars over 160 kilometers in just over three hours. Over short periods of time surface winds can be quite variable.

Wind develops as a result of spatial differences in atmospheric pressure. Generally, these differences occur because of uneven absorption of solar radiation at the Earth's surface (**Figure 14-1**). Wind speed tends to be at its greatest during the daytime when the greatest spatial extremes in atmospheric temperature and pressure exist.



**Figure 14-1:** Formation of wind as a result of localized temperature differences.

Wind is often described by two characteristics: wind speed and wind direction. Wind speed is the velocity attained by a mass of air traveling horizontally through the atmosphere. Wind speed is often measured with an anemometer in kilometers per hour (kmph), miles per hour (mph), knots, or meters per second (mps) (**Fig. 14-2**).



**Figure 14-2:** Meteorological instruments used to measure wind speed and direction.

Wind direction is measured as the direction from where a wind comes from. For example, a southerly wind comes from the south and blows to the north. Direction is measured by an instrument called a wind vane (Figure 7n-2). Both of these instruments are positioned in the atmospheric environment at a standard distance of 10 meters above the ground surface. Wind speed can also be measured without the aid of instruments using the

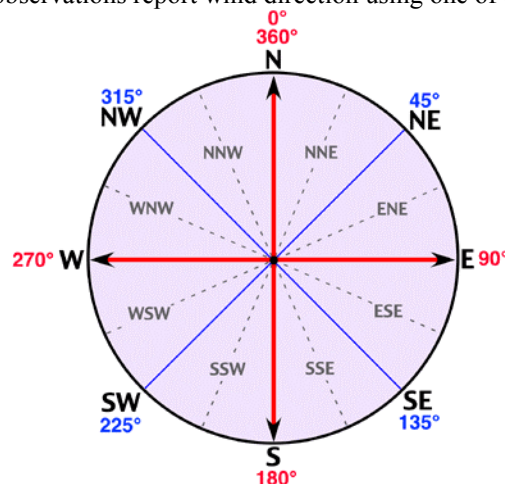
Beaufort wind scale (**Table 14-1**). This descriptive scale was originally developed by Admiral Beaufort of the British Navy in the first decade of the 17th century. The purpose for this system was to allow mariners to determine wind speed from simple observations. The Beaufort system has undergone several modifications to standardise its measurement scale and to allow for its use on land. Users of this scale look for specific effects of the wind on the environment to determine speed.

Wind speed is commonly measured with an anemometer. An anemometer consists of three open cups attached to a rotating spindle. The speed of rotation is then converted into a measurement of wind speed. Wind direction is measured with a wind vane. On the photograph above, the wind vane instrument has a bullet shaped nose attached to a finned tail by a metal bar.

**Table 14-1:** Beaufort wind speed scale.

Beaufort Code	Speed Miles per Hour	Speed Kilometers Per Hour	Description	Effects on the Environment
0	< 1	< 1	calm	smoke rises vertically
1	2 - 3	1 - 5	light air	smoke drifts slowly
2	4 - 7	6 - 11	light breeze	leaves rustle, wind can be felt, wind vanes move
3	8 - 12	12 - 19	gentle breeze	leaves and twigs on trees move
4	13 - 18	20 - 29	moderate breeze	small tree branches move, dust is picked up from the ground surface
5	19 - 24	30 - 38	fresh breeze	small trees move
6	25 - 31	39 - 51	strong breeze	large branches move, telephone and power overhead wires whistle
7	32 - 38	51 - 61	near gale	trees move, difficult to walk in the wind
8	39 - 46	62 - 74	gale	twigs break off from trees
9	47 - 54	75 - 86	strong gale	branches break off from trees, shingles blown off roofs
10	55 - 63	87 - 101	whole gale	trees become uprooted, structural damage on buildings
11	64 - 74	102 - 120	storm	widespread damage to buildings and trees
12	> 75	> 120	hurricane	severe damage to buildings and trees

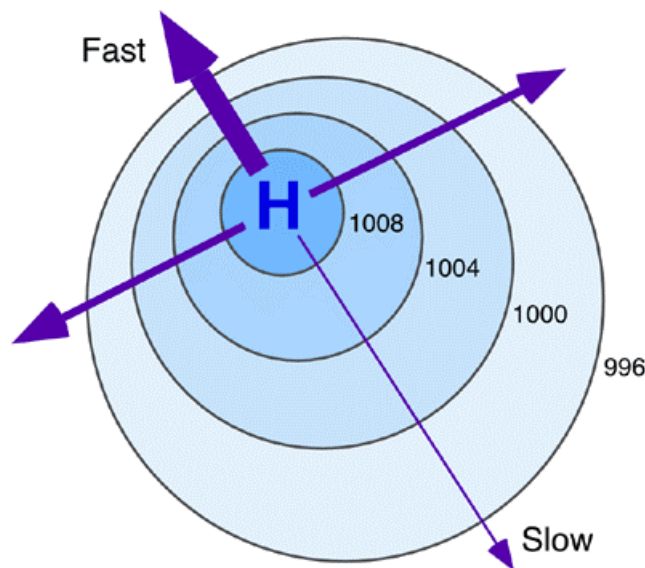
Winds are named according to the compass direction of their source. Thus, a wind from the north blowing toward the south is called a northerly wind. **Figure 14-3** describes the sixteen principal bearings of wind direction. Most meteorological observations report wind direction using one of these sixteen bearings.



**Figure 14-3:** Wind compass describing the sixteen principal bearings used to measure wind direction. This compass is based on the 360 degrees found in a circle.

Horizontally, at the Earth's surface wind always blows from areas of high pressure to areas of low pressure (vertically, winds move from areas of low pressure to areas of high pressure), usually at speeds determined by the rate of air pressure change between pressure centers. This situation is comparable to someone skiing down a hill. The skier will of course move from the top of the hill to the bottom of the hill, with the speed of their descent controlled by the gradient or steepness of the slope. Likewise, wind speed is a function of the steepness or gradient of atmospheric air pressure found between high and low pressure systems. When expressed scientifically, pressure change over a unit distance is called pressure gradient force, and the greater this force the faster the winds will blow.

On weather maps, pressure is indicated by drawing isolines of pressure, called isobars, at regular 4 millibar intervals (e.g., 996 mb, 1000 mb, 1004 mb, etc.). If the isobars are closely spaced, we can expect the pressure gradient force to be great, and wind speed to be high (see **Figure 14-4**). In areas where the isobars are spaced widely apart, the pressure gradient is low and light winds normally exist. High speed winds develop in areas where isobars are closer.



**Figure 14-4:** Association between wind speed and distance between isobars. In the illustration above thicker arrows represent relatively faster winds.

### Driving Forces

To better understand wind we must recognise that it is the result of a limited number of accelerating and decelerating forces, and that the action of these forces is controlled by specific fundamental natural laws. Sir Isaac Newton formulated these laws as several laws of motion. The first law suggests that an object that is stationary will remain stationary, and an object in motion will stay in motion as long as no opposing force is put on the object. As a result of this law, a puck sent in flight from a blade of a hockey stick will remain in motion until friction slows it down or the goalie makes a save. This law also suggests that once in motion an object's path should be straight.

Newton's second law of motion suggests that the force put on an object equals its mass multiplied by the acceleration produced. The term force in this law refers to the total or net effect of all the forces acting on an object. Mathematically, this law is written as:

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

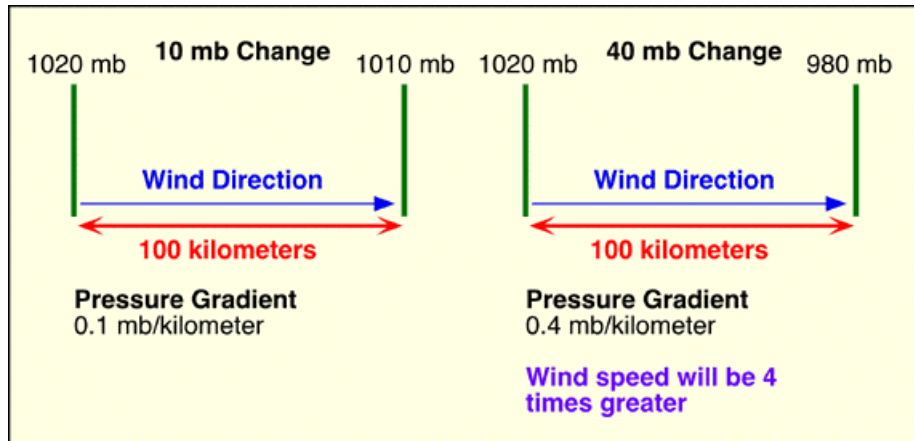
or

$$\text{Acceleration} = \text{Force}/\text{Mass}$$

From this natural law of motion we can see that the acceleration of an object is directly proportional to the net force pushing or pulling that body and inversely proportional to the mass of the body. Thus, the greater the force created by the movement of a hockey player's stick the faster the puck will travel. This law also suggests that if the player used a larger (more massive) puck more force would have to be applied to it to get it to travel as fast as a less massive puck.

In the previous lecture we briefly examined one of the forces, pressure gradient force, acting on wind. Let us return to this force and examine it in greater detail and in relation to Newton's laws of motion. We will also examine the effects of three other forces that act on air in motion.

Pressure gradient force is the primary force influencing the formation of wind from local to global scales. This force is determined by the spatial pattern of atmospheric pressure at any given moment in time. Figure 12-5 illustrates two different pressure gradient scenarios and their relative effect on wind speed.



**Figure 14-5:** Effect of pressure gradient on wind speed.

The two diagrams display the relative relationship between pressure gradient and wind speed. This relationship is linear and positive. As a result, quadrupling the pressure gradient increases wind speed by a factor of four. This is what we would expect according to Newton's second law of motion, assuming the mass of the wind is unchanged.

We can also describe pressure gradient acceleration mathematically with the following equation:

$$F(ms^{-1}) = \left| \frac{1}{D} \cdot \left( \frac{P_1 - P_2}{n} \right) \right|$$

where:

**D** = density of air (average density of surface air is 1.29 kilograms per cubic meter)

**P<sub>2</sub>** = pressure at point 2 in newtons

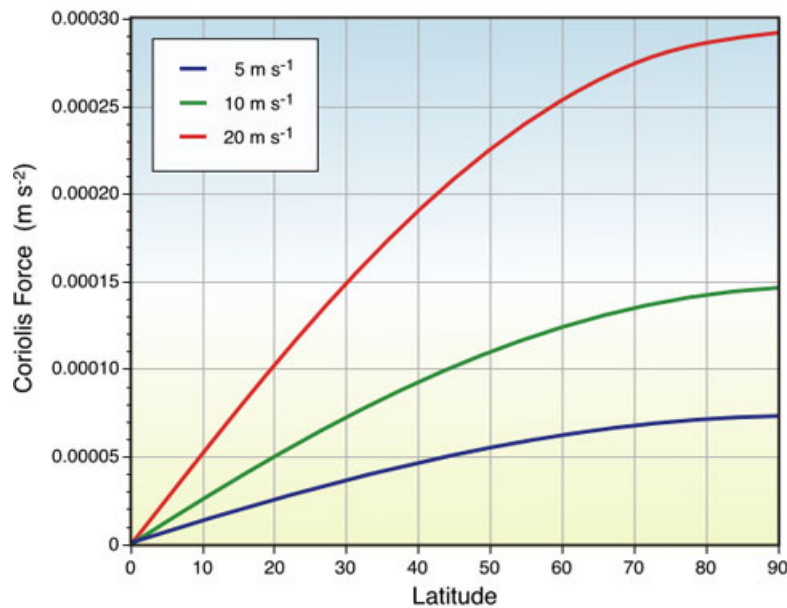
**P<sub>1</sub>** = pressure at point 1 in newtons

**n** = distance between the two points in meters

From this equation we can determine the speed of moving air between two points in meters per second by knowing three variables: the density of the moving air; the change in pressure between the points of interest in newtons; and the distance between the two points in meters. For example, to determine the wind speed between two points for moving air with a density of 1.29 kilograms per cubic meter, a pressure difference of 400 newtons, and a distance of 300,000 meters, the following calculations would be performed:

$$F(ms^{-1}) = \left| \frac{1}{1.29} \cdot \left( \frac{400}{300\,000} \right) \right| = 0.00103 \, ms^{-1}$$

The rotation of the Earth creates another force, termed Coriolis force, which acts upon wind and other objects in motion in very predictable ways. According to Newton's first law of motion, air will remain moving in a straight line unless it is influenced by an unbalancing force. The consequence of Coriolis force opposing pressure gradient acceleration is that the moving air changes direction. Instead of wind blowing directly from high to low pressure, the rotation of the Earth causes wind to be deflected off course. In the Northern Hemisphere, wind is deflected to the right of its path, while in the Southern Hemisphere it is deflected to the left. The magnitude of the Coriolis force varies with the velocity and the latitude of the object (see **Figure 14-6**). Coriolis force is absent at the equator, and its strength increases as one approaches either pole. Furthermore, an increase in wind speed also results in a stronger Coriolis force, and thus in greater deflection of the wind. Coriolis force only acts on air when it has been sent into motion by pressure gradient force. Finally, Coriolis force only influences wind direction and never wind speed.



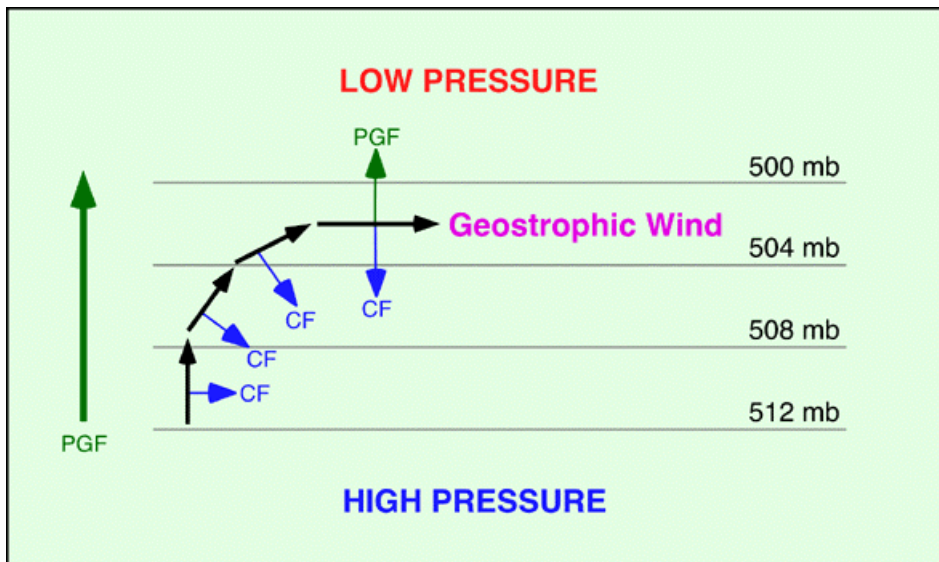
**Figure 14-6:** The strength of Coriolis force is influenced by latitude and the speed of the moving object.

Centripetal acceleration is the third force that can act on moving air. It acts only on air that is flowing around centers of circulation. Centripetal acceleration is also another force that can influence the direction of wind. Centripetal acceleration creates a force directed at right angles to the flow of the wind and inwards towards the centers of rotation (e.g., low and high pressure centers). This force produces a circular pattern of flow around centers of high and low pressure. Centripetal acceleration is much more important for circulations smaller than the mid-latitude cyclone.

The last force that can influence moving air is frictional deceleration. Friction can exert an influence on wind only after the air is in motion. Frictional drag acts in a direction opposite to the path of motion causing the moving air to decelerate (see Newton's first and second laws of motion). Frictional effects are limited to the lower one kilometer above the Earth's surface.

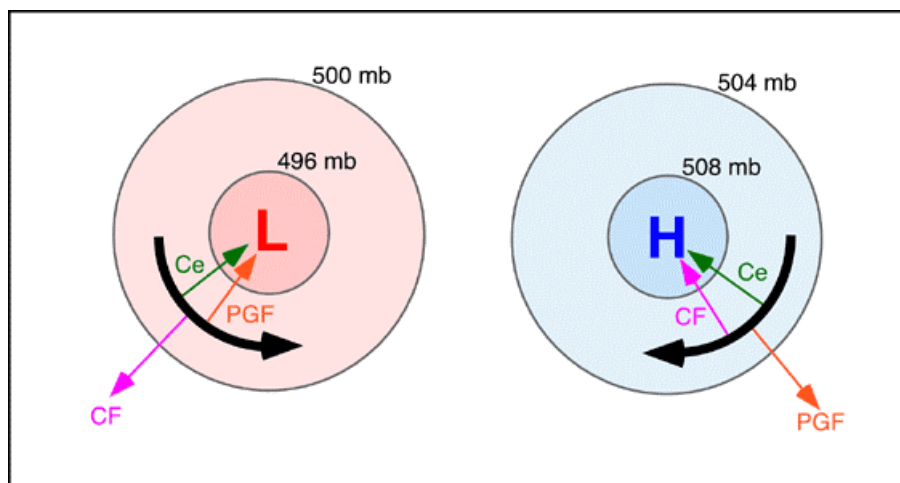
### Geostrophic Wind

Air under the influence of both the pressure gradient force and Coriolis force tends to move parallel to isobars in conditions where friction is low (1000 meters above the surface of the Earth) and isobars are straight. Winds of this type are usually called geostrophic winds. Geostrophic winds come about because pressure gradient force and Coriolis force come into balance after the air begins to move (**Figure 14-7**).



**Figure 14-7:** A geostrophic wind flows parallel to the isobars. In this model of wind flow in the Northern Hemisphere, wind begins as a flow of air perpendicular to the isobars (measured in millibars) under the primary influence of the pressure gradient force (PGF). As the movement begins, the Coriolis force (CF) begins to influence the moving air causing it to deflect to the right of its path. This deflection continues until the pressure gradient force and Coriolis force are opposite and in balance with each other.

**Figure 14-7** models air flow in the Northern Hemisphere. In the Southern Hemisphere, Coriolis acceleration acts on moving air by deflecting it to the left instead of the right. Finally, Buys Ballot's Law states that when you stand with your back to a geostrophic wind in the Northern Hemisphere the center of low pressure will be to your left and the high pressure to your right. The opposite is true for the Southern Hemisphere.



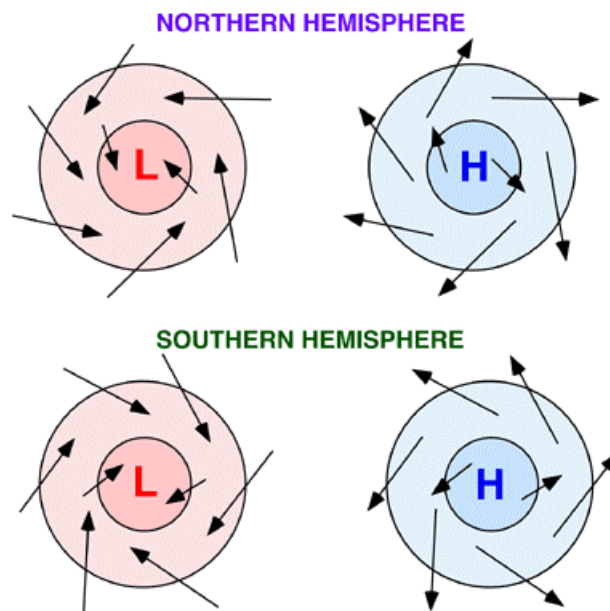
**Figure 14-8:** The balance of forces that create a gradient wind in the Northern Hemisphere (PGF = pressure gradient force; CF = Coriolis force; Ce = centripetal force). In this diagram,  $CF = Ce + PGF$  for the low, and  $PGF = CF + Ce$  for the high.

### Gradient Wind

Wind above the Earth's surface does not always travel in straight lines. In many cases winds flow around the curved isobars of a high (anticyclone) or low (cyclone) pressure center. A wind that blows around curved isobars above the level of friction is called a gradient wind. Gradient winds are slightly more complex than geostrophic winds because they include the action of yet another physical force. This force is known as centripetal force and it is always directed toward the center of rotation. The following figure describes the forces that produce gradient winds around high and low pressure centers (**Figure 14-8**). Around a low, the gradient wind consists of the pressure gradient force and centripetal force acting toward the center of rotation, while Coriolis force acts away from the center of the low. In a high pressure center, the Coriolis and centripetal forces are directed toward the center of the high, while the pressure gradient force is directed outward.

### Friction Layer Wind

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 degrees. Close to the Earth's surface, friction reduces the wind speed, which in turn reduces the Coriolis force. As a result, the reduced Coriolis force 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 force. Thus, we find surface winds blowing counterclockwise and inward into a surface low, and clockwise and out of a surface high in the Northern Hemisphere. In the Southern Hemisphere, the Coriolis force 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 (see **Figure 14-9** below).

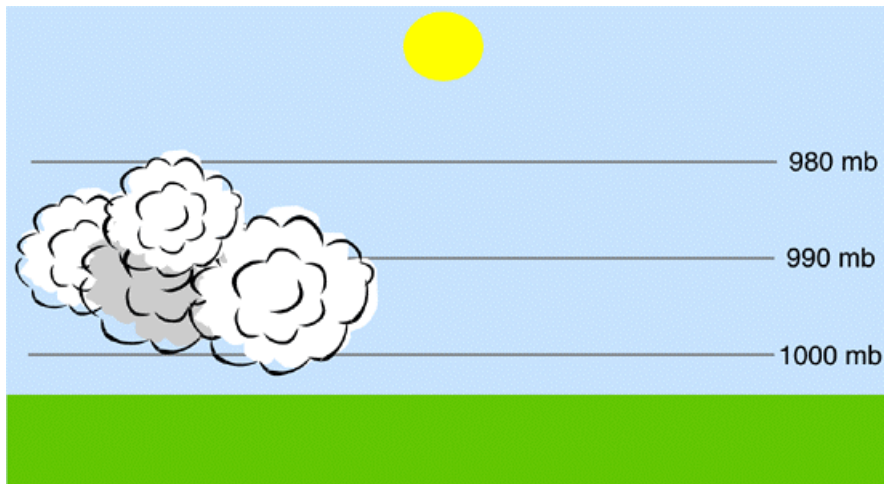


**Figure 14-9:** Circulation patterns of high and low pressure systems in the North and South Hemisphere.

## 15. Local and Regional Wind Systems

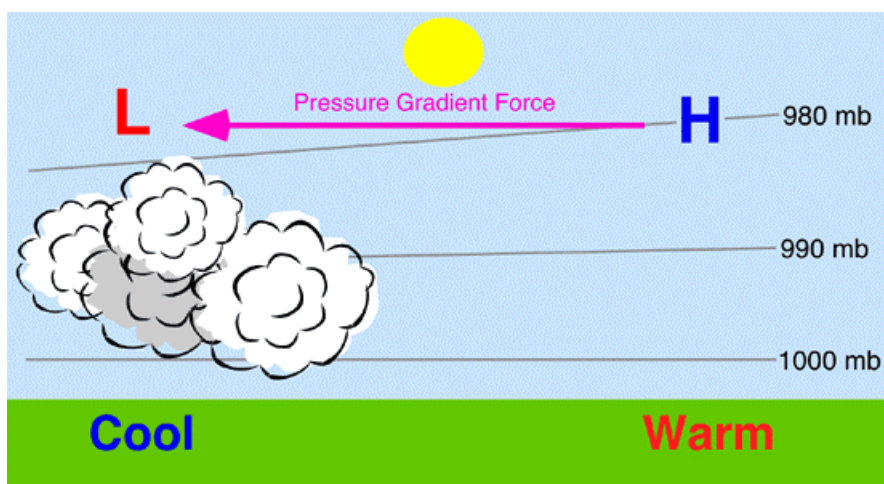
### Thermal Circulations

As discussed earlier, winds blow because of differences in atmospheric pressure. Pressure gradients may develop on a local to a global scale because of differences in the heating and cooling of the Earth's surface. Heating and cooling cycles that develop daily or annually can create several common local or regional thermal wind systems. The basic circulation system that develops is described in the **illustrations** below.



**Figure 15-1:** Cross-section of the atmosphere with uniform horizontal atmospheric pressure.

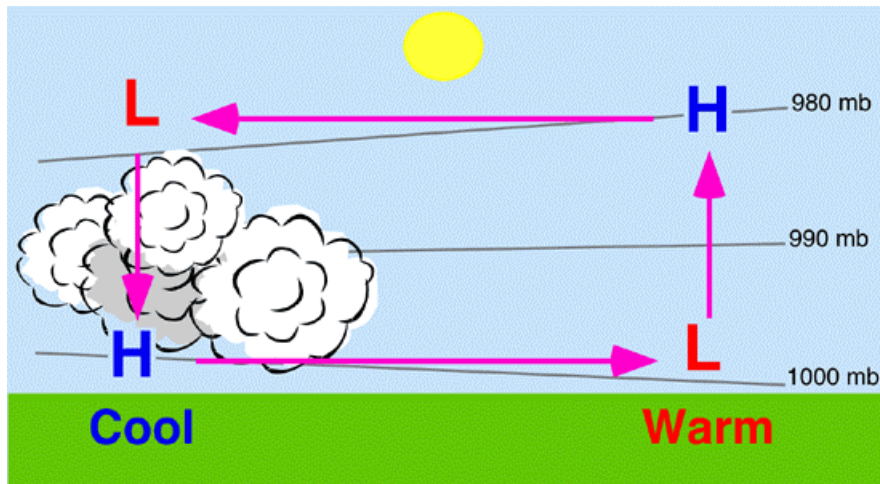
In this first **diagram** (Figure 15-1), there is no horizontal temperature or pressure gradient and therefore no wind. Atmospheric pressure decreases with altitude as depicted by the drawn isobars (1000 to 980 millibars). In the second **diagram** (Figure 15-2), the potential for solar heating is added which creates contrasting surface areas of temperature and atmospheric pressure. The area to the right receives more solar radiation and the air begins to warm from heat energy transferred from the ground through conduction and convection. The vertical distance between the isobars becomes greater as the air rises. To the far left, less radiation is received because of the presence of cloud, and this area becomes relatively cooler than the area to the right. In the upper atmosphere, a pressure gradient begins to form because of the rising air and upward spreading of the isobars. The air then begins to flow in the upper atmosphere from high pressure to low pressure.



**Figure 15-2:** Development of air flow in the upper atmosphere because of surface heating.

**Figure 15-3** shows the full circulation system in action. Beneath the upper atmosphere high is a thermal low pressure center created from the heating of the ground surface. Below the upper atmosphere low is a thermal high created by the relatively cooler air temperatures and the descend air from above. Surface air temperatures

are cooler here because of the obstruction of shortwave radiation absorption at the Earth's surface by the cloud. At the surface, the wind blows from the high to the low pressure. Once at the low, the wind rises up to the upper air high pressure system because of thermal buoyancy and outflow in the upper atmosphere. From the upper high, the air then travels to the upper air low, and then back down to the surface high to complete the circulation cell. The circulation cell is a closed system that redistributes air in an equitable manner. It is driven by the greater heating of the surface air in the right of the diagram.

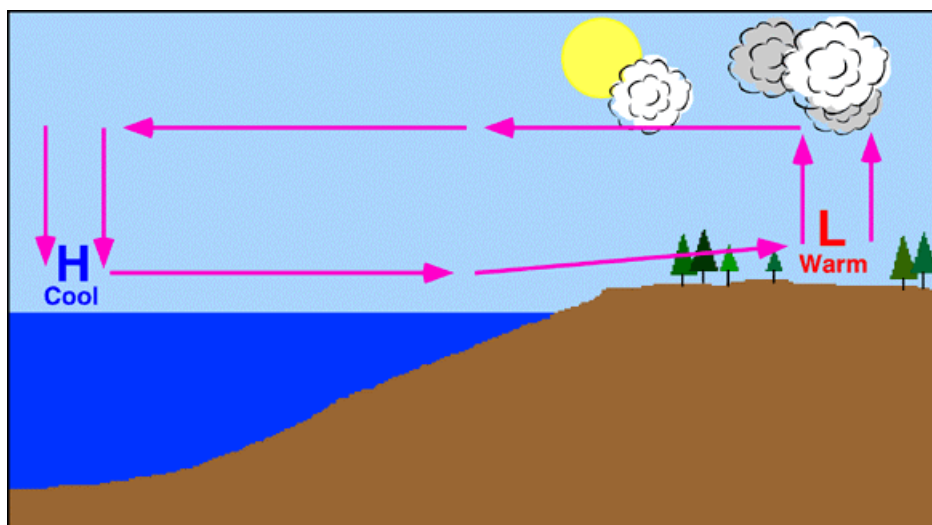


**Figure 15-3:** Development of a closed atmospheric circulation cell because of surface heating.

#### Sea and Land Breezes

Sea and land breezes are types of thermal circulation systems that develop at the interface of land and ocean. At this interface, the dissimilar heating and cooling characteristics of land and water initiate the development of an atmospheric pressure gradient which causes the air in these areas to flow.

During the daytime land heats up much faster than water as it receives solar radiation from the sun (**Figure 15-4**). The warmer air over the land then begins to expand and rise forming a thermal low. At the same time, the air over the ocean becomes a cool high because of water's slower rate of heating. Air begins to flow as soon as there is a significant difference in air temperature and pressure across the land to sea gradient. The development of this pressure gradient causes the heavier cooler air over the ocean to move toward the land and to replace the air rising in the thermal low. This localised air flow system is called a sea breeze. Sea breeze usually begins in midmorning and reaches its maximum strength in the later afternoon when the greatest temperature and pressure contrasts exist. It dies down at sunset when air temperature and pressure once again become similar across the two surfaces.



**Figure 15-4:** Daytime development of sea breeze.

At sunset, the land surface stops receiving radiation from the sun (Figure 15-5). As night continues the land surface begins losing heat energy at a much faster rate than the water surface. After a few hours, air temperature and pressure contrasts begin to develop between the land and ocean surfaces. The land surface being cooler than the water becomes a thermal high pressure area. The ocean becomes a warm thermal low. Wind flow now moves from the land to the open ocean. This type of localised air flow is called a land breeze.

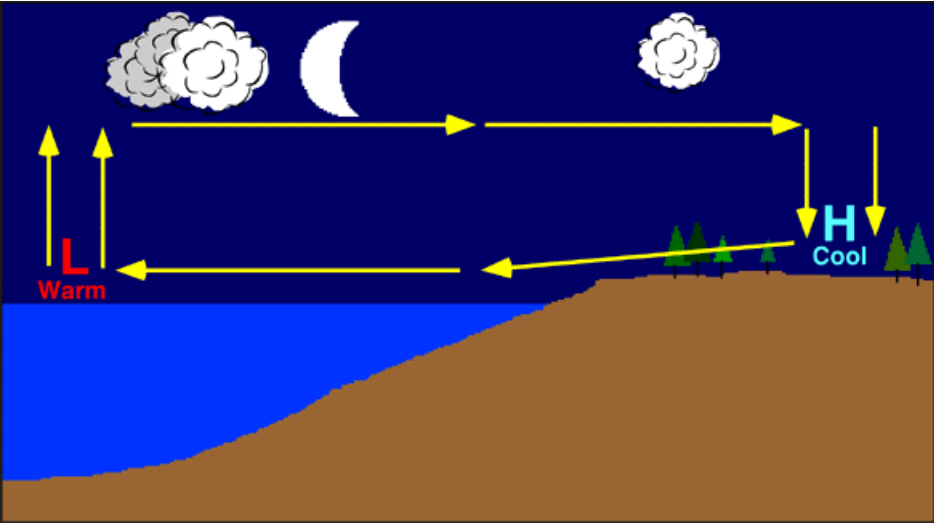


Figure 15-5: Night-time development of land breeze.

**Mountain and Valley Breezes**

Mountain and valley breezes are common in regions with great topographic relief (Figure 15-6 and 15-7). A valley breeze develops during the day as the sun heats the land surface and air at the valley bottom and sides (Figure 15-6). As the air heats it becomes less dense and buoyant and begins to flow gently up the valley sides. Vertical ascent of the air rising along the sides of the mountain is usually limited by the presence of a temperature inversion layer. When the ascending air currents encounter the inversion they are forced to move horizontally and then back down to the valley floor. This creates a self-contained circulation system. If conditions are right, the rising air can condense and form into cumuliform clouds.

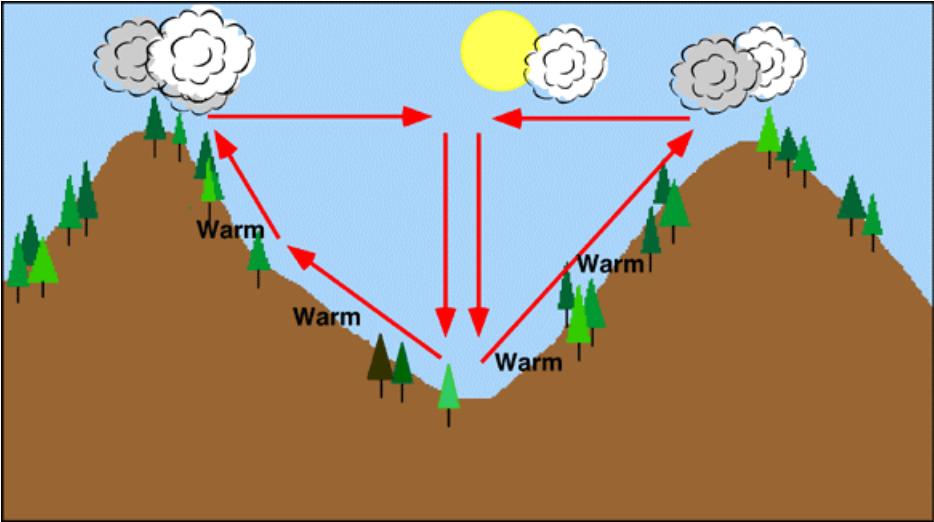
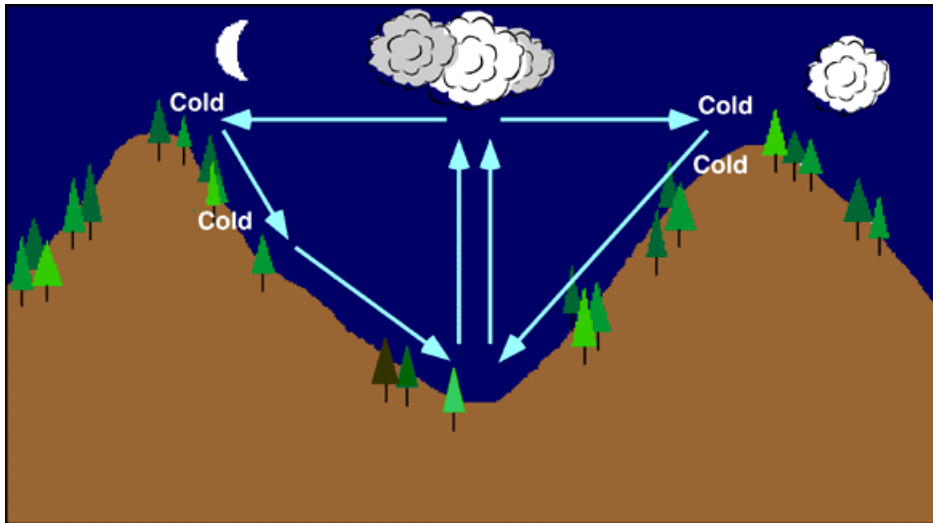


Figure 15-6: Daytime development of valley breeze.

During the night, the air along the mountain slopes begins to cool quickly because of longwave radiation loss (Figure 15-7). As the air cools, it becomes more dense and begins to flow downslope causing a mountain breeze. Convergence of the draining air occurs at the valley floor and forces the air to move vertically upward. The upward movement is usually limited by the presence of a temperature inversion which forces the air to begin moving horizontally. This horizontal movement completes the circulation cell system. In narrowing terrain,

mountain winds can accelerate in speed because of the **venturi** effect. Such winds can attain speeds as high as 150 kilometers per hour.



**Figure 15-7:** Night-time development of mountain breeze.

### Monsoon Winds

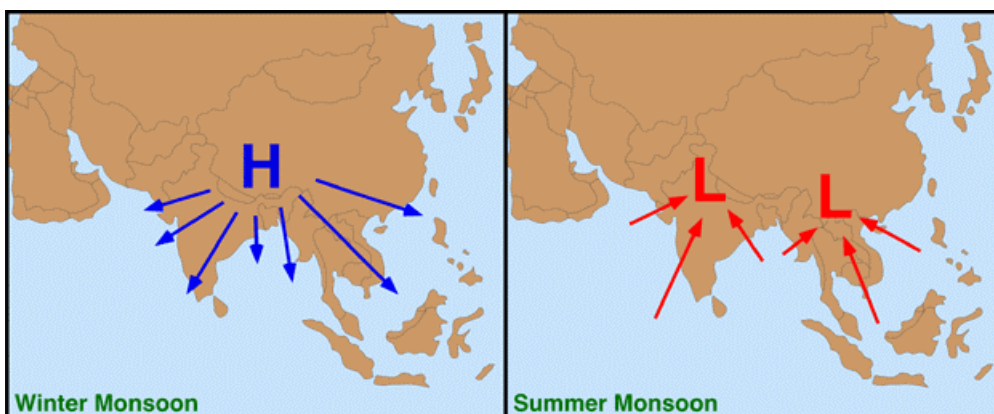
Monsoons are regional scale wind systems that predictably change direction with the passing of the seasons. Like land/sea breezes, these wind systems are created by the temperature contrasts that exist between the surfaces of land and ocean. However, monsoons are different from land/sea breezes both spatially and temporally. Monsoons occur over distances of thousands of kilometers, and their two dominant patterns of wind flow act over an annual time scale.

During the summer, monsoon winds blow from the cooler ocean surfaces onto the warmer continents. In the summer, the continents become much warmer than the oceans because of a number of factors. These factors include:

- Specific heat differences between land and water.
- Greater evaporation over water surfaces.
- Subsurface mixing in ocean basins which redistributes heat energy through a deeper layer.

Precipitation is normally associated with the summer monsoons. Onshore winds blowing inland from the warm ocean are very high in humidity, and slight cooling of these air masses causes condensation and rain. In some cases, this precipitation can be greatly intensified by orographic uplift. Some highland areas in Asia receive more than 10 meters of rain during the summer months.

In the winter, the wind patterns reverse as the ocean surfaces are now warmer. With little solar energy available, the continents begin cooling rapidly as longwave radiation is emitted to space. The ocean surface retains its heat energy longer because of water's high specific heat and subsurface mixing. The winter monsoons bring clear dry weather and winds that flow from land to sea.



**Figure 15-8:** Winter and summer monsoon wind patterns for southeast Asia.

**Figure 15-8** illustrates the general wind patterns associated with the winter and summer monsoons in Asia. The Asiatic monsoon is the result of a complex climatic interaction between the distribution of land and water, topography, and tropical and mid-latitude circulation. In the summer, a low pressure center forms over northern India and northern Southeast Asia because of higher levels of received solar insolation. Warm moist air is drawn into the thermal lows from air masses over the Indian Ocean. Summer heating also causes the development of a strong latitudinal pressure gradient and the development of an easterly jet stream at an altitude of about 15 kilometers and a latitude of 25 degrees North. The jet stream enhances rainfall in Southeast Asia, in the Arabian Sea, and in South Africa. When autumn returns to Asia the thermal extremes between land and ocean decrease and the westerlies of the mid-latitudes move in. The easterly jet stream is replaced with strong westerly winds in the upper atmosphere. Subsidence from an upper atmosphere cold low above the Himalayas produces outflow that creates a surface high pressure system that dominates the weather in India and Southeast Asia.

Monsoon wind systems also exist in Australia, Africa, South America, and North America.

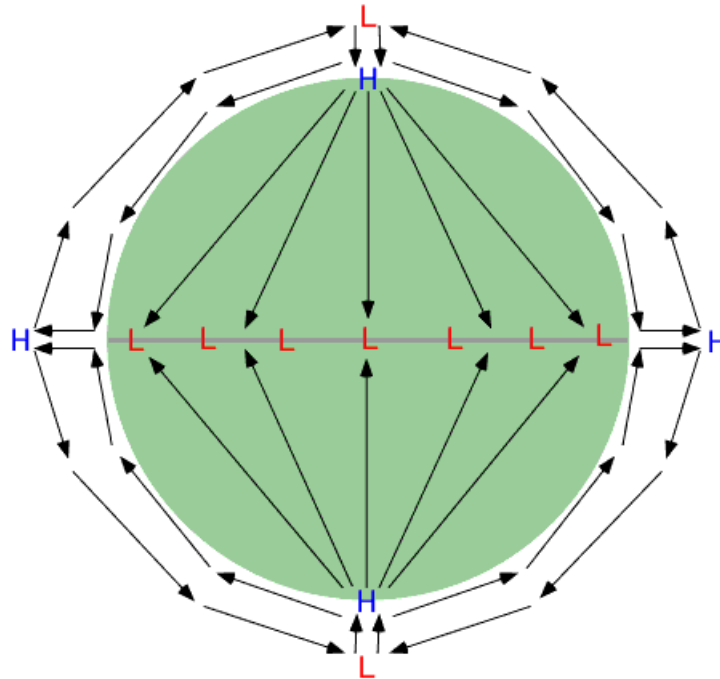
## 16. Global Scale Circulation of the Atmosphere

### Simple Model of Global Circulation

We can gain an understanding of how global circulation works by developing two simplified graphical models of processes that produce this system. The first model will be founded on the following simplifying assumptions:

- The Earth is not rotating in space.
- The Earth's surface is composed of similar materials.
- The global reception of solar insolation and loss of longwave radiation cause a temperature gradient of hotter air at the equator and colder air at the poles.

Based on these assumptions, air circulation on the Earth should approximate the patterns shown on **Figure 16-1**. In this illustration, each hemisphere contains one three-dimensional circulation cell.



**Figure 16-1:** Simplified one-cell global air circulation patterns.

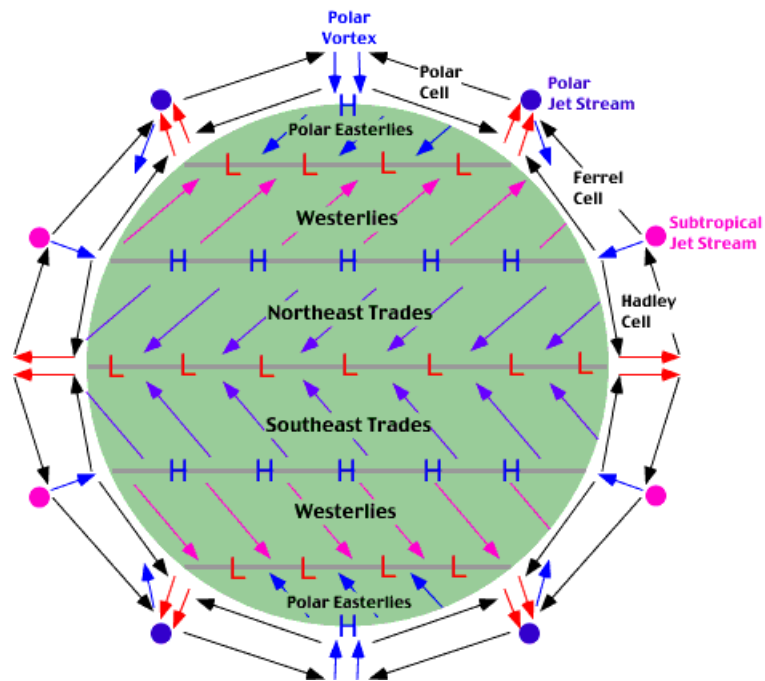
As described in the diagram above, surface air flow is from the poles to the equator. When the air reaches the equator, it is lifted vertically by the processes of convection and convergence. When it reaches the top of the troposphere, it begins to flow once again horizontally. However, the direction of flow is now from the equator to the poles. At the poles, the air in the upper atmosphere then descends to the Earth's surface to complete the cycle of flow.

### Three Cell Model of Global Circulation

If we eliminate the first assumption, the pattern of flow described in the model above would be altered, and the mesoscale flow of the atmosphere would more closely approximate the actual global circulation on the Earth. Planetary rotation would cause the development of three circulation cells in each hemisphere rather than one (see **Figure 16-2**). These three circulation cells are known as the: Hadley cell; Ferrel cell; and Polar cell.

In the new model, the equator still remains the warmest location on the Earth. This area of greater heat acts as zone of thermal lows known as the intertropical convergence zone (**ITCZ**). The Intertropical Convergence Zone draws in surface air from the subtropics. When this subtropical air reaches the equator, it rises into the upper atmosphere because of convergence and convection. It attains a maximum vertical altitude of about 14 kilometers (top of the troposphere), and then begins flowing horizontally to the North and South Poles. Coriolis force causes the deflection of this moving air in the upper atmosphere, and by about 30 degrees of latitude the air begins to flow zonally from west to east. This zonal flow is known as the subtropical jet stream. The zonal flow also causes the accumulation of air in the upper atmosphere as it is no longer flowing meridionally. To compensate for this accumulation, some of the air in the upper atmosphere sinks back to the surface creating the subtropical high pressure zone. From this zone, the surface air travels in two directions. A portion of the air

moves back toward the equator completing the circulation system known as the Hadley cell. This moving air is also deflected by the Coriolis effect to create the Northeast Trades (right deflection) and Southeast Trades (left deflection). The surface air moving towards the poles from the subtropical high zone is also deflected by Coriolis acceleration producing the Westerlies. Between the latitudes of 30 to 60 degrees North and South, upper air winds blow generally towards the poles. Once again, Coriolis force deflects this wind to cause it to flow west to east forming the polar jet stream at roughly 60 degrees North and South. On the Earth's surface at 60 degrees North and South latitude, the subtropical Westerlies collide with cold air travelling from the poles. This collision results in frontal uplift and the creation of the subpolar lows or mid-latitude cyclones. A small portion of this lifted air is sent back into the Ferrel cell after it reaches the top of the troposphere. Most of this lifted air is directed to the polar vortex where it moves downward to create the polar high.



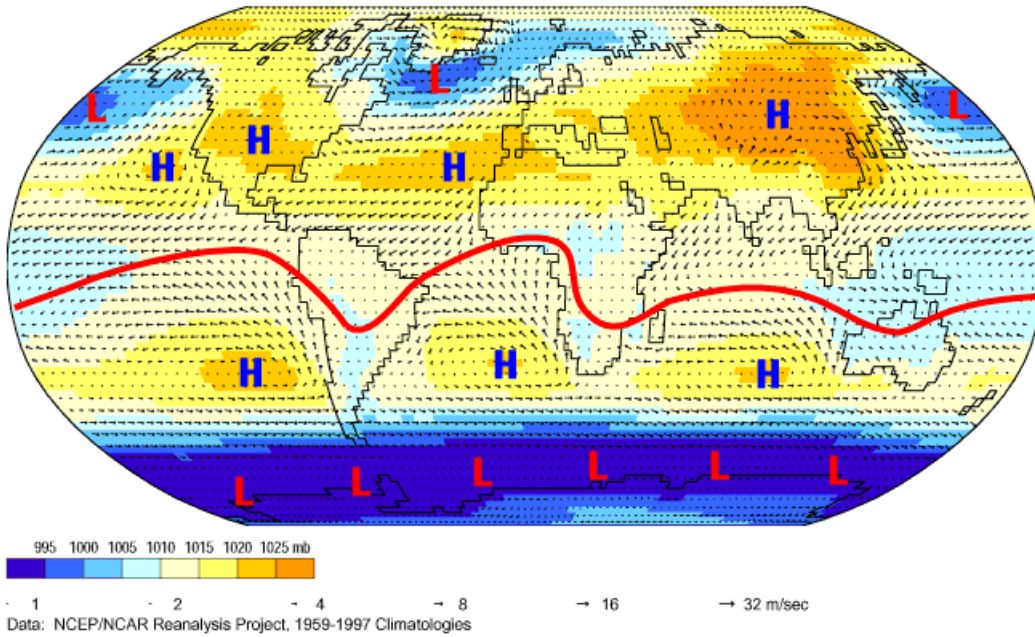
**Figure 16-2:** Simplified global three-cell surface and upper air circulation patterns.

#### Actual Global Surface Circulation

**Figure 16-3 and 16-4** describe the actual surface circulation for the Earth for January and July, respectively as determined from 39 years of record. The circulation patterns seen differ somewhat from the three cell model in **Figure 16-2**. These differences are caused primarily by two factors. First, the Earth's surface is not composed of uniform materials. The two surface materials that dominate are water and land. These two materials behave differently in terms of heating and cooling causing latitudinal pressure zones to be less uniform. The second factor influencing actual circulation patterns is elevation. Elevation tends to cause pressure centers to become intensified when altitude is increased. This is especially true of high pressure systems.

Sea-Level Pressure and Surface Winds

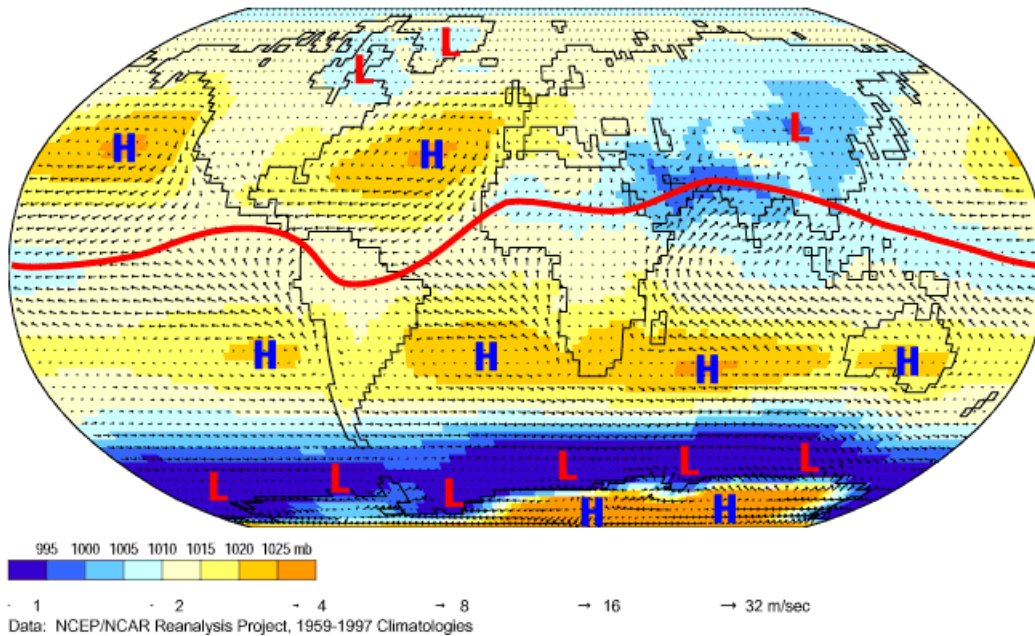
Jan



**Figure 16-3:** Mean January prevailing surface winds and centers of atmospheric pressure, 1959-1997. The red line on this image represents the intertropical convergence zone (ITCZ). Centers of high and low pressure have also been labelled. (**Source:** Climate Lab Section of the Environmental Change Research Group, University of Oregon)

Sea-Level Pressure and Surface Winds

Jul



**Figure 16-4:** Mean July prevailing surface winds and centers of atmospheric pressure, 1959-1997. The red line on this image represents the intertropical convergence zone (ITCZ). Centers of high and low pressure have also been labelled.

On these graphics, we can visualize the intertropical convergence zone (ITCZ), subtropical high pressure zone, and the subpolar lows. The intertropical convergence zone is identified on the figures by a red line. The

formation of this band of low pressure is the result of solar heating and the convergence of the trade winds. In January, the intertropical convergence zone is found south of the equator (**Figure 16-3**). During this time period, the Southern Hemisphere is tilted towards the sun and receives higher inputs of shortwave radiation. Note that the line representing the intertropical convergence zone is not straight and parallel to the lines of latitude. Bends in the line occur because of the different heating characteristics of land and water. Over the continents of Africa, South America, and Australia, these bends are toward the South Pole. This phenomenon occurs because land heats up faster than ocean.

During July, the intertropical convergence zone (ITCZ) is generally found north of the equator (**Figure 16-4**). This shift in position occurs because the altitude of the sun is now higher in the Northern Hemisphere. The greatest spatial shift in the ITCZ, from January to July, occurs in the eastern half of the image. This shift is about 40 degrees of latitude in some places. The more intense July sun causes land areas of Northern Africa and Asia rapidly warm creating the **Asiatic Low** which becomes part of the ITCZ. In the winter months, the intertropical convergence zone is pushed south by the development of an intense high pressure system over central Asia (compare **Figures 16-3** and **16-4**). The extreme movement of the ITCZ in this part of the world also helps to intensify the development of a regional winds system called the Asian monsoon.

The subtropical high pressure zone does not form a uniform area of high pressure stretching around the world in reality. Instead, the system consists of several localized anticyclonic cells of high pressure. These systems are located roughly at about 20 to 30 degrees of latitude and are labeled with the letter **H** on **Figures 16-3** and **16-4**. The subtropical high pressure systems develop because of the presence of descending air currents from the Hadley cell. These systems intensify over the ocean during the summer or high sun season. During this season, the air over the ocean bodies remains relatively cool because of the slower heating of water relative to land surfaces. Over land, intensification takes place in the winter months. At this time, land cools off quickly, relative to ocean, forming large cold continental air masses.

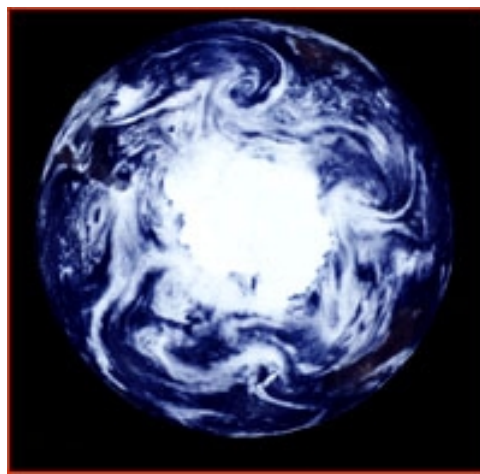
The subpolar lows form a continuous zone of low pressure in the Southern Hemisphere at a latitude of between 50 and 70 degrees (**Figures 16-3** and **16-4**). The intensity of the subpolar lows varies with season. This zone is most intense during Southern Hemisphere summer (**Figure 16-3**). At this time, greater differences in temperature exist between air masses found either side of this zone. North of subpolar low belt, summer heating warms subtropical air masses. South of the zone, the ice covered surface of Antarctica reflects much of the incoming solar radiation back to space. As a consequence, air masses above Antarctica remain cold because very little heating of the ground surface takes place. The meeting of the warm subtropical and cold polar air masses at the subpolar low zone enhances frontal uplift and the formation of intense low pressure systems.

In the Northern Hemisphere, the subpolar lows do not form a continuous belt circling the globe (**Figures 16-3** and **16-4**). Instead, they exist as localized cyclonic centers of low pressure. In the Northern Hemisphere winter, these pressure centers are intense and located over the oceans just to the south of Greenland and the Aleutian Islands (**Figure 16-3**). These areas of low pressure are responsible for spawning many mid-latitude cyclones. The development of the subpolar lows in summer only occurs weakly (**Figure 16-4** - over Greenland and Baffin Island, Canada), unlike the Southern Hemisphere. The reason for this phenomenon is that considerable heating of the Earth's surface occurs from 60 to 90 degrees North. As a result, cold polar air masses generally do not form.

## 17. Upper Air Winds and the Jet Streams

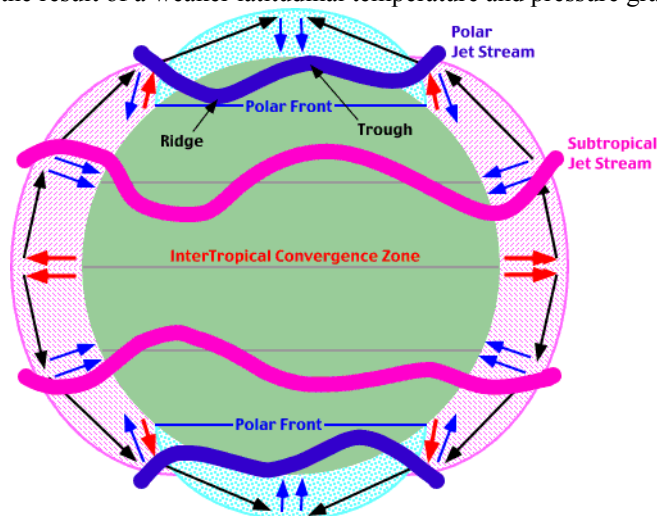
Winds at the top of the troposphere are generally poleward and westerly in direction. **Figure 16-2** above describes these upper air westerlies along with some other associated weather features. Three zones of westerlies can be seen in each hemisphere on this **illustration**. Each zone is associated with either the Hadley, Ferrel, or Polar circulation cell. The polar jet stream is formed by the deflection of upper air winds by Coriolis acceleration (see **Figure 17-2** below). It resembles a stream of water moving west to east and has an altitude of about 10 kilometers. Its air flow is intensified by the strong temperature and pressure gradient that develops when cold air from the poles meets warm air from the tropics. Wind velocity is highest in the core of the polar jet stream where speeds can be as high as 300 kilometers per hour. The jet stream core is surrounded by slower moving air that has an average velocity of 130 kilometers per hour in winter and 65 kilometers per hour in summer.

Associated with the polar jet stream is the polar front. The polar front represents the zone where warm air from the subtropics (**pink**) and cold air (**blue**) from the poles meet (see **Figure 17-2** below). At this zone, massive exchanges of energy occur in the form of storms known as the mid-latitude cyclones. The shape and position of waves in the polar jet stream determine the location and the intensity of the mid-latitude cyclones. In general, mid-latitude cyclones form beneath polar jet stream troughs. The following satellite **image** (**Figure 17-1**), taken from above the South Pole, shows a number of mid-latitude cyclones circling Antarctica. Each mid-latitude cyclone wave is defined by the cloud development associated with frontal uplift.



**Figure 17-1:** Satellite view of the atmospheric circulation at the South Pole. (Source: NASA).

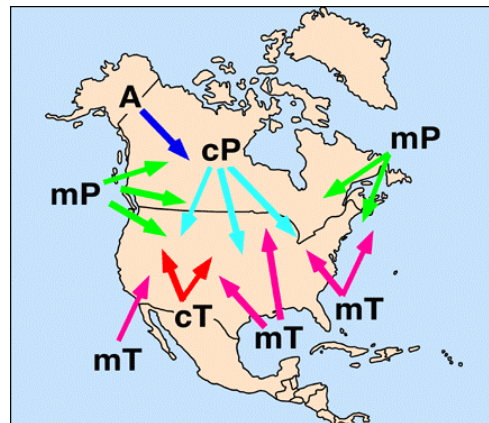
The subtropical jet stream is located approximately 13 kilometers above the subtropical high pressure zone. The reason for its formation is similar to the polar jet stream. However, the subtropical jet stream is weaker. Its slower wind speeds are the result of a weaker latitudinal temperature and pressure gradient.



**Figure 17-2:** Polar and subtropical jet streams.

## 18. Air Masses and Frontal Transitional Zones

An air mass is a large body of air of relatively similar temperature and humidity characteristics covering thousands of square kilometers. Typically, air masses are classified according to the characteristics of their source region or area of formation. A source region can have one of four temperature attributes: **equatorial**, **tropical**, **polar** or **arctic**. Air masses are also classified as being either **continental** or **maritime** in terms of moisture characteristics. Combining these two categories, several possibilities are commonly found associated with North America: **maritime polar (mP)**, **continental polar (cP)**, **maritime tropical (mT)**, **continental tropical (cT)**, and **continental arctic (A)**. The following diagram (**Figure 18-1**) describes the source regions and common patterns of movement for the various types of air masses associated with North America.

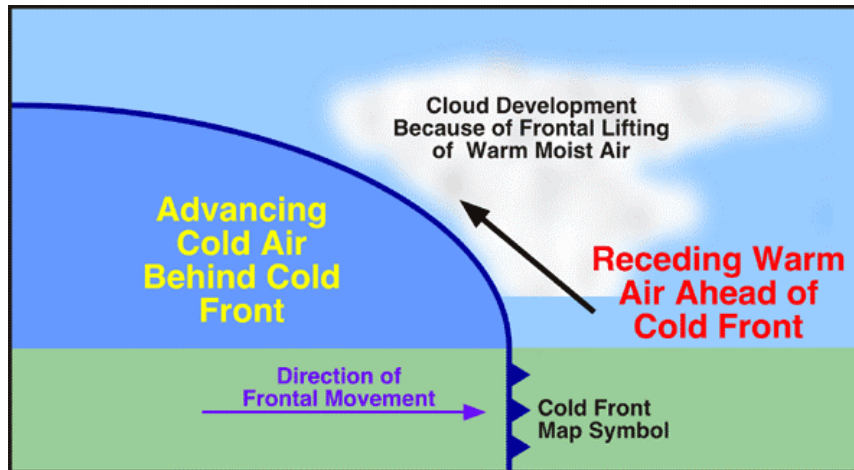


**Figure 18-1:** Source sites and movement patterns for North America's major air masses.

Frequently, two air masses, especially in the middle latitudes, develop a sharp boundary or interface, where the temperature difference between them becomes intensified. Such an area of intensification is called **a frontal zone or a front**. The boundary between the warm and cold air masses always slopes upwards over the cold air. This is due to the fact that cold air is much denser than warm air. The sloping of warm air over the cold air leads to a forced uplifting (**frontal lifting**) of the warm air if one air mass is moving toward the other. In turn, this uplifting causes condensation to occur and the possibility of precipitation along the frontal boundary. Frontal zones where the air masses are not moving against each other are called **stationary fronts**. In transitional areas where there is some air mass movement, cold or warm fronts can develop. **Figure 18-2** illustrates a vertical cross-section of a cold front. A **cold front** is the transition zone in the atmosphere where an advancing cold, dry stable air mass displaces a warm, moist unstable subtropical air mass. On a weather map, the cold front is drawn as a solid blue line with triangles. The position of the triangles shows the direction of frontal movement. Cold fronts move between 15 to 50 kilometers per hour in a southeast to east direction. The formation of clouds and precipitation at the frontal zone is caused by frontal lifting. High altitude cirrus clouds are found well in advance of the front. Above the surface location of the cold front, high altitude cirrostratus and middle altitude altocumulus are common. Precipitation is normally found just behind the front where frontal lifting has caused the development of towering cumulus and cumulonimbus clouds. **Table 18-1** describes some of the weather conditions associated with a cold front.

**Table 18-1:** Weather conditions associated with a cold front.

Weather Phenomenon	Prior to the Passing of the Front	Contact with the Front	After the Passing of the Front
Temperature	Warm	Cooling suddenly	Cold and getting colder
Atmospheric Pressure	Decreasing steadily	Leveling off then increasing	Increasing steadily
Winds	South to southeast	Variable and gusty	West to northwest
Precipitation	Showers	Heavy rain or snow, hail sometimes	Showers then clearing
Clouds	Cirrus and cirrostratus changing later to cumulus and cumulonimbus	Cumulus and cumulonimbus	Cumulus

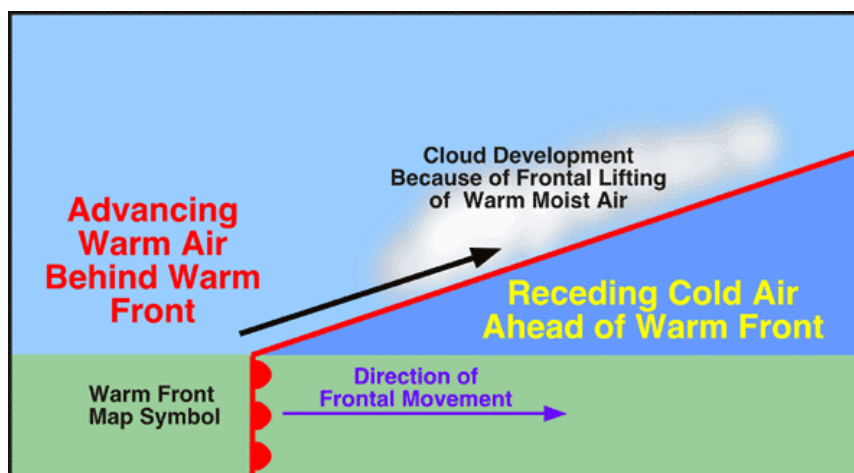


**Figure 18-2:** Atmospheric cross-section of a cold front.

A warm front is illustrated in the cross-section diagram below (**Figure 18-3**). A **warm front** is the transition zone in the atmosphere where an advancing warm subtropical, moist air mass replaces a retreating cold, dry polar air mass. On a weather map, a warm front is drawn as a solid red line with half-circles. The position of the half-circles shows the direction of frontal movement. Warm fronts move about 10 kilometers per hour in a northeast direction. This is less than half the speed of a cold front. The formation of clouds and precipitation ahead of the frontal zone is caused by gradual frontal lifting. High altitude cirrus, cirrostratus and middle altitude altostratus clouds are found well in advance of the front. About 600 kilometers ahead of the front, nimbostratus clouds occur. These clouds produce precipitation in the form of snow or rain. Between the nimbostratus clouds and the surface location of the warm front, low altitude stratus clouds are found. Finally, a few hundred kilometers behind the front scattered stratocumulus are common in the lower troposphere. **Table 18-2** describes some of the weather conditions associated with a warm front.

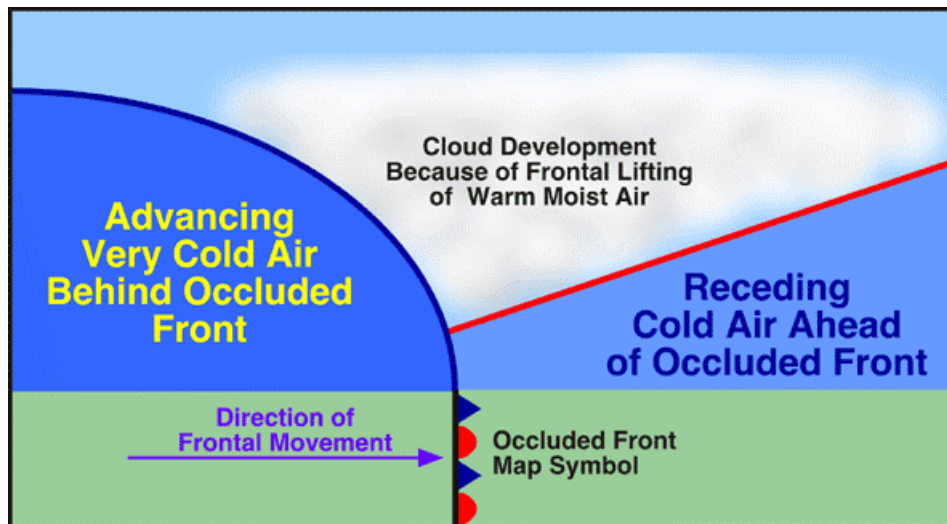
**Table 18-2:** Weather conditions associated with a warm front.

Weather Phenomenon	Prior to the Passing of the Front	Contact with the Front	After the Passing of the Front
Temperature	Cool	Warming suddenly	Warmer then leveling off
Atmospheric Pressure	Decreasing steadily	Leveling off	Slight rise followed by a decrease
Winds	South to southeast	Variable	South to southwest
Precipitation	Showers, snow, sleet or drizzle	Light drizzle	None
Clouds	Cirrus, cirrostratus, altostratus, nimbostratus, and then stratus	Stratus, cumulonimbus	Clearing with scattered stratus, or cumulonimbus



**Figure 18-3:** Atmospheric cross-section of a warm front.

Occluded fronts are produced when a fast moving cold front catches and overtakes a slower moving warm front. Two types of occluded fronts are generally recognised. A **cold type occluded front** occurs when the air behind the front is colder than the air ahead of the front. When the air behind the front is warmer than the air ahead of the front a **warm type occluded front** is produced. Warm type occlusions are common on the west coast of continents and generally form when maritime polar air collides with continental polar or arctic air. The cross-section diagram in **Figure 18-4** illustrates a **cold type occlusion**. Note that in the occlusion process the invading mild moist air that was found behind the warm front has been lifted into the upper troposphere. Finally, the frontal systems described on this page are often associated with a storm system known as the mid-latitude cyclone.



**Figure 18-4:** Atmospheric cross-section of a occluded front.

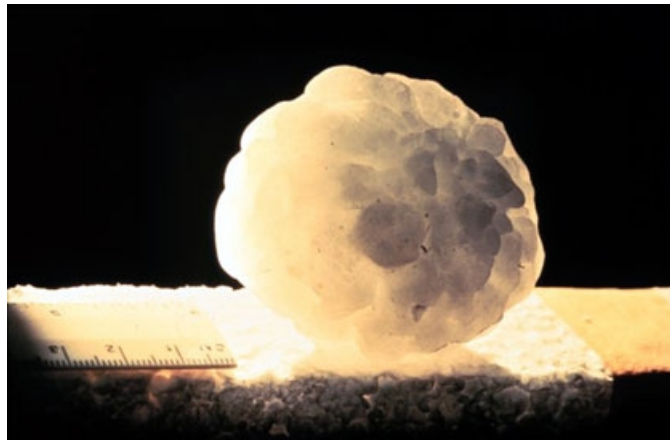
## 19. Thunderstorms and Tornadoes

### Thunderstorms

Thunderstorms form when moist, unstable air is lifted vertically into the atmosphere. Lifting of this air results in condensation and the release of latent heat. The process to initiate vertical lifting can be caused by:

- 1) Unequal warming of the surface of the Earth.
- 2) Orographic lifting due to topographic obstruction of air flow.
- 3) Dynamic lifting because of the presence of a frontal zone.

Immediately after lifting begins, the rising parcel of warm moist air begins to cool because of adiabatic expansion. At a certain elevation the dew point is reached resulting in condensation and the formation of a cumulus cloud. For the cumulus cloud to form into a thunderstorm, continued uplift must occur in an unstable atmosphere. With the vertical extension of the air parcel, the cumulus cloud grows into a cumulonimbus cloud. Cumulonimbus clouds can reach heights of 20 kilometers above the Earth's surface. Severe weather associated with some these clouds includes hail, strong winds, thunder, lightning, intense rain, and tornadoes.



**Figure 19-1:** Hail stone measuring 21 centimeters in diameter. (Source: NOAA Photo Collection Website).



**Figure 19-2:** Multiple lightning strikes from a thunderstorm occurring at night. (Source: NOAA Photo Collection Website).

Generally, two types of thunderstorms are common:

- 1) Air mass thunderstorms which occur in the mid-latitudes in summer and at the equator all year long.
- 2) Thunderstorms associated with mid-latitude cyclone cold fronts or dry lines. This type of thunderstorm often has severe weather associated with it.

The most common type of thunderstorm is the air mass storm. Air mass thunderstorms normally develop in late afternoon hours when surface heating produces the maximum number of convection currents in the atmosphere. The life cycle of these weather events has three distinct stages. The first stage of air mass thunderstorm development is called the **cumulus stage (Figure 19-3)**. In this stage, parcels of warm humid air rise and cool to

form clusters of puffy white cumulus clouds. The clouds are the result of condensation and deposition which releases large quantities of latent heat. The added heat energy keeps the air inside the cloud warmer than the air around it. The cloud continues to develop as long as more humid air is added to it from below. Updrafts dominate the circulation patterns within the cloud.



**Figure 19-3:** Developing thunderstorm cloud at the cumulus stage.

When the updrafts reach their maximum altitude in the developing cloud, usually 12 to 14 kilometers, they change their direction 180 degrees and become downdrafts. This marks the **mature stage**. With the downdrafts, precipitation begins to form through collision and coalescence. The storm is also at its most intense stage of development and is now a cumulonimbus cloud (**Figure 19-4**). The top of the cloud takes on the familiar anvil shape, as strong stratospheric upper-level winds spread ice crystals in the top of the cloud horizontally. At its base, the thunderstorm is several kilometers in diameter. The mature air mass thunderstorm contains heavy rain, thunder, lightning, and produces wind gusts at the surface.



**Figure 19-4:** Mature thunderstorm cloud with typical anvil shaped cloud. (Source: NOAA Photo Collection Website).

The mature thunderstorm begins to decrease in intensity and enters the **dissipating stage** after about half an hour. Air currents within the convective storm are now mainly downdrafts as the supply of warm moist air from the lower atmosphere is depleted. Within about 1 hour, the storm is finished and precipitation has stopped. Thunderstorms could form to as far north from the equator as Alaska, USA. They occur most commonly in the tropics where convective heating of moist surface air occurs year round. Many tropical land based locations experience over 100 thunderstorm days per year. Thunderstorm formation over tropical oceans is less frequent

because these surfaces do not warm rapidly. Outside the tropics, thunderstorm formation is more seasonal occurring in those months where heating is most intense.

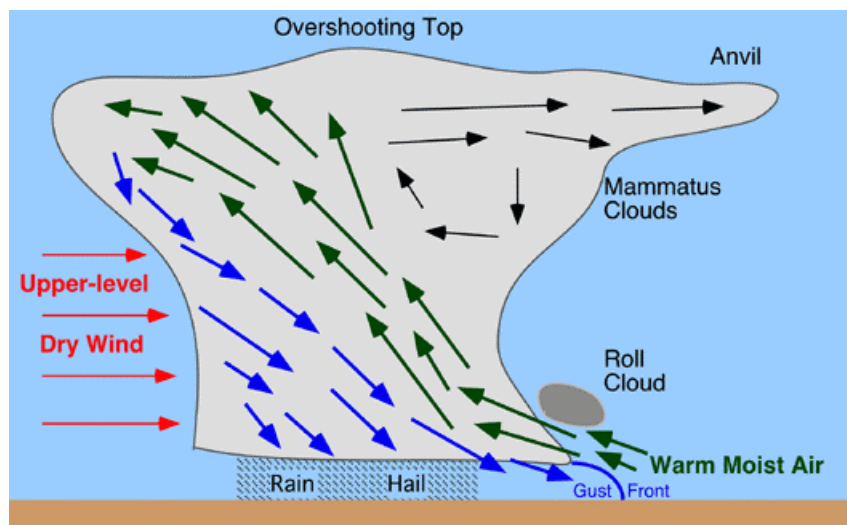
The extreme solar heating is not the only requirement for thunderstorm formation. Another important prerequisite is the availability of warm moist air. For example, in the United States, the Gulf of Mexico supplies adjacent continental areas with moist maritime tropical air masses. These air masses are relatively unstable quickly forming cumulonimbus clouds when surface heating is intense. Besides that, there is another climatic factor that could provide thunderstorm activity – orographic effect or simply mountains. Mountain slopes that face the sun absorb more direct solar radiation and become relatively warmer creating strong updrafts that form into cumulus clouds. If the differential heating is also supplemented by winds, the cumulus clouds are further enhanced to become thunderstorms. The opposite example is the west coast of the United States where few thunderstorms occur. This region is dominated by cool maritime polar air masses which suppress convectational uplift over land.

### Severe Thunderstorms

Most thunderstorms are of the variety described above. However, some can form into more severe storms if the conditions exist to enhance and prolong the mature stage of development. Severe thunderstorms are defined as convective storms with frequent lightning, accompanied by local wind gusts of 97 kilometers per hour, or hail that is 2 centimeters in diameter or larger. Severe thunderstorms can also have tornadoes!

In most severe thunderstorms, the movement of the storm, in roughly an easterly direction, can refresh the storm's supply of warm humid air. With a continual supply of latent heat energy, the updrafts and downdrafts within the storm become balanced and the storm maintains itself indefinitely. Movement of the severe storm is usually caused by the presence of a mid-latitude cyclone, cold front or a dry line some 100 to 300 kilometers ahead of a cold front. In the spring and early summer, frontal cyclones are common weather events that move from west to east in the mid-latitudes. At the same time, the ground surface in the mid-latitudes is receiving elevated levels of insolation which creates ideal conditions for air mass thunderstorm formation. When the cold front or dry line of a frontal cyclone comes in contact with this warm air it pushes it like a bulldozer both horizontally and vertically. If this air has a high humidity and extends some distance to the east, the movement of the mid-latitude cyclone enhances vertical uplift in storm and keeps the thunderstorms supplied with moisture and energy. Thus, the mid-latitude cyclone converts air mass thunderstorms into severe thunderstorms that last for many hours. Severe thunderstorms dissipate only when no more warm moist air is encountered. This condition occurs several hours after nightfall when the atmosphere begins to cool off.

**Figure 19-5** illustrates the features associated with a severe thunderstorm. This storm would be moving from left to right because of the motion associated with a mid-latitude cyclone. The upper-level dry air wind is generated from the mid-latitude cyclone. It causes the tilting of vertical air currents within the storm so that the updrafts move up and over the downdrafts. The **green arrows** represent the updrafts which are created as warm moist air is forced into the front of the storm. At the back end of the cloud, the updrafts swing around and become downdrafts (**blue arrows**). The leading edge of the downdrafts produces a gust front near the surface. As the gust front passes, the wind on the surface shifts and becomes strong with gusts exceeding 100 kilometers per hour, temperatures become cold, and the surface pressure rises. Warm moist air that rises over the gust front may form a roll cloud. These clouds are especially prevalent when an inversion exists near the base of the thunderstorm.



**Figure 19-5:** Model of the major features and circulation patterns associated with a severe thunderstorm.

Some severe thunderstorms develop a strong vertical updraft, commonly known as a mesocyclone. Mesocyclones measure about 3 to 10 kilometers across and extend from the storm's base to its top. They are also found in the southwest quadrant of the storm. In some cases, mesocyclones can overshoot the top of the storm and form a cloud dome (**Figure 19-5**). About half of all mesocyclones spawn tornadoes. When a tornado occurs, the mesocyclone lengthens vertically, constricts, and spirals down to the ground surface. Scientists speculate that mesocyclones form when strong horizontal upper air winds interact with normally occurring updrafts. The shearing effect of this interaction forces the horizontal wind to flow upward intensifying the updraft.

### **Tornadoes**

A tornado is a vortex of rapidly moving air associated with some severe thunderstorms (see **Figure 19-6**). Tornadoes that travel across lakes or oceans are called waterspouts. Winds within the tornado funnel may exceed 500 kilometers per hour. High velocity winds cause most of the damage associated with these weather events. Tornadoes also cause damage through air pressure reductions. The air pressure at the tornado center is approximately 800 millibars (average sea-level pressure is 1014 millibars) and many human made structures collapse outward when subject to pressure drops of this magnitude. The destructive path of a tornado is usually about half a kilometer wide, and usually no more than 25 kilometers long. However, a spring tornado in 1917 traveled 570 kilometers across Illinois and Indiana lasting well over 7 hours.



**Figure 19-6: Tornado.**

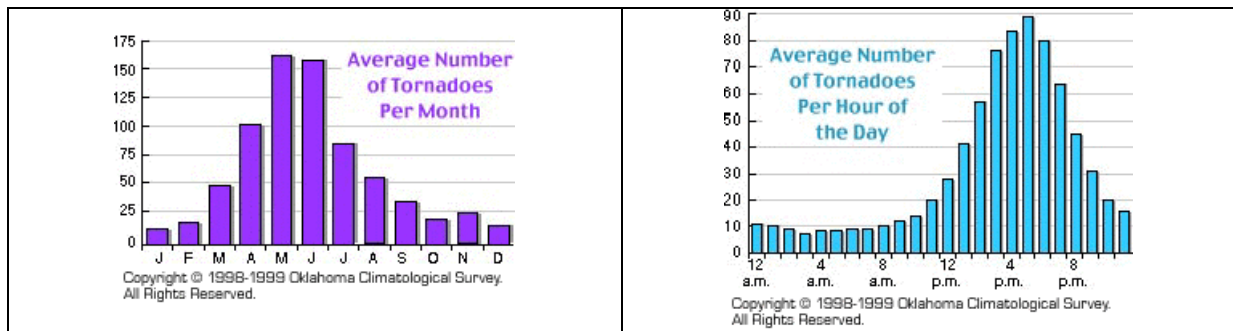
About 74 % of all tornadoes have wind speeds between 65 and 181 kilometers per hour. These events are classified according to the Fujita tornado intensity scale as being weak (**Table 19-1**). Damage from these tornadoes varies from broken windows and tree branches to shingles blowing off roofs and moving cars pushed from roads. Weak tornadoes have a path that is about 1.5 kilometers long and 100 meters wide, and they generally last for only 1 to 3 minutes. According to the Fujita scale, strong tornadoes can have wind speeds between 182 and 332 kilometers per hour. These phenomena cause considerable damage and occur about 25 % of the time. Strong tornadoes can have a course up to 100 kilometers long and half a kilometer wide, and they can last for more than 2 hours. The rarest tornadoes are those with either a F4 or F5 rating. These events have wind speeds between 333 to 513 kilometers per hour and are very destructive and violent. F4 tornadoes occur only about 1 % of the time, while F5 are even more rare with a chance of about 1 in 1000 of happening.

Tornadoes occur in many parts of the world. Some notable hotspots include South Africa, Australia, Europe, New Zealand, northern India, Canada, Argentina, Uruguay, and the United States. Of these locations, the United States has some specific regions within its boundaries that have an extremely high number of events per year. In the United States the highest number of tornadoes occurs in the southern plains (also called Tornado Alley), south of Lake Michigan, and west central Florida.

Tornado occurrence has some interesting temporal characteristics. In the United States, most tornadoes occur in April, May, June, and July (**Figure 19-7**). It is during these months that we get the conditions necessary for the formation of severe thunderstorms (see severe thunderstorm discussion above). Tornadoes also have particular times of the day in which they form. Most tornadoes form in the afternoon. Few develop in the late evening or early morning. During these times, heating of the Earth's surface is minimal or not occurring. Intense heating enhances updrafts in severe thunderstorms. It is these updrafts that can cause a tornado to form.

**Table 19-1: Fujita tornado intensity scale.**

F-Scale	Category	Kilometers per Hour (Miles per Hour)	Comments
0	Weak	65-118 (40-73)	Damage is light. Chimneys on houses may be damaged; trees have broken branches; shallow-rooted trees pushed over; some windows broken; damage to sign boards.
1	Weak	119-181 (74-112)	Shingles on roofs blown off; mobile homes pushed off foundations or overturned; moving cars pushed off roads.
2	Strong	182-253 (113-157)	Considerable damage. Roofs torn off houses; mobile homes destroyed; train boxcars pushed over; large trees snapped or uprooted; light-objects thrown like missiles.
3	Strong	254-332 (158-206)	Damage is severe. Roofs and walls torn off better constructed homes, businesses, and schools; trains overturned; most trees uprooted; heavy cars lifted off ground and thrown some distance.
4	Violent	333-419 (207-260)	Better constructed homes completely levelled; structures with weak foundation blown off some distance.
5	Violent	420-513 (261-318)	Better constructed homes lifted off foundations and carried considerable distance where they disintegrate; trees debarked; cars thrown in excess of 100 meters.



**Figure 19-7: Average number of tornadoes per month and per hour of the day in the United States. (Source: Oklahoma Climatological Survey).**

In the United States, about 40,000 tornadoes have occurred in the last fifty years (1950-1999). Data for the period 1916 to 1996 indicates that the frequency of tornadoes in the United States has increased substantially. Total damage from tornadoes over the last 50 years has been estimated to be about 25 billion dollars. Tornadoes also take a heavy toll on human lives. **Table 19-2** describes the five deadliest tornado events in the United States. However, weather forecasting technology has played an important role in reducing the number of lives lost. In the decade of the 1930s, before the advent of severe weather forecasting, 1945 people were killed by tornadoes. From 1986 to 1995, only 418 individuals perished suggesting a 90% decrease in fatalities. This reduction is even more astonishing when you consider that the population of the United States doubled from 1935 to 1990.

**Table 19-2: Ten deadliest tornado events in the United States.**

DATE	LOCATION(S)	DEATHS
March 18, 1925	Missouri, Illinois, Indiana	689
May 27, 1896	St. Louis, Missouri	255
April 5, 1936	Tupelo, Mississippi	216
April 9, 1947	Woodward, Oklahoma	181
May 11, 1953	Waco, Texas	114

## 20. Tropical Weather and Hurricanes

### Tropical Weather

The tropics can be defined as the area of the Earth found between the Tropic of Cancer and the Tropic Capricorn. In this region, the sun will be directly overhead during some part of the year. The temperature of the tropics does not vary much from season to season because considerable solar insolation is received by locations regardless of the season. Weather in the tropics is dominated by convective storms that develop mainly along the intertropical convergence zone, the subtropical high pressure zone, and oceanic disturbances in the trade winds that sometimes develop into hurricanes.

One of the most important weather features found in the tropics is the intertropical convergence zone. The intertropical convergence zone is distinguished by a wide band of cumulus and cumulonimbus clouds that are created by dynamic atmospheric lifting due to convergence and convection.

Normally, the intertropical convergence zone delineates the location where the noonday sun is directly overhead on the globe. Because of the high sun, the intertropical convergence zone receives the greatest quantity of daily solar insolation in the tropics. At the intertropical convergence zone, this energy is used to evaporate large amounts of water and is converted into sensible heat at the ground surface and within the atmosphere. Often, these processes lead to an almost daily development of convective thunderstorms by providing moisture and heat for the development of cumulonimbus clouds.

The intertropical convergence zone also represents the location of convergence of the northeast and southeast trade winds. The convergence of these wind systems enhances the development of convective rain clouds at the tropics.

The intertropical convergence zone moves seasonally with the tilt of the Earth's axis (see **Figures 16-3 and 16-4** above). The convective rains that accompany the passage of the intertropical convergence zone are the primary source of precipitation for locations roughly 10 to 23.5° North and South latitude.

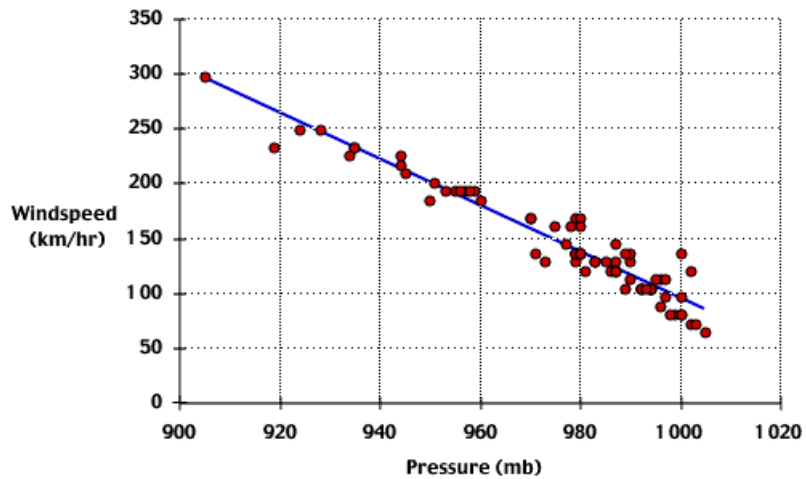
Weather disturbances in the trade winds, known as easterly waves, are another source of cloud development and precipitation in the tropics. Easterly waves develop first as a weak disturbance in the atmosphere usually because of the presence of localized warmer sea temperatures. This is seen on a weather map as a wave in the isobars. On the eastern side of the wave, convergence occurs forming thunderstorms (divergence on the western side). If the convergence is strong enough the storm system may evolve into a hurricane.

The other important weather feature in the tropics is the subtropical high pressure zone. Air flow in the subtropical high pressure zone is primarily descending. This creates clear skies, low humidity and hot daytime temperatures. Like the intertropical convergence zone, the subtropical high pressure zone migrates seasonally (see **Figures 16-3 and 16-4** above). It generally influences locations 10 to 23.5 degrees North and South during some part of the year.

### Hurricanes

Hurricanes are intense cyclonic storms that develop over the warm oceans of the tropics (e.g. **Figure 20-2**). These tropical storms go by other names in the various parts of the world: India/Australia - cyclones; western North Pacific - typhoons; and the Philippines - baguio. By international agreement, the term **tropical cyclone** is used by most nations to describe hurricane-like storms that originated over tropical oceans. Surface atmospheric pressure in the center of a hurricane tends to be extreme low. The lowest pressure reading ever recorded for a hurricane (typhoon Tip, 1979) is 870 millibars (mb). However, most storms have an average pressure of 950 millibars. To be classified as a hurricane, sustained wind speeds must be greater than 118 kilometers per hour at the storm's center. Wind speed in a hurricane is directly related to the surface pressure of the storm. The following **graph (Figure 20-1)** shows the relationship between surface pressure and sustained wind speed for a number of tropical low pressure systems.

Hurricanes have no fronts associated with them like the mid-latitude cyclones of the polar front. They are also smaller than the mid-latitude cyclone, measuring on average 550 kilometers in diameter. Mature hurricanes usually develop a cloud-free eye at their center (**Figure 20-2 and 20-3**). In the eye, air is descending creating clear skies. The eye of the hurricane may be 20 to 50 kilometers in diameter. Surrounding the eye are bands of organised thunderstorm clouds formed as warm air move in and up into the storm. The strongest winds and heaviest precipitation are found in the area next to the eye where a vertical wall of thunderstorm clouds develops from the Earth's surface to the top of the troposphere.



**Figure 20-1:** Relationship between surface pressure and wind speed for a number of tropical low pressure systems. Tropical low pressure systems are classified as hurricanes when their pressure is 980 millibars or lower, and sustained wind speeds are greater than 118 kilometers per hour.

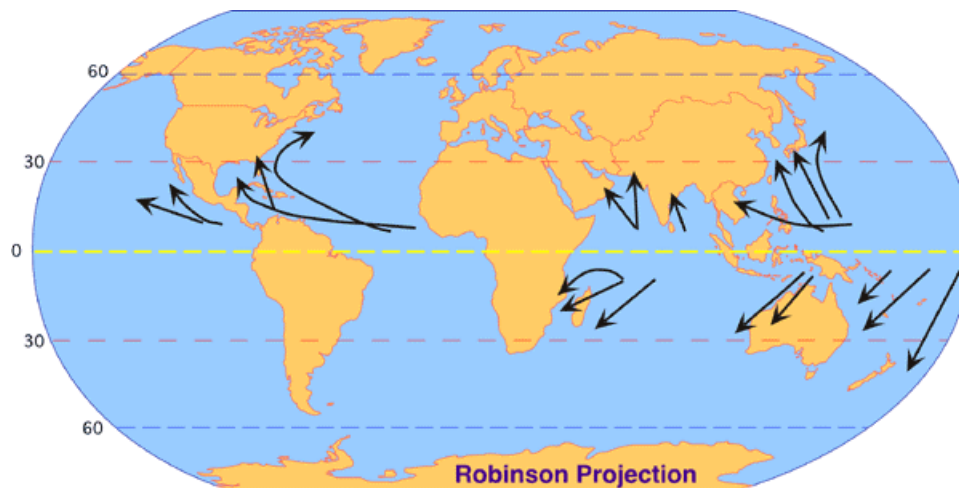


**Figure 20-2:** Hurricane as seen from the space shuttle (**Source:** NASA).



**Figure 20-3:** Satellite view of hurricane Floyd just before it made landfall in North Carolina, Sept. 15, 1999. The eye is clearly visible in this image

Hurricanes are powered by the latent heat energy released from condensation. To form and develop they must be supplied with a constant supply of warm humid air for this process. Surface air with enough energy to generate a hurricane only exists over oceans with a temperature greater than 26.5 degrees Celsius. Ocean temperatures this high only occur in selected regions and during particular seasons. Hurricane development does not occur if a temperature inversion exists in the atmosphere. Inversions develop in the tropics when subtropical high pressure systems produce sinking air. Also, hurricanes do not develop in the region 5 degrees either side of the equator. Within this region Coriolis force is negligible. Coriolis force is required for the initiation of cyclonic flow. Hurricanes dissipate when their energy supply is substantially reduced. This occurs either with landfall or storm movement into cooler seas. Most hurricanes live for about a week. However, if a hurricane remains over warm water its life can be extended. In 1992, hurricane Tina was an active tropical storm for 24 days over the North Pacific. The **map** in **Figure 20-4** shows the typical areas of hurricane development and the usual paths they take during their life.



**Figure 20-4:** Typical areas where hurricanes begin their development and the common paths of storm movement.

Hurricanes go through a number of different stages of development. Initially, these powerful storms begin their lives as an unorganised group of thunderstorms that develop over the specific areas of the tropical oceans. However, not all of these types of tropical disturbances become hurricanes. To develop into a hurricane, significant cyclonic circulation must occur around the disturbances. This type of circulation enhances the development of the group of thunderstorms by providing additional moisture and latent heat energy. With more moisture and latent heat energy, the strength and number of the thunderstorms in the tropical disturbance increases causing the disturbance to intensify. The thunderstorms also begin to organise themselves into spiral bands that swirl cyclonically toward the center of the storm. If the sustained wind speed around the disturbance increases to between 37 and 63 kilometers per hour, the storm becomes classified as a tropical depression. Tropical depressions appear on the weather map as a cyclonic low with several closed isobars circling the storm's center. A tropical depression can continue to intensify and become a tropical storm which is the next stage in hurricane development. Tropical storms have a lower central pressure, several more closed isobars on a weather map, and winds that are between 64 and 118 kilometers per hour. Finally, tropical storms officially become hurricanes when their sustained wind speed exceeds 118 kilometers per hour.

Tropical storms and hurricanes are the most deadly and destructive type of severe weather on our planet. One of the most destructive hurricanes this century was Andrew in August of 1992. This storm, which had a minimal pressure reading of 922 millibars, caused an estimated 26 billion dollars worth of damage mainly in Dade County, Florida. The deadliest storm this century is probably hurricane Mitch which hit Central America in late October and early November 1998. Estimates suggest that over 11,000 people died from this storm. Most of these deaths were caused by flooding and mudslides due to heavy rains.

The damage that hurricanes inflict is caused by high wind speeds, heavy rainfall, storm surge and tornadoes. Wind speed in a hurricane is usually directly related to atmospheric pressure (see **Figure 20-1** above). The lower the pressure the faster the winds blow. Wind speed also varies within the storm. As discussed earlier, winds are usually strongest at the edge of the hurricane's eye. High winds inflict damage by blowing down objects, creating choppy waves and high seas, and by inundating coastal areas with seawater. Rainfall within a hurricane can often exceed 60 centimeters in a 24 hour period. If this rainfall occurs on land, flooding normally occurs. Storm surge is an increase in the height of the ocean's surface in the region beneath and around the eye of the storm. It occurs when low atmospheric pressure causes the ocean surface to expand and because the hurricane's cyclonic winds

blow seawater towards the eye. Hurricane Camille (1969) had a storm surge of more than seven meters with a central pressure of 909 millibars. A considerable amount of damage can also occur because of hurricane generated tornadoes. About 25 % of the hurricanes that make landfall have tornadoes. Some scientists also suspect that the thunderstorms that occur near the eye of a hurricane can produce very strong downbursts (vertical downward movements of air).

The year 1998 was extremely bad for the development of tropical storms and hurricanes in the Atlantic ocean. During the late summer and fall of that year fourteen tropical storms developed of which ten became hurricanes. **Table 20-1** describes some of the characteristics of each of the storms that developed into hurricanes. Seven of the tropical storms and hurricanes made landfall in the United States causing about 6.5 billion dollars worth of damage. The strongest hurricane of the 1998 season was hurricane Mitch. This storm made landfall in Honduras and killed over 11,000 people in Central America.

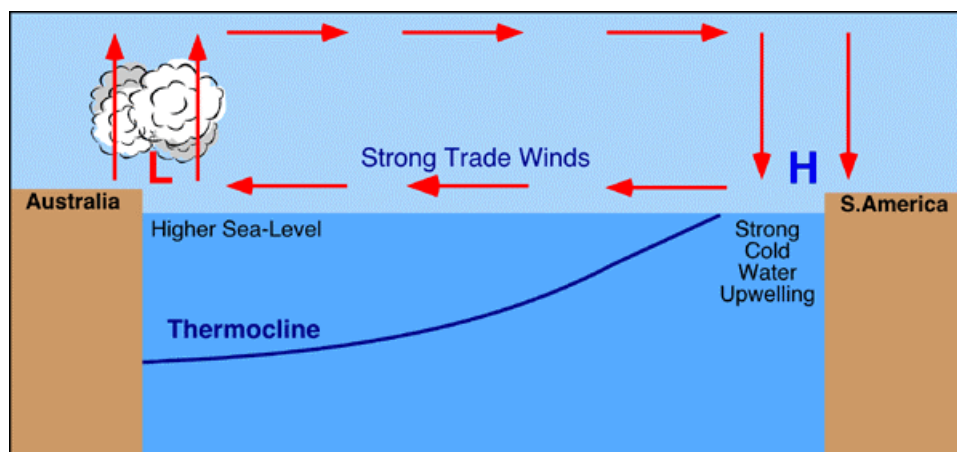
**Table 20-1: Characteristics of the Atlantic hurricanes of the 1998 season.**

Name of Hurricane	Born	Died	Lifespan	Maximum Sustained Winds	Minimum Storm Pressure	Damage in US Dollars	Direct Deaths
Bonnie	Aug 19	Aug 30	10.5 days	185 km/hr	954 mb	1 Billion	3
Danielle	Aug 24	Sept 3	10.5 days	169 km/hr	955 mb	Minimal (Bermuda)	None
Earl	Aug 31	Sept 3	3 days	161 km/hr	986 mb	80 Million	3
Georges	Sept 15	Sept 29	14 days	241 km/hr	938 mb	5.1 Billion	602
Ivan	Sept 20	Sept 26	6.5 days	145 km/hr	975 mb	Minimal (Azores)	None
Jeanne	Sept 21	Sept 30	9 days	169 km/hr	970 mb	Minimal (Azores)	None
Karl	Sept 23	Sept 27	4 days	169 km/hr	970 mb	None	None
Lisa	Oct 5	Oct 9	4 days	121 km/hr	987 mb	None	None
Mitch	Oct 21	Nov 5	14.5 days	290 km/hr	906 mb	Over 10 Billion	Over 11,000
Nicole	Nov 24	Dec 1	7 days	137 km/hr	979 mb	None	None

## 21. El Nino, La Nina and the Southern Oscillation

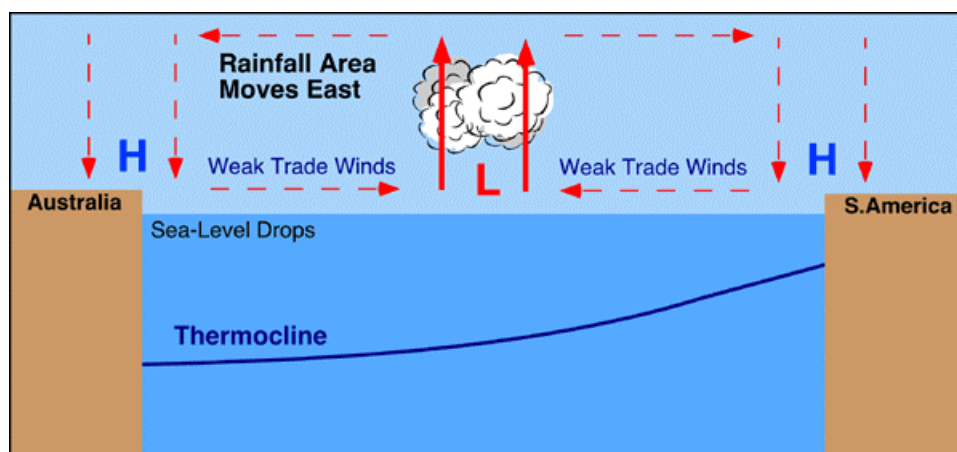
**El Nino** is the name given to the occasional development of warm ocean surface waters along the coast of Ecuador and Peru. When this warming occurs the usual **upwelling** of cold, nutrient rich deep ocean water is significantly reduced. El Nino normally occurs around Christmas and lasts usually for a few weeks to a few months. Sometimes an extremely warm event can develop that lasts for much longer time periods. In the 1990s, strong El Ninos developed in 1991 and lasted until 1995, and from fall 1997 to spring 1998.

The formation of an El Nino is linked with the cycling of a Pacific Ocean circulation pattern known as the southern oscillation. In a normal year, a surface low pressure develops in the region of northern Australia and Indonesia and a high pressure system over the coast of Peru (see **Figure 21-1** below). As a result, the trade winds over the Pacific Ocean move strongly from east to west. The easterly flow of the trade winds carries warm surface waters westward, bringing convective storms to Indonesia and coastal Australia. Along the coast of Peru, cold bottom water wells up to the surface to replace the warm water that is pulled to the west.

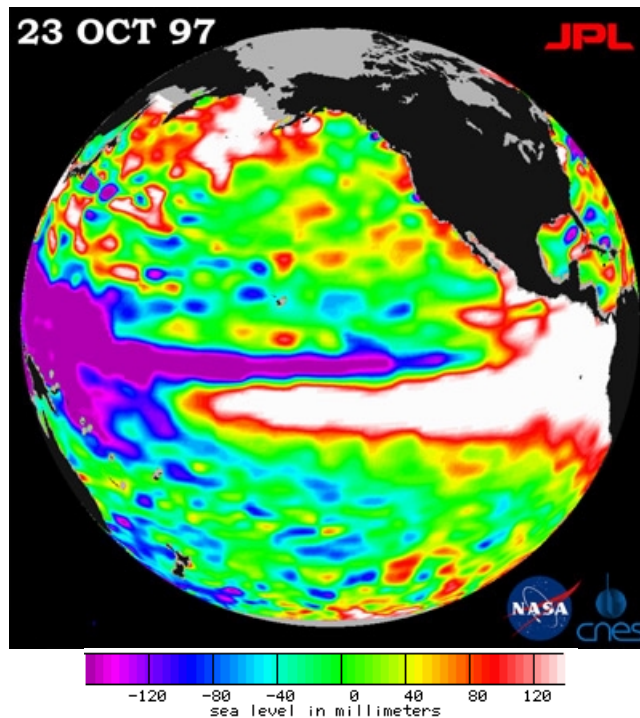


**Figure 21-1:** This cross-section of the Pacific ocean, along the equator, illustrates the pattern of atmospheric circulation typically found at the equatorial Pacific. Note the position of the **thermocline**.

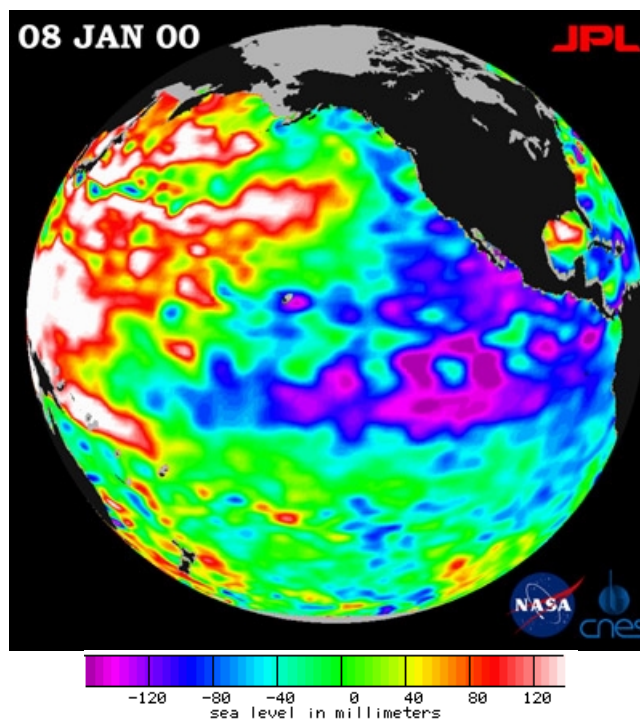
In an El Nino year, air pressure drops over large areas of the central Pacific and along the coast of South America (see **Figure 21-2** below). The normal low pressure system is replaced by a weak high in the western Pacific (the southern oscillation). This change in pressure pattern causes the trade winds to be reduced. This reduction allows the equatorial counter current (which flows west to east) to accumulate warm ocean water along the coastlines of Peru and Ecuador (**Figure 21-3**). This accumulation of warm water causes the **thermocline** to drop in the eastern part of Pacific Ocean which cuts off the upwelling of cold deep ocean water along the coast of Peru. Climatically, the development of an El Nino brings drought to the western Pacific, rains to the equatorial coast of South America, and convective storms and hurricanes to the central Pacific.



**Figure 21-2:** This cross-section of the Pacific ocean, along the equator, illustrates the pattern of atmospheric circulation that causes the formation of the El Nino. Note how position of the thermocline has changed from **Fig. 21-1**



**Figure 21-3:** NASA's TOPEX/Poseidon satellite is being used to monitor the presence of El Niño. Sensors on the satellite measure the height of the Pacific Ocean. The scale below describes the relationship between image colour and the relative surface height of the ocean. In the image above, we can see the presence of a strong El Niño event in the eastern Pacific (October, 1997). The presence of the El Niño causes the height of the ocean along the equator to increase from the middle of the image to the coastline of Central and South America. (Source: NASA - TOPEX/Poseidon).



**Figure 21-4:** TOPEX/Poseidon satellite image of a moderate La Niña condition (January, 2000). The scale below describes the relationship between image colour and the relative surface height of the ocean. The presence of the La Niña causes the height of the ocean either side of the equator to decrease from the middle of the image to the coastline of North, Central, and South America.

After an El Niño event weather conditions usually return back to normal. However, in some years the trade winds can become extremely strong and an abnormal accumulation of cold water can occur in the central and eastern Pacific (**Figure 21-4**). This event is called a **La Niña**. A strong La Niña occurred in 1988 and scientists believe that it may have been responsible for the summer drought over central North America. The most recent La Niña began developing in the middle of 1998 and have been persistent into the winter of 2000. During this period, the Atlantic ocean has seen very active hurricane seasons in 1998 and 1999. In 1998, ten tropical storm developed of which six become full-blown hurricanes. One of the hurricanes that developed, named Mitch, was the strongest October hurricane ever to develop in about 100 years of record keeping. Some of the other weather effects of La Niña include abnormally heavy monsoons in India and Southeast Asia, cool and wet winter weather in southeastern Africa, wet weather in eastern Australia, cold winter in western Canada and northwestern United States, winter drought in the southern United States, warm and wet weather in northeastern United States, and an extremely wet winter in southwestern Canada and northwestern United States.

Prior to the 1980s and 1990s, strong El Niño events occurred on average every 10 to 20 years. In the early 1980s, the first of a series of strong events developed. The El Niño of 1982-83 brought extreme warming to the equatorial Pacific. Surface sea temperatures in some regions of the Pacific Ocean rose 6 degrees Celsius above normal. The warmer waters had a devastating effect on marine life existing off the coast of Peru and Ecuador. Fish catches off the coast of South America were 50 % lower than the previous year. The 1982-83 El Niño also had a pronounced influence on weather in the equatorial Pacific region and world wide. Severe droughts occurred in Australia, Indonesia, India and southern Africa. Dry conditions in Australia resulted in a 2 billion dollar loss in crops, and millions of sheep and cattle died from lack of water. Heavy rains were experienced in California, Ecuador, and the Gulf of Mexico.

Our understanding of the processes responsible for the development of El Niño is still incomplete. Scientists are able to predict the future development of an event by noting the occurrence of particular weather precursors. Researchers also now have a pretty complete understanding of the global weather effects caused by the formation of an El Niño (see **Figure 21-5**).



**Figure 21-5:** Global climatological effects of the El Niño.

## 22. Climate Classification and Climatic Regions of the World

### Climate Classification

The **Köppen Climate Classification System** is the most widely used system for classifying the world's climates. Its categories are based on the annual and monthly averages of temperature and precipitation. The Köppen system recognizes five major climatic types; each type is designated by a capital letter.

**A** - Tropical Moist Climates: all months have average temperatures above 18 degrees Celsius.

**B** - Dry Climates: with deficient precipitation during most of the year.

**C** - Moist Mid-latitude Climates with Mild Winters.

**D** - Moist Mid-Latitude Climates with Cold Winters.

**E** - Polar Climates: with extremely cold winters and summers.

### Tropical Moist Climates (A)

**Tropical moist climates** extend northward and southward from the equator to about 15 to 25 degrees of latitude. In these climates all months have average temperatures greater than 18 degrees Celsius. Annual precipitation is greater than 1500 mm. Three minor Köppen climate types exist in the A group, and their designation is based on seasonal distribution of rainfall. **Af** or **tropical wet** is a tropical climate where precipitation occurs all year long. Monthly temperature variations in this climate are less than 3 degrees Celsius. Because of intense surface heating and high humidity, cumulus and cumulonimbus clouds form early in the afternoons almost every day. Daily highs are about 32 degrees Celsius, while night time temperatures average 22 degrees Celsius. **Am** is a **tropical monsoon** climate. Annual rainfall is equal to or greater than **Af**, but most of the precipitation falls in the 7 to 9 hottest months. During the dry season very little rainfall occurs. The **tropical wet and dry** or savanna (**Aw**) has an extended dry season during winter. Precipitation during the wet season is usually less than 1000 millimeters, and only during the summer season.

### Dry Climates (B)

The most obvious climatic feature of this climate is that potential evaporation and transpiration exceed precipitation. These climates extend from 20 - 35 degrees North and South of the equator and in large continental regions of the mid-latitudes often surrounded by mountains. Minor types of this climate include:

- **Bw - dry arid** (desert) is a true desert climate. It covers 12 % of the Earth's land surface and is dominated by xerophytic vegetation.
- **Bs - dry semiarid** (steppe). Is a grassland climate that covers 14% of the Earth's land surface. It receives more precipitation than the **Bw** either from the intertropical convergence zone or from mid-latitude cyclones.

### Moist Subtropical Mid-Latitude Climates (C)

This climate generally has warm and humid summers with mild winters. Its extent is from 30 to 50 degrees of latitude mainly on the eastern and western borders of most continents. During the winter, the main weather feature is the mid-latitude cyclone. Convective thunderstorms dominate summer months. Three minor types exist: **Cfa - humid subtropical**; **Cs - Mediterranean**; and **Cfb - marine**. The humid subtropical climate (**Cfa**) has hot muggy summers and frequent thunderstorms. Winters are mild and precipitation during this season comes from mid-latitude cyclones. A good example of a **Cfa** climate is the southeastern USA. **Cfb** marine climates are found on the western coasts of continents. They have a humid climate with short dry summer. Heavy precipitation occurs during the mild winters because of the continuous presence of mid-latitude cyclones. Mediterranean climates (**Cs**) receive rain primarily during winter season from the mid-latitude cyclone. Extreme summer aridity is caused by the sinking air of the subtropical highs and may exist for up to 5 months. Locations in North America are from Portland, Oregon to all of California.

### Moist Continental Mid-latitude Climates (D)

Moist continental mid-latitude climates have warm to cool summers and cold winters. The location of these climates is poleward of the C climates. The average temperature of the warmest month is greater than 10 degrees Celsius, while the coldest month is less than -30 degrees Celsius. Winters are severe with snowstorms, strong winds, and bitter cold from Continental Polar or Arctic air masses. Like the C climates there are three minor types: **Dw - dry winters**; **Ds - dry summers**; and **Df - wet all seasons**.

## Polar Climates (E)

Polar climates have year-round cold temperatures with the warmest month less than 10 degrees Celsius. Polar climates are found on the northern coastal areas of North America, Europe, Asia, and on the landmasses of Greenland and Antarctica. Two minor climate types exist. **ET** or **polar tundra** is a climate where the soil is permanently frozen to depths of hundreds of meters, a condition known as permafrost. Vegetation is dominated by mosses, lichens, dwarf trees and scattered woody shrubs. **EF** or **polar ice caps** has a surface that is permanently covered with snow and ice.

### Factors Influencing the World Climatic Regions

So far in this course we have discovered that the climate of a particular place is the function of a number of factors. These factors include:

- 1) Latitude and its influence on solar radiation received.
- 2) Air mass influences.
- 3) Location of global high and low pressure zones.
- 4) Heat exchange from ocean currents.
- 5) Distribution of mountain barriers.
- 6) Pattern of prevailing winds.
- 7) Distribution of land and sea.
- 8) Altitude.

At a macro-level, the first three factors are most important in influencing a region's climate. **Figures 16-3 and 16-4** provide a generalized model of the Earth's annual climatic variations. It also describes the latitudinal effects of these top three factors through the following climatic features:

- Relative annual latitudinal location of the overhead sun at solar noon.
- Intertropical convergence zone and its area of uplift, cloud development and precipitation.
- Subtropical high pressure zone and its associated descending air currents and clear skies.
- Polar front and its area of uplift, cloud development and precipitation.
- Polar vortex and its associated descending air currents and clear skies.
- Relative location of tropical/subtropical and polar air masses.

In the animation we can see that the intertropical convergence zone, the subtropical high pressure zone, polar front and the position of tropical/subtropical and polar air masses all move in response to the seasonal movements of the sun. It is important to understand this concept because of its climatic ramifications for locations on the globe. The type of climate that a location experiences is to a large extent a function of seasonal migration of these weather features. For example, a location at 15 degrees North latitude is influenced by the subtropical high pressure zone during winter solstice and by the intertropical convergence zone during the summer solstice. Another location, at 60 degrees North latitude, would be influenced by polar air masses during the winter solstice, the polar front during the equinoxes, and by subtropical air masses and the subtropical high pressure zone during the summer solstice.

### Climatic Region Descriptions

The following discussion organizes the climatic regions of the world into eight different groups. Categorization of these climates is based on their **Köppen classification** and seasonal dominance of air masses.

#### Tropical Wet

- Köppen Classification - **Af**.
- Dominated by Maritime Tropical air masses all year long.

The tropical wet climate is characterized by somewhat consistent daily high temperatures ranging between 20 to 30 degrees Celsius. The monthly temperature averages vary from 24 to 30 degrees Celsius. Annual range of monthly temperatures is about 3 degrees Celsius. It has reasonably uniform precipitation all year round, and total rainfall over 2000 millimeters or greater.

The region experiencing this climate lies within the effects of the intertropical convergence zone all year long. Convergence and high maritime humidities create cumulus clouds and thunderstorms almost daily.

**Andagoya, Columbia 5°N**, Elevation: 65 m

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. °C	27	27	28	28	27	27	27	27	27	27	27	27	27
Precip. mm	554	519	557	620	655	655	572	574	561	563	563	512	6905

**Iquitos, Peru 4°S , Elevation: 104 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	27	27	27	27	26	26	25	27	27	27	27	27	26
Precip. mm	256	276	349	306	271	199	165	157	191	214	244	217	2845

**Tropical Wet and Dry**

- Köppen Classification - **Aw, Am** and **BS**.
- Maritime Tropical air masses high sun season and Continental Tropical air masses low sun season.

This climate has distinct wet/dry periods. The seasonal pattern of moisture is due to the migration of the intertropical convergence zone. The wet season is synchronous with the high sun and the presence of the convergence zone. The dry season is a result of the more stable air developing from the subsidence associated with the presence of the subtropical high zone during the low sun season.

During the rainy season, the climate of this location is similar to the tropical wet climate: warm, humid, and has frequent thunderstorms. During the dry season more or less semi-desert conditions prevail. Some regions may experience intensification of rainfall because of monsoon development and orographic uplift.

**Calcutta, India 22.5°N , Elevation: 6 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	20	23	28	30	31	30	29	29	30	28	24	21	27
Precip. mm	13	24	27	43	121	259	301	306	290	160	35	3	1582

**Mangalore, India 13°N , Elevation: 22 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	27	27	28	29	29	27	26	26	26	27	27	27	27
Precip. mm	5	2	9	40	233	982	1059	577	267	206	71	18	3467

**Cuiaba, Brazil 13.5°S , Elevation: 165 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	27	27	27	27	26	24	24	26	28	28	28	27	27
Precip. mm	216	198	232	116	52	13	9	12	37	130	165	195	1375

**Darwin, Australia 12.5°S , Elevation: 27 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	28	28	28	28	27	25	25	26	28	29	29	29	28
Precip. mm	341	338	274	121	9	1	2	5	17	66	156	233	1563

**Tropical Desert**

- Köppen Classification - **BW**.
- Dominated by Continental Tropical air masses all year.

This climate type covers 25 percent of all land area on the continents. The heart of the tropical desert climate is found near the tropics of Cancer and Capricorn, usually toward the western side of the continents. Regions with this climate have the following common climatic characteristics:

- low relative humidity and cloud cover.
- low frequency and amount of precipitation.
- high mean annual temperature.
- high monthly temperatures.
- high diurnal temperature ranges.
- high wind velocities.

The tropical desert climate is influenced by upper air stability and subsidence which is the result of the presence of the subtropical high pressure zone. Relative humidity is normally low, averaging 10 to 30 percent in interior locations. Precipitation is very low in quantity and very infrequent in distribution, both temporally and spatially. Temperature varies greatly both diurnally and annually. The highest average monthly temperatures on the Earth are found in the tropical desert. They range between 29 to 35 degrees Celsius. Winter monthly temperatures can be 15 to 25 degrees cooler than summer temperatures. This climate also has extreme diurnal ranges of temperature. The average diurnal range is from 14 to 25 degrees Celsius.

**Wadi Halfa, Sudan 22°N , Elevation: 160 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. °C	15	17	21	26	31	32	32	33	30	28	22	17	25
Precip. mm	0	0	0	0	1	0	1	0	0	1	0	0	3

**Berbera, Somalia 10.5°N , Elevation: 8 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. °C	25	26	27	29	32	37	37	37	34	29	26	26	30
Precip. mm	8	2	5	12	8	1	1	2	1	2	5	5	52

**Alice Springs, Australia 23.5°S , Elevation: 579 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. °C	28	28	25	20	15	12	12	14	18	23	26	27	21
Precip. mm	44	34	28	10	15	13	7	8	7	18	29	39	252

### Mid-Latitude Wet

- Köppen Classification - **Cf** and **Df**.
- Maritime Tropical in summer and Maritime Polar in winter.

The Mid-Latitude Wet climate is found in the Northern Hemisphere in the region from 60 degrees North to 25 to 30 degrees North mainly along the eastern margins of the continents. In North America, this climate extends from the Pacific coast of Canada at latitudes above 55 degrees eastward to the Atlantic coast where it dominates the eastern half of the continent. In the Southern Hemisphere, this climate exists on the Southeastern tip of South America, New Zealand and the Southeast coast of Australia.

Summer weather is dominated by Maritime Tropical air masses which produce many thunderstorms from daytime heating. Monthly average temperature ranges from 21 to 26 degrees Celsius with the tropical areas going as high as 29 degrees Celsius. This is slightly warmer than the humid tropics. Frontal weather associated with the mid-latitude cyclone dominates the climate of more polar areas and is more frequent in all regions in the winter.

Precipitation in this climate is fairly evenly distributed throughout the year. Annual totals of precipitation are quite variable and depend on the latitude and continental position of the regions. During the summer and on the equatorial margins, convective rainfall is the primary mechanism of precipitation. The southeast of the United States averages 40 to 60 days of thunderstorms per year. The frequency of thunderstorms decreases rapidly from south to north. Hurricanes also provide a mechanism for producing precipitation in more tropical regions of this climate.

**New Orleans, USA 30°N , Elevation: 1 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. °C	12	13	16	20	24	27	28	28	26	21	16	13	20
Precip. mm	98	101	136	116	111	113	171	136	128	72	85	104	1371

**Williston, North Dakota 47.5°N , Elevation: 579 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. °C	-12	-10	-4	6	13	17	22	20	14	8	-2	-8	5
Precip. mm	14	12	18	24	36	84	48	38	28	19	15	13	349

**Buenos Aires, Argentina 34.5°S , Elevation: 27 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	23	23	21	17	13	9	10	11	13	15	19	22	16
Precip. mm	103	82	122	90	79	68	61	68	80	100	90	83	1026

**London, England 51.5° N , Elevation: 5 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	4	4	7	9	12	16	18	17	15	11	7	5	10
Precip. mm	54	40	37	38	46	46	56	59	50	57	64	48	595

**Mid-Latitude Winter-Dry**

- Köppen Classification - **Cw** and **Dw**.
- Maritime Tropical air masses in summer and Continental Polar air masses in winter.

This climate is characterized by a strong seasonal pattern of both temperature and precipitation. The normal location of the Mid-Latitude Winter-Dry climate is in the interior of the continents in the mid-latitudes. This continental location causes a large annual temperature range because of continentality.

This climate receives Maritime Tropical air masses in the summer with occasional Continental Tropical air masses from the adjacent deserts. Summers are hot and humid with intense summer convective storms. Continental Polar air masses are dominant in the winter with an occasional outbreak of Maritime Polar air. Continental Polar air masses are associated with cold, dry weather conditions. Precipitation mainly occurs in the summer from thunderstorm activity. The mid-latitude cyclone produces a smaller quantity of precipitation in the winter.

**Calgary, Canada 51°N , Elevation: 1140 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	-10	-9	-4	4	10	13	17	15	11	5	-2	-7	4
Precip. mm	17	20	26	35	52	88	58	59	35	23	16	15	444

**Omaha, USA 41°N , Elevation: 298 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	-5	-3	3	11	17	23	26	25	19	13	4	-2	11
Precip. mm	21	24	37	65	88	115	86	101	67	44	32	20	700

**Mid-Latitude Summer-Dry**

- Köppen Classification - **Cs** and **Ds**.
- Summer weather is dominated by Continental Tropical air, while in the winter, Maritime Polar air masses are frequent.

The Mid-Latitude Summer-Dry climate is found on the western margins of the continents between 30 to 40 degrees of latitude. Usually, this climate does not spread into the continents very far. This climate is often called a Mediterranean climate.

Precipitation falls mainly in the winter in this climate via the mid-latitude cyclone. During the summer these areas are influenced by stable subtropical highs, that give them dry, warm weather.

**Santiago, Chile 33.5°S , Elevation: 512 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	19	19	17	13	11	8	8	9	11	13	16	19	14
Precip. Mm	3	3	5	13	64	84	76	56	30	13	8	5	360

**Los Angeles, USA 34°N , Elevation: 37 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	13	14	15	17	18	20	23	23	22	18	17	15	18
Precip. mm	78	85	57	30	4	2	0	1	6	10	27	73	373

**Rome, Italy 42°N , Elevation: 131 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	8	8	10	13	17	22	24	24	21	16	12	9	15
Precip. mm	76	88	77	72	63	48	14	22	70	128	116	106	881

**Polar Wet and Dry**

- Köppen Classification - **ET**.
- Maritime Polar in summer and Continental Polar or Arctic in winter.

The polar wet and dry climate is characterized by cold winters, cool summers, and a summer rainfall regime. Areas experiencing this climate are the North American Arctic coast, Iceland, coastal Greenland, the Arctic coast of Europe and Asia, and the Southern Hemisphere islands of McQuarie, Kerguelen, and South Georgia. Annual precipitation averages less than 250 mm for most locations and most of this precipitation falls during the summer.

**Isachsen, Canada 79°N , Elevation: 35 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	-35	-37	-35	-24	-12	0	4	1	-8	-19	-28	-32	-19
Precip. mm	2	2	1	4	8	3	22	23	18	10	4	2	98

**Nord, Greenland 81.5°N , Elevation: 35 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	-30	-30	-33	-23	-11	0	4	2	-8	-19	-24	-26	-16
Precip. mm	23	20	8	5	3	5	12	19	21	16	35	37	204

**Polar Desert**

- Köppen Classification - **EF**.
- Continental Arctic and Continental Polar air masses dominate.

Polar Desert climates are located in the high latitudes over continental areas, like Greenland and the Antarctica. This climate type covers a vast area of the Earth. For half of the year no solar radiation is received. During the summer months, available insolation is fairly high because of long days and a relatively transparent atmosphere. However, the albedo of snow-covered surfaces reflects up 90 percent of the insolation back to space. Average monthly temperatures are all generally below zero degrees Celsius. Winds are consistent and velocity is high enough to produce blizzard conditions most of the time.

**Mirny, Antarctica 66.5°S , Elevation: 30 m**

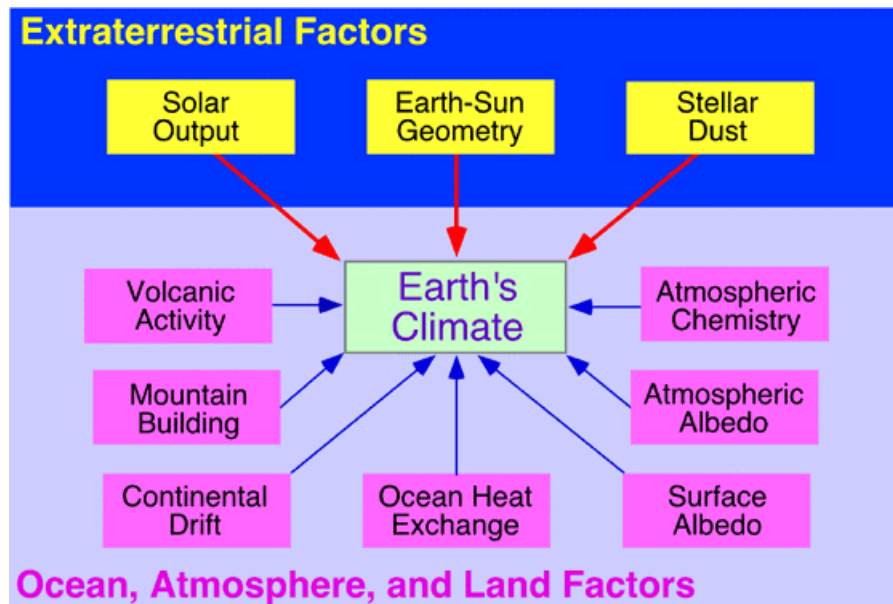
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	-2	-5	-10	-14	-16	-16	-17	-17	-17	-14	-7	-3	-12
Precip. mm	13	19	51	44	92	67	77	95	52	43	46	26	625

**Plateau Station, Antarctica 79°S , Elevation: 3625 m**

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Temp. ° C	-34	-44	-57	-66	-66	-69	-68	-71	-65	-60	-44	-32	-56
Precip. mm	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

## 23. Causes of Climate Change

**Figure 23-1** illustrates the basic components that influence the state of the Earth's climatic system. Changes in the state of this system can occur externally (from extraterrestrial systems) or internally (from ocean, atmosphere and land systems) through any one of the described components. For example, an external change may involve a variation in the sun's output which would externally vary the amount of solar radiation received by the Earth's atmosphere and surface. Internal variations in the Earth's climatic system may be caused by changes in the concentrations of atmospheric gases, mountain building, volcanic activity, and changes in surface or atmospheric albedo.



**Figure 23-1:** Factors that influence the Earth's climate.

The work of climatologists has found evidence to suggest that only a limited number of factors are primarily responsible for most of the past episodes of climate change on the Earth. These factors include:

- Variations in the Earth's orbital characteristics.
- Atmospheric carbon dioxide variations.
- Volcanic eruptions
- Variations in solar output.
- 

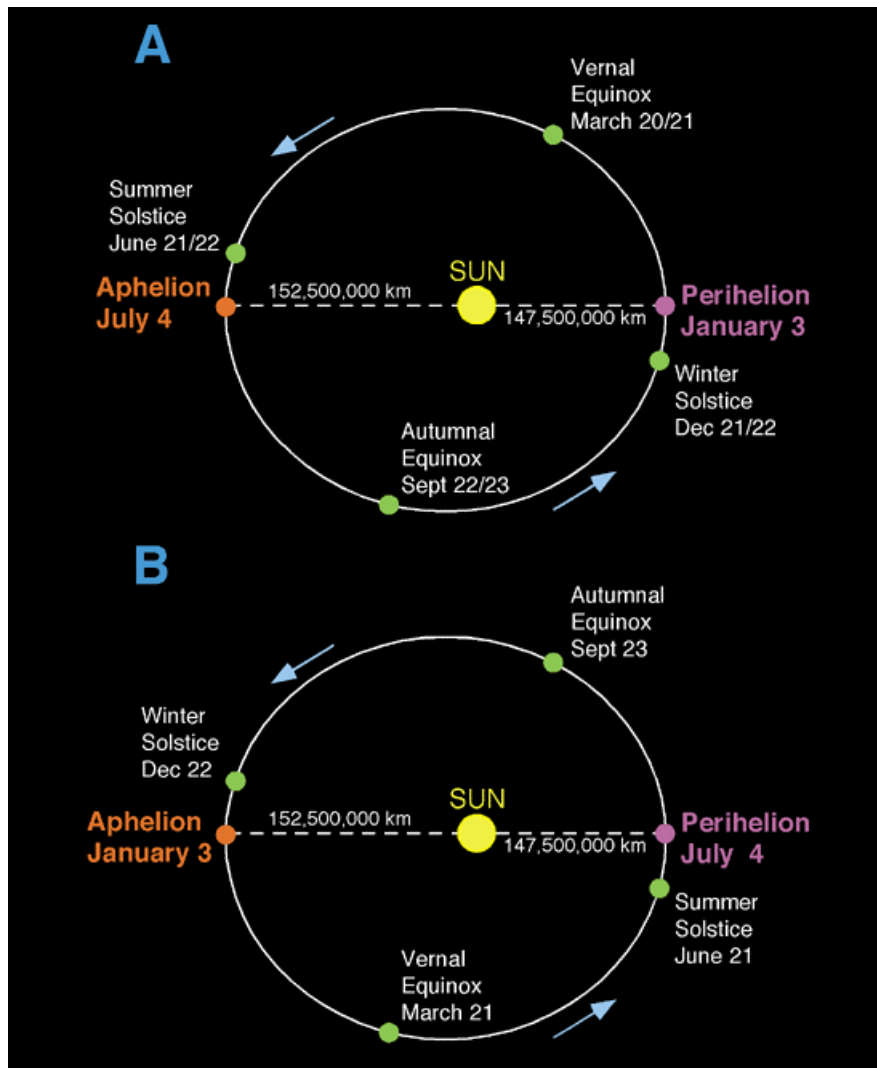
### Variations in the Earth's Orbital Characteristics

The **Milankovitch theory** suggests that normal cyclical variations in three of the Earth's orbital characteristics is probably responsible for some past climatic change. The basic idea behind this theory assumes that over time these three cyclic events vary the amount of solar radiation that is received on the Earth's surface.

The first cyclical variation, known as eccentricity, controls the shape of the Earth's orbit around the sun. The orbit gradually changes from being elliptical to being nearly circular and then back to elliptical in a period of about 100,000 years. The greater the eccentricity of the orbit (i.e., the more elliptical it is), the greater the variation in solar energy received at the top of the atmosphere between the Earth's closest (**perihelion**) and farthest (**aphelion**) approach to the sun. Currently, the Earth is experiencing a period of low eccentricity. The difference in the Earth's distance from the sun between perihelion and aphelion (which is only about 3 %) is responsible for approximately a 7 % variation in the amount of solar energy received at the top of the atmosphere. When the difference in this distance is at its maximum (9 %), the difference in solar energy received is about 20 %.

The second cyclical variation results from the fact that, as the Earth rotates on its polar axis, it wobbles like a spinning top changing the orbital timing of the equinoxes and solstices (see **Figure 23-2** below). This effect is known as the precession of the equinox. The **precession of the equinox** has a cycle of approximately 23,000 years. According to **illustration A**, the Earth is closer to the sun in January (perihelion) and farther away in July (aphelion) at the present time. Because of precession, the reverse will be true in 11,500 years and the Earth will then be closer to the sun in July (**illustration B**). This means, of course, that if everything else remains constant,

11,500 years from now seasonal variations in the Northern Hemisphere should be greater than at present (colder winters and warmer summers) because of the closer proximity of the Earth to the sun.



**Figure 23-2:** Modification of the timing of aphelion and perihelion over time (**A** = today; **B** = 11,500 years into the future).

The third cyclical variation is related to the changes in the tilt (**obliquity**) of the Earth's axis of rotation over a 41,000 year period. During the 41,000 year cycle the tilt can deviate from approximately 22.5 to 24.5 degrees. At the present time, the tilt of the Earth's axis is 23.5 degrees. When the tilt is small there is less climatic variation between the summer and winter seasons in the middle and high latitudes. Winters tend to be milder and summers cooler. Warmer winters allow for more snow to fall in the high latitude regions. When the atmosphere is warmer it has a greater ability to hold water vapor and therefore more snow is produced at areas of frontal or orographic uplift. Cooler summers cause snow and ice to accumulate on the Earth's surface because less of this frozen water is melted. Thus, the net effect of a smaller tilt would be more extensive formation of glaciers in the polar latitudes.

Periods of a larger tilt result in greater seasonal climatic variation in the middle and high latitudes. At these times, winters tend to be colder and summers warmer. Colder winters produce less snow because of lower atmospheric temperatures. As a result, less snow and ice accumulates on the ground surface. Moreover, the warmer summers produced by the larger tilt provide additional energy to melt and evaporate the snow that fell and accumulated during the winter months. In conclusion, glaciers in the polar regions should be generally receding, with other contributing factors constant, during this part of the **obliquity** cycle.

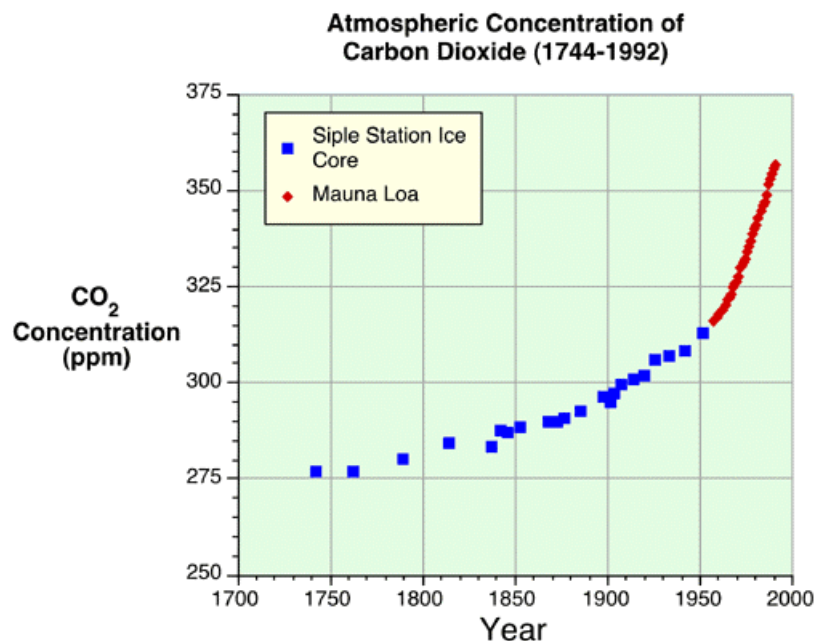
Computer models and historical evidence suggest that the Milankovitch cycles exert their greatest cooling and warming influence when the troughs and peaks of all three cycles coincide with each other.

### Atmospheric Carbon Dioxide Variations

Studies of long term climate change have discovered a connection between the concentration of carbon dioxide in the atmosphere and mean global temperature. Carbon dioxide is one of the more important gases responsible for the greenhouse effect. Certain atmospheric gases, like carbon dioxide, water vapour and methane, are able to alter the energy balance of the Earth by being able to absorb longwave radiation emitted from the Earth's surface. The net result of this process and the re-emission of longwave back to the Earth's surface increases the quantity of heat energy in the Earth's climatic system. Without the greenhouse effect, the average global temperature of the Earth would be a cold -18 degrees Celsius rather than the present 15 degrees Celsius.

Researchers of the 1970s CLIMAP project found strong evidence in deep-ocean sediments of variations in the Earth's global temperature during the past several hundred thousand years of the Earth's history. Other subsequent studies have confirmed these findings and have discovered that these temperature variations were closely correlated to the concentration of carbon dioxide in the atmosphere and variations in solar radiation received by the planet as controlled by the Milankovitch cycles. Measurements indicated that atmospheric carbon dioxide levels were about 30 % lower during colder glacial periods. It was also theorised that the oceans were a major store of carbon dioxide and that they controlled the movement of this gas to and from the atmosphere. The amount of carbon dioxide that can be held in oceans is a function of temperature. Carbon dioxide is released from the oceans when global temperatures become warmer and diffuses into the ocean when temperatures are cooler. Initial changes in global temperature were triggered by changes in received solar radiation by the Earth through the Milankovitch cycles. The increase in carbon dioxide then amplified the global warming by enhancing the greenhouse effect.

Over the past three centuries, the concentration of carbon dioxide has been increasing in the Earth's atmosphere because of human influences (Fig. 21-3). Human activities like the burning of fossil fuels, conversion of natural prairie to farmland, and deforestation have caused the release of carbon dioxide into the atmosphere. From the early 1700s, carbon dioxide has increased from 280 parts per million to 360 parts per million in 1990. Many scientists believe that higher concentrations of carbon dioxide in the atmosphere will enhance the greenhouse effect making the planet warmer. Scientists believe we are already experiencing global warming due to an enhancement of the greenhouse effect. Most computer climate models suggest that the globe will warm up by 1.5 - 4.5 degrees Celsius if carbon dioxide reaches the predicted level of 600 parts per million by the year 2050.



**Figure 23-3:** The following graph illustrates the rise in atmospheric carbon dioxide from 1744 to 1992. Note that the increase in carbon dioxide's concentration in the atmosphere has been **exponential** during the period examined. An extrapolation into the immediate future would suggest continued increases. (Source: Neftel, A., H. Friedli, E. Moore, H. Lotscher, H. Oeschger, U. Siegenthaler, and B. Stauffer. 1994. Historical carbon dioxide record from the Siple Station ice core. pp. 11-14. In T.A. Boden, D.P. Kaiser, R.J. Sepanski, and F.W. Stoss (eds.) **Trends'93: A Compendium of Data on Global Change**. ORNL/CDIAC-65. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn. U.S.A. and Keeling, C.D., and T.P. Whorf. 1994. Atmospheric carbon dioxide records from sites in the SIO air sampling network. Pp. 16-26. In TA Boden, DP Kaiser, R.J. Sepanski, and F.W. Stoss (eds.) **Trends'93: A Compendium of Data on Global Change**.

### Volcanic Eruptions

For many years, climatologists have noticed a connection between large explosive volcanic eruptions and short term climatic change (**Figure 23-4**). For example, one of the coldest years in the last two centuries occurred the year following the Tambora volcanic eruption in 1815. Accounts of very cold weather were documented in the year following this eruption in a number of regions across the planet. Several other major volcanic events also show a pattern of cooler global temperatures lasting 1 to 3 years after their eruption.



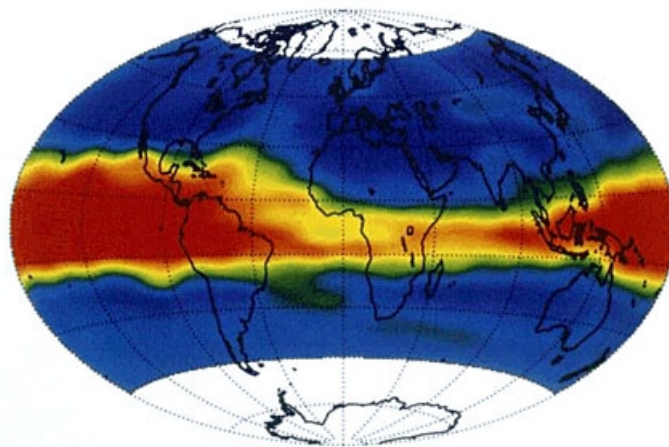
**Figure 23-4:** Explosive volcanic eruptions have been shown to have a short-term cooling effect on the atmosphere if they eject large quantities of sulphur dioxide into the stratosphere. This image shows the eruption of Mount St. Helens on 18.05.1980 which had a local effect on climate because of ash reducing the reception of solar radiation on the Earth's surface. Mount St. Helens had very minimal global effect on the climate because the eruption occurred at an oblique angle putting little sulphur dioxide into the stratosphere. (**Source:** U.S. Geol. Survey, photo by Austin Post).

At first, scientists thought that the dust emitted into the atmosphere from large volcanic eruptions was responsible for the cooling by partially blocking the transmission of solar radiation to the Earth's surface. However, measurements indicate that most of the dust thrown in the atmosphere returned to the Earth's surface within six months. Recent stratospheric data suggests that large explosive volcanic eruptions also eject large quantities of sulphur dioxide gas which remains in the atmosphere for as long as three years. Atmospheric chemists have determined that the ejected sulphur dioxide gas reacts with water vapour commonly found in the stratosphere to form a dense optically bright haze layer that reduces the atmospheric transmission of some of the sun's incoming radiation.

In the last century, two significant climate modifying eruptions have occurred. El Chichon in Mexico erupted in April of 1982, and Mount Pinatubo went off in the Philippines during June, 1991 (**Figure 23-5**). Of these two volcanic events, Mount Pinatubo had a greater effect on the Earth's climate and ejected about 20 million tons of sulphur dioxide into the stratosphere (**Figure 23-6**). Researchers believe that the Pinatubo eruption was primarily responsible for the 0.8 degree Celsius drop in global average air temperature in 1992. The global climatic effects of the eruption of Mount Pinatubo are believed to have peaked in late 1993. Satellite data confirmed the connection between the Mount Pinatubo eruption and the global temperature decrease in 1992 and 1993. The satellite data indicated that the sulphur dioxide plume from the eruption caused a several percent increase in the amount of sunlight reflected by the Earth's atmosphere back to space causing the surface of the planet to cool.



**Figure 23-5:** Ash column generated by the eruption of Mount Pinatubo on June 12, 1991. The strongest eruption of Mount Pinatubo occurred three days later on June 15, 1991. (**Source:** US Geological Survey).



**Figure 23-6:** The following satellite image shows the distribution of Mount Pinatubo's sulfur dioxide and dust aerosol plume (red and yellow areas) between June 14 and July 26, 1991. Approximately 45 days after the eruption, the aerosol plume completely circled the Earth around the equator forming a band 20 to 50 degrees of latitude wide. Areas outside this band were clear of volcanic aerosols. Within a year, the sulfur dioxide continued to migrate towards the North and South Pole until it covered the entire Earth because of the dominant poleward flow of stratospheric winds (stratospheric winds circulate from the equator to the polar vortices at the North and South Poles). These observed patterns of aerosol movement suggest that tropical explosive volcanic eruptions probably have the greatest effect on the Earth's climate. Diffusion of aerosols by stratospheric winds from a tropical source results in the greatest latitudinal coverage of the sulfur dioxide across both the Northern and Southern Hemispheres. (**Source:** SAGE II Satellite Project - NASA).

### Variations in Solar Output

Until recently, many scientists thought that the sun's output of radiation only varied by a fraction of a percent over many years. However, measurements made by satellites equipped with radiometers in the 1980s and 1990s suggested that the sun's energy output may be more variable than was once thought (**Figure 21-7**). Measurements made during the early 1980s showed a decrease of 0.1% in the total amount of solar energy reaching the Earth over just an 18 month time period. If this trend were to extend over several decades, it could influence global climate. Numerical climatic models predict that a change in solar output of only 1% per century would alter the Earth's average temperature by between 0.5°C to 1.0°C.



**Figure 23-7:** The sun as seen at sunset. The sun is essentially the only source of energy for running the Earth's climate. Thus any change in its output will result in changes in the reception of insolation and the generation of heat energy which drives the climate system.

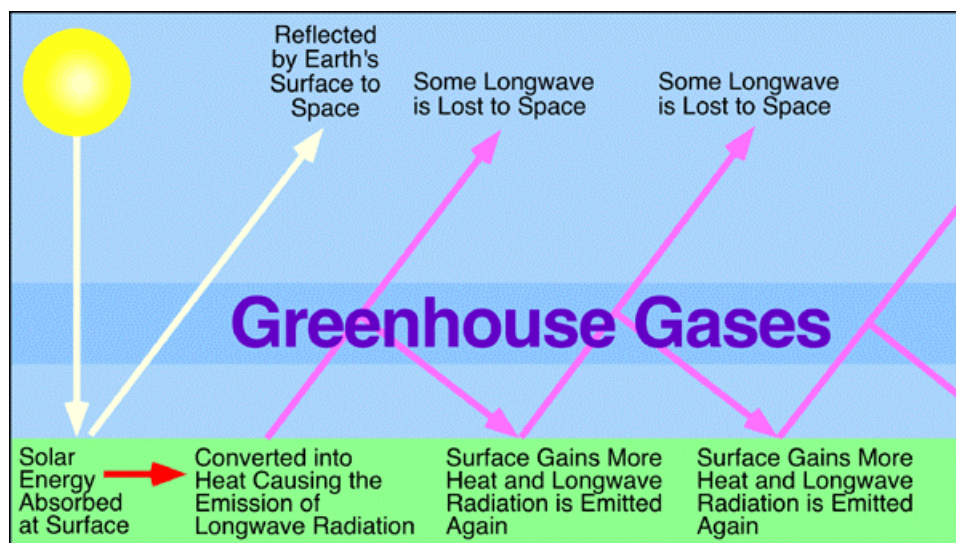
Scientists have long tried to also link sunspots to climatic. Sunspots are huge magnetic storms that are seen as dark (cooler) areas on the sun's surface. The number and size of sunspots show cyclical patterns, reaching a maximum about every 11, 90, and 180 years. The decrease in solar energy observed in the early 1980s correspond to a period of maximum sunspot activity based on the 11 year cycle. In addition, measurements made with a solar telescope from 1976 to 1980 showed that during this period, as the number and size of sunspots increased, the sun's surface cooled by about 6 degrees Celsius. Apparently, the sunspots prevented some of the sun's energy from leaving its surface. However, these findings tend to contradict observations made on longer times scales. Observations of the sun during the middle of the Little Ice Age (1650 to 1750) indicated that very little sunspot activity was occurring on the sun's surface. The **Little Ice Age** was a time of a much cooler global climate and some scientists correlate this occurrence with a reduction in solar activity over a period of 90 or 180 years. Measurements have shown that these 90 and 180 year cycles influence the amplitude of the 11 year sunspot cycle. It is hypothesised that during times of low amplitude, like the Maunder Minimum, the sun's output of radiation is reduced. Observations by astronomers during this period (1645 to 1715) noticed very little sunspot activity occurring on the sun.

During periods of maximum sunspot activity, the sun's magnetic field is strong. When sunspot activity is low, the sun's magnetic field weakens. The magnetic field of the sun also reverses every 22 years, during a sunspot minimum. Some scientists believe that the periodic droughts on the Great Plains of the United States are in someway correlated with this 22 year cycle.

## 24. The Greenhouse Effect

The greenhouse effect is a naturally occurring process that aids in heating the Earth's surface and atmosphere. It results from the fact that certain atmospheric gases, such as CO<sub>2</sub>, **water vapour**, and methane, are able to change the energy balance of the planet by absorbing longwave radiation emitted from the Earth's surface. Without the greenhouse effect life on this planet would probably not exist as the average temperature of the Earth would be a chilly -18°C, rather than the present 15°C.

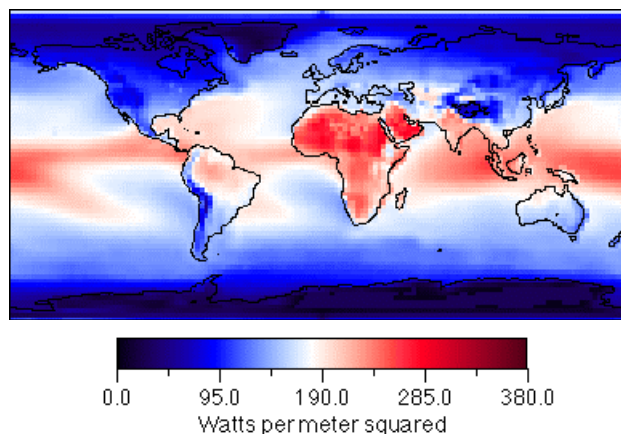
As energy from the sun passes through the atmosphere a number of things take place. A portion of the energy (26 % globally) is reflected back to space by clouds and particles. About 19% of the energy available is absorbed by clouds, gases (like ozone), and particles in the atmosphere. Of the remaining 55% of the solar energy passing through the Earth's atmosphere, 4% is reflected from the surface back to space. On average, about 51% of the sun's radiation reaches the surface. This energy is then used in a number of processes, including the heating of the ground surface; the melting of ice and snow and the evaporation of water; and plant photosynthesis.



**Figure 24-1:** The diagram above illustrates the greenhouse effect. This process begins with the absorption of shortwave radiation from the sun. Absorption causes the solar energy to be converted into sensible heat at the Earth's surface. Some of this heat is transferred to the lower atmosphere by conduction and convection. After the heating of the ground and the lower atmosphere, these surfaces become radiators of infrared or longwave radiation and they begin to cool. This emission of energy is directed to space. However, only a portion of this energy actually makes it through the atmosphere. About 70% of the longwave radiation emitted from the Earth's surface is absorbed by the atmosphere's greenhouse gases. Absorption of this energy causes heat energy to be added to the Earth's atmospheric system through the warming of greenhouse gas molecules. The greenhouse gas molecules then begin radiating longwave energy primarily back to the Earth's surface where it once again creates heat energy. The heating of the ground by the longwave radiation causes the ground surface to once again radiate, repeating the cycle described above, again and again, until no more infrared radiation is available for surface absorption. In conclusion, the **greenhouse effect** is an increase in the creation and storage of heat energy to the Earth's atmosphere and ground surface

The heating of the ground by sunlight causes the Earth's surface to become a radiator of energy in the longwave band (sometimes called infrared radiation). This emission of energy is generally directed to space (see Figure 24-1). However, only a small portion of this energy actually makes it back to space. The majority of the outgoing infrared radiation is absorbed by the greenhouse gases (see **Figure 24-2** below).

Absorption of longwave radiation by the atmosphere causes additional heat energy to be added to the Earth's atmospheric system. The now warmer atmospheric greenhouse gas molecules begin radiating longwave energy in all directions. Over 90% of this emission of longwave energy is directed back to the Earth's surface where it once again is absorbed by the surface. The heating of the ground by the longwave radiation causes the ground surface to once again radiate, repeating the cycle described above, again and again, until no more longwave is available for absorption.



**Figure 24-2:** Annual (1987) quantity of outgoing longwave radiation absorbed in the atmosphere.

The amount of heat energy added to the atmosphere by the greenhouse effect is controlled by the concentration of greenhouse gases in the Earth's atmosphere. All of the major greenhouse gases have increased in concentration since the beginning of the Industrial Revolution (about 1700 AD). As a result of these higher concentrations, scientists predict that the greenhouse effect will be **enhanced** and the Earth's climate will become warmer. Predicting the amount of warming is accomplished by computer modeling. Computer models suggest that a doubling of the concentration of the main greenhouse gas, carbon dioxide, may raise the average global temperature between 1 and 3 degrees Celsius. However, the numeric equations of computer models do not accurately simulate the effects of a number of possible negative feedbacks. For example, many of the models cannot properly simulate the negative effects that increased cloud cover would have on the radiation balance of a warmer Earth. Increasing the Earth's temperature would cause the oceans to evaporate greater amounts of water, causing the atmosphere to become cloudier. These extra clouds would then reflect a greater proportion of the sun's energy back to space reducing the amount of solar radiation absorbed by the atmosphere and the Earth's surface. With less solar energy being absorbed at the surface, the effects of an enhanced greenhouse effect may be counteracted.

A number of gases are involved in the greenhouse effect (see **Table 24-1** below). These gases include: carbon dioxide (CO<sub>2</sub>); methane (CH<sub>4</sub>); nitrous oxide (N<sub>2</sub>O); chlorofluorocarbons (CF<sub>x</sub>Cl<sub>x</sub>); and tropospheric ozone (O<sub>3</sub>). Of these gases, the single most important gas is carbon dioxide which accounts for about 55 % of the change in the intensity of the Earth's greenhouse effect. The contributions of the other gases are 25 % for chlorofluorocarbons, 15 % for methane, and 5 % for nitrous oxide. Ozone's contribution to the **enhancement** of greenhouse effect is still yet to be quantified.

Concentrations of carbon dioxide (CO<sub>2</sub>) in the atmosphere are now approaching 360 parts per million. Prior to 1700, levels of carbon dioxide were about 280 parts per million. This increase in CO<sub>2</sub> in the atmosphere is primarily due to the activities of humans. Beginning in 1700, societal changes brought about by the Industrial Revolution increased the amount of carbon dioxide entering the atmosphere. The major sources of this gas include fossil fuel combustion for industry, transportation, space heating, electricity generation and cooking; and vegetation changes in natural prairie, woodland, and forested ecosystems. Emissions from fossil fuel combustion account for about 65% of the extra CO<sub>2</sub> now found in our atmosphere. The remaining 35% is derived from deforestation and the conversion of prairie, woodland, and forested ecosystems primarily into agricultural systems. Natural ecosystems can hold 20 to 100 times more CO<sub>2</sub> per unit area than agricultural systems. Artificially created chlorofluorocarbons are the strongest greenhouse gas per molecule. However, low concentrations in the atmosphere reduce their overall importance in the **enhancement** of the greenhouse effect. Current measurements in the atmosphere indicate that the concentration of these chemicals may soon begin declining because of reduced emissions. Reports of the development of ozone holes over the North and South Poles and a general decline in global stratospheric ozone levels over the last two decades has caused many nations to cutback on their production and use of these chemicals. In 1987, the signing of the Montreal Protocol agreement by forty-six nations established an immediate timetable for the global reduction of chlorofluorocarbons production and use.

Since 1750, methane concentrations in the atmosphere have increased by more than 140%. The primary sources for the additional methane added to the atmosphere (in order of importance) are rice cultivation, domestic grazing animals, termites, landfills, coal mining, and oil and gas extraction. Anaerobic conditions associated with rice paddy flooding results in the formation of methane gas. However, an accurate estimate of how much methane is being produced from rice paddies has been difficult to obtain. More than 60 % of all rice paddies are found in India and China where scientific data concerning emission rates are unavailable. Nevertheless, scientists believe that the contribution of rice paddies is large because this form of crop production has more than doubled

since 1950. Grazing animals release methane to the environment as a result of herbaceous digestion. Some researchers believe the addition of methane from this source has more than quadrupled over the last century. Termites also release methane through similar processes. Land-use change in the tropics, due to deforestation, ranching, and farming, may be causing termite numbers to expand. If this assumption is correct, the contribution from these insects may be important. Methane is also released from landfills, coal mines, and gas and oil drilling. Landfills produce methane as organic wastes decompose over time. Coal, oil, and natural gas deposits release methane to the atmosphere when these deposits are excavated or drilled.

The average concentration of nitrous oxide in the atmosphere is now increasing at a rate of 0.2 to 0.3% per year. Sources for this increase include land-use conversion; fossil fuel combustion; biomass burning; and soil fertilisation. Most of the nitrous oxide added to the atmosphere each year comes from deforestation and the conversion of forest, savannah and grassland ecosystems into agricultural fields and rangeland. Both of these processes reduce the amount of nitrogen stored in living vegetation and soil through the decomposition of organic matter. Nitrous oxide is also released into the atmosphere when fossil fuels and biomass are burned. However, the combined contribution of these sources to the increase of this gas in the atmosphere is thought to be minor. The use of nitrate and ammonium fertilisers to enhance plant growth is another source of nitrous oxide. Accurate measurements of how much nitrous oxide is being released from fertilisation have been difficult to obtain. Estimates suggest that the contribution from this source may represent from 50% to 0.2% of nitrous oxide added to the atmosphere annually.

Ozone's role in the enhancement of the greenhouse effect has been difficult to determine scientifically. Accurate measurements of past long-term (more than 25 years in the past) levels of this gas in the atmosphere are currently unavailable. Concentrations of ozone gas are found in two different regions of the Earth's atmosphere. The majority of the ozone (about 97 %) found in the atmosphere is localised in the stratosphere at an altitude of 15 to 55 kilometers above the Earth's surface. In recent years, the concentration of the stratospheric ozone has been decreasing because of the buildup of chlorofluorocarbons in the atmosphere. Since the late 1970s, scientists have discovered that total column ozone amounts over Antarctica in the springtime have decreased by as much as 70 %. Satellite measurements have indicated that the zone from 65°N to 65°S latitude has had a 3 % decrease in stratospheric ozone since 1978. Ozone is also highly concentrated at the Earth's surface. Most of this ozone is created as an artificial by product of photochemical smog.

In summary, the **greenhouse effect** causes the atmosphere to trap more heat energy at the Earth's surface and within the atmosphere by absorbing and re-emitting longwave energy. Of the longwave energy emitted back to space, 90% is intercepted and absorbed by greenhouse gases. Without the greenhouse effect the Earth's average global temperature would be  $-18^{\circ}\text{C}$ , rather than the present  $15^{\circ}\text{C}$ . In the last few centuries, the activities of humans have directly or indirectly caused the concentration of the major greenhouse gases to increase. Scientists predict that this increase may **enhance** the greenhouse effect making the planet warmer. Some experts estimate that the Earth's average global temperature has already increased by  $0.3^{\circ}\text{C}$  to  $0.6^{\circ}\text{C}$ , since the beginning of this century, because of this enhancement. Predictions of future climates indicate that by the middle of the next century the Earth's global temperature may be  $1^{\circ}\text{C}$  to  $3^{\circ}\text{C}$  higher than today.

**Table 24-1: Gases involved in the Greenhouse Effect: past and present concentration and sources.**

Greenhouse Gas	Concentration 1750	Concentration 1995	Percent Change	Natural and Anthropogenic Sources
Carbon Dioxide	280 ppm	360 ppm	29 %	Organic decay; Forest fires; Volcanoes; Burning fossil fuels; Deforestation; Land-use change
Methane	0.70 ppm	1.70 ppm	143 %	Wetlands; Organic decay; Termites; Natural gas & oil extraction; Biomass burning; Rice cultivation; Cattle; Refuse landfills
Nitrous Oxide	280 ppb	310 ppb	11 %	Forests; Grasslands; Oceans; Soils; Soil cultivation; Fertilizers; Biomass burning; Burning of fossil fuels
Chlorofluorocarbons (CFCs)	0	900 ppt	Not Applicable	Refrigerators; Aerosol spray propellants; Cleaning solvents
Ozone	Unknown	Varies with latitude and altitude in the atmosphere	Generally decreased in the stratosph. and increased near the E. surface	Created naturally by the action of sunlight on molecular oxygen and artificially through photochemical smog production

# GLOSSARY

## A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

### - A -

**Abiotic**

Non-living thing. Usually refers to the physical and chemical components of an organism's environment. Also called inorganic.

**Absolute Humidity**

Measurement of atmospheric humidity. Absolute humidity is the mass of water vapor in a given volume of air (this measurement is not influenced by the mass of the air). Normally expressed in grams of water vapor per cubic meter of atmosphere at a specific temperature.

**Absolute Zero**

Temperature of - 273.15 degrees Celsius. At this temperature atomic motion stops.

**Absorption (Atmospheric)**

Atmospheric absorption is defined as a process in which solar radiation is retained by a substance and converted into heat energy. The creation of heat energy also causes the substance to emit its own radiation. In general, the absorption of solar radiation by substances in the Earth's atmosphere results in temperatures that get no higher than 1800 degrees Celsius. According to Wien's Law, bodies with temperatures at this level or lower would emit their radiation in the longwave band.

**Acclimation**

Slow adjustment of an organism to new conditions in its environment.

**Acid Rain**

Rain with a pH less than 5.6. Normal pH of precipitation is 5.6.

**Active Layer**

Upper zone of soil in higher latitude locations that experiences daily and seasonal freeze-thaw cycles.

**Active Remote Sensing**

Form of remote sensing where the sensor provides its own source of electromagnetic radiation to illuminate the object under study. Radar is an example of an active remote sensing device.

**Actual Evapotranspiration**

Is the amount of water that is actually removed from a surface due to the processes of evaporation and transpiration.

**Actual Mixing Ratio**

Another term used to describe mixing ratio.

**Adiabatic**

A process in which heat does not enter or leave a system. In the atmospheric sciences, adiabatic processes are often used to model internal energy changes in rising and descending parcels of air in the atmosphere. When a parcel of air rises it expands because of a reduction in pressure. If no other non-adiabatic processes occur (like condensation, evaporation and radiation), expansion causes the parcel of air to cool at a set rate of 0.98°/100m. The opposite occurs when a parcel of air descends in the atmosphere. The air in a descending parcel becomes compressed. Compression causes the temperature within the parcel to increase at a rate of 0.98°/100m.

**Adiabatic Cooling**

The cooling of a rising parcel of air due to adiabatic processes.

**Advection**

Advection involves the transfer of heat energy by means of horizontal mass motions through a medium.

**Advection Fog**

Fog generated by winds that contrast in temperature with the Earth's surface. Warm air advection can produce fog through contact cooling with a cold surface.

**Air Mass**

A body of air whose temperature and humidity characteristics remain relatively constant over a horizontal distance of hundreds to thousands of kilometers. Air masses develop their climatic characteristics by remaining stationary over a source region for a number of days. Air masses are classified according to their temperature and humidity characteristics.

**Air Pollution**

Toxification of the atmosphere through the addition of one or more harmful substances in the air. Substance must be in concentrations high enough to be hazardous to humans, other animals, vegetation, or materials.

**Albedo**

Is the reflectivity of a surface.

**Aleutian Low**

Subpolar low pressure system found near the Aleutian Islands. Most developed during the winter season. This large-scale pressure system spawns mid-latitude cyclones.

**Altitude**

Vertical distance above sea-level.

**Altostratus Clouds**

Middle altitude cloud that is colored from white to gray. This cloud is composed of a mixture of water droplets and ice crystals. It appears in the atmosphere as layers or patches that are well rounded and commonly wavelike. Found in an altitude range from 2,000 to 8,000 m.

**Altostratus Clouds**

Gray-looking middle altitude cloud that is composed of water droplets and ice crystals. Appears in the atmosphere as dense sheet like layer. Can be recognized from stratus clouds by the fact that you can see the sun through it. Found in an altitude range from 2,000 to 8,000 meters.

**Anemometer**

Mechanical instrument used to measure wind speed. These instruments commonly employ three methods to measure this phenomenon: 1) A device with three or four open cups attached to a rotating spinal. The speed of rotation is then converted into a measurement of wind speed; 2) A pressure plate that measures the force exerted by the moving wind at right angles; 3) A device consisting of a heated-wire where electrical resistance (temperature of the wire) is adjusted to account for heat lost by air flow. The faster the wind the greater the heat loss and thus the more energy that is required to keep the wire at a constant temperature. As a result, wind speed is measured through the drain of electrical current.

**Aneroid Barometer**

Barometer that measures atmospheric pressure via the expansion and contraction of a sealed hollow cell which is partially depleted of air.

**Antarctic Circle**

Latitude of 66.5°S. The northern limit of the area of the Earth that experiences 24 hours of darkness or 24 hours of day at least one day during the year.

**Antarctic High**

A region of high pressure that occupies central Antarctic throughout the year. This pressure system is responsible for very cold temperatures and extremely low humidity.

**Anticyclone**

An atmospheric pressure system consisting of an area of high pressure and outward circular surface wind flow. In the Northern Hemisphere winds from an anticyclone blow clockwise, while Southern Hemisphere systems blow counterclockwise.

**Aphelion**

It is the point in the Earth's orbit when it is farthest from the sun (152.5 million kilometers). Aphelion occurs on the 3rd or 4th of July.

**Arctic Circle**

Latitude of 66.5°N. The southern limit of the area of the Earth that experiences 24 hours of darkness or 24 hours of day at least one day during the year.

**Atmosphere**

The atmosphere is the vast gaseous envelope of air that surrounds the Earth. Its boundaries are not easily defined. The atmosphere contains a complex system of gases and suspended particles that behave in many ways like fluids. Many of its constituents are derived from the Earth by way of chemical and biochemical reactions.

**Atmospheric Pressure**

Weight of the atmosphere on a surface. At sea-level, the average atmospheric pressure is 1013.25 millibars. Pressure is measured by a device called a barometer.

**Atmospheric Stability**

Relative stability of parcels of air relative to the atmosphere that surrounds them. Three conditions are generally described: stable, unstable, and neutral.

**Autumnal Equinox**

One of the two periods when the declination of the sun is at the equator. The autumnal equinox occurs on September 21 or 22.

**Average Global Temperature**

Average annual temperature of the Earth's entire surface atmosphere.

**Azimuth**

A system that measures direction clockwise from North over 360 degrees.

**Azores High**

High pressure system that develops over the western subtropical North Atlantic. Also called *Bermuda High*.

**- B -****Backscattering**

Portion of solar radiation directed back into space as a result of particle scattering in the atmosphere.

**Barometer**

Instrument that measures atmospheric pressure.

**Beaufort Wind Scale**

Descriptive system that determines wind speed by noting the effect of the wind on the environment. Originally developed for use at sea by Admiral Beaufort of the British Navy in 1806.

**Bermuda High**

High pressure system that develops over the western subtropical North Atlantic. Also called *Azores High*.

**Biogeochemical Cycling**

Cycling of chemicals through the biosphere, lithosphere, hydrosphere, and atmosphere.

**Blizzard**

Winter severe weather condition characterized by strong wind, blowing snow, and cold temperatures.

**Bora**

Term used to describe a katabatic wind in Yugoslavia.

**British Thermal Unit (Btu)**

Measurement unit for heat. It is the amount of energy required to raise the temperature of one pound of water one degree from 62 to 63°F. One Btu is equal to 252 calories and to 1055 joules.

**- C -****Calorie**

Quantity of energy. Equals the amount of heat required to raise 1 gram of pure water from 14.5 to 15.5°C at standard atmospheric pressure.

**Canadian High**

High pressure system that develops in winter over central North America.

**Carbon Cycle**

Storage and cyclic movement of organic and inorganic forms of carbon between the biosphere, lithosphere, hydrosphere, and atmosphere.

**Carbon Dioxide**

Common gas found in the atmosphere. Has the ability to selectively absorb radiation in the longwave band. This absorption causes the greenhouse effect. The concentration of this gas has been steadily increasing in the atmosphere over the last three centuries due to the burning of fossil fuels, deforestation, and land-use change. Some scientists believe higher concentrations of carbon dioxide and other greenhouse gases will result in an enhancement of the greenhouse effect and global warming. The chemical formula for carbon dioxide is CO<sub>2</sub>.

**Carbon Monoxide**

A colorless, odorless, and tasteless gas that is produced by the incomplete burning of fossil fuels. The chemical formula for carbon dioxide is CO.

**Celsius Scale**

Scale for measuring temperature. In this scale, water boils at 100 degrees and freezes at 0 degrees.

**Centripetal Force**

Force required to keep an object moving in a circular pattern around a center of rotation. This force is directed towards the center of rotation. Common in meteorological phenomena like tornadoes and hurricanes.

**Chinook Wind**

The name of a North American wind that occurs on the leeward side of mountains. This wind is warm and has a low humidity.

**Chlorofluorocarbons (CFCs)**

Is an artificially created gas that has become concentrated in the Earth's atmosphere. This very strong greenhouse gas is released from aerosol sprays, refrigerants, and the production of foams. The basic chemical formula for chlorofluorocarbons is  $CF_xCl_x$ .

**Cirrocumulus Clouds**

Patchy white high altitude cloud composed of ice crystals. Found in an altitude range from 5,000 to 18,000 meters.

**Cirrostratus Clouds**

High altitude sheet like clouds composed of ice crystals. These thin clouds often cover the entire sky. Found in an altitude range from 5,000 to 18,000 meters.

**Cirrus Clouds**

High altitude cloud composed of ice crystals. The appearance of these clouds is white feather like patches, filaments or thin bands. Found in an altitude range from 5,000 to 18,000 meters.

**CLIMAP Project**

Multiuniversity research project that reconstructed the Earth's climate for the last million years by examining proxy data from ocean sediment cores.

**Climate**

General pattern of weather conditions for a region over a long period time (at least 30 years).

**Climatology**

Scientific study of the Earth's climate over long time spans (greater than several days). May also involve the investigation of climate's influence on the biotic and the abiotic environment.

**Climograph**

Two dimensional graph that plots a location's air temperature and precipitation on times scales that range from a 24 hour period to a year.

**Closed System**

Is a system closed with respect to matter, but energy may be transferred between the system and its surroundings. Earth is essentially a closed system.

**Cloud**

A collection of tiny particles of liquid or solid water occurring above the Earth's surface. Clouds are classified accord to their height of occurrence and shape. The major types of clouds include: Cirrus, Cirrocumulus, Cirrostratus, Altocumulus, Altostratus, Nimbostratus, Stratocumulus, Stratus, Cumulus, and Cumulonimbus.

**Cold Desert**

Desert found in the high latitudes and at high altitudes where precipitation is low. Surface air temperatures are generally cold in these dry environments.

**Cold Front**

A transition zone in the atmosphere where an advancing cold air mass displaces a warm air mass.

**Condensation**

The change in state of matter from vapor to liquid that occurs with cooling. Usually used in meteorology when discussing the formation of liquid water from vapor. This process releases latent heat energy to the environment.

**Condensation Nuclei**

Microscopic particle of dust, smoke or salt that allows for condensation of water vapor to water droplets in the atmosphere. Nucleus for the formation of a rain drop. Condensation normally occurs on these particles when relative humidity becomes 100 %. Some condensation nuclei, like salt, are hygroscopic and water can condense on them at relative humidities lower than 100%.

**Conduction**

Conduction consists of energy transfer directly from atom to atom and represents the flow of energy along a temperature gradient.

**Continental Arctic Air Mass (A)**

Air mass that forms over extensive landmass areas of the high latitudes. In the Northern Hemisphere, these systems form only in winter over Greenland, northern Canada, northern Siberia, and the Arctic Basin.

Continental Arctic air masses are very cold and extremely dry. These air masses are also very stable.

**Continental Effect**

The effect that continental surfaces have on the climate of locations or regions. This effect results in a greater range in surface air temperature at both daily and annual scales. Also see maritime effect.

**Continental Polar Air Mass (cP)**

Air mass that forms over extensive landmass areas of middle to high latitudes. In North America, these systems form over northern Canada. Continental Polar air masses are cold and very dry in the winter and cool and dry in the summer. These air masses are also atmospherically stable in both seasons.

**Continental Tropical Air Mass (cT)**

Air mass that forms over extensive landmass areas of the low latitudes. In North America, these systems form over southwestern United States and northern Mexico. Continental Tropical air masses are warm and dry in the winter and hot and dry in the summer. These air masses are also generally unstable in the winter and stable in the summer.

**Convection**

Convection involves the transfer of heat energy by means of vertical mass motions through a medium.

**Convection Current**

The movement of a gas or a fluid in chaotic vertical mass motions because of heating.

**Convective Lifting**

The vertical lifting of parcels of air through convective heating of the atmosphere. This process can initiate adiabatic processes inside the air parcel.

**Convective Precipitation**

Is the formation of precipitation due to surface heating of the air at the ground surface. If enough heating occurs, the mass of air becomes warmer and lighter than the air in the surrounding environment, and just like a hot air balloon it begins to rise, expand and cool. When sufficient cooling has taken place saturation occurs forming precipitation. This process is active in the interior of continents and near the equator forming cumulus clouds and possible later thunderstorms. Rain is usually the precipitation type that is formed, and in most cases this moisture is delivered in large amounts over short periods of time in extremely localized areas.

**Convergence**

Horizontal inflow of wind into an area. Once at the area, the wind then travels vertically.

**Convergence Precipitation**

The formation of precipitation due to the convergence of two air masses. In most cases, the two air masses have different climatological characteristics. One is usually warm and moist, while the other is cold and dry. The leading edge of the latter air mass acts as an inclined wall or front causing the moist warm air to be lifted. Of course the lifting causes the warm moist air mass to cool due to expansion resulting in saturation. This precipitation type is common at the mid-latitudes where cyclones form along the polar front. Also called *frontal precipitation*.

**Convergent Lifting**

The vertical lifting of parcels of air through the convergence of opposing air masses in the atmosphere. This process can initiate adiabatic processes inside the air parcel.

**Coriolis Force**

An apparent force due to the Earth's rotation. Causes moving objects to be deflected to the right in the Northern Hemisphere and to the left in the Southern hemisphere. Coriolis force does not exist on the equator. This force is responsible for the direction of flow in meteorological phenomena like mid-latitude cyclones, hurricanes, and anticyclones.

**Counter-Radiation**

Redirection of the Earth's longwave radiation back to the surface because of the greenhouse effect.

**Cumulus Cloud**

Puffy clouds with relatively flat bases. Cumulus clouds form when moist warm air bubbles vertically escape from the Earth's surface. Found in an altitude range from 300 to 2,000 meters.

**Cumulonimbus Cloud**

A well developed vertical cloud that often has top shaped like an anvil. These clouds are very dense with condensed and deposited water. Weather associated with this cloud includes: strong winds; hail; lightning; tornadoes; thunder; and heavy rain. When this weather occurs these clouds are then thunderstorms. Can extend in altitude from a few hundred meters above the surface to more than 12,000 meters.

**Cyclogenesis**

Process of cyclone formation, maturation, and death.

**Cyclone**

Area of low pressure in the atmosphere that displays circular inward movement of air. In the Northern Hemisphere circulation is counterclockwise, while Southern Hemisphere cyclones have clockwise wind patterns.

**- D -****Day Length**

Period of time for a location on the Earth when insolation from the sun is being received.

**Declination**

Location (latitude) on the Earth where the location of the sun on a particular day is directly overhead at solar noon. This location is somewhere between 23.5°N and 23.5°S depending on the time of the year.

**Density (of Matter)**

Refers to the quantity of mass per unit volume. For gases, density involves the number of atoms and molecules per unit volume.

**Deposition**

The change in state of matter from gas to solid that occurs with cooling. Usually used in meteorology when discussing the formation of ice from water vapor. This process releases latent heat energy to the environment.

**Deposition Nuclei**

Six-sided microscopic particle that allows for deposition of water as ice crystals in the atmosphere. Nucleus for the formation of snowflakes. Deposition normally occurs on these particles when relative humidity becomes 100 %.

**Depression**

Term used to describe an open atmospheric low pressure system or sometimes a cyclone.

**Desert**

Area that receives low precipitation. There evaporation exceeds precipitation and the average amount of precipitation is less than 250 mm/year.

**Dew**

Condensation of water on the Earth's surface because of atmospheric cooling.

**Dew Point**

Dew point is the temperature at which water vapor saturates from an air mass into liquid or solid usually forming rain, snow, frost or dew. Dew point normally occurs when a mass of air has a relative humidity of 100 %. If the dew point is below freezing, it is referred to as the frost point.

**Diffused Solar Radiation**

Solar radiation received by the Earth's atmosphere or surface that has been modified by atmospheric scattering.

**Diffusion**

Redirection or refraction of solar insolation in many directions. Process cause the beam of traveling radiation to become less intense.

**Direct Solar Radiation**

Solar radiation received by the Earth's atmosphere or surface which has not been modified by atmospheric scattering.

**Disturbance (atmospheric)**

Cyclonic low pressure system.

**Divergence**

Horizontal outflow of wind from an area. In a divergence, outflow originates from the upper atmosphere.

**Drainage Wind**

A wind common to mountainous regions that involves heavy cold air flowing from high to low elevations because of gravity.

**Drought**

Climatic condition where water loss due to evapotranspiration is greater than water inputs through precipitation.

**Dry Adiabatic Lapse Rate (DALR)**

The rate of decline in the temperature of a rising parcel of air before it has reached saturation. This rate of temperature decline is 9.8 degrees Celsius per 1000 meters because of adiabatic cooling.

**Dry-Bulb Thermometer**

Thermometer on a psychrometer used to determine current air temperature. This measurement and the reading from a wet-bulb thermometer are then used for the determination of relative humidity or dew point from a psychrometric table.

**Dry Line**

A boundary that separates dry and moist air in the warm sector of a mid-latitude cyclone wave. Found ahead of the cold front.

**- E -****Earth Albedo**

Is the reflectivity of the Earth's atmosphere and surface combined. Measurements indicate that the average Earth albedo is approximately 30 %.

**Earth Revolution**

Refers to the orbit of the Earth around the sun. This celestial motion takes 365 1/4 days to complete one cycle. Further, the Earth's orbit around the sun is not circular, but elliptical.

**Earth Rotation**

Refers to the spinning of the Earth on its polar axis.

**Easterly Wave**

Atmospheric disturbance in the tropical trade winds. Occasionally these systems intensify into hurricanes.

**Eccentricity**

Geometric shape of the Earth's orbit. This shape varies from being elliptical to almost circular.

**Eddy**

A localized chaotic movement of air or liquid in a generally uniform larger flow.

**Electromagnetic Energy**

Energy stored in electromagnetic waves or radiation. Energy is released when the waves are absorbed by a surface. Any object with a temperature above absolute zero (-273°C) emits this type of energy. The intensity of energy released is a function of the temperature of the radiating surface. The higher the temperature the greater the quantity of energy released.

**Electromagnetic Radiation (Waves)**

Emission of energy in the form of electromagnetic waves. All objects above the temperature of absolute zero (-273.15°C) radiate energy to their surrounding environment. The amount of electromagnetic radiation emitted by a body is proportionally related to its temperature.

**El Nino**

Name given to the occasional development of warm ocean surface waters along the coast of Ecuador and Peru. When this warming occurs the tropical Pacific trade winds weaken and the usual upwelling of cold, nutrient rich deep ocean water off the coast of Ecuador and Peru is reduced. The El Nino normally occurs around Christmas and lasts usually for a few weeks to a few months. Sometimes an extremely warm event can develop that lasts for much longer time periods.

**Emissivity**

The ratio of total radiative output from a body per unit time per unit area at a specific temperature and wavelength to that of a black body under the same environmental conditions.

**Energy**

Is defined as the capacity for doing work. Energy can exist the following forms: radiation; kinetic energy; potential energy; chemical energy; atomic energy; electromagnetic energy; electrical energy; and heat energy.

**Energy Flux**

The rate of energy flow from, into, or through a substance.

**Environmental Lapse Rate (ELR)**

The rate of air temperature increase or decrease with altitude. The average ELR in the troposphere is an air temperature decrease of 6.5°C per 1000 meters rise in elevation.

**Equator**

Location on the Earth that has a latitude of 0 degrees.

**Equinox**

Two periods when the declination of the sun is at the equator. The autumnal equinox occurs on March 21 or 22. The vernal equinox occurs on September 22 or 23.

**Evaporation**

Evaporation can be defined as the process by which liquid water is converted into a gaseous state.

Evaporation can only occur when water is available. It also requires that the humidity of the atmosphere be less than the evaporating surface (at 100 % relative humidity there is no more evaporation). The evaporation process requires large amounts of energy. For example, the evaporation of one gram of water at a temperature of 100 degrees Celsius requires 540 calories of heat energy (600 calories at 0°C).

**Evaporation Fog**

Fog generated from cold air advection over warm water or warm or moist land. This type of fog is sometimes called *steam fog* or *sea smoke*.

**Evaporation Pan**

Meteorological instrument that is used to measure evaporation rates.

**Evapotranspiration**

Combined loss of water to the atmosphere via the processes of evaporation and transpiration.

**Exosphere**

The outermost zone in the Earth's atmosphere. This layer has an altitude greater than 480 kilometers and is primarily composed of hydrogen and helium gas.

**Eye**

Area in the center of a hurricane that is devoid of clouds.

- F -

**Fahrenheit Scale**

Scale for measuring temperature. In this scale, water boils at 212 degrees and freezes at 32 degrees.

**Fall**

Season between summer and winter. Astronomically it is the period from the autumnal equinox to the winter solstice in the Northern Hemisphere.

**Ferrel Cell**

Three-dimensional atmospheric circulation cell located at roughly 30 to 60 degrees north and south of the equator.

**Fetch**

The distance of open water in one direction across a body of water over which wind can blow.

**First Law of Thermodynamics**

Law of Conservation of Energy.

**Föhn Wind**

The name of alpine wind that occurs on the leeward side of mountains. This wind is warm and has a low humidity. American equivalent is *chinook wind*.

**Fog**

Fog exists if the atmospheric visibility near the Earth's surface is reduced to 1 kilometer or less. Fog can be composed of water droplets, ice crystals or smoke particles. Fogs composed primarily of water droplets are classified according to the process that causes the air to cool to saturation. Common types of this type of fog include: radiation fog; upslope fog; advection fog; evaporation fog; ice fog; and frontal fog.

Process that changes the state of rest or motion of a body.

**Freezing**

The change in state of matter from liquid to solid that occurs with cooling. Usually used in meteorology when discussing the formation of ice from liquid water.

**Freezing Rain**

Type of precipitation. Occurs when rain hits a cold surface and freeze. For this to occur a surface temperature inversion is required. In such an inversion, the surface must have a temperature below freezing, while the temperature of the atmosphere where the precipitation forms is above freezing. Surface inversions may develop from a variety of causes, but typically they occur near the leading edge of cold air from the north as it pushes southward.

**Freeze-Thaw Action**

Processes associated with daily and seasonal cycles of freezing and melting.

**Friction**

Resistance between the contact surfaces of two bodies in motion.

**Frictional Force**

Force acting on wind near the Earth's surface due to frictional roughness. Causes the deceleration of wind.

**Front**

Transition zone between air masses with different weather characteristics.

**Frontal Fog**

Fog produced when weather fronts, especially warm fronts, pass through an area. Precipitation falling into the colder air ahead of the warm front may evaporate enough water to cause the formation of small droplets as fog near the ground.

**Frontal Lifting**

Lifting of a warmer or less dense air mass by a colder or more dense air mass at a frontal transitional zone.

**Frontal Precipitation**

See convergence precipitation.

**Frost**

Deposition of ice at the Earth's surface because of atmospheric cooling.

**Frost Point**

Is the temperature at which water vapor saturates from an air mass into solid usually forming snow or frost. Frost point normally occurs when a mass of air has a relative humidity of 100 %.

**Fujita Tornado Intensity Scale**

Tornado classification system developed by T. Theodore Fujita. This system six levels from F0 to F5. These levels are based on the estimated speed of the tornado's winds from proxy information like property damage.

**Funnel Cloud**

A tornado which is beginning its descent from the base of a cumulonimbus cloud. This severe weather event may or may not reach the ground surface.

- G -

**Gaia Hypothesis**

The Gaia hypothesis states that the temperature and composition of the Earth's surface are actively controlled by life on the planet. It suggests that if changes in the gas composition, temperature or oxidation state of the Earth are induced by astronomical, biological, lithological, or other perturbations, life responds to these changes by growth and metabolism.

**Gas**

A state of matter where molecules are free to move in any direction they like. The state of matter where the substance completely fills any container that it occupies.

**General Circulation Model (GCM)**

Computer-based climate model that produces future forecast of weather and climate conditions for regions of the Earth or the complete planet. Uses complex mathematical equations and physical relationships to determine a variety of climate variables in a three-dimensional grid.

**Geographical Coordinate System**

System that uses the measures of latitude and longitude to locate points on the spherical surface of the Earth.

**Geoid**

True shape of the Earth, which deviates from a perfect sphere because of a slight bulge at the equator.

**Geostrophic Wind**

Horizontal wind in the upper atmosphere that moves parallel to isobars. Results from a balance between pressure gradient force and Coriolis force.

### **Geothermal Energy**

Heat energy derived from the Earth's interior.

### **Glaze**

Coating of ice that forms when rain falls on a surface with a temperature below freezing.

### **Global Warming**

Warming of the Earth's average global temperature because of an increase in the concentration of greenhouse gases. A greater concentration in greenhouse gases in the atmosphere is believed to result in an enhancement of the greenhouse effect.

### **GOES (Geostationary Operational Environmental Satellite)**

Series of geostationary meteorological satellites launched by the United States starting in 1968. The main purpose behind these satellites was to use a variety of remote sensing devices for weather forecasting and environmental monitoring.

### **Gradient**

The steepness of a slope as measured in degrees, percentage, or as a distance ratio (*rise/run*).

### **Gradient Wind**

Horizontal wind in the upper atmosphere that moves parallel to curved isobars. Results from a balance between pressure gradient force, Coriolis force, and centripetal force.

### **Graupel**

A type of precipitation that consists of a snow crystal and a raindrop frozen together.

### **Gravity**

Is the process where any body of mass found in the universe attracts other bodies with a force proportional to the product of their masses and inversely proportional to the distance that separates them. First proposed by Sir Issac Newton in 1686.

### **Greenhouse Effect**

The greenhouse effect causes the atmosphere to trap more heat energy at the Earth's surface and within the atmosphere by absorbing and re-emitting longwave energy. Of the longwave energy emitted back to space, 90% is intercepted and absorbed by greenhouse gases. Without the greenhouse effect the Earth's average global temperature would be  $-18^{\circ}\text{C}$ , rather than the present  $15^{\circ}\text{C}$ . In the last few centuries, the activities of humans have directly or indirectly caused the concentration of the major greenhouse gases to increase. Scientists predict that this increase may **enhance** the greenhouse effect making the planet warmer. Some experts estimate that the Earth's average global temperature has already increased by  $0.3$  to  $0.6^{\circ}\text{C}$ , since the beginning of this century, because of this enhancement.

### **Greenhouse Gases**

Gases responsible for the greenhouse effect. These gases include: carbon dioxide ( $\text{CO}_2$ ); methane ( $\text{CH}_4$ ); nitrous oxide ( $\text{N}_2\text{O}$ ); chlorofluorocarbons ( $\text{CF}_x\text{Cl}_x$ ); and tropospheric ozone ( $\text{O}_3$ ).

### **Ground Frost**

Frost that penetrates the soil surface in response to freezing temperatures.

### **Gulf Stream**

Warm ocean current that originates in and around the Caribbean and flows across the North Atlantic to northwest Europe.

### **Gust Front**

A boundary found ahead of a thunderstorm that separates cold storm downdrafts from warm humid surface air. Winds in this phenomenon are strong and fast.

- H -

### **Hadley Cell**

Three-dimensional atmospheric circulation cell located at roughly  $0^{\circ}$  to  $30^{\circ}$  north and south of the equator. The Hadley cell consists of rising air (intertropical convergence zone) at the equator and descending air (subtropical highs) at  $30^{\circ}$  north and south.

### **Hail**

Hail is a destructive form of precipitation that is 5 to 190 millimeters in diameter. The large downdrafts in mature thunderstorm clouds provide the mechanism for hail formation. Hailstones normally have concentric

shells of ice alternating between those with a milky appearance and those that are clear. The milky white shells, containing bubbles and partially melted snowflakes, correspond to a period of rapid freezing, while the clear shells develop as the liquid water freezes much more slowly.

**Hair Hygrometer**

Hygrometer that uses the expansion and contraction of hair to determine atmospheric humidity.

**Hawaiian High**

High pressure system that develops over the central Pacific Ocean near the Hawaiian Islands. Also called *Pacific High*.

**Heat**

Heat is defined as energy in the process of being transferred from one object to another because of the temperature difference between them. In the atmosphere, heat is commonly transferred by conduction, convection, advection, and radiation.

**Heat Capacity**

Is the ratio of the amount of heat energy absorbed by a substance compared to its corresponding temperature rise.

**Heat Energy**

A form of energy representing aggregated internal energy of motions of atoms and molecules in a body.

**Heterosphere**

The upper layer in a two part classification of the atmosphere based on the general homogeneity of chemical composition. In this layer, oxygen atoms and nitrogen molecules dominate and remain constant in their relative quantities. The heterosphere extends upward from a height of 80 to 100 km depending on latitude. Below this layer is the homosphere.

**High Pressure**

An area of atmospheric pressure within the Earth's atmosphere that is above average. If this system is on the Earth's surface and contains circular wind flow and enclosed isobars it is called an anticyclone.

**Homosphere**

The lower layer in a two part classification of the atmosphere based on the general homogeneity of chemical composition. In this layer, nitrogen, oxygen, argon, carbon dioxide, and the trace gases dominate and remain constant in their relative proportions. The homosphere extends from the Earth's surface to a height of 80 to 100 km depending on latitude. Above this layer is the heterosphere.

**Humidity**

A general term used to describe the amount of water vapour found in the atmosphere.

**Hurricane**

An intense cyclonic storm consisting of an organized mass of thunderstorms that develops over the warm oceans of the tropics. To be classified as a hurricane, winds speeds in the storm must be greater than 118 km/hour.

**Hydrologic Cycle**

Model that describes the movement of water between the hydrosphere, lithosphere, atmosphere, and biosphere.

**Hygrometer**

An instrument for measuring atmospheric humidity.

- I -

**Ice Fog**

Fog composed of suspended ice crystals. Common in Arctic locations when temperatures are below  $-30^{\circ}\text{C}$  and a abundant supply of water vapor exists.

**Icelandic Low**

Subpolar low pressure system found near Iceland. Most developed during the winter season. This large-scale pressure system spawns mid-latitude cyclones.

**Ideal Gas Law**

This law describes the physical relationships that exist between pressure, temperature, volume, and density for gases. Two mathematical equations are commonly used to describe this law:

$$P \times V = \text{Const.} \times T \quad \text{and} \quad P = D \times \text{Const.} \times T$$

**Industrial Smog**

Form of air pollution that develops in urban areas. This type of air pollution consists of a combination of sulfur dioxide, suspended droplets of sulfuric acid, and a variety of suspended solid particles. Also see photochemical smog.

**Infrared Radiation**

Form of electromagnetic radiation with a wavelength between 0.7 and 100 micrometers ( $\mu\text{m}$ ). Also called longwave radiation. Form of

**Insolation**

Direct or diffused shortwave solar radiation that is received in the Earth's atmosphere or at its surface.

**Instability**

Atmospheric condition where a parcel of air is warmer than the surrounding air in the immediate environment. This condition causes the parcel to rise in the atmosphere.

**International Date Line**

A line drawn almost parallel to the 180 degree longitude meridian that marks the location where each day officially begins. The location of the International Date Line was decided upon by international agreement.

**Intertropical Convergence Zone (ITCZ)**

Zone of low atmospheric pressure and ascending air located at or near the equator. Rising air currents are due to global wind convergence and convection from thermal heating. Location of the thermal equator.

**Ionosphere**

A region in the atmosphere above 50 km from the surface where relatively large concentrations of ions and free electrons exist. The ionosphere is important for human communications because it re-directs AM radio transmissions. This process extends the distance that radio transmissions can travel.

**Isobar**

Lines on a map joining points of equal atmospheric pressure.

**Isoline**

Lines on a map joining points of equal value.

**Isotherm**

Lines on a map joining points of equal temperature.

**Isothermal Layer**

Vertical layer in the atmosphere where temperature remains unchanged. In the Earth's atmosphere three isothermal layers commonly exist: tropopause, stratopause, and the mesopause.

**- J -**

**Jet Stream**

Relatively fast uniform winds concentrated within the upper atmosphere in a narrow band. A number of jet streams have been identified in the atmosphere. The polar jet stream exists in the mid-latitudes at an altitude of approximately 10 km. This jet stream flows from west to east at average speeds, depending on the time of year, between 110 to 185 km/h. Another strong jet stream occurs above the sub-tropical highs at an altitude of 13 km. This jet stream is commonly called the subtropical jet stream. The subtropical jet stream's winds are not as strong as the polar jet stream.

**Joule**

Is the energy used by a force of one Newton in moving its point of application in the direction of the force *one meter*.

**- K -**

**Katabatic Wind**

Any wind blowing down the slope of a mountain.

**Kelvin Scale**

Scale for measuring temperature. In this scale, absolute zero is 0 Kelvins, water boils at 373.15 Kelvins and freezes at 273.15 Kelvins.

**Kilocalorie (Kcal)**

Unit of energy equal to 1,000 calories.

**Kilopascal (kPa)**

A unit measurements for quantifying force. Used to measure atmospheric pressure. Equivalent to 10,000 dynes per cm<sup>2</sup>.

**Kilowatt (kw)**

Unit of electrical power equal to 1,000 Watts.

**Kinetic Energy**

The energy due to motion.

**Kirchhoff's Law**

This law suggests that good emitters of radiation are also good absorbers of radiation at specific electromagnetic radiation wavelength bands. It also suggests that poor emitters of radiation are also poor absorbers of radiation at specific wavelength bands.

**Köppen Climate Classification**

System that uses monthly precipitation and temperature data and total annual precipitation data to classify a location's climate into one of five main categories: Tropical Moist Climates; Dry Climates; Moist Mid-latitude Climates with Mild Winters; Moist Mid-Latitude Climates with Cold Winters; and Polar Climates. These categories are further divided into number of subcategories. First developed in 1918 by German biologist W. Köppen, this system has undergone a number of modifications.

- L -

**Land Breeze**

Local thermal circulation pattern found at the interface between land and water. In this circulation system, surface winds blow from land to water during the night.

**Landfall**

The coastline location where a tropical storm or hurricane moves from ocean onto land.

**Landsat**

Series of satellites launched by NASA for the purpose of remotely monitoring resources on the Earth. The first Landsat satellite was launched by the United States in 1972. Landsat uses two types of sensors to monitor the Earth: Thematic Mapper and Multispectral Scanner.

**Langley**

Unit of the intensity of radiation measured per minute and equal to one calorie.

**La Nina**

Condition opposite of an El Nino. In a La Nina, the tropical Pacific trade winds become very strong and an abnormal accumulation of cold water occurs in the central and eastern Pacific Ocean.

**Latent Heat**

Is the energy required to change a substance to a higher state of matter (solid > liquid > gas). This same energy is released from the substance when the change of state is reversed (gas > liquid > solid).

**Latent Heat Flux**

Latent heat flux is the global movement of latent heat energy through circulations of air and water. Atmospheric circulation moves latent heat energy vertically and horizontally to cooler locations where it is condensed as rain or is deposited as snow releasing the heat energy stored within it. Large quantities of radiation energy are transferred into the Earth's tropical oceans. Radiant energy enters these water bodies at the surface when absorbed radiation is converted into heat energy. The warmed surface water is then transferred downward into the water column by conduction and convection. Horizontal transfer of this heat energy from the equator to the poles is accomplished by ocean currents.

**Latent Heat of Condensation**

The amount of heat energy release to the environment when a gas changes its state to a liquid. For one gram of water, the amount of heat energy released is 540 calories at a temperature of 100°C.

**Latent Heat of Vaporization**

The amount of heat energy required from the environment to change the state of a liquid to a gas. For one gram of water, the amount of heat energy required is 540 calories at a temperature of 100°C.

**Latitude**

Latitude is a north-south measurement of position on the Earth. It is defined by the angle measured from a horizontal plane located at the Earth's center that is perpendicular to the polar axis. A line connecting all places of the same latitude is termed a parallel. Latitude is measured in degrees, minutes, and seconds. Measurements of latitude range from equator (0°) to 90° North and South from this point.

**Law of Conservation of Energy**

This law states that energy can be transferred from one system to another in many forms, however, it can not be created nor destroyed. Thus, the total amount of energy available in the universe is constant.

**Lee**

Side of a slope that is opposite to the direction of flow of ice, wind, or water. Opposite of stoss.

**Leeward**

Downwind side of an elevated area like a mountain. Opposite of windward.

**Light**

A humanly visible form of electromagnetic radiation. This radiation has a wavelength between 0.40 and 0.71 micrometers (μm).

**Lightning**

Visible discharge of electricity created by thunderstorms.

**Longitude**

Longitude is a west-east measurement of position on the Earth. It is defined by the angle measured from a vertical plane (running through the polar axis and the prime meridian). A line connecting all places of the same longitude is termed a meridian. Longitude is measured in degrees, minutes, and seconds.

Measurements of longitude range from prime meridian (0°) to 180° West and East from this point.

**Long Wave**

A large wave in the polar jet stream and the westerlies that extends from the middle to the upper troposphere. Often associated with the formation of a mid-latitude cyclone at the ground surface. Contrasts with short waves. Also called *Rossby waves*.

**Longwave Radiation**

Infrared radiation.

**Low Pressure**

An area of atmospheric pressure within the Earth's atmosphere that is below average. If this system is on the Earth's surface and contains circular wind flow and enclosed isobars it is called a cyclone.

**Lysimeter**

Meteorological instrument used to measure potential and actual evapotranspiration.

**- M -****Marine**

With reference to ocean environments and processes.

**Maritime Effect**

The effect that large ocean bodies have on the climate of locations or regions. This effect results in a lower range in surface air temperature at both daily and annual scales.

**Maritime Polar Air Mass (mP)**

Air mass that forms over extensive ocean areas of the middle to high latitudes. Maritime Polar air masses are mild and humid in summer and cool and humid in winter. In the Northern Hemisphere, maritime polar air masses are normally unstable during the winter. In the summer, atmospheric stability depends on the position of the air mass relative to a continent. Around North America, Maritime Polar air masses found over the Atlantic are stable in summer, while Pacific systems tend to be unstable.

**Maritime Tropical Air Mass (mT)**

Air mass that forms over extensive ocean areas of the low latitudes. Maritime Tropical air masses are warm and humid in both winter and summer. In the Northern Hemisphere, maritime tropical air masses can normally be stable during the whole year if they form just west of a continent. If they form just east of a continent, these air masses will be unstable in both winter and summer.

**Mass**

Refers to the amount of material found in an object (usually of unit volume).

**Maunder Minimum**

Period from 1645 to 1715 during which the sun had very little sunspot activity.

**Mean Sea-Level**

The average height of the ocean surface as determined from the mean of all tidal levels recorded at hourly intervals.

**Mean Solar Day**

Time it takes to complete one Earth rotation.

**Melting**

The physical process of a solid becoming a liquid. For water, this process requires approximately 80 calories of heat energy for each gram converted.

**Mercury Barometer**

Type of barometer that measures changes in atmospheric pressure by the height of a column of mercury in a U-shaped tube which has one end sealed and the other end immersed in an open container of mercury. The force of the pressure exerted by the atmosphere on the mercury in the open container pushes mercury up the other end of the tube. The height of this level is then used as a measure of atmospheric pressure relative to the surface level of the mercury in the container.

**Meridian**

A circular arc that meets at the poles and connects all places of the same longitude.

**Meridional**

Movement of wind or ocean waters in a direction that is roughly perpendicular to the lines of latitude.

**Meridional Transport**

Transport of atmospheric and oceanic energy from the equator to the poles.

**Mesocyclone**

A cylinder of cyclonically flowing air that form vertically in a severe thunderstorm. They measure about 3 to 10 km across. About 50% of them spawn tornadoes.

**Mesopause**

Isothermic layer at the top of the mesosphere. This boundary layer in between the mesosphere and the thermosphere is usually found at an average altitude of 85 km. Coldest temperatures in the atmosphere are found here.

**Mesoscale Convective Complex**

A cluster of thunderstorms covering an area of 100,000 km or more. Convective circulation within this system encourages the growth of new thunderstorms for up to 18 hours.

**Mesosphere**

Atmospheric layer found between the stratosphere and the thermosphere. Usually located at an average altitude of 50 to 80 km above the Earth's surface.

**Meteorology**

The scientific study of the atmosphere and its associated phenomena.

**Methane**

Methane is very strong greenhouse gas found in the atmosphere. Methane concentrations in the atmosphere have increased by more than 140% since 1750. The primary sources for the additional methane added to the atmosphere (in order of importance) are: rice cultivation, domestic grazing animals, termites, landfills, coal mining, and oil and gas extraction. Chemical formula for methane is CH<sub>4</sub>.

**Mid-Latitude Cyclone**

Cyclonic storm that forms primarily in the middle latitudes. Its formation is triggered by the development of troughs in the polar jet stream. These storms also contain warm, cold and occluded fronts. Atmospheric pressure in their center can get as low as 970 mb. Also called *wave cyclones* or *frontal cyclones*.

**Milankovitch Theory**

Theory proposed by Milutin Milankovitch that suggests that changes in the Earth's climate are caused by variations in solar radiation received at the Earth's surface. These variations are due to cyclical changes in the geometric relationship between the Earth and the sun.

**Millibar (mb)**

A unit measurements for quantifying force. Used to measure atmospheric pressure. Equivalent to 1000 dynes/cm<sup>2</sup>.

**Mistral**

Term used to describe a katabatic wind in southern France.

**Mixing Ratio**

The ratio between the weight (mass) of water vapor (or some other gas) held in the atmosphere compared to the weight of the dry air in a given volume of air. Usually measured in grams water vapour (or gas) per kg of dry air.

**Moist Adiabatic Lapse Rate**

Saturated adiabatic lapse rate.

**Monsoon**

A regional scale wind system that predictably change direction with the passing of the seasons. Monsoon winds blow from land to sea in the winter, and from sea to land in the summer. Summer monsoons are often accompanied with precipitation.

**Montreal Protocol**

Treaty signed in 1987 by 24 nations to cut the emissions of chlorofluorocarbons (CFCs) into the atmosphere. Since 1987 the treaty has been amended to quicken the reduction in CFC production and use.

**Mountain Breeze**

Local thermal circulation pattern found in areas of topographic relief. In this circulation system, surface winds blow from areas of higher elevation to valley bottoms during the night.

**Multispectral Scanner (MSS)**

Remote sensing device found on Landsat satellites that acquires images in four spectral bands from visible to reflected infrared.

- N -

**Net Longwave Radiation (Balance)**

Balance between incoming and outgoing longwave radiation. Mathematically expressed as:

$L^* = (LD - LU)$ , where  $L^*$  is **net longwave radiation** at the surface,  $LD$  is atmospheric counter-radiation (greenhouse effect) directed to the Earth's surface, and  $LU$  is longwave radiation lost from the Earth's surface.

**Net Radiation (Balance)**

Balance between incoming and outgoing shortwave and longwave radiations. Mathematically expressed as:

$Q^* = (K + k)(1 - a) - LU + LD$ , where  $Q^*$  is surface net radiation (global annual values of  $Q^* = 0$ , because input equals output, local values can be positive or negative),  $K$  is surface direct shortwave radiation,  $k$  is diffused shortwave radiation (scattered insolation) at the surface,  $a$  is the albedo of surface,  $LD$  is atmospheric counter-radiation (greenhouse effect) directed to the Earth's surface, and  $LU$  is longwave radiation lost from the Earth's surface.

**Net Shortwave Radiation (Balance)**

Balance between incoming and outgoing shortwave radiations. Mathematically expressed as:

$K^* = (K + k)(1 - a)$  where  $K^*$  is surface **net shortwave radiation**,  $K$  is surface direct shortwave radiation,  $k$  is diffused shortwave radiation (scattered insolation) at the surface, and  $a$  is the albedo of surface.

**Neutral Atmosphere**

Condition in the atmosphere where isolated air parcels do not have a tendency to rise or sink. The parcels of air tend to be same temperature as the air that surrounds them.

**Newton**

A unit of force that creates an acceleration on a mass of 1 kg equal to 1 m/s.

**Nimbostratus Clouds**

Dark, gray low altitude cloud that produces continuous precipitation in the form of rain or snow. Found in an altitude range from the surface to 3,000 m.

**Nitric Oxide**

A gas produced by bacterial action in the soil and by high temperature combustion. Nitrogen oxide is a component in the production of photochemical smog. This colorless gas has the chemical formula is NO.

**Nitrogen Dioxide**

A gas produced by bacterial action in the soil and by high temperature combustion. Nitrogen dioxide is a component in the production of photochemical smog. This reddish brown gas has the chemical formula  $NO_2$ .

**Nitrogen Oxides**

Consists of two gases nitric oxide (NO) and nitrogen dioxide ( $NO_2$ ). These gases are produced by bacterial action in the soil and by the high temperature combustion. Both gases are components in the production of photochemical smog.

**Nitrous Oxide**

Gas found in the atmosphere that contributes to the greenhouse effect. Sources for nitrous oxide include: land-use conversion; fossil fuel combustion; biomass burning; and soil fertilization. Chemical formula for nitrous oxide is  $N_2O$ .

**Noctilucent Clouds**

High altitude clouds composed of ice crystals that appear to glow silver or bright blue shortly after sunset.

**Northeast Trade Winds**

See trade winds.

**Nucleus**

Dense central portion of an atom that is composed of neutrons and protons.

- O -

**Obliquity**

Tilt of the Earth's polar axis as measured from the perpendicular to the plane of the Earth's orbit around the sun. The angle of this tilt varies from 22.5 to 24.5 degrees over a 41,000 year period. Current obliquity is 23.5 degrees.

**Occluded Front**

A transition zone in the atmosphere where an advancing cold air mass sandwiches a warm air mass between another cold air mass pushing the warm air into the upper atmosphere.

**Ocean Current**

Large scale horizontal flow of ocean water that is persistent and driven by atmospheric circulation.

**Orographic Uplift**

Uplift of an air mass because of a topographic obstruction. Uplift also causes the cooling of the air mass. If enough cooling occurs condensation can occur and form into orographic precipitation.

**Orographic Precipitation**

Is precipitation that forms when air is forced to rise because of the physical presence of elevated land. As the parcel rises it cools as a result of adiabatic expansion at a rate of approximately  $10^{\circ}C$  1,000 m. until saturation. The large amounts of precipitation along the west coast of Canada are due mainly to this process.

**Ozone**

Tri-atomic oxygen that exists in the Earth's atmosphere as a gas. Ozone is highest in concentration in the stratosphere (10-50 km above the Earth's surface) where it absorbs the sun's ultraviolet radiation. Stratospheric ozone is produced naturally and helps to protect life from the harmful effects of solar UV radiation. Over the last few decades levels of stratospheric ozone have been declining globally, especially in Antarctica. Scientists have determined that chlorine molecules released from the decomposition of chlorofluorocarbons are primarily responsible for ozone destruction in the stratosphere. It is also abundant near the the Earth's surface in highly polluted urban centers. In these areas, it forms as a by product of photochemical smog, and is hazardous to human health.

**Ozone Hole**

Is a sharp seasonal decrease in stratospheric ozone concentration that occurs over Antarctica in the spring. First detected in the late 1970s, the ozone hole continues to appear as a result of complex chemical reaction in the atmosphere that involves CFCs.

**Ozone Layer**

Atmospheric concentration of ozone found at an altitude of 10 to 50 km above the Earth's surface. This layer is important to life on the Earth because ozone absorbs harmful ultraviolet radiation (UV).

**Ozonosphere**

Another name for the ozone layer.

- P -

**Pacific High**

High pressure system that develops over the central Pacific Ocean near the Hawaiian Islands. Also called the *Hawaiian High*.

**Paleoclimate**

Climatic conditions in the geological past reconstructed from a direct or indirect data source.

**Paleoclimatology**

Scientific study of the Earth's climate during the past.

**Pan or PAN**

Collection of chemicals found in photochemical smog : PeroxyAcyl Nitrates. Formed from photochemical reactions involving nitric oxide (NO) and volatile organic compounds (VOCs). Quite damaging to plants.

**Parallel**

A line parallel to the equator and connecting all places of the same latitude.

**Parts Per Billion (ppb)**

Number of parts of a substance found in one billion parts of a particular gas, liquid, or solid.

**Particulate Matter**

Particles of dust, soot, salt, sulfate compounds, pollen, or other particles suspended in the atmosphere.

**Parts Per Million (ppm)**

Number of parts of a substance found in one million parts of a particular gas, liquid, or solid.

**Passive Remote Sensing**

Form of remote sensing where the sensor passively captures electromagnetic radiation reflected or emitted by an object.

**Perihelion**

It is the point in the Earth's orbit when it is closest to the sun (147.5 million km). Perihelion occurs on the 3rd or 4th of January.

**pH**

Scale used to measure the alkalinity or acidity of a substance through the determination of the concentration of hydrogen ions in solution. A pH of 7.0 is neutral. Values below 7.0, to a minimum of 0.0, indicate increasing acidity. Values above 7.0, to a maximum of 14.0, indicate increasing alkalinity.

**Phase Change**

Reorganization of a substance at the atomic or molecular level resulting in a change of the physical state of matter. For example, a change from solid to liquid to a gas.

**Photochemical Smog**

Photochemical smog is a condition that develops when primary pollutants (oxides of nitrogen and volatile organic compounds created from fossil fuel combustion) interact under the influence of *sunlight* to produce a mixture of hundreds of different and hazardous chemicals known as secondary pollutants. Also see industrial smog.

**Photon**

A discrete unit of radiant energy.

**Photosphere**

Visible surface of sun from which radiant energy is release.

**Photosynthesis**

Is the chemical process where plants and some bacteria can capture and organically fix the energy of the sun. This chemical reaction can be described by the following simple equation:



The main product of photosynthesis is a carbohydrate, such as the sugar glucose, and oxygen which is released to the atmosphere. All of the sugar produced in the photosynthetic cells of plants and other organisms is derived from the initial chemical combining of carbon dioxide and water with sunlight. This chemical reaction is catalyzed by chlorophyll acting in concert with other pigment, lipid, sugars, protein, and nucleic acid molecules. Sugars created in photosynthesis can be later converted by the plant to starch for storage, or it can be combined with other sugar molecules to form specialized carbohydrates such as cellulose, or it can be combined with other nutrients such as nitrogen, phosphorus, and sulfur, to build complex molecules such as proteins and nucleic acids. Also see chemosynthesis.

**Plane of the Ecliptic**

Hypothetical two-dimensional surface in which the Earth's orbit around the sun occurs.

**Polar Axis**

Is a line drawn through the Earth around the planet rotates. The point at which the polar axis intercepts the Earth's surface in the Northern Hemisphere is called the North Pole. Likewise, the point at which the polar axis intercepts the Earth's surface in the Southern Hemisphere is called the South Pole.

**Polar Cell**

Three-dimensional atmospheric circulation cell located at roughly 60° to 90° north and south of the equator. Vertical air flow in the Polar cell consists of rising air at the polar front and descending air at the polar vortex.

**Polar Easterlies**

Winds that originate at the polar highs and blow to the subpolar lows in a east to west direction.

**Polar Front**

Weather front located typically in the mid-latitudes that separates arctic and polar air masses from tropical air masses. Along the polar front we get the development of the mid-latitude cyclone. Above the polar front exists the polar jet stream.

**Polar High**

Surface area of atmospheric high pressure located at about 90° north and south latitude. These high pressure systems produced by vertically descending air currents from the polar vortex.

**Polar Jet Stream**

Relatively fast uniform winds concentrated within the upper atmosphere in a narrow band. The polar jet stream exists in the mid-latitudes at an altitude of approximately 10 km. This jet stream flows from west to east at speeds between 110 to 185 km/h.

**Polar Stratospheric Clouds**

High altitude clouds found in the stratosphere where the temperature is less than -85°C. Commonly found over Antarctica. Have a role in the creation of the ozone hole over Antarctica.

**Polar Vortex**

High pressure system located in the upper atmosphere at the polar regions. In this system, air in the upper troposphere moves into the vortex center and then descends to the Earth's surface to create the polar highs.

**Potential Energy**

Is the energy that a body possesses by virtue of its position and that is potentially transformable into another form of energy.

**Potential Evapotranspiration**

Is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no limitation on water supply.

**Precession of the Equinox**

Wobble in the Earth's polar axis. This motion influences the timing aphelion and perihelion over a cyclical period of 23,000 years.

**Precipitable Water**

Amount of water potentially available in the atmosphere for precipitation. Usually measured in a vertical column that extends from the Earth's surface to the upper edge of the troposphere.

**Precipitation**

Is any aqueous deposit, in liquid or solid form, that develops in a saturated atmosphere (relative humidity equals 100%) and falls to the ground generally from clouds. Most clouds, however, do not produce precipitation. In many clouds, water droplets and ice crystals are too small to overcome natural updrafts found in the atmosphere. As a result, the tiny water droplets and ice crystals remain suspended in the atmosphere as clouds.

**Pressure**

Is defined as the force acting on a surface from another mass per unit area.

**Pressure Gradient Force**

Force due to spatial differences in atmospheric pressure. Usually expressed in millibars or kilopascals per unit distance (meters or kilometers). This force is primarily responsible for the formation of wind.

**Prevailing Wind**

Dominant direction that a wind blows from for a location or region.

**Primary Pollutant**

Air pollutants that enter the atmosphere directly. Also see secondary pollutant.

**Prime Meridian**

The location from which meridians of longitude are measured. Has the measure of 0° of longitude. The prime meridian was selected by international agreement to run through Greenwich, England.

**Proton**

A sub-particle of an atom that contains a positive charge.

**Proxy Data**

Data that measures the cause and effect relationship between two variables indirectly.

**Psychrometer**

Instrument used to measure atmospheric humidity. It consists of two thermometers (wet-bulb and a dry-bulb) one of which has its bulb covered by a moistened wick. Humidity is determined by the difference in readings between the two thermometers after air has passed over both of them for a specific time period.

**Psychrometric Table**

Table of values that allows for the determination of relative humidity and dew point from dry-bulb and wet-bulb temperatures recorded on a psychrometer.

**- R -**

**Radiant Energy**

Energy in the form of electromagnetic waves. In some cases it refers to the radiation emitted from the sun.

**Radiation**

The emission and propagation of energy in the form of electromagnetic waves.

**Radiation Fog**

Type of fog. Also called **ground fog**. Fog generated through the Earth's surface cooling by radiation loss at night. This type of fog is normally quite shallow.

**Radiometer**

General name for an instrument used to measure radiation over a specific wavelength range.

**Rain**

Is any liquid deposit that falls from the atmosphere to the surface and has a diameter greater than 0.5 mm. Form of precipitation.

**Rain Gauge**

Instrument that measures the rain that falls at a location over a period of time.

**Rainshadow Effect**

Reduction of precipitation commonly found on the leeward side of a mountain. The reduction in precipitation is the result of compression warming of descending air.

**Reflected Infrared Radiation**

Form of electromagnetic radiation with a wavelength between 0.7 to 3.0 micrometers ( $\mu\text{m}$ ).

**Reflection (Atmospheric)**

Process where insolation is redirect by  $180^\circ$  after striking a particle. This redirection causes 100 % loss. Most of the reflection in the Earth's atmosphere occurs in clouds because of light's interception with particles of liquid and frozen water. The reflectivity of a cloud can range from 40-90%.

**Refraction**

Process where insolation is redirect to a new direction of travel after entering another medium.

**Relative Humidity**

The ratio between the actual amount of water vapor held in the atmosphere compared to the amount required for saturation. Relative humidity is influence by temperature and atmospheric pressure.

**Relief**

The range of topographic elevation within a specific area.

**Remote Sensing**

The gathering of information from an object or surface without direct contact.

**Remote Sensor**

Mechanical devices used to remotely sense an object or phenomenon.

**Respiration**

Is the typical process where mitochondria of cells of organisms release chemical energy from sugar and other organic molecules through chemical oxidation. This process occurs in both plants and animals. In most organisms, respiration releases the energy required for all metabolic processes. This chemical reaction can be described by the following simple equation:  $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 = 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{released energy}$

**Rime**

Deposit of ice crystals that occurs when fog or overcooled water droplets comes in contact with an object with a temperature below freezing ( $0^\circ\text{C}$ ). This deposit develops outward on the windward side of the object.

**Roll Cloud**

A dense, cigar shaped cloud found above the gust front of a thunderstorm. Air within the cloud rotates around the long axis.

**Rosby Wave**

A large wave in the polar jet stream and the westerlies that extends from the middle to the upper troposphere. Often associated with the formation of a mid-latitude cyclone at the ground surface. Contrasts with short waves. Also called long wave.

- S -

**Santa Ana Wind**

A warm, dry foen- or chinook-like wind that occurs in southern California. Originates from the east off an elevated desert plateau.

**Saturated Adiabatic Lapse Rate (SALR)**

The rate of decline in the temperature of a rising parcel of air after it has reached saturation ( $\approx 0.6^\circ\text{C}$ ). This rate is less than the dry adiabatic lapse rate ( $0.98^\circ\text{C}$  per 100 m) because of the heat energy added to the ascending air parcel from condensation and deposition processes.

**Saturation**

Atmospheric condition where water is changing its phase to liquid or solid. At saturation relative humidity is 100% unless there is a shortage of deposition or condensation nuclei. Generally this process is caused by the cooling of the atmosphere.

**Saturation Mixing Ratio**

Mass of water vapor that a kilogram of dry air can hold at saturation. Measured in grams.

**Scale**

A specific relative or proportional size or extent of a phenomena as measured through space and/or time.

**Scattering (Atmospheric)**

Is an atmospheric process where small particles and gas molecules diffuse part of the incoming solar radiation in random directions without any alteration to the wavelength of the electromagnetic energy. Scattering does, however, reduce the amount of incoming radiation reaching the Earth's surface. A significant proportion of scattered shortwave solar radiation is redirected back to space. The amount of scattering that takes place is dependent on two factors: wavelength of the incoming radiation and the size of the scattering particle or gas molecule. In the Earth's atmosphere, the presence of a large number of particles with a size of about  $0.5\ \mu\text{m}$  results in shorter wavelengths being preferentially scattered. This factor also causes our sky to look blue because this color corresponds to those wavelengths that are best diffused.

**Sea Breeze**

Local thermal circulation pattern found at the interface between land and water. In this circulation system, surface winds blow from water to land during the daytime.

**Sea-Level**

The average surface elevation of the world's oceans.

**Sea-Level Pressure**

Average atmospheric pressure at sea-level. This value is 1013.25 mb.

**Seasons**

Time periods generally based on the changes in the intensity and duration of sunlight as received in the middle and high latitudes. Four seasons are normally recognized: Spring; Summer; Fall; and Winter. The astronomical definition is more precise and suggests the following time periods for the four seasons: Spring - March 22 to June 21; Summer - June 22 to September 22; Fall - September 23 to December 22; and Winter - December 23 to March 21.

**Secondary Pollutant**

Atmospheric pollutants that are created chemically in the atmosphere when primary pollutants and other components of the air react.

**Second Law of Thermodynamics**

This law states that heat can never pass spontaneously from a colder to a hotter body. As a result of this fact, natural processes that involve energy transfer must have one direction, and all natural processes are irreversible. This law also predicts that the entropy of an isolated system always increases with time.

**Sensible Heat**

Heat that can be measured by a thermometer and thus sensed by humans.

**Sensible Heat Flux**

Process where excess heat energy is transferred into the atmosphere. The process first involves the movement of heat energy from the Earth's surface to the atmosphere by conduction and convection. The heat energy then can move horizontally advection (atmospheric circulation).

**Short Wave**

A small wave in the polar jet stream and the westerlies that extends from the middle to the upper troposphere. Often associated with the formation of a mid-latitude cyclone at the ground surface. Contrasts with long waves.

**Shortwave Radiation**

Electromagnetic radiation with a wavelength between 0.1 and 0.7  $\mu\text{m}$ . Commonly used to describe the radiation emitted from the sun.

**Siberian High**

High pressure system that develops in winter over northern central Asia.

**Smog**

Generic term used to describe mixtures of pollutants in the atmosphere.

**Snow**

Type of precipitation that forms in air with temperatures below freezing. Snow forms when water vapor deposits directly as a solid on a deposition nuclei, by passing the liquid state. A snowflake forms first as a very tiny crystal developing on a six-sided hexagonal deposition nuclei. The ice crystal then grows fastest at the six points as these area are more directly exposed to the atmosphere's water vapor. Snow is most common in winter just north of the center of mid-latitude cyclones. As the warm moist air travels around the center of lowest pressure, it overrides colder air located north of the low and is cooled to its saturation temperature, producing rainfall and snow. Snow generally occurs with east winds, since the winds at locations north of a mid-latitude cyclone are from the east.

**Snow Pellets**

Type of precipitation. Snow pellets are white, spherical grains of ice 2 to 5 mm in diameter. They can be distinguished from packed snowflakes since snow pellets are firm enough to bounce when they hit the ground. Snow pellets develop as supercooled droplets freeze on ice crystals. They may fall for a brief period as the precipitation changes from ice pellets to snow.

**Soil-Heat Flux**

The rate of flow of heat energy into, from, or through the soil.

**Solar Altitude**

Height of the sun above the horizon from either True North or True South.

**Solar Constant**

A term used to describe the average quantity of solar insolation received by a horizontal surface at the edge of the Earth's atmosphere. This value is approximately  $1370 \text{ W/m}^2$ .

**Solar Day**

Time required for the Earth to complete one rotation relative to the sun.

**Solar Energy**

See Insolation.

**Solar Noon**

Point of time during the day when the sun is aligned with True North and True South.

**Solar Radiation**

Electromagnetic radiation that originates from the sun. Most of the sun's radiation is emitted at wavelengths between 1.0 and 0.1  $\mu\text{m}$ .

**Solar Year**

The time it takes the Earth to make one orbit around the sun. This is approximately 365.2422 days.

**Solstice**

Dates when the declination of the sun is at  $23.5^\circ$  North or South of the equator. For the Northern Hemisphere this date falls on June 21 or 22 (Summer Solstice). In the Southern Hemisphere the date is December 21 or 22 (Winter Solstice).

**Source Region**

Area where air masses originate and come to possess their moisture and temperature characteristics.

**Southeast Trade Winds**

See Trade winds.

**Southern Oscillation**

Reversal of atmospheric circulation in tropical Pacific Ocean that triggers the development of an El Niño.

**Specific Gravity**

The ratio of the mass of a body to the mass of an identical volume of water at a specific temperature.

**Specific Heat**

Is the heat capacity of a unit mass of a substance or heat needed to raise the temperature of 1 gram (g) of a substance on 1°C.

**Specific Humidity**

Measurement of atmospheric humidity. Specific humidity is the mass of water vapour in a given mass of air. Normally expressed in grams of water vapour per kg air at a specific temperature.

**Spectrum**

Is a graph that describes the quantity of radiation that is emitted from a body at particular wavelengths.

**Speed of Light**

Velocity of light in a vacuum. This velocity is approximately  $3 \times 10^8$  m/s. It takes light from the sun 8 minutes and 20 seconds to reach the Earth.

**SPOT (Centre National d'Etudes Spatiales)**

Series of satellites developed by the French Space Agency, with the cooperation with Belgium and Sweden for the purpose of remotely monitoring resources on the Earth. The first SPOT satellite was launched in 1986.

**Spring**

Season between winter and summer. Astronomically it is the period from the vernal equinox to the summer solstice in the Northern Hemisphere.

**Spring Tide**

Tide that occurs every 14 to 15 days and coincides with the new and full moon. This tide has a large tidal range because the gravitational forces of the moon and sun are complementary to each other.

**Squall Line**

A band of thunderstorm development found ahead of a cold front.

**Stable Atmosphere**

Condition in the atmosphere where isolated air parcels have a tendency to sink. The parcels of air tend to be cooler than the air that surrounds them.

**Standard Atmospheric Pressure**

A pressure of 101.325 *kilopascals* or 1013.25 millibars.

**State of Matter**

Form of matter. Matter can exist in three different forms gas, liquid, and solid.

**Stationary Front**

A transition zone in the atmosphere where there is little movement of opposing air masses and winds blow towards the front from opposite directions.

**Stephan-Boltzmann Law**

This radiation law suggests the amount of radiation given off by a body is proportional to the 4th power of its temperature as measured in Kelvin units. This law can be expressed by the following simple equation:

$E^* = \sigma T^4$ , where  $E^*$  is the amount of radiation emitted by the body in  $W/m^2$ ,  $\sigma$  is a constant equal to 0.000000567, and  $T$  is the temperature of the body in Kelvins.

**Storm Surge**

Relatively rapid rise in the height of the ocean along a coastline. Often caused by the storm winds pushing water towards land.

**Storm Track**

The path taken by a storm (thunderstorm, mid-latitude cyclone or hurricane) or the average path taken by storms.

**Stoss**

Side of a slope that faces the direction of flow of ice, wind, or water. Opposite of lee.

**Stratocumulus Clouds**

Low altitude gray colored cloud composed of water droplets that has a patchy appearance. Each cloud patch consists of a rounded mass. This cloud has a somewhat uniform base and normally covers the entire sky.

Between the patches blue sky can be seen. Found in an altitude range from the surface to 3,000 m.

**Stratopause**

The stratopause is an atmospheric layer that extends from approximately 48 to 50 km above the Earth's surface. In this layer, temperature remains constant (isothermal).

**Stratosphere**

Atmospheric layer found at an average altitude of 20 to 48 km above the Earth's surface. Within the stratosphere exists the ozone layer. Ozone's absorption of ultraviolet sunlight causes air temperature within the stratosphere to increase with altitude.

**Stratus Clouds**

Low altitude gray colored cloud composed of water droplets. This cloud has a uniform base and normally covers the entire sky. It is also quite thick and can obscure the sun. Light precipitation is often found falling from it. Found in an altitude range from the surface to 3,000 m.

**Sublimation**

Process where ice changes into water vapor without first becoming liquid. This process requires approximately 680 calories of heat energy for each gram of water converted.

**Subpolar Lows**

Surface zone of atmospheric low pressure located at about 60° north and south latitude. These low pressure systems are produced by the frontal lifting of subtropical air masses over polar air.

**Subsolar Point**

The location on the Earth where the sun is directly overhead.

**Subtropical High Pressure Zone**

Surface zone of atmospheric high pressure located at about 30° north and south latitude. These high pressure systems produced by vertically descending air currents from the Hadley cell.

**Subtropical Jet Stream**

Relatively fast uniform winds concentrated within the upper atmosphere in a narrow band. The subtropical jet stream exists in the subtropics at an altitude of approximately 13 km. This jet stream flows from west to east and has a speed that is somewhat slower than the polar jet stream.

**Sulfur Dioxide**

A gas produced from volcanic eruptions, ocean spray, organic decomposition and the burning of fossil fuels. Sulfur dioxide is a component in the creation of acid precipitation. This colorless gas has the chemical formula  $\text{SO}_2$ .

**Sulfate Aerosol**

Type of solid compound commonly found in the atmosphere. These particles play an important role in reflecting, absorbing, and scattering incoming insolation. The source of these compounds is both natural and human-made. Most of the human-made particles come from the combustion of fossil fuels.

**Summer**

Season between spring and fall. Astronomically it is the period from the summer solstice to the autumnal equinox in the Northern Hemisphere.

**Summer Solstice**

Date when the declination of the sun is at 23.5 degrees North of the equator. This date is usually June 21 or 22.

**Sun**

Luminous star around which the Earth and other planets revolve around. The sun emits  $63,000,000 \text{ W/m}^2$  of electromagnetic radiation. The sun has an average distance from the Earth of about 150,000,000 kilometers. The Earth's orbit is not circular but elliptical.

**Supercooled Water**

Cooling of water below  $0^\circ\text{C}$  without freezing. Common in clouds where there is a deficiency of condensation nuclei.

**Super-Saturation**

Atmospheric condition where saturation occurs at a relative humidity greater than 100% because of a shortage of deposition or condensation nuclei.

**Surface Heat Flux**

Process where excess heat energy is transferred into the ground.

**Surge**

A large, destructive ocean wave caused by very low atmospheric pressure and strong winds. Hurricanes often cause a surge of the ocean surface.

**Synoptic Scale**

Scale of geographic coverage used on daily weather maps to describe large scale atmospheric phenomenon (for example, mid-latitude cyclone, air masses, fronts, and hurricanes).

## - T -

### **Taku**

Name for a katabatic type of cold wind that occurs in Alaska.

### **Temperature**

Temperature is defined as the measure of the average speed of atoms and molecules. The higher the temperature the faster they move.

### **Temperature Inversion**

Situation where a layer of warmer air exists above the Earth's surface in a normal atmosphere where air temperature decreases with altitude. In the warmer layer of air, temperature increases with altitude.

### **Terminal Fall Velocity**

Velocity at which a particle being transported by wind or water falls out of the moving medium. This velocity is dependent on the size of the particle.

### **Thematic Map**

Map that displays the geographical distribution of one phenomenon or the spatial associations that occur between a few phenomena.

### **Thematic Mapper**

Remote sensing device found on Landsat satellites that scans images in seven spectral bands from visible to thermal infrared.

### **Thermal Circulation**

Atmospheric circulation caused by the heating and cooling of air.

### **Thermal Equator**

Continuous area on the globe that has the highest surface temperatures because of the presence of the Intertropical Convergence Zone.

### **Thermal High**

Area of high pressure in the atmosphere caused by surface temperatures.

### **Thermal Infrared Radiation**

Form of electromagnetic radiation with a wavelength between 3 to 14  $\mu\text{m}$ .

### **Thermal Low**

Area of low pressure in the atmosphere caused by surface temperatures.

### **Thermocline**

Boundary in a body of water that where the greater vertical change in temperature occurs.

### **Thermodynamic Equilibrium**

This type of equilibrium describes a condition in a system where the distribution of mass and energy moves towards maximum entropy.

### **Thermodynamic Laws**

Laws that describe the physical processes, relationships, and phenomena associated with heat.

### **Thermometer**

Device used to measure temperature.

### **Thermosphere**

Atmospheric layer above the mesosphere (above 85 km) where air temperatures rise rapidly with height. The thermosphere is the hottest layer in the atmosphere. In the thermosphere gamma, X-ray, and specific wavelengths of ultraviolet radiation are absorbed by certain gases in the atmosphere. The absorbed radiation is then converted into heat energy. Temperatures in this layer can get as high as 1300-1800°C.

### **Third Law of Thermodynamics**

This law states if all the *thermal motion* of molecules (kinetic energy) could be removed, a state called absolute zero would result and all energy would be randomly distributed.

### **Thunder**

Sound created when lightning causes the rapid expansion of atmospheric gases along its strike path.

### **Thunderstorm**

A storm several kilometers in diameter created by the rapid lifting of moist warm air which creates a cumulonimbus cloud. Thunderstorms can have the following severe weather associated with them: strong winds, hail, lightning, tornadoes, thunder, and heavy rain.

### **Tide**

Cyclical rise and fall of the surface of the oceans. Caused by the gravitational attraction of the sun and moon on the Earth.

**TIROS (Television and Infrared Observation Satellite)**

Series of meteorological satellites launched by the United States starting in 1960. The main purpose behind these satellites was to use a variety of remote sensing devices for weather forecasting. TIROS program was very successful, providing the first accurate weather forecasts based on data gathered from space. TIROS began continuous monitoring of the Earth's weather in 1962.

**Tornado**

A vortex of rapidly moving air associated with some severe thunderstorms. Winds within the tornado funnel may exceed 500 kilometers per hour.

**Tornado Alley**

Region in North America which receives an extraordinary high number of tornadoes. This region stretches from central Texas to Illinois and Indiana.

**Tornado Warning**

A warning issued to the public that a tornado has been observed by an individual in a specified region. This warning can also be issued if meteorological information indicates a high probability that a tornado will develop in a specified region.

**Tornado Watch**

A forecast issued to the public that a tornado may occur in a specified region.

**Total Column Ozone**

A measurement of ozone concentration in the atmosphere.

**Trade Winds**

Surface winds that generally dominate air flow in the tropics. These winds blow from about 30 degrees north and south latitude (subtropical high pressure zone) to the equator (intertropical convergence zone). Trade winds in the Northern Hemisphere have northeast to southwest direction and are referred to as the *Northeast Trades*. Southern Hemisphere trade winds have southeast to northwest direction but are called the *Southeast Trades*.

**Transpiration**

Transpiration is the process of water loss from plants through stomata. Stomata are small openings found on the underside of leaves that are connected to vascular plant tissues. Some dry environment plants do have the ability to open and close their stomata. Transpiration is a passive process largely controlled by the humidity of the atmosphere and the moisture content of the soil. Of the transpired water passing through a plant only 1% is used in the growth process. Transpiration also transports nutrients from the soil into the roots and carries them to the various cells of the plant.

**Tropical Cyclone**

Another name for hurricane.

**Tropical Depression**

An organized group of thunderstorms often found over a tropical ocean that generates a cyclonic flow of between 37 and 63 km/hour. Can develop into a hurricane.

**Tropical Disturbance**

An organized group of thunderstorms often found over a tropical ocean that generates a slight cyclonic flow of less than 37 km/h. Can develop into a hurricane.

**Tropical Storm**

An organized group of thunderstorms often found over a tropical ocean that generates a cyclonic flow of between 64 and 118 km/h. Often develops into a hurricane.

**Tropic of Cancer**

Latitude of 23.5°N. Northern limit of the sun's declination.

**Tropic of Capricorn**

Latitude of 23.5°S. Southern limit of the sun's declination.

**Tropopause**

The tropopause is an atmospheric layer that extends from approximately 11 to 20 km above the Earth's surface. In this layer temperature remains constant (isothermal). It is also the layer in the atmosphere where the jet stream exists.

**Troposphere**

Layer in the atmosphere found from the surface to approximately 11 km of altitude. This layer contains about 75 % of the total mass of the atmosphere. It is also the layer where the majority of our weather occurs. Maximum air temperature occurs near the Earth's surface in this layer. With increasing altitude air temperature drops uniformly with increasing height at an *average* rate of 6.5°C per 1000 m (commonly

called the Environmental Lapse Rate), until an average temperature of  $-55^{\circ}\text{C}$  is reached at the top of the troposphere.

**Trough**

An elongated area of low pressure in the atmosphere.

**True North**

Direction of the North Pole from an observer on the Earth.

**True South**

Direction of the South Pole from an observer on the Earth.

**Turbulent Flow**

Movement of water within a stream that occurs as discrete eddies and vortices. Turbulent flow is caused by channel topography and friction.

**Typhoon**

Another name for hurricane.

**- U -**

**Ultraviolet Radiation**

Electromagnetic radiation with a wavelength between 0.1 and 0.4  $\mu\text{m}$ .

**Unstable Atmosphere**

Condition in the atmosphere where isolated air parcels have a tendency to rise. The parcels of air tend to be warmer than the air that surrounds them.

**Updraft**

Upward movement of air.

**Upper Air Westerlies**

Consistent winds that exist in the upper troposphere that flow east to west from about  $20^{\circ}$  of latitude to the poles.

**Upslope Fog**

Fog generated by airflow over topographic barriers. As the air is forced to rise upward where the atmospheric pressure is less, it is cooled by expansion and produces fog on the windward slopes of hills or mountains.

**Upwelling**

The movement of nutrient-rich deep seawater to the ocean's surface.

**- V -**

**Valley Breeze**

Local thermal circulation pattern found in areas of topographic relief. In this circulation system, surface winds blow from the valley bottom to areas of higher elevation during the daytime.

**Valley Fog**

Fog formed by the movement of cooler, more dense air from higher elevations to the warm valley bottom.

**Vapour Pressure**

Pressure exerted by water vapor molecules in a given quantity of atmosphere.

**Venturi**

An increase in the velocity of a fluid or gas due to the constriction of flow.

**Vernal Equinox**

One of the two periods when the declination of the sun is at the equator. The vernal equinox occurs on March 22 or 23.

**Volatile Organic Compounds (VOCs)**

Organic molecules that are mainly composed of carbon and hydrogen atoms (hydrocarbons). The most common volatile organic compound release into the atmosphere is methane. Involved in the formation of photochemical smog.

**Volume**

The occupation of space in three dimensions. Measured in cubic units.

**Vortex**

A rapid spiraling motion of air or liquid around a center of rotation.

## - W -

**Warm Desert**

Desert found in the subtropics or interiors of continents at the middle latitudes where precipitation is low and surface air temperatures are high.

**Warm Front**

A transition zone in the atmosphere where an advancing warm air mass displaces a cold air mass.

**Waterspout**

A vortex of rapidly moving air over water that is associated with some thunderstorms.

**Watt**

A metric unit of measurement of the intensity of radiation in Watts over a square meter surface. 1 langley/min = 697.3 W/m<sup>2</sup>

**Wave**

A moving swell or ridge on the surface of a solid or liquid or within the medium of a gas. Electromagnetic radiation also travels in waves.

**Wave Crest**

The curved tops or ridges of an oscillating wave.

**Wavelength**

Distance between two successive wave crests or troughs.

**Wave Period**

The time elapsed for a wave to travel the distance of one wavelength.

**Wave Refraction**

The re-orientation of a wave so that it approaches a shoreline at a more perpendicular angle. This process is caused by the differential reduction of water depth as a linear wave approaches a curved shoreline. A reduction in water depth causes a wave to slow down causing the waves approaching a nonlinear shoreline to curve with the shore's shape.

**Wave Trough**

Area in between wave crests.

**Weather**

The state of the atmosphere at a specific time and place.

**Weather Map**

Map that displays the condition of the physical state of the atmosphere and its circulation at a specific time over a region of the Earth.

**Westerlies**

Dominant winds of the mid-latitudes. These winds move from the subtropical highs to the subpolar lows from west to east.

**Wet-Bulb Depression**

The value calculated by subtracting a wet-bulb thermometer reading from a dry-bulb thermometer reading. Used to determine the air's relative humidity or dew point from a psychrometric table.

**Wet-Bulb Thermometer**

Thermometer on a psychrometer that has a moistened wick on its reservoir bulb. When ventilated this thermometer records a temperature that is modified by the cooling effects of evaporation. This measurement and the temperature reading from a dry-bulb thermometer are then used to determine the air's relative humidity or dew point from a psychrometric table.

**Wien's Law**

This radiation law suggests that the wavelength of maximum emission of any body is inversely proportional to its absolute temperature. The following equation mathematically describes this law:

$\lambda_{\max} = C/T$ , where  $\lambda_{\max}$  is the body's maximum emitted wavelength of radiation in micrometers ( $\mu\text{m}$ ), **C** is a constant equal to 0.2897, and **T** is the temperature of the body in Kelvins.

**Wind**

Air moving horizontally and/or vertically.

**Wind Vane**

A mechanical device used to measure the direction of wind flow. Usually consists of a horizontal bar with a fin at one end and a aerodynamic pointer at the other end. The center of horizontal is attached to a vertical spindle which is connected to a mechanical device that records direction.

**Windward**

Upwind side or side directly influenced to the direction that the wind blows from. Opposite of leeward.

**Winter**

Season between fall and spring. Astronomically it is the period from the winter solstice to the vernal equinox in the Northern Hemisphere.

**Winter Solstice**

Date when the declination of the sun is at 23.5°S of the equator. This date is usually December 21 or 22.

- X -

**X-Ray Radiation**

Form of electromagnetic radiation with a wavelenth between 0.03 to 30 nanometers.

- Z -

**Zonal**

Movement of wind or ocean waters in a direction that is roughly parallel to the lines of latitude.