Air Pressure & Winds

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1 Introduction

All weather events on earth are driven by atmospheric circulation at varying scales. This is in turn driven by differences in pressure.

2 Atmospheric Pressure

The atmosphere is essentially a layer of gas that surrounds the planet bound by the gravitational pull of the earth. The weight of the gas above any given area in the atmosphere causes the gas to exert pressure on that area. Therefore, atmospheric pressure is generally greatest at the surface, and decreases with altitude as the mass of the overlying atmosphere decreases.

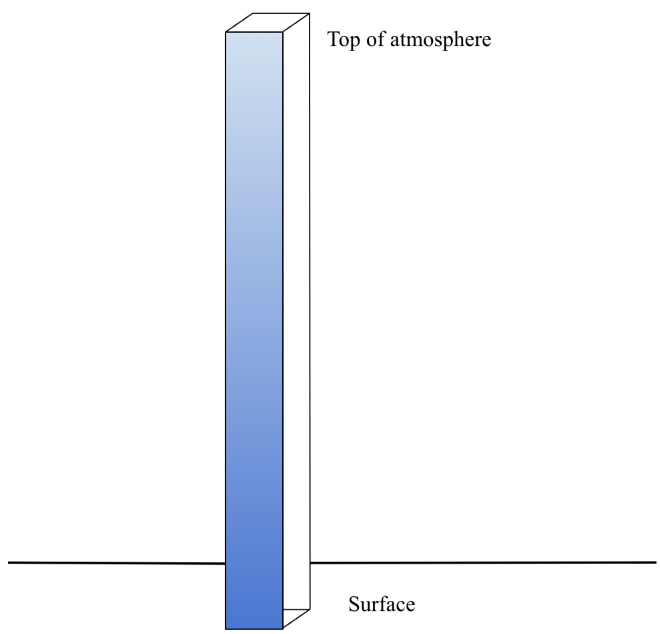


Fig. 1: Air pressure decreases with altitude as the weight of overlying air decreases

You may also recall that the pressure of a gas (assuming constant volume) increases with increasing temperature. While this exact relationship doesn't hold true in the atmosphere, cold and dense air occupies a lower volume than warmer air when exerting the same pressure.

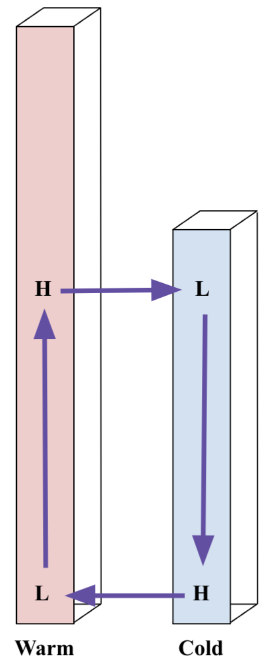


Fig. 2: Air pressure decreases with altitude as the weight of overlying air decreases

Visualize a column of air. Assuming the column of air contains a constant amount of gas, the amount of gas above a given altitude is greater when the air below is warmer and less dense. In the picture, at the altitude aloft, pressure is higher in the warmer column (marked by an ”H”). Likewise, this quantity is lower when air below is cooler and denser. As a result, pressure aloft in this column of air is higher when surface pressure is lower, and pressure aloft is lower when surface pressure is higher.

The average atmospheric pressure at sea level on earth is 1013.25 millibars, or 101.325 kilopascals. Meteorologists usually use millibars (mb) to measure atmospheric pressure. Standard upper charts are usually at around 500 mb, though they can be centered at anywhere from 200-850 mb. These charts usually have contours depicting the elevation (in tens of meters) at which the set pressure can be found, along with other features, which may include relative humidity and/or vorticity isopleths. (These are lines that connect points that have equal values for a specific meteorological feature, for example, a 50% relative humidity isopleth connects places which have a 50% relative humidity). For more information about upper air charts, see this article (link).

3 Forces Behind Winds

This brings us to the forces that govern winds:

3.1 Pressure Gradient

The pressure gradient force is the name given to the force that causes air to move from higher pressure to lower pressure. The pressure gradient is usually expressed in terms of an acceleration in the direction of the greatest change in pressure (as the name suggests). However, for the purposes of gaining an introductory understanding to the meteorology discussed in this handout, it is only important to resolve the fact that:

- Wind is the movement of air in response to a pressure gradient
- Wind speed is dependent on the strength of the pressure gradient

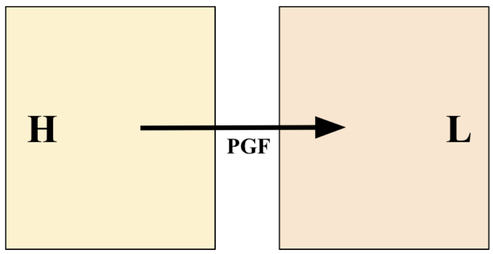


Fig. 3: Wind follows the pressure gradient from high to low pressure

Pressure gradients on earth can be produced in various different ways. Generally, pressure gradients that we are concerned with are the result of temperature differences arising from the differential heating of the surface of the earth.

3.2 Coriolis Force

The Coriolis force is a fictitious force that alters the path of wind with respect to an observer on earth. This occurs because while the path of wind follows the pressure gradient, the surface of the earth rotates beneath it, causing the path of the wind to appear curved. This deflection is to the right in the northern hemisphere, and to the left in the southern hemisphere. The role of the Coriolis force will be discussed further in the sections that follow.

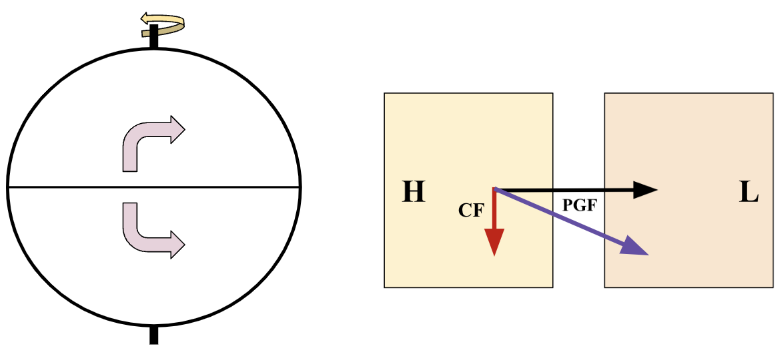


Fig. 4: The Coriolis force deflects wind to the right in the northern hemisphere, and to the left in the southern hemisphere. Thus, the net direction of wind from Fig. 3 in the northern hemisphere is shown by the purple arrow. Also note that this is near the surface where geostrophic balance is not present.

4 Isobaric Charts

Mapping surface pressure is done using surface charts. One method of accomplishing this is mapping isopleths across points of equal pressure at a given altitude. For example, a map might connect all points with a pressure of 1000 mb, 1002 mb, 1004 mb, etc. This produces a contour map, usually at a sea level, of atmospheric pressure. This is usually termed a surface weather map.

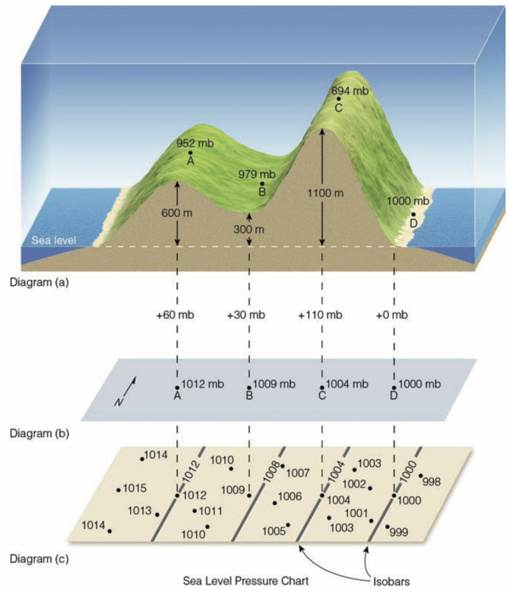


Fig. 5: A diagram showing a surface pressure chart. (Source: Ahrens)

There is however, a problem with surface weather maps: pressure is dependent on elevation, and therefore pressures taken at a higher elevation than sea level will have to be corrected to produce a surface weather map.

A solution to this problem is the *isobaric chart*. On an isobaric chart, isopleths connect points of equal altitude for a given pressure (called isobars). This can be seen in the figure below where the 500 mb surface connects all points under a pressure of 500 mb. Note that these are not strictly isobars (lines that are one-dimensional), but instead a 500 mb *surface* (two-dimensional, since the figure depicts a three-dimensional space).

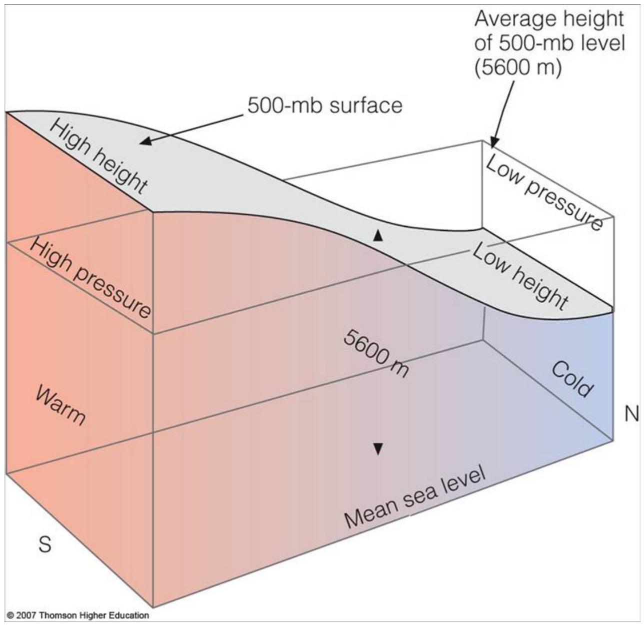


Fig. 6: A constant pressure surface is used to produce an isobaric chart, where elevations are mapped rather than pressures.

As a column of denser and colder air is more 'compressed' than a column of warmer, less dense air, lower isobars represent areas where pressure is higher than average, while higher isobars represent areas where pressure is lower than average. The more closely spaced isobars are, the greater the change in pressure over a given distance. This indicates a higher pressure gradient, resulting in higher wind velocities.

On a non-rotating Earth, winds will travel perpendicular to isobars, from high to low pressure. With the Coriolis force present however, the wind direction is modified. The extent that Coriolis force plays a role in wind direction however, is not fixed, and varies based on several factors that are covered later.

Surface features on earth can influence wind. Obstructions including trees, buildings, etc. impart friction on passing air. The layer of air above the ground where frictional forces are great enough to influence the path of wind is termed the *planetary boundary layer.*

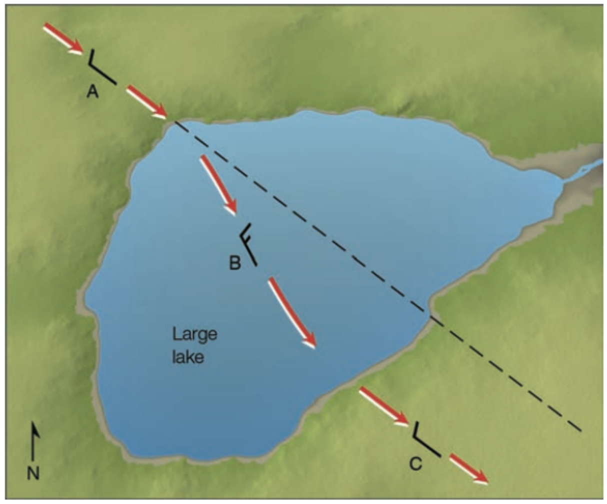


Fig.7: Winds blowing over a body of water often change in velocity, as the lower friction over the water's surface allows speeds to increase, producing a greater Coriolis deflection. (Source: Ahrens)

As the magnitude of Coriolis deflection is dependent on flow velocity, surface winds experience a lesser Coriolis deflection due to friction compared to upper level winds.
Due to Coriolis deflection, air flows towards zones of low pressure and away from zones of high pressure in a cyclonic manner. As a result of this cyclonic movement of air around centers of low and high pressure, we call winds surrounding low pressure centers *cyclones* and high pressure centers *anticyclones*.

4.1 Upper Level Charts

An isobaric chart that maps lower pressures, which occur at higher elevations, is called an upper level chart.

An important consideration when examining an isobaric chart is that isobars generally decrease in height polewards. As average temperatures are lowest at the poles and highest near the tropics, a given column of air will extend higher at the tropics than at the poles. If the earth were a uniform surface, lacking the continents that cause regional pressure variations (explained in more detail in later sections), isobars would appear perfectly parallel to the equator, with the constant pressure surface successively decreasing in attitude towards the poles.

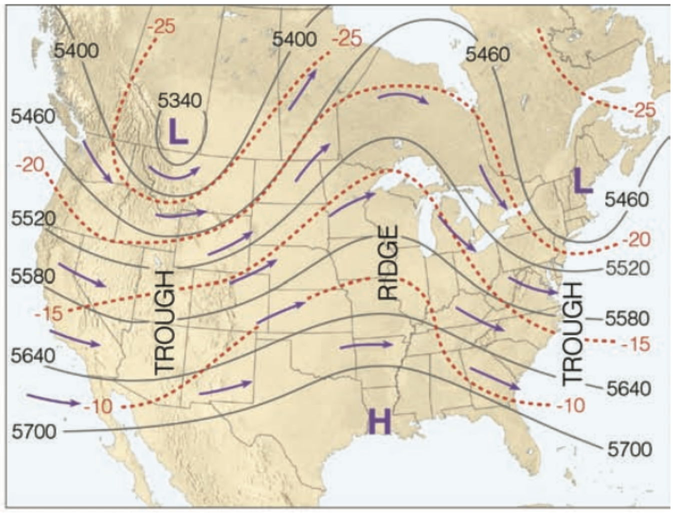


Fig. 8: Upper level charts map lower pressures located aloft. (Source: Ahrens)

The direction of surface winds, as stated earlier, is usually an angle from the isobars, from high to low pressure. However, winds aloft tend to flow parallel to isobars. Why is this the case?

The answer lies in the absence of the planetary boundary layer: without friction to slow down winds, air aloft accelerates along the pressure gradient, concurrently experiencing a deflection (right in the northern hemisphere, left in the southern hemisphere) due to Coriolis force. These forces eventually balance, and wind flows parallel to isobars. These winds are known as *geostrophic winds*. Winds aloft are usually in geostrophic balance.

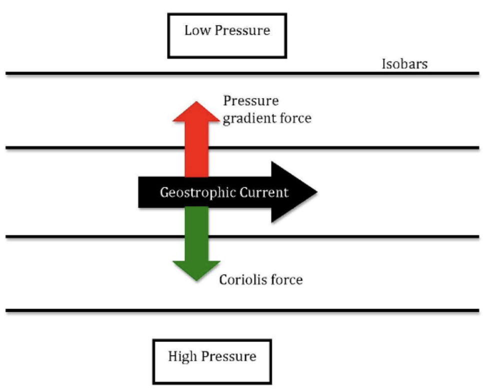


Fig. 9: Geostrophic winds occur when the pressure gradient force and Coriolis force are balanced.

Looking at examples of upper level charts, it is possible to identify features called *ridges* and *troughs*. These are regions where pressure aloft deviates from the average pressure.

- **Ridges** are areas where isobars extend further polewards than average. This indicates an extended region of high pressure.
- **Troughs** are areas where isobars extend in the opposing direction of ridges. These are extended regions of low pressure.

Surface cyclones and anticyclones are maintained by corresponding pressure systems aloft. When winds converge towards a center of low pressure, air is displaced, and pushed upwards. This produces the vertical movement of air upwards, where it *diverges*. Similarly, there is a zone of convergence above a system of surface high pressure, as air flows anti cyclonically out of a high pressure center, drawing air aloft down. These vertical air motions are necessary for the maintenance of pressure systems; if a surface low/high is not paired with upper level divergence/convergence, the pressure gradient will eventually equalize, and the pressure system ceases to exist.[1]
With the analysis of both upper level charts and surface charts, the behavior of pressure systems and thus the movement of weather systems can be predicted.

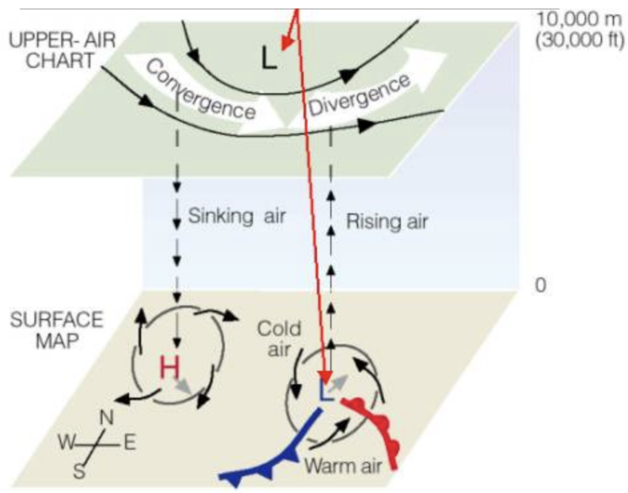


Fig. 10: Surface anticyclones are convergence aloft, white surface cyclones are accompanied by divergence aloft.

5 Global Circulation

Prior to a discussion on smaller local wind systems, it is necessary to understand global circulation. The driver of global circulation is fundamentally the uneven heating of Earth's surface. The angle of incident sunlight at the tropics is greater than at the poles, resulting in greater insolation at the tropics. Equatorial air is heated and rises, while air at the poles is cooled and sinks. Assuming that the earth is non-rotating and has a smooth, uniform surface without continents, this produces a single convective cell in each hemisphere, with surface winds traveling from the poles to the equator. Air aloft completes the convection cell, as heated air travels northwards, cooling and sinking.

[1]This topic can be expanded on - for example, it might be worth learning about vorticity. I would once again recommend perusing this article (link).

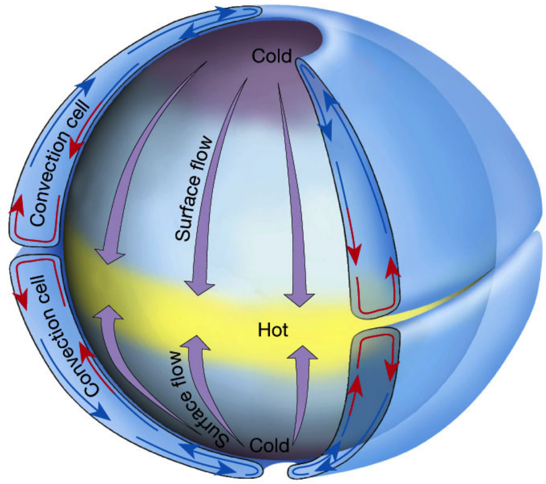


Fig. 11: On a homogenous non-rotating earth, circulation would follow the single cell model, with only one convection cell in each hemisphere.

5.1 The Three Cell Model

This simple single-celled model does not exist. The earth rotates, meaning that the equatorial movement of surface winds is deflected.

A useful model for understanding global circulation is the three cell model, which retains the assumptions that the earth is uniform, but applies it to a spinning planet.

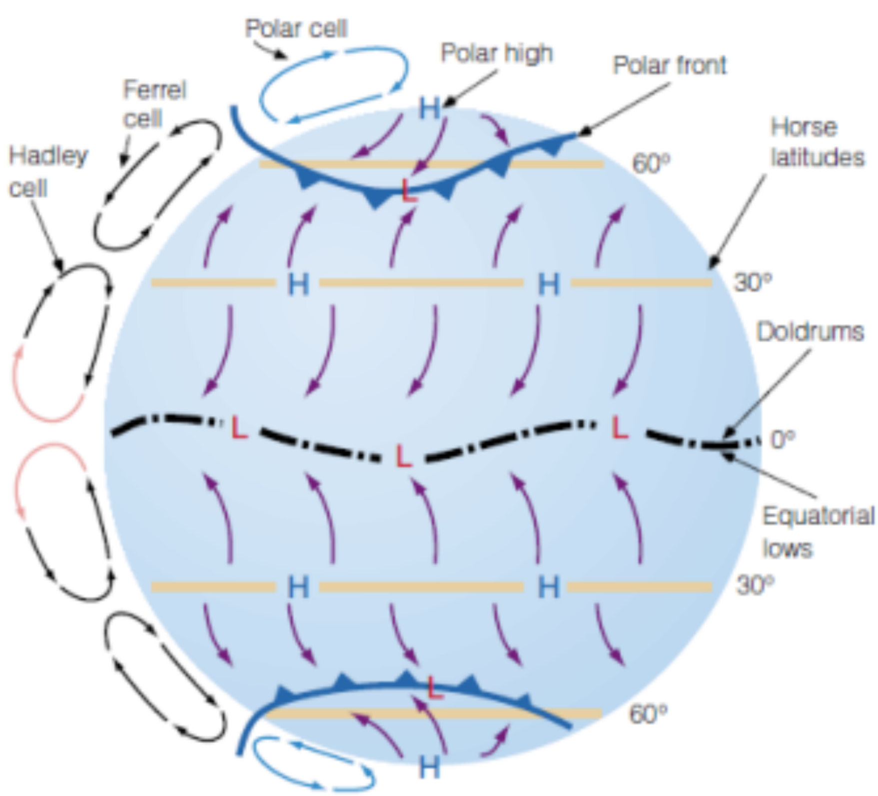


Fig. 12: Three cell model

The three cell model contains three cells in each hemisphere. There is still a zone of surface low pressure at the equator and surface high pressure at the poles. However, as this model accounts for Coriolis deflection, the single cell is divided into three.
These cells are divided by three boundaries. The first cell, just above the equator, is the *Hadley* cell. Warm air at the equator rises, reaching the tropopause, where it spreads laterally towards the poles. The air is deflected by the Coriolis force, forming westerly winds aloft. As the air moves polewards, it cools radiatively. The cooling air converges near latitudes of 30º, producing a zone of high pressure, forcing air to descend. The descending air is heated by compressional heating, producing warm temperatures, still winds, and clear skies. This belt of subsiding air is often called the *horse latitudes*.
To complete the Hadley cell, some of the warm air from the horse latitudes moves back towards the equator. Deflected by the Coriolis force, this air produces the easterly *trade winds*. Trade winds from either hemisphere converge near the equator at the *intertropical convergence zone* or ITCZ, where it once again rises.

Air at the horse latitudes that does not move back towards the equator moves polewards. This produces the *prevailing westerlies*. At around 60º north and south, the westerlies meet the *polar front*, where the two air masses converge. The converging air rises, where a portion moves back towards the mid latitudes, completing the circulation cell. This middle cell is the *Ferrel cell*.

Finally, air at the poles forms the Polar cell, with rising air moving polewards. The air converges aloft near latitudes of 90º, forming a center of high pressure known as the polar high. Air moving back towards the equator forms the *polar easterlies*.

These general circulation cells control regional climates. At the ITCZ where warm air rises, large convective thunderstorms are produced. At the horse latitudes, the converging air produces clear skies and weak winds with little precipitation. As a result, many major dry regions are located along these areas.

The three cell model is obviously useful in understanding the basis of global circulation. However, there are glaring discrepancies present upon further inspection. Winds do not perfectly align with those predicted by the three cell model, and average surface pressure systems are distributed differently due to the presence of continents.

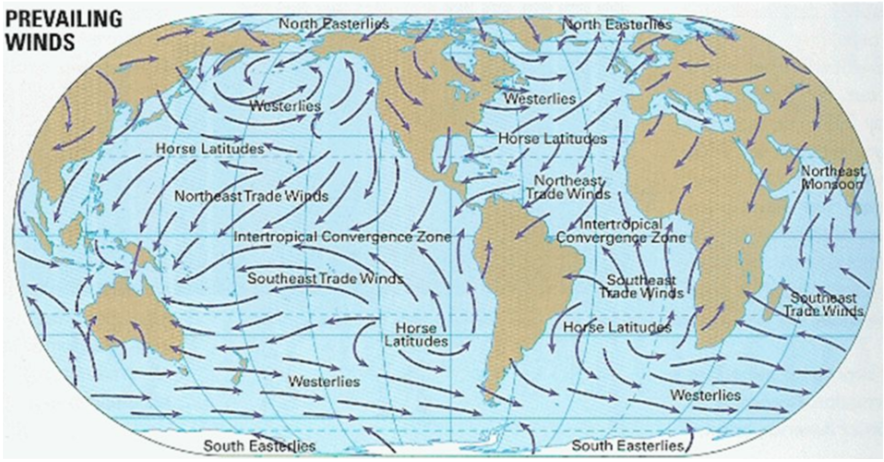


Fig. 13: Discrepancies in observed winds

Looking at a map of average surface pressures and winds, systems of high and low pressure can be observed. These are known as semi permanent highs and lows, as they persist through the year while experiencing slight seasonal changes.

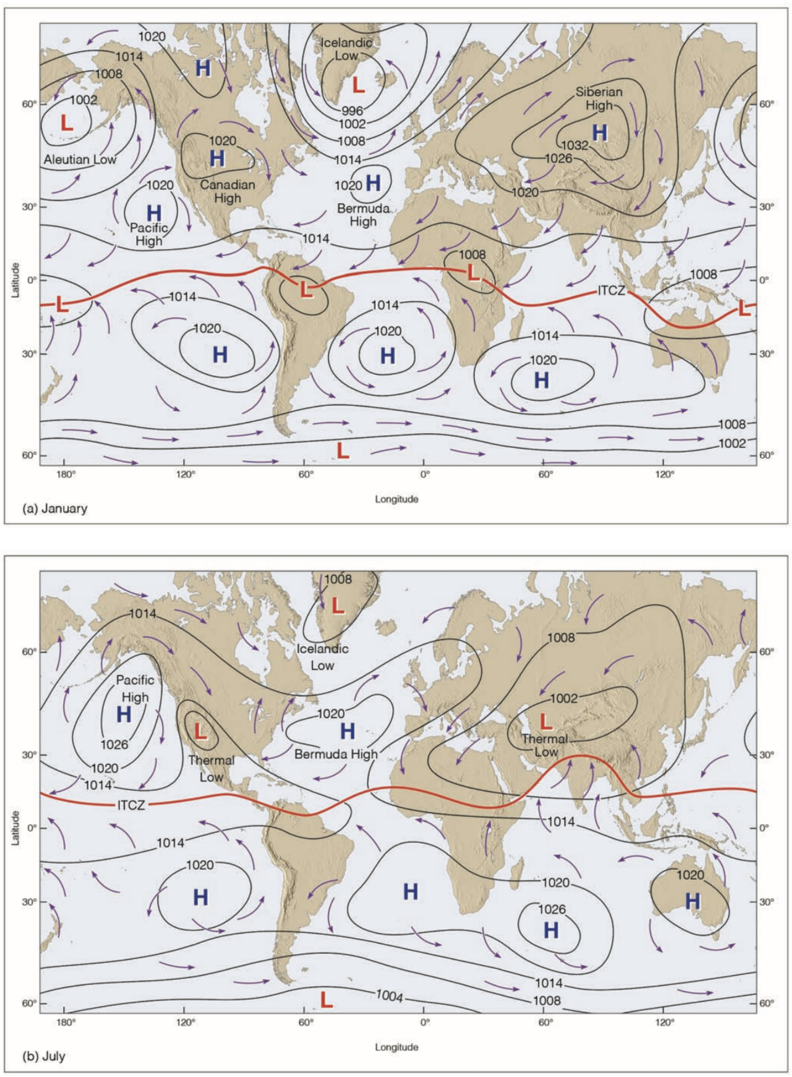


Fig. 14: Maps of semi permanent pressure systems in July and January. (Source: Ahrens)

There are four of these systems in the northern hemisphere during the winter: the Bermuda-Azores high, Pacific high, Icelandic low, and Aleutian low. In the southern hemisphere, three high pressure systems are present (South Pacific, South Atlantic, and South Indian subtropical highs), with one belt of low pressure encircling the globe at high latitudes.
In the summer, land warms, and some of the zones of high pressure are replaced by low pressure. These are called *thermal lows*.
As the zone of maximum surface heating shifts to the northern hemisphere during July, the ITCZ also shifts northwards. The opposite is true during winter.

5.2 Jet Streams

Jet streams are narrow bands of wind traveling at high velocities near the tropopause. The *subtropical jet* lies around 30ºN, while the polar jet lies at around 60º of latitude at the polar front.

These jets form due to the steep pressure gradient that occurs along the polar and subtropical fronts.
The location of the jets change throughout the year as the polar and subtropical fronts change. During the northern hemisphere winter, the polar front extends southwards, bringing the polar jet with it. As temperature differences are most pronounced during the winter, the polar and subtropical jets are strongest during the winter seasons of either hemisphere.

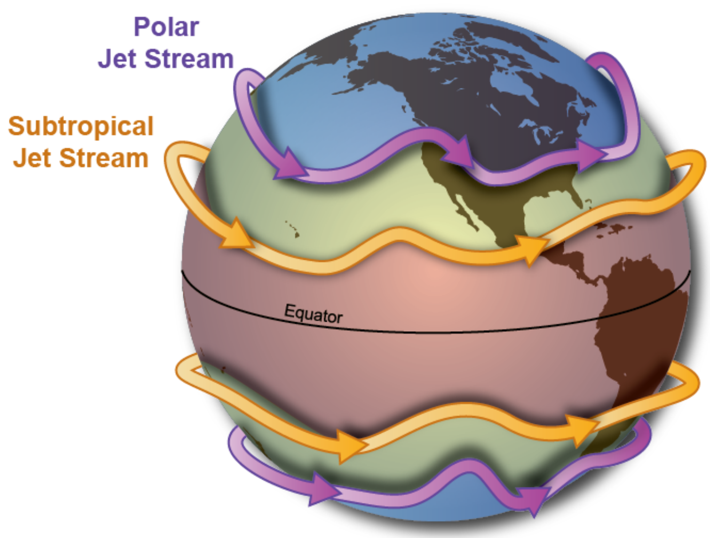


Fig. 15: Diagram of the subtropical and polar jets (source: NWS)

6 Local Wind Systems

Air circulation can occur at different scales, from microscale to planetary scale. Here, we discuss several small scale wind systems.

6.1 Land/Sea Breezes

Sea and land breezes are a form of thermal circulation which produces a wind that reverses direction at night near bodies of water. During the daytime, land is heated faster than water due to its lower heat capacity. This produces a zone of low pressure above the land, producing a wind blowing from the water to the shore. This is the *sea breeze.*

At night, the land cools faster than the adjacent body of water. A thermal low forms above the water, and a wind blows from the shore out to the water. This is called a *land breeze.* Land and sea breezes are not limited to forming along coastlines however. They are also found along lakes and other bodies of water (sometimes called lake breezes).

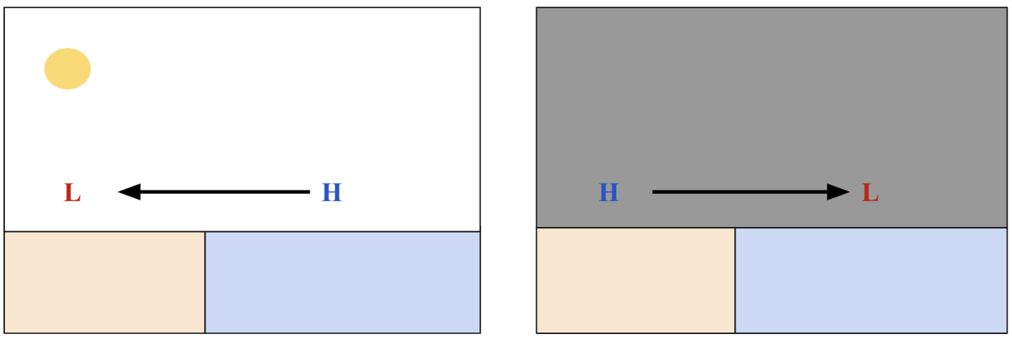


Fig. 16: Diagram of sea breezes (left) and land breezes (right)

The same phenomenon produces large convective thunderstorms over Florida, as either side of the peninsula experiences sea breezes during the daytime which converge and rise, strengthening thunderstorms.

6.2 Mountain and Valley Breezes

During the daytime, mountain slopes are warmed, causing air to rise up from the valley. This produces a *valley breeze.* At night, the mountain slopes cool, chilling the surrounding air. The dense air flows down the mountain, producing a *mountain breeze.* Valley breezes can sometimes produce cumulus clouds above mountain peaks, which sometimes produce showers.

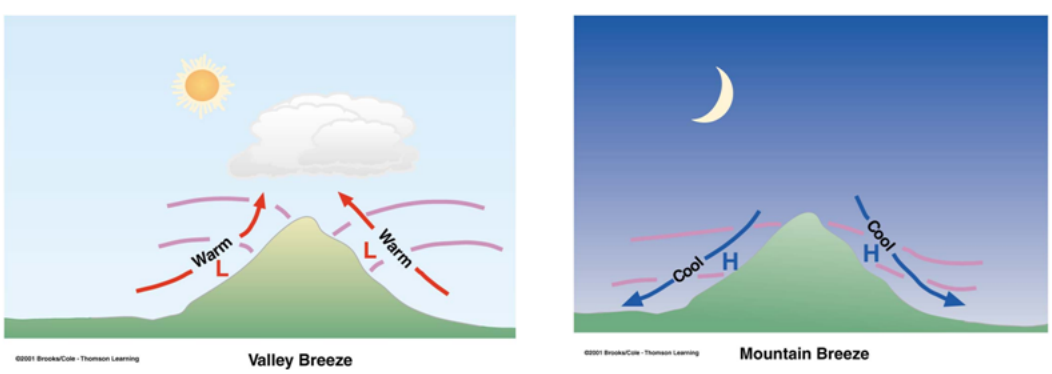


Fig. 17: Diagram of mountain and valley breezes

6.3 Katabatic Winds

Katabatic winds are downslope winds that have higher speeds than typical mountain winds. They are commonly found around elevated plateaus surrounded by mountains, with an opening that allows for air to travel rapidly downhill. During winter snows, air surrounding the plateau becomes extremely cold, forming a dome of high pressure. This produces a pressure gradient that forces air through the aforementioned openings, allowing the air to flow downslope. Wind speeds are often less than 20 km/hr, however in constricted areas, they can reach 180 km/hr or more.

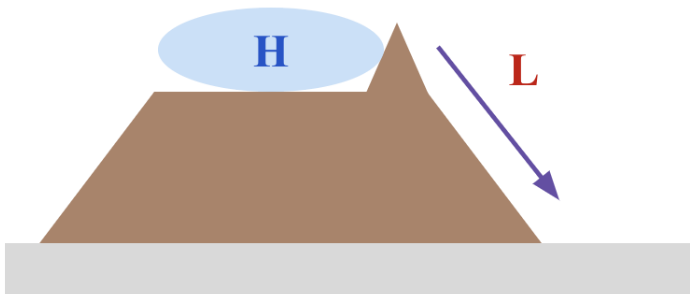


Fig. 18: Diagram of katabatic winds. A raised plateau contains cooler air, forming a zone of high pressure. Katabatic winds blow downslope from openings.

6.4 Chinook/Foehn Winds

Chinook winds are dry downslope winds that descend from the leeward sides of mountains. You may recognize these as the result of warm, dry air produced by the rain shadow effect. Chinook winds occur when a strong wind blows across the windward side of the mountain, producing a trough of low pressure on the leeward side. This forces air downslope, warming it through compressional heating. This air is often dry following cloud formation and precipitation along the windward side, and is further heated by latent heat released during cloud formation. The descending air is thus considerably warmer and drier than air on the windward face.

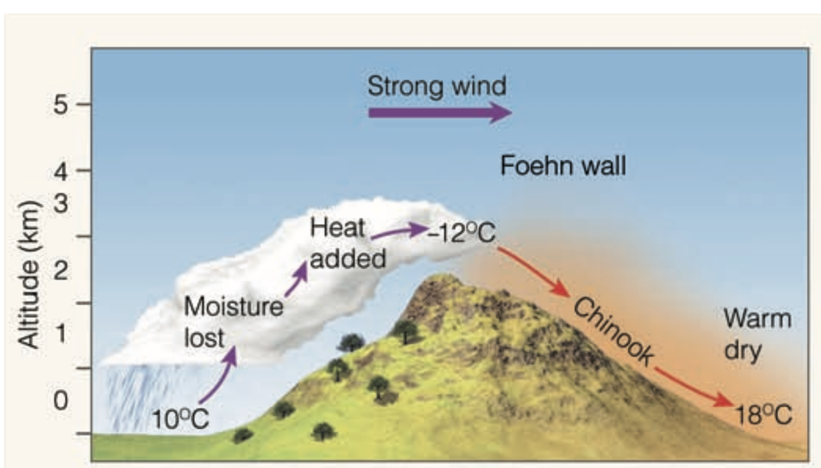


Fig. 19: Diagram of Chinook wind formation (Source: Ahrens)

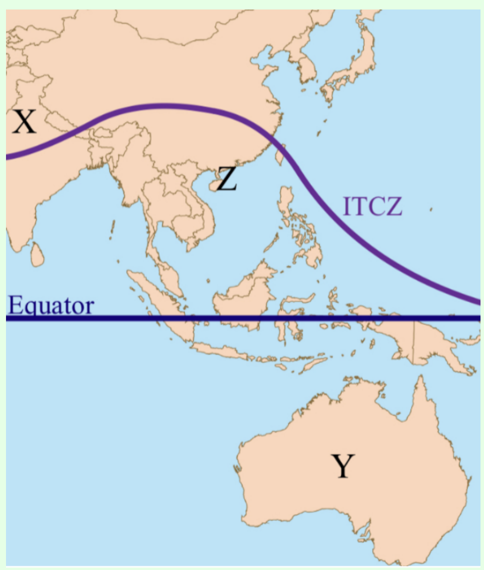
7 Sample Questions

Example 4.1 (USESO Open Round 2022, Question 7) A ridge on an upper-air map would dissipate most quickly if directly underlain on the surface by a:

(A) High-Pressure region
(B) Low-Pressure region
(C) Ridge
(D) Trough

Solution: Recall that regions of divergence aloft are sustained by convergence at the surface. A region of divergence aloft would thus dissipate when underlain by a region of divergence at the surface (a system in such a configuration cannot exist). Therefore, the correct choice is A.

Example 5.1 (USESO Open Round 2021, Question 10a) Shown below is a figure of the position of the ITCZ (Intertropical Convergence Zone) in East Asia. X, Y, and Z refer to labeled locations on the map.



Identify all of the following statements concerning the figure that are likely true. [0.1 in]
(A) This figure represents the ITCZ in January
(B) This figure represents the ITCZ in July
(C) Location X is a surface low-pressure center, and location Y is likely a surface high-pressure center
(D) Location X is a surface high-pressure center, and location Y is likely a surface low-pressure center
(E) The ITCZ represents a zone where winds converge aloft, instead of at the surface

Solution: The ITCZ roughly follows the latitude of maximum insolation, which is north of the Equator in July. Location X is located near the ITCZ, an area of low pressure due to air converging and rising at the surface. During the Northern Hemisphere summer, the land heats up more than the ocean, so surface air pressure is lower over land. Location Y represents the position of a surface subtropical high, a region of sinking air. Rising air diverges aloft near the ITCZ. Thus, we pick options B and C.

Example 6.1 (USESO Training Camp 2020 Atmosphere Exam, Question 15) Choose all of the following statements that are true about land and sea breezes.

(A) Land breezes blow towards land.
(B) At night, a low surface pressure zone is created above the ocean.
(C) Significant cloud cover would strengthen land and sea breezes.
(D) Ignoring physical obstructions, areas with coastal cities experience stronger sea breezes than similar rural coastal areas.
(E) Ignoring physical obstructions, areas with coastal cities experience stronger land breezes than similar rural coastal areas.
(F) Ignoring physical obstructions, areas with coastal cities experience weaker sea breezes than similar rural coastal areas.
(G) Ignoring physical obstructions, areas with coastal cities experience weaker land breezes than similar rural coastal areas.

Solution: A is incorrect, land breezes blow from the land towards the sea at nighttime. B is correct - since land cools more quickly than water at night, a convection cell is set up where warmer air from the sea rises and cooler air over land sinks. Thus, a low pressure zone is created over the ocean at night. C is incorrect since cloud cover has a moderating effect on temperatures both during the day and at night - during the day, clouds reduce the amount of sunlight reaching the surface, and at night, clouds redirect outgoing infrared radiation back to the surface. A lesser temperature difference between land and sea would weaken both land and sea breezes. For the last four options, we must examine the urban heat island effect - temperatures are warmer in urban areas both during the day and during the night. During the day, this increases the temperature difference between the land and the sea, but during the night, it has the opposite effect. Thus, sea breezes (that occur during the day) are stronger in urban areas as compared to rural areas, whereas land breezes (that occur during the night) are weaker. By this reasoning, we deduce that D and G are correct while E and F are not. Finally, we pick options B, D, and G.

Example 6.4 (USESO Open Round 2021, Question 23) Oftentimes, a sudden warm wind may descend from mountains and evaporate up to a foot of snow in less than a day, leading to their nickname, “snow eaters.” Why do Chinook winds such as “snow eaters” lead to a sudden increase in temperature?

(A) A chinook wind travels long distances over desert areas, retaining heat, before being

diverted into cooler areas nearby
(B) A chinook wind warms through adiabatic heating after traveling over and descending from a mountain
(C) A chinook wind gains moisture after traveling over a body of water, leading to an increased environmental lapse rate that warms the wind
(D) A chinook wind follows a warm front, bringing heat to previously cold areas

Solution: Recall that Chinook winds form as winds flow over mountain ranges (ex. westerly winds flowing across the Rockies). This produces a trough of low pressure on the lee side of the range, forcing air downslope. The air is compressed as it descends, and warms at the dry adiabatic lapse rate. This process, in conjunction with the fact that moisture is removed along the windward face of the mountain range, produces particularly hot and dry winds. Thus, we pick option B.