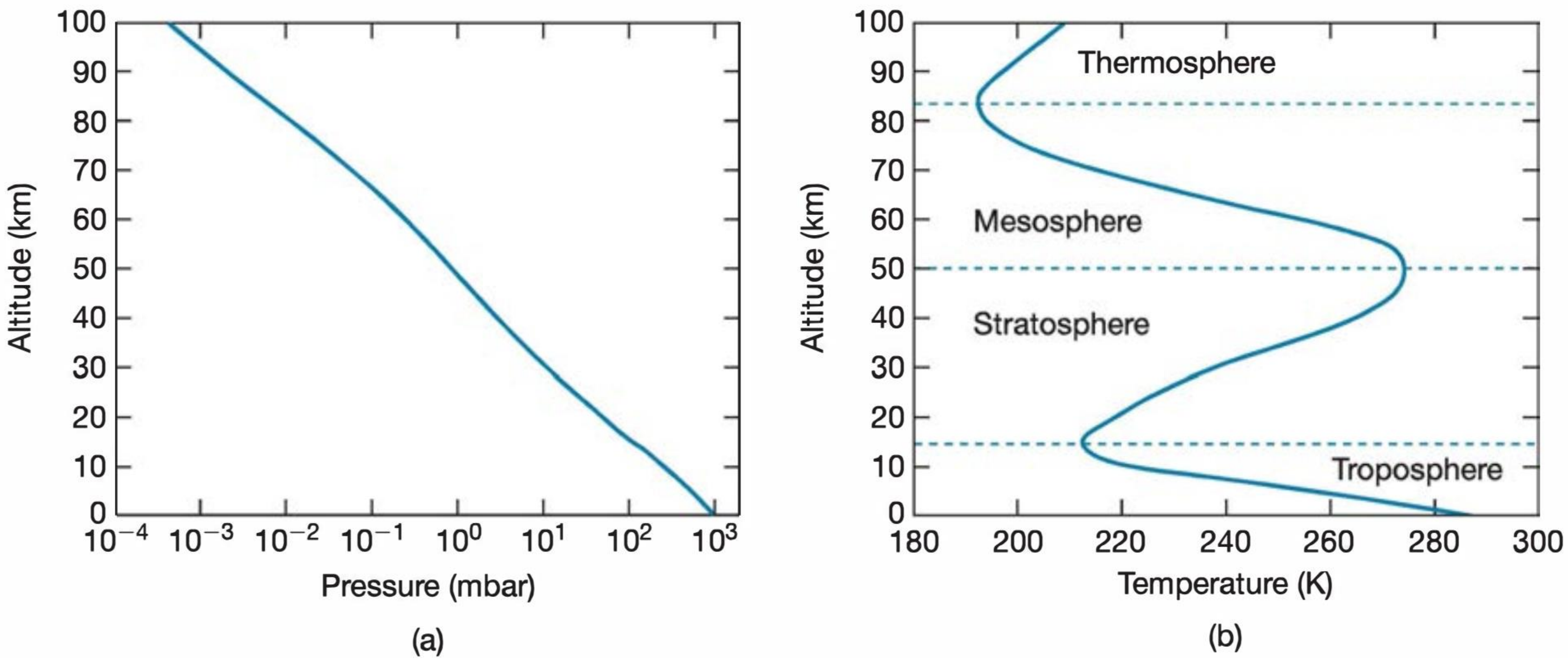
Earth System Processes (ES1201)

The Atmospheric Circulation
(Spring 2025 by Gaurav Shukla)

Book: ***The Earth System*** **by L.R. Kump, J.F. Kasting and R.G. Crane**

Atmospheric Circulation

Atmospheric pressure and temperature variation.



- **Note that the pressure profile is NOT A LINEAR function of altitude.**

Atmospheric pressure and temperature variation.

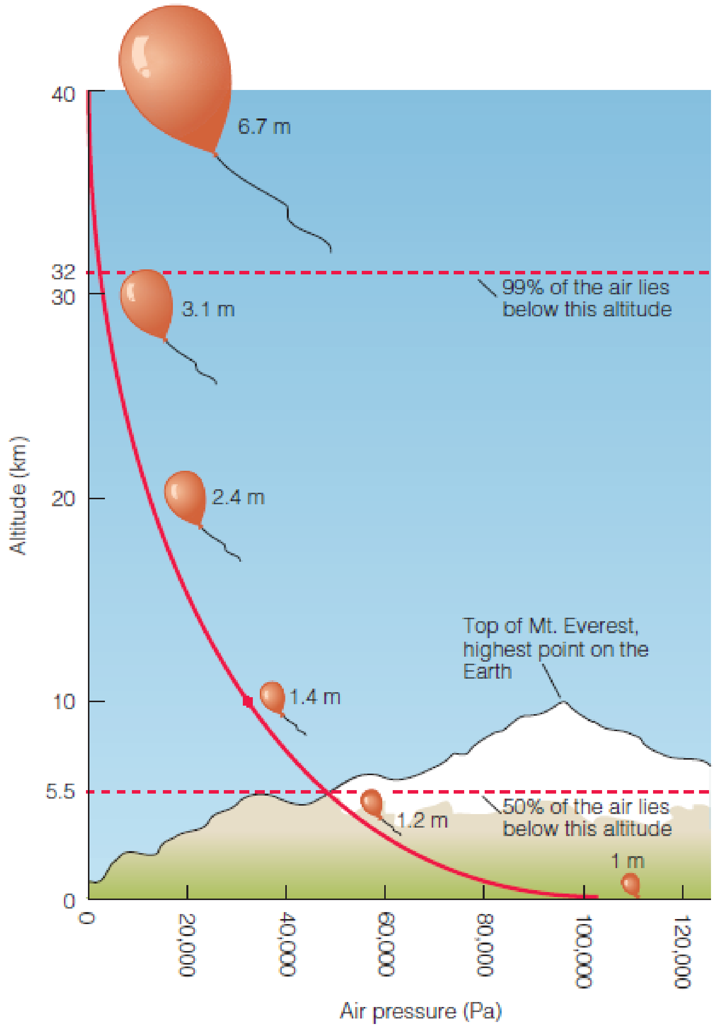


FIGURE 11.13 **Change in air pressure with altitude**
Air pressure decreases smoothly with altitude. If a helium balloon 1 m in diameter is released at sea level, it expands as it floats upward because of the pressure decrease. If the balloon did not burst, it would be 6.7 m in diameter at a height of 40 km.

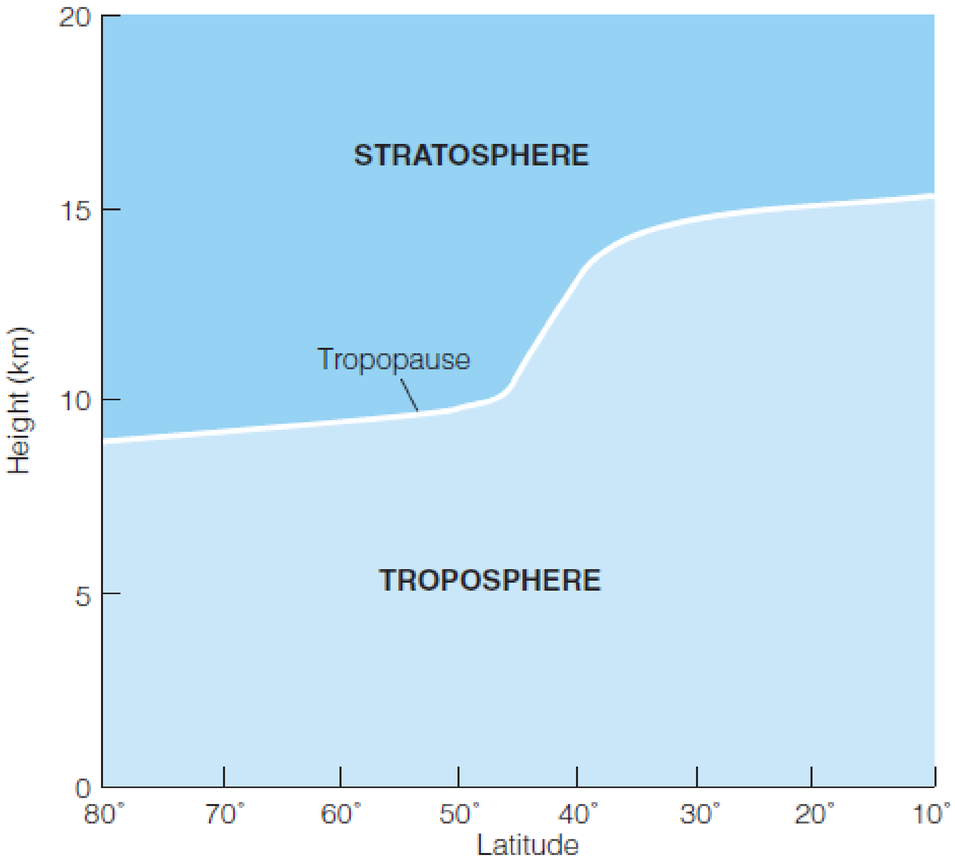


FIGURE 11.9 **Altitude of the tropopause**
The altitude of the tropopause varies with latitude. It is high from the equator to about 40° latitude, where it drops precipitously, continuing at this lower level and declining gently toward the poles. The precipitous drop at 40° latitude facilitates the development of jet streams.

Atmospheric Circulation

Global energy distribution

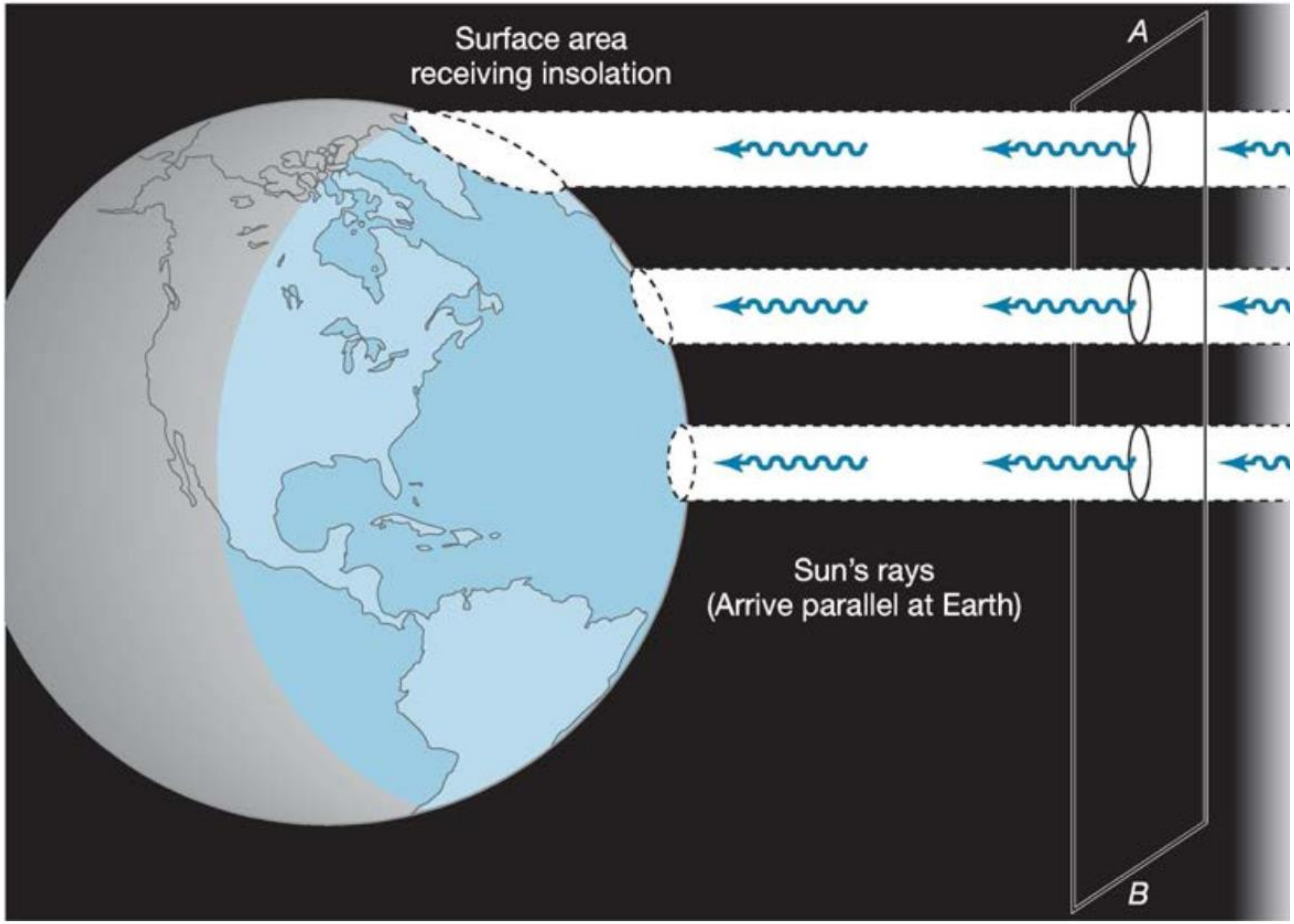


FIGURE 4-1 Variation of incoming solar energy with latitude. The radiation reaching Earth is spread over larger and larger areas as we move from the equator to the poles. Each square meter of the surface receives proportionately less energy as we move to higher latitudes. (*Source:* From R.W. Christopherson, *Geosystems: An Introduction to Physical Geography*, 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Atmospheric Circulation

Global energy distribution

- The maximum absorbed solar energy is found in the tropics and decreases rapidly towards the poles.

- The higher (IR) emission in the tropics are due to high surface temperature there.

- The gradient in the *net radiation* suggests that tropics would get warmer while the poles get progressively colder. However, this does not happen due to **atmospheric circulations**.

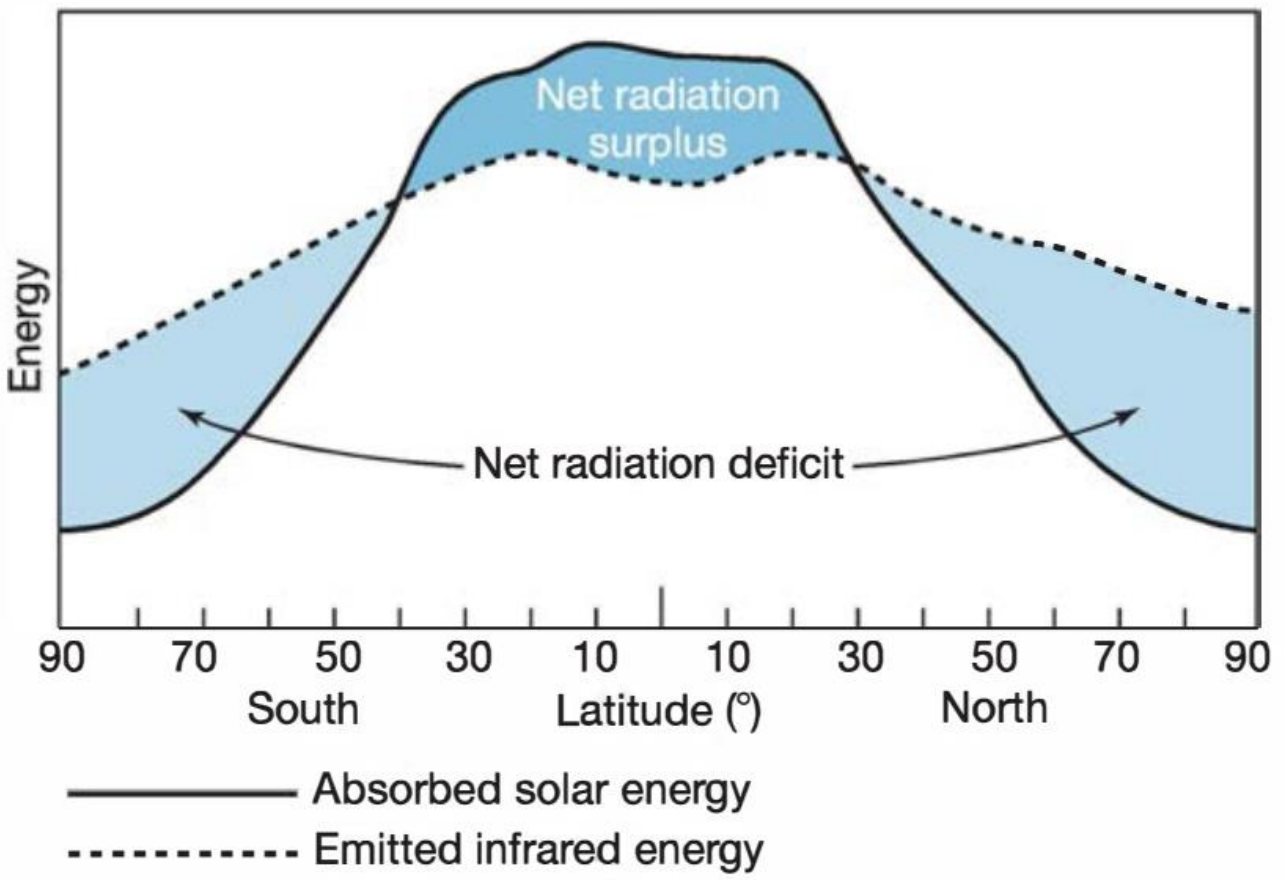


FIGURE 4-2 The distribution of absorbed solar and emitted infrared radiation with latitude. There is a surplus of energy in the tropics, where incoming radiation is greater than outgoing, and a deficit at high latitudes, where more radiation is emitted than is received.

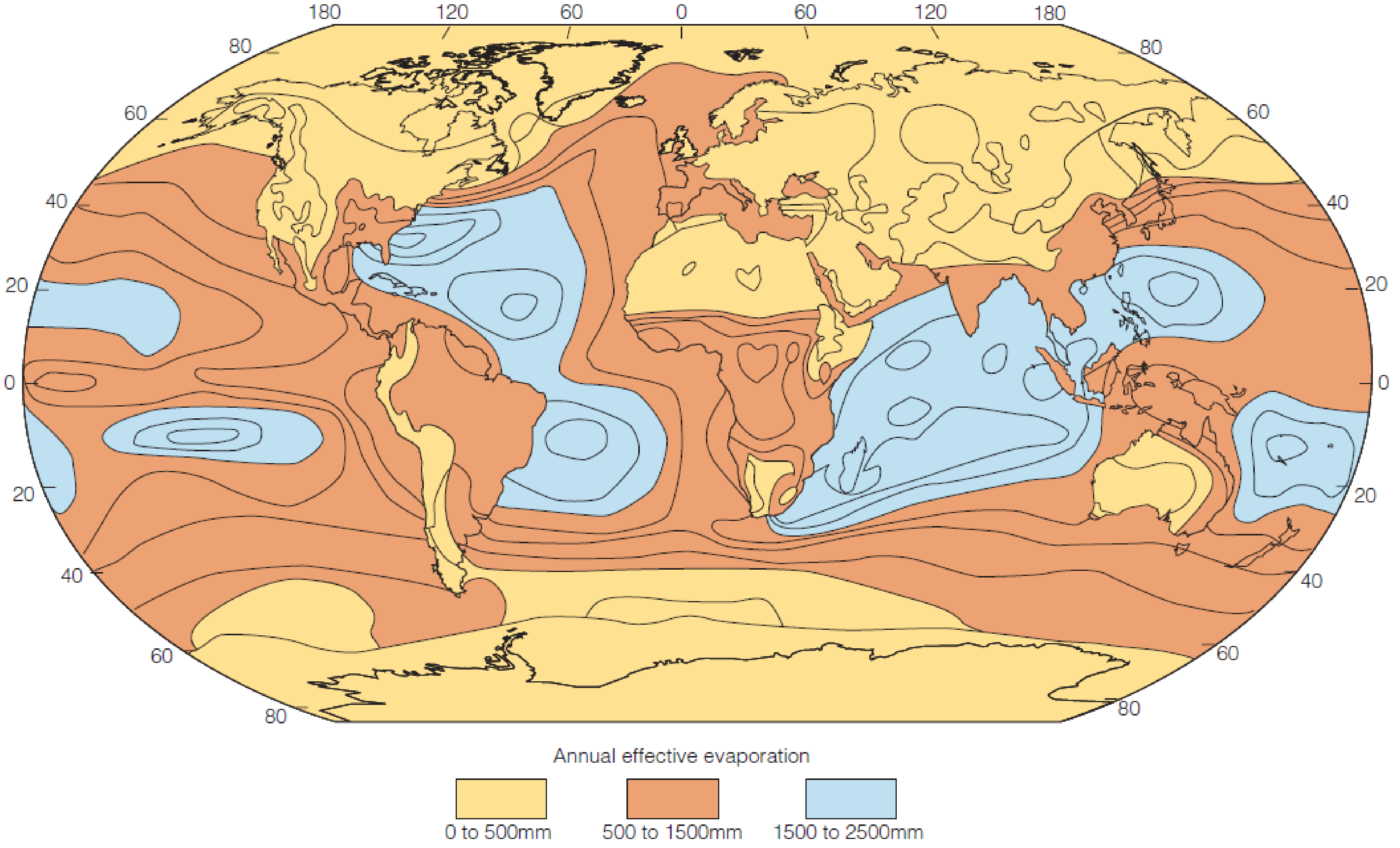


FIGURE 11.16 Evaporation and water vapor in the atmosphere
This map shows the annual addition of water vapor to the atmosphere as a function of geography. The amount evaporated per year is measured in millimeters of water. Areas of highest evaporation (blue) are over the ocean in equatorial and midlatitudes. Evaporation is low in the deserts (gold) because deserts have little water available for evaporation.

Adiabatic Lapse Rate

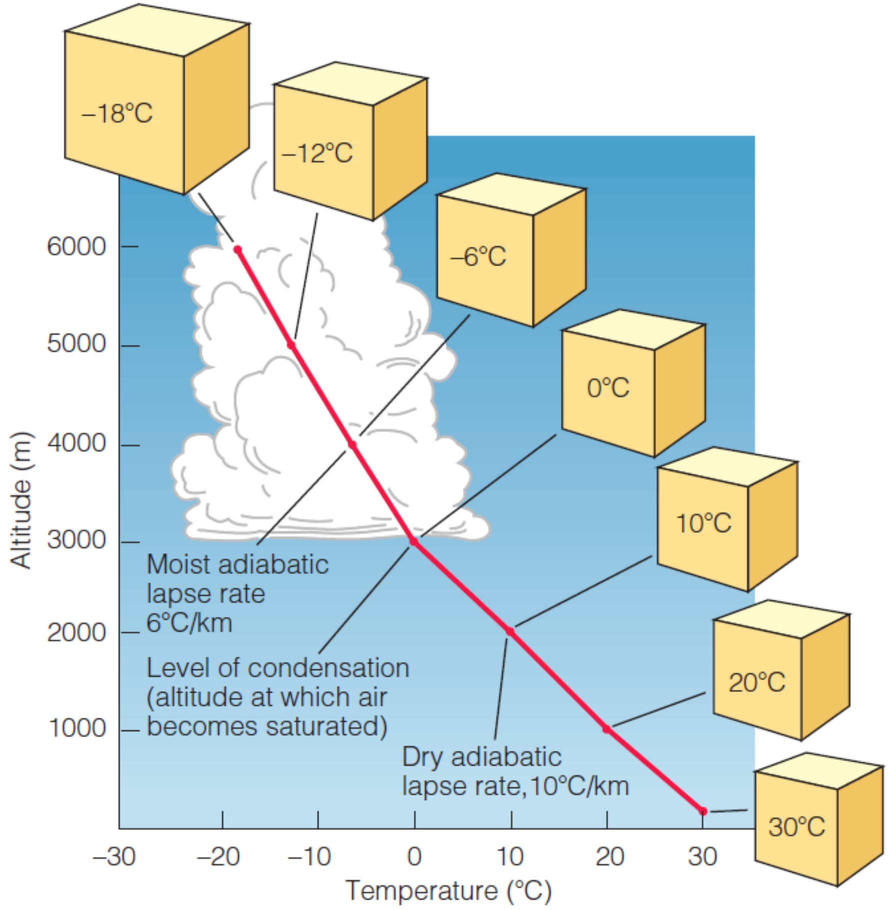
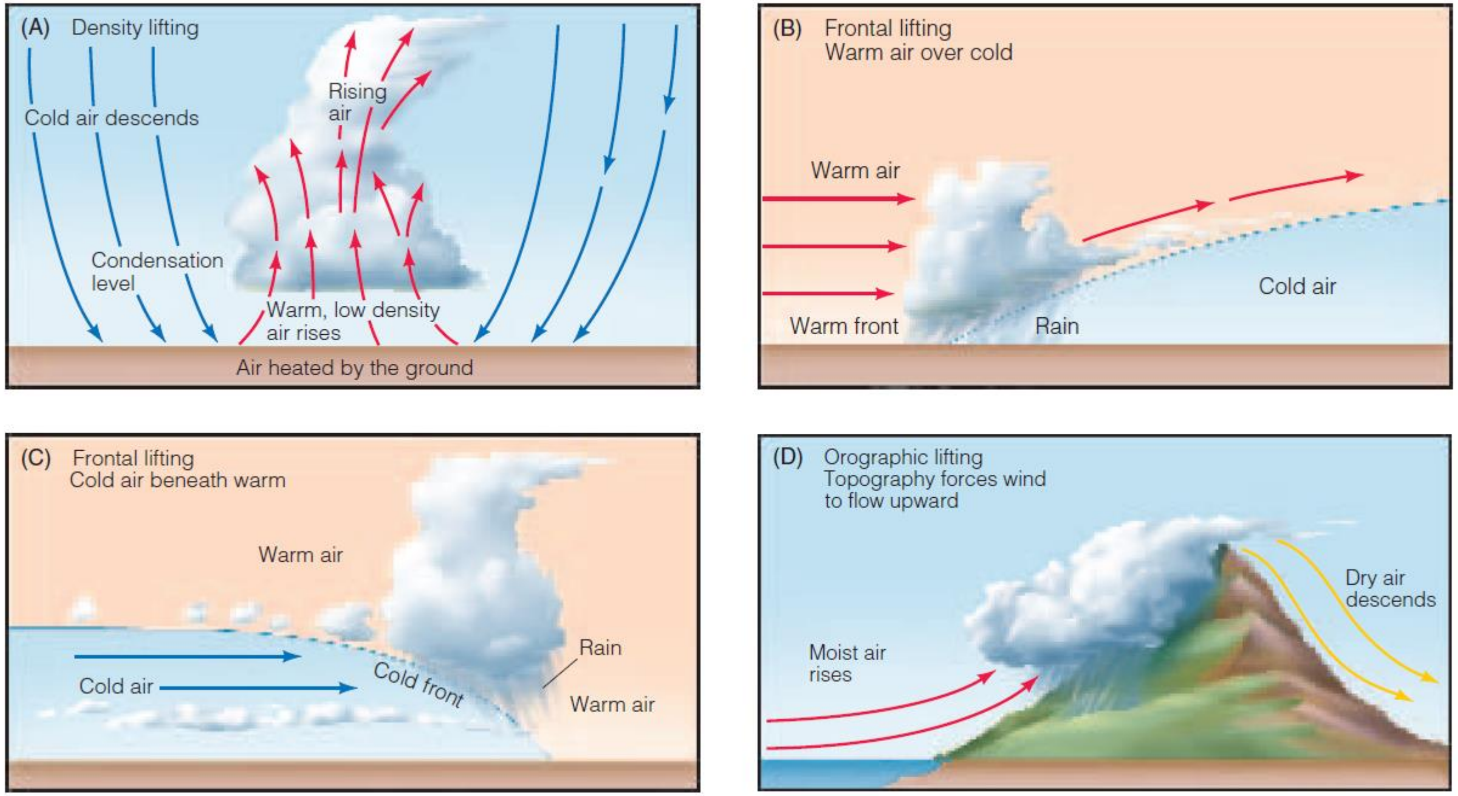


FIGURE 11.17 Adiabatic lapse rate
As an unsaturated mass of air rises, it expands and cools at the dry adiabatic lapse rate (10°C/km). When the dry air temperature falls to the point where the air is saturated, condensation commences and latent heat is released. With further altitude increase, the air temperature decreases at the moist adiabatic lapse rate (6°C/km). Also shown is the change in volume of a mass of rising air that starts as a cube 1 km on an edge.

Cloud Formation



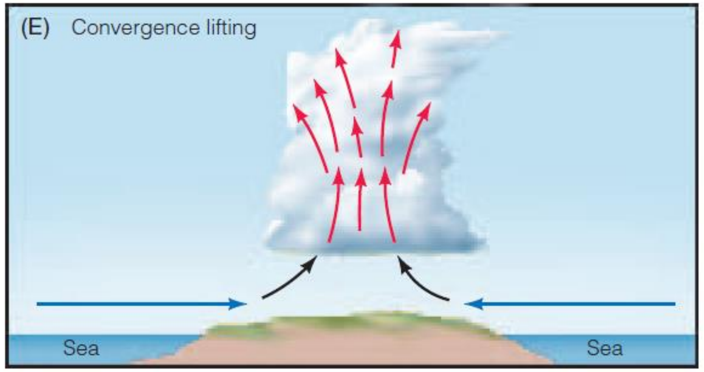


FIGURE 11.18 Lifting forces
These are the main lifting forces that lead to cloud formation. Under most circumstances two or more lifting forces operate at the same time. (A) Density lifting causes a convection cell as warm, low-density air rises and cold, higher-density air sinks. (B) Frontal lifting and a warm front occur when flowing warm air overrides cold air and is forced upward. (C) Frontal lifting and a cold front occur when a wedge of forward-moving cold air slides under a warm air mass and forces it upward. (D) Orographic lifting occurs when flowing air is forced upward by mountains or other sloping ground. (E) Convergence lifting occurs when masses of air collide and are forced upward.

Atmospheric Circulation

- Usually, there is significant imbalance in the distribution of energy at various latitudes: the tropics receive surplus radiative energy whereas the poles run a deficit.

- This imbalance causes an equator-to-pole a temperature gradient that results in pressure and density differences in the atmosphere.

- The pressure and density differences cause air to move in a global scale pattern of the wind belts, which are modified by **Earth's rotation (Coriolis effect)** and by **the distribution of land and water**.

Atmospheric Circulation

- The net effect is to restore the latitudinal energy balance by moving surplus energy away from tropics to cancel out the deficit at poles.

- In the process, energy is used to evaporate water from the land and ocean surfaces, water vapor is carried by the wind, and energy is released when the vapor condenses to form clouds. Thus, there are close interactions between transport of energy and of water by means of circulating air.

- We would be focussing on atmospheric circulation in the troposphere, the lowermost atmospheric layer.

Atmospheric Circulation

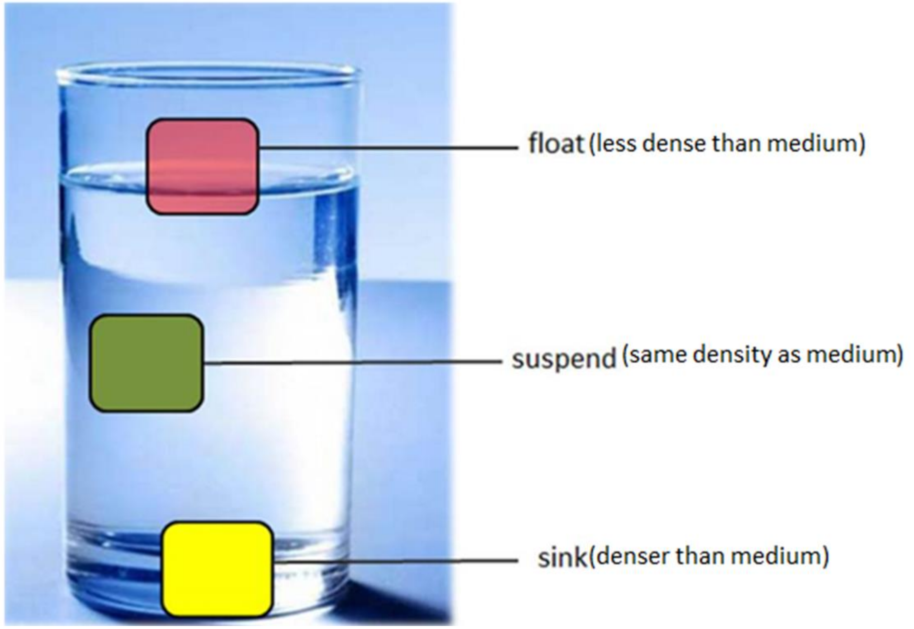
- Air moves horizontally over the Earth's surface due to horizontal pressure gradient.

- The vertical movement of the air is mainly due to **buoyancy**.

- Buoyancy is controlled by the differences in the *density* between the object and fluid.

- Density variations in the air are mainly caused by thermal variations.

- **Therefore, all these horizontal and vertical movement of air can be mostly attributed to differences in temperature across the globe.**



Atmospheric Circulation

Two important points about air movements:

1. Air tends to move from an area of higher pressure to an area of lower pressure until two pressure are equalized.

2. If the air is heated until its density is lower than that of its surroundings, the lower density air will rise (*convection*). Conversely, if an air mass is cooled until its density is higher than that of the underlying air, it will sink (*subsidence*).

Atmospheric Circulation

Global energy distribution

- The average global temperature is determined by the balance between the solar energy absorbed by the Earth and the infrared radiation emitted to space (Global Energy Balance).

- However, neither the radiation received from the sun or nor the infrared emission from the Earth is distributed uniformly across the Earth's surface.

- The incoming solar energy varies with latitude and with season, whereas the outgoing terrestrial radiation depends on the surface temperature and atmosphere at each location.

Atmospheric Circulation

General circulation of the atmosphere

- The large solar input to the tropics heats the surface (primarily ocean), which in turn heats the overlying air. When heated from below, air will rise by convection creating a low-pressure region there.

- This rising air is replaced by surface air moving equatorward from an area of high pressure to an area of low pressure.

- The converging air mass that meet at the tropics and rise make up *intertropical convergence zone* (ITCZ).

Atmospheric Circulation

General circulation of the atmosphere

- This layer (ITCZ) is characterized by extensive area of cloud cover and heavy precipitation.
- Clouds can often extend up to the tropopause.
- As we know that temperatures generally increase in stratosphere.
- This higher temperature limits the convection and rising air in the ITCZ, upon reaching this barrier, is forced to diverge poleward.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

- This poleward moving air subsides at about 30° N and 30° S latitude, replacing the air that is moving equatorward at the surface. This pattern of air circulation is called **Hadley cell**.

- The subsiding air at 30° N and 30° S latitude gets warm, which prevents the condensation and cloud formation.

- These regions are characterized by clear skies and low rainfall.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

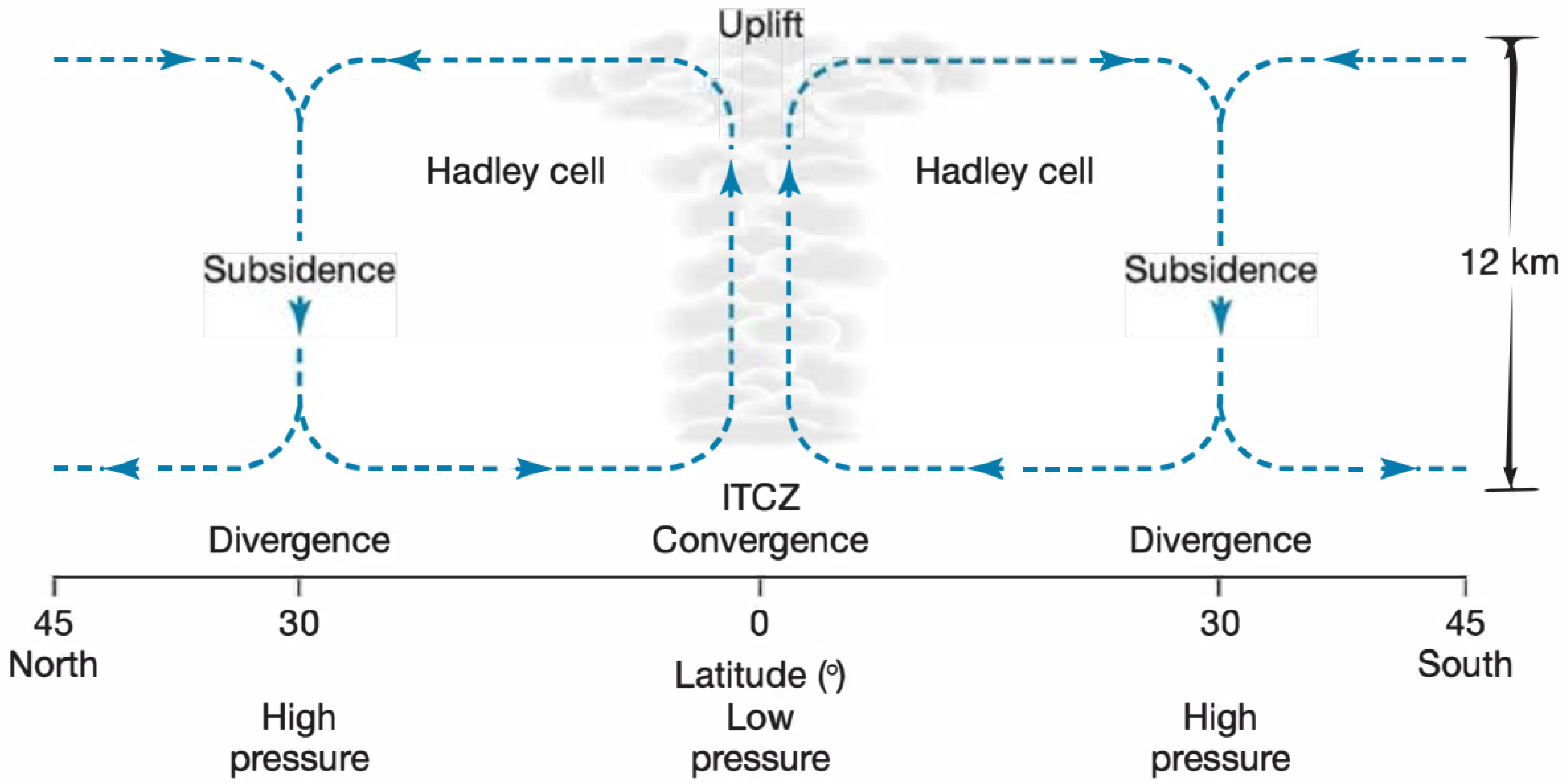


FIGURE 4-3 Convergence, divergence, and the Hadley circulation in the tropics. There is a Hadley cell on either side of the intertropical convergence zone (ITCZ), located over the equator. Rising air in the ITCZ is replaced by inflowing air (convergence) at the surface. Outflowing air (divergence) in the upper troposphere sinks at about 30° N and 30° S, completing the circulations in the two cells.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

- The very low temperatures at the poles result in increased air density and high pressure near the surface, which leads to divergence and movement of the cold air at the surface equatorward. The divergence is accompanied by subsidence from above.

- The equatorward moving cold air meets the warm air from subtropics, producing a zone of steep temperature gradients known as **polar front zone** at about 60° N and 60° S latitude.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

- These cold and warm air masses do not mix easily. Due to density difference, cold air sinks below the warm air when these air masses meet. Therefore, the polar front zone slopes poleward with increasing altitude in the atmosphere (Figure 4.7)

- Based on the description of Hadley and mid latitude circulation, the general pattern of the surface wind looks like as shown in Figure 4.8.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

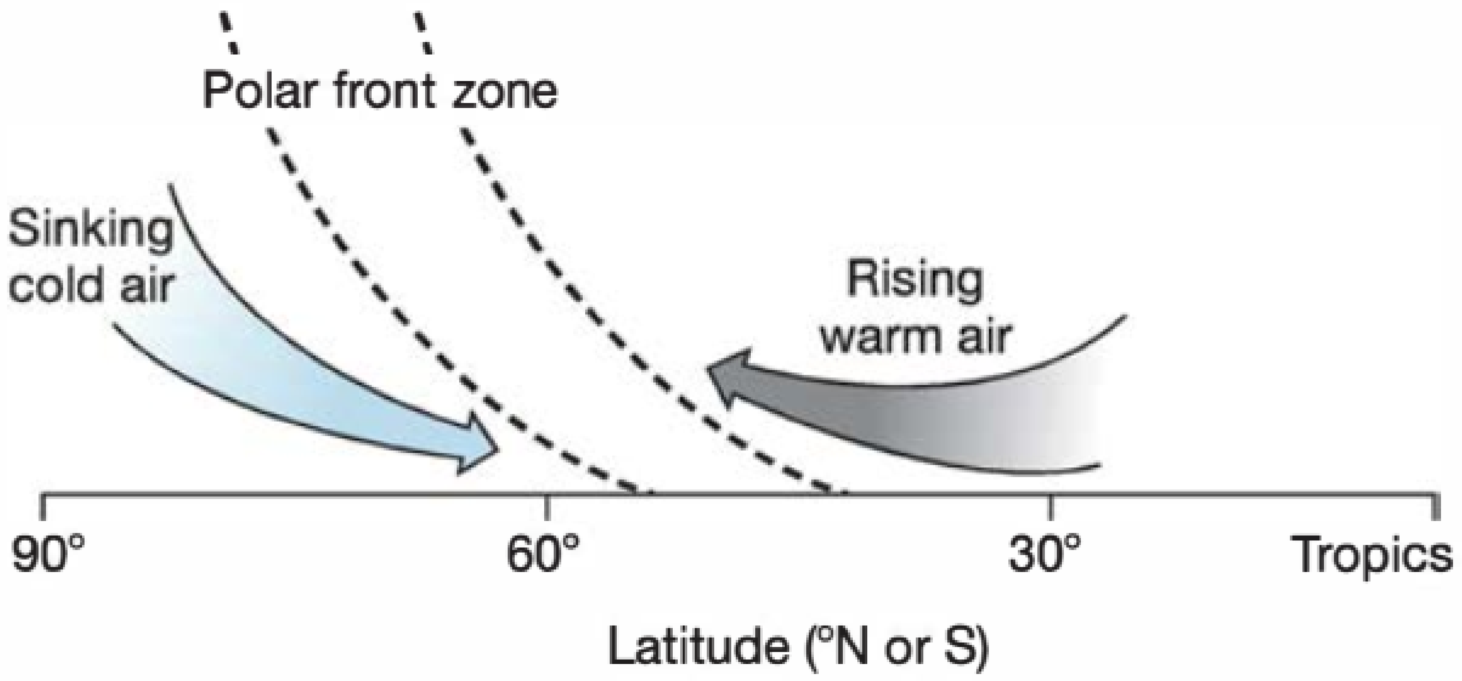


FIGURE 4-6 Mixing of air in the midlatitudes. The lower-density warm air from the tropics rises above the colder air moving equatorward from high latitudes. These contrasting air masses do not mix very easily. This zone is characterized by large temperature contrasts over very short distances.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

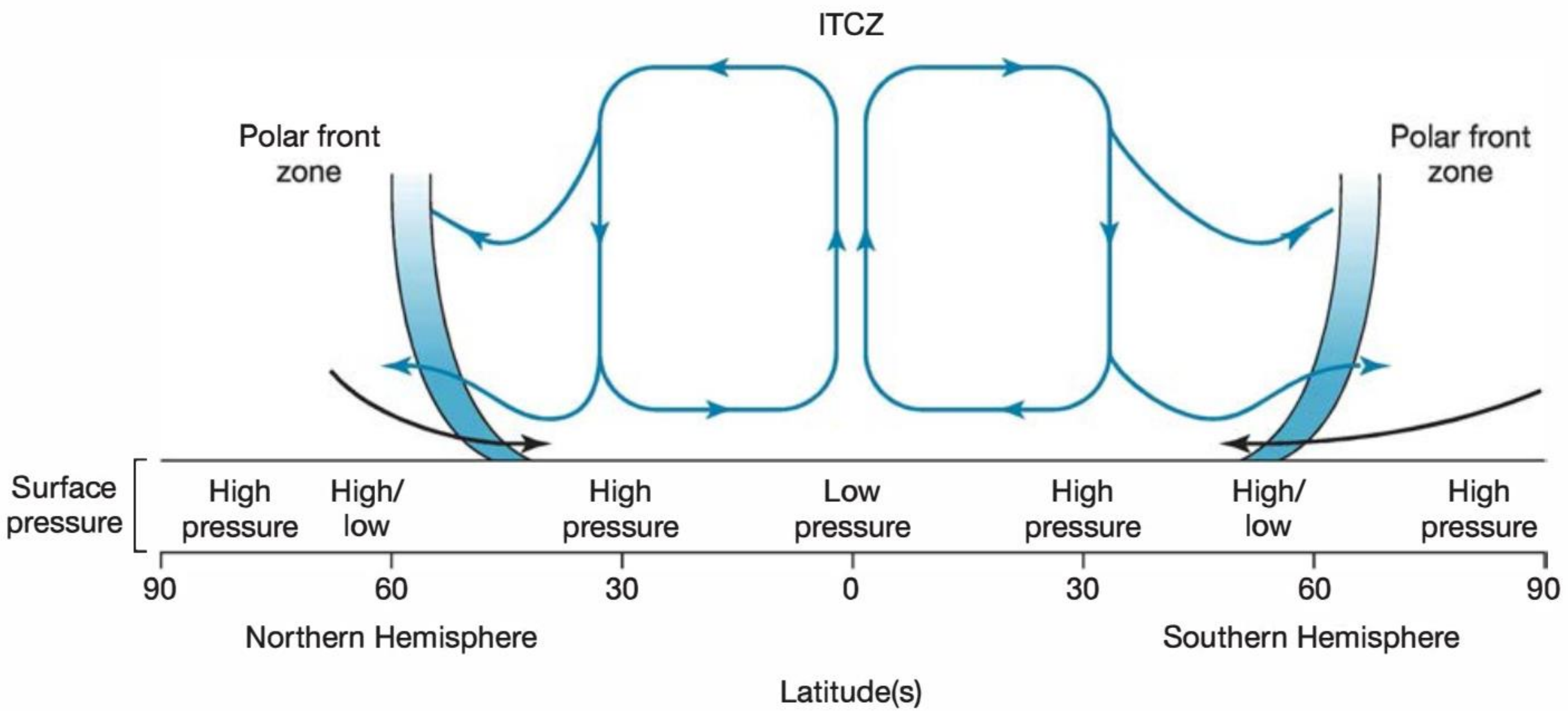


FIGURE 4-7 The north–south (meridional) circulation of the troposphere. The tropical circulation is dominated by the Hadley circulation, whereas midlatitude circulation and weather are controlled by the location of the polar front zone and the mixing of cold polar air with warm air from the tropics.

Atmospheric Circulation

General circulation of the atmosphere (Contd.)

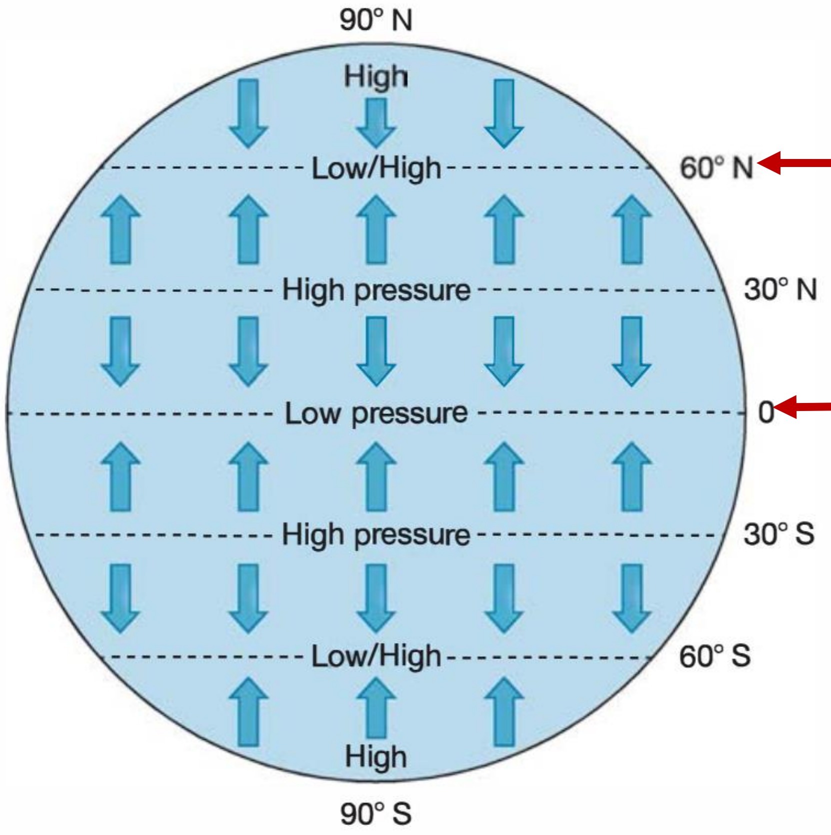


FIGURE 4-8 A possible model of the surface winds obtained by plotting, on a globe, the pattern of surface winds that would be deduced from Figure 4-7. Surface winds blow out of the high-pressure zones at the poles and at 30° N and 30° S and blow toward the low-pressure zones at the equator and in the midlatitudes.

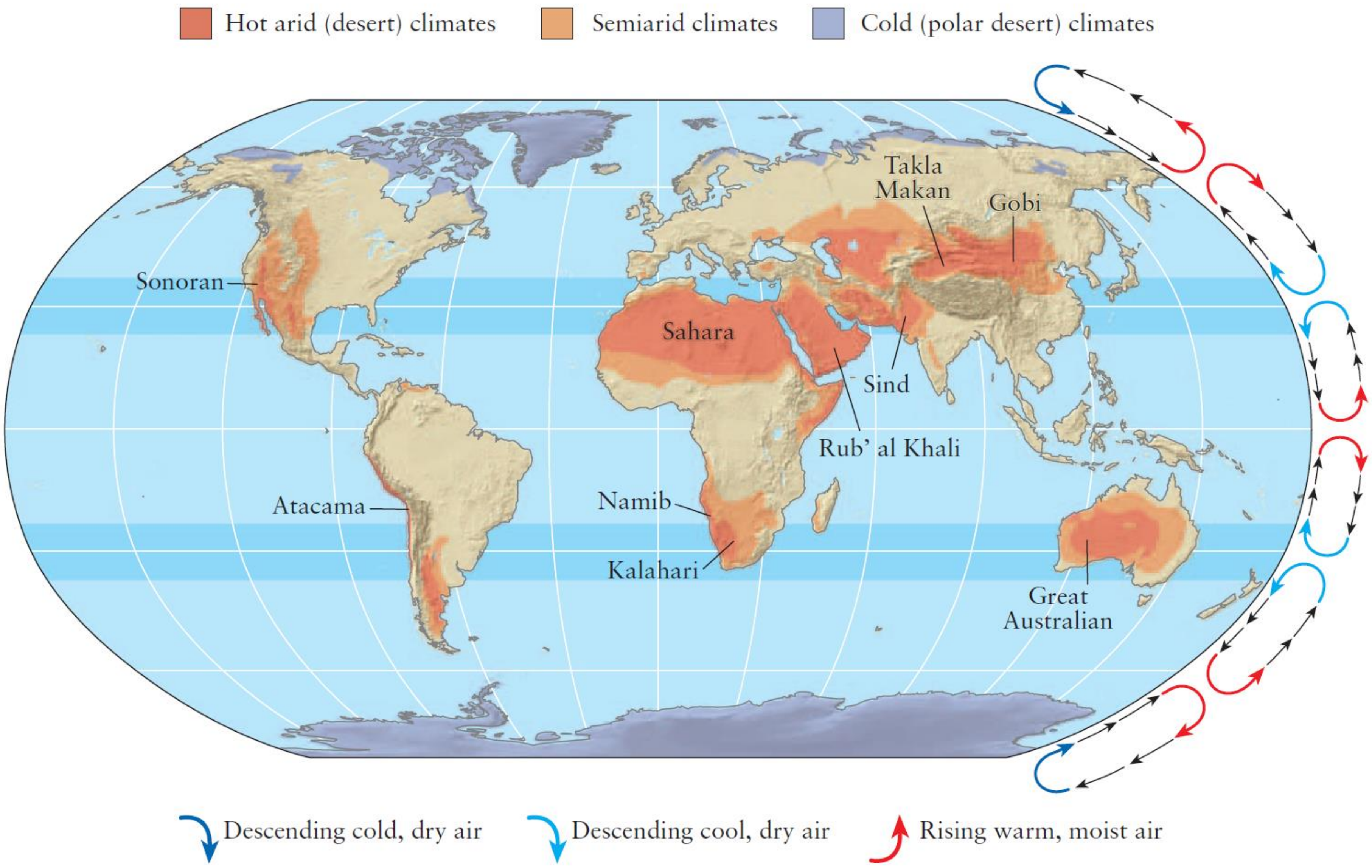
Polar front zone (High- and low-pressure region)

Divergence

ITCZ Convergence

This pattern shows only north-south movement of the wind. However, we know that wind tends to move in east-west direction as well. To understand east-west movement, we need to take into account the effect of **Coriolis** force.

FIGURE 12.25 Deserts and atmospheric circulation
This map shows the distribution of arid and semiarid climates and the major deserts associated with them. Many of the world's great deserts are located where belts of dry air descend near the 30° N and 30° S latitudes. Notice also that regions of cold, descending air also surround both of the poles. Despite being covered by ice, the polar regions receive little precipitation and are considered to be frozen deserts.



Atmospheric Circulation

Coriolis Effect

- The tendency for a fluid (air or water) moving across Earth's surface to be deflected from its straight-line path due to Earth's rotational motion.

- In Newtonian mechanics, the equation of motion for an object in an inertial (non-accelerating) frame is $\boldsymbol{F} = m\boldsymbol{a}$, where $\boldsymbol{F}$ is the force acting on the object of mass m and $\boldsymbol{a}$ is the acceleration of the object with respect inertial frame. (Bold represent the vector quantities)

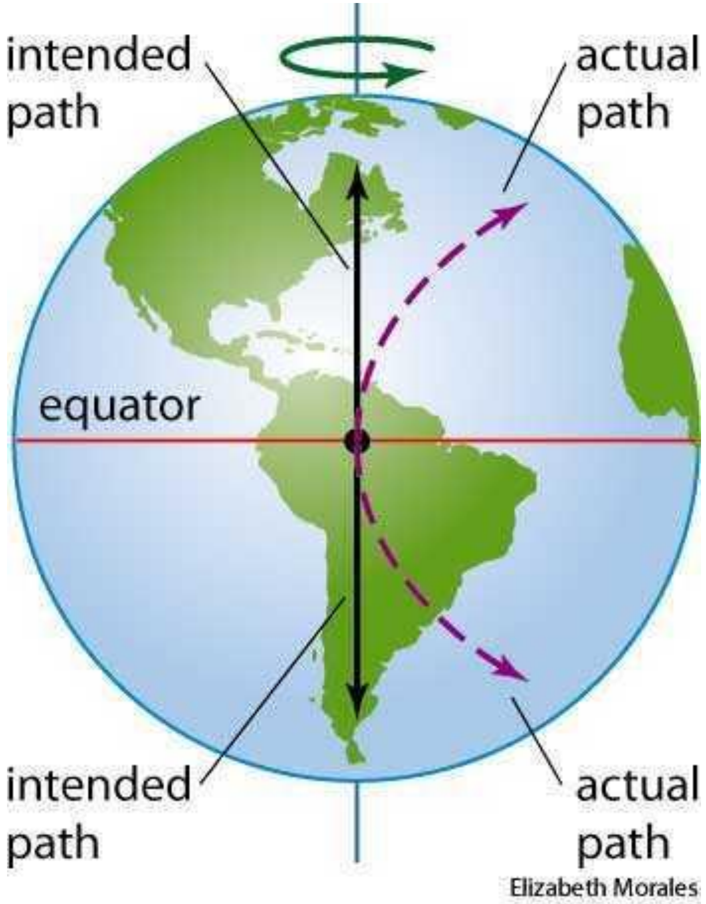
- However, with respect to a rotating (with a fixed axis of rotation and constant angular velocity ω) frame of reference, equation of motion for an object of mass m moving with linear velocity v changes to

$$\boldsymbol{F} - \underbrace{2m\,\boldsymbol{\omega} \times \boldsymbol{v}}_{\text{Coriolis Force}} - \underbrace{m\,\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{r})}_{\text{Centrifugal Force}} = m\boldsymbol{a}.$$

Atmospheric Circulation

Coriolis Effect

Due to Coriolis force, north-south moving object will be deflected to east or west. Air mass moving in the **Northern Hemisphere** always gets deflected to the **right** of the initial motion, whereas in the **Southern Hemisphere** it gets deflected to **left** (because direction of rotation changes from anticlockwise to clockwise).



Atmospheric Circulation

Coriolis Effect

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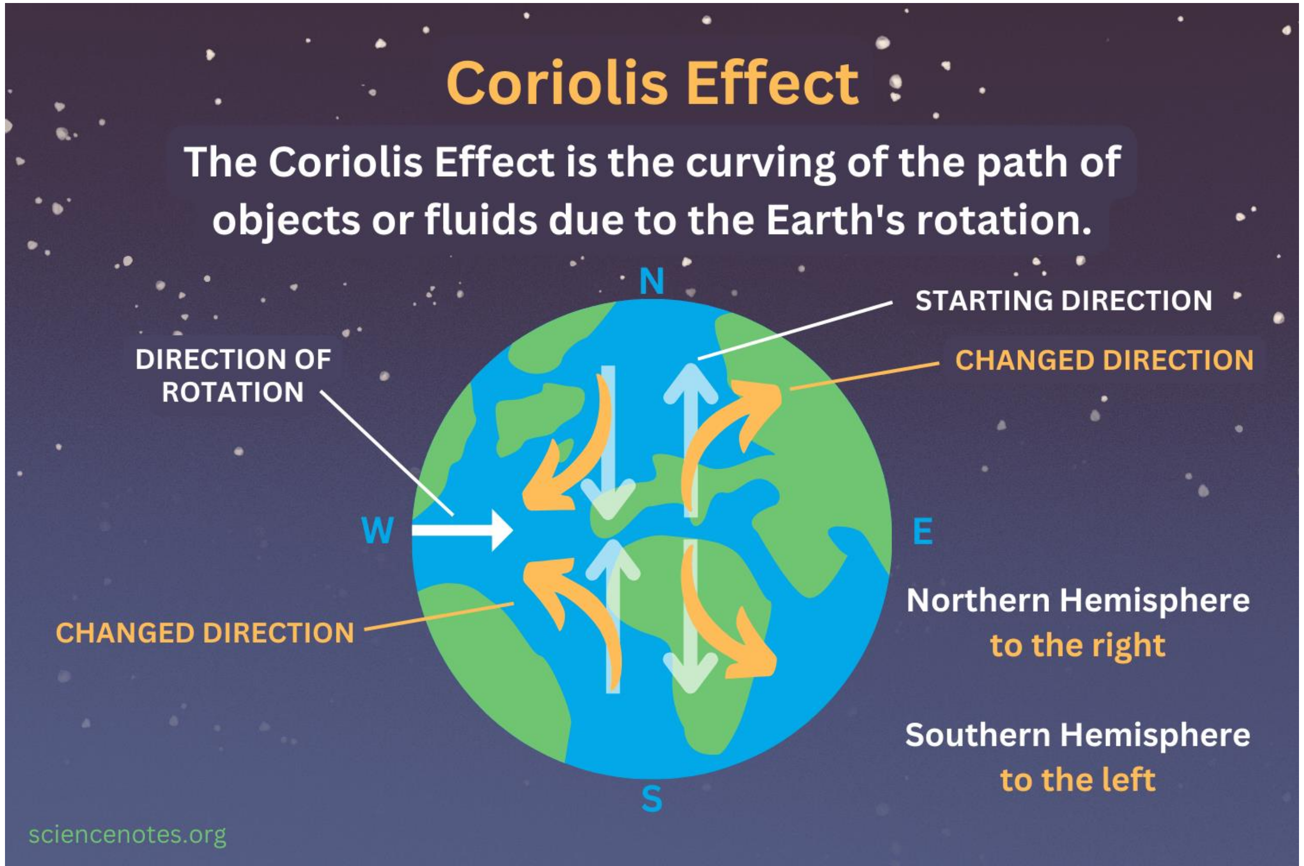
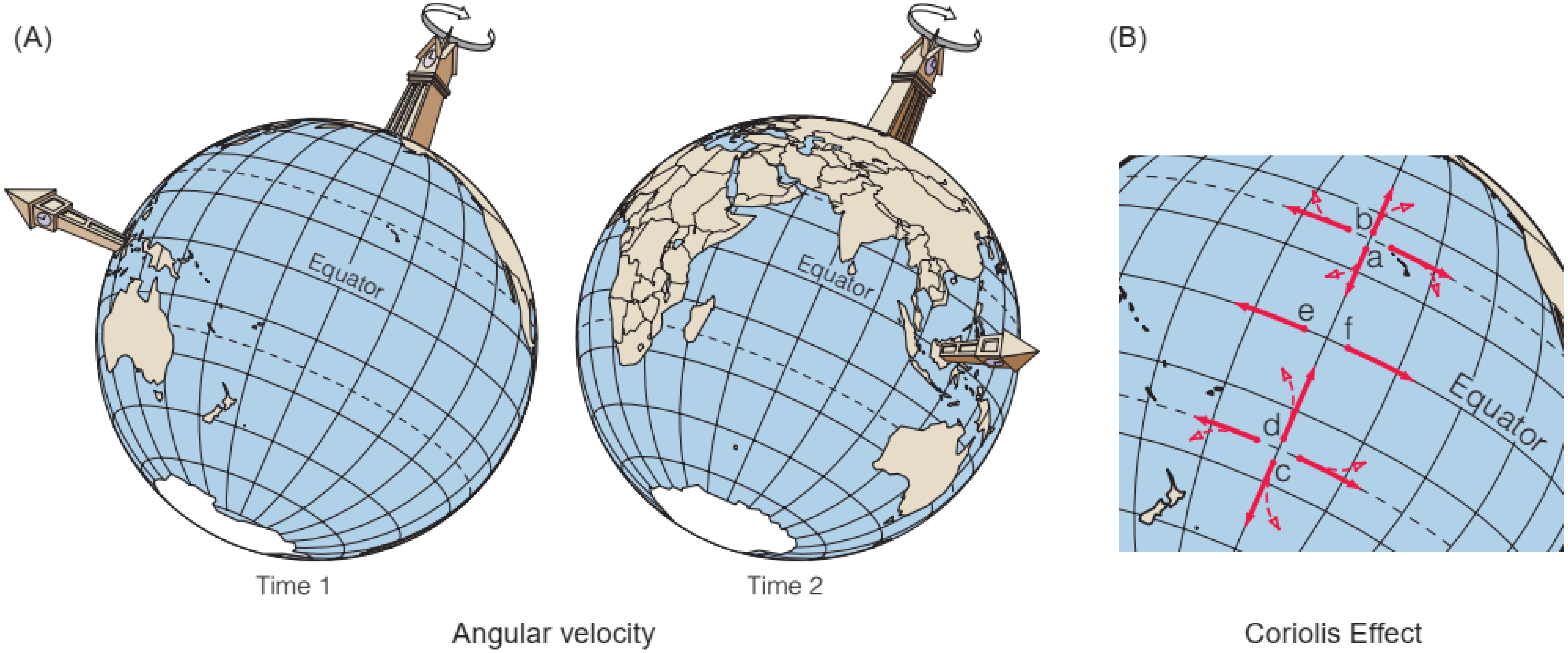


FIGURE B10.1 Coriolis force

The Coriolis force results from the influence of angular momentum on the movement of bodies on the surface of a rotating planet. (A) A body at the pole rotates completely around every 24 hours, whereas a body on the equator goes end-over-end but does not rotate. The face on the tower at the pole rotates with respect to an external observer, whereas a tower on the equator always faces the same direction. This demonstrates that angular momentum is highest at the poles, decreasing to zero for objects at the equator. (B) On the rotating Earth, an object freely moving in the northern hemisphere (*a*, *b*) is deflected by the Coriolis force to the right, whereas in the southern hemisphere (*c*, *d*) it is deflected to the left. A moving object at the equator (*e*, *f*) is not deflected.



Atmospheric Circulation

General circulation of the atmosphere

By combining the effect of Coriolis effect and simple north-south circulation, we obtain the more realistic pattern for the surface wind.

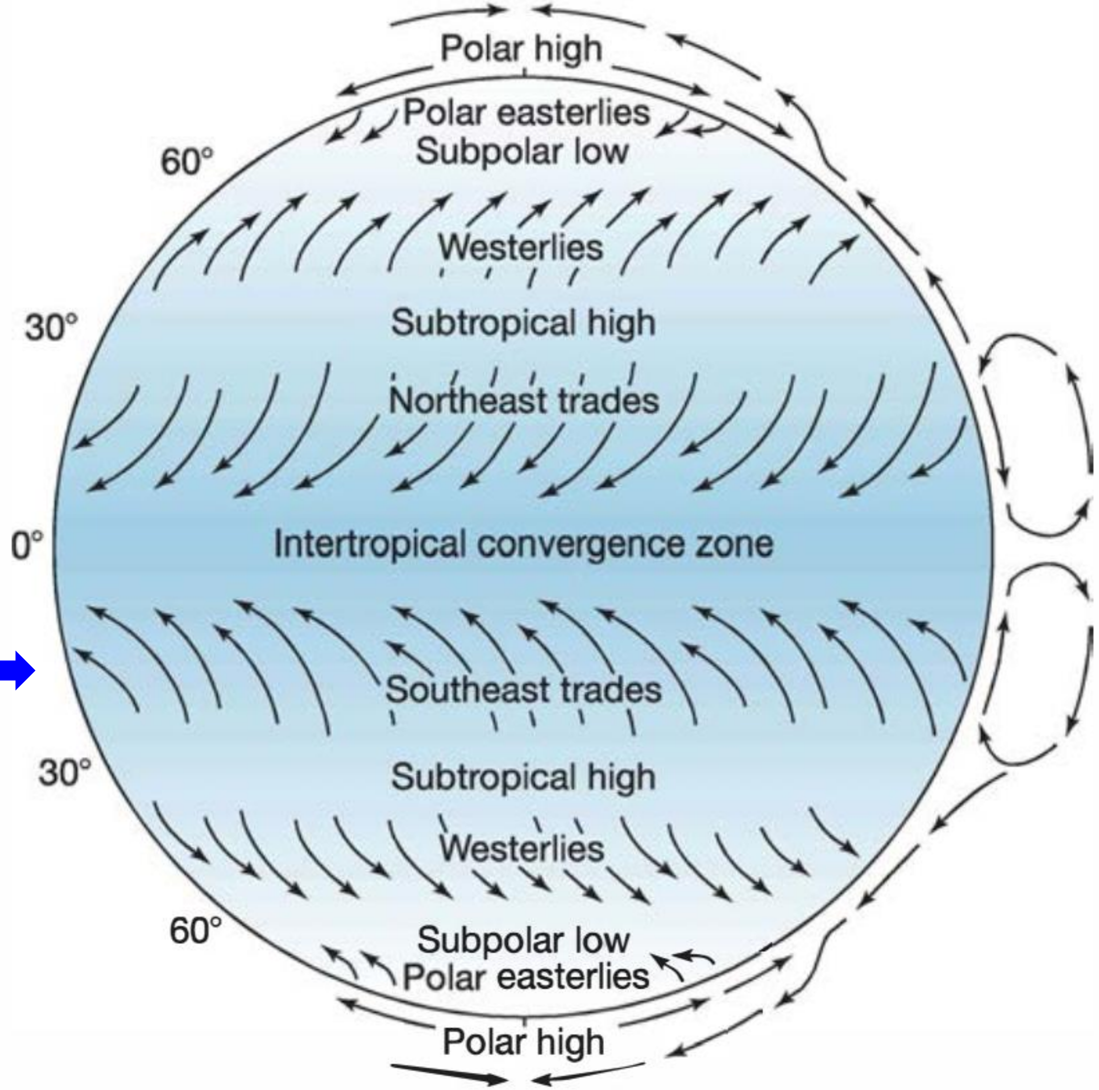
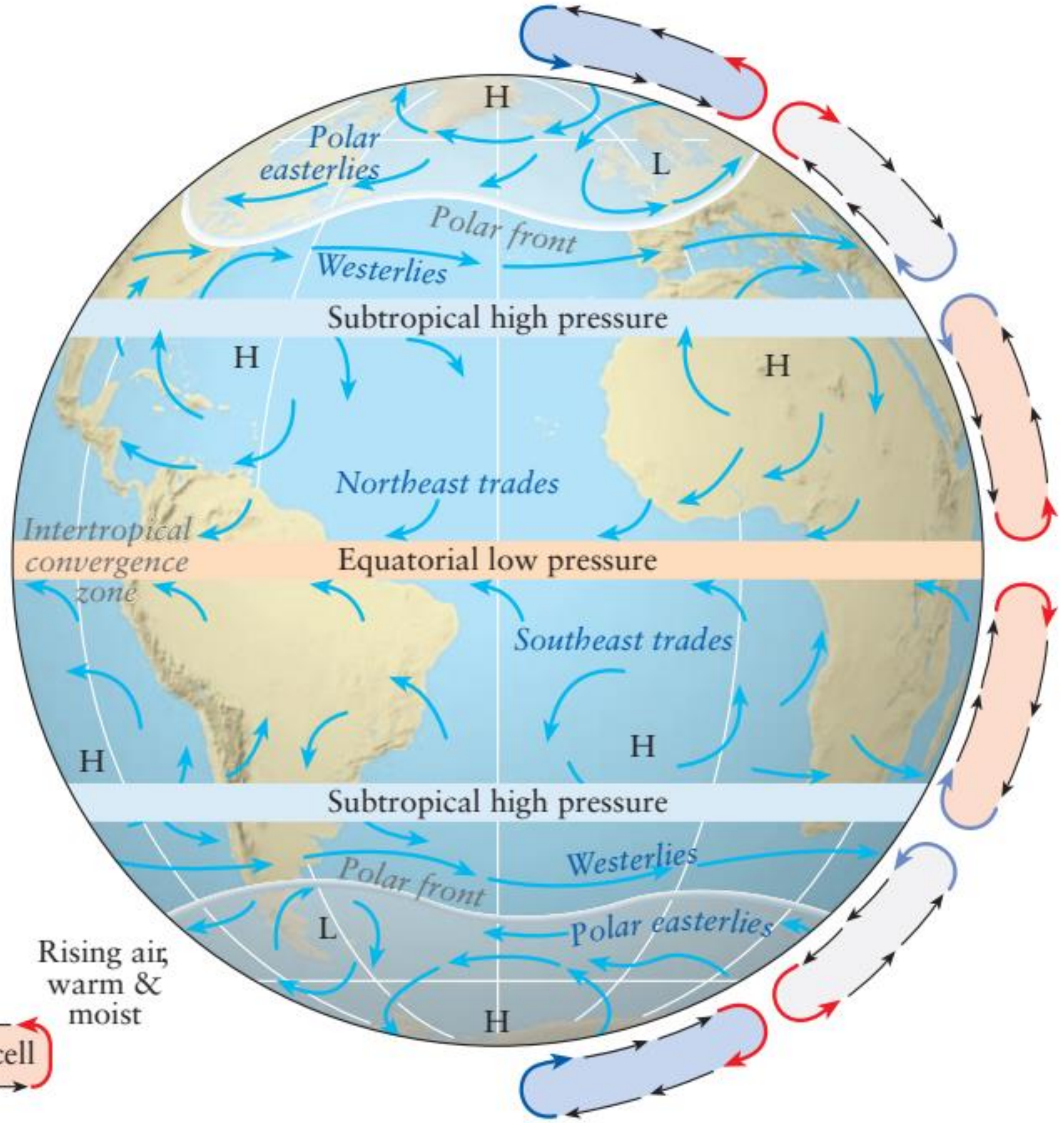
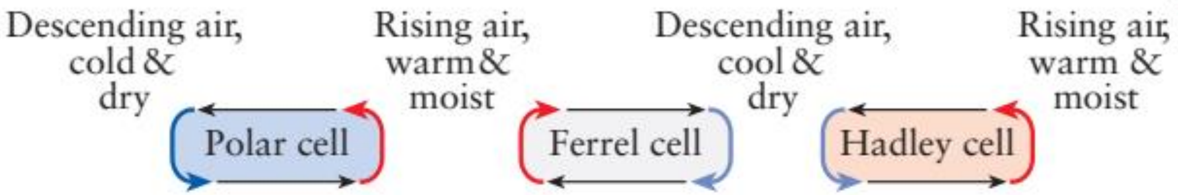


FIGURE 4-11 The pattern of surface winds. This shows the same general pattern of winds as Figure 4-8, but the wind directions have been changed to include the deflection due to the Coriolis effect. (*Source:* From T. McKnight, *Physical Geography: A Landscape Appreciation*, 6/e, 1999. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

FIGURE 12.11 Global atmospheric circulation
Earth rotates, with the result that the flow of air toward the poles and the return flow toward the equator are constantly deflected sideways. This results in three major sets of circulating air masses: Hadley cells, Ferrel cells, and polar cells. The cells shift somewhat in location, but they are permanent features of Earth's atmosphere and therefore have a great influence on both day-to-day weather and long-term climate.





Seasonal Variability

- Considerations of pressure differences (pressure gradient force), buoyancy, and the Coriolis force have led us to obtain simple (a good first approximation) understanding of general circulation of the atmosphere (Figure 4.11).

- However, this simple pattern of atmospheric circulation is also modified by seasonal variations.

- The difference in the distance between Earth and Sun and (more importantly) the Earth's *tilt* or *obliquity* (~23.5°) are responsible for seasonal variations.

- The solar energy distribution varies with the seasons. (Figure 4.15)

Seasonal Variability

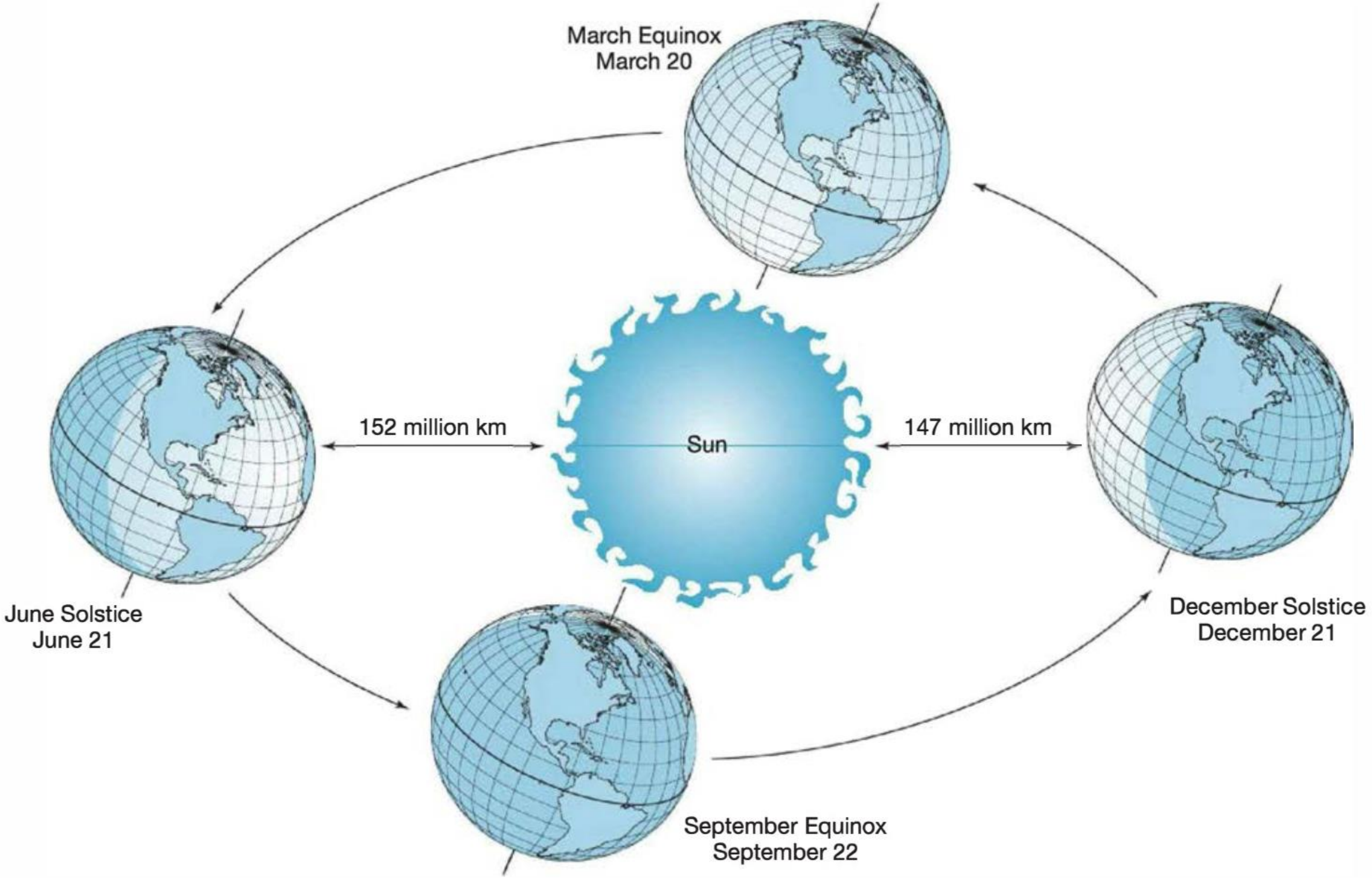


FIGURE 4-15 The seasons. The seasons are controlled by Earth's obliquity and Earth's orbit around the Sun. The hemisphere that is "tilted" toward the Sun experiences summer while it is winter for the hemisphere that is "tilted" away from the Sun. The equinoxes (when the Sun is directly overhead at the equator) mark the transition seasons: fall and spring. (*Source:* From T. McKnight, *Physical Geography: A Landscape Appreciation*, 6/e, 1999. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Atmospheric Circulation

Seasonal Variability

- The seasonal variability in the incoming energy shifts the atmospheric circulation patterns northward and southward as the season change.

- Due to tilt, Sun shines continuously for six month at each pole. The hemisphere experiencing summer has less of temperature gradient between tropics and the pole than that of the opposite hemisphere.

- The reduced temperature gradient weakens the strength of the atmospheric circulation.

- At the same time, because the Sun is directly overhead somewhere away from equator (due to tilt), the steepest temperature gradients are shifted toward the poles and circulation patterns are also shifted poleward. (Figure 4.16)

Atmospheric Circulation

Seasonal Variability

- In the hemisphere experiencing winter, the equator-to-pole temperature gradient is much stronger and the steepest gradients are shifted equatorward. Therefore, the atmospheric circulation is more intense and the circulation patterns are shifted equatorward.

- The ITCZ also moves northward and southward as the season shifts. The ITCZ will reach its maximum northward location late in the Northern Hemisphere summer. It will then migrate southward crossing the equator in the fall and reaching its most southern location late in the winter (Southern Hemisphere summer). (Figure 4.16)

- The upper tropospheric circulation is also affected by seasonal variations with more intense wind speeds in the winter and *jet streams* shifting north and south with seasons.

Atmospheric Circulation

Seasonal Variability

Notice the curvature of winds moving over equator as ITCZ shifts northward or southward.

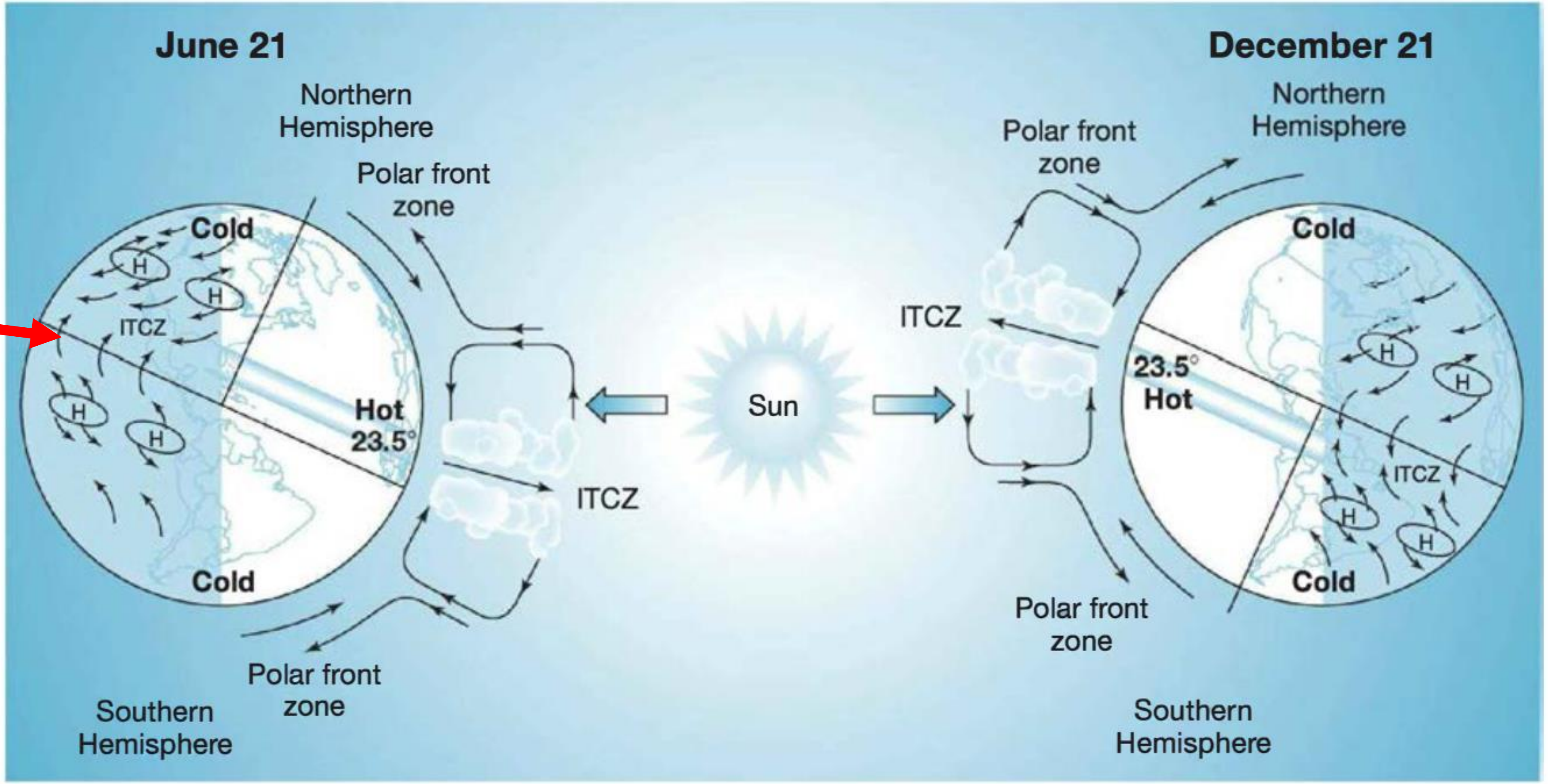


FIGURE 4-16 Seasonal migration of the atmospheric circulation patterns. The ITCZ is found in the summer hemisphere, where the circulation is weaker and the patterns are shifted toward the pole. The subtropical high-pressure cells that mark the descending arms of the Hadley circulations are denoted by H.

Global Distribution of Temperature and Rainfall

- As we understood that the cause of atmospheric circulation is the distribution of available solar energy. We need to keep in mind that interaction between temperature and circulation is not a one-way process. The circulation is an important component of the Earth's thermoregulatory system. Therefore, the global temperature and rainfall distributions are strongly affected by the atmospheric circulation.

- In general, temperature, precipitation, and atmospheric circulation are all closely linked and interactions and feedbacks exist among all three of these components of Earth's climate.

Global Distribution of Temperature and Rainfall

Land-Ocean Contrasts and Continentality

- Beyond the latitudinal distribution of solar energy, the global temperature patterns are strongly influenced by the distribution of land and ocean.

- Since the albedo of the ocean surface is considerably lower than that of land surfaces, oceans absorb more of the available solar energy than do the land surfaces at the same latitude.

- An ocean surface **rapidly** transfers heat to atmosphere by convection and downward by turbulent mixing. The land surface also transfers heat to atmosphere by convection, but it transfers heat downward relatively **slowly by *conduction*** because **water has high thermal conductivity, whereas land surfaces have low thermal conductivities.**

- The heat capacity (a measure of energy required to change the temperature of an object) of **water is about three to four times** that of the dry soil. **Thus, the input of a given amount of energy will raise land temperatures much more than it will raise sea-surface temperatures**.

Global Distribution of Temperature and Rainfall

Land-Ocean Contrasts and Continentality

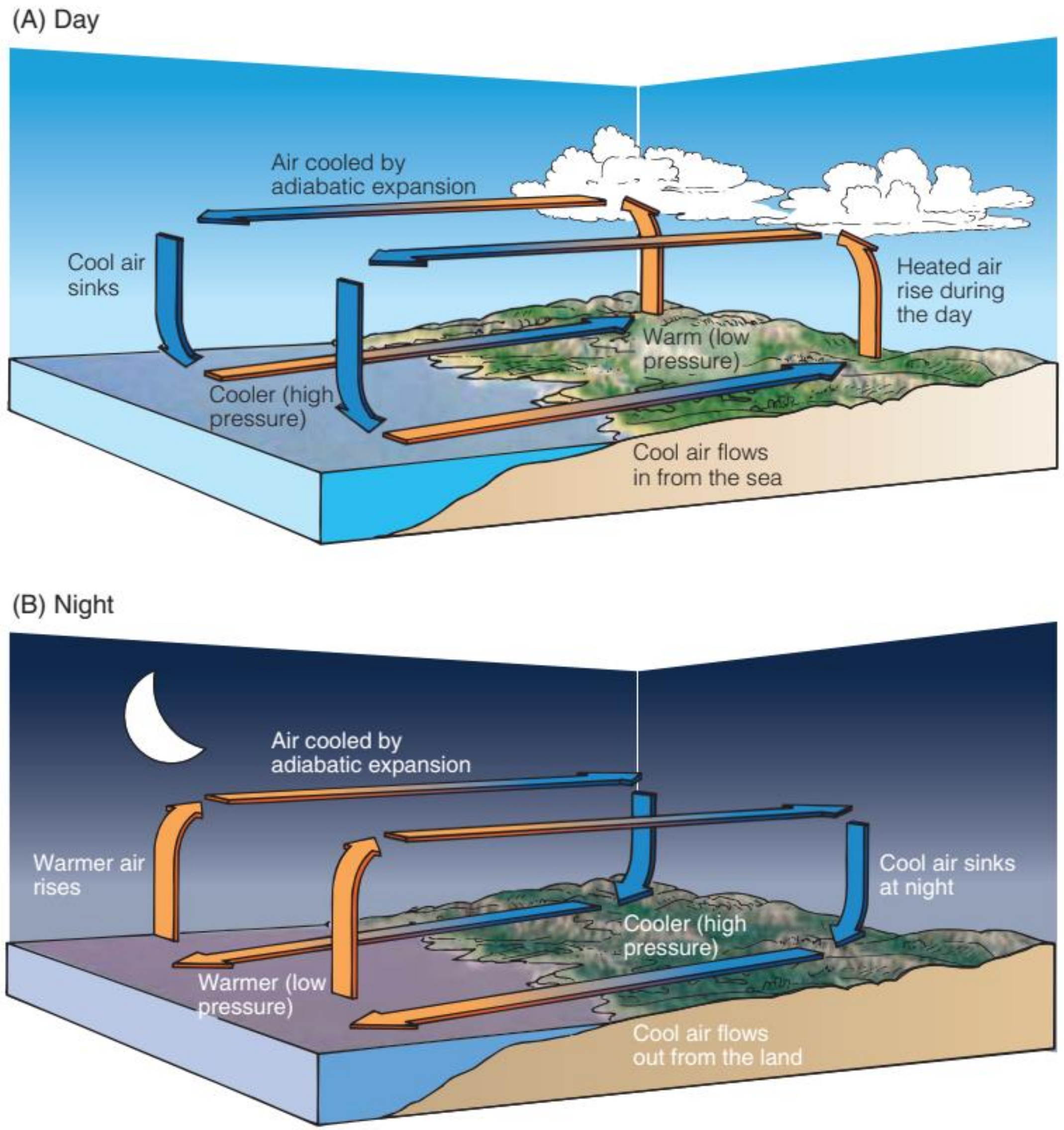
- Land surfaces heat up quickly during the day and cool quickly at night, whereas ocean surfaces warm slowly in the day and temperatures drops very little at night. The sea breeze that occurs at coastlines is a direct consequence of this diurnal variability.

- As we have already seen that seasonal variations over midlatitudes and high latitudes is much greater than in the tropics (due to tilt). This variability is much stronger over the land surface than over the oceans because of their different thermal characteristics. This property is called ***continentality***.

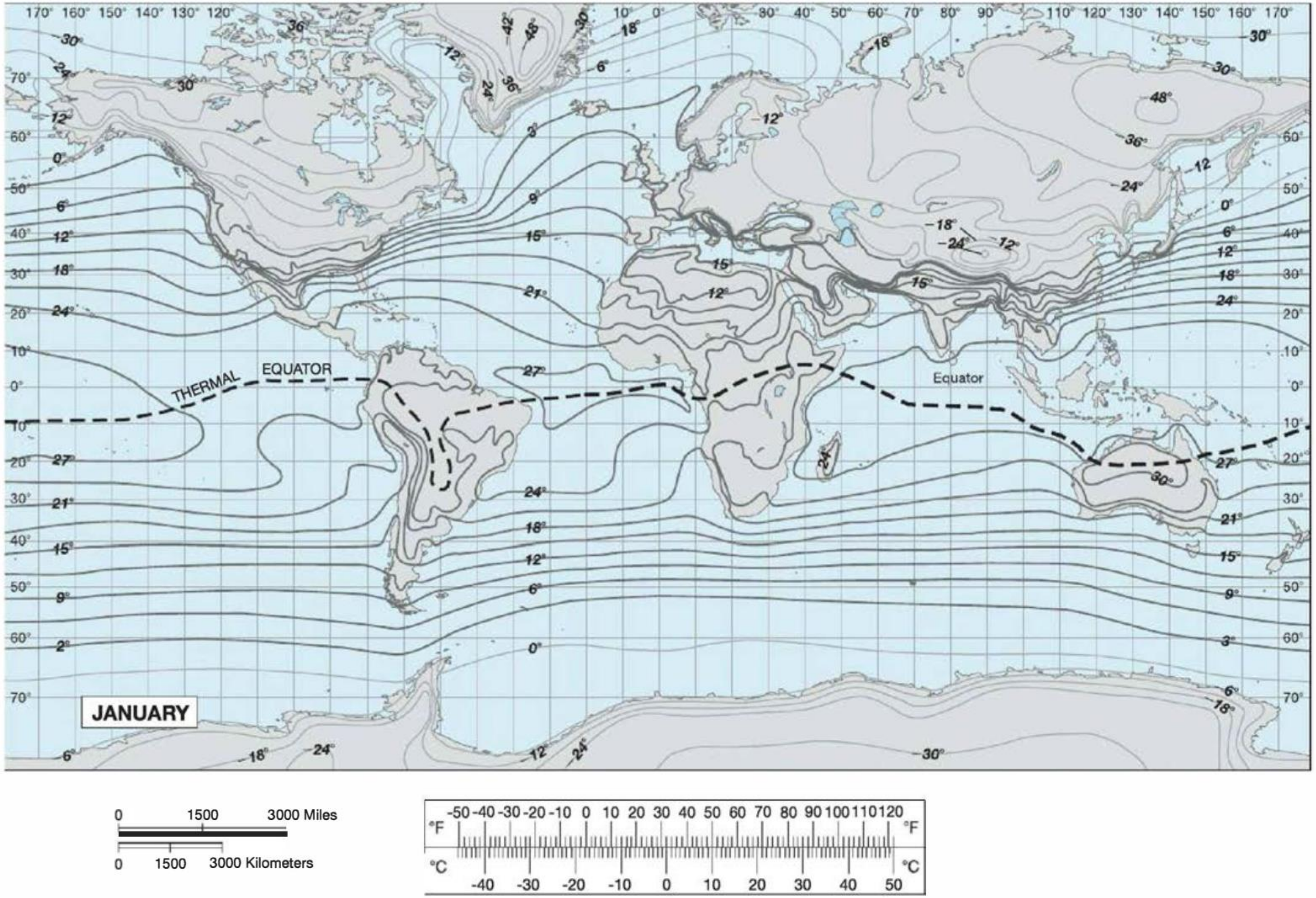
- Land surfaces are much warmer than ocean surfaces in summer and much colder in the winter.

- The greatest seasonal variability is found in the interior of large continental masses and the lowest variability over the tropical oceans. The oceans provide a <u>moderating effect</u> in the coastal regions that reduces the temperature extremes. (Figure 4.18)

FIGURE 12.19 Land and sea breezes
(A) During the day, the land heats up more rapidly than does the sea. Air rises over the land, creating a low-pressure area. Cooler air flows in to this area from the sea, creating a sea breeze. (B) During the night, the land cools more rapidly than the sea, and the reverse flow, a land breeze, occurs.



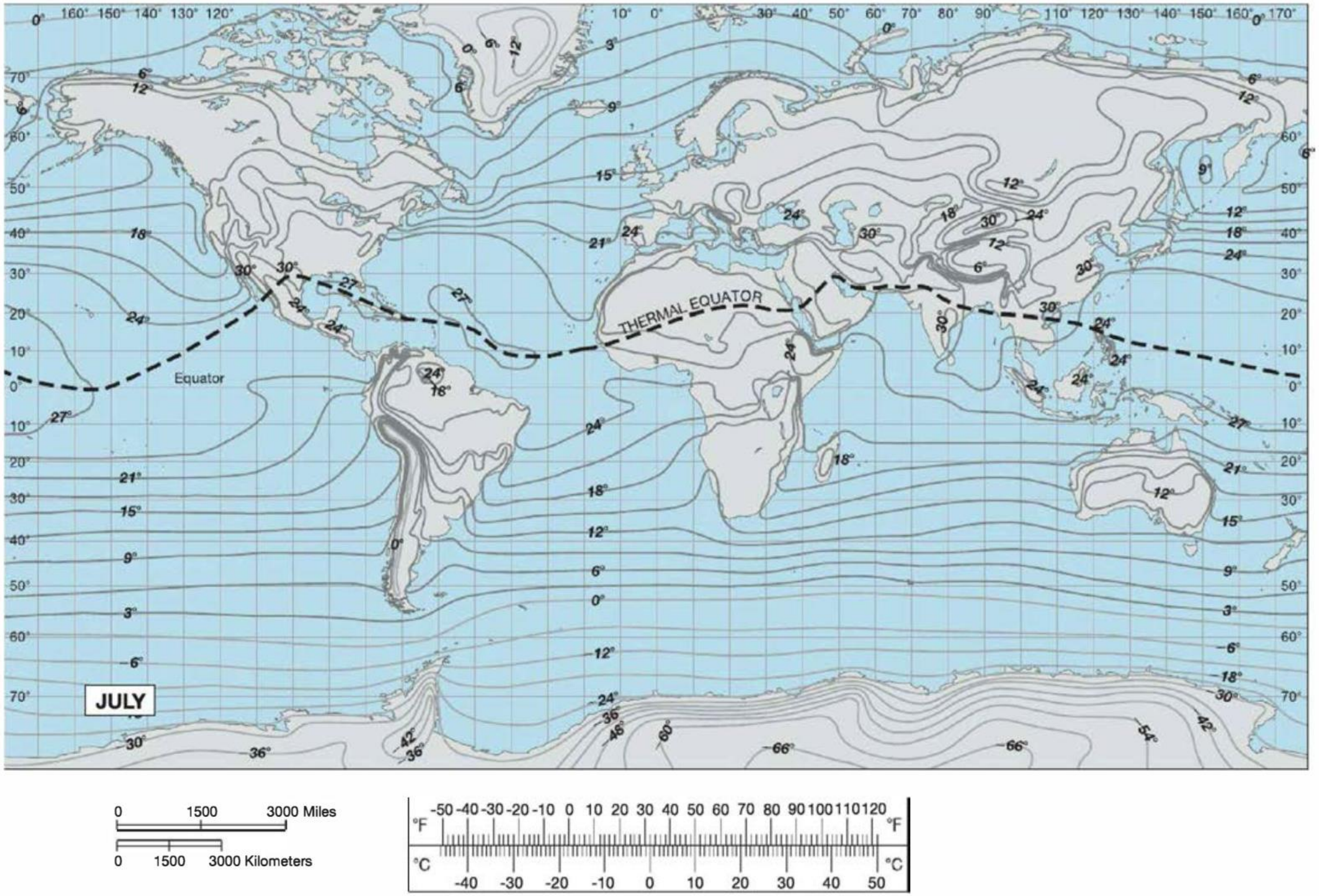
Global Distribution of Temperatures



(a)

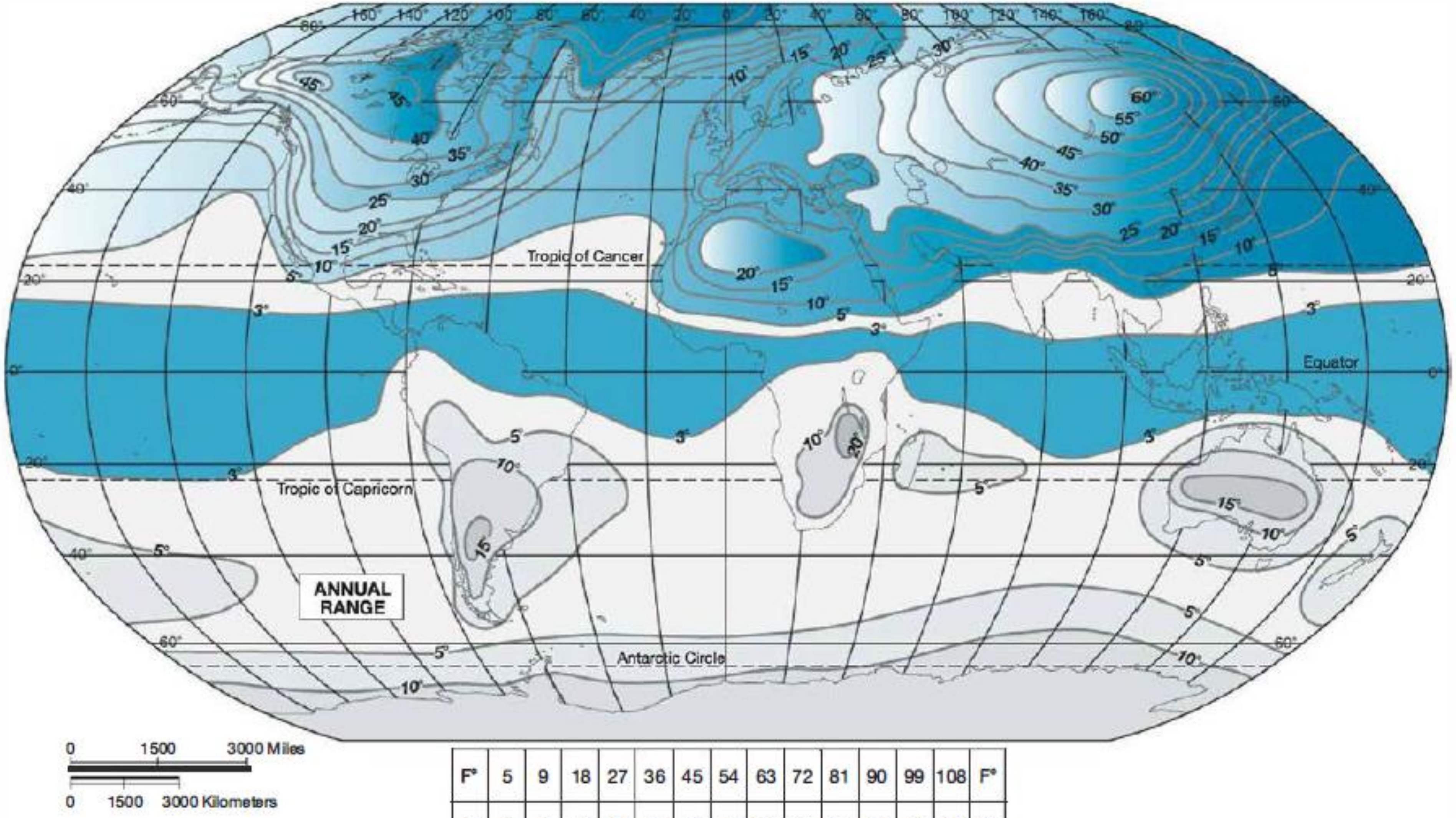
FIGURE 4-18 Global temperature distributions in degrees Celsius for (a) January, (b) July, and (c) the annual range (difference between summer and winter). (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography*, 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Global Distribution of Temperatures



(b)

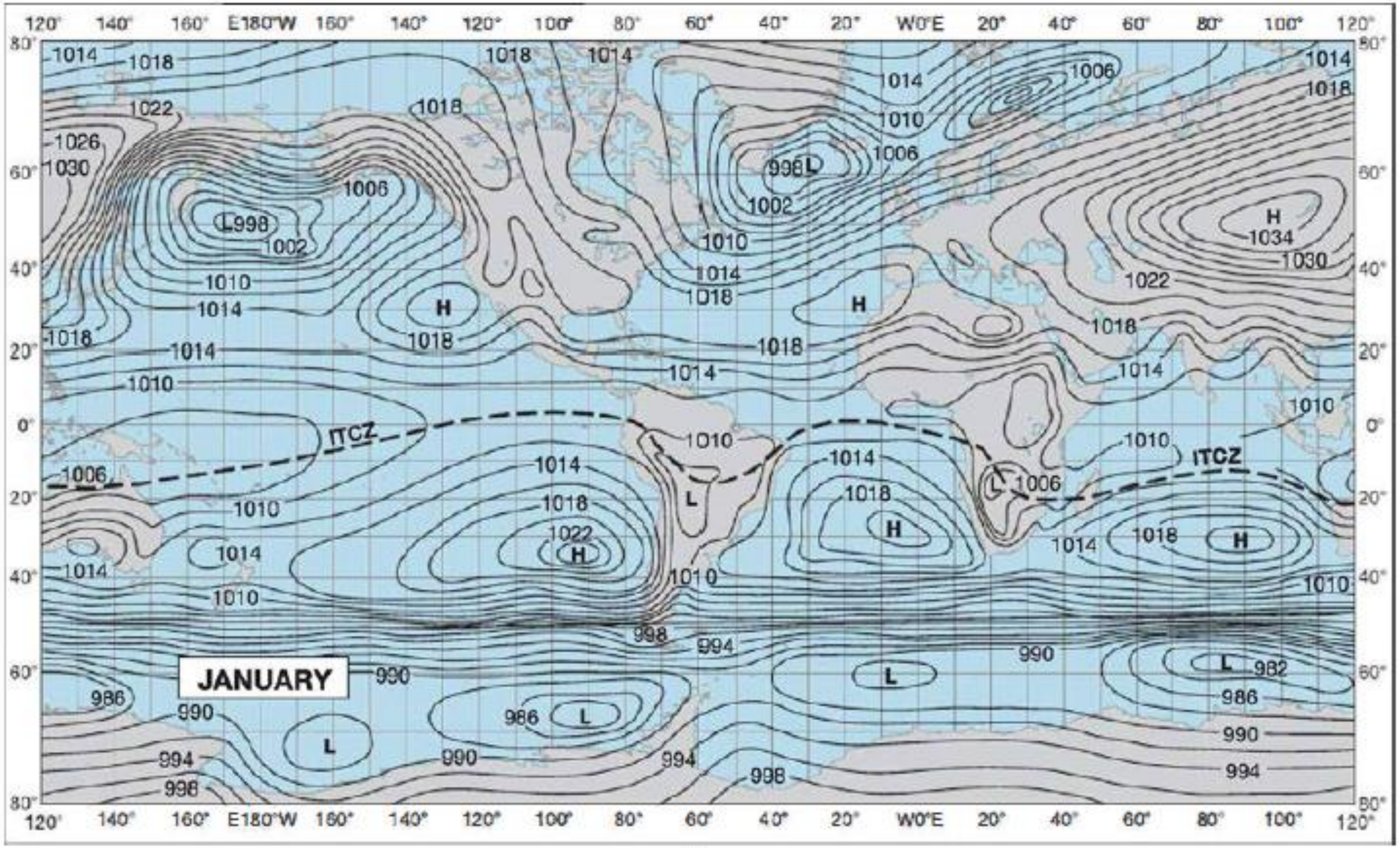
Global Distribution of Temperatures (Annual Range: The difference between summer and winter)



F°	5	9	18	27	36	45	54	63	72	81	90	99	108	F°
C°	3	5	10	15	20	25	30	35	40	45	50	55	60	C°

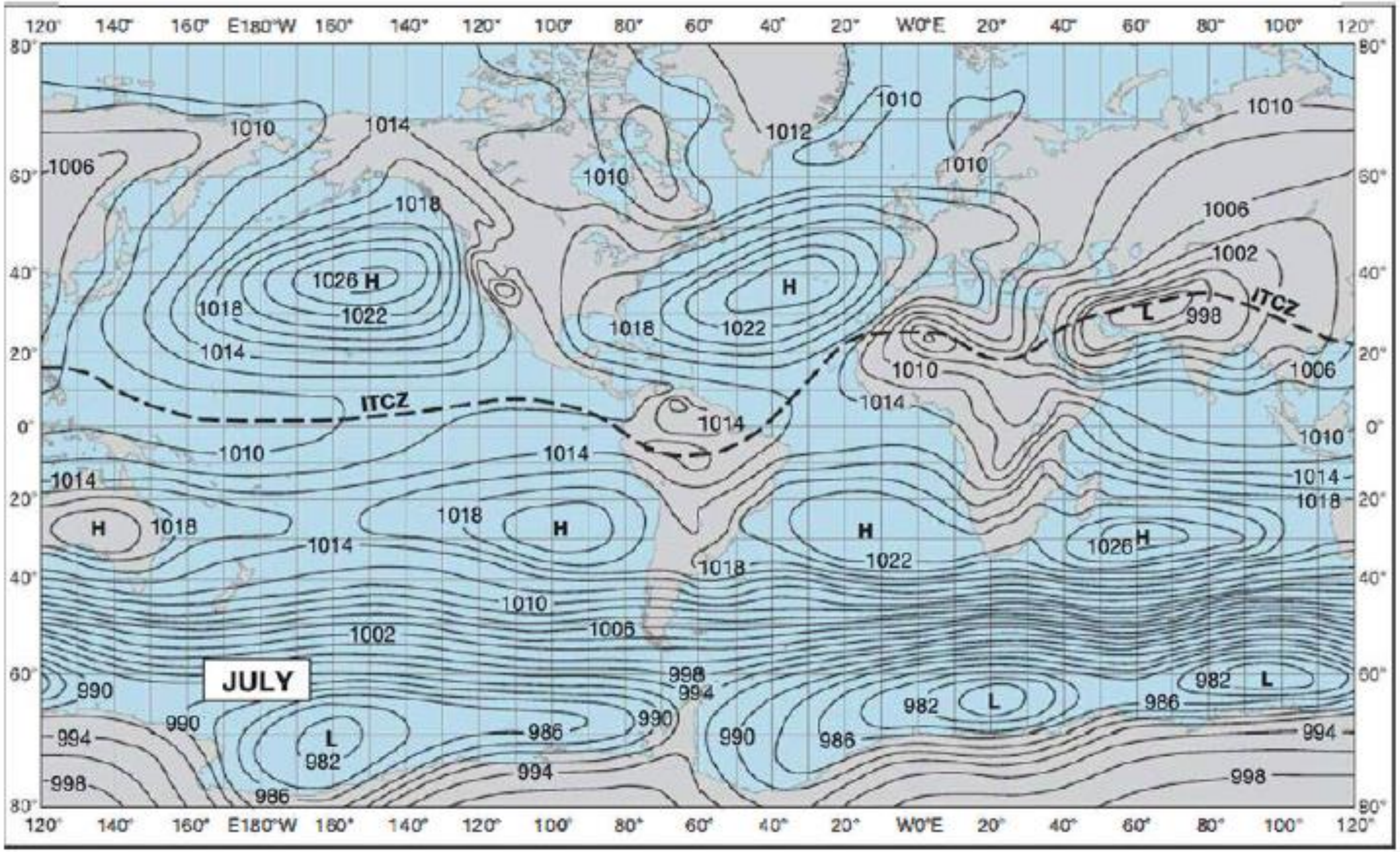
(c)

Average Sea-level Pressure



(a)

Average Sea-level Pressure



Monsoons

- The *monsoon* is a seasonal reversal in the surface wind. In summer the large Asian landmass, with its high elevations in the Tibetan Plateau of central Asia, causes high surface temperatures, low atmospheric pressures, and intense convection of air above surface.

- The rising air is replaced by air moving in from the high-pressure region over the Indian Ocean to the south.

- The **moist** air drawn in from Indian Ocean cools as it rises above the mountains of southwest India and over the Himalayas.

Monsoons

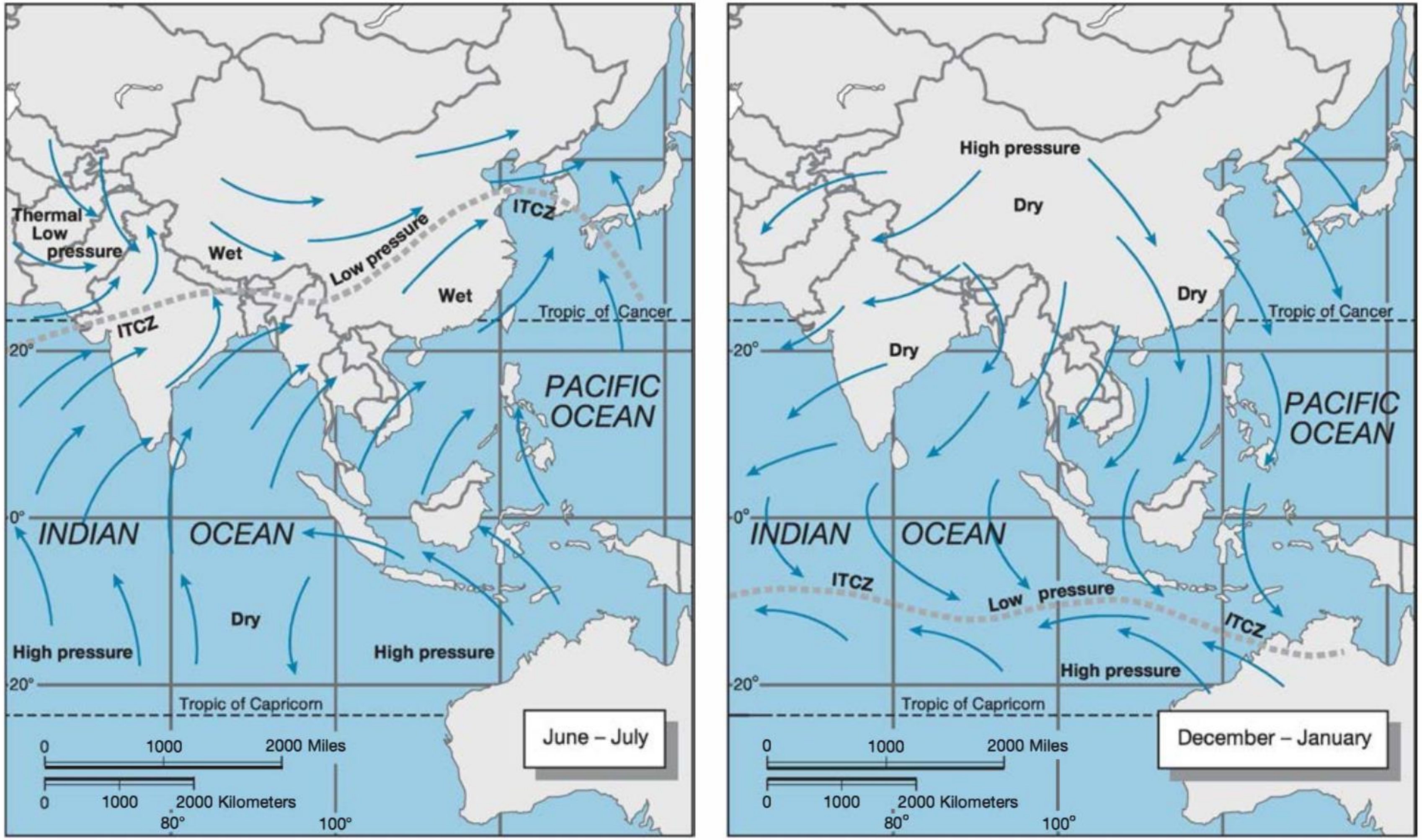
- In both the instances the rising air produces cloud and heavy rainfall (the monsoon rain).

- In winter, the pattern reverses: High elevations and persistent snow cover enhances the continentality, producing even low temperatures.

- This results in high atmospheric pressure and subsidence of air over the continent and a southward flow of air. (Figure 4.21)

Monsoons

Looks carefully the wind patterns.



(a) (b)

FIGURE 4-21 The monsoon flow over southeast Asia. (a) Summer heating of the Tibetan Plateau produces intense convection and low surface pressures, drawing in moist air from the Indian Ocean to the south. (b) The reverse occurs in winter, when low temperatures and extensive snow cover on the plateau produce high surface pressures, subsidence, and outflowing air. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography*, 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

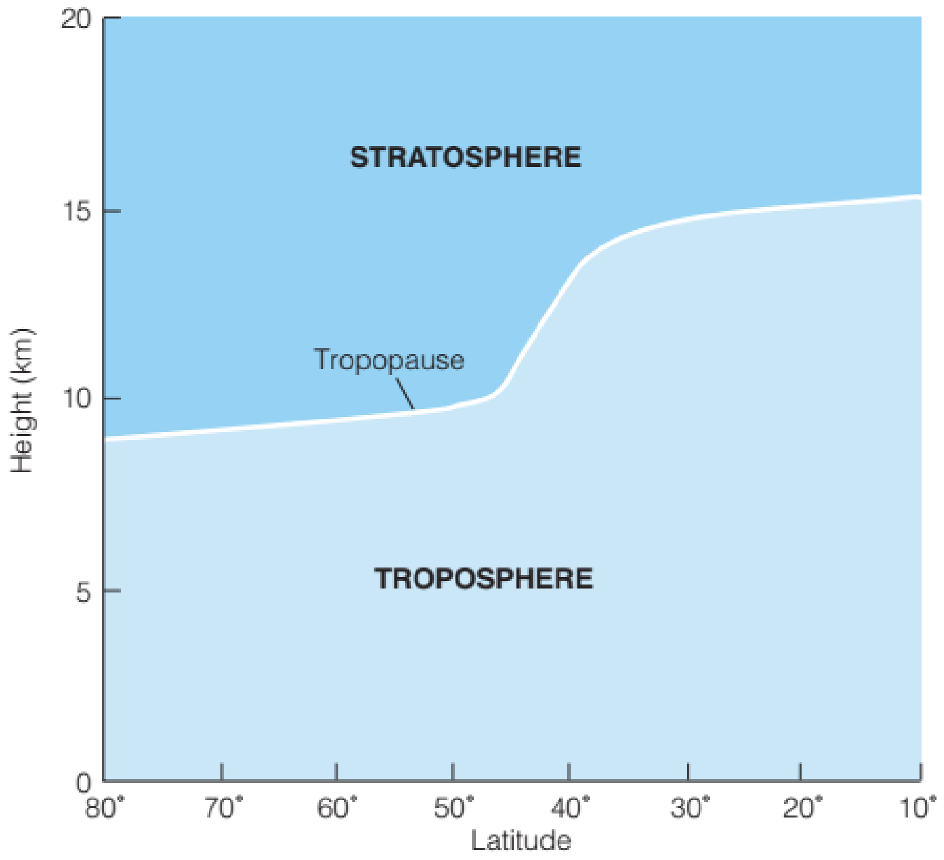


FIGURE 11.9 Altitude of the tropopause
The altitude of the tropopause varies with latitude. It is high from the equator to about 40° latitude, where it drops precipitously, continuing at this lower level and declining gently toward the poles. The precipitous drop at 40° latitude facilitates the development of jet streams.

The Blue Planet: An Introduction to Earth System Sciences, 3rd Edition by Skinner and Murck

Atmospheric Circulation

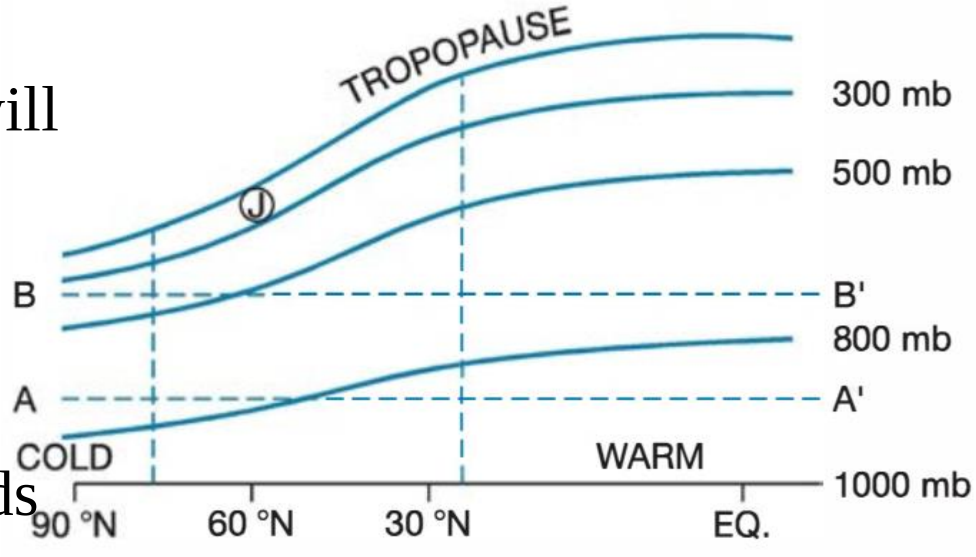
Upper-level flow

- Based on the solar energy distribution, on the large scale, troposphere has warm air in the tropics and relatively cooler air at the poles.

- As the warmer air expands and cooler air contracts, then the depth of the troposphere changes with latitude. As a consequence, the troposphere is thicker in the tropics that at the poles. Therefore, the change in the pressure with height must be slower in the tropics.

- At the upper troposphere (away from the surface), the pressure is always higher on the equatorward side. Air will flow down the pressure gradient (from tropics to pole).

- The wind speed will be greatest at the steepest pressure gradient. In the upper troposphere, this happens at midlatitude (~60° N and S). Belts of the highspeed winds are known as ***jet streams***.



(c)

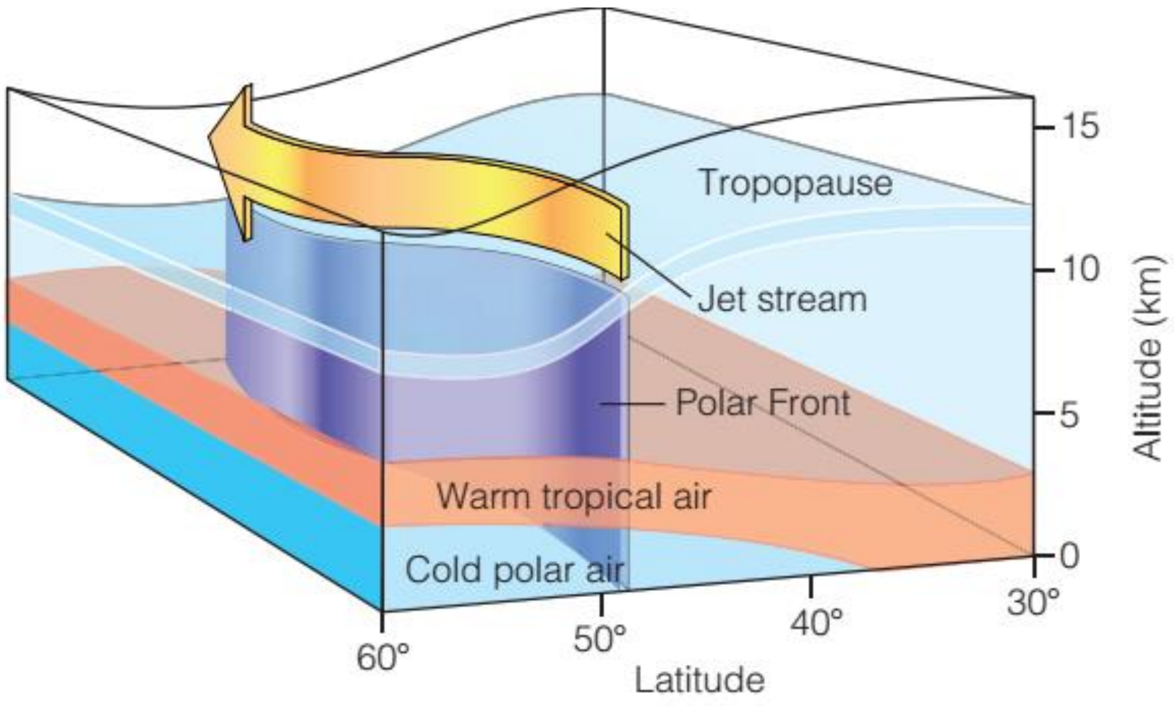


FIGURE 12.13 Jet stream

The jet stream is a high-speed westerly geostrophic wind that occurs at the top of the troposphere over the polar front, where a steep pressure gradient exists between cold polar air and warm subtropical air. At this location, the altitude of the tropopause declines precipitously.

Atmospheric Circulation

Geostrophic winds

- Due to pressure gradient force, air parcel flows (perpendicular to isobars) from high to low pressure.

- Under the influence of Coriolis force (always perpendicular to the path of air the parcel), poleward moving air will curve to right in the Northern Hemisphere and to the left in the Southern Hemisphere.

- As seen in the Figure, as the air parcel moves, the pressure gradient force is eventually balanced by the Coriolis force resulting in the steady flow (zero acceleration) of air parcel. This flow of air is called *geostrophic wind*.

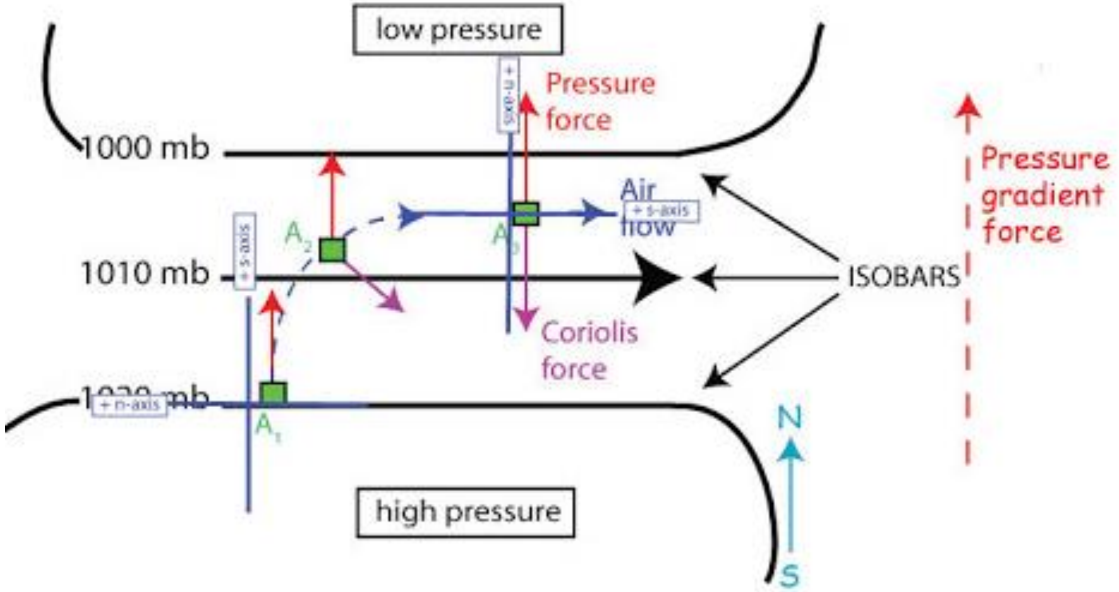
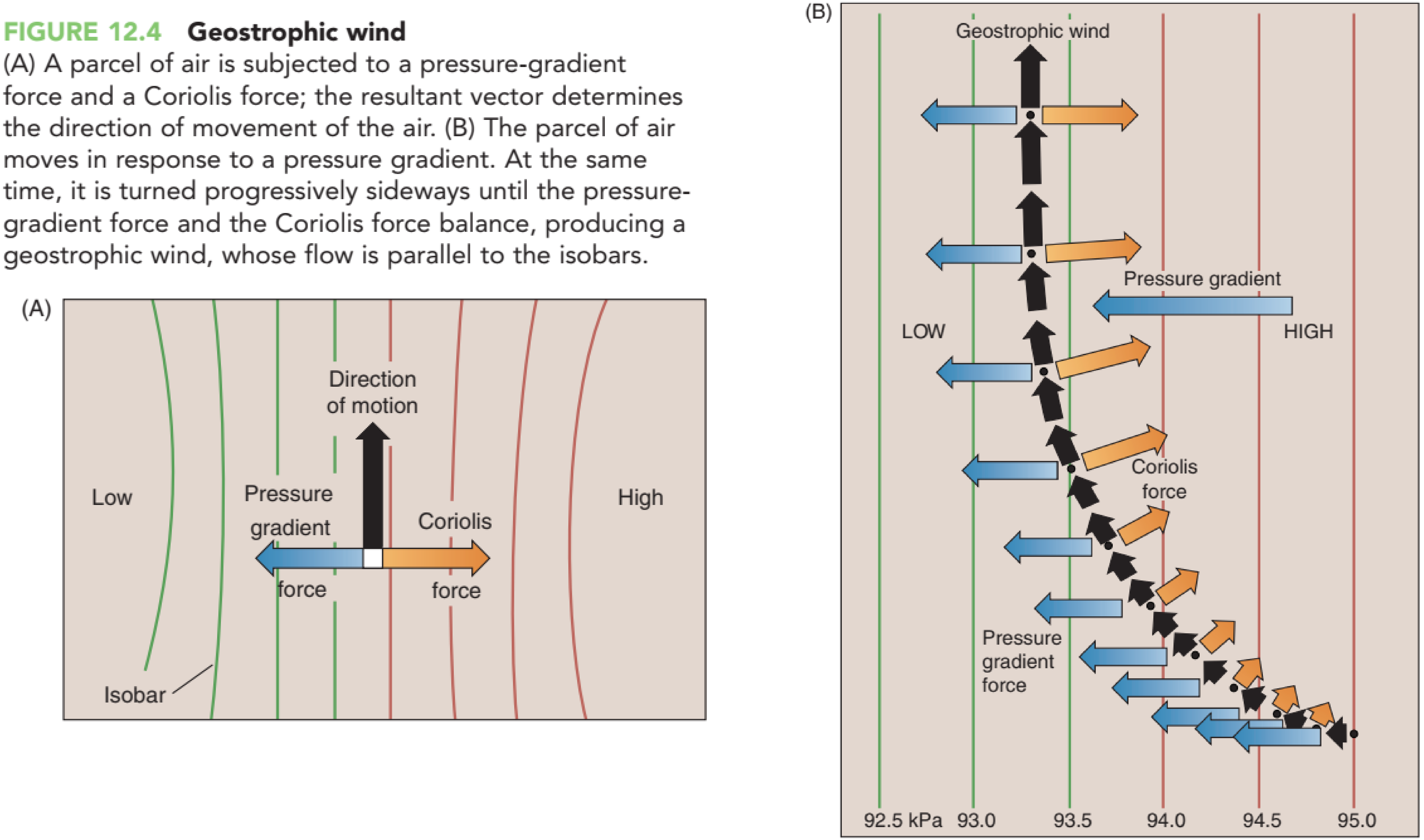
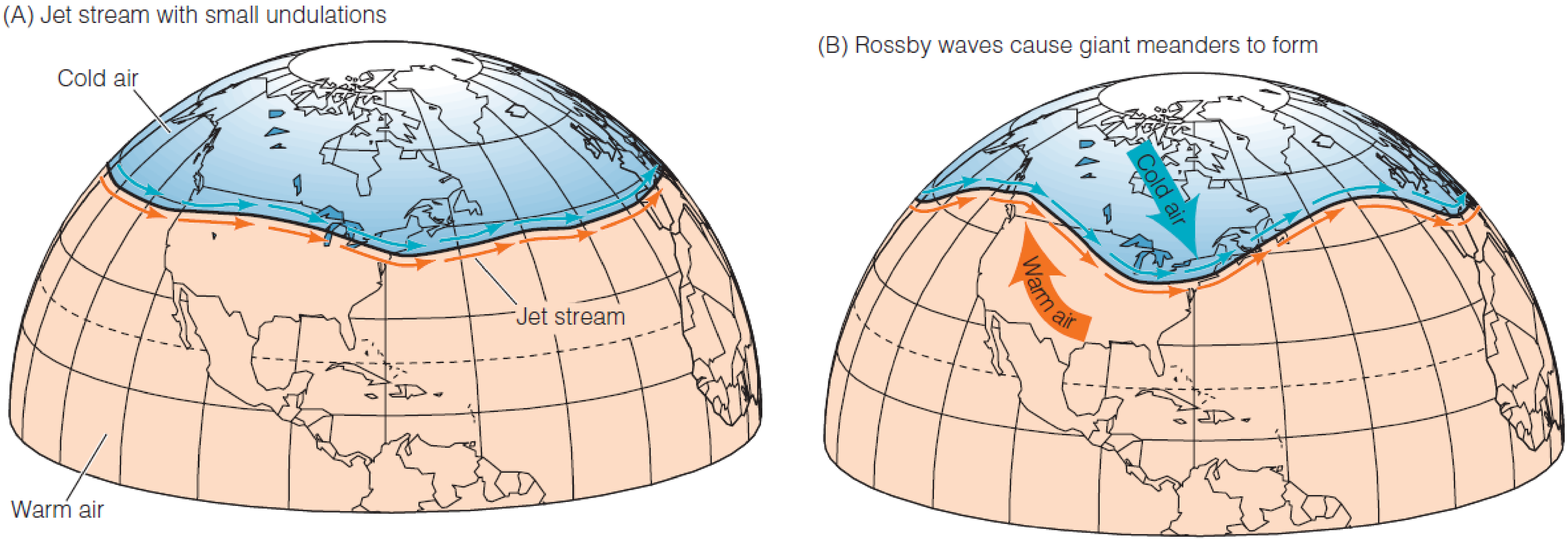


FIGURE 12.4 Geostrophic wind
(A) A parcel of air is subjected to a pressure-gradient force and a Coriolis force; the resultant vector determines the direction of movement of the air. (B) The parcel of air moves in response to a pressure gradient. At the same time, it is turned progressively sideways until the pressure-gradient force and the Coriolis force balance, producing a geostrophic wind, whose flow is parallel to the isobars.




(A) Jet stream with small undulations
Cold air
Jet stream
Warm air
(B) Rossby waves cause giant meanders to form
Cold air
Warm air

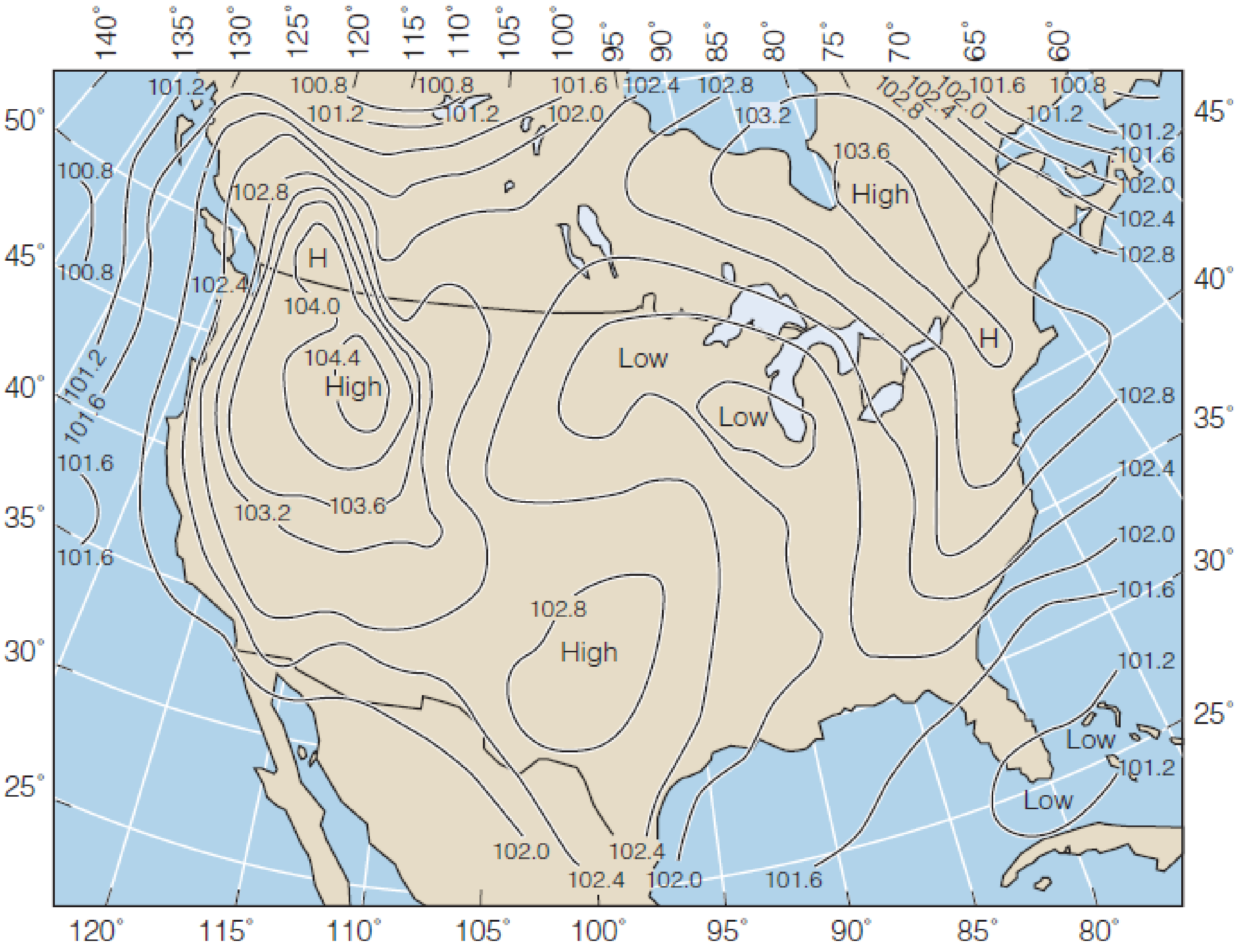


FIGURE 12.2 Isobars
This is a typical air pressure map of the United States and part of Canada. The blue lines are isobars, lines of equal air pressure, and the numbers are air pressure in kPa. (Weather maps often report air pressure in millibars; to convert kPa to mb, multiply by 10.)

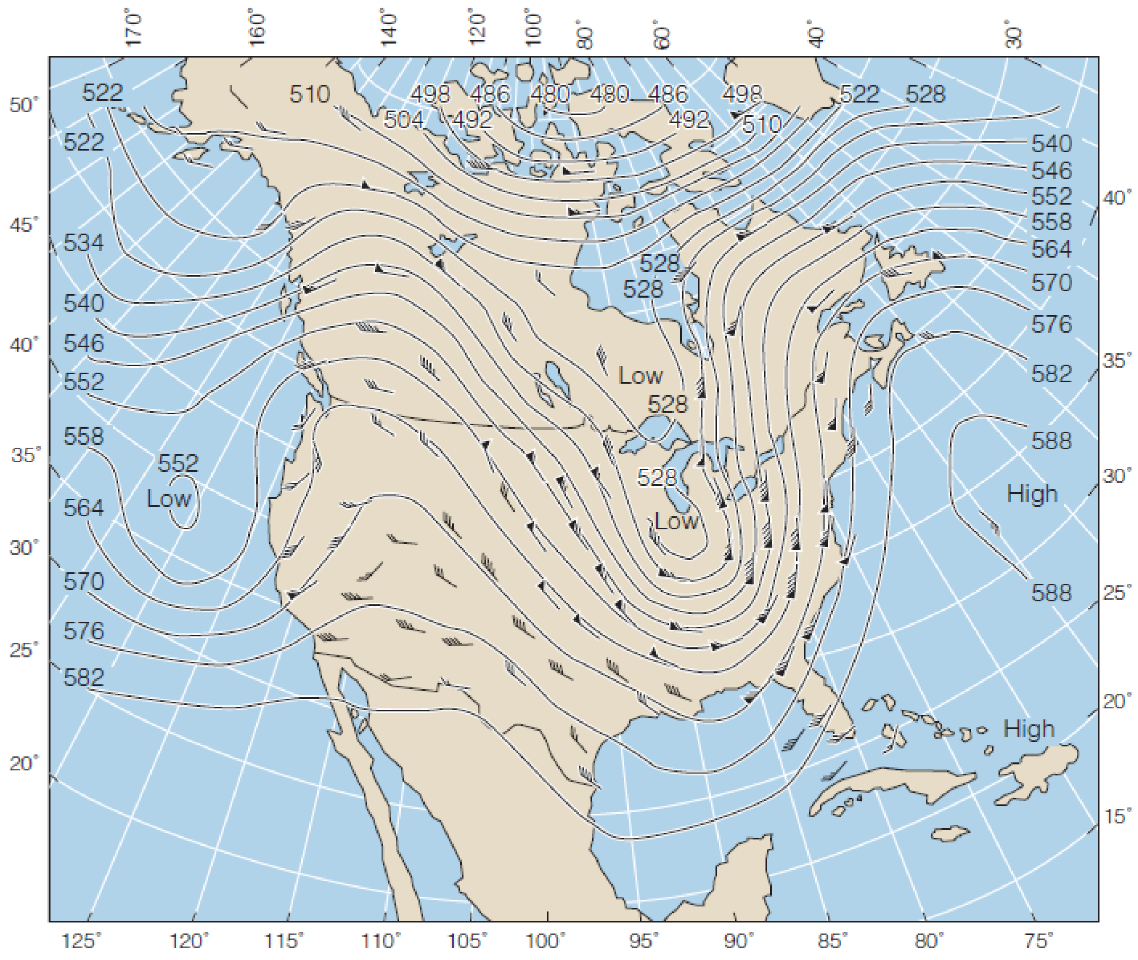
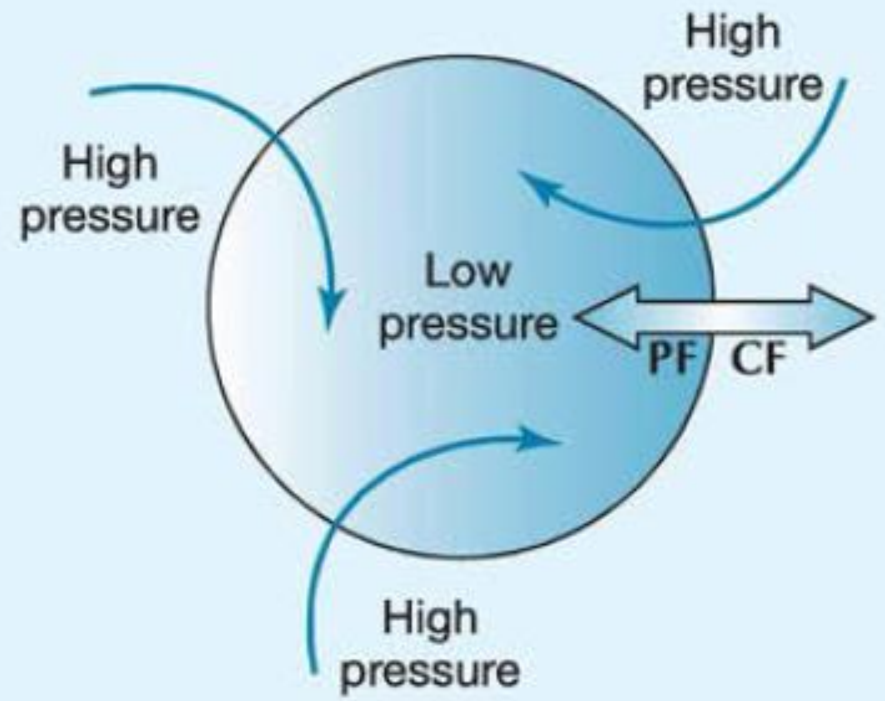


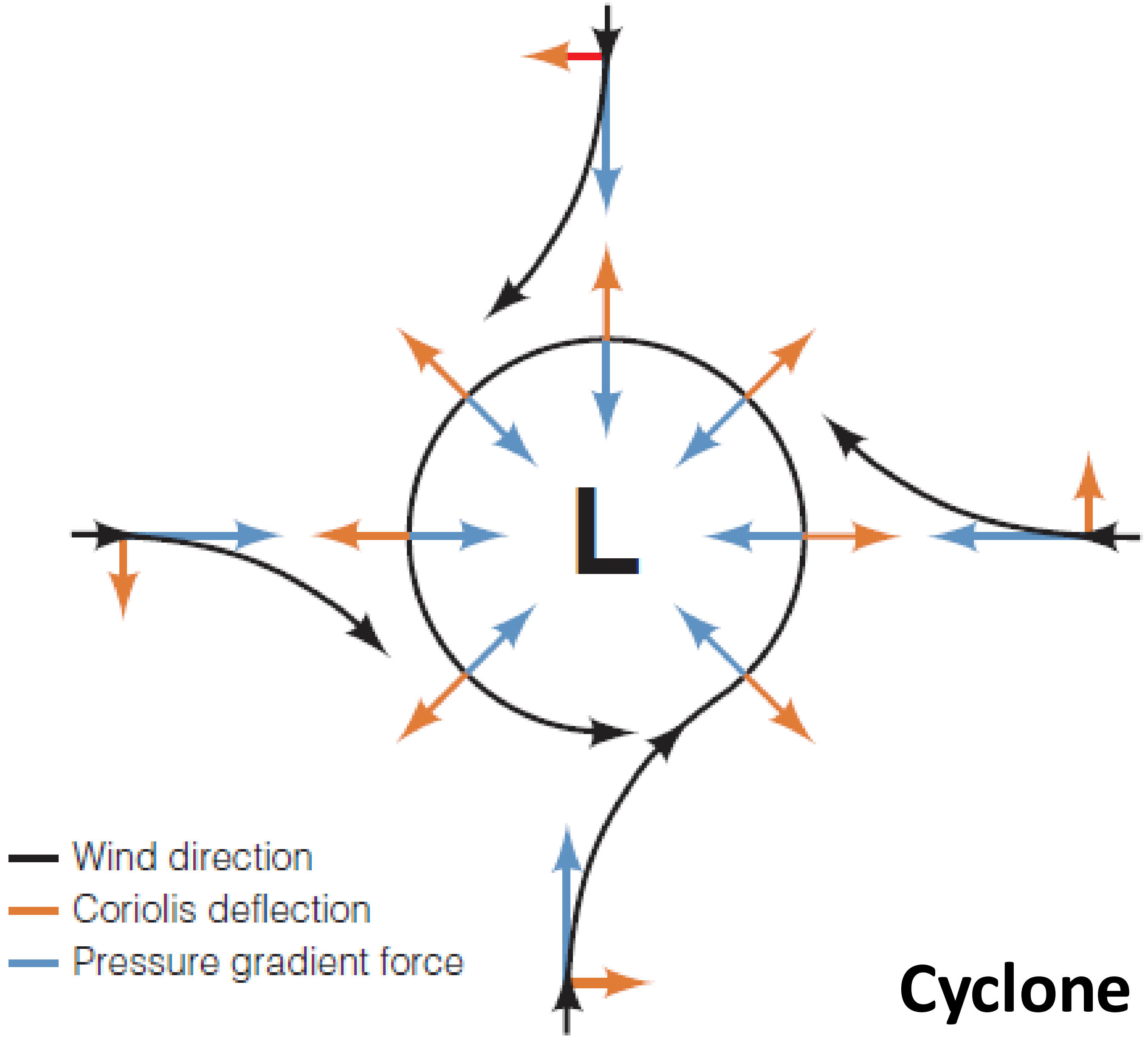
FIGURE 12.5 High-altitude geostrophic winds
This map of North America shows upper-atmosphere wind flow. The lines (shown here in millibars, mb) represent the air pressure contours at a height above sea level of 5.5 km. Note that the winds are nearly all parallel to the isobars and therefore are geostrophic. This is based on a map compiled by the National Weather Service.

Convergence and Divergence



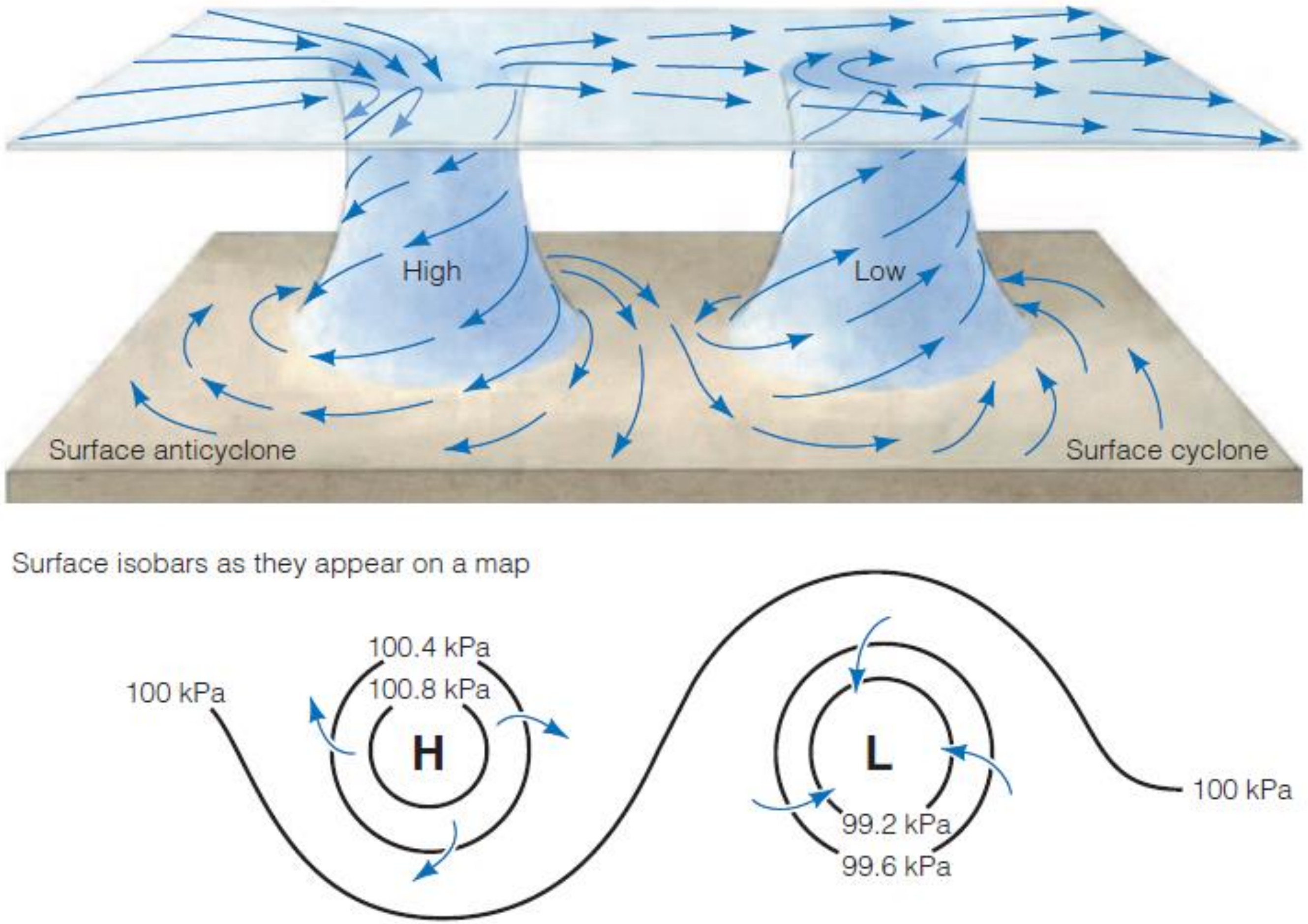
BOX FIGURE 4-1 Schematic diagram of a Northern Hemisphere hurricane. The circle represents an isobar (a line of constant pressure). The arrow labeled PF represents the pressure force; the arrow labeled CF represents the Coriolis force. The winds blow counterclockwise turning to the right as they move from high to low pressure.

Convergence and Divergence

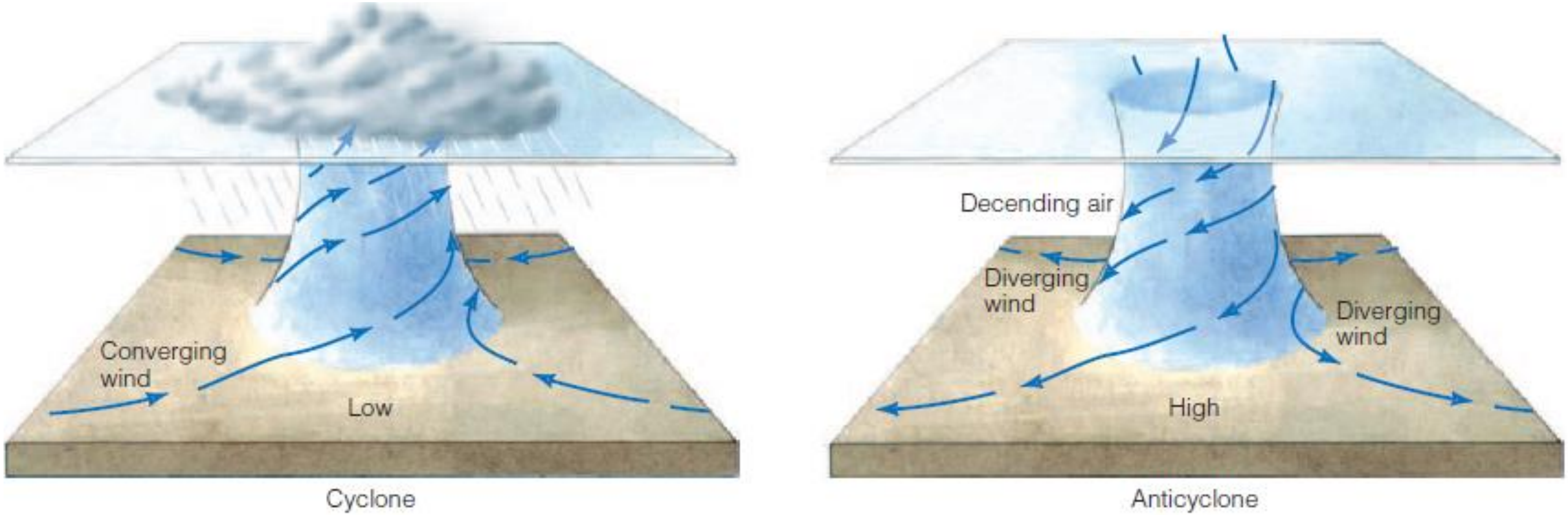


Cyclone Formation

Convergence and Divergence



Convergence and Divergence



Convergence and Divergence

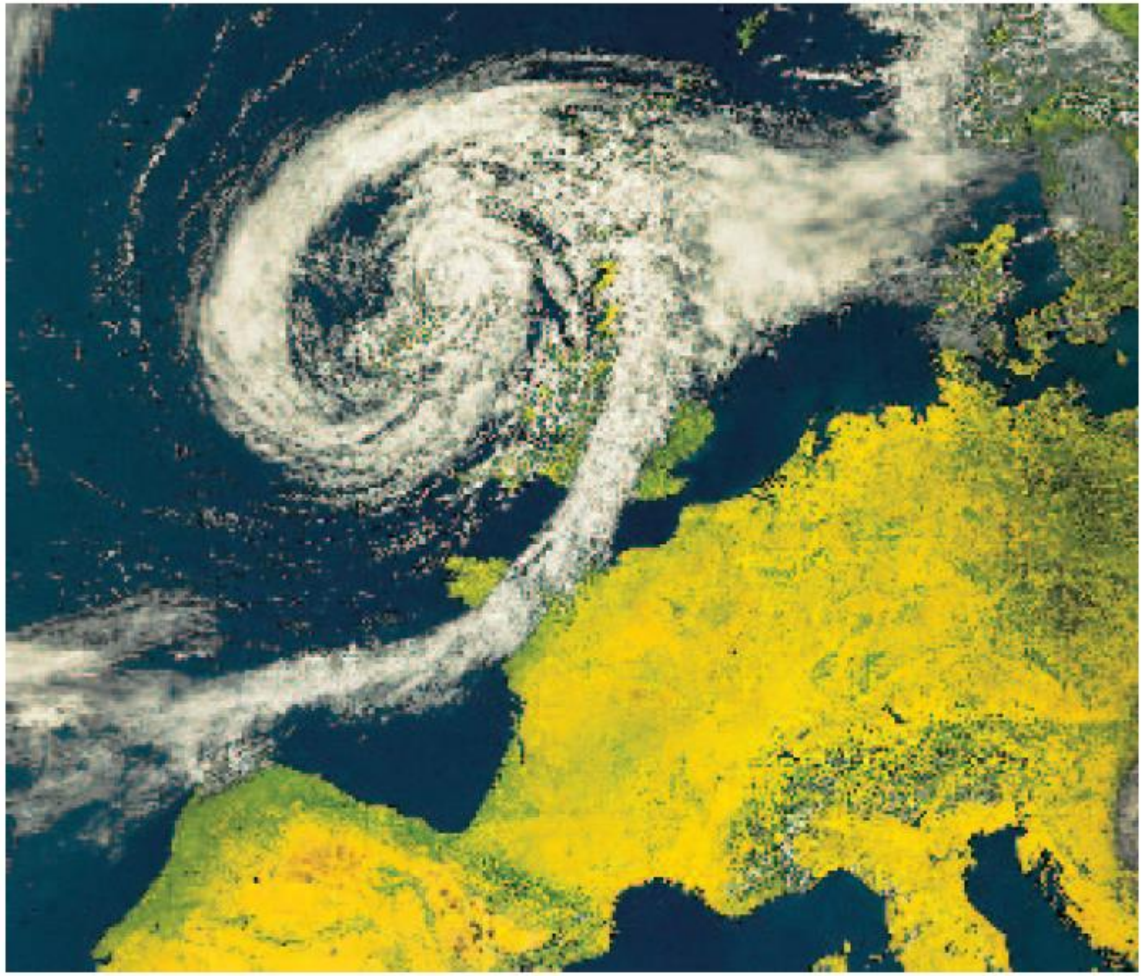
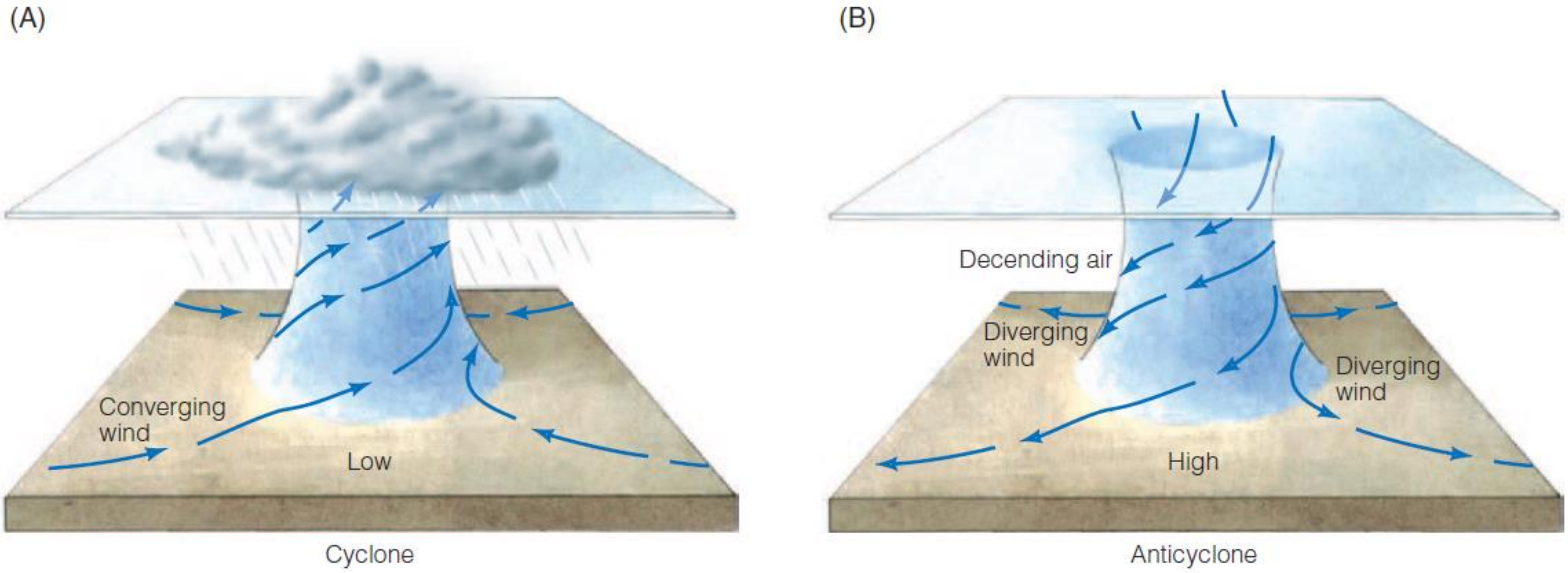


FIGURE 12.7 **Low-pressure convergence**
This low-pressure center (a cyclonic system) is centered over Ireland and moving eastward over Europe. The counterclockwise winds characteristic of a Northern Hemisphere low are clearly shown by the spiral cloud pattern.

Convergence and Divergence

FIGURE 12.8 Cyclone and anticyclone
(A) Convergence in a cyclone causes a rising updraft of air and with it clouds and probably precipitation. (B) Divergence in an anticyclone draws in dry, high-altitude air, creating a downdraft; clear skies and fair weather are the result.



Global Precipitation Patterns

- Most precipitation takes place as air cools when it is forced to rise. Two process that result in uplift:

1. Large-scale uplift that occurs with the mixing of air masses of different densities (polar front zone), and

2. Uplift due to convection.

- Therefore, there is heavy precipitation along the polar front zone in the midlatitude (~60°N and S) and in the vicinity of ITCZ.

Global Precipitation Patterns

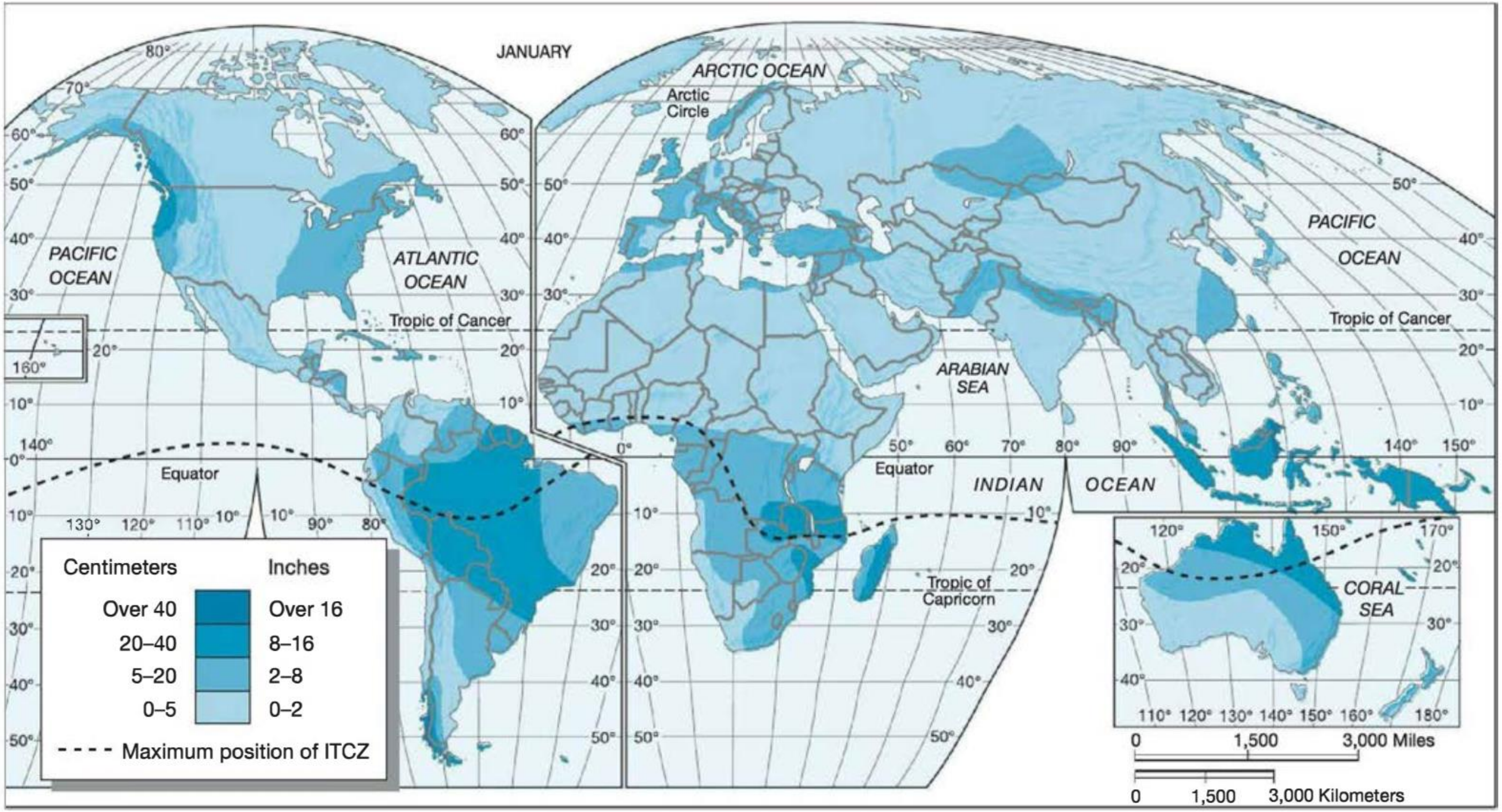
- There is also a third process that forces air to rise. The confrontation between a moving air mass and a mountain range. Such encounters cause *orographic* precipitation on the windward (upwind) slopes of the mountains.

- There are regions where precipitation is inhibited. We call such areas *deserts*. In general, precipitation is low in the interior of large landmasses due to the distance from the moisture supplies.

- Deserts are located in the vicinity of the descending arms of the **Hadley cells (30° N and S)** and on the **leeward (downwind) slopes of the mountains**.

Global Distribution of Temperature and Rainfall

Global Precipitation Patterns (January)



Global Distribution of Temperature and Rainfall

Global Precipitation Patterns (July)

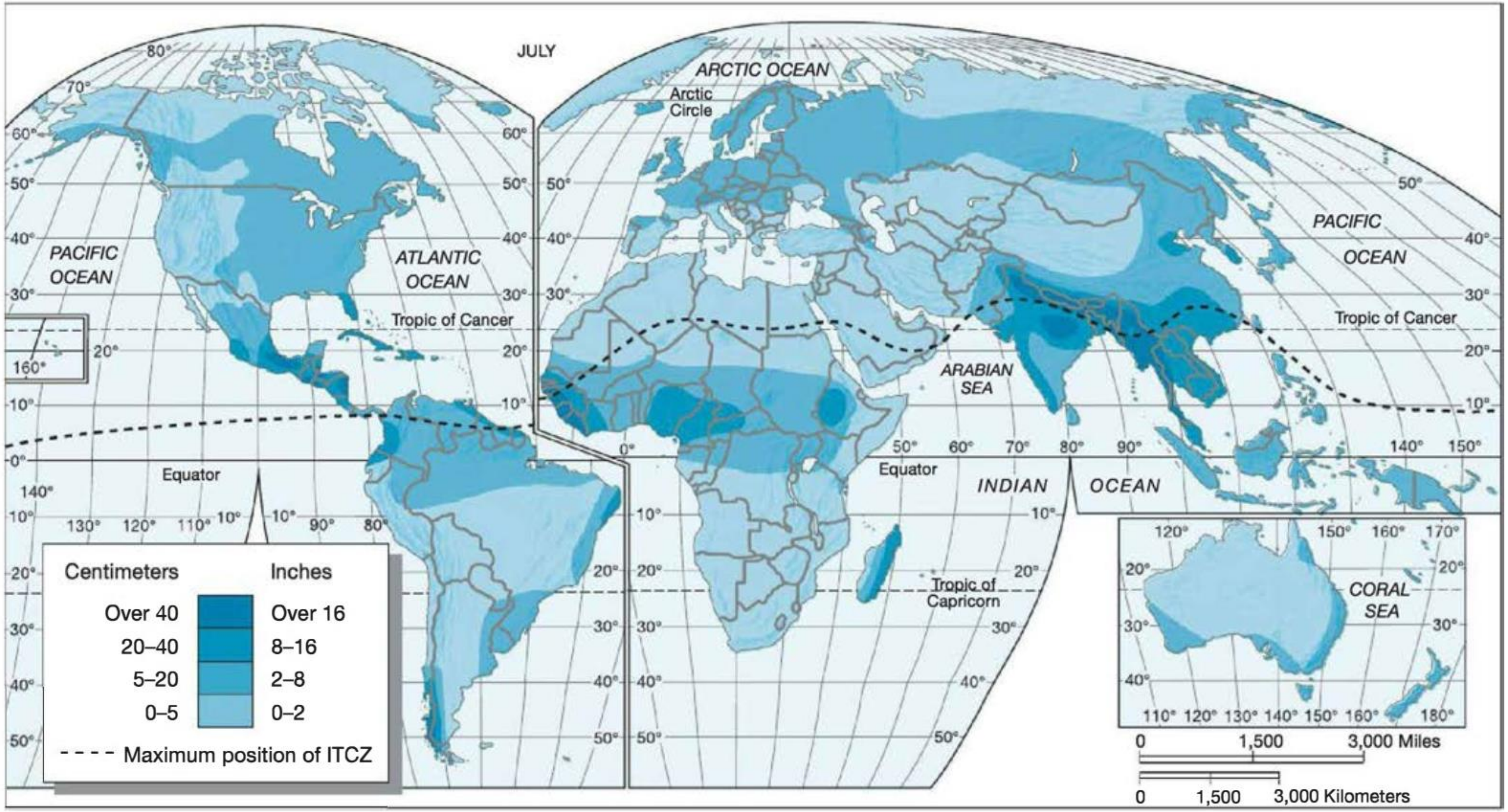
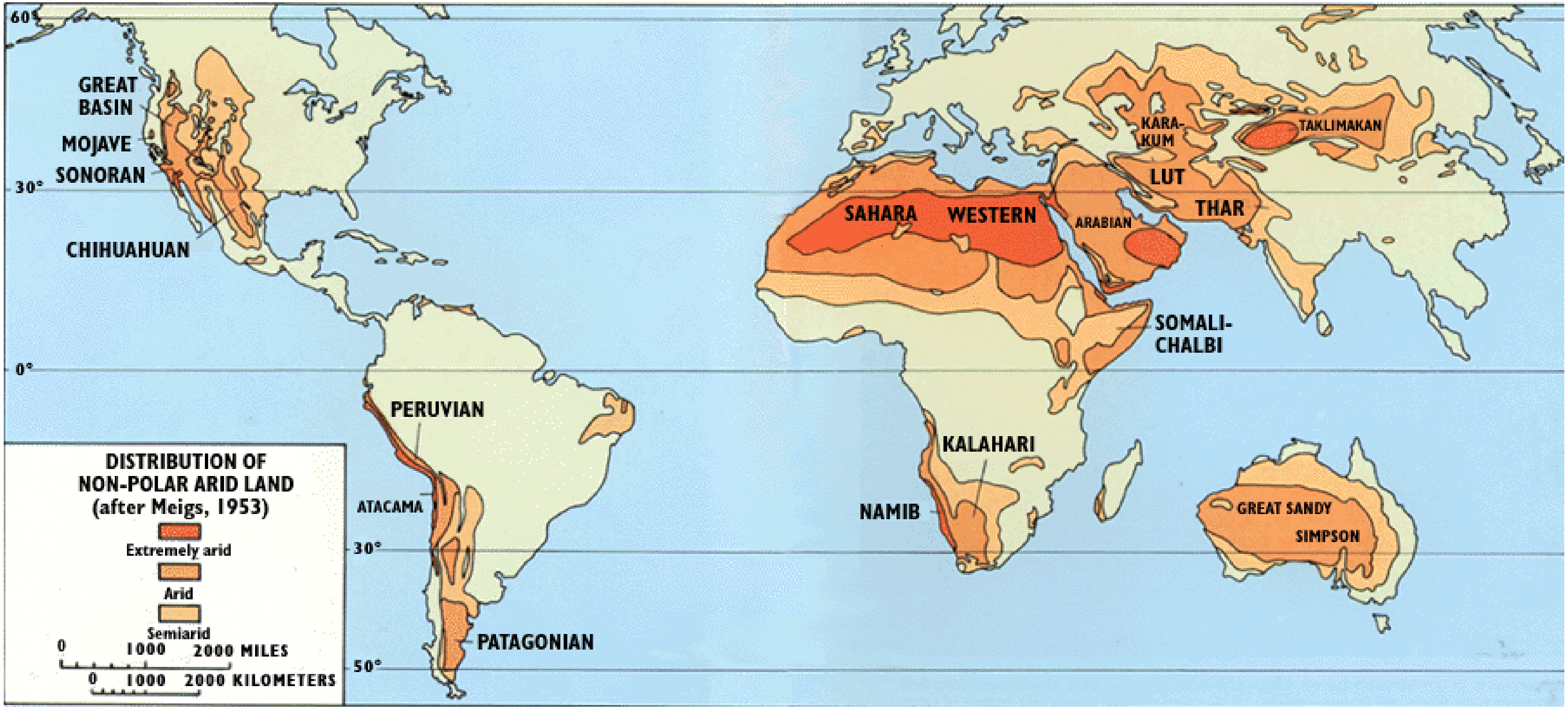


FIGURE 4-26 Global distributions of precipitation over land in (a) January and (b) July. (*Source:* From T. McKnight, *Physical Geography: A Landscape Appreciation*, 6/e, 1999. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Global Distribution of Temperature and Rainfall

Distribution of Deserts



From: https://pubs.usgs.gov/gip/deserts/what/world.html

Cloud Formation

Clouds are visible aggregations of minute water droplets, tiny ice crystals, or both. Clouds form when air rises and becomes saturated with moisture in response to adiabatic cooling, leading to condensation.

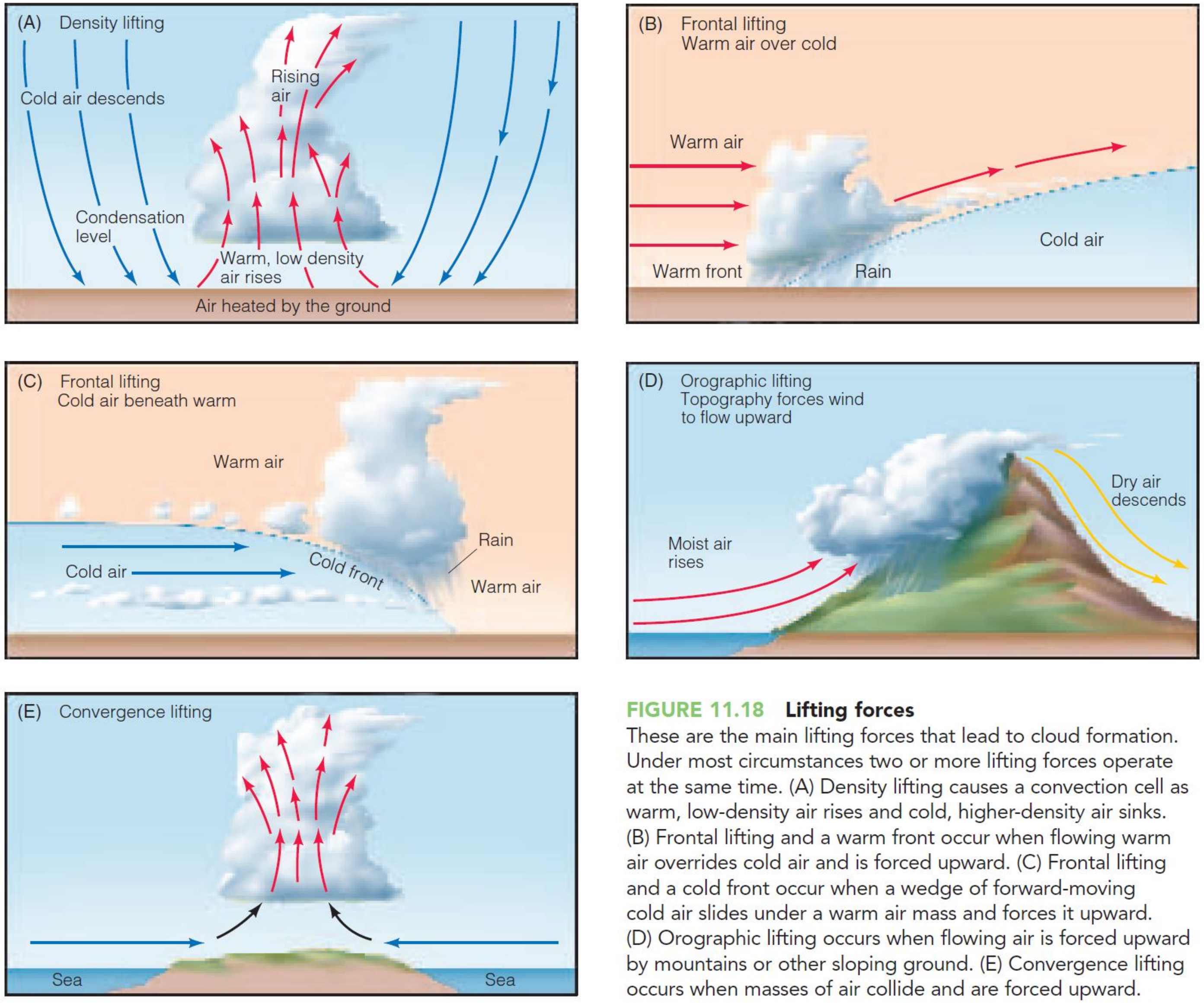


FIGURE 11.18 Lifting forces
These are the main lifting forces that lead to cloud formation. Under most circumstances two or more lifting forces operate at the same time. (A) Density lifting causes a convection cell as warm, low-density air rises and cold, higher-density air sinks. (B) Frontal lifting and a warm front occur when flowing warm air overrides cold air and is forced upward. (C) Frontal lifting and a cold front occur when a wedge of forward-moving cold air slides under a warm air mass and forces it upward. (D) Orographic lifting occurs when flowing air is forced upward by mountains or other sloping ground. (E) Convergence lifting occurs when masses of air collide and are forced upward.