12 The Planetary Circulation System

Learning Goals

After studying this chapter, students should be able to:

1. *describe* and *account* for the global patterns of pressure, wind patterns and ocean currents (pp. 281–308);
2. *explain* how models are used to help us understand the planetary circulation (pp. 297–300).
3. *explain* why the upper airflow of the mid-latitudes forms waves, and evaluate the importance of these waves to weather patterns (pp. 303–305);
4. *apply* the complete general circulation model to account for the steadiness of tropical weather compared to the variability of mid-latitude weather (pp. 299–300);
5. *describe* the four climate oscillations and their effects on weather (pp. 308–313).

© Oxford University Press Canada, 2017

Summary

1. The planetary circulation describes the average pattern of pressure and winds, and ocean currents, on Earth. The driving force behind the planetary circulation is the latitudinal imbalance in radiation. There is a surplus of radiation between roughly 40° N and 40° S, while there is a deficit of radiation poleward of these latitudes. To prevent tropical regions from getting warmer and polar regions from getting colder, heat is transferred poleward by winds and ocean currents. In addition to transporting energy, Earth's circulation system also transports momentum.

2. Many decades of observations of sea-level pressure indicate that across Earth's surface there are areas where pressure tends to be low on average and areas where pressure tends to be high on average. This pressure variation tends to correspond roughly with latitude. Heating in equatorial regions creates the region of low pressure we know as the **equatorial low**. Sinking air in the subtropics creates the regions of high pressure known as the **subtropical highs**. Air rising at fronts in the mid-latitudes produces the **subpolar lows**, while cold air at the poles is responsible for the **polar highs**. Air blowing from the regions of high pressure to those of low pressure, and acted upon by the Coriolis force, create planetary-scale winds. In the tropics, the winds are easterly; these are the **trade winds**. The zone along the equator where the trade winds from either hemisphere converge is known as the **Intertropical Convergence Zone** (ITCZ). Average winds in the mid-latitudes are westerly, while average winds in the polar latitudes are easterly. In addition to latitude, the planetary circulation is also affected by the seasons, which cause pressure and wind patterns to shift north and south, and by the differential heating of land and water, which causes the pressure zones to be discontinuous around Earth.

3. The tropical circulation forms a thermally direct cell known as the **Hadley cell**. Warm air rises in the equatorial low, flows poleward aloft, and sinks at approximately 30° N and S, where it forms the subtropical highs. To complete the cell, air flows from the subtropical highs toward the equatorial low, or ITCZ, forming the easterly trade winds. Locations influenced by the ITCZ are wet, while deserts form due to the subtropical highs.

4. Outside the tropics, the circulation is more complex and weather conditions are more variable. In the mid-latitudes, warm tropical air meets cold polar air at fronts, causing low-pressure systems to form; these systems create most of the precipitation of the mid-latitudes. These systems are carried eastward by westerly winds.

5. The equator-to-pole temperature gradient creates upper-air pressure gradients with high pressure above equatorial regions and low pressure above the poles. This pressure gradient combines with the effects of Earth's rotation to produce a westerly flow aloft over most of the planet. Two types of jet streams develop in this westerly flow: the **subtropical jet streams**, which occur partly to conserve angular momentum, and the **polar front jet streams**, which occur due to the temperature gradients associated with the polar fronts. The polar front jet streams take on a meandering pattern. The meanders are known as **Rossby waves**.

6. We use models to explain the general circulation. Hadley's simple model that is based on a single, thermally direct cell accounts for the equatorial low, the polar highs, and the upper-air westerlies. Ferrel's three-cell model accounts for the subpolar lows and the subtropical highs, as well as the equatorial low and the polar highs. This model also explains the surface winds over the planet: the trade winds, the mid-latitude westerlies, and the polar easterlies. A simple physical model, known as a dishpan model, shows that the Hadley cell is a good representation of the

tropical circulation, where the effects of Earth's rotation are small. The model also tells us that the reason the flow breaks down into eddies and waves in the mid-latitudes is that the effects of Earth's rotation are greater than they are in the tropics. The Hadley cells of the tropics, in combination with the waves and eddies of the mid-latitudes, are able to accomplish the necessary transfer of heat and momentum from the equator to the poles.

7. **Vorticity** is a measure of spin. Air spinning cyclonically has positive vorticity and air spinning anticyclonically has negative vorticity in the northern hemisphere. **Planetary vorticity** arises due to the rotation of Earth and increases with latitude. **Relative vorticity** develops when a fluid moves along a curving path or when there is shear in the flow. **Absolute vorticity** is the sum of planetary vorticity and relative vorticity; it increases with time in converging air and decreases with time in diverging air. It follows that convergence results in cyclonic spin, while divergence results in anticyclonic spin.

8. Convergence and divergence are associated with vertical motions in the atmosphere; therefore, vertical motions influence vorticity. A stretching air column will spin faster, while a shrinking air column will spin more slowly. When there is no convergence or divergence occurring, absolute vorticity is conserved. The conservation of absolute vorticity can be applied to explain the existence and behavior of Rossby waves. Planetary vorticity varies with latitude, so that air moving across latitudes must curve to conserve absolute vorticity. Thus, Earth's rotation creates the Rossby waves. Air moving across latitudes will also experience temperature changes. Because temperature changes can cause vertical motions, temperature changes affect spin and, therefore, the character of the Rossby waves. Thus, although Earth's rotation alone causes waves to form, these waves are modified by the equator-to-pole temperature gradient.

9. As the prevailing winds of the planetary circulation blow over the oceans, they produce currents in surface waters that extend to depths of roughly 100 m. In general, cold currents flow equatorward along west coasts, while warm currents flow poleward along east coasts. Along with winds, these currents help to redistribute heat, reducing equator-to-pole temperature differences. Seawater also rises and sinks. These vertical motions create deep ocean currents. Together, surface currents, deep currents, and vertical motions lead to a global-scale ocean circulation system that resembles a giant conveyor belt and is called the **thermohaline circulation**.

10. Climate oscillations are somewhat regular fluctuations in factors that control climate. These oscillations often appear to be connected to interactions between the oceans and the atmosphere. Climate oscillations can have far-reaching influences on weather. Thus, they are often referred to as **teleconnections**.

Key Terms

Absolute vorticity The sum of planetary vorticity and relative vorticity. (p. 302)

Aleutian low The subpolar low over the northern Pacific Ocean. (p. 289)

Angular momentum The momentum associated with motion along a circular path. (p. 281)

Baroclinic instability A type of instability that occurs when there are strong horizontal temperature gradients that lead to thermal advection. (p. 304)

Barotropic instability A type of instability that arises due to the rotation of Earth. (p. 303)

Bermuda-Azores high The subtropical high over the northern Atlantic Ocean. (p. 287)

Canadian high A thermal high that forms over Canada in the winter. (p. 290)

Equatorial low A region of low pressure that develops at, or near, the equator. (p. 282)

Ekman spiral The pattern created by the gradual turning of ocean currents with depth. (p. 306)

Extratropical Relating to regions lying poleward of the tropics. (p. 294)

Hadley cell A thermally driven convection cell located between latitude 30° N and the equator, or between latitude 30° S and the equator. (p. 286)

Icelandic low The subpolar low over the northern Atlantic Ocean. (p. 289)

Intertropical convergence zone (ITCZ) The location in the tropics where the northeasterly trade winds converge with the southeasterly trade winds. (p. 283)

Jet streak A zone within the jet stream in which the winds flow the fastest. (p. 294)

Meridional Relating to or varying along a meridian, or in the north–south direction. (p. 294)

Monsoon A circulation pattern that leads to very wet summers and very dry winters. (p. 290)

Ocean current A mass of ocean water that moves in a fairly regular—and therefore predictable—direction. (p. 305)

Pacific high The subtropical high over the northern Pacific Ocean. (p. 287)

Planetary vorticity Vorticity that arises due to Earth's rotation. (p. 300)

Polar front An idealized front that represents the meeting of cold polar air with warm tropical air. (p. 289)

Polar high A region of high pressure occurring at the poles. (p. 282)

Polar vortex A region of swirling air over the North Pole or South Pole, created by the upper air westerly winds, that isolates very cold polar air from warmer air of lower latitudes and that extends from the middle troposphere up into the stratosphere. (p. 291)

Relative vorticity Vorticity occurring due to a fluid's own motion. (p. 300)

Rossby waves Waves in the upper-air westerly flow of the mid-latitudes, with wavelengths of several thousand kilometres. (p. 295)

Siberian high A thermal high that forms over Siberia in the winter. (p. 290)

Subpolar low A region of average low pressure occurring in the mid-latitudes. (p. 282)

Subtropical high A region of high pressure occurring in the subtropics. (p. 282)

Subtropical jet stream A narrow band of very fast westerly wind that occurs near the top of the troposphere at about 30° N or S. (p. 291)

Teleconnections Linkages that result because atmosphere–ocean interactions in one part of the world affect the large-scale atmospheric circulation and, thus, weather in another part of the world. (p. 308)

Thermohaline circulation The global-scale ocean circulation system that includes both surface currents and deep currents and that is driven by density differences resulting from variations in temperature and salinity. (p. 307)

Trade winds The steady winds of the tropical region. (p. 283)

Vorticity A measure of spin in a fluid. (p. 300)

Zonal Relating to or varying in the east–west direction. (p. 294)

Key Equations

Absolute vorticity

$$f_c + \zeta_r = \zeta_a$$

Absolute vorticity changes due to convergence or divergence

$$\left[\frac{1}{f_c + \zeta_r}\right]\left[\frac{\Delta(f_c + \zeta_r)}{\Delta t}\right] = -D$$

Answers to Selected Review Questions (p. 314)

1. **What is the driving force behind the planetary circulation of Earth?**

   The driving force is the latitudinal imbalance in radiation.

3. **What are the three major surface winds that exist in each hemisphere? Why do these winds arise?**

   The three major surface winds are the trade winds, the mid-latitude westerlies, and the polar easterlies. The trade winds arise from air flowing from the subtropical highs toward the equatorial low that is deflected slightly by the Coriolis force. The mid-latitude westerlies arise from air flowing from the subtropical highs toward the subpolar lows that experience much greater deflection by the Coriolis force than the trade winds. The polar easterlies arise from air flowing from the polar highs to the subpolar lows that is deflected by the Coriolis force.

5. **What is the cause of the subtropical deserts?**
   Subtropical deserts form as a result of subtropical highs. These highs form due to sinking air. As a consequence, subsidence inversions develop; these inversions prevent air from rising far from the surface. As a result, skies are almost always clear and little rain falls.

7. **What is the cause of the upper-air westerly winds? What is the cause of the polar front jet streams?**

   The poleward decrease in temperature creates a pressure gradient aloft. As air flows along this pressure gradient (from equator-to-pole), it is deflected by the Coriolis force resulting in the upper-air westerly winds. The large temperature gradients associated with polar fronts interrupt the generally gradual temperature gradients that exist from the equator to the poles, creating strong pressure gradients that result in the polar front jet streams.

9. **How is the polar front jet stream of the northern hemisphere influenced by the seasons? How does this jet stream influence mid-latitude weather?**

Because the temperature contrast across a polar front is greater in winter than in summer, the jet stream is fastest in winter. Because mid-latitude cyclones form in association with the polar front jet streams, they are carried from west to east, and places located along the jet streams' paths experience stormier weather than those away from jet streams. As the jet stream shifts position seasonally, it carries the storms with it and therefore will impact different areas.

11. **How does the planetary circulation transfer energy and momentum?**

Because of the relatively small Coriolis force near the equator the winds aloft in the tropics are not quite westerly, so they transfer warm winds poleward. The Rossby waves also transfer heat (a ridge of high pressure is a wave of warm air moving toward the poles). Cyclones and anticyclones also transfer heat because they add a strong meridional component to the flow. In order to maintain the westerly winds of the mid-latitudes, momentum must be transferred from the tropics. Momentum transfer is accomplished because the waves of the upper flow tend to move from the southwest to the northeast. Such movement carries westerly momentum toward the poles.

13. **How does the concept of vorticity explain why convergence results in cyclonic spin, while divergence results in anticyclonic spin?**

If air converges at Earth's surface, its absolute vorticity must increase. If the air is not noticeably spinning than for its absolute vorticity to increase, the air must attain positive relative vorticity and thus must start to spin cyclonically. When air diverges at Earth's surface, it must cause a decrease in vorticity with time. For this to happen, relative vorticity must become negative; the air must start to spin anticyclonically.

15. **How are ocean currents produced? Why do cold currents tend to flow along west coasts, while warm currents tend to flow along east coasts?**

Ocean currents are produced by winds blowing over the surface of the water, or driven by density differences. In the mid-latitudes, westerlies produce ocean currents that travel toward the east. When these currents reach the continents, they are turned back toward the equator, forming cold ocean currents along west coasts. Easterly trade winds carry seawater westward; when these currents encounter continents, they are deflected poleward, creating warm currents along east coasts.

17. **How do density differences drive the thermohaline circulation system?**

Denser water sinks, while less dense water rises. This upwelling and downwelling links surface currents and deep currents to drive the thermohaline circulation.

© Oxford University Press Canada, 2017

Study Questions

For suggested answers, see below.

1. How and why do large-scale pressure cells shift seasonally?
2. Why do subtropical deserts tend to occur on the western side of continents?
3. How can the path of the polar front jet streams cause an area to experience unseasonal temperatures?
4. How was Ferrel's model of the general circulation an improvement on Hadley's model?
5. Even when air is spinning anticyclonically, why will its absolute vorticity likely be positive in the northern hemisphere?
6. What are the three phases of the El Niño–Southern Oscillation, and how do they differ?

Answers to Study Questions

1. In January, the subpolar lows are dominant over the oceans in the northern hemisphere (the Aleutian low in Pacific and the Icelandic low in the Atlantic). The high-pressure cells above the continents are the Canadian high and the Siberian high. The pattern develops because the relative cold of the continents causes pressure to be higher over land than over water. The subtropical highs (the Pacific high and the Bermuda high) are relatively insignificant in January. However, these two highs dominate in July, forming large cells over the oceans. In July thermal lows form over the continents because they are warmer than the oceans. (p. 290)

2. The air is drier and the subsidence is stronger on the eastern sides of the subtropical highs than it is on their western sides. As air flows equator-ward on the eastern sides of the highs, it flows over cold water and, as a result, picks up little water vapour. Subsidence inversions on the eastern sides of the highs are often only about 500 m above the surface making cloud formation impossible. In contrast, air on the western sides of the highs has travelled over the warm tropical oceans, picking up water vapour along the way. This additional moisture, coupled with the weaker subsidence, means that clouds and precipitation are more likely to develop. (pp. 285–286)

3. Locations to the north of a great loop in a jet stream will have below-average temperatures, while locations to the south will have above-average temperatures. (p. 296)

4. Ferrel reduced the extent of the Hadley cell to the tropics and added a mid-latitude cell and a polar cell. Ferrel's model accounts for the existence of the subtropical highs and the subpolar lows. It also accounts for the surface winds: the trade winds, the mid-latitude westerlies, and the polar easterlies. (p. 298)

5. Its absolute vorticity will likely be positive because planetary vorticity is always positive in the northern hemisphere, and planetary vorticity is almost always greater than relative vorticity. (p. 302)

6. The three phases are neutral, La Niña and El Niño. During the normal phase the high pressure over the eastern tropical Pacific Ocean and low pressure over the western tropical Pacific Ocean maintain the trade winds promoting upwelling of cold water in the east and forcing warm surface water to flow toward the west. During the La Niña phase, conditions are similar but the trade winds strengthen, making the water of the eastern tropical Pacific Ocean even colder than normal. During the El Niño phase, the trade winds weaken, or reverse, allowing warm water to flow toward the east, creating a large pool of warm water in the tropical Pacific Ocean. (p. 309)

© Oxford University Press Canada, 2017