

Thursday, February 4, 2021

Differential heating of Earth's surface (p 60) (+ Feb 9 asynchronous)

Circulation and energy surplus/deficit) (p 61) (+ Feb 9 asynchronous)

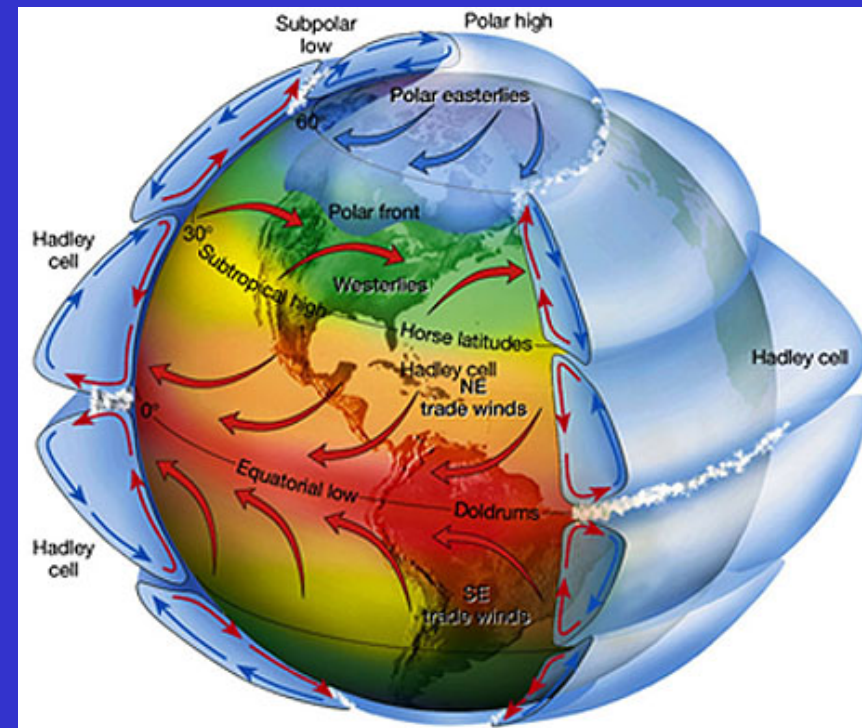
Heat-driven circulation (Hadley) (p 61-62)

Convergence/Divergence (p 61-62)

Distribution of surface winds(p 62-66)

Coriolis effect and mid-latitude weather systems (fronts) (p 63-64)

Continentality, climate and biomes



## Accouncements

Midterm 1 next week (Thursday, February 11, 12:45 pm)

Designed to take 1 hour, on Chapters 1-4 + Feb 2 video

Questions? We will be available M-W next week for help.

Open house next Tuesday will include review

Look for summary of topics for Midterm 1 (on Canvas)

Homework 2 - Climate Variability (due Thursday, February 25)

Please work in groups of no more than 4

## Other Asynchronous Material (review)

Water vapor and feedback on Earth's surface temperature  
(p 53, 79)

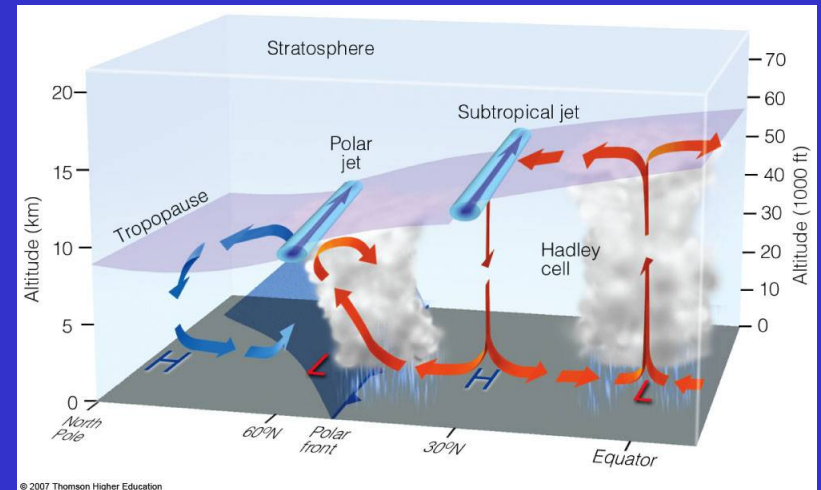
Clouds and feedbacks (p 50-51, 54)

Weather fronts (p 62-63)

More on Coriolis (63-65)

Geostrophy and force balance (p 66)

General circulation on a rotating Earth (p 65)



## Learning Objectives

Curvature and latitudinal variations in albedo lead to differential heating (pole-to-equator gradient) that drives circulation of atmosphere and oceans.

The “Hadley circulation” is the equator-to-pole circulation that is driven by heating in the tropics and cooling in the polar regions. This circulation explains many features of Earth’s climate, including trade winds, warm/wet tropics, and cool/dry midlatitudes.

Earth’s rotation is responsible for the Coriolis effect which, when in balance with the pressure-gradient force, causes winds to travel in specific directions that are responsible for our weather patterns.

Climates vary from place to place Earth, but we can learn a lot about ranges in temperature, humidity, and precipitation by looking at the general circulation (see Homework 2)



## What we know (1)

Earth's global mean temperature represents a balance between absorbed incoming solar radiation and outgoing thermal emission.

Incoming radiation is affected by the solar constant (distance of orbit from sun, brightness of sun) and reflection by surfaces (clouds, ice, aerosols, dust, land surfaces)

Outgoing radiation is mainly determined by the composition of the atmosphere – greenhouse gases that radiate infrared energy back to space. Some surface infrared radiation escapes to space in atmospheric windows, but these windows can be blocked by addition of greenhouse gases, thereby heating the surface even more.

## What we know (con't - 2)

The Earth system receives 99% of its heat in the form of radiation from the sun primarily in the visible and near-IR

Of a total of 100 units of solar energy incident on Earth, 30% is reflected back to space by clouds and bright surface regions (ice, deserts), and 45 are absorbed by the surface. Added to these 45 units are 88 units of heat energy (thermal IR) emitted by the atmosphere (the “greenhouse effect”).

Earth’s surface maintains thermal balance by convection of warm, less dense, air carrying heat upward, by evaporating water (“latent heat”) and by radiating the remainder upward.

Of the 104 units of energy radiated by the surface, 4 escape directly to space through “windows” in the IR spectrum of the atmosphere.

# Why do we have weather?

Let's start where we left off last time

- Earth isn't flat
- Earth rotates (important for moving fluids)
- Water is complex (water vapor, clouds, and ice are highly variable)  
(most of this will be asynchronous)

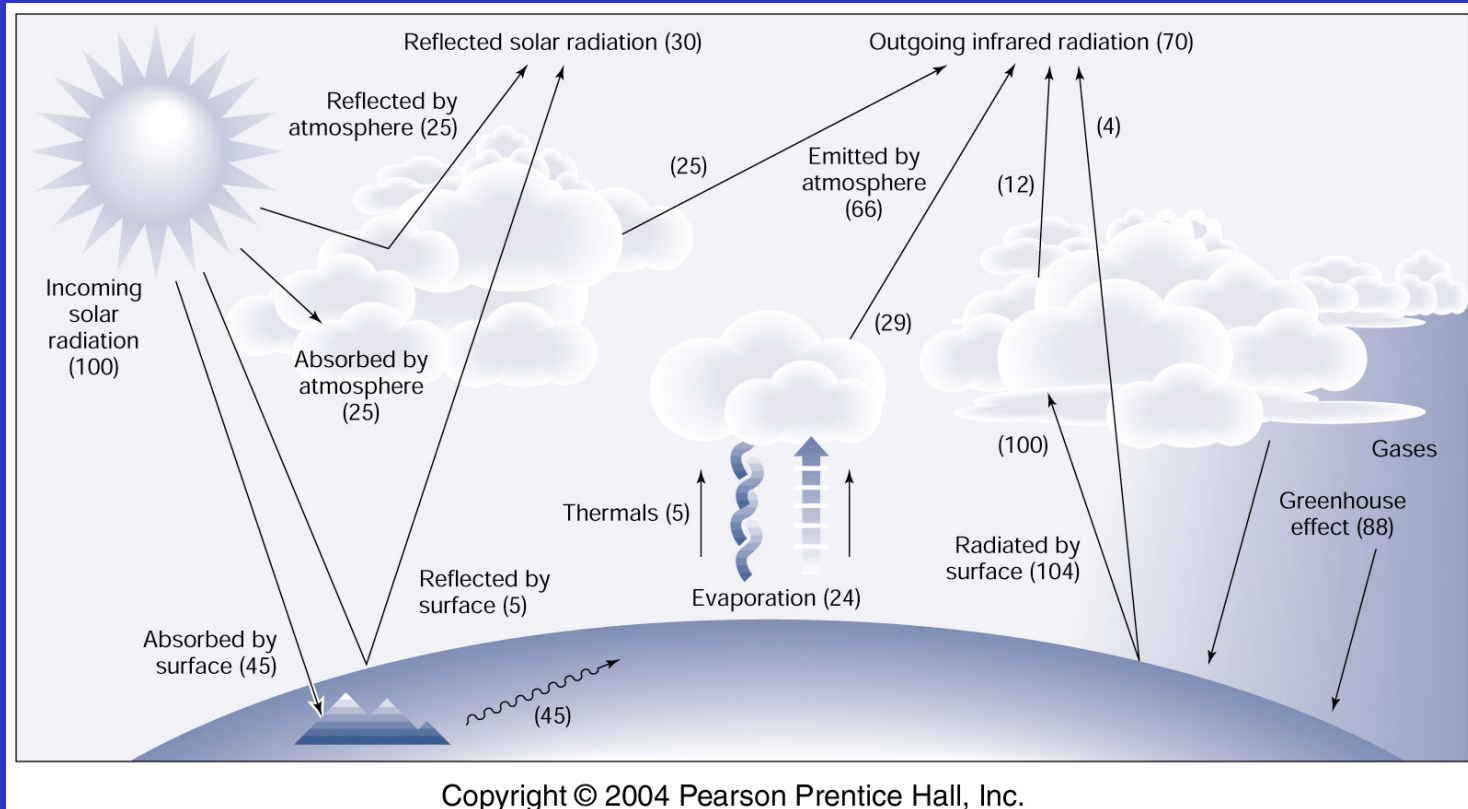


Fig. 3.19

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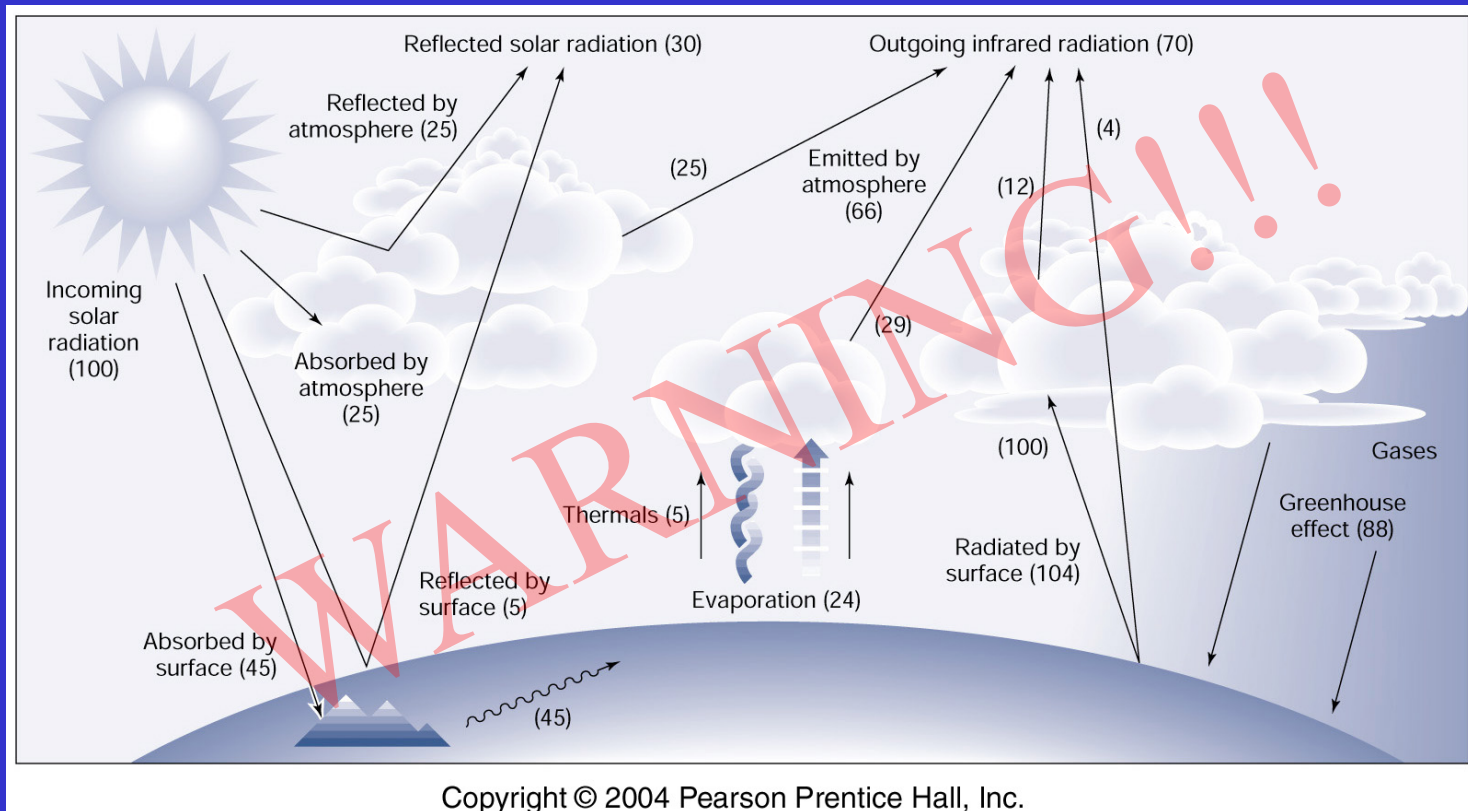


Fig. 3.19

# Water vapor and clouds (some Asynchronous)

- We've already talked about ice and albedo (positive feedback). This will be important when we look at pole-to-equator temperature gradient
- Clouds are different from greenhouse gases – they can trap heat (warm the surface), but they also reflect visible light (cool the surface). Both positive and negative feedback, which is more important?
- Warm air can hold more water vapor than cold air. Positive feedback.

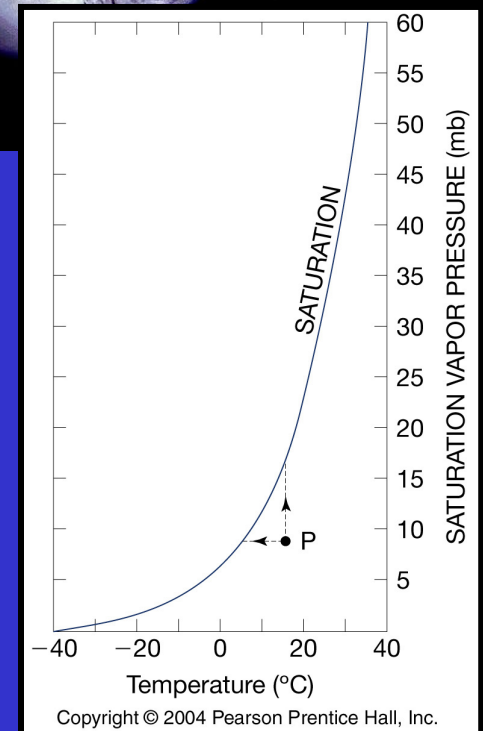
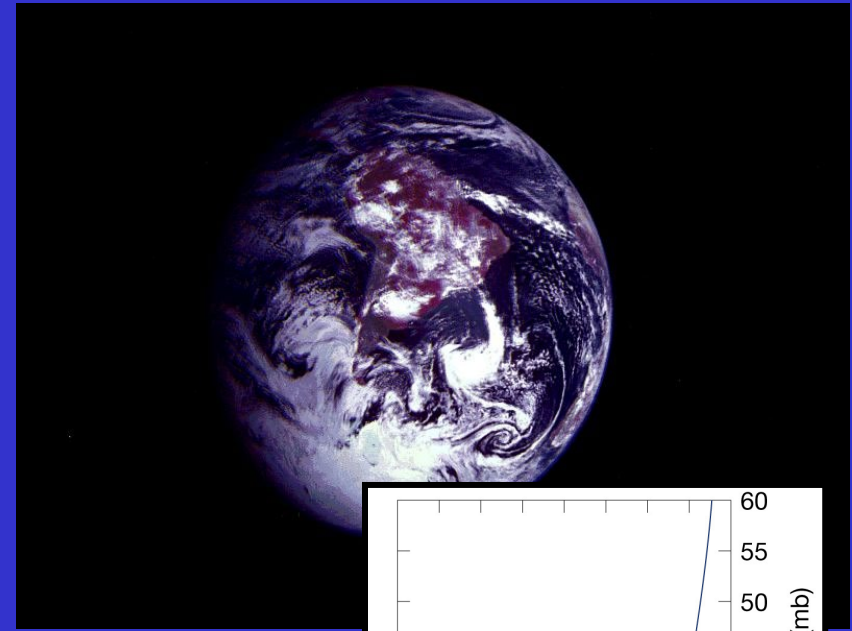


Fig. 4.25

# Water and its phases

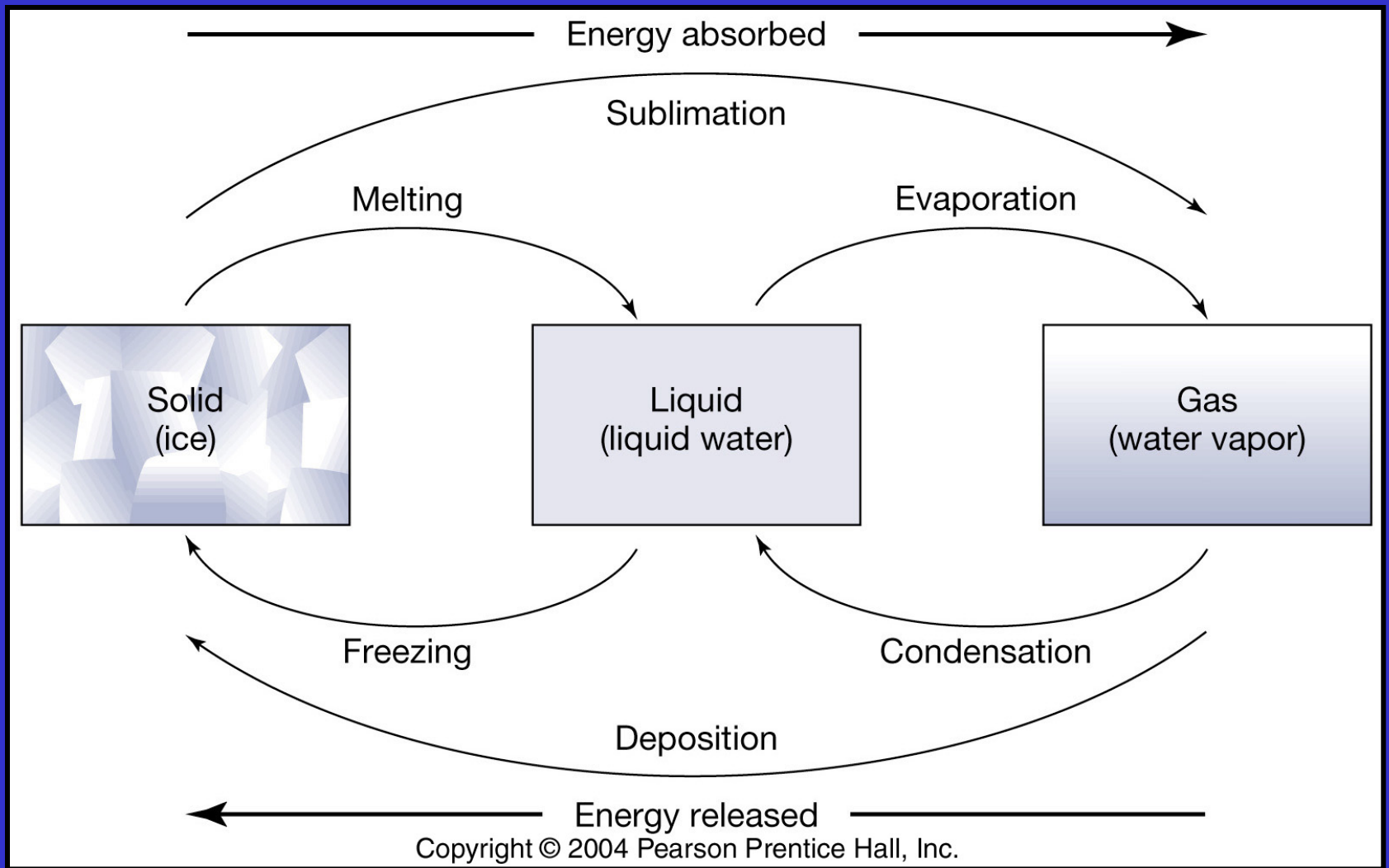
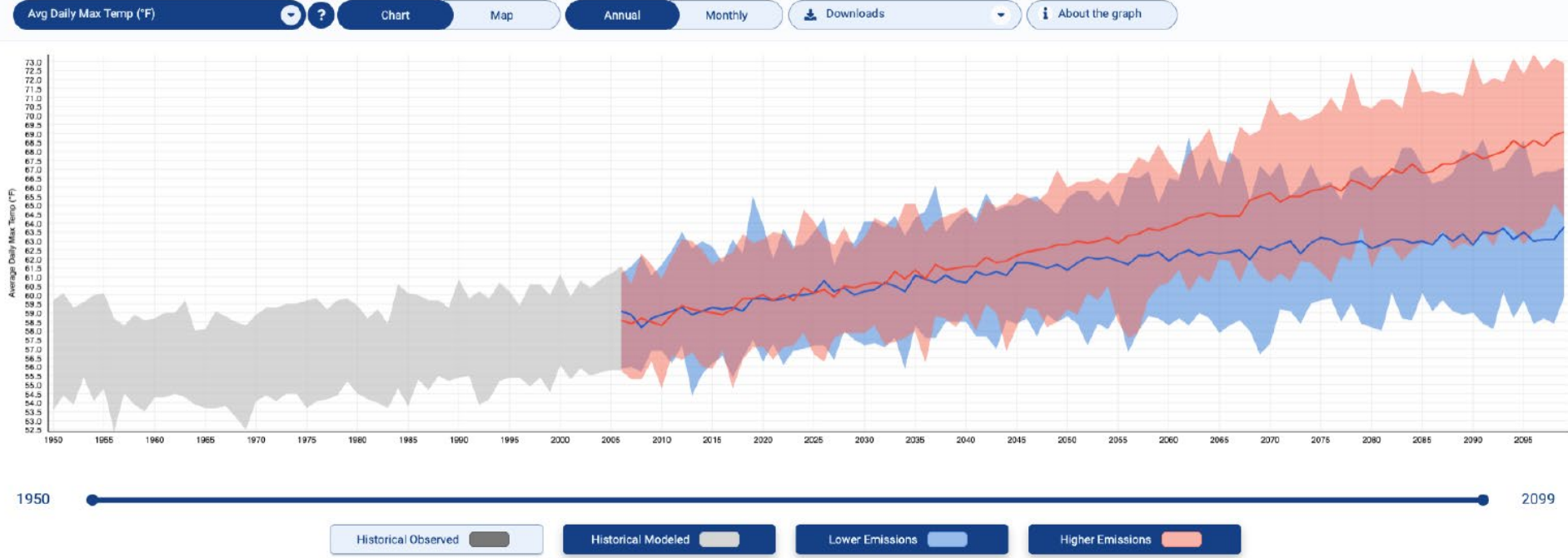


Fig. 4.23





## Breakout room activity 2

- What is the difference between climate and weather?
- How do you think weather will change with our changing climate?
- Go to: <https://crt-climate-explorer.nemac.org/>
  - See how climate is changing in your hometown

## iClicker Question 1

Which of the following is more of a measure of “climate” than a feature of “weather?”

- (A) a warm and sunny day.
- (B) Heavy snowfall in Colorado in March.
- (C) A decade of severe drought in the Southwest U.S.
- (D) Flooding in Louisiana in August.
- (E) Santa Ana winds in Southern California in October.



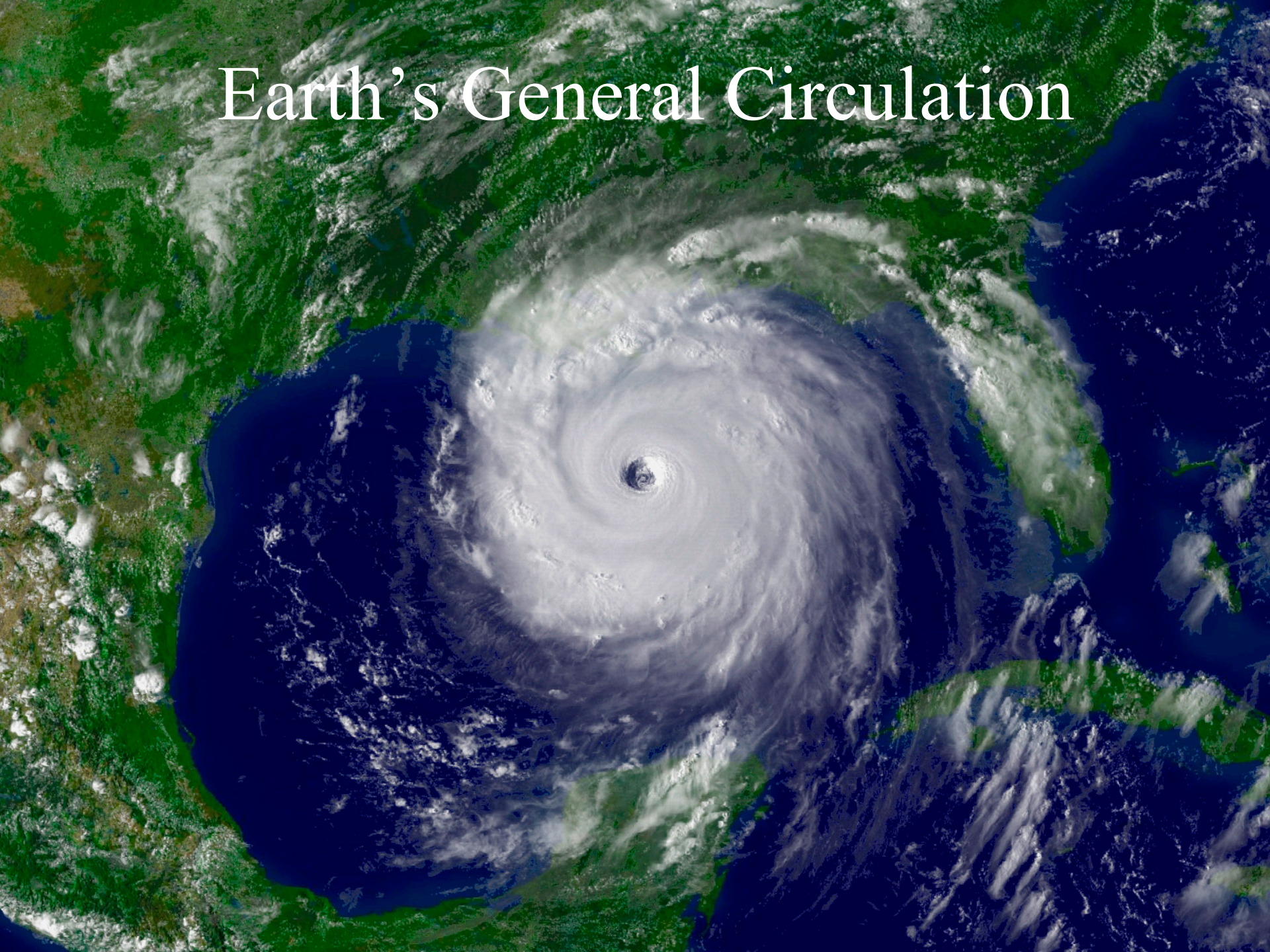
The real world is far more complex (and far more interesting!)  
than this simple picture of average energy.



Why! Because Earth isn't flat!

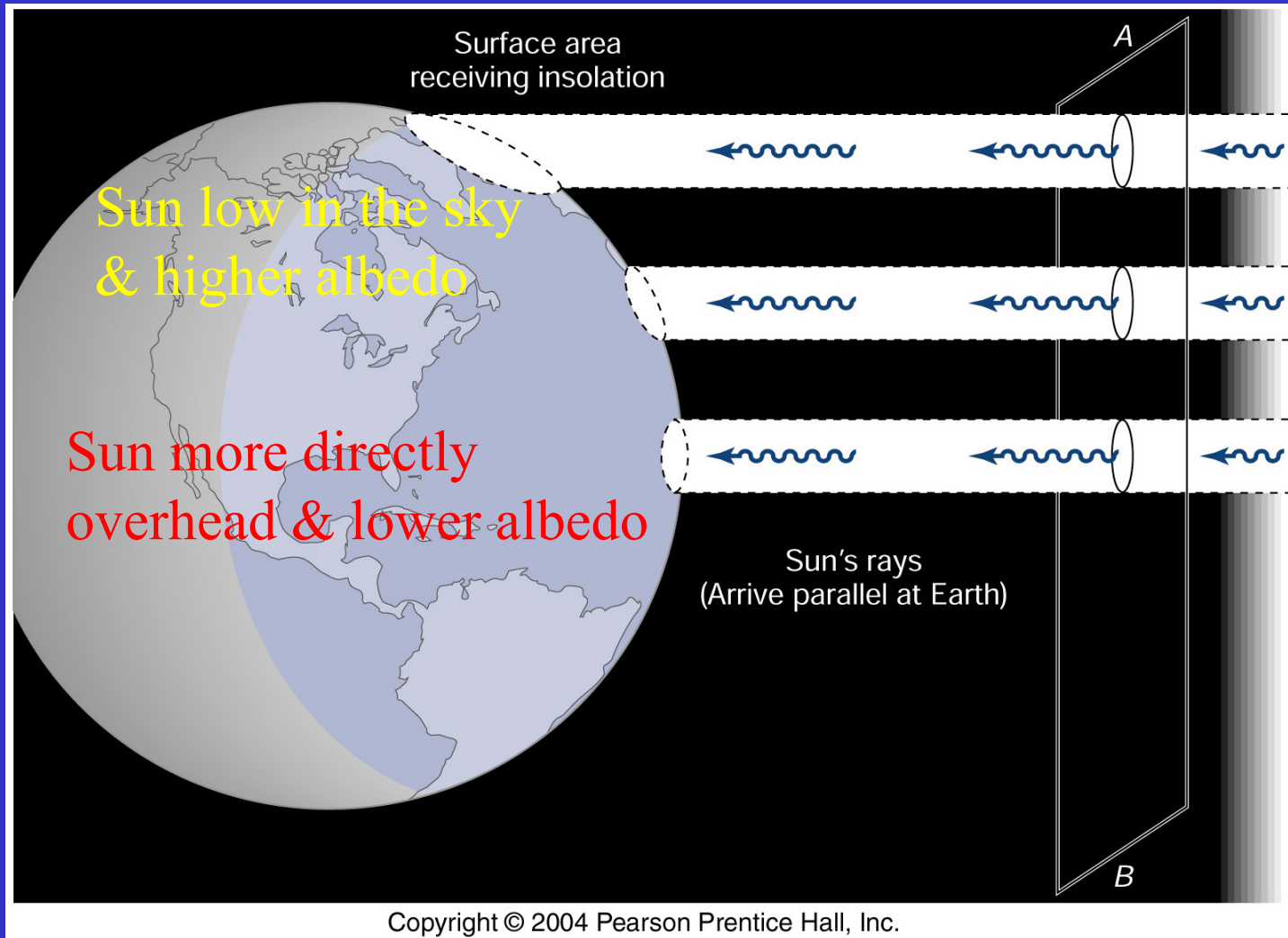


# Earth's General Circulation





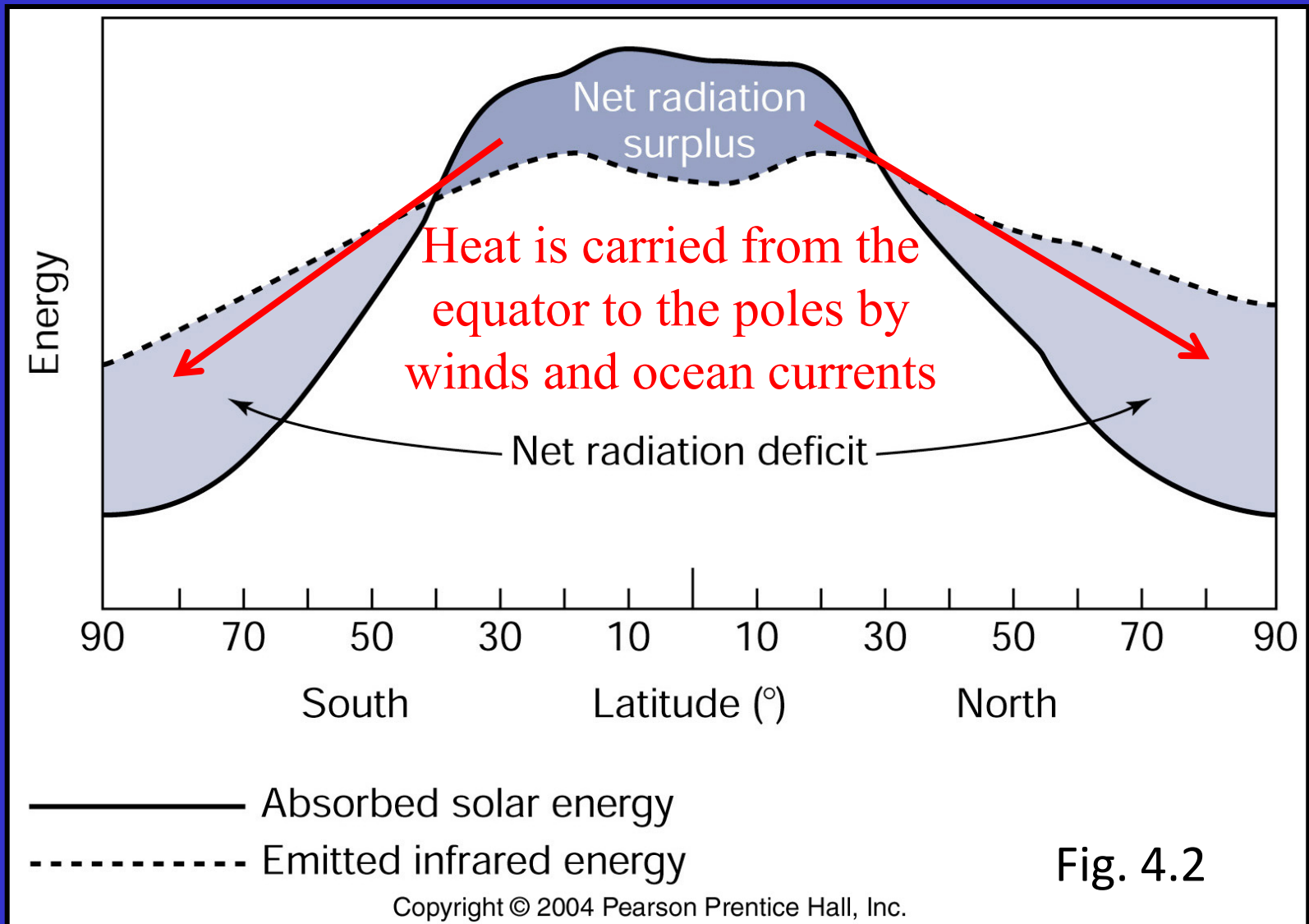
Chapter 4 - The surface is heated differentially due to the curvature and variations in albedo  
(see asynchronous video Feb 9)



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Fig. 4.1

# Pole-to-Equator Gradient in Energy Balance (see asynchronous video for February 9)



## Pole-to-Equator Gradient in Energy Balance (see asynchronous video for February 9)

When we examine radiation to space from Earth as a function of latitude, we find that the tropics emit less heat than we expect based on absorption of solar energy in the tropics. There is more incoming solar radiation than outgoing thermal radiation. We call this a SURPLUS of solar radiation!

The opposite is true in the polar regions, where more heat is radiated in the infrared than is absorbed in the visible. There is less incoming solar radiation than outgoing thermal radiation. We call this a DEFICIT of solar radiation.

Earth is in radiative balance overall when we average over the entire globe, (incoming solar = outgoing thermal), but there is a significant shift in heat from one part of the globe to another. The tropics are cooler than we expect and the poles are warmer than we expect. This is due to circulation of the atmosphere and oceans.

## What is going on?

The atmosphere and oceans are fluids, which can move. This carries heat from the warm regions of the planet to the cold ones.

This is what allows life to survive in the tropics without being scorched and what allows life to survive at high latitudes without being freeze dried!

Chapter 4 – we will look at the circulation of the atmosphere

Chapter 5 – we will look at the circulation of the oceans

Why it matters: Both the atmosphere and oceans will play important roles in redistributing heat from the tropics to the polar regions

Differential heating and cooling of Earth sets up a pattern of vertical motions (uplift, or convection, and subsidence) that drives Earth's *general circulation*. This is the first step in determining Earth's *climate zones* (places that experience certain types of weather ...winds, temperatures, precipitation, seasons)

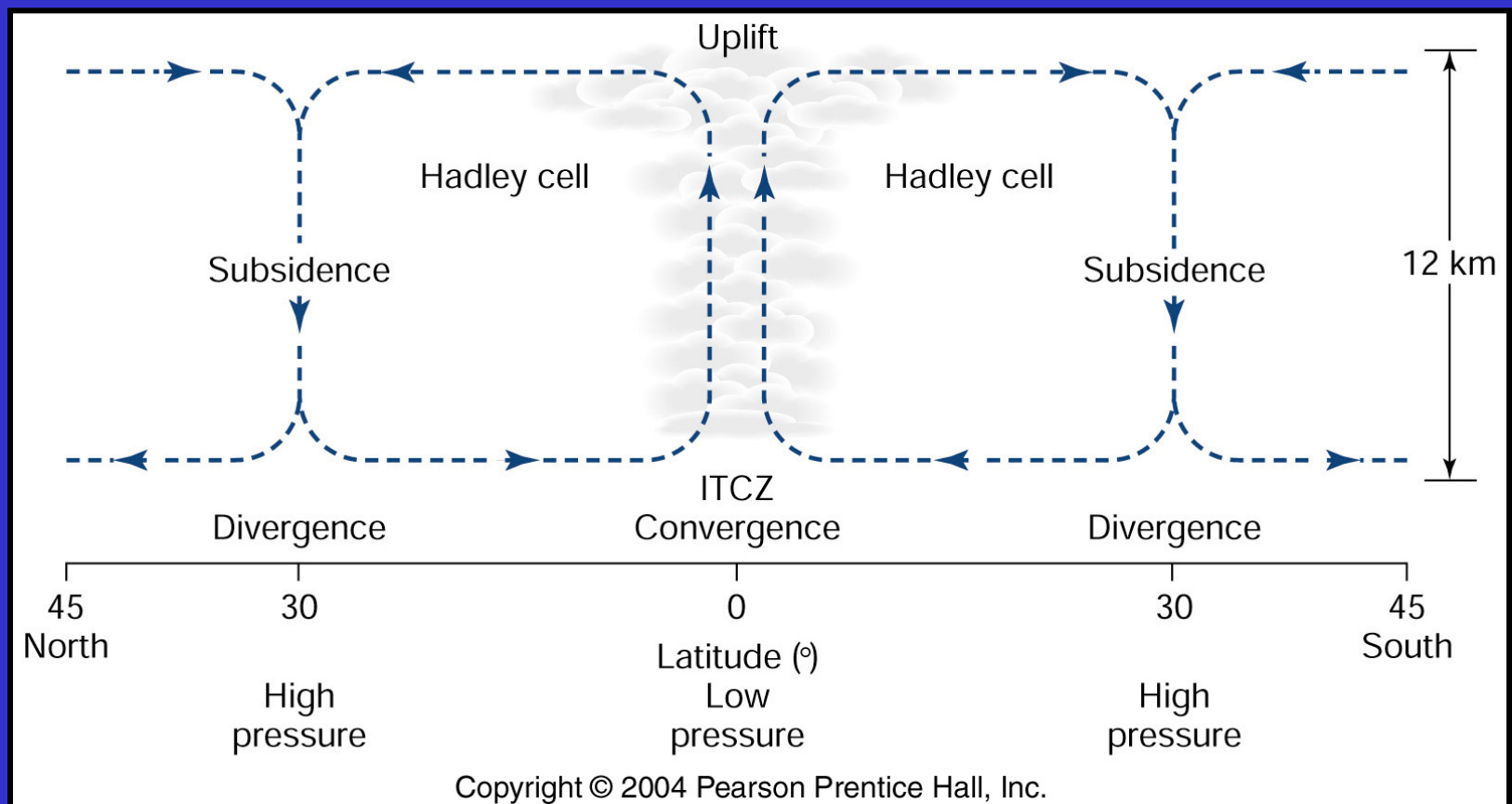


Figure 4-3

## Ideal Gas Law ( $PV = nRT$ )

Air expands when it is heated. This is because pressure is constant if a gas is uncontained, so an increase in temperature forces an increase in volume. This causes a decrease in density, and the less dense air becomes buoyant.

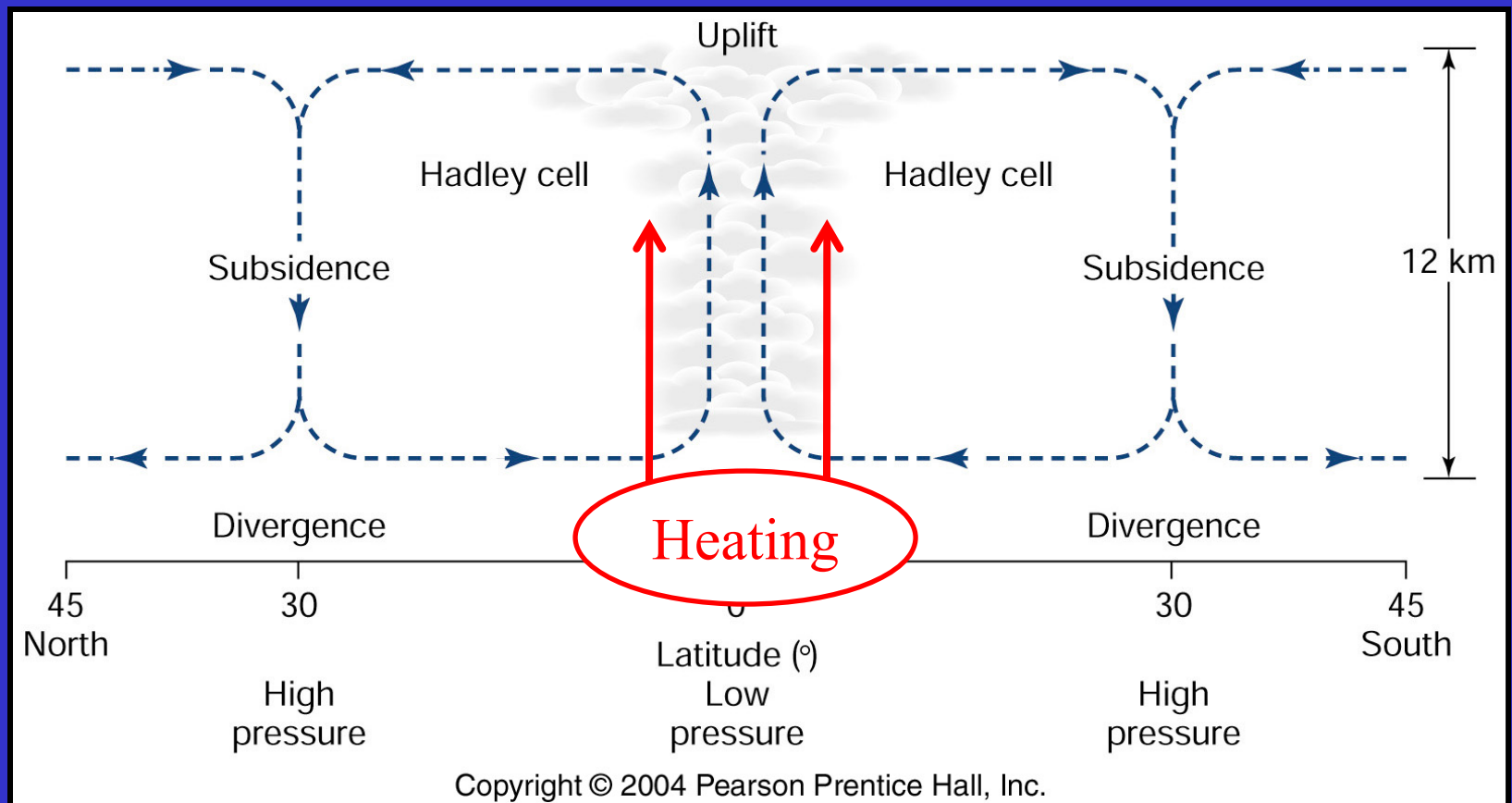


Figure 4-3



## Rising Air leaves a Low Pressure at the Surface

The upward movement of warm air in the tropics reduces the pressure at the surface. This low pressure acts to pull in higher pressure air at higher latitudes, inducing a pole-to-equator surface flow of air.

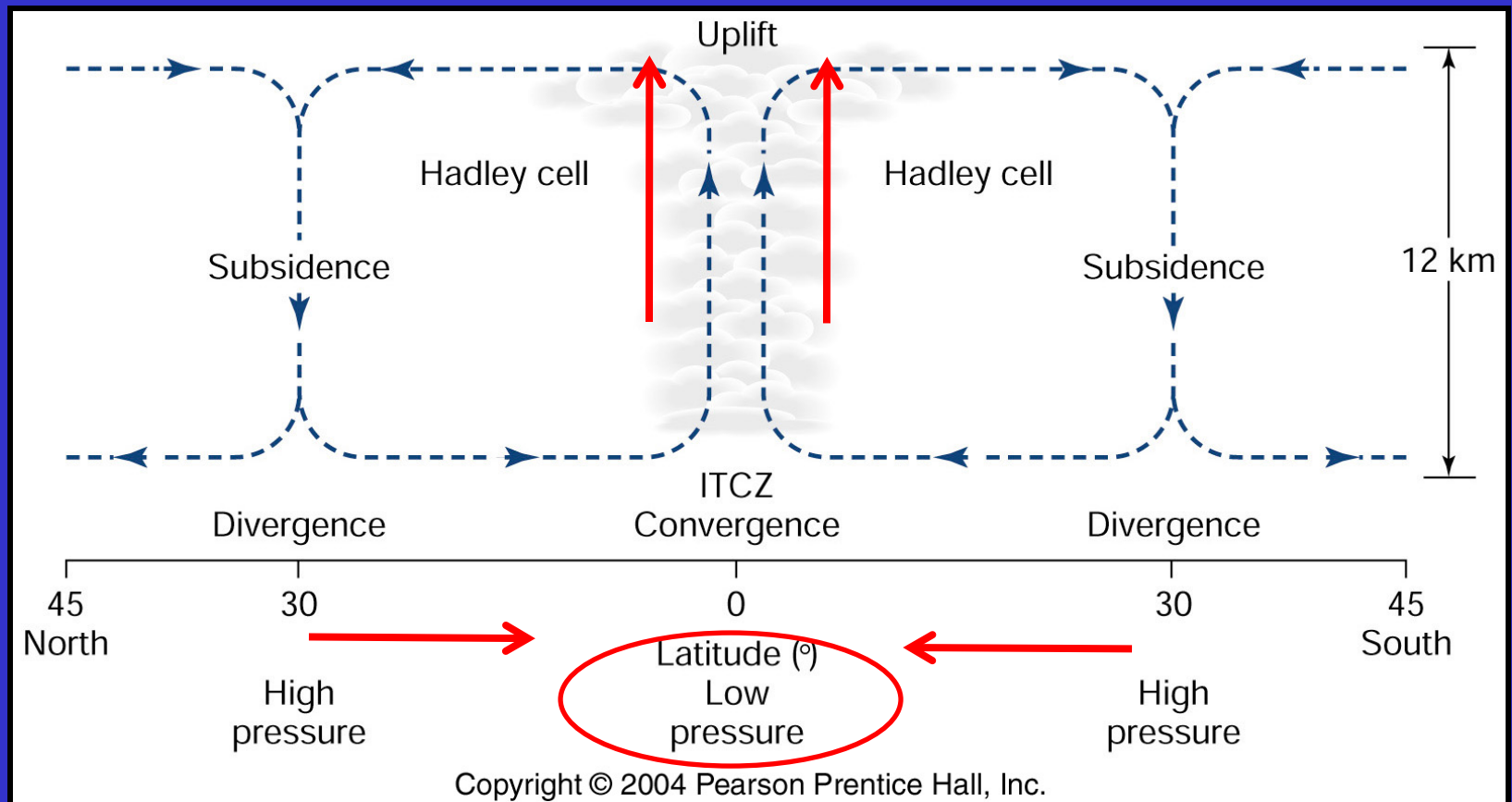


Figure 4-3

## Cooling Air Aloft Leads to Descent at Higher Latitudes

As warm air ascends to the colder upper regions of the atmosphere, it will radiate heat to space, becoming cooler and more dense. It begins to sink, reinforcing the surface high pressure at mid-latitudes.

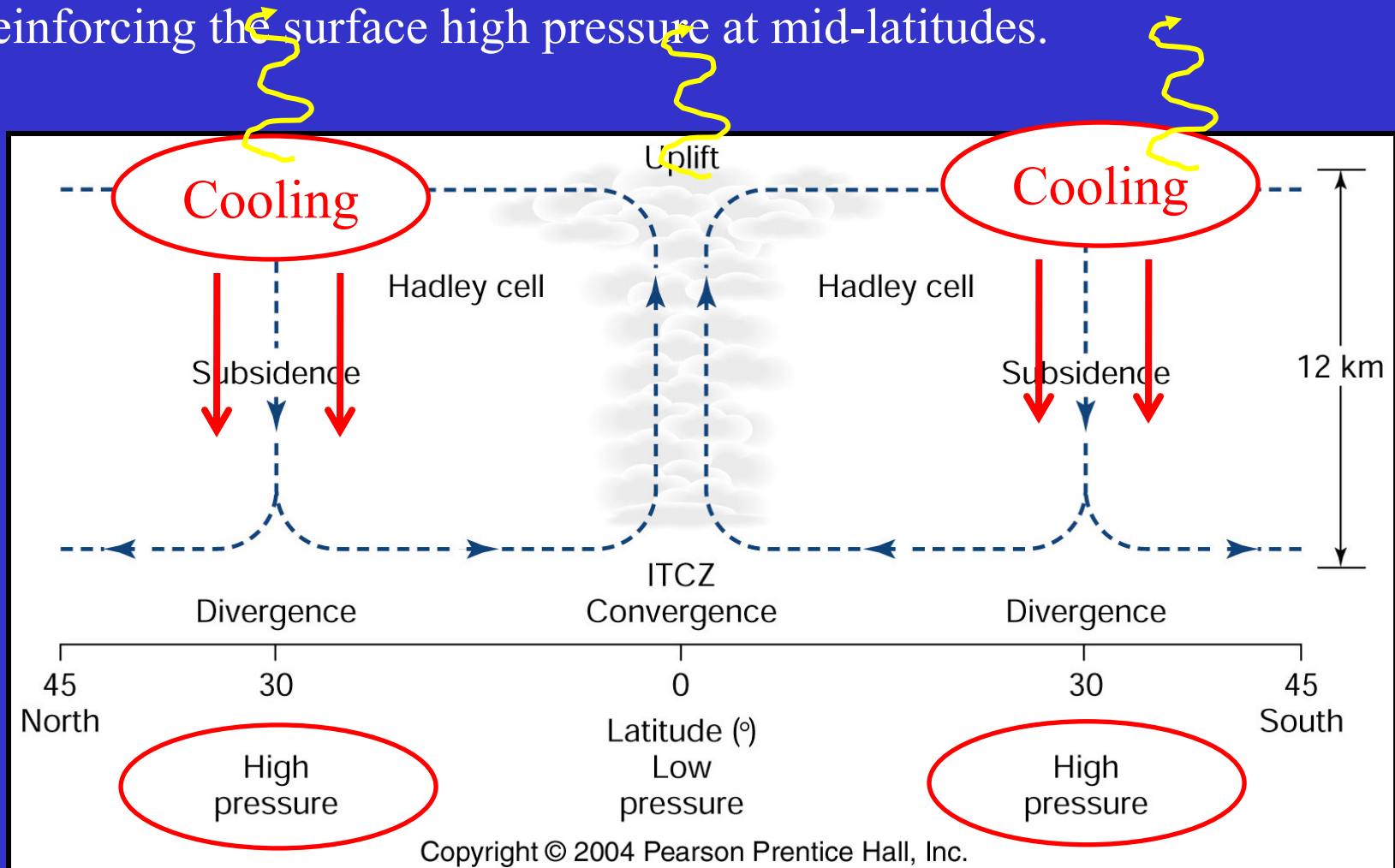
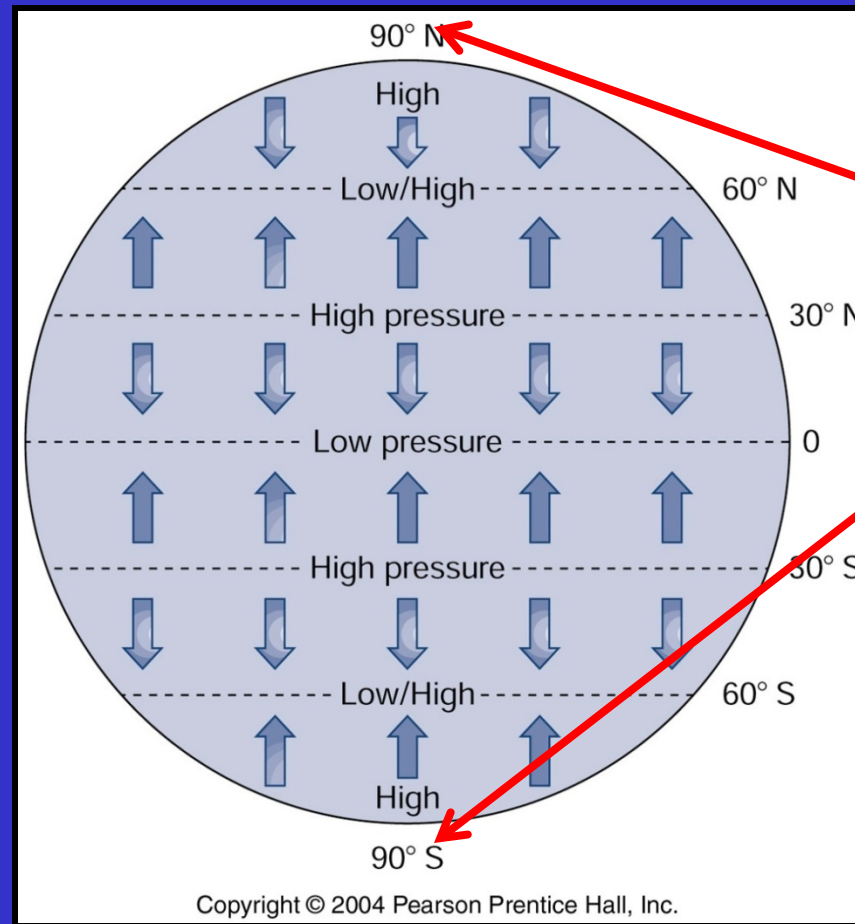


Figure 4-3

What air flow at the surface would look like, based on observed pressures alone – air would move from high to low pressure. Areas where air is rising due to solar heating (e.g., tropics) have low pressure at the surface, areas where air is sinking due to cooling (e.g., north and south poles) have high pressures. Areas in between can have either high or low pressures, depending on what is happening to air at other latitudes.

We can now begin to see climate bands!

Places where it is often warm and wet, like the tropics, places that are cool and dry, like the polar regions. Places in between (like the US) will have more variable climates!



Air over the poles is sinking because it is cooling.

Fig. 4.8

## Low pressures and Inclement (rainy) weather

The pressure must decrease where air is rising. This is because the pressure at the surface is due to the weight of the column of air above, and if that column of air is less dense (lighter) than the surrounding air, the pressure at the bottom of that column will be smaller. We call this *low pressure*.

Since the air above a surface low pressure region is rising, it is cooling and clouds are forming, so we often associate low surface pressures with '*bad (or inclement) weather*'.

This low pressure will attract higher pressure air inward. This is called *convergence*. Note that air from outside a low pressure region is converging toward that low pressure.

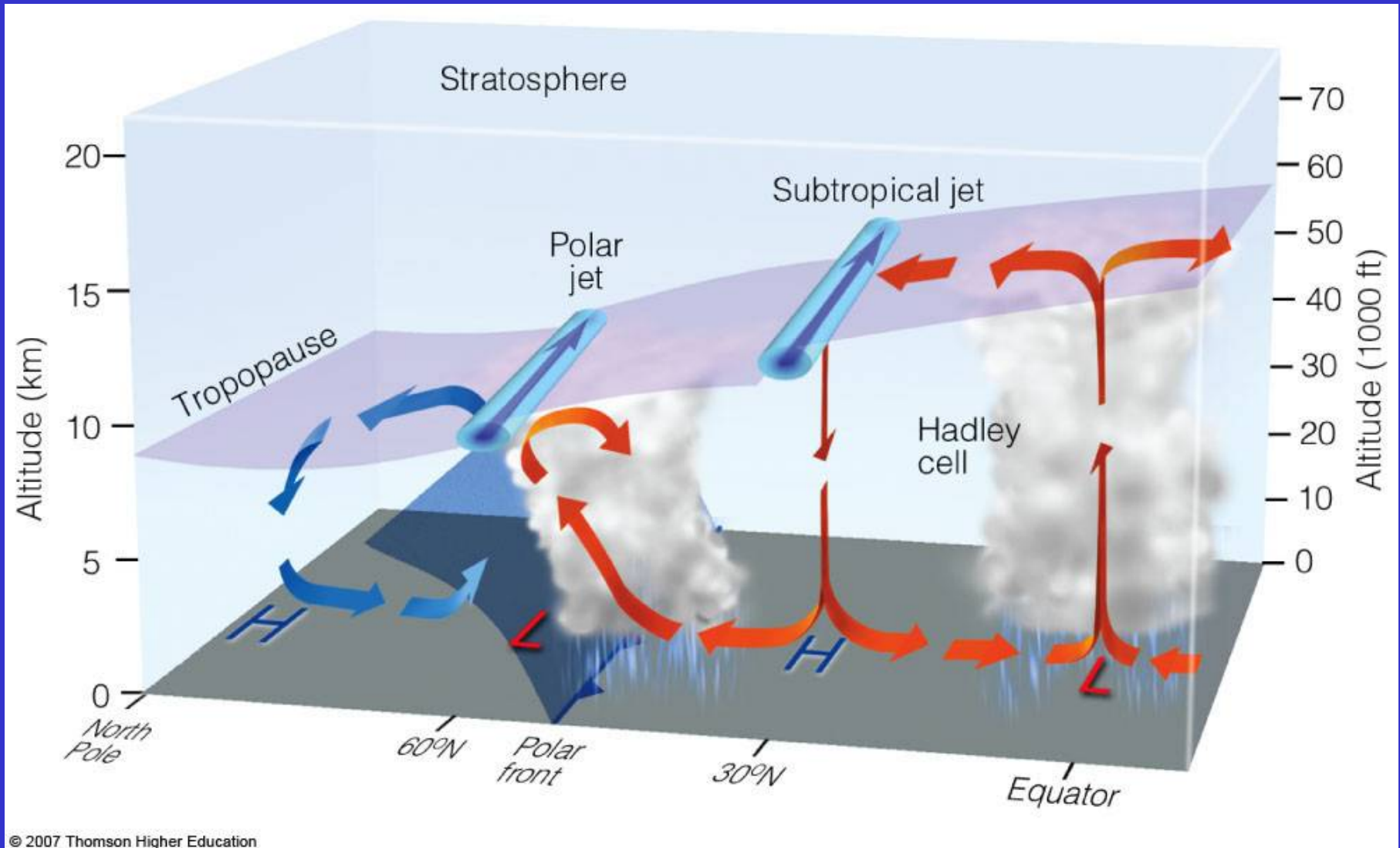
## High Pressures and Good Weather

The pressure will be high where air is sinking. This is because that column of air is more dense (heavier) than the surrounding air. We call this *high pressure*.

Since the air above a surface high pressure region is sinking, it is warming, any clouds will evaporate, and the weather tends to be clear. So we often associate high surface pressures with *good weather*.

This high pressure will tend to push air outward toward lower pressures. This is called *divergence*. Note that air from inside a high pressure region is diverging away from that high pressure.

# A pole-to-equator “slice” through the atmosphere



We also see this type of flow driven by differential heating in local weather patterns

## Sea (and land) Breeze

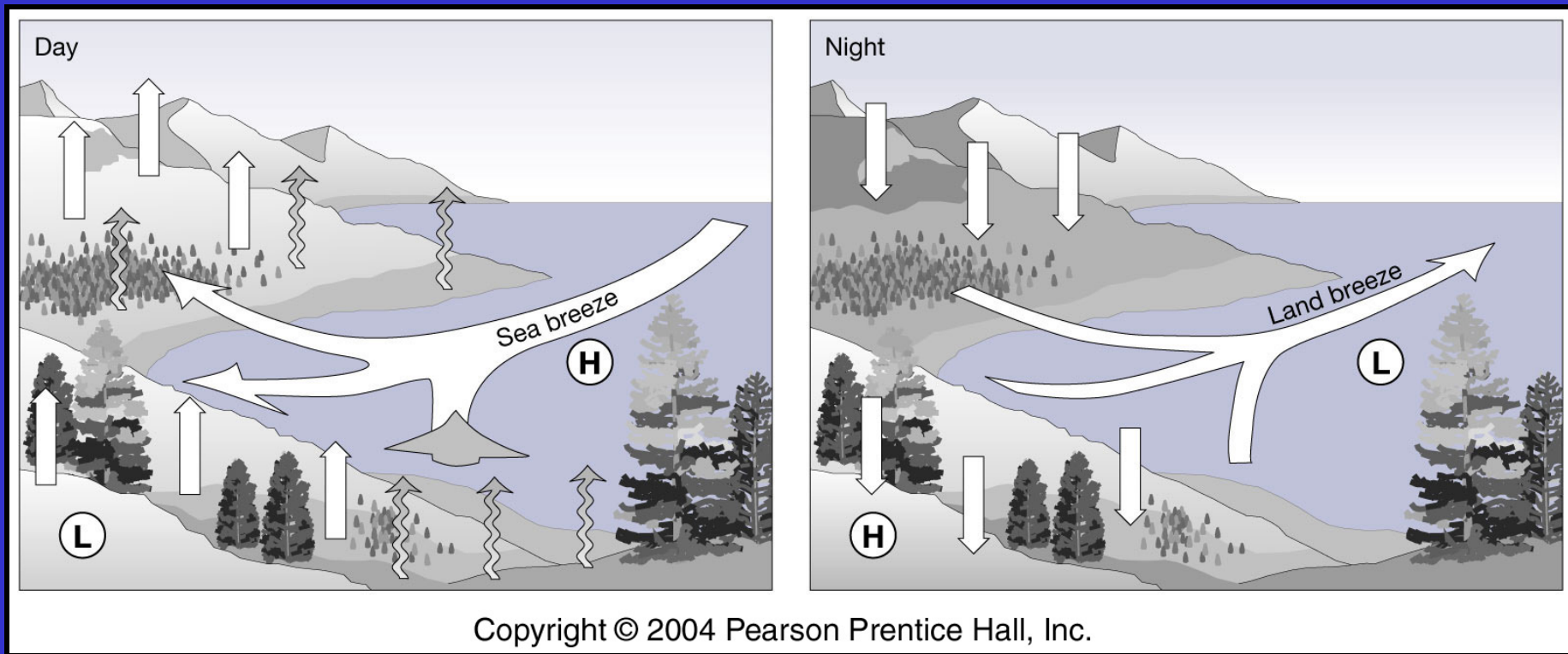
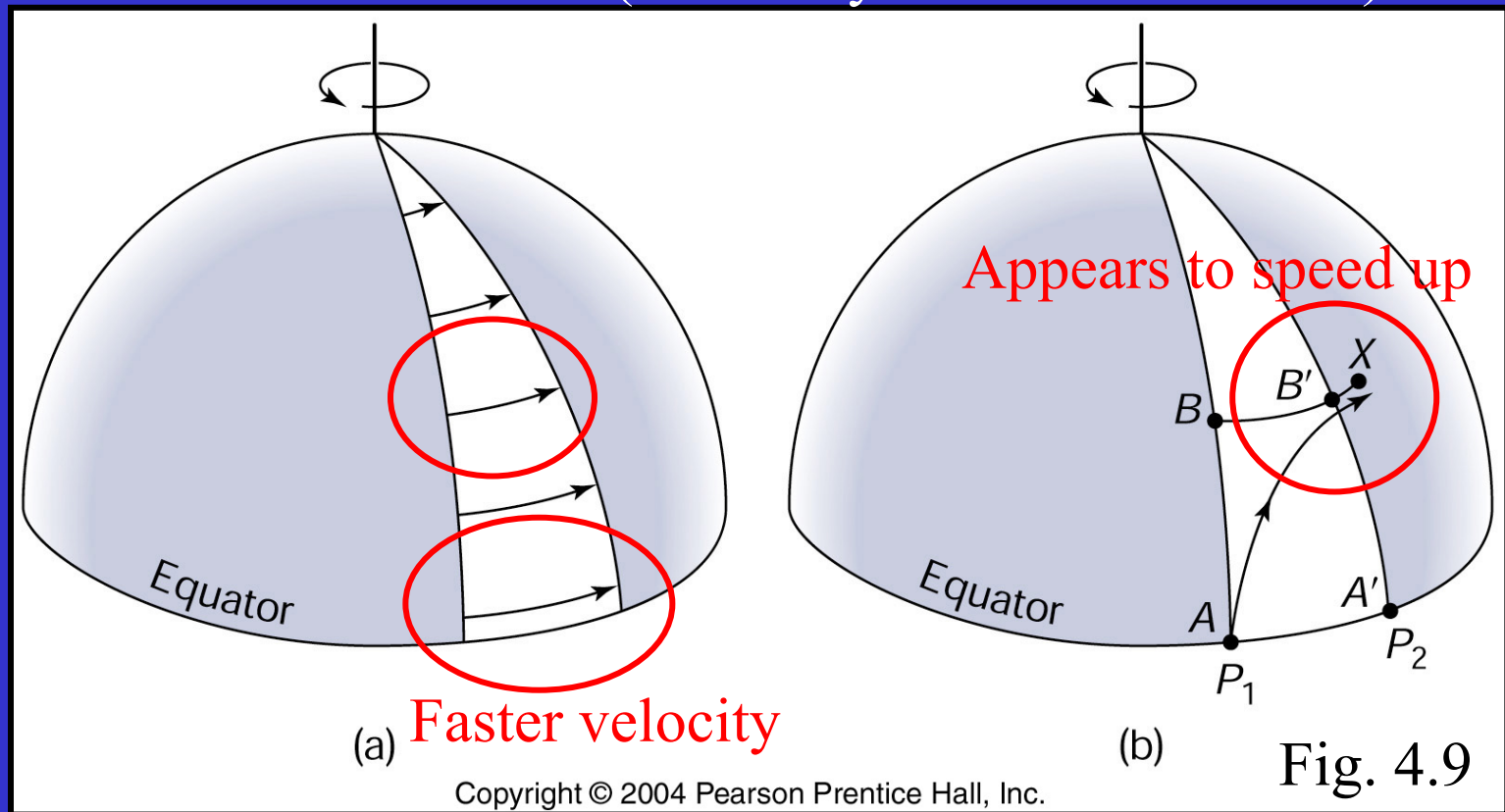


Fig. 4.17



On large scales, however, Earth is rotating!  
The Coriolis effect (some Asynchronous material)

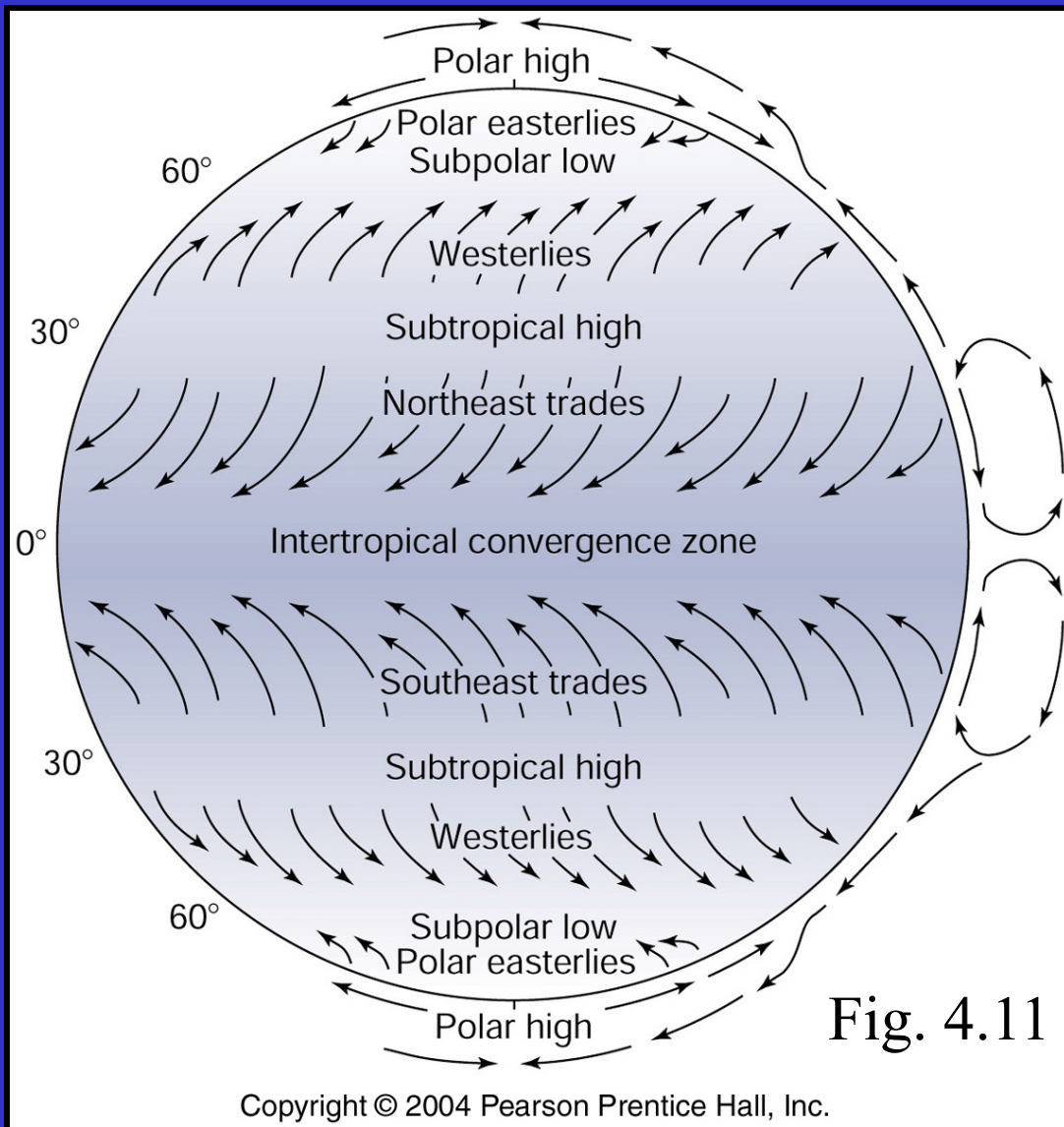


Air traveling northward has larger eastward speed, so it appears to speed up (“lead”) as it travels toward the pole. Conversely, air traveling southward “lags” as it travels toward the equator.

View is for Northern Hemisphere – S.H. is just the opposite.



# Consequences of Coriolis Effect (i.e., rotation)



Air does not travel in a straight north/south direction, but rather is steered in an east/west direction

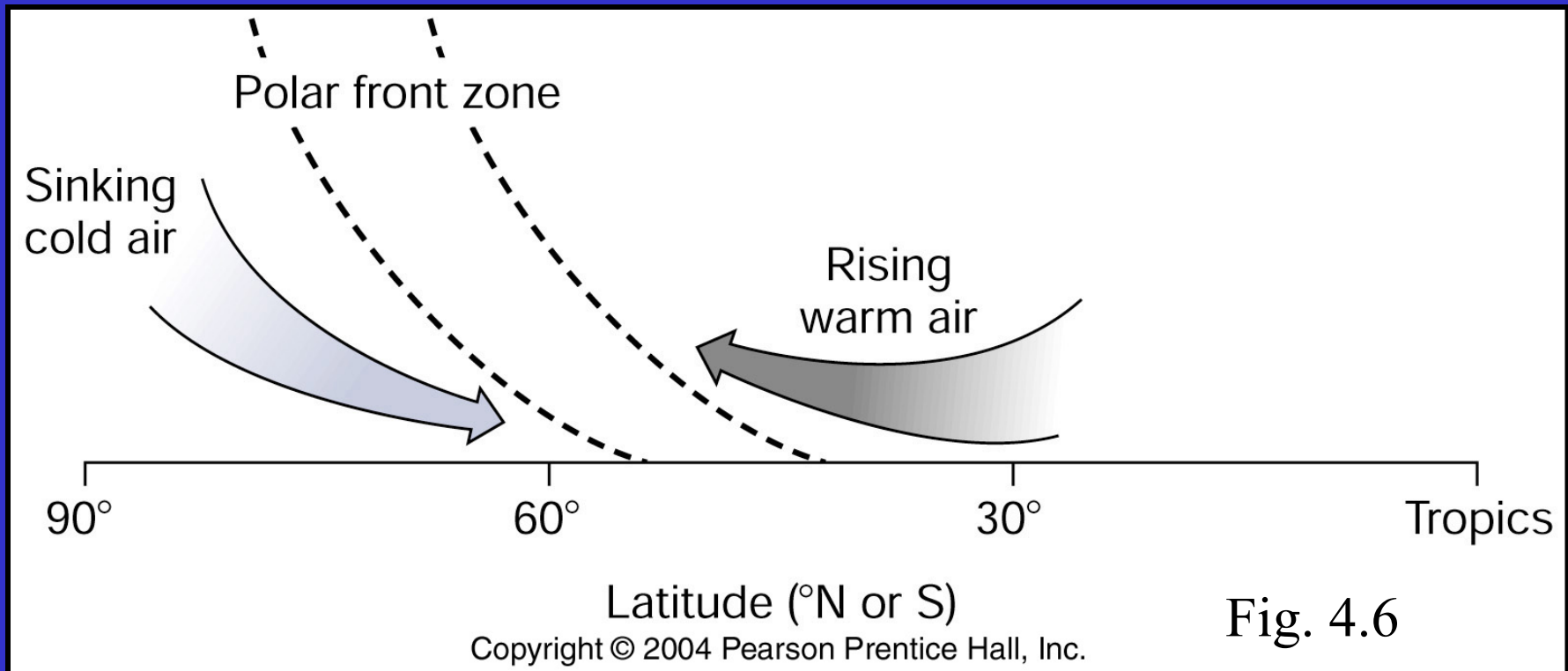
This gives rise to strong gradients that separate warm and cold air masses

(look at current weather in Denver compared to New England)

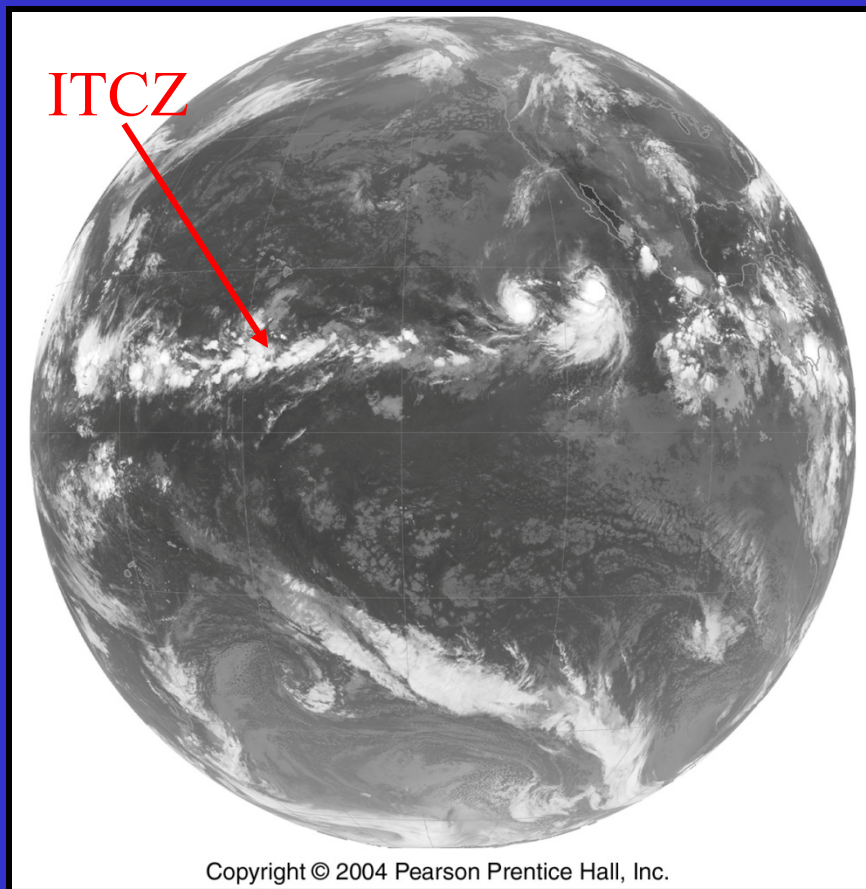
Midlatitude “westerlies”  
Tropical easterlies

# Weather “Fronts”

The convergence of northerlies (cold) and southerlies (warm) leads to weather ‘fronts’ at mid-latitudes. When a region is in a warm sector, temperatures and humidities are more like tropical air, when a region is in a cold sector, air is cool and dry.



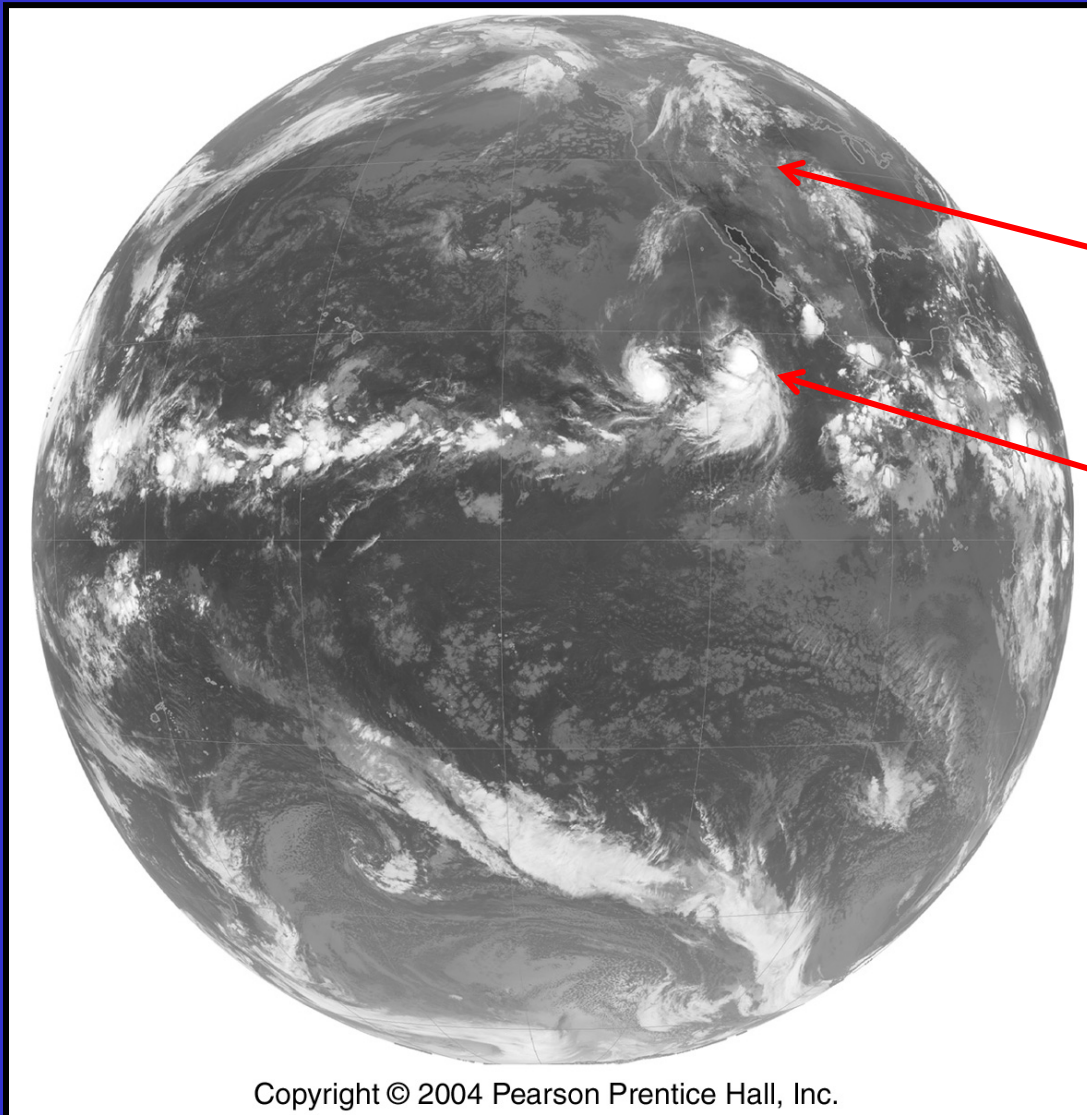
We can see the effects of rising air on cloudiness. As air rises, it cools (because it is expanding as it encounters lower pressures). When the temperature reaches the condensation point, water becomes saturated, forms small droplets of water – a cloud!



We call the band of clouds in the tropics where air is rising due to solar heating the InterTropical Convergence Zone (ITCZ).

Fig. 4.4

This creates a pattern of rising air near the tropics and sinking air at higher latitudes.

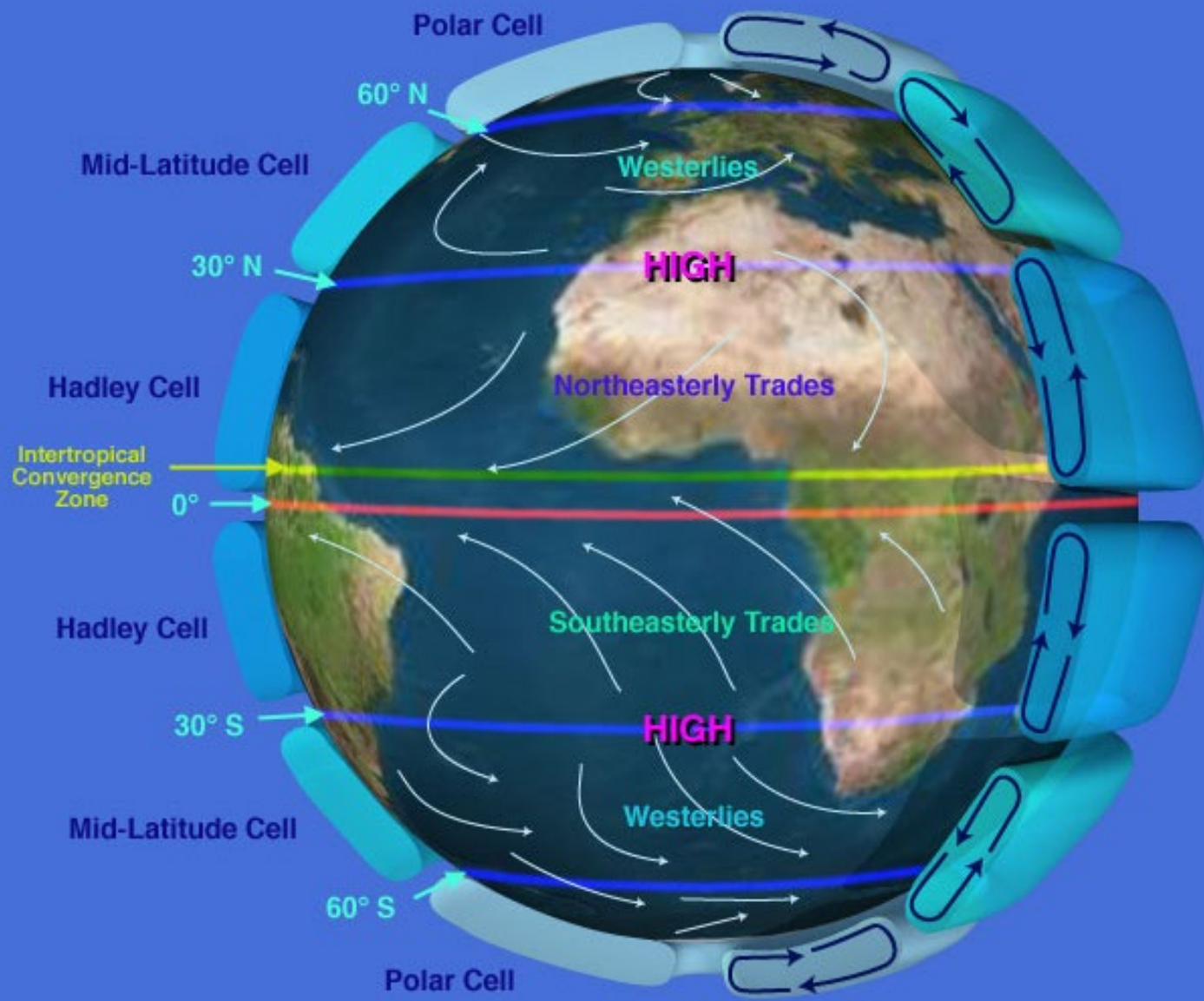


Sinking air, dry  
(deserts, droughts)

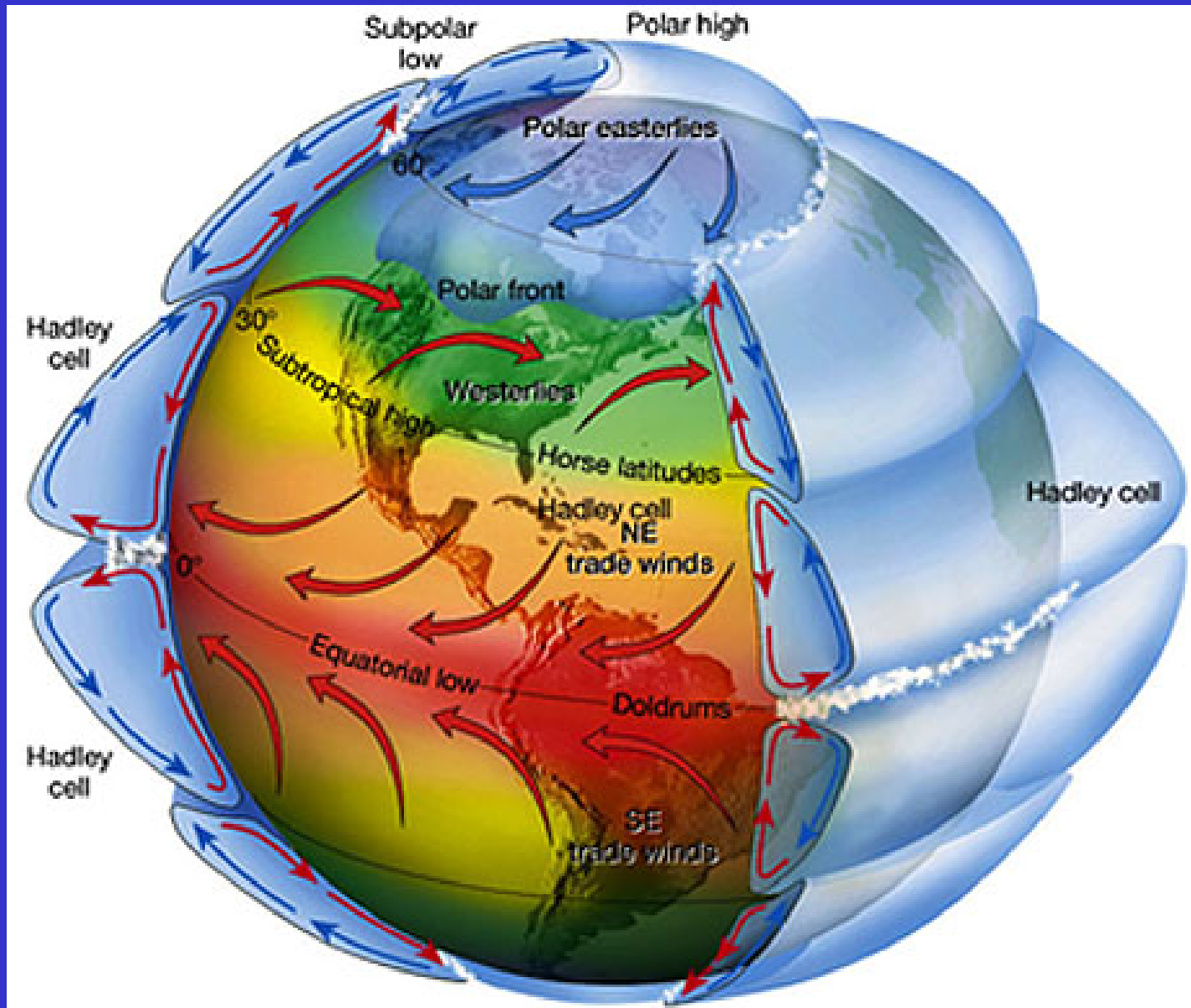
Rising air, wet  
(rain forests and  
floods)

Fig. 4.4





# Another “view” of 3D circulation



# Asynchronous

## What do seasons do to the general circulation?

The place where air rises (i.e., the ITCZ) shifts with season – rainy weather shifts between the hemispheres

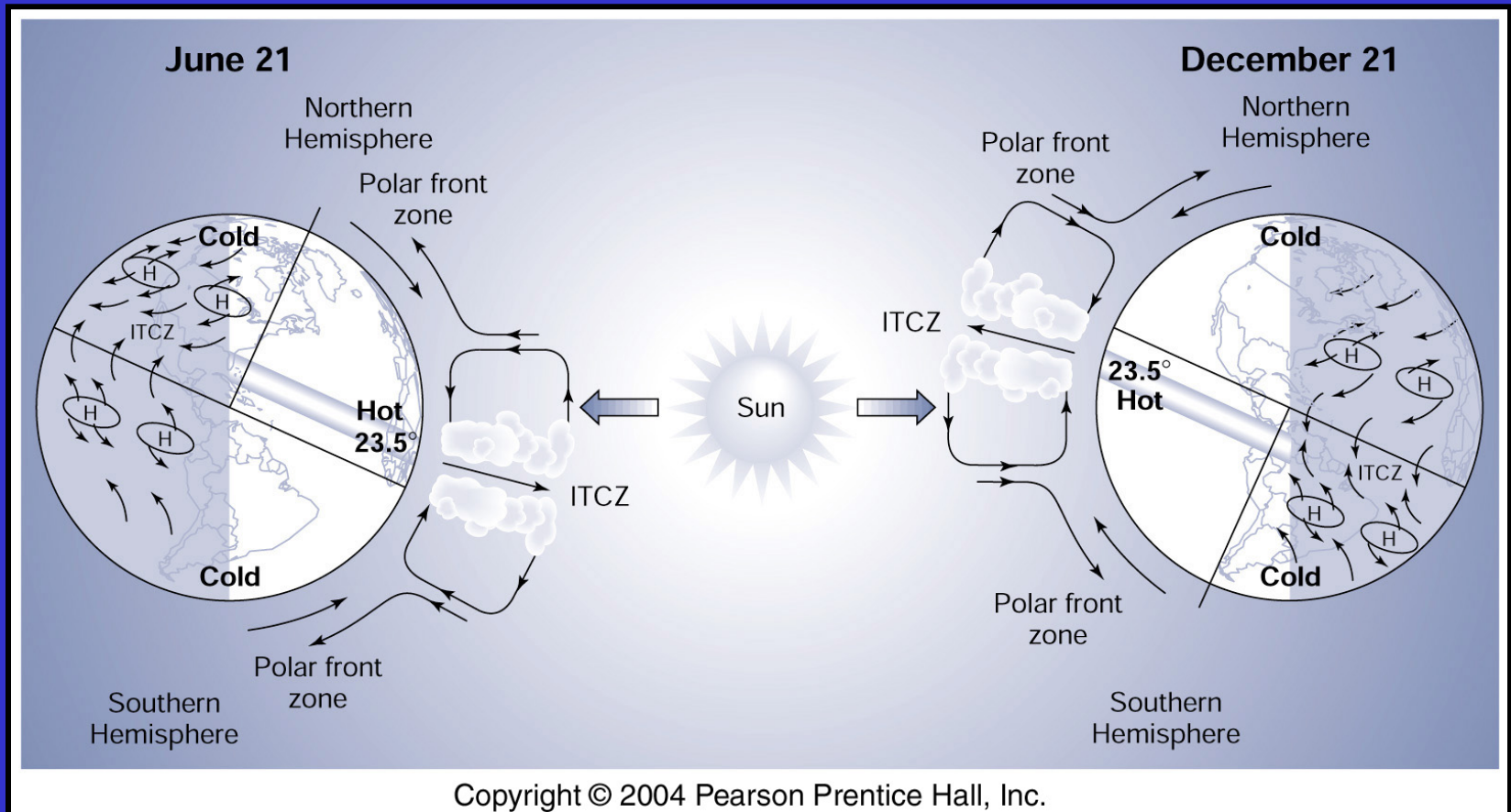


Fig. 4.16

## What do seasons do to the general circulation?

One of the interesting consequences of a shift in the tropical zone for rising air is that places that are close to the equator experience two “cloudy/rainy” seasons. This is due to the passing overhead of the ITCZ. For example, it tends to rain in Quito, Ecuador, in February through May and again from October through December.

<http://www.climatestotravel.com/climate/ecuador>

Mountain climbers, such as those attempting to summit Mount Everest, know more about the climate there than most meteorologists. This is because they know that their lives depend on it! So when are the best times to summit Mount Everest? May and November. This is when the precipitation and winds are lowest.

Seasonal shift in winds is called “monsoon” (it’s doesn’t mean torrential rain, but often the rains change when wind direction changes)



We can start to connect the dots – between weather and climate.

General circulation tells us a lot about the “context” – tropics, mid-latitudes, polar regions. But the surface of the Earth isn't uniform, and we have seasons. This means that different places on Earth experience different patterns of weather.

So while the average “climate” may appear to be moderate, there could be important changes that get averaged out. So we need to look at the details of weather to really understand what we mean by “climate.”

## Why does all this matter?

First, note that we can use pretty simple principles to explain some very basic (“average”) features of Earth’s climate (in fact, these principles apply to other planets as well). Things like “air rises when it is heated, because warm air is less dense than cold air at the same pressure” and “when air travels northward, the Coriolis effect will act to turn the air to the right of the direction of motion.”

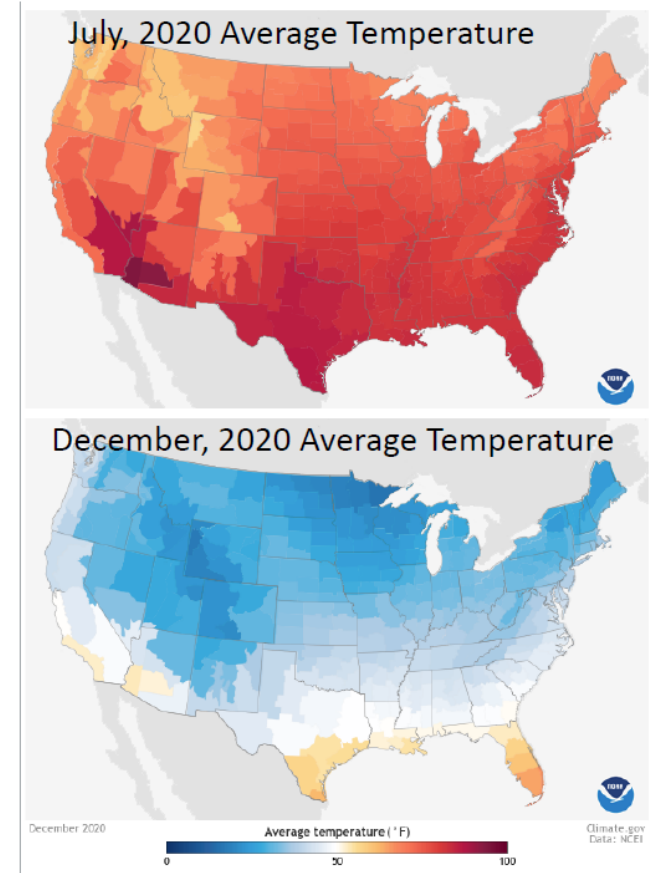
But it isn’t long before these simple principles become more complicated. For example, “geostrophy” represents a condition where two forces balance each other. This is the most simple form of balance ( $A=B$ ). In fact, friction matters. And, so too does the centripetal (or “centrifugal”) force. When we add these in, we discover that air deviates a little from its “geostrophic” direction of motion.

Second, in order for us to explain the basic features of Earth's climate "zones" (the stuff that matters when we look at long-term changes, as opposed to weather), we can figure out most of what we need simply by assuming that winds are geostrophic. That is, we can use maps of average surface pressure to estimate the average direction of the winds. For predicting individual weather events, like storms, this won't be good enough (in fact, the deviations from geostrophic balance are responsible for changes in the weather).

We can look at weather maps and examine things like droughts (which occur in places where surface pressures tend to be high over long periods). We'll look for rain or snow where surface pressures are low, and we'll look for fronts to move in the direction of geostrophic winds – winds that, in the northern hemisphere, travel in a direction that maintains high pressure to the right.

# Breakout room activity 1

- What is the weather like where you are?
- How strong are seasonal changes?
- Do you know what climate features drives weather where you live?



## Clicker Question 2

Which hemisphere has larger seasonal variations in temperature?

(A) The Northern hemisphere

(B) The Southern hemisphere

(C) Neither – both have the same variations, they are just offset by 6 months.



# July temperatures

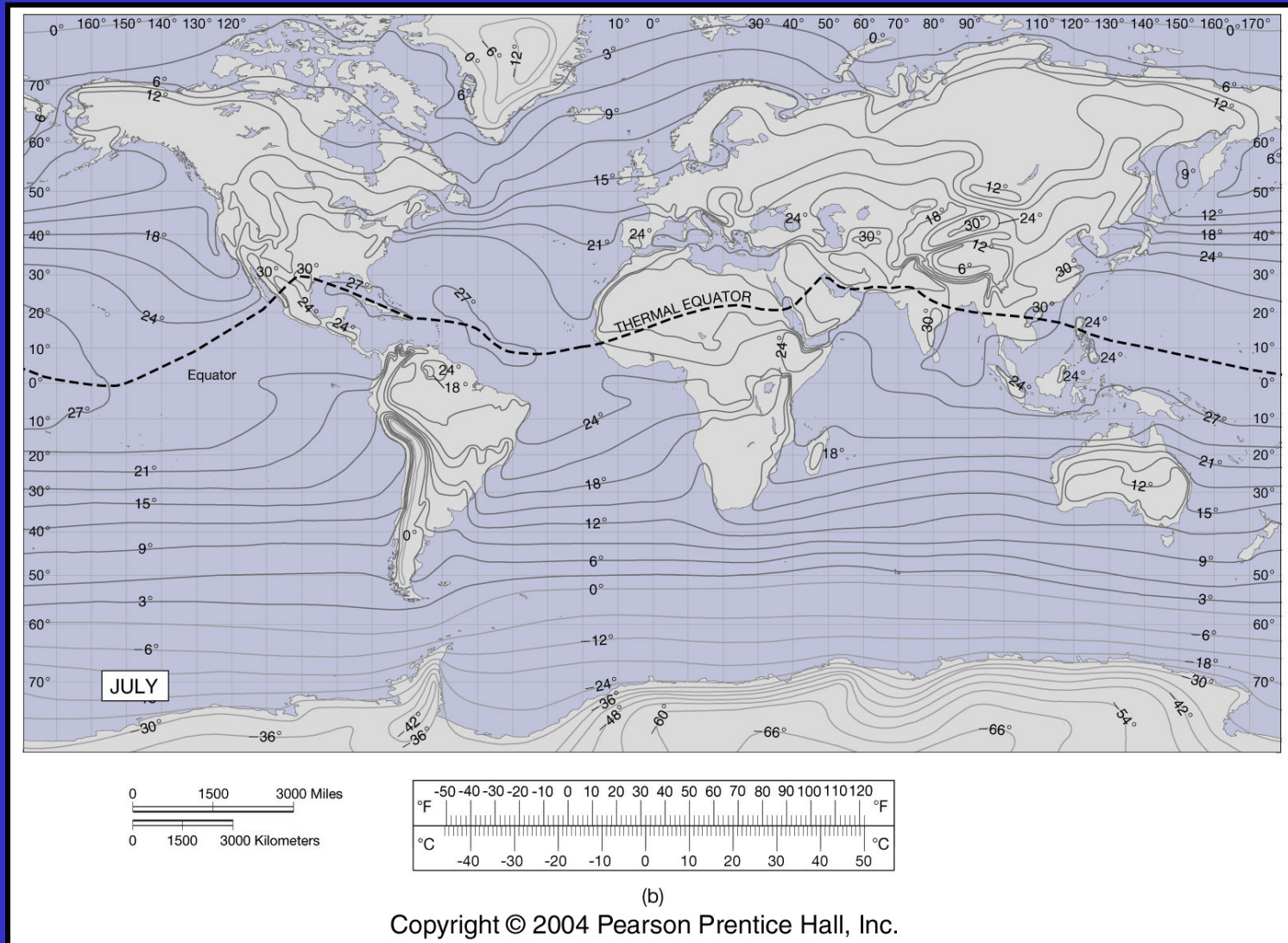


Fig. 4.18

# January temperatures

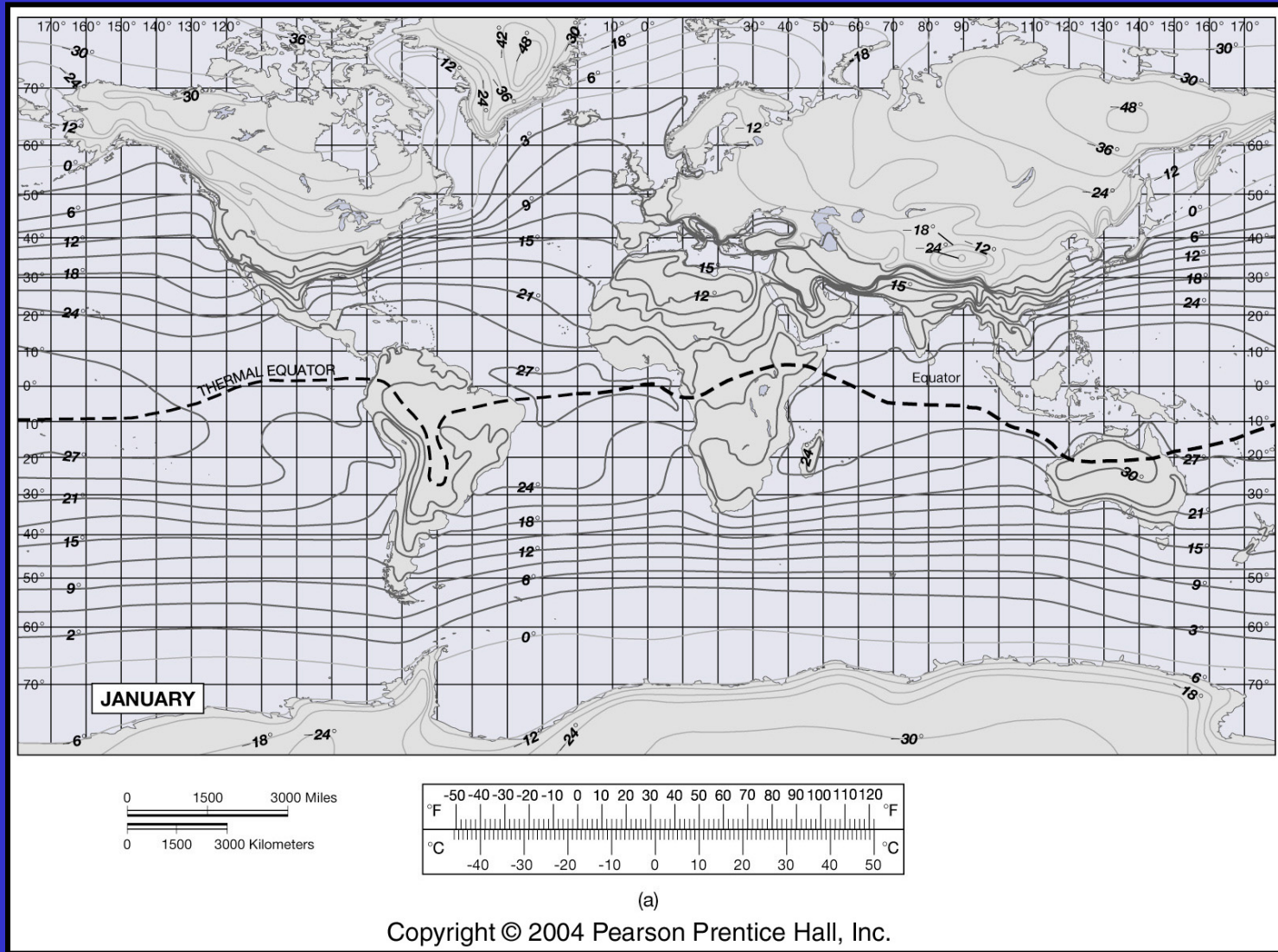


Fig. 4.18

# Summer/winter temperature differences

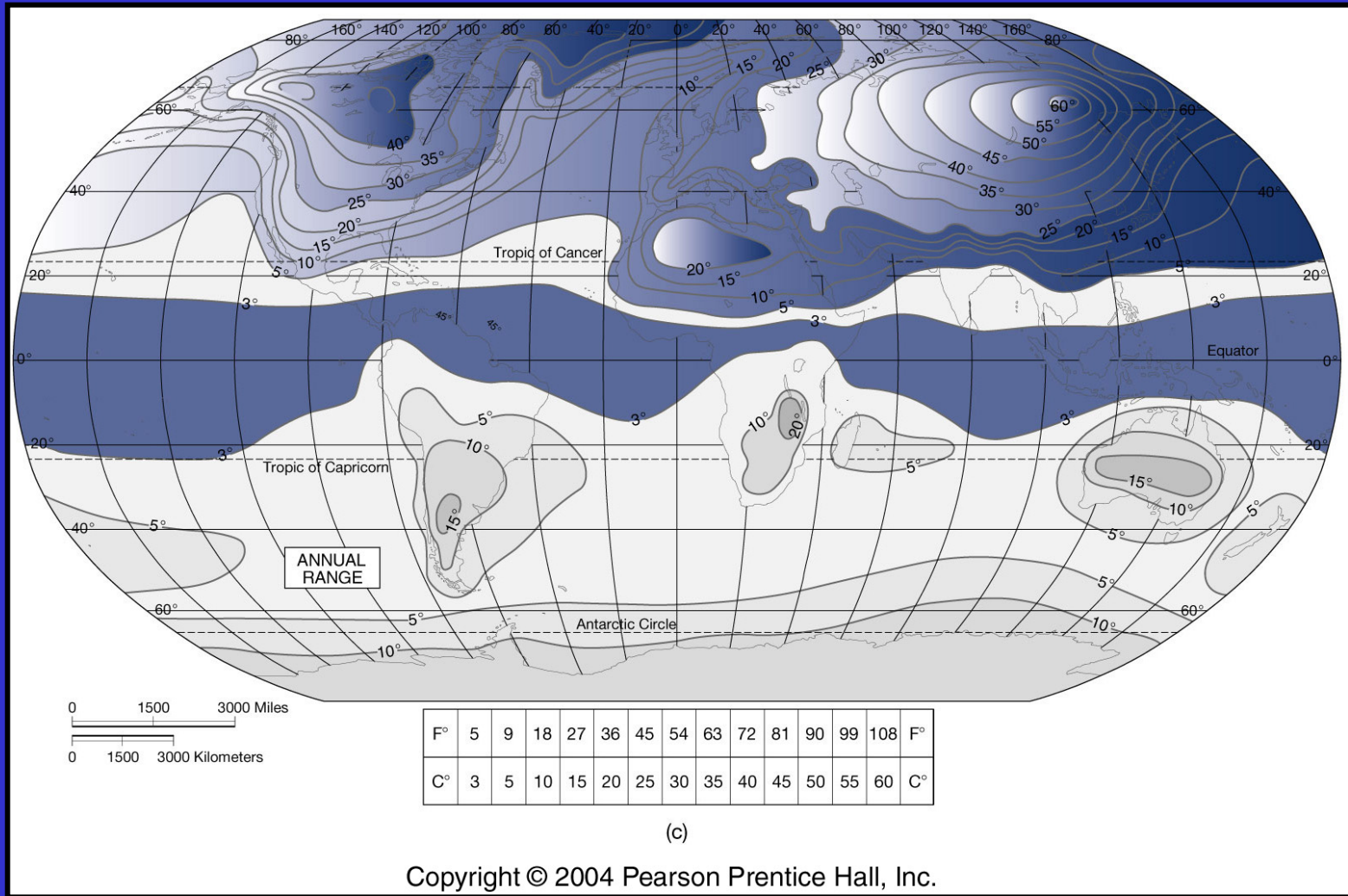


Fig. 4.18



# Average sea-level pressure patterns - January

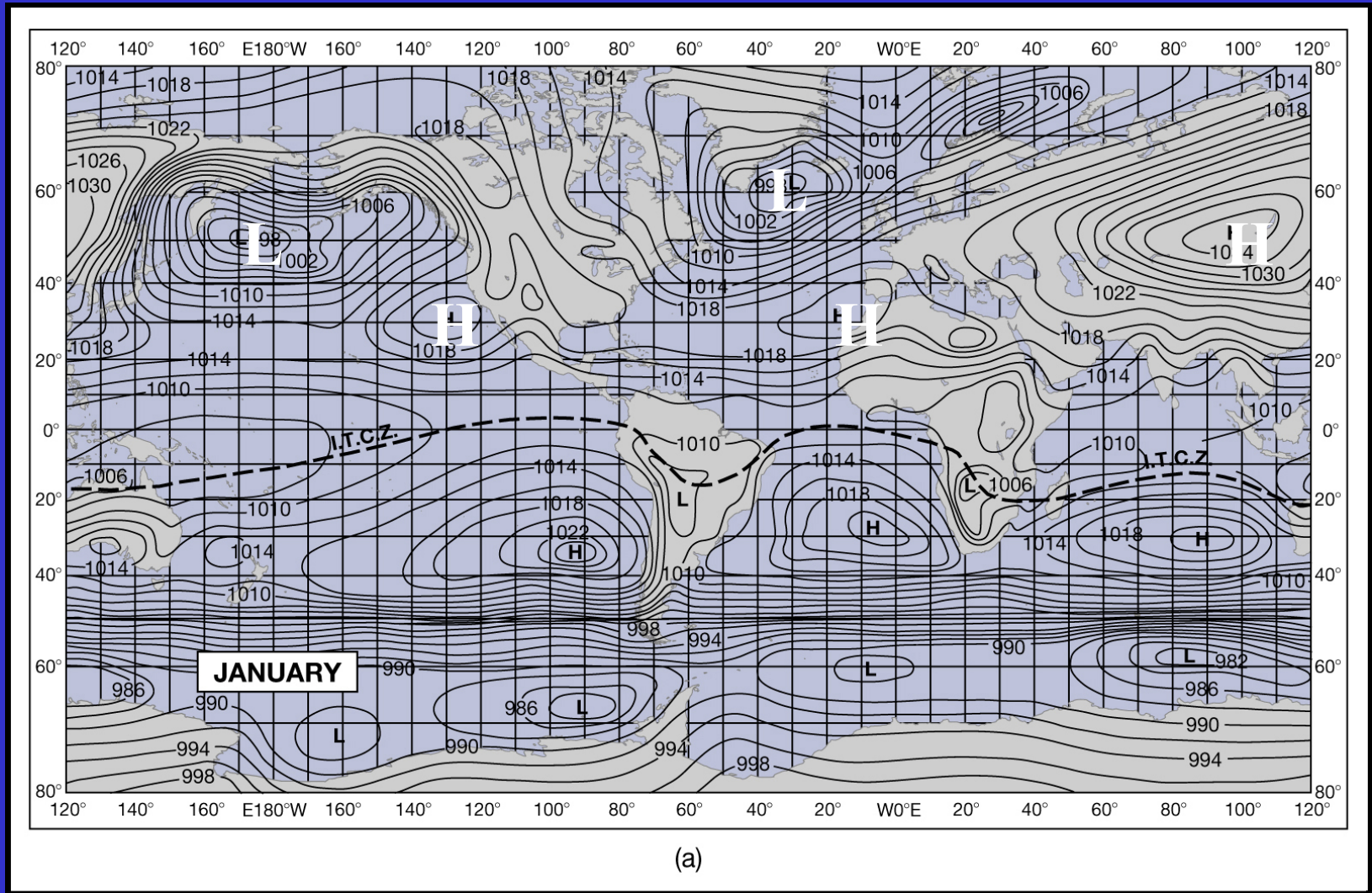
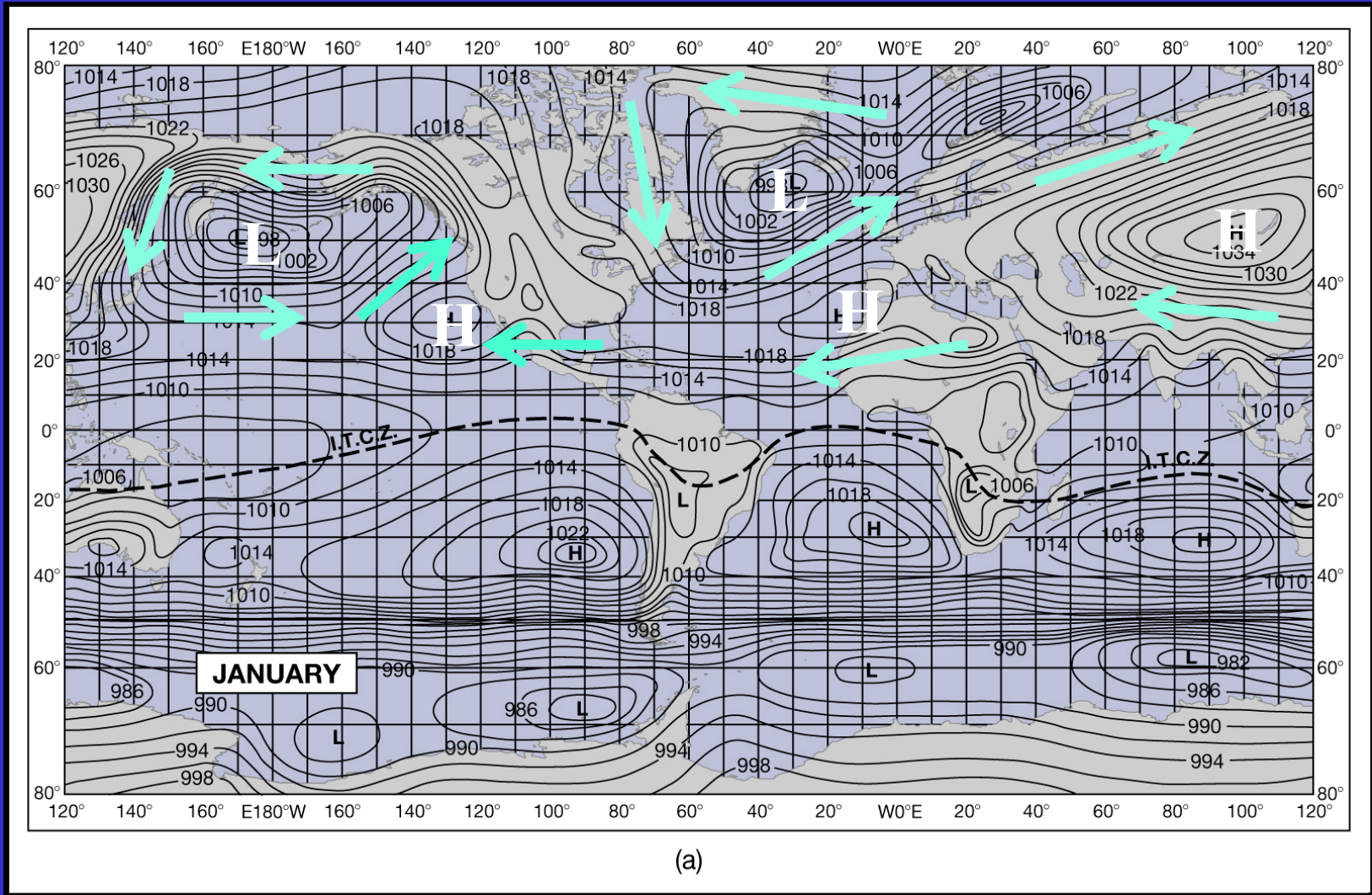


Fig. 4.19

# Northern hemispheric average winds, January



Air flows in a direction that keeps high pressure  
the right of the wind direction in the NH

Fig. 4.19



# Average sea-level pressure patterns - July

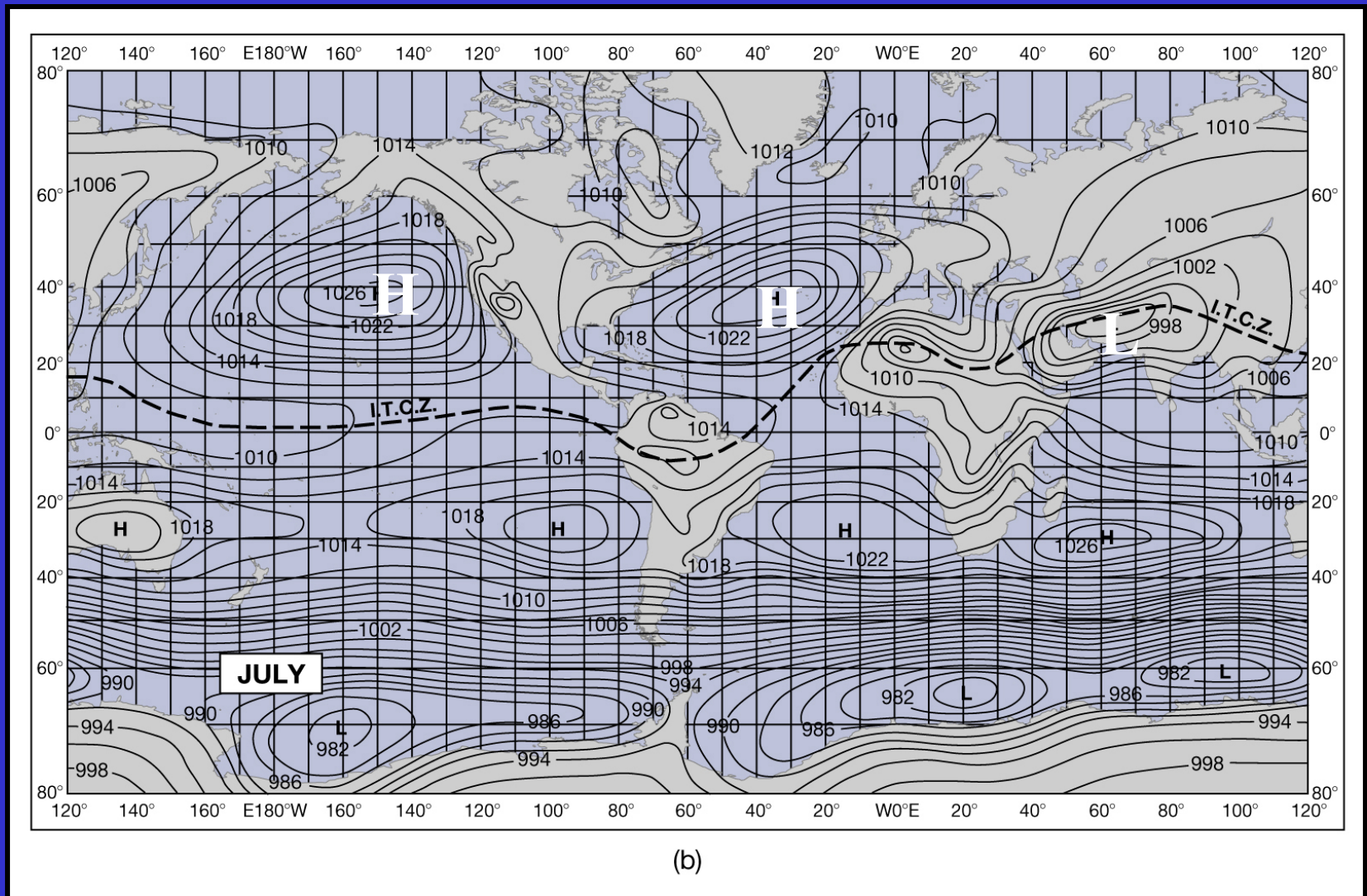


Fig. 4.19

# Mean wind directions in NH, July

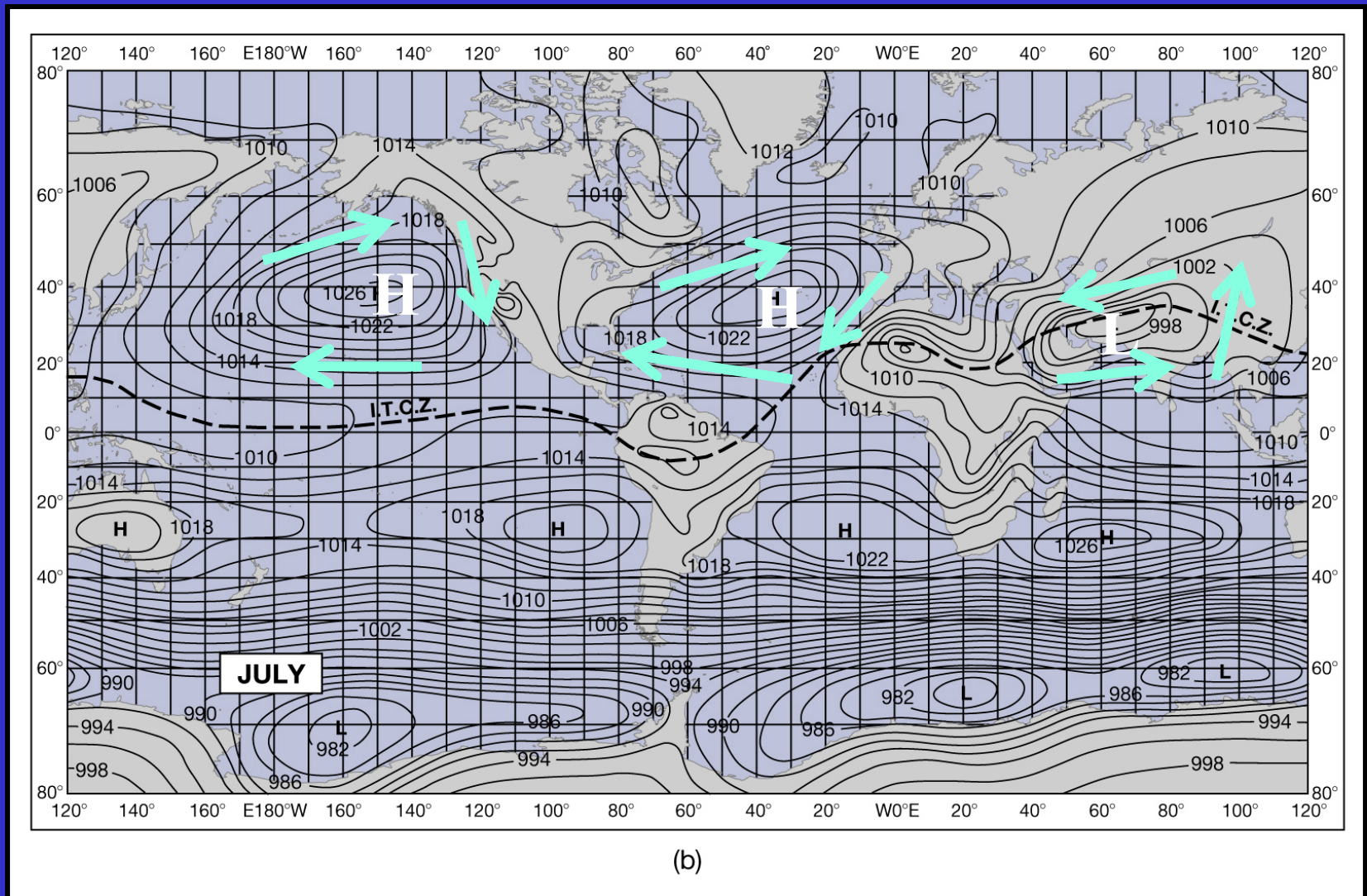


Fig. 4.19

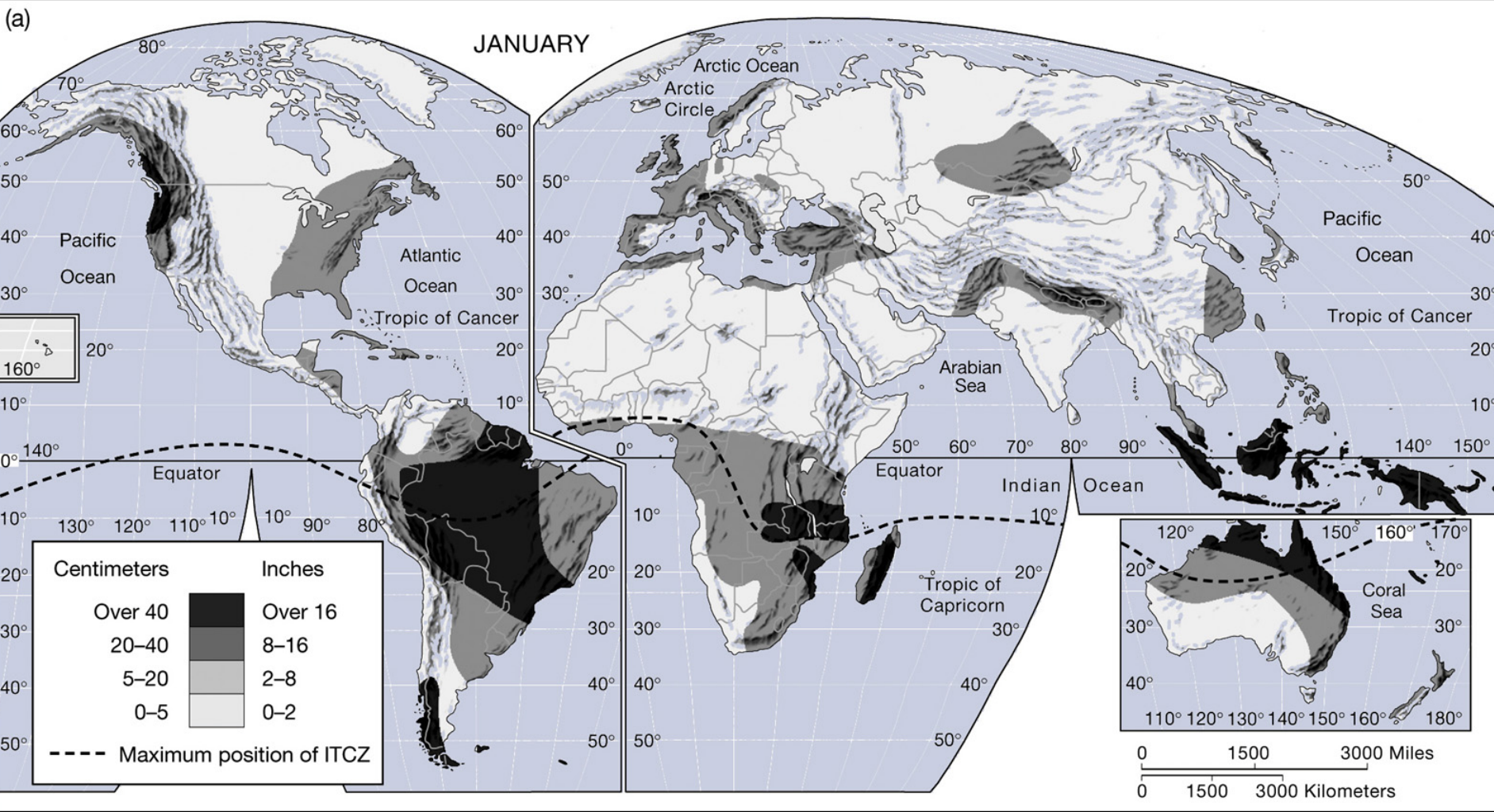
## Using geostrophy to deduce climates

Note that, based on geostrophic flow and mean surface pressure fields, we can deduce general patterns of climate in different places. For example, the west coast of the US experiences a mean wind direction from the north-northwest during July, keeping weather cool near of the coasts of states like Oregon, Washington, and many parts of California. In January, the mean flow towards Washington state is from the southwest, bringing warm, wet air from near Hawaii (the “pineapple express.”)

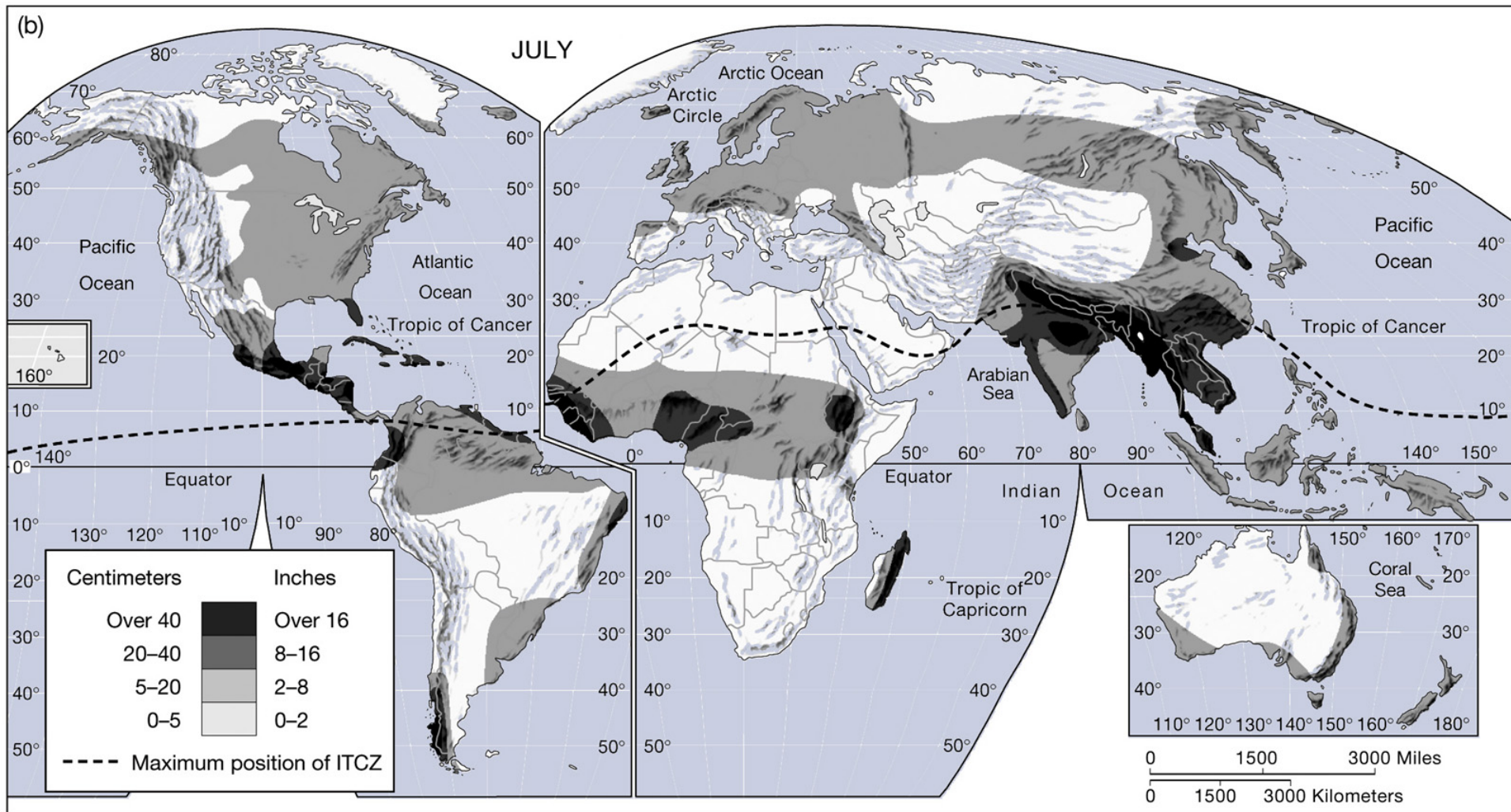
Note that weather in the UK comes from the west-southwest both months, even though the pattern switches from high to low. This is because the position of the highs and lows shifts. The UK typically has wet weather in both July and January.

Will go over these very quickly (all one concept)





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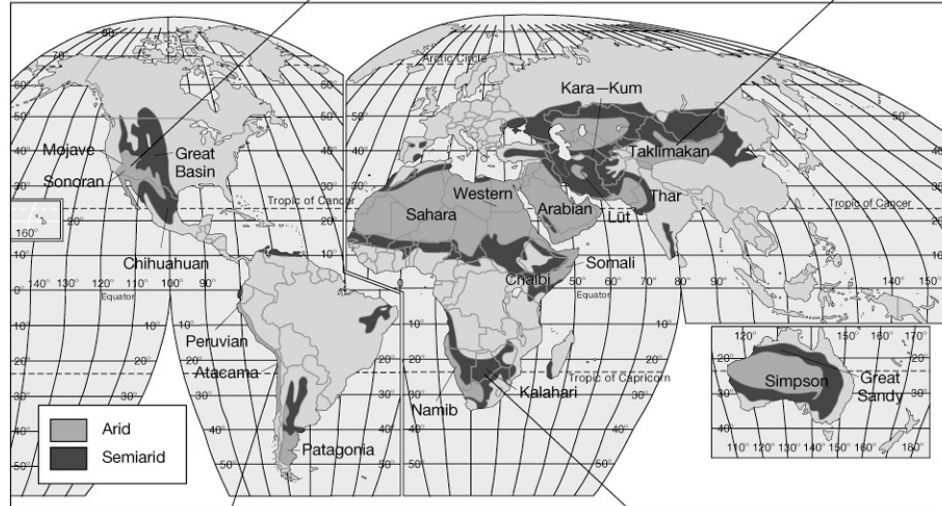




(a) Sonoran



(b) Taklimakan



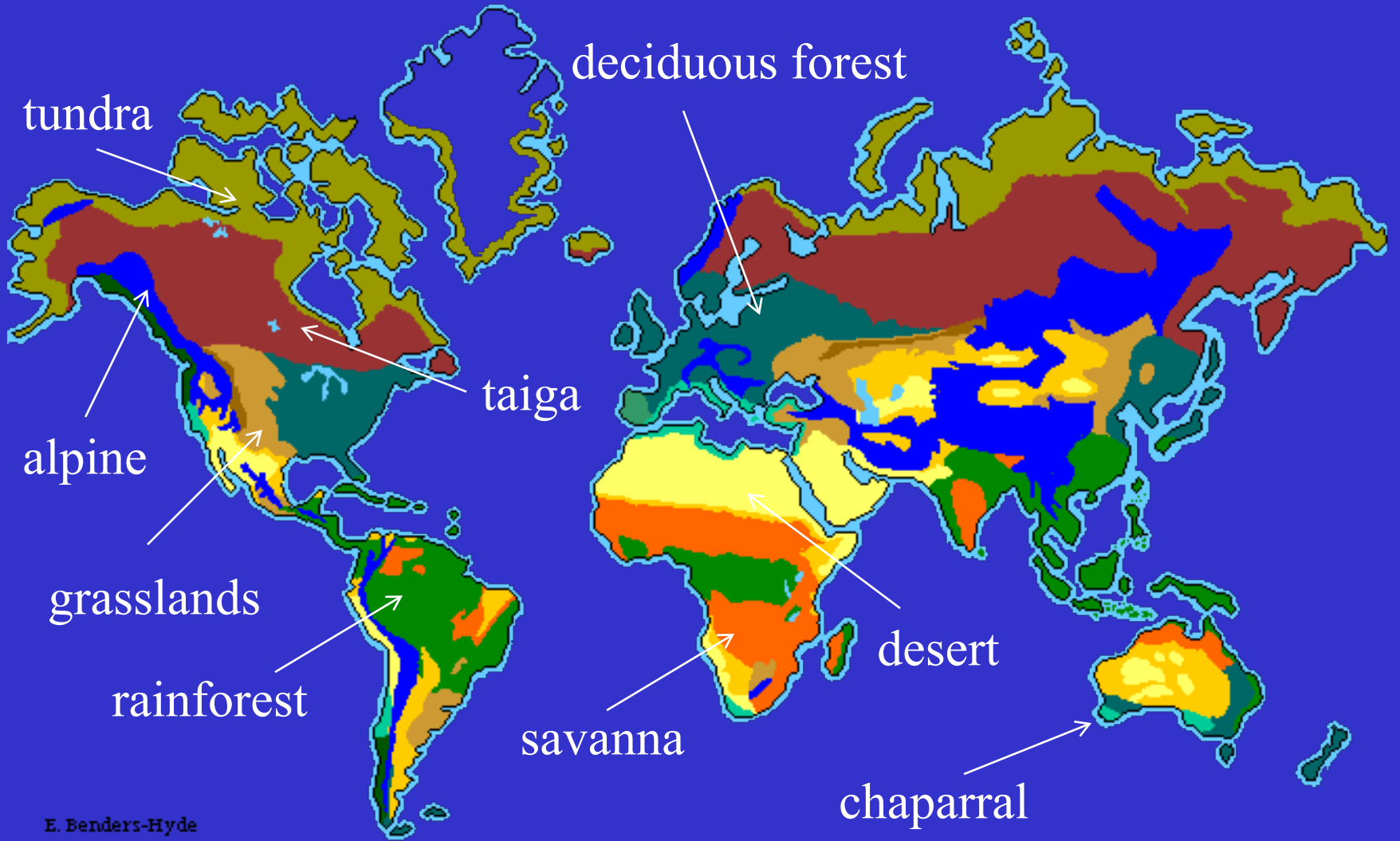
(c) Atacama



(d) Kalahari

Biomes (regions with distinct types of plants) can tell us something important about climate!

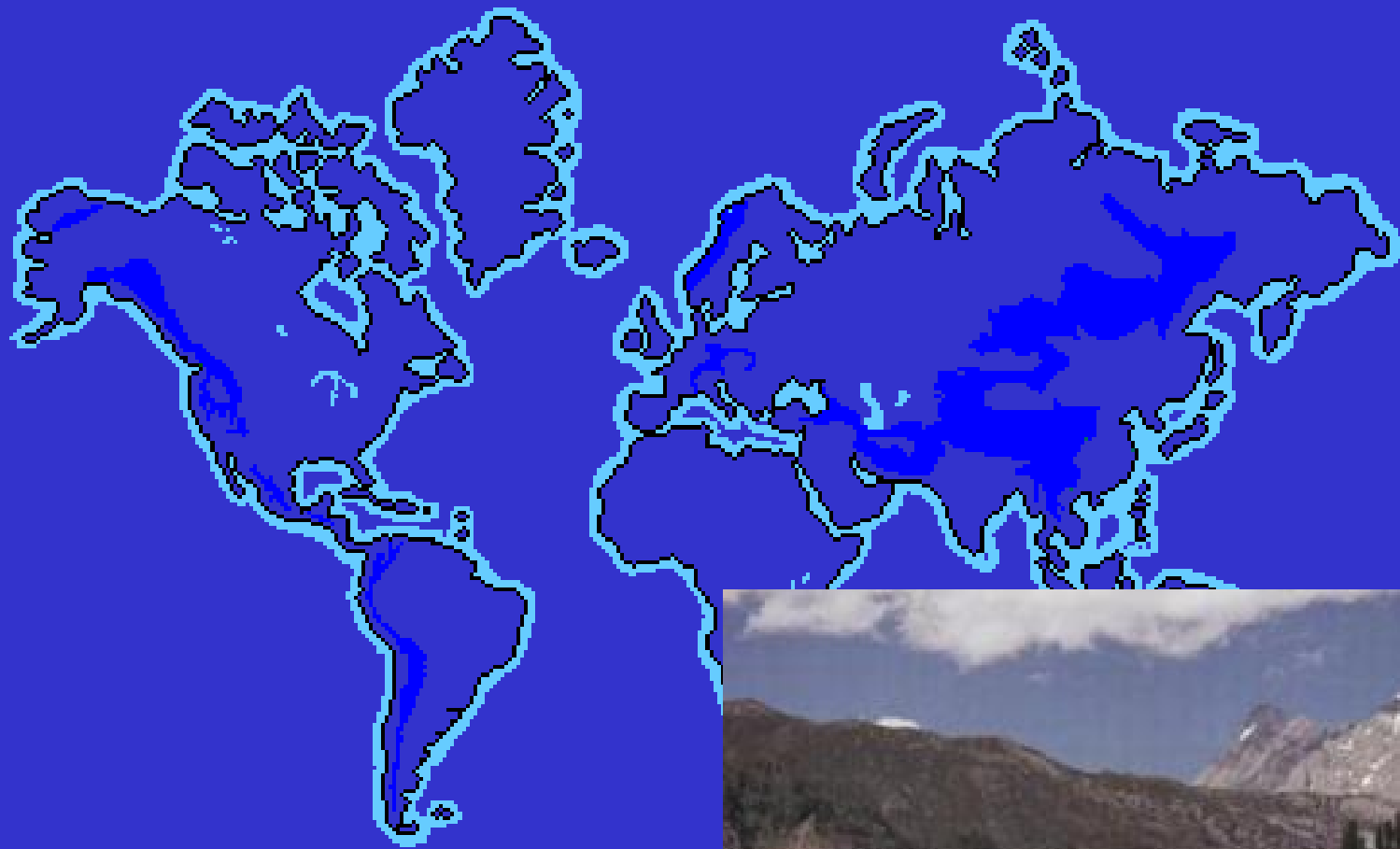
Fig. 4.27



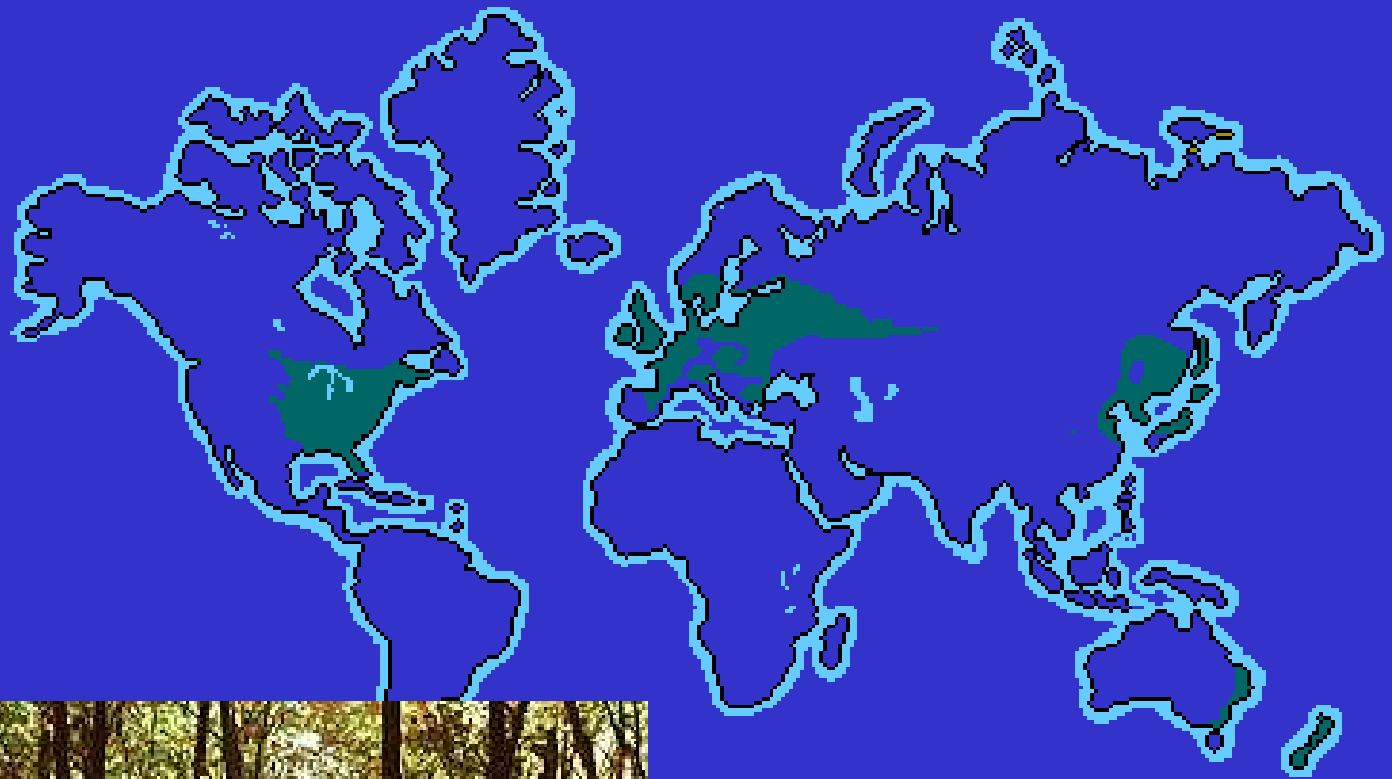


chaparral





alpine



deciduous forest



savanna





desert





taiga



# What do clouds do?

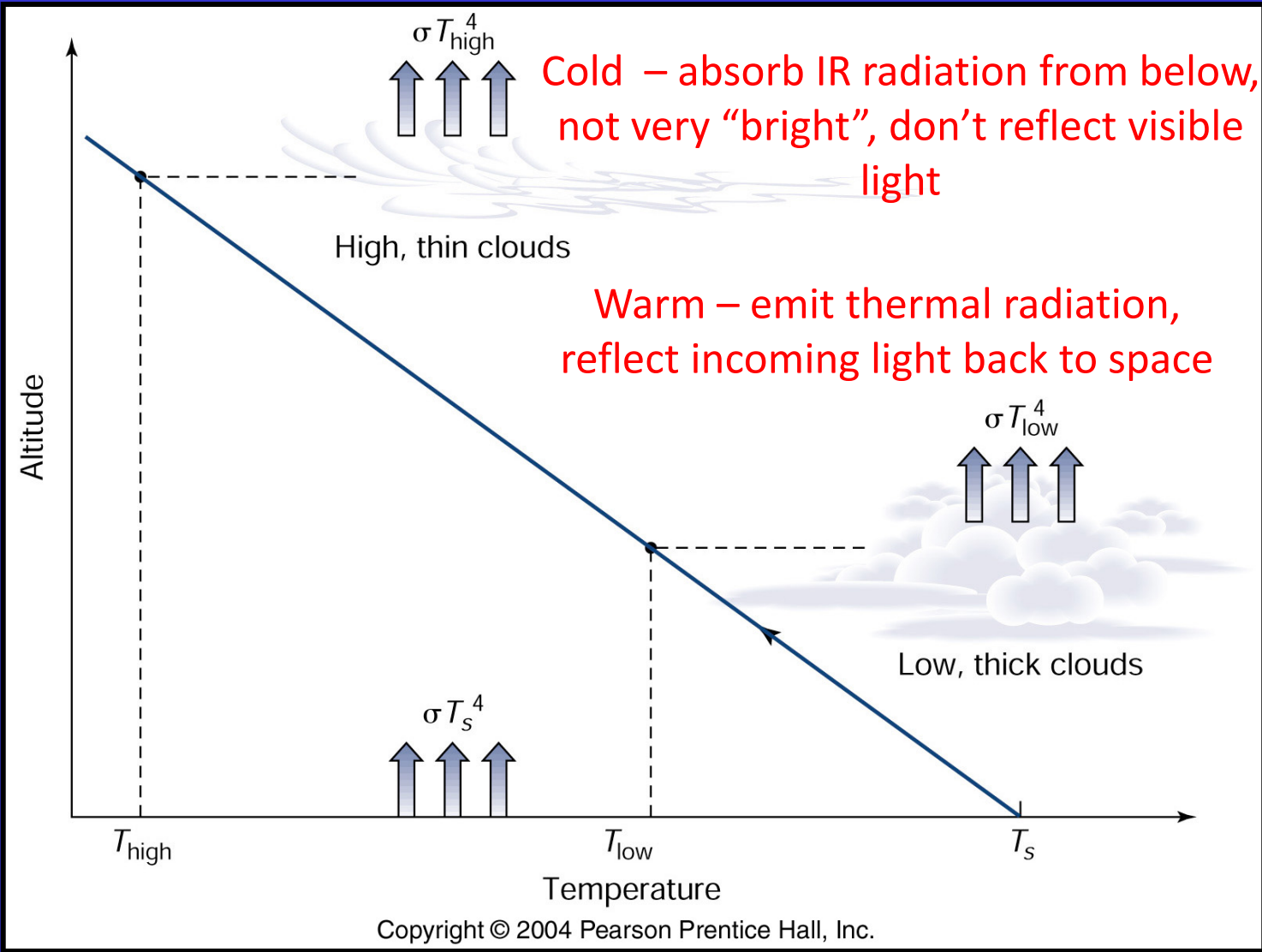


Fig. 3.18

It depends!

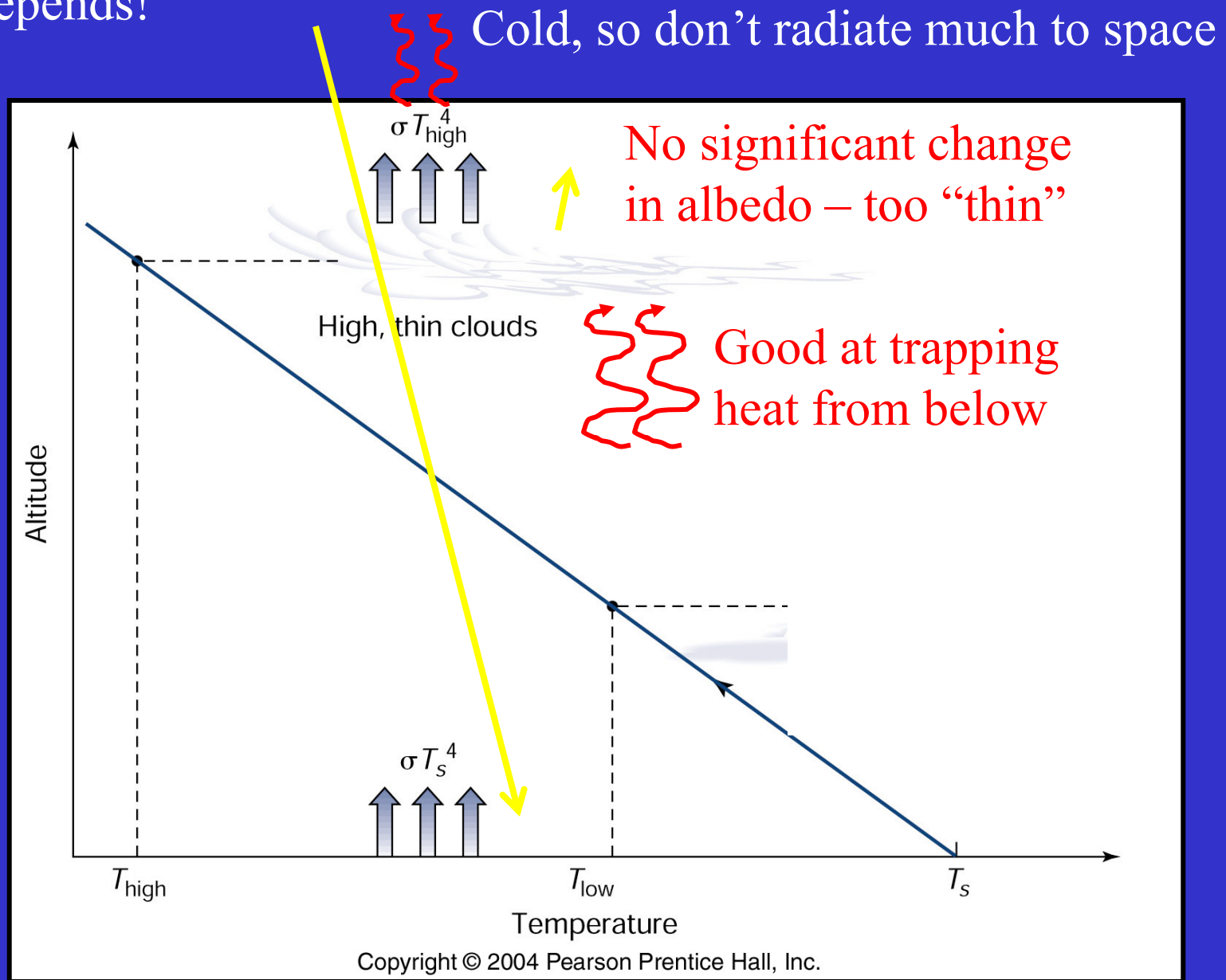
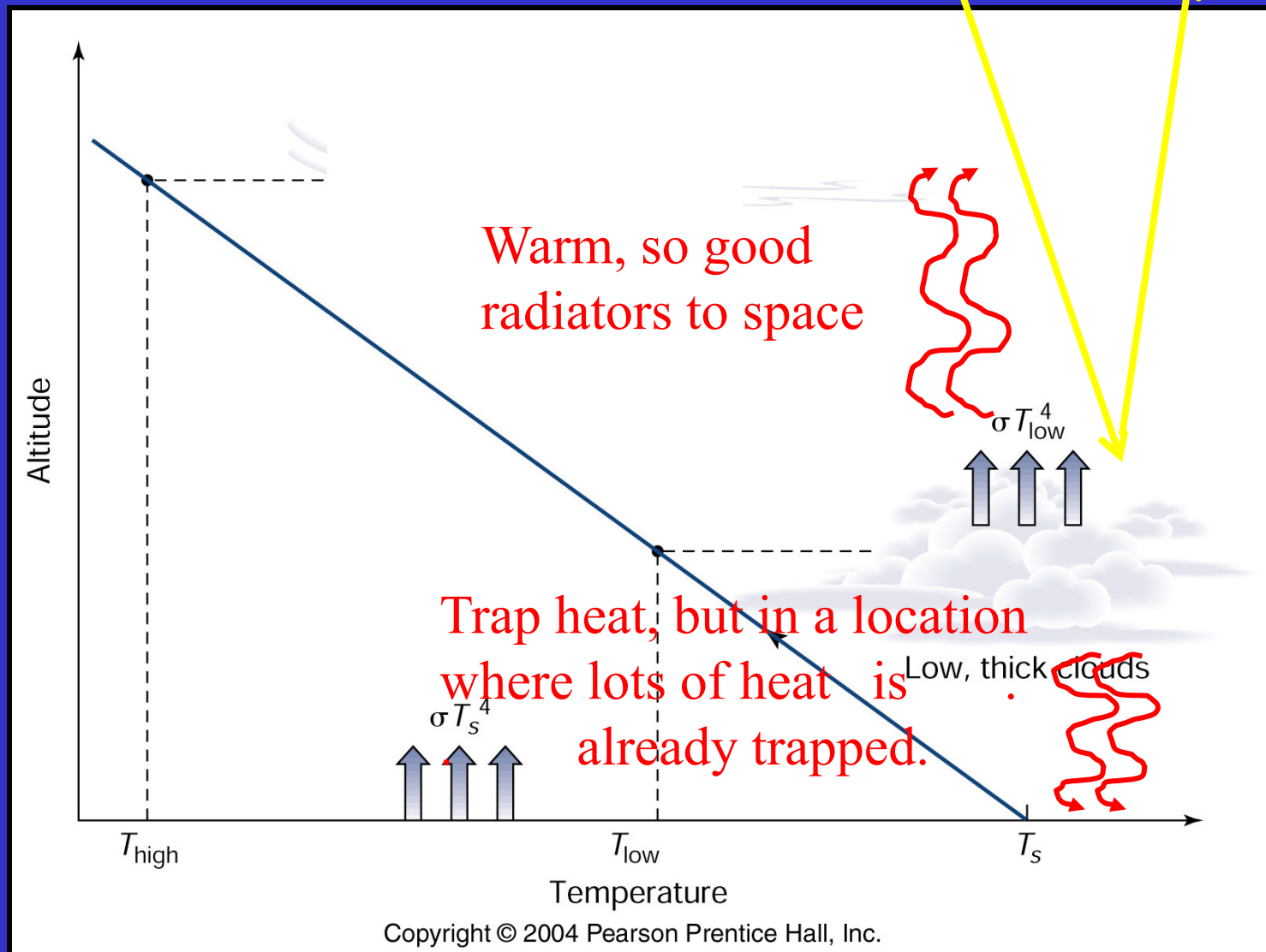


Fig. 3.18

Low, warm, thick clouds

Increase albedo



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Fig. 3.18



## Asynchronous

### Why does Earth have seasons?

Watch this video clip, and be prepared to be surprised. You might be thinking the same wrong answer as some Harvard students!

<https://ed.ted.com/on/xKxsSA5w>

Still think Earth has seasons because it gets closer and farther from the Sun (i.e., during summer Earth is closer to the Sun and during winter Earth is farther from the Sun?). Don't worry, you aren't alone! But you are wrong.

<http://sciencenetlinks.com/student-teacher-sheets/misconceptions-about-why-seasons-occur/>

# We need to remember that seasons affect the general circulation

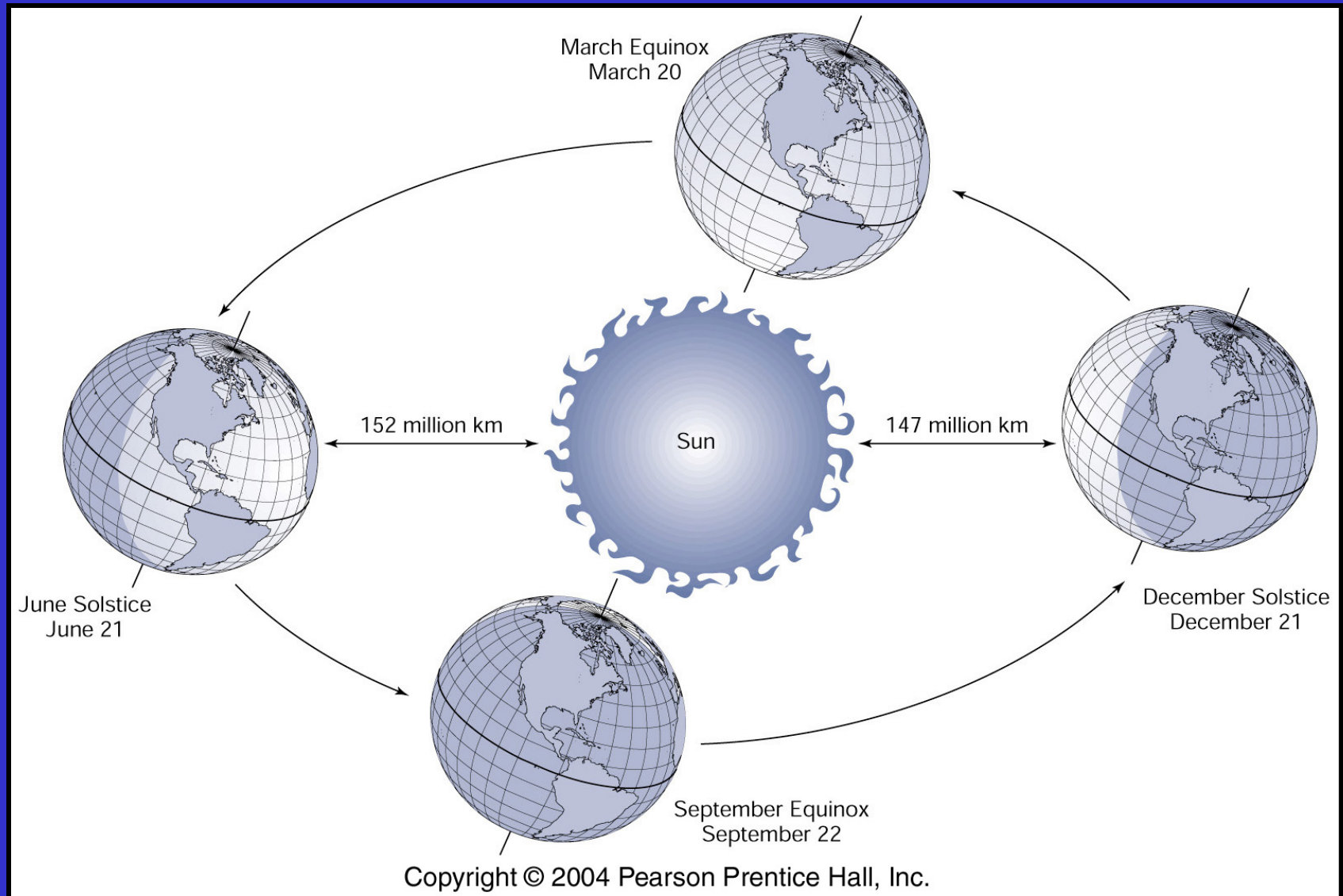


Fig. 4.15

Note that Earth is farther from the Sun during the summer for those of us who live north of the equator (the opposite is true south of the equator)?

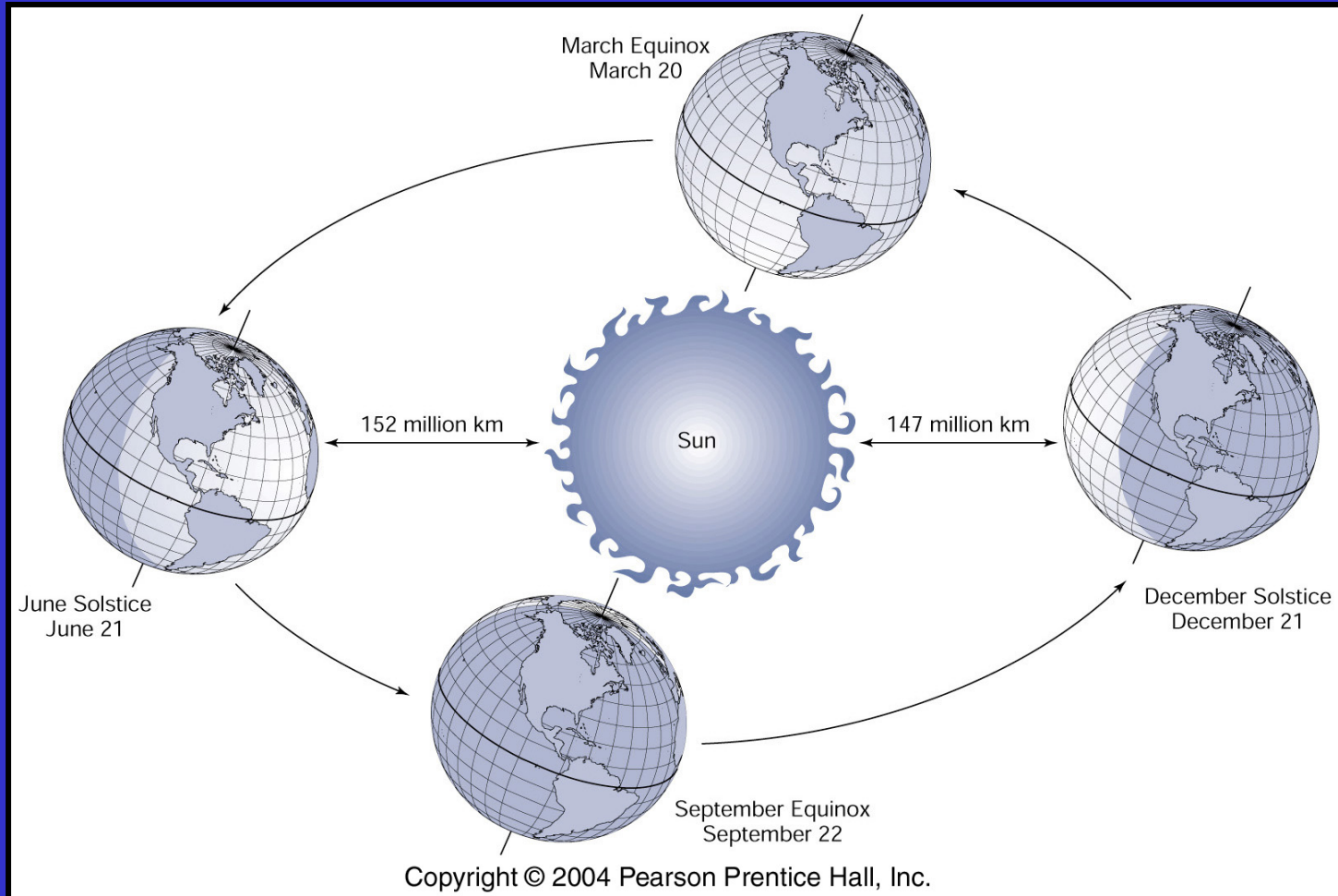
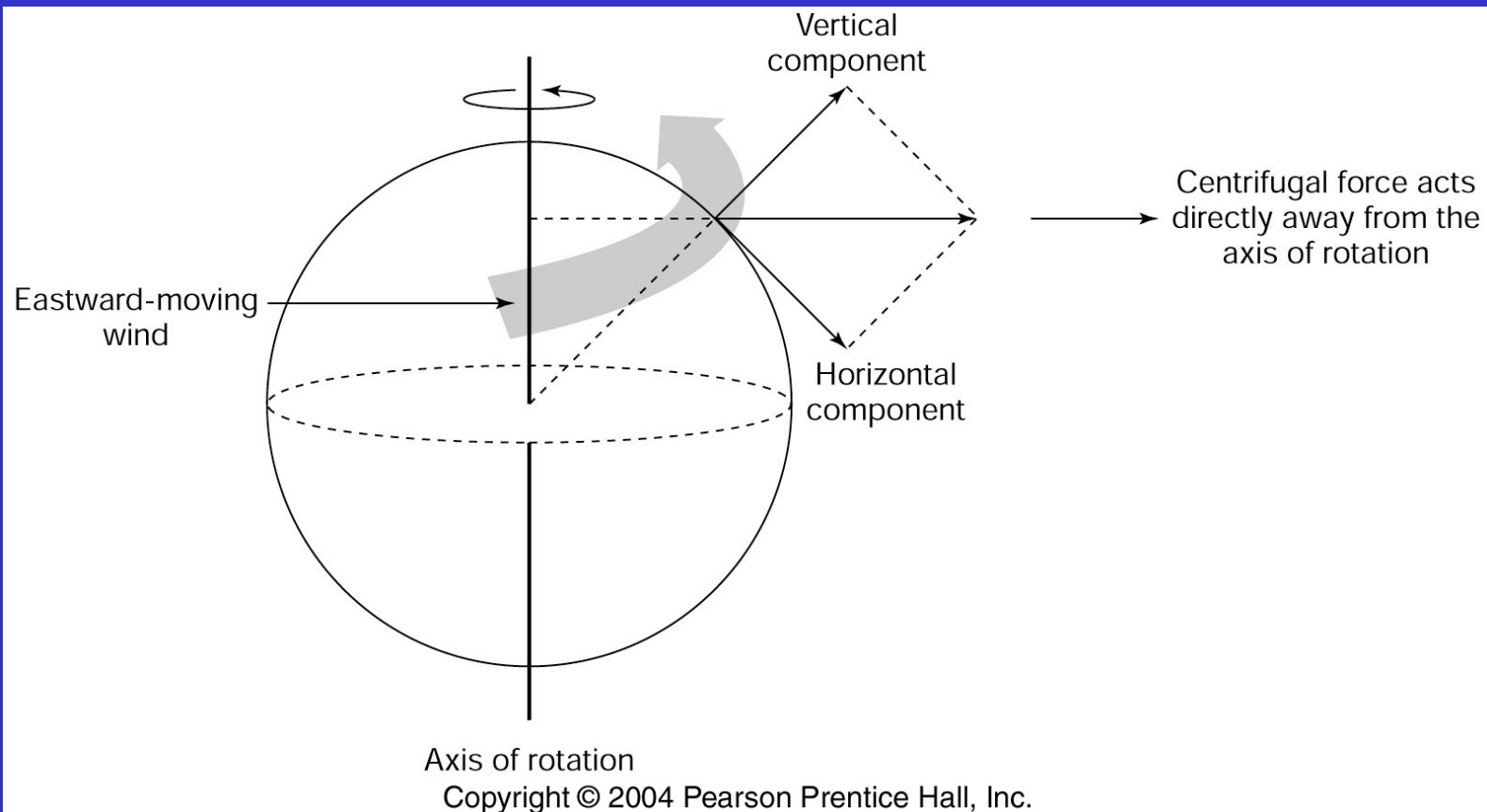


Fig. 4.15

The coriolis effect works in three dimensions – like a vector, or a “force”. We have to deal with the horizontal component of that force. The vertical can’t do much working against the much larger vertical force of gravity.

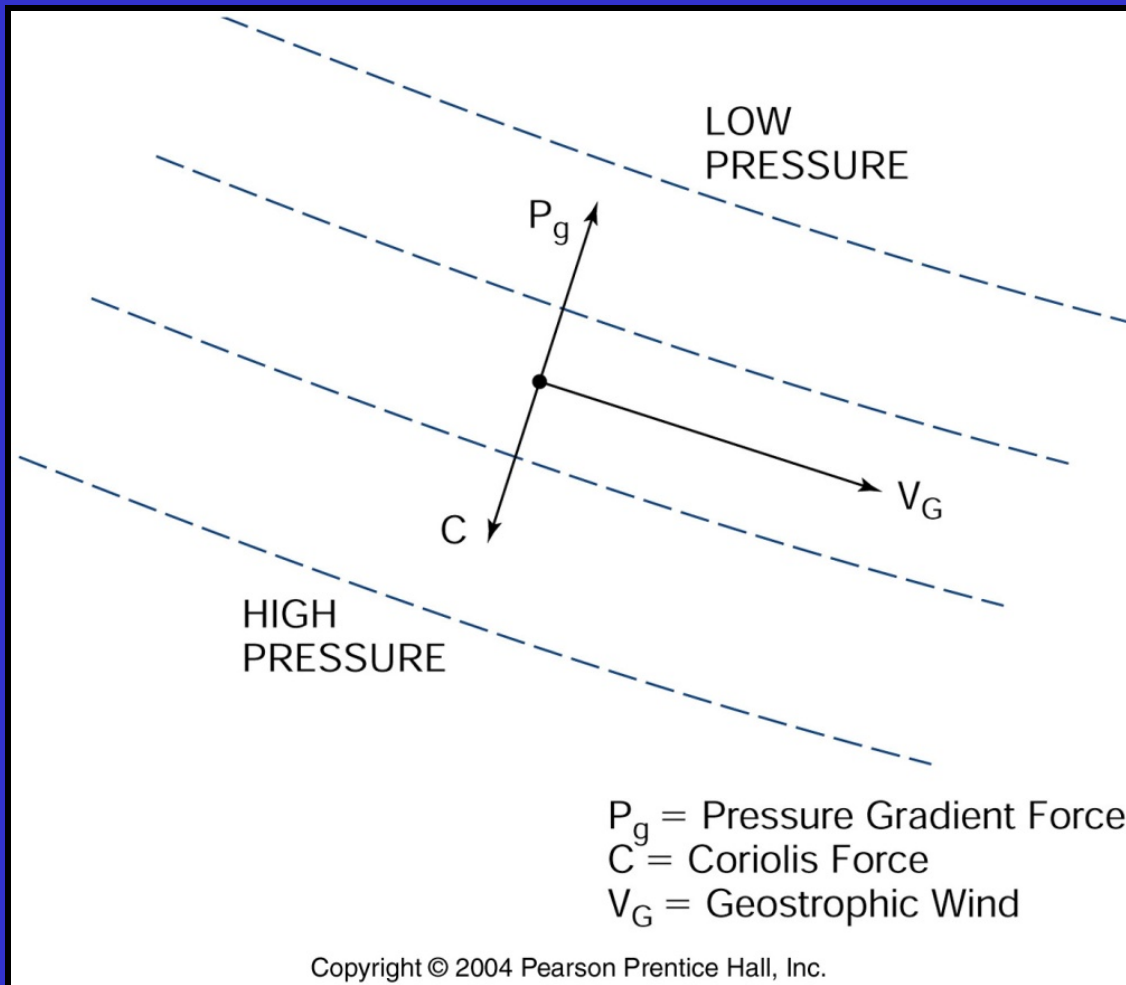


## Asynchronous The Geostrophic Wind

At mid and high latitudes, the coriolis effect is larger than it is in the tropics (in fact, in the tropics it is very small). Air will move if subjected to a force. Therefore, it will respond to both differences in pressure and to the coriolis “force”. Because air experiences very little friction, it will eventually travel in a direction where the two forces cancel. This direction ends up being perpendicular to the pressure force. It’s easy to know where way the wind blows simply by noting that in the northern hemisphere, high pressure will be to the right of the wind direction. We call the ‘balanced wind’ the ‘geostrophic wind.’



When winds obey the condition where the pressure force balances the coriolis force, we call it “geostrophy”. At high latitudes, winds are usually nearly geostrophic, in that the air travels in a direction perpendicular to the pressure force.



However, friction causes the true winds to be a little slower than expected, which leads to waves that create moving weather systems (what we often hear called “steering currents” on news reports).

Fig. 4.13

For this class, we will use that the winds are nearly geostrophic, which will allow us to use maps of pressure to estimate the direction of the winds. For predicting weather, this won't be perfect (in fact, the deviations from geostrophic balance are responsible for changes in the weather). However, for climate and trends, assuming winds are geostrophic will be quite useful.

We will look for droughts in places where surface pressure tends to be high. We'll look for rain or snow where surface pressures are low, and we'll look for fronts to move in the direction of geostrophic winds – winds that, in the northern hemisphere, maintain high pressure to the right of the wind direction.

This approach will tell us a lot about climate zones – places on earth where certain types of biomes occur. It will also tell us the directions of the major ocean gyres!