Chapter 7

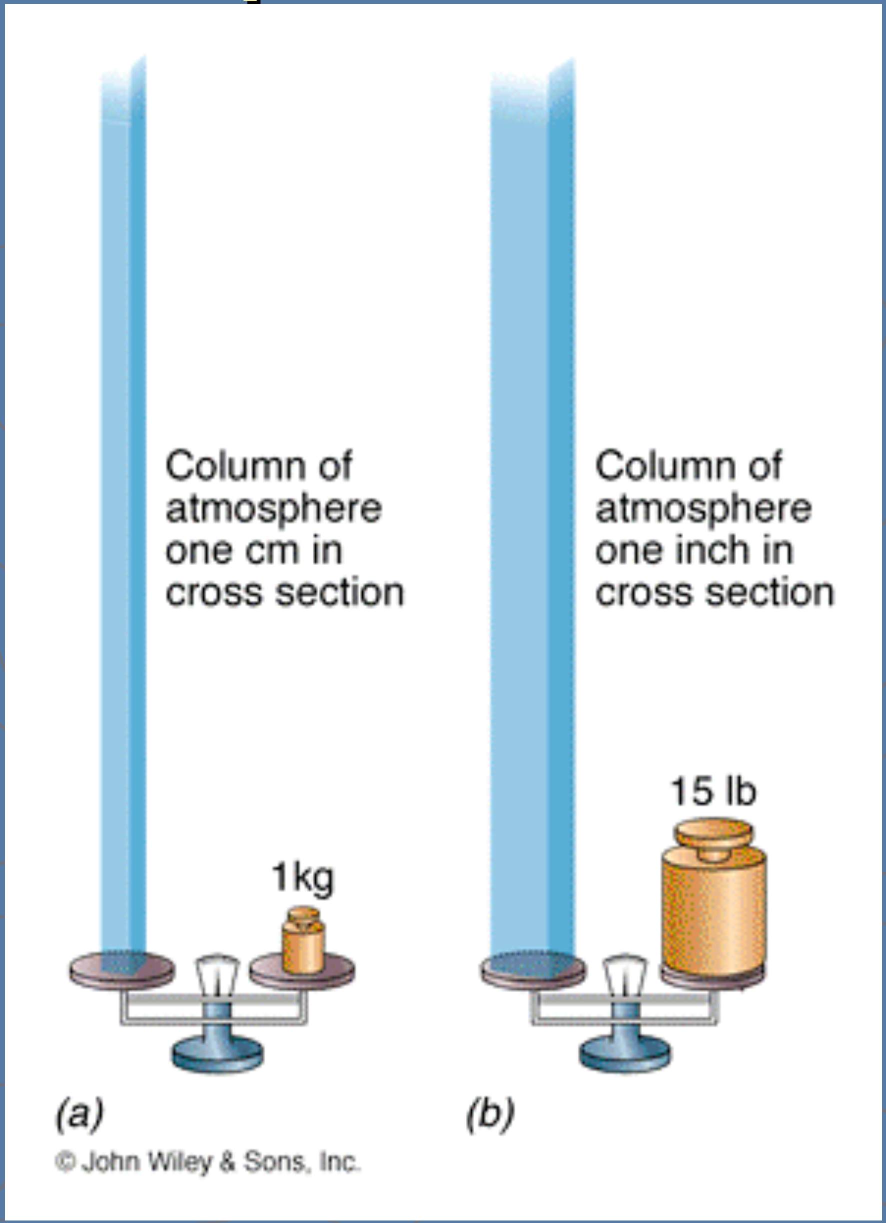
Winds and the Global Circulation System

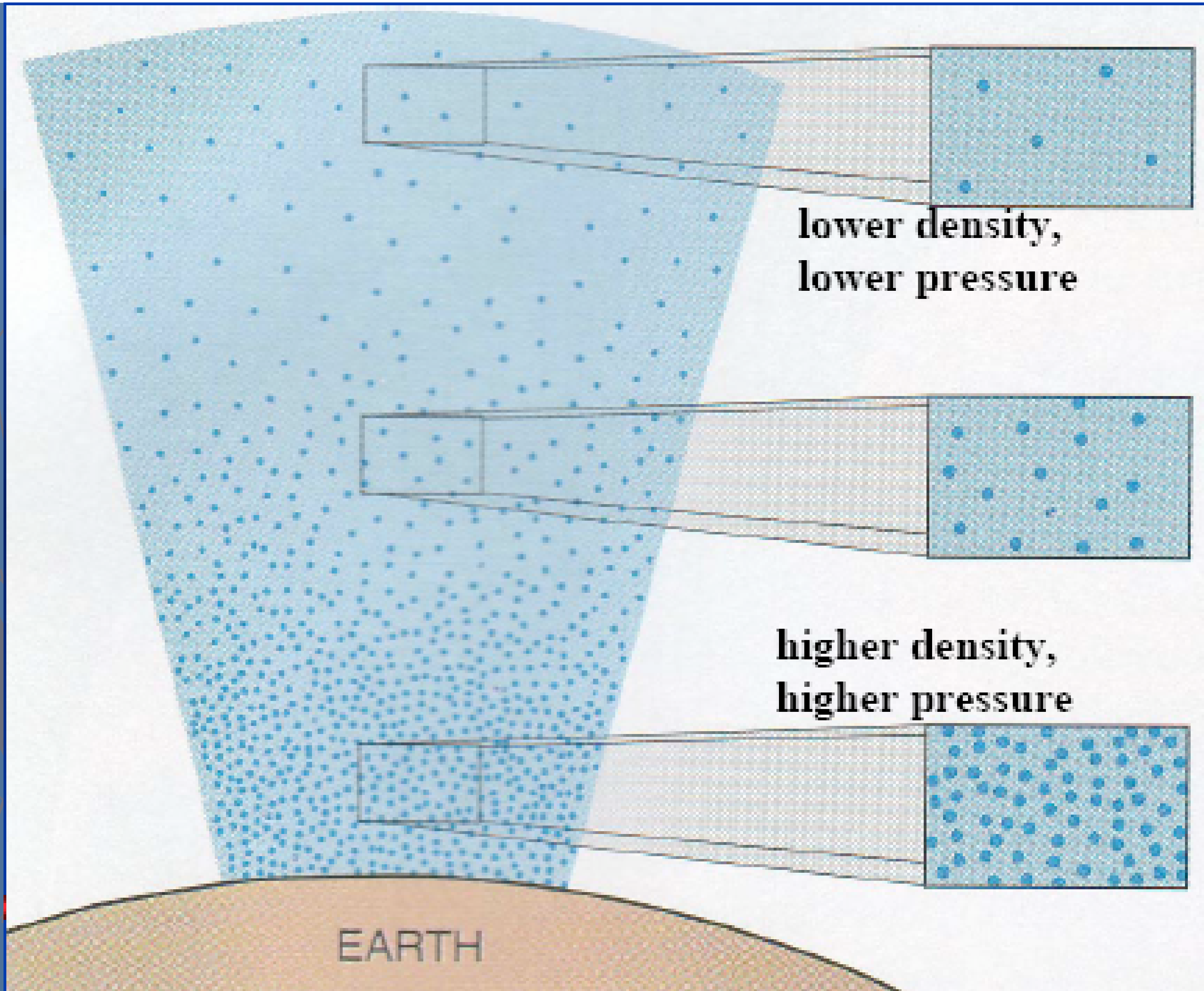
What is atmospheric pressure?

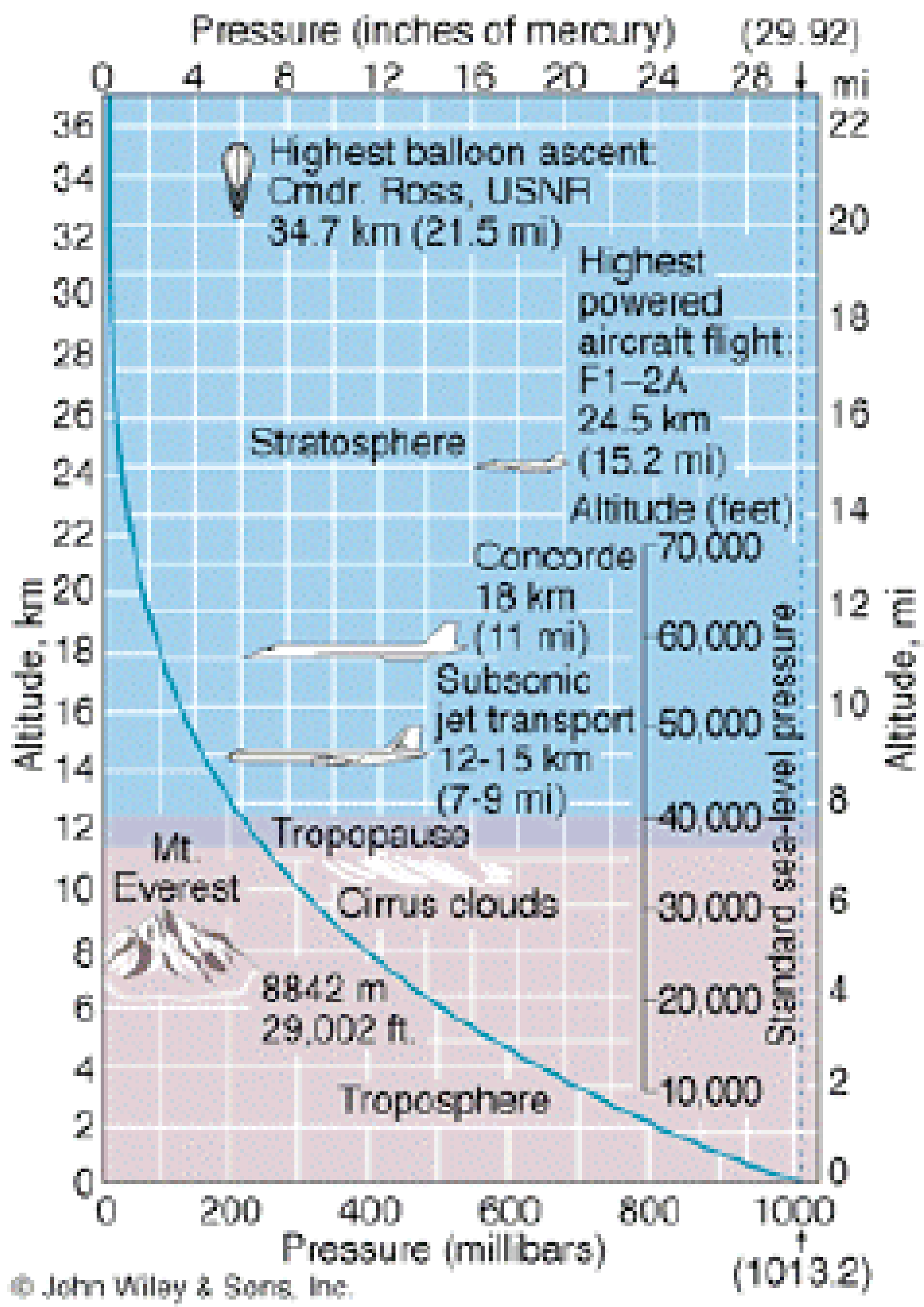
Atmospheric Pressure

- We live at the bottom of an ocean of air
- Since this air has mass, it will exert pressure on the surface below it
- The more air, the greater the pressure – thus, pressure decreases with altitude
- Air is easily compressible – thus, its density decreases with altitude

Atmospheric Pressure




lower density,
lower pressure
higher density,
higher pressure
EARTH



-The density of the atmosphere decreases with height, therefore the force (pressure) of the overlying atmosphere also decreases

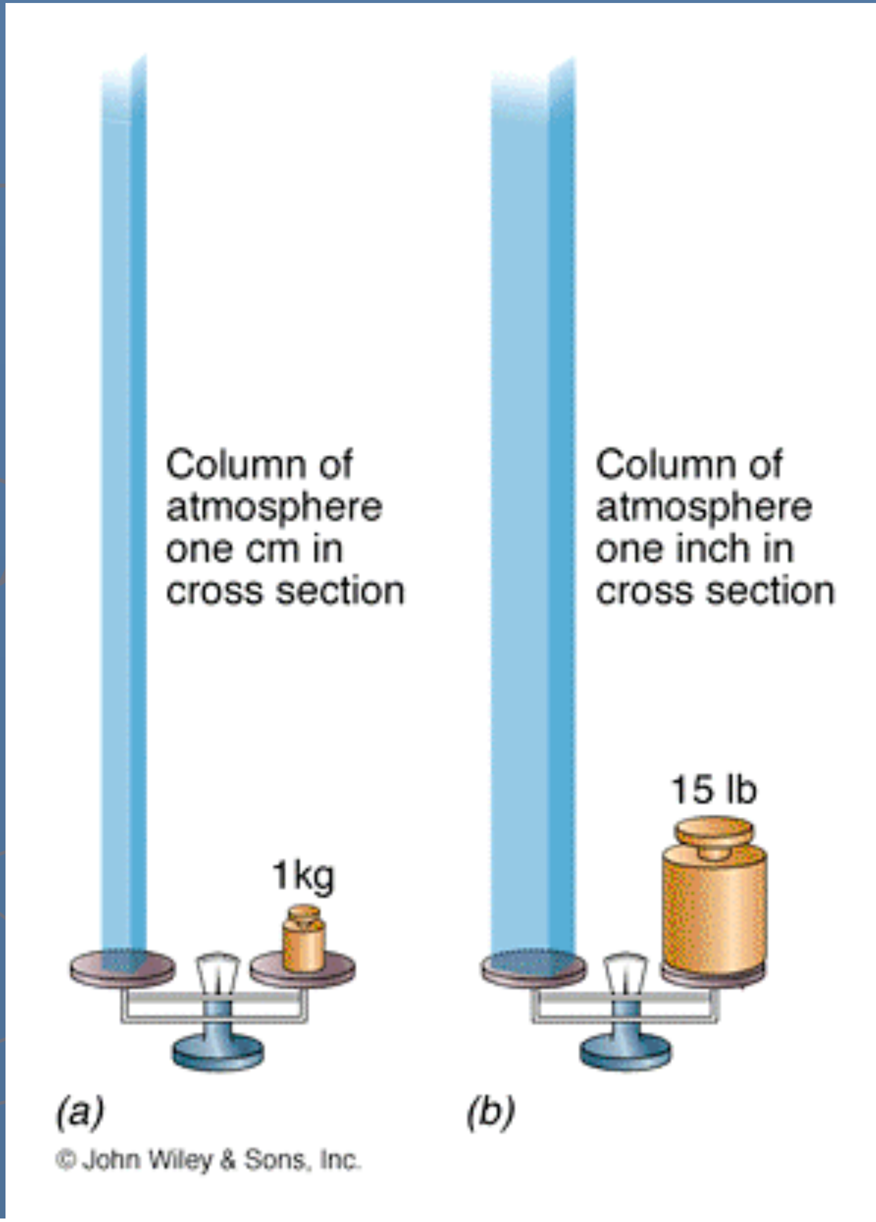
-Half of the molecules are held within 5.5 km of the surface

What determines atmospheric pressure?

Atmospheric Pressure

-Pressure = force per unit area

-Due to gravity the atmosphere exerts a force



- According to the Ideal Gas Law: density (ρ) and temperature (T) control atmospheric pressure (P)

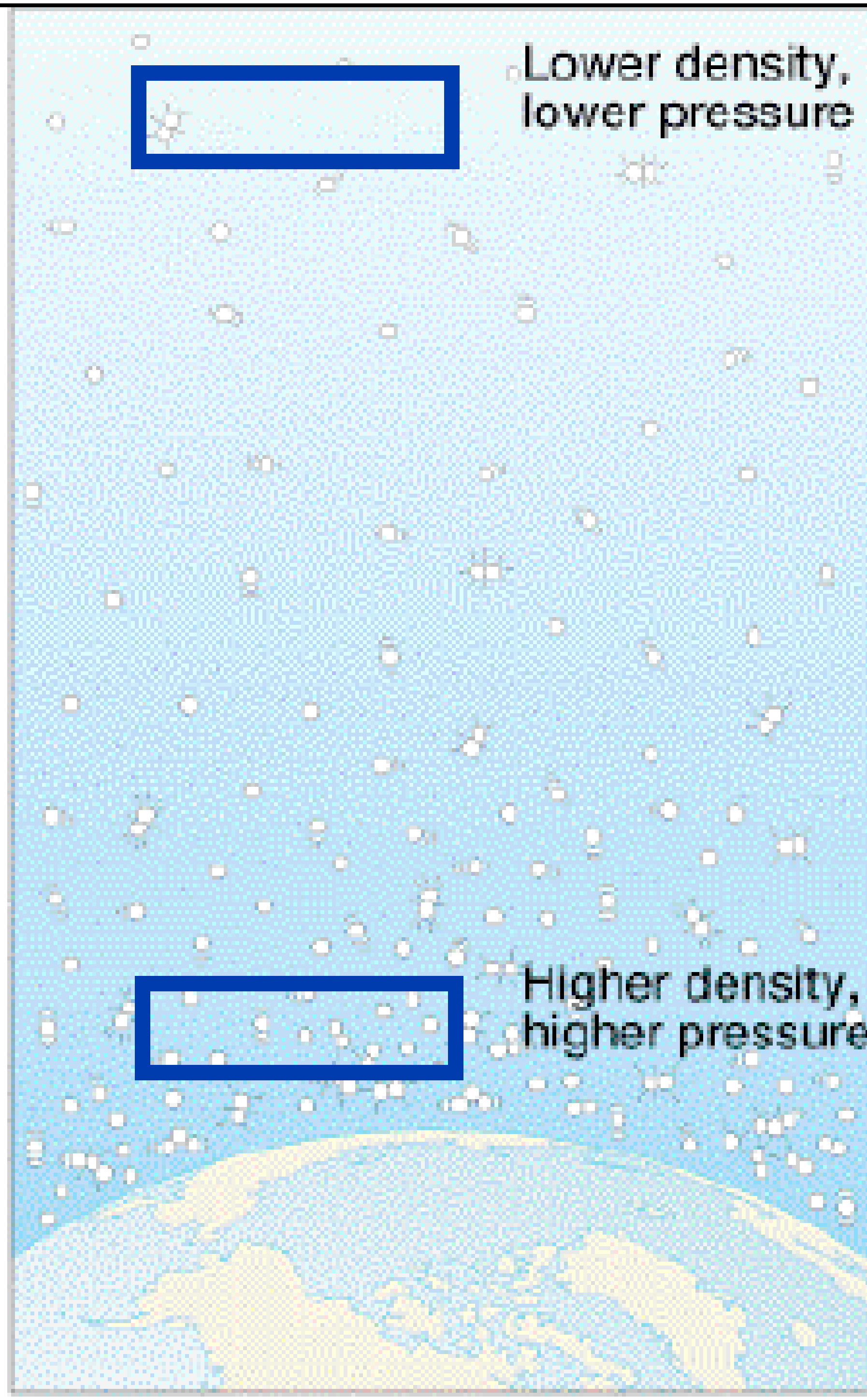
$$P = \rho RT$$

R = a constant

Pressure, Density & Temperature

Density (ρ)

- Amount of matter (mass) per unit volume (kg/m^3)
- Density (of a gas) is directly proportional to pressure
- Density varies with altitude


Lower density,
lower pressure
Higher density,
higher pressure

Pressure, Density & Temperature

Temperature (T)

- Molecules move faster in hot air than cold air
- Faster = more collisions (more force) and therefore higher pressure
- Temperature is directly proportional to pressure

Pressure, Density & Temperature

- In the atmosphere density and temperature do not change independently

Example:

When air in the atmosphere is heated it expands and causes a decrease in density and pressure

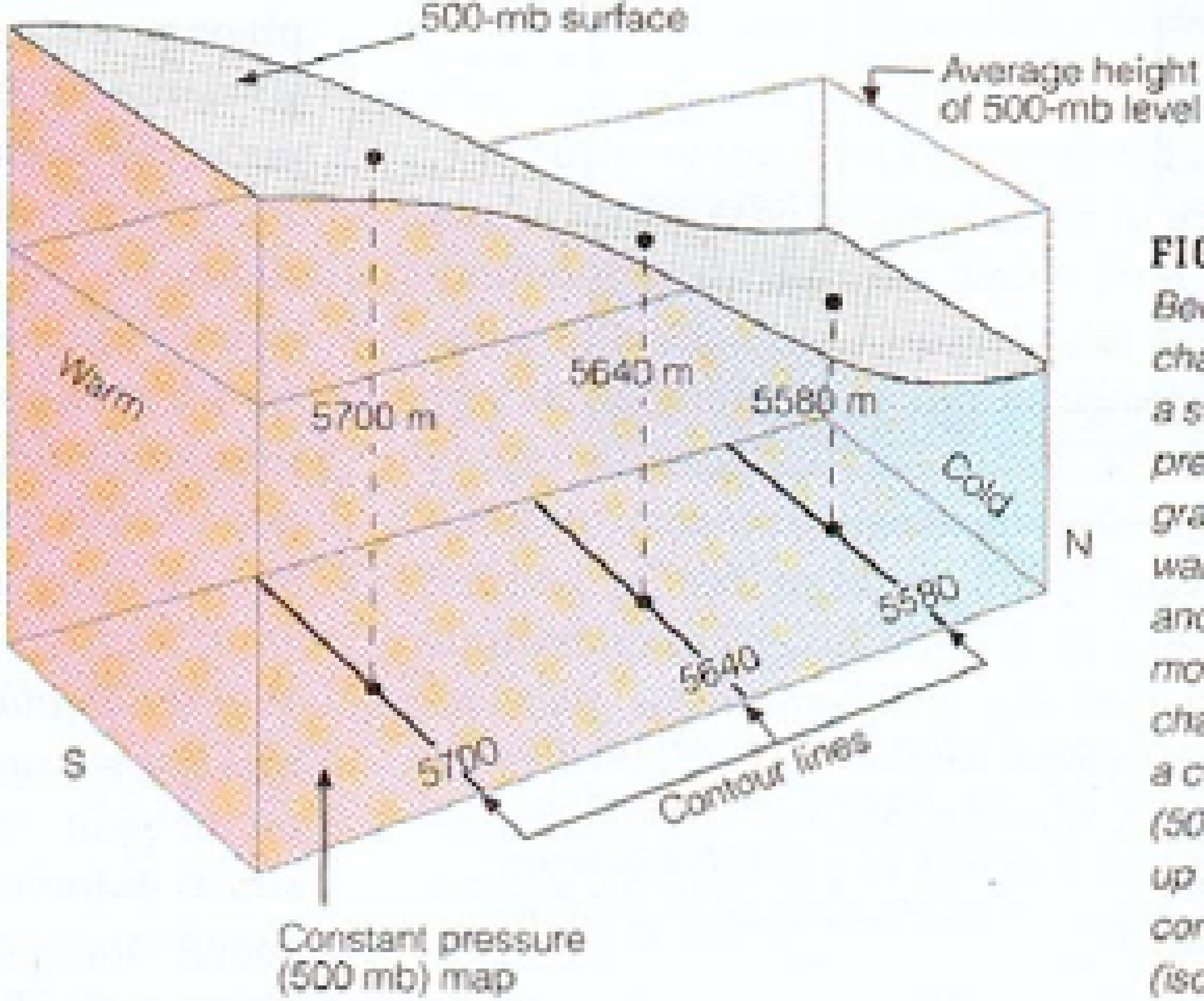


FIGURE 2
Because of the changes in air density, a surface of constant pressure (the shaded gray area) rises in warm, less dense air and lowers in cold, more dense air. These changes in elevation of a constant pressure (500-mb) surface show up as contour lines on a constant pressure (isobaric) 500-mb map.

How is atmospheric pressure measured?

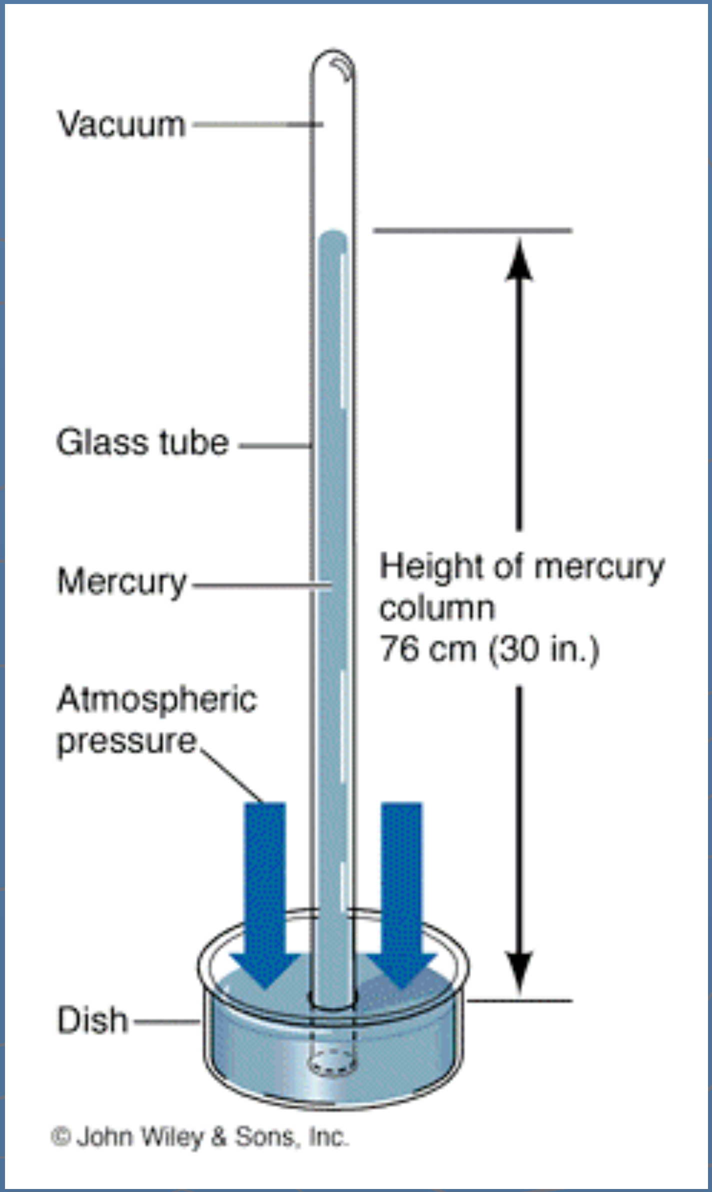
Atmospheric Pressure

- Atmospheric pressure is often measured in millibars (mb)
- Atmospheric pressure at sea level is 1013.25 millibars (standard pressure)
- At the earth's surface, pressure varies from 980 mb to 1030 mb (about 5%)

Atmospheric Pressure

- Atmospheric pressure is measured using and instrument called a barometer
- A mercurial barometer measures atmospheric pressure with a column of mercury
- Sea-level pressure also can be defined as 29.92 inches of mercury (in. Hg)

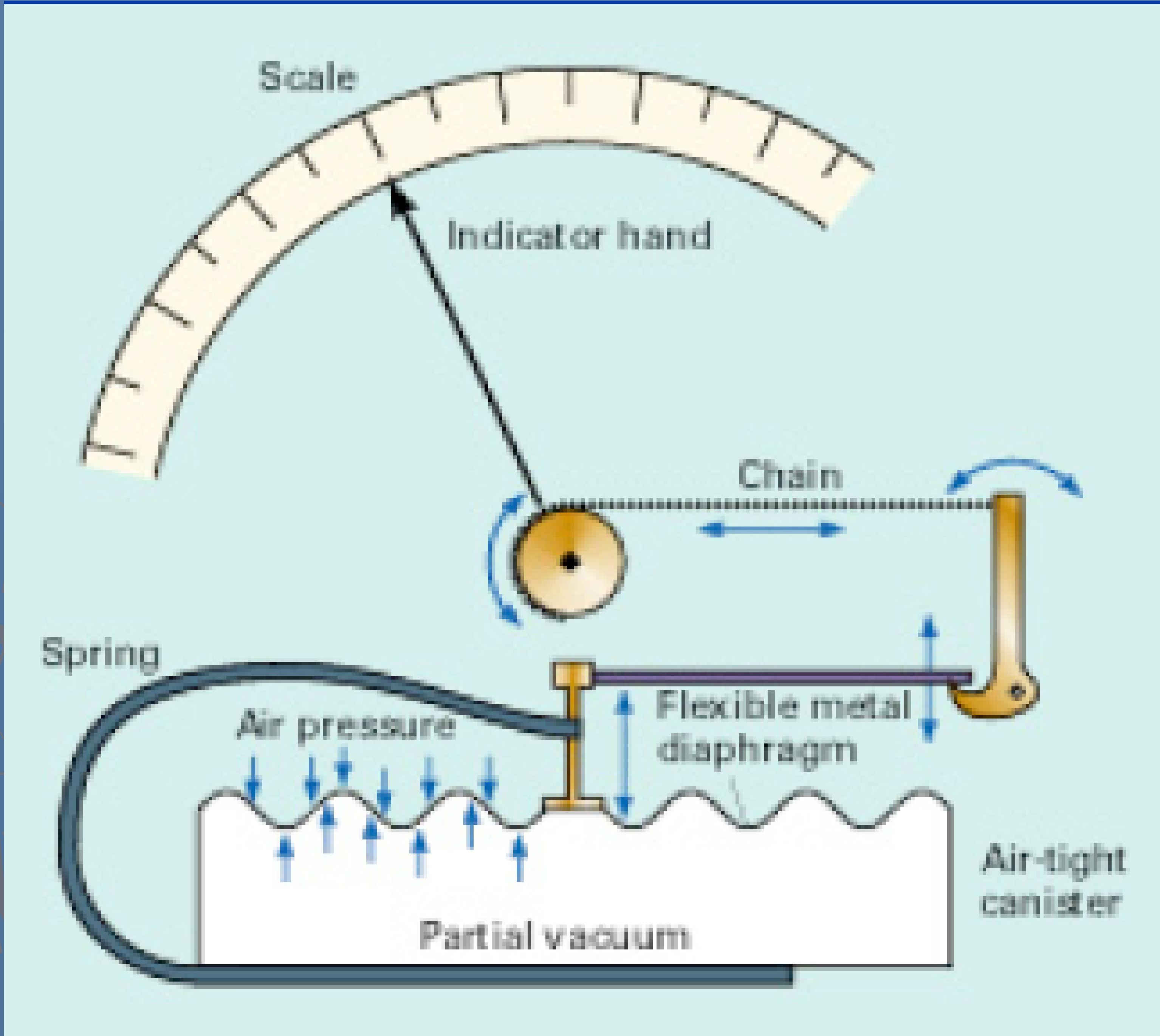
A Mercurial Barometer



Atmospheric Pressure

- A more common type of barometer is the ***aneroid barometer***

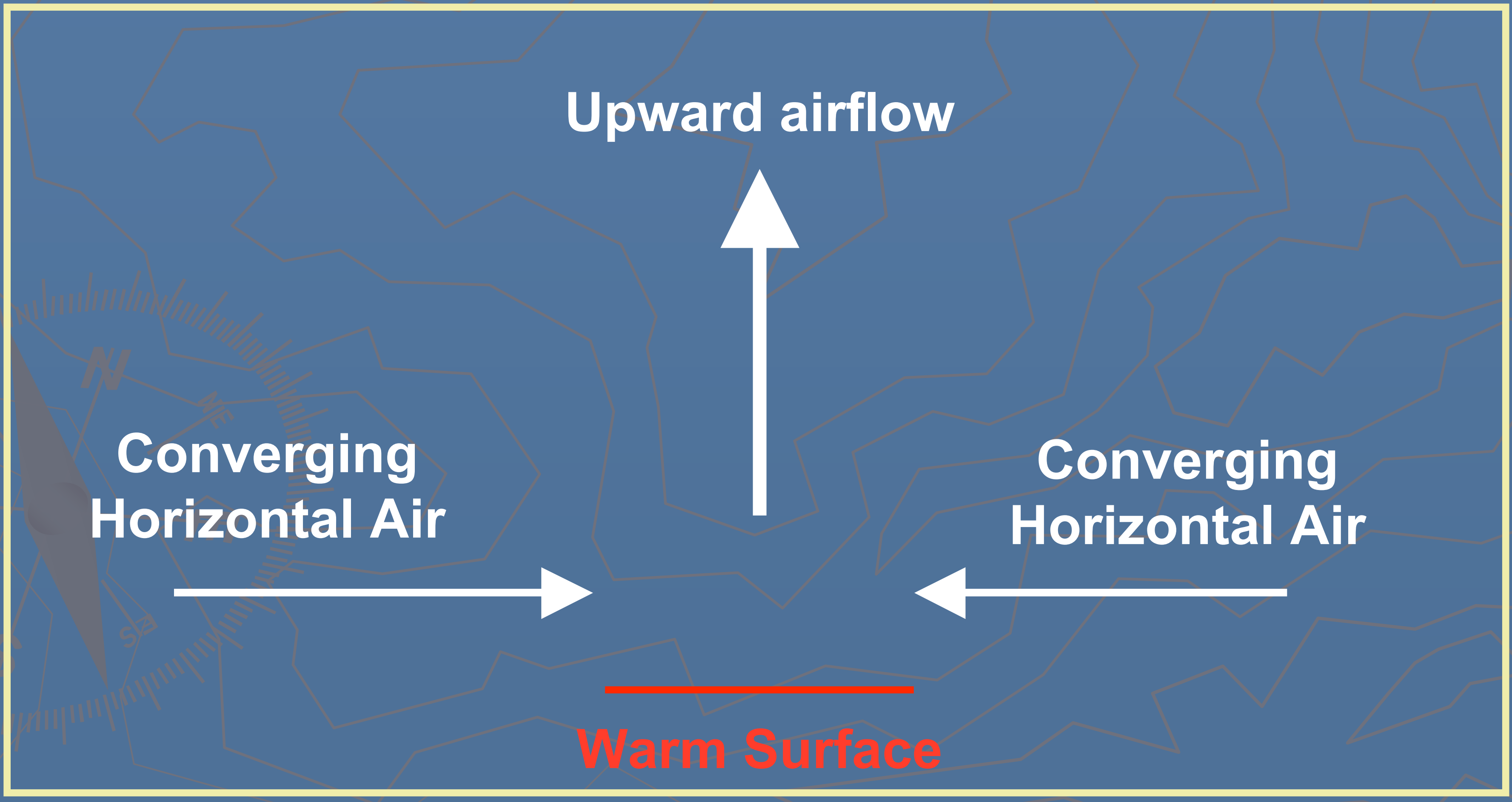
- It uses the pressure exerted against a partial vacuum to measure air pressure


Scale
Indicator hand
Chain
Spring
Air pressure
Flexible metal diaphragm
Air-tight canister
Partial vacuum

What causes differences in pressure?

Surface Heating and Vertical Motion

Warm surfaces encourage upward vertical motion



Temperature Gradient

- Temperature Gradient – variation in air temperature from one place to another
- Warm air is less dense than cold air, so it exerts less pressure than cold air
- Temperature gradients create pressure gradients

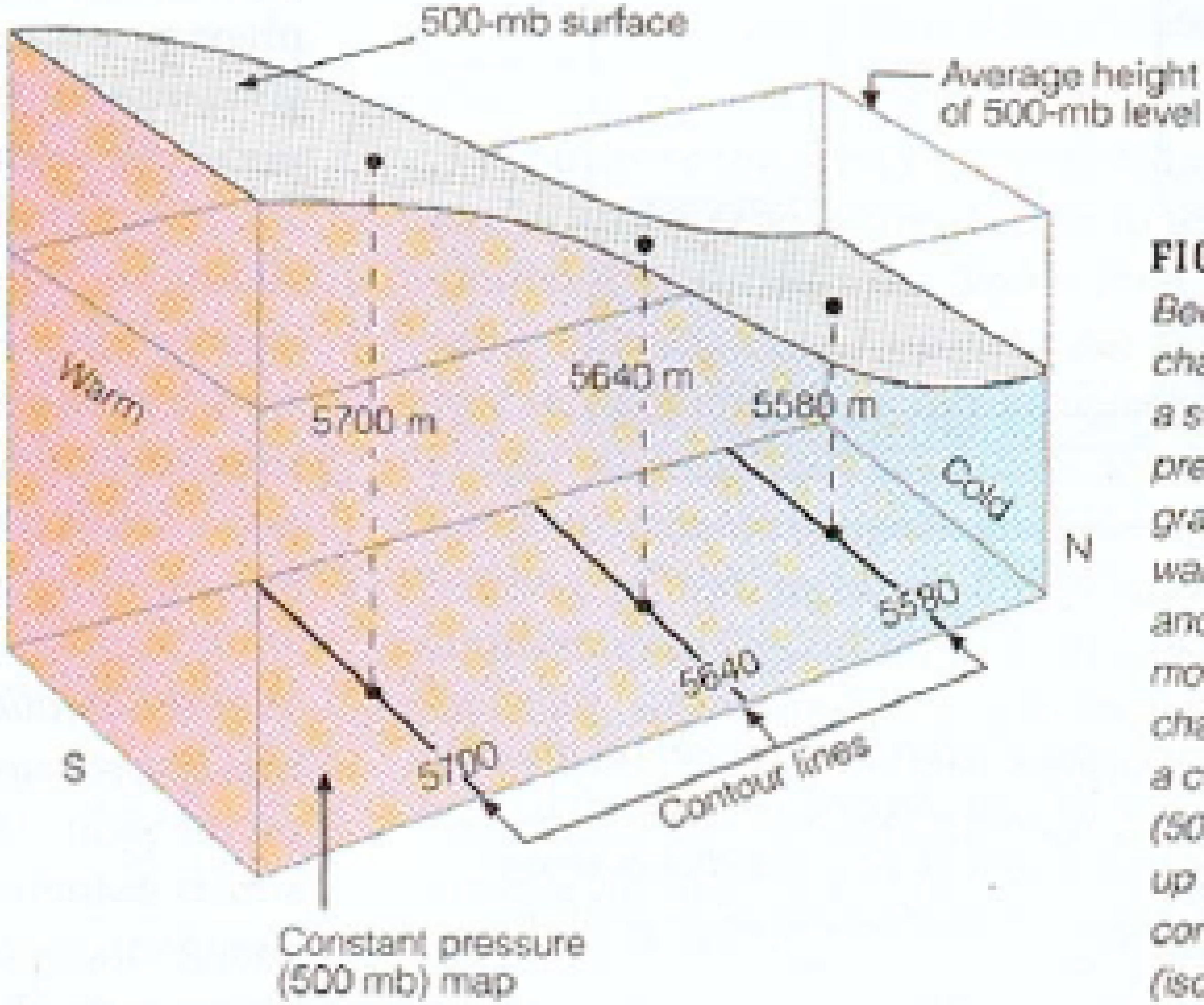
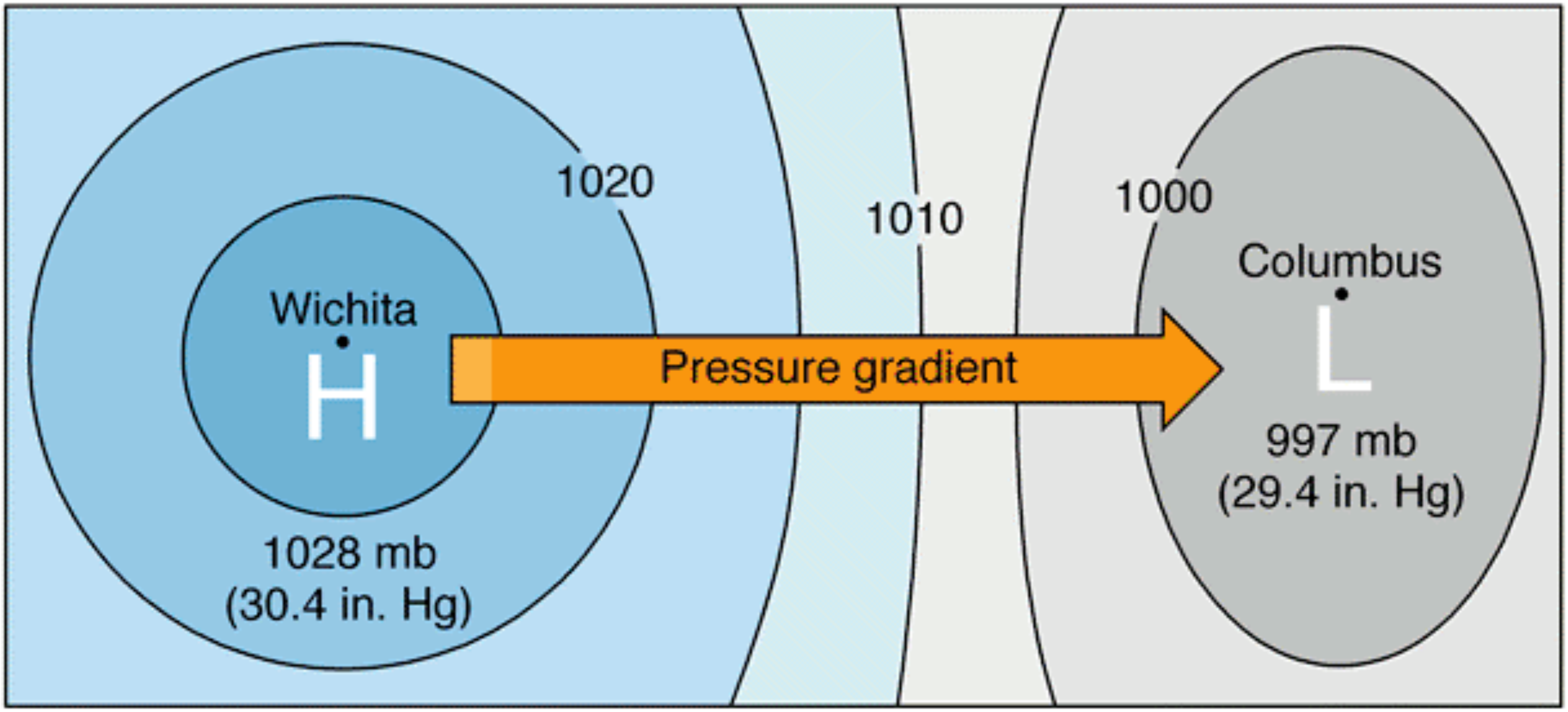


FIGURE 2
Because of the changes in air density, a surface of constant pressure (the shaded gray area) rises in warm, less dense air and lowers in cold, more dense air. These changes in elevation of a constant pressure (500-mb) surface show up as contour lines on a constant pressure (isobaric) 500-mb map.

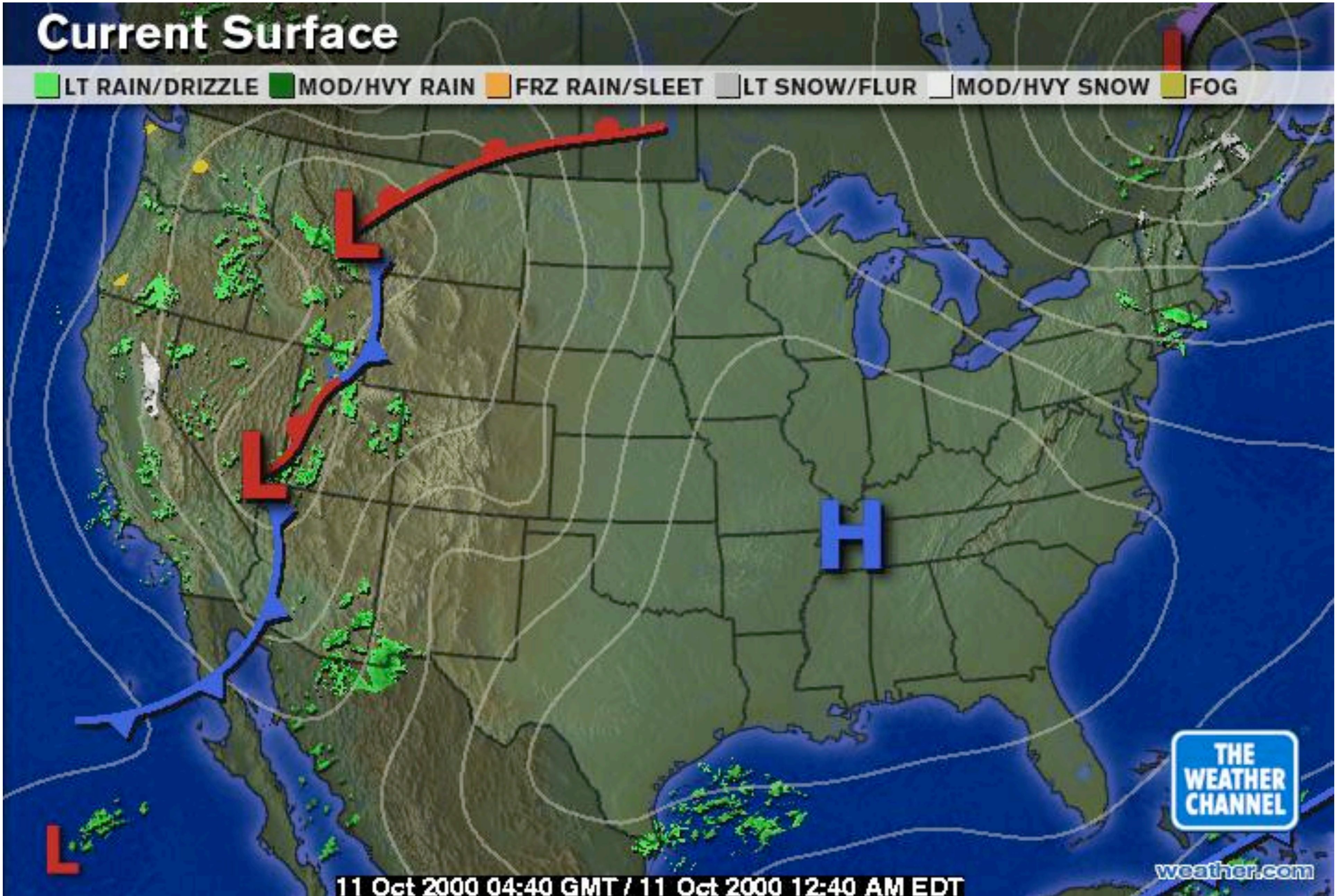
Atmospheric Pressure

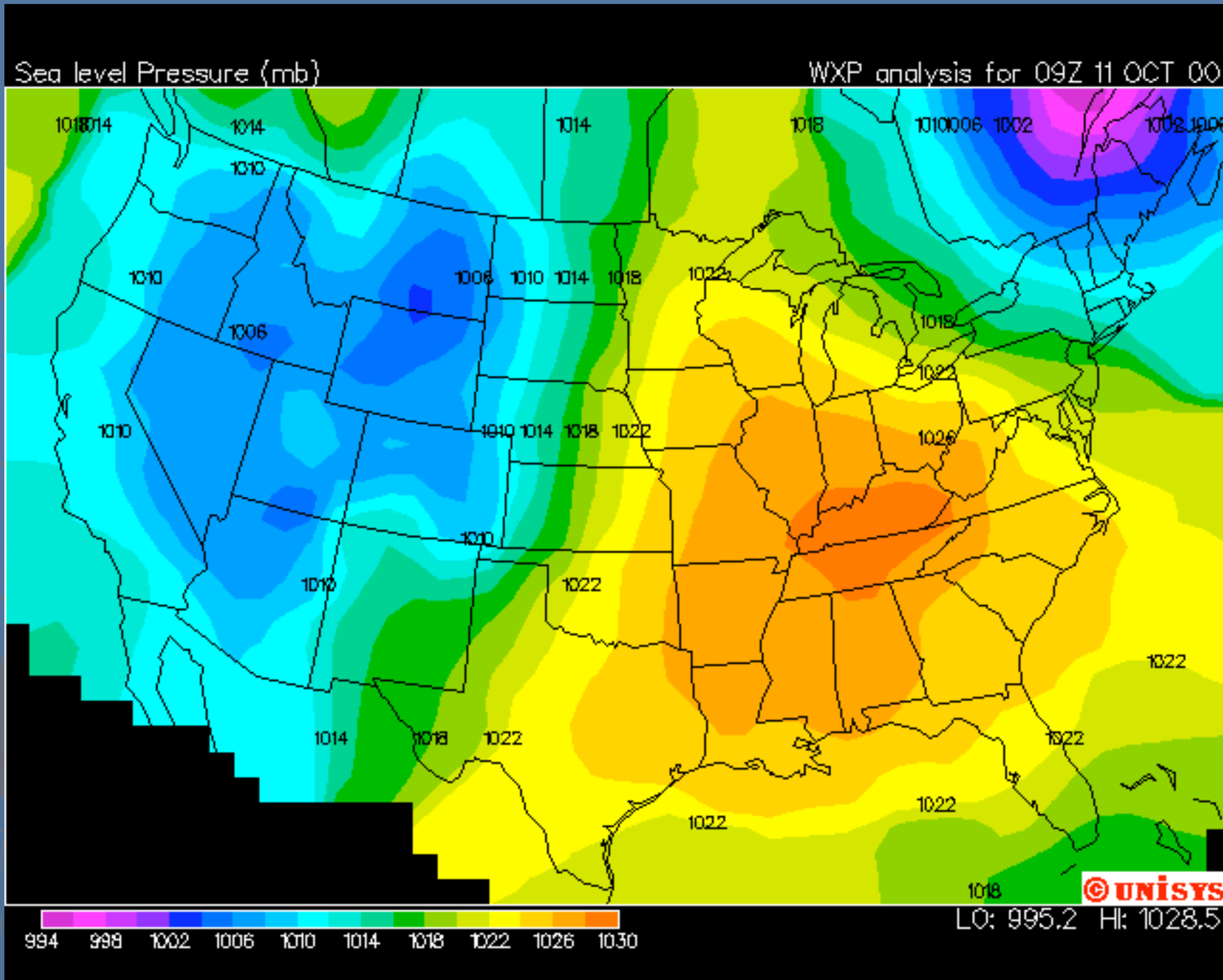
- ***Pressure Gradient*** – variation in atmospheric pressure from one place to another
- In nature, anytime a gradient exists, there will be a force created that attempts to equalize the gradient
- With pressure, we call this gradient the ***Pressure Gradient Force***
- The pressure gradient force always acts in a direction from higher to lower pressure


1020
1010
1000
Wichita
H
1028 mb
(30.4 in. Hg)
Pressure gradient
Columbus
L
997 mb
(29.4 in. Hg)

Atmospheric Pressure

- In the presence of the pressure gradient force, the air will be forced to move – ***wind***
- Winds flow from an area of higher pressure to an area of lower pressure
- ***Isobars*** – lines of constant pressure
- Winds usually flow across isobars

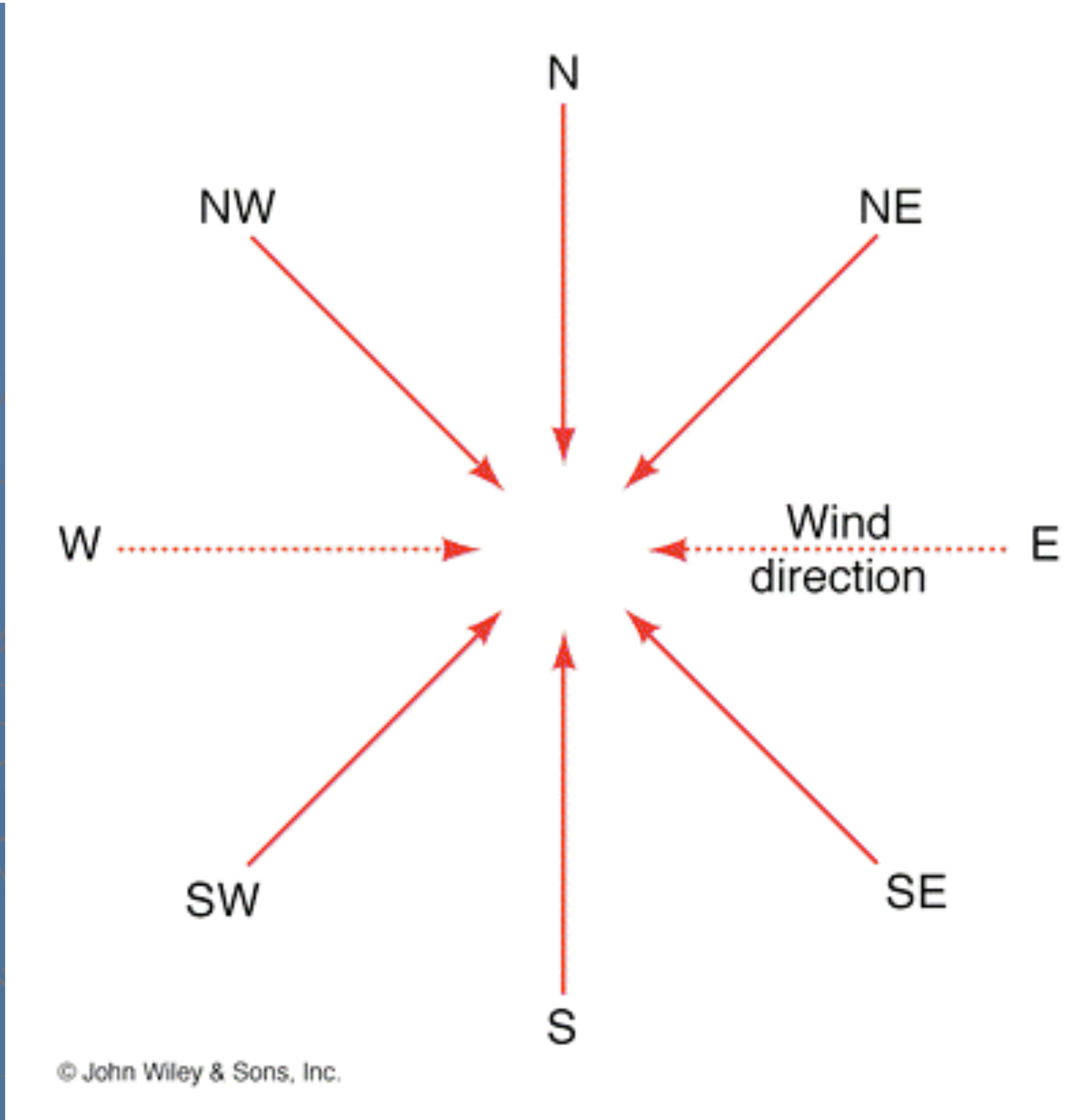

Current Surface
LT RAIN/DRIZZLE
MOD/HVY RAIN
FRZ RAIN/SLEET
LT SNOW/FLUR
MOD/HVY SNOW
FOG
L
L
L
H
THE WEATHER CHANNEL
weather.com
11 Oct 2000 04:40 GMT / 11 Oct 2000 12:40 AM EDT


Sea level Pressure (mb)
WXP analysis for 09Z 11 OCT 00
LO: 995.2 HI: 1028.5
994
998
1002
1006
1010
1014
1018
1022
1026
1030
© UNISYS

Atmospheric Pressure

- Winds, however, are defined in the direction ***from which they come***

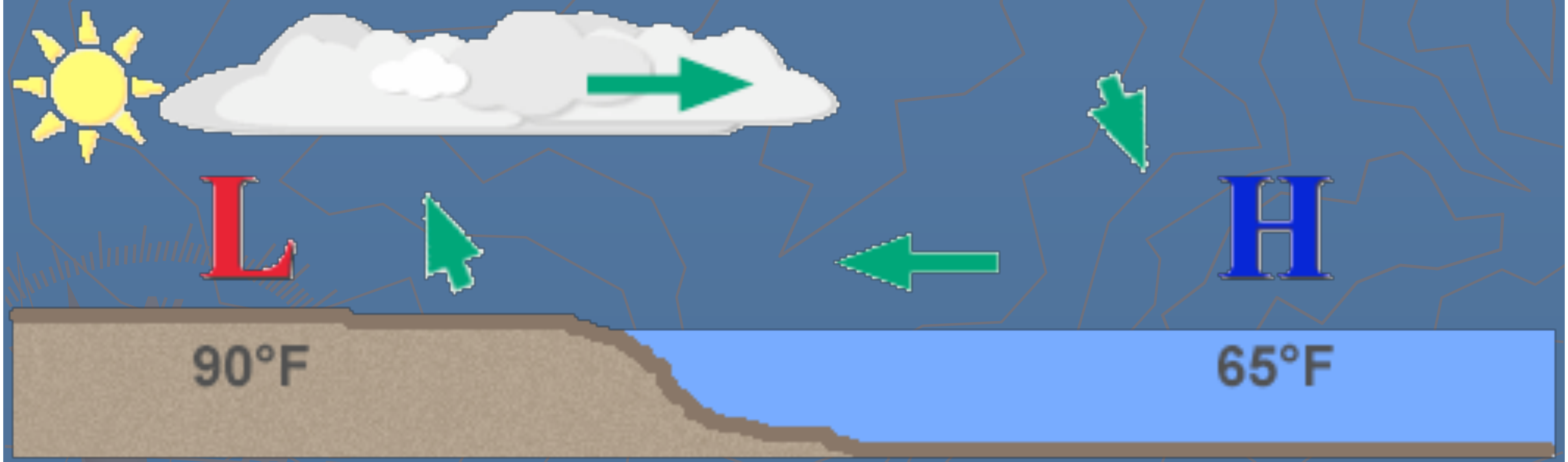
- Thus, a north wind comes from the north, even though it is moving south


N
NW
NE
W
Wind
direction
E
SW
SE
S
© John Wiley & Sons, Inc.

Land/Ocean Contrasts

- Since land heats faster and cools down faster than water, we should expect pressure gradients to exist
- In the afternoon, the land is warmer than the water. Thus, a low pressure forms over the land and a high pressure forms over water.
- Air is forced to flow onshore – a ***sea breeze***

A Sea Breeze



Land/Ocean Contrasts

- In the evening, the opposite situation exists
- The water is warmer than the land. Thus, a high pressure forms over the land and a low pressure forms over water.
- Air is forced to flow offshore – a ***land breeze***

A Land Breeze

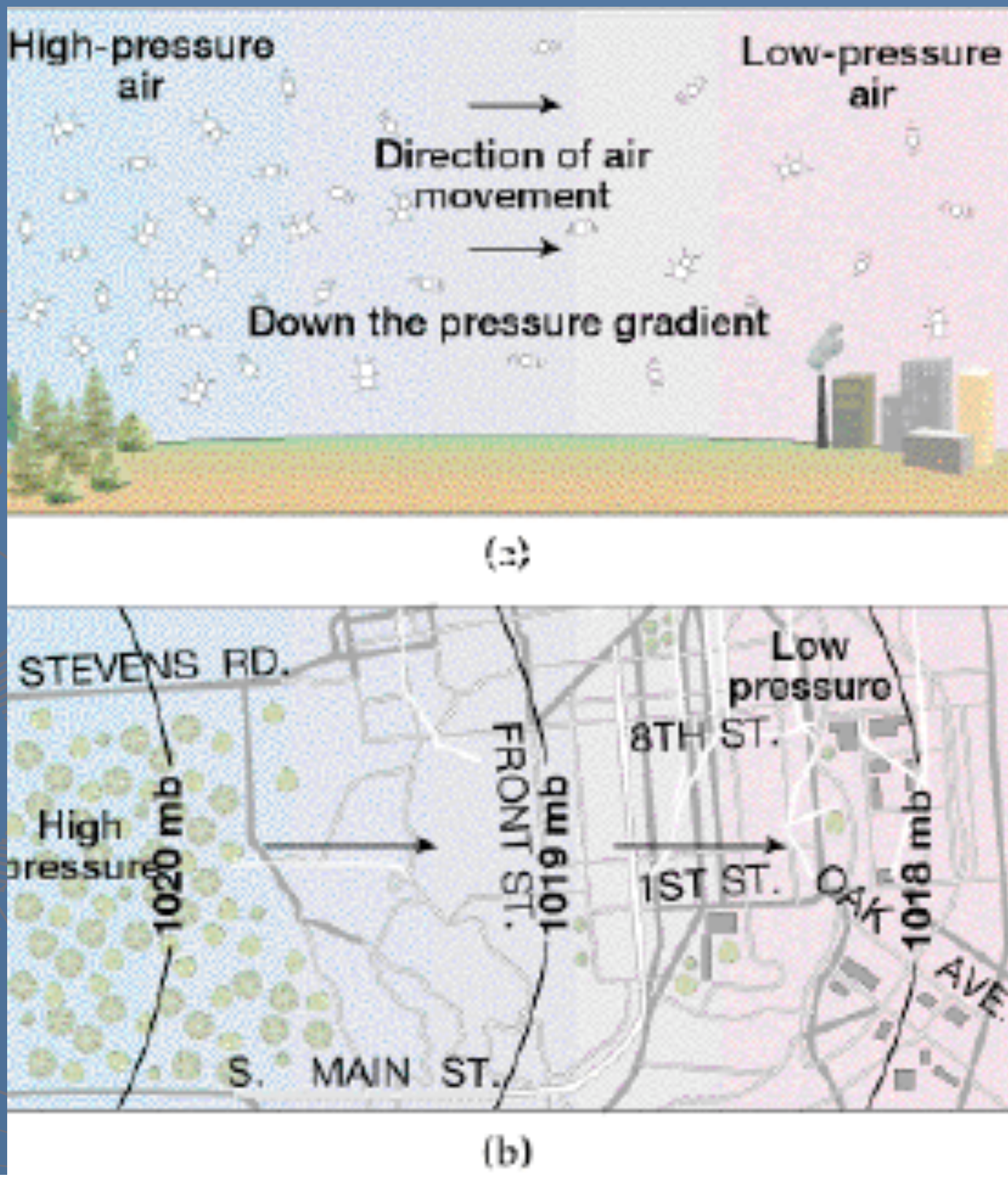
Factors that determine wind speed and direction

1. Pressure Gradient Force (pgf)

2. Coriolis effect (force*)

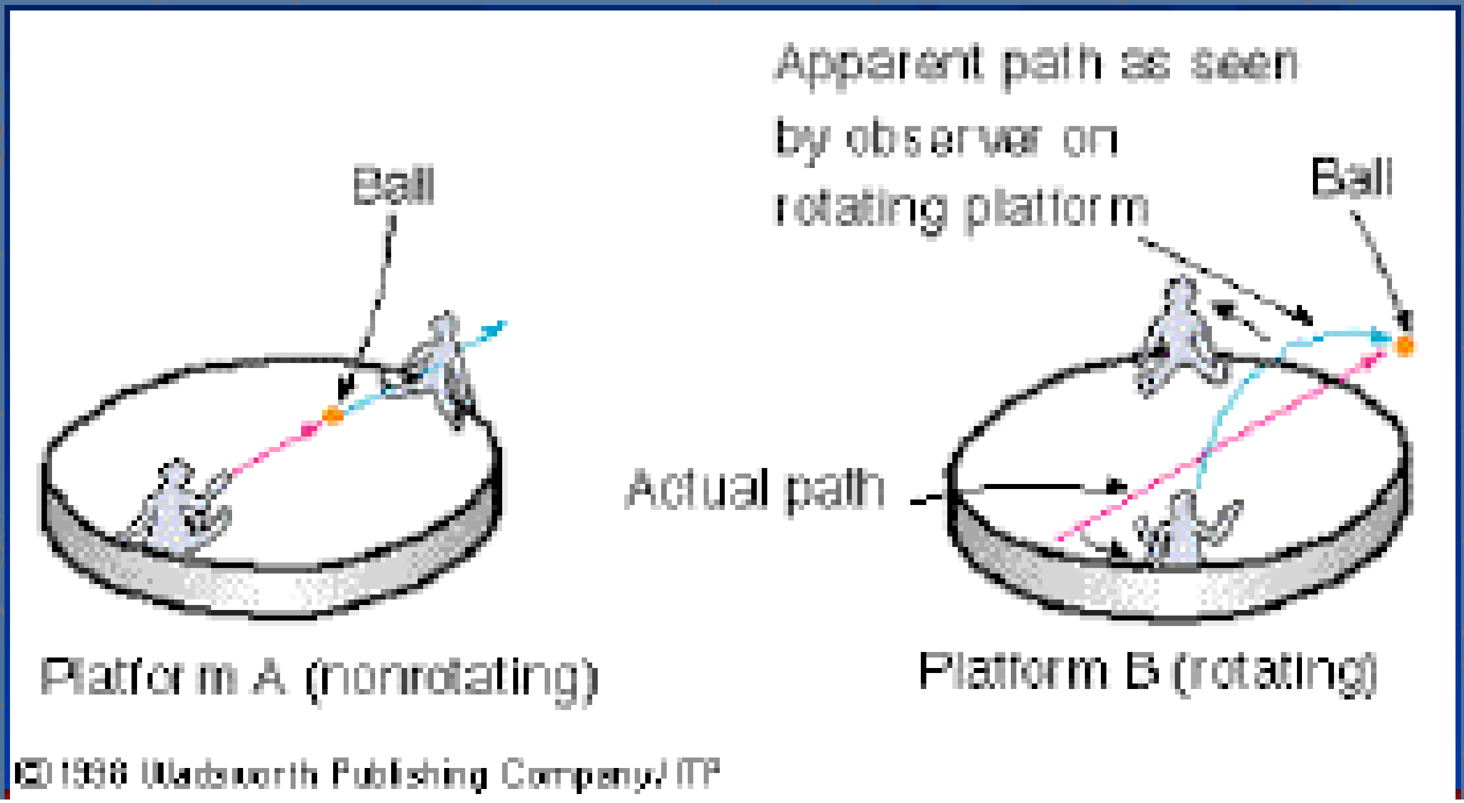
3. Friction force

Pressure Gradient Force causes the wind to blow



Coriolis Effect (Force)

- Because of the rotation of the earth, any object moving freely near the surface appears to deflect to the right in the NH and to the left in the SH



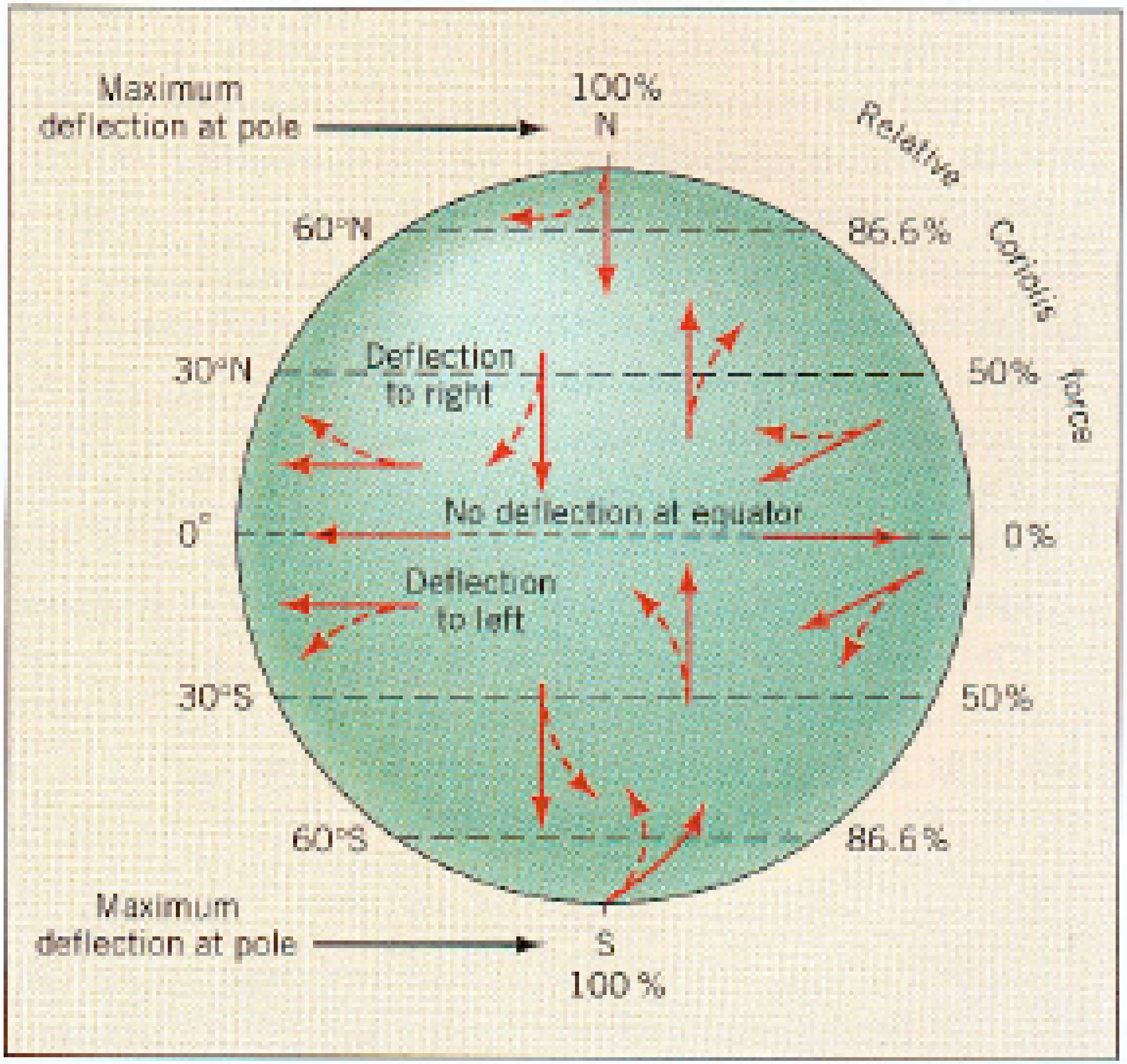


FIGURE 9-6 Latitudinal variation in the Coriolis force: deflection is zero at the equator, increases with latitude, and is most pronounced at each pole (note the percentages along the right side of the globe).

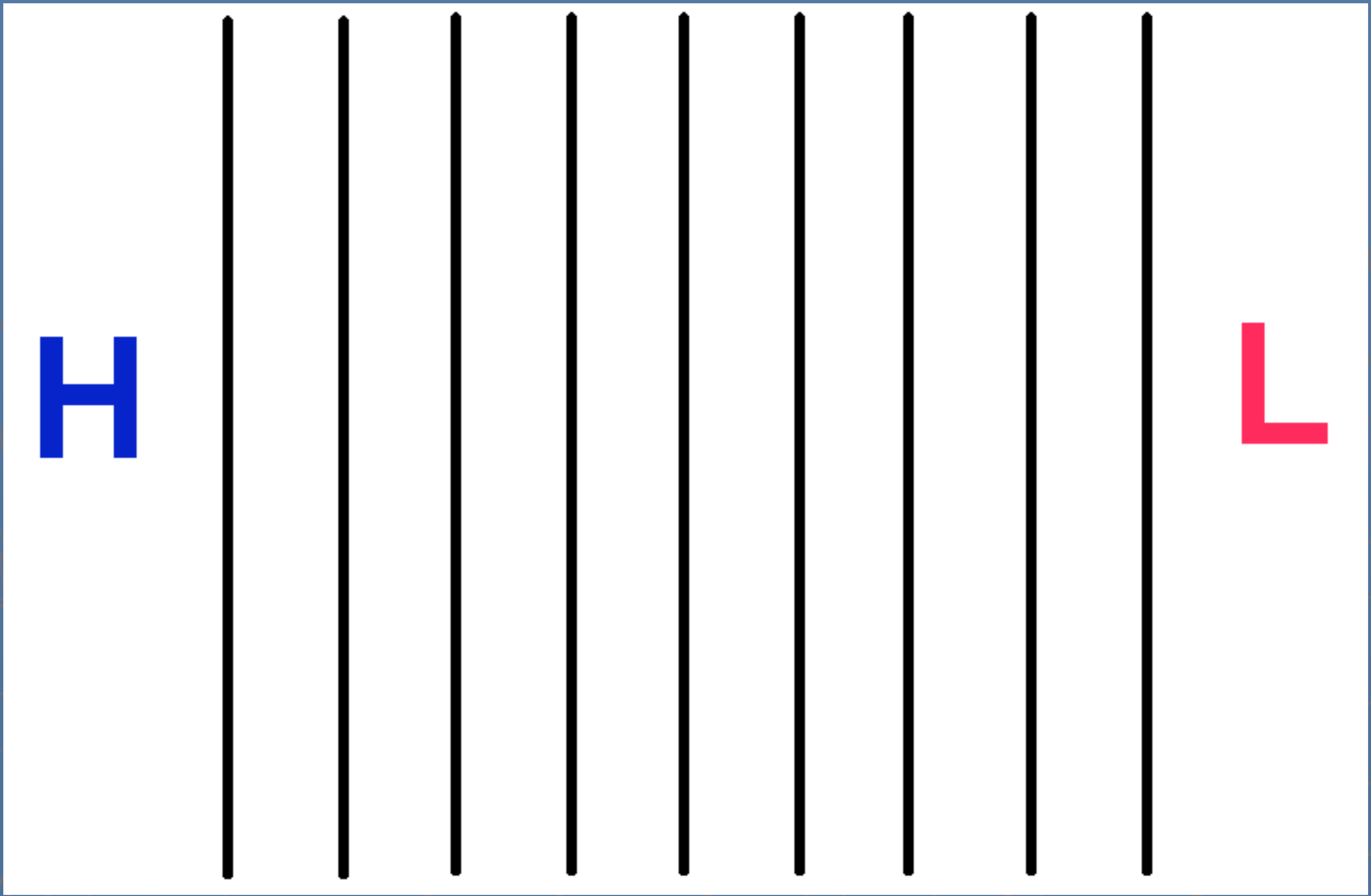
Winds and Global Circulation

Let's start simple:

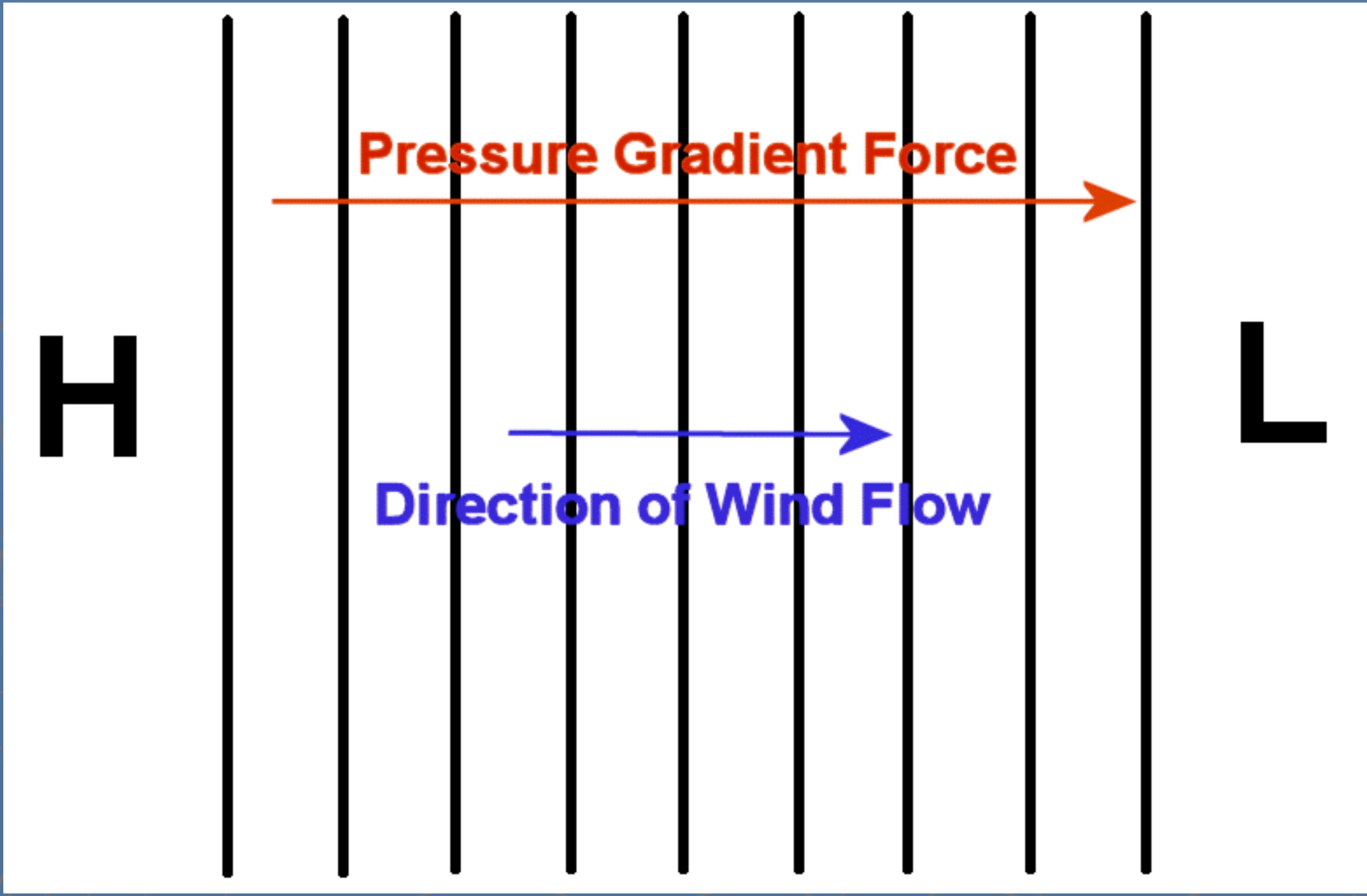
A homogeneous, non-rotating earth

Winds and Global Circulation

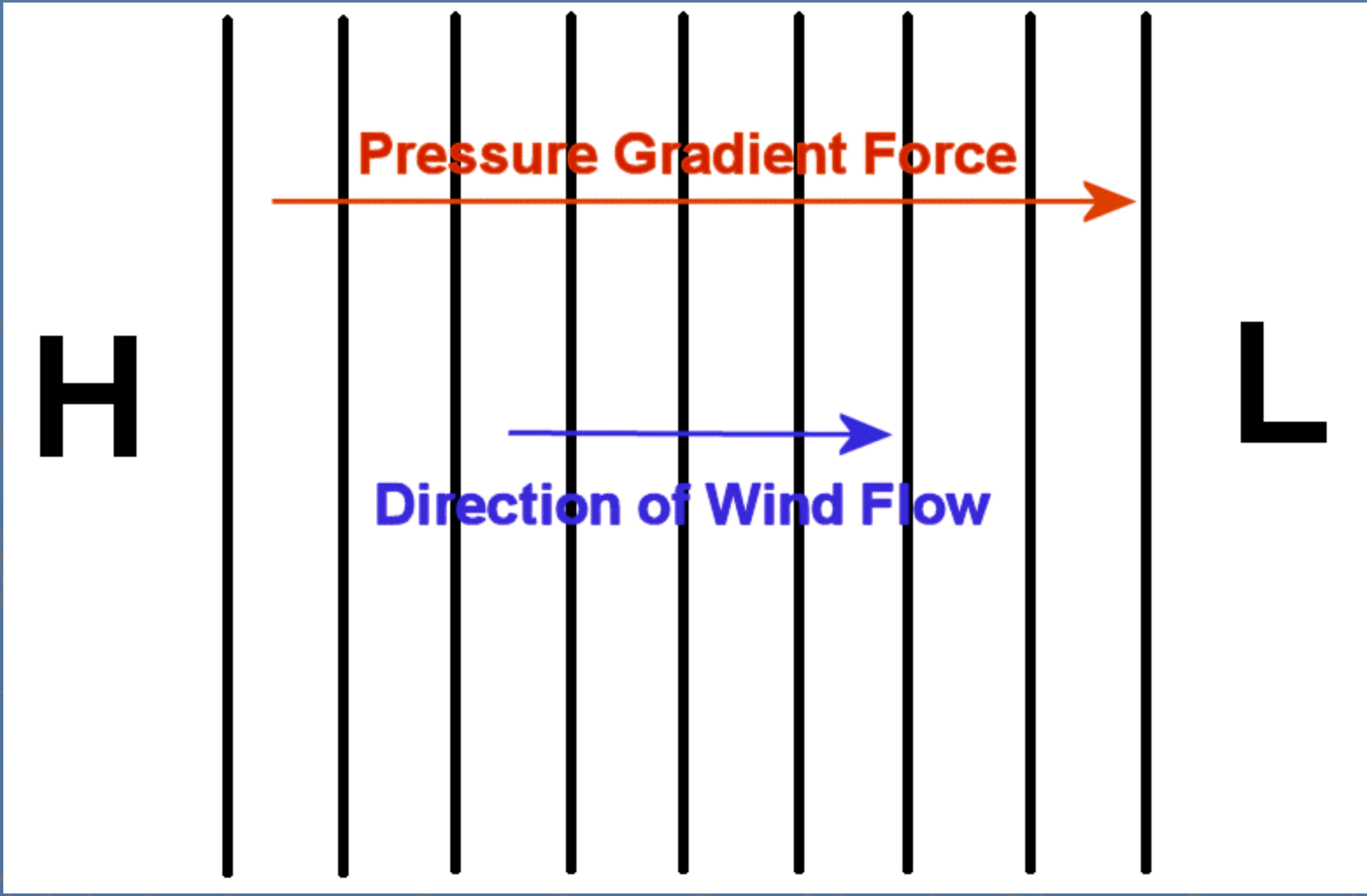
- Homogeneous – no land-water contrasts
- Non-rotating – no rotation about an axis
- Forces in Action:
  - Pressure Gradient Force

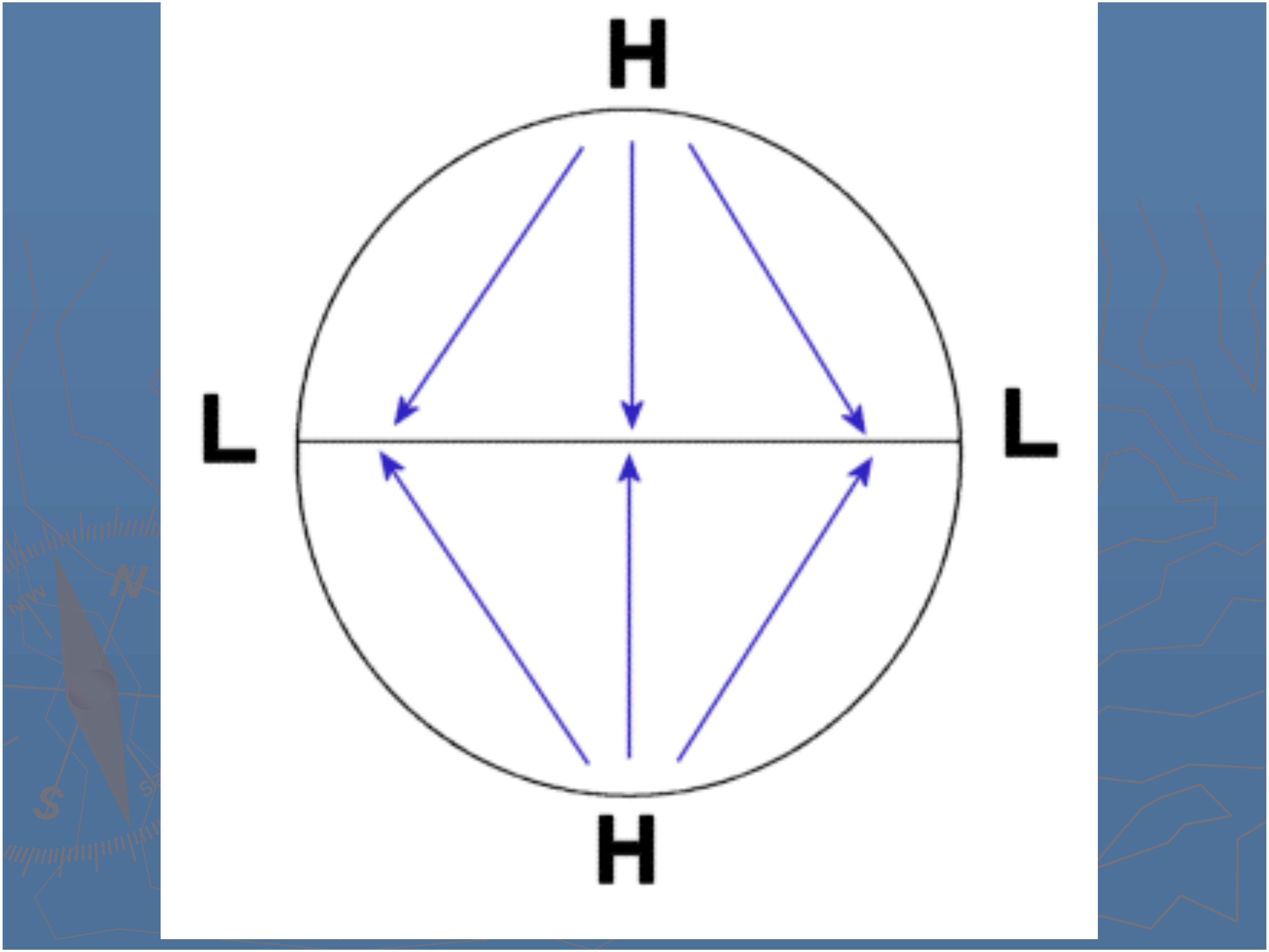

H
L

Northern Hemisphere



Southern Hemisphere




H
L
L
H

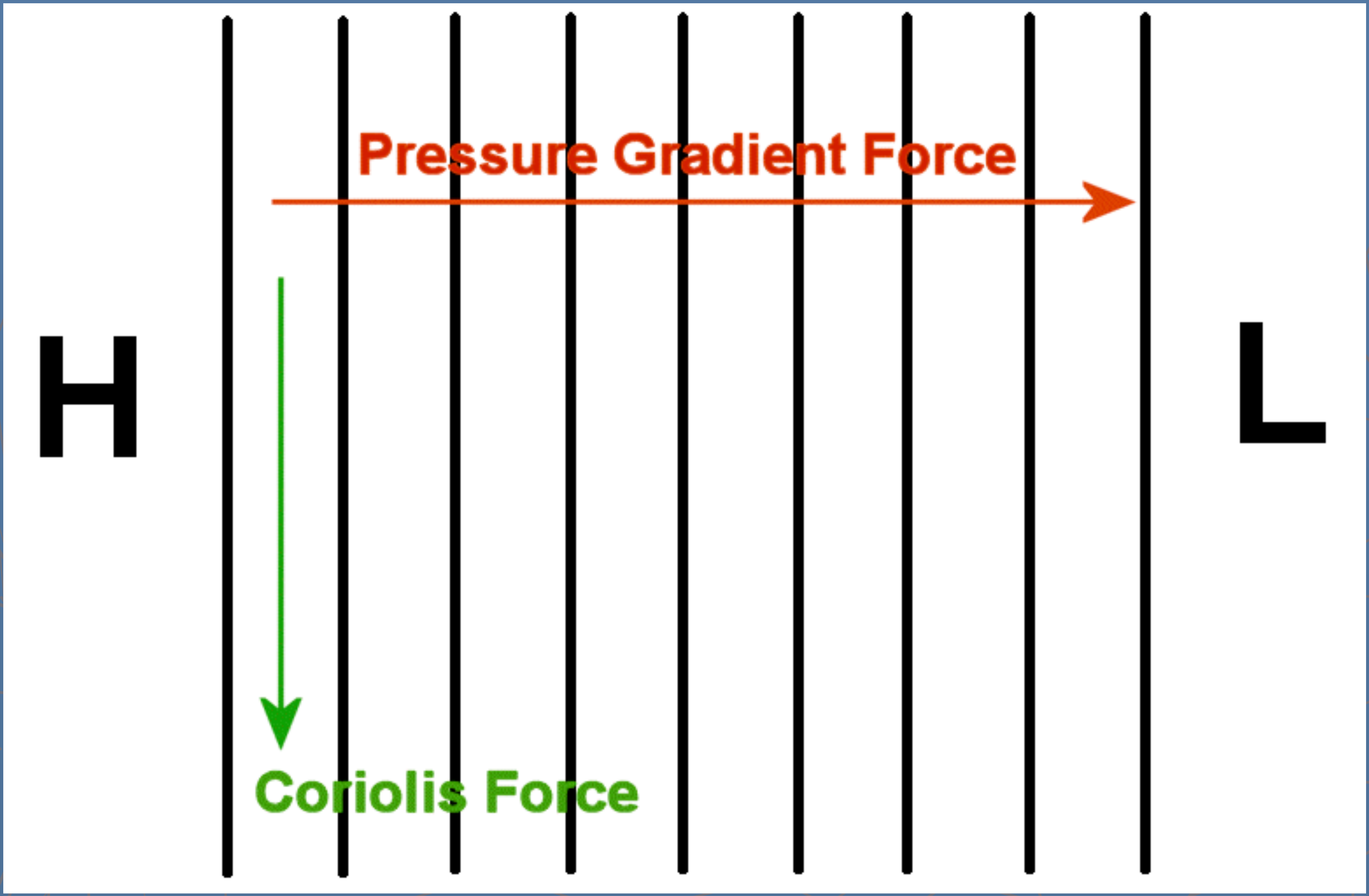
Winds and Global Circulation

- Homogeneous – no land-water contrasts
- Rotating – rotation about the earth's axis
- Forces in Action:
  - Pressure Gradient Force
  - ???

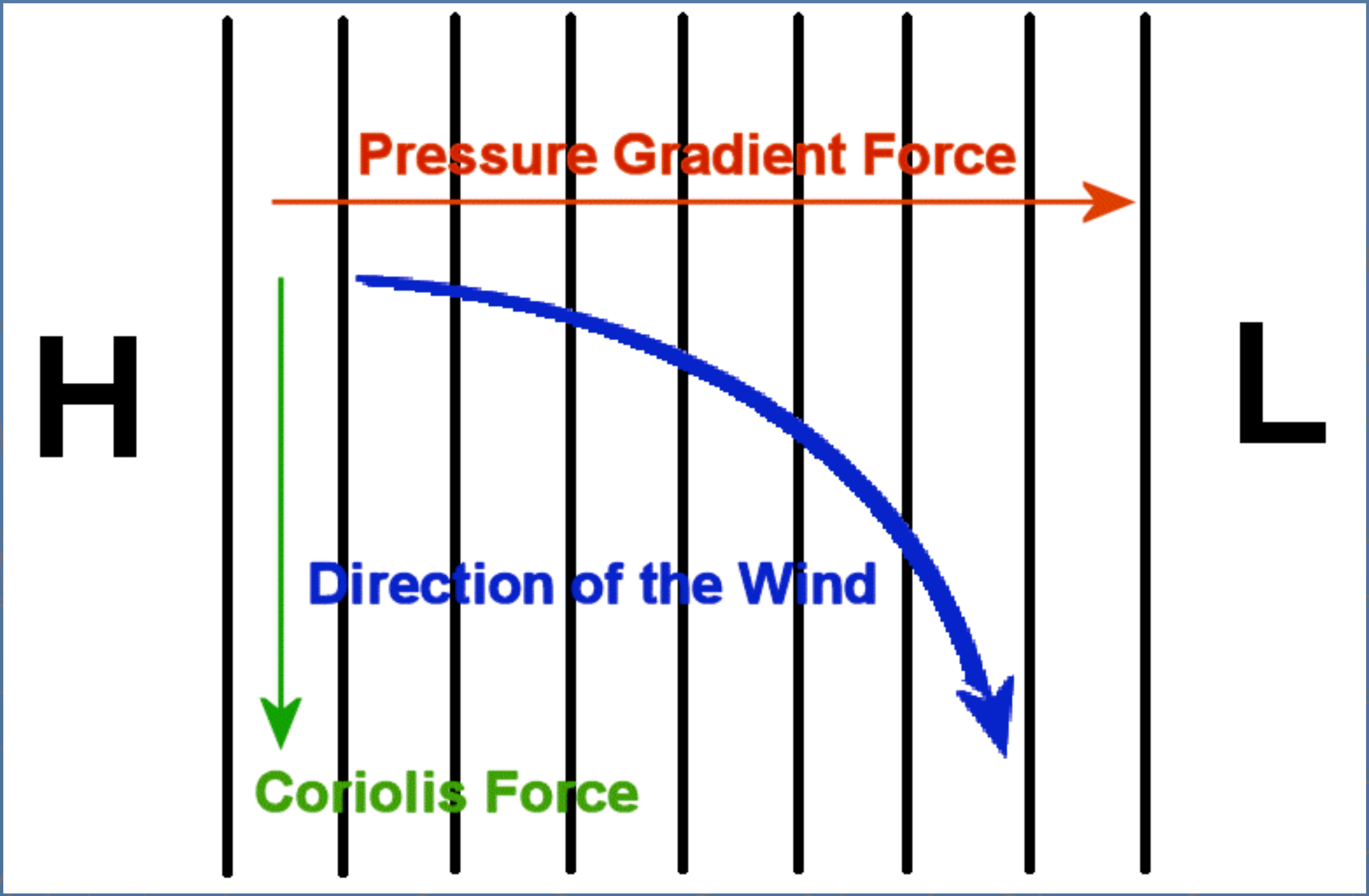
Winds and Global Circulation

- Homogeneous – no land-water contrasts
- Rotating – rotation about the earth's axis
- Forces in Action:
  - Pressure Gradient Force
  - ***Coriolis Force*** – apparent force caused by the rotation of the earth. Causes objects to be deflected to the right of their path of motion in the Northern Hemisphere and to the left of their path of motion in the Southern Hemisphere

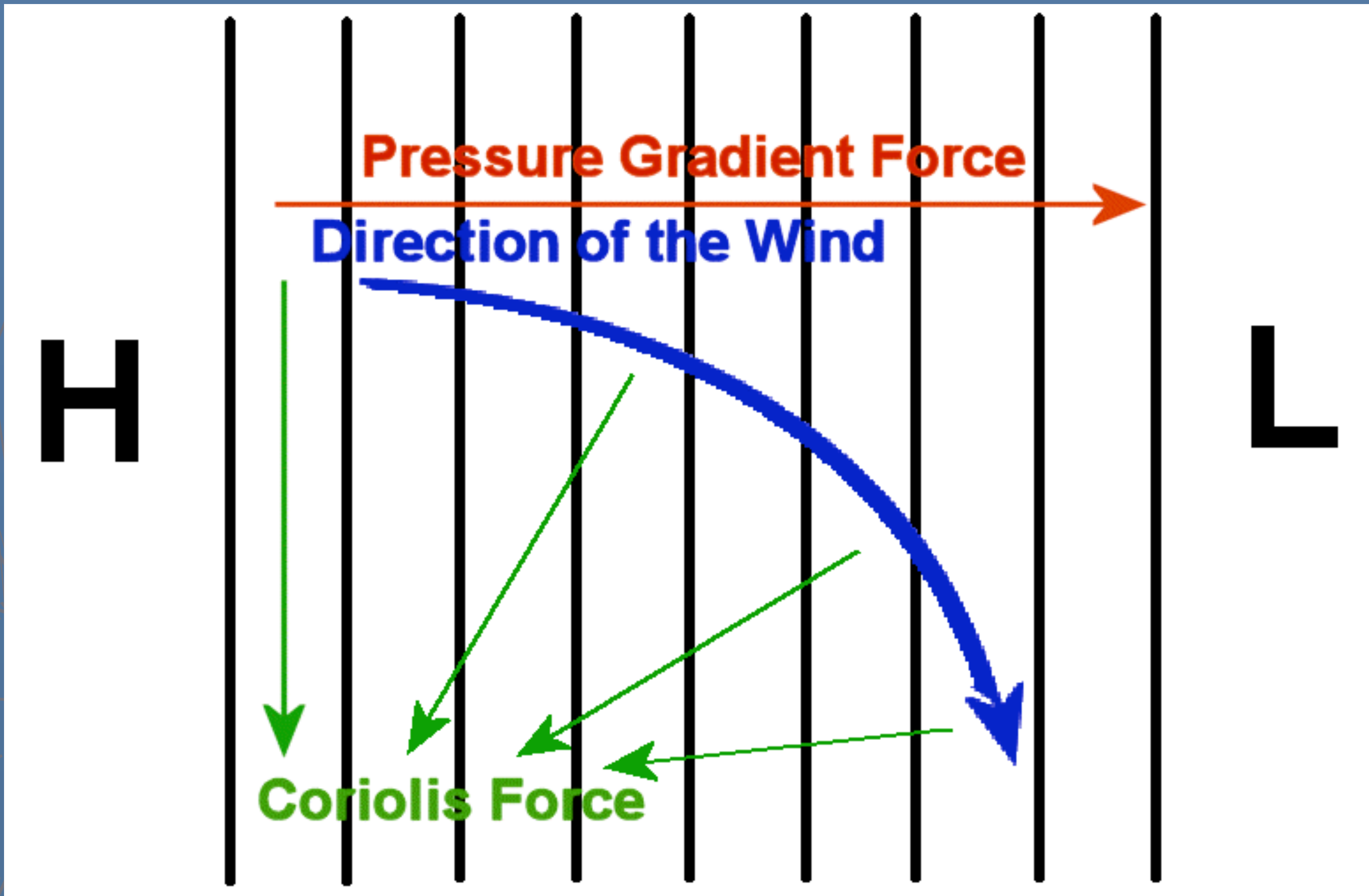
Northern Hemisphere



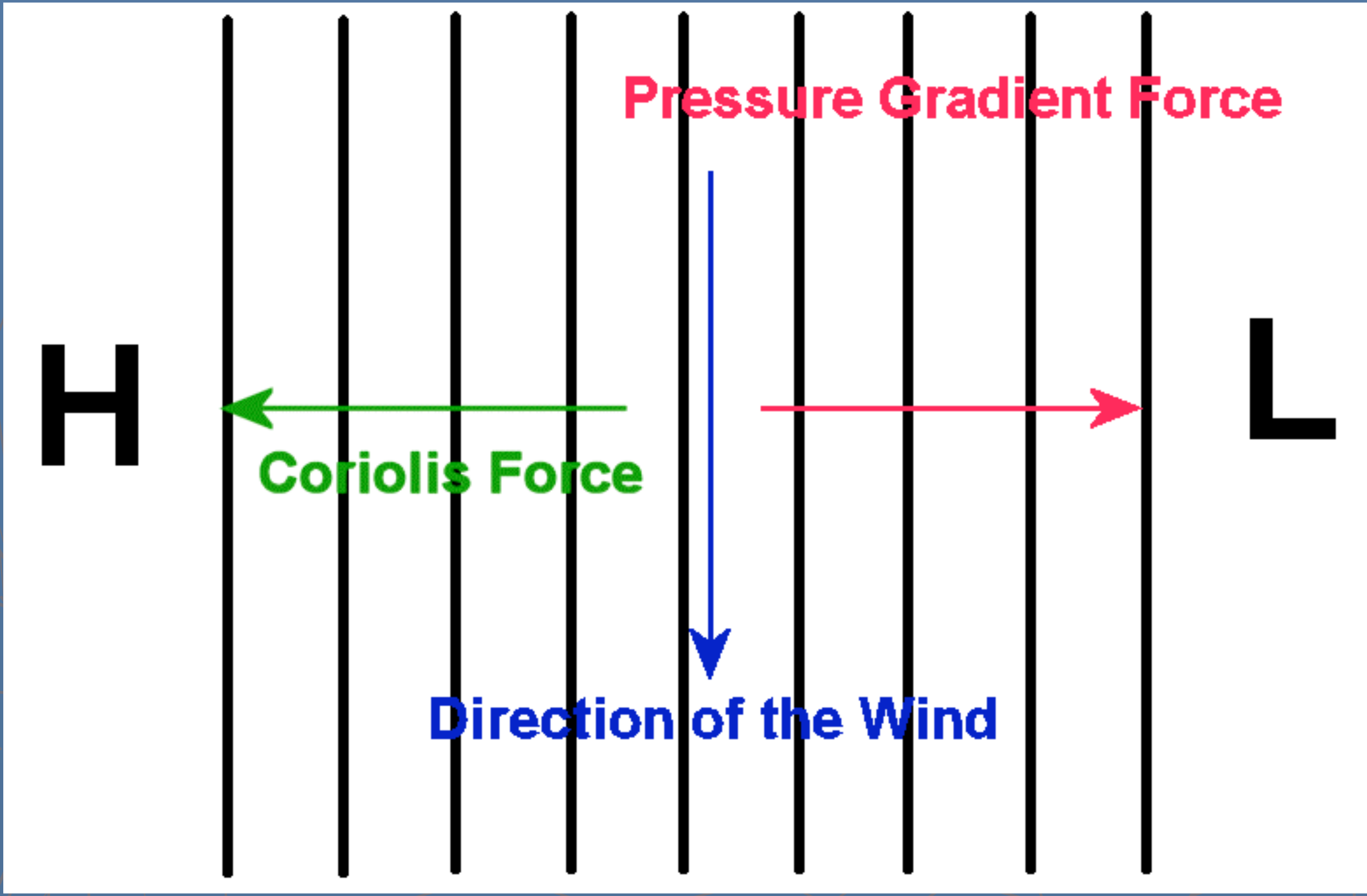
Northern Hemisphere

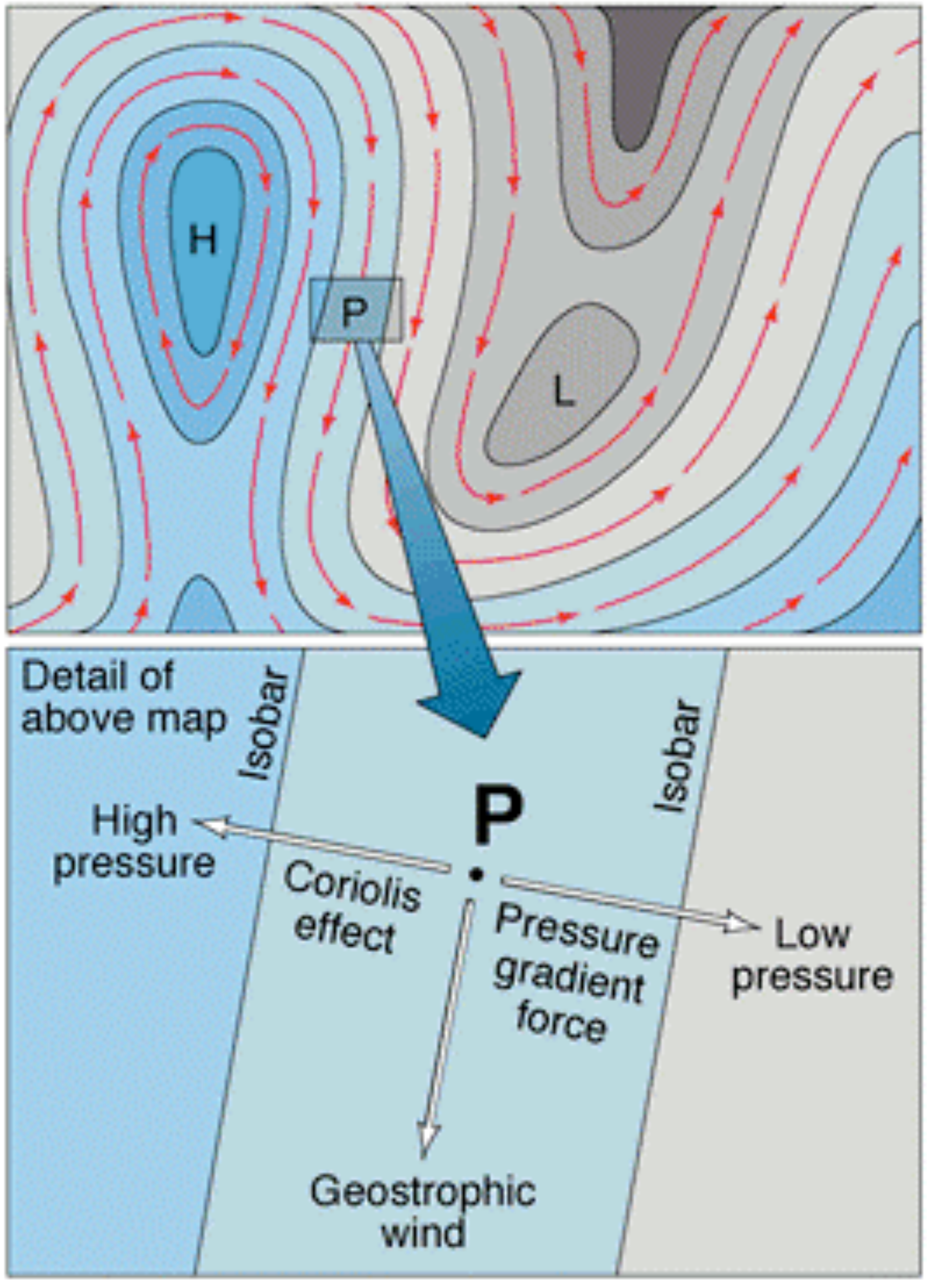


Northern Hemisphere

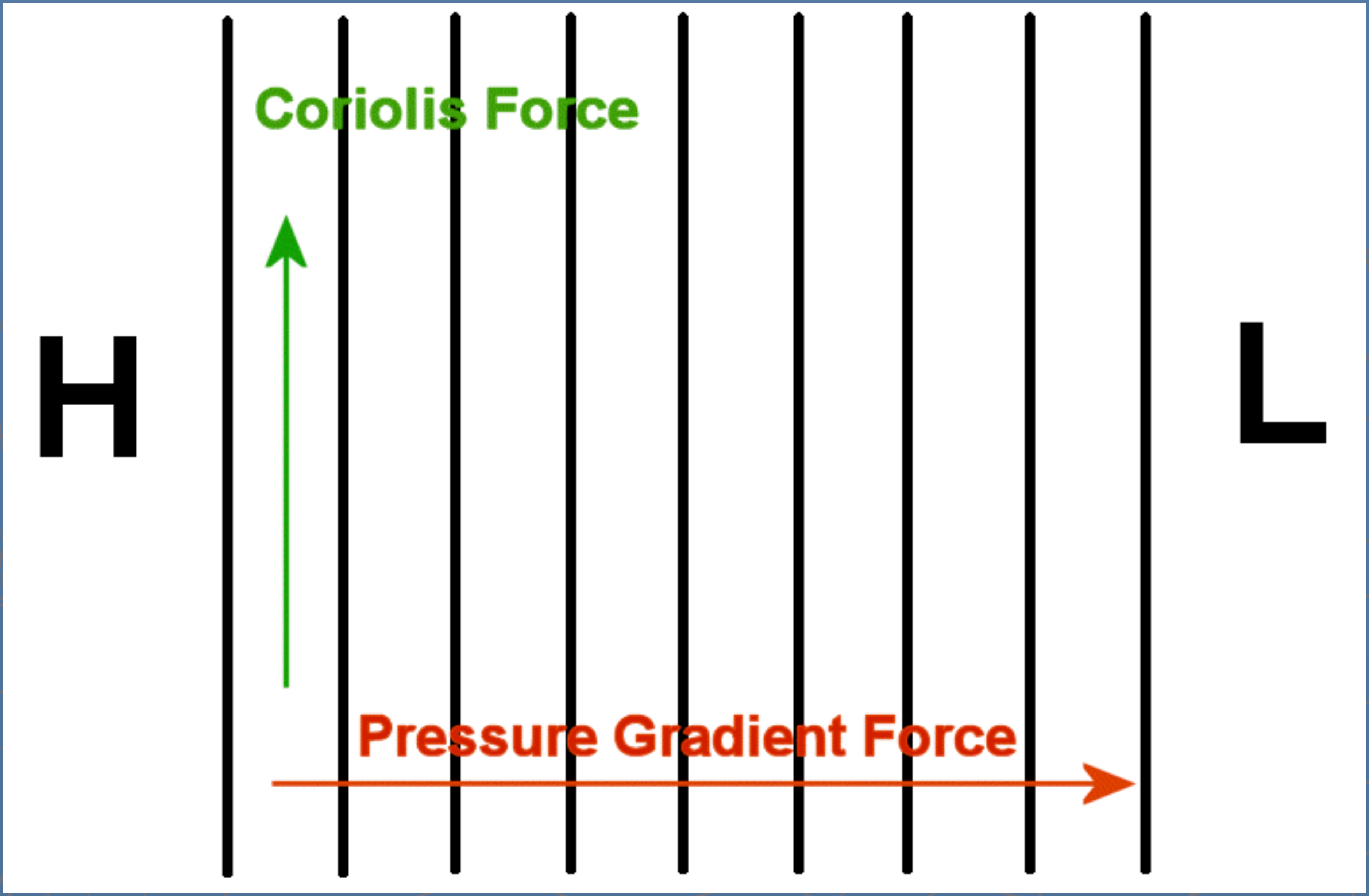


Northern Hemisphere

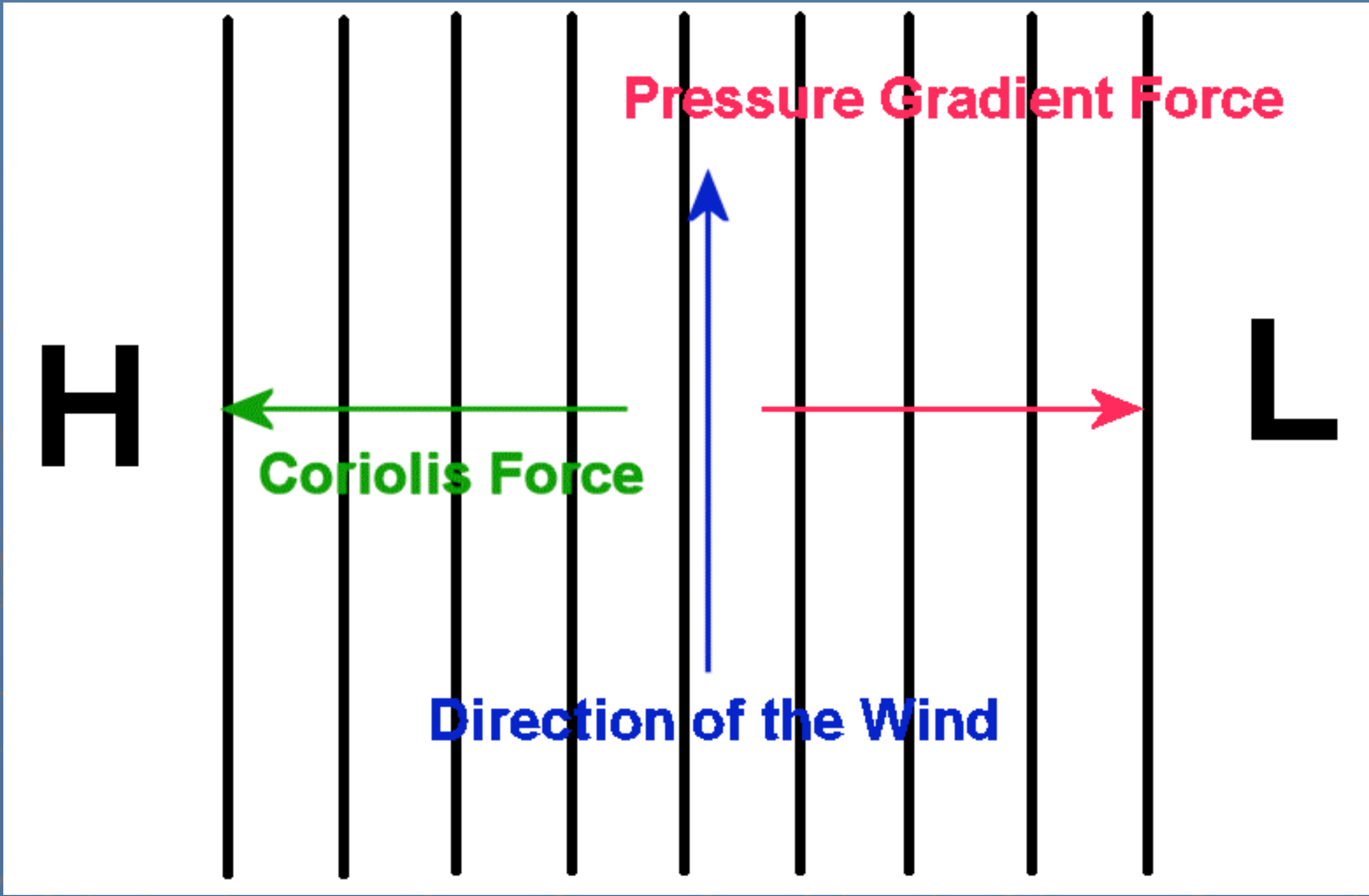


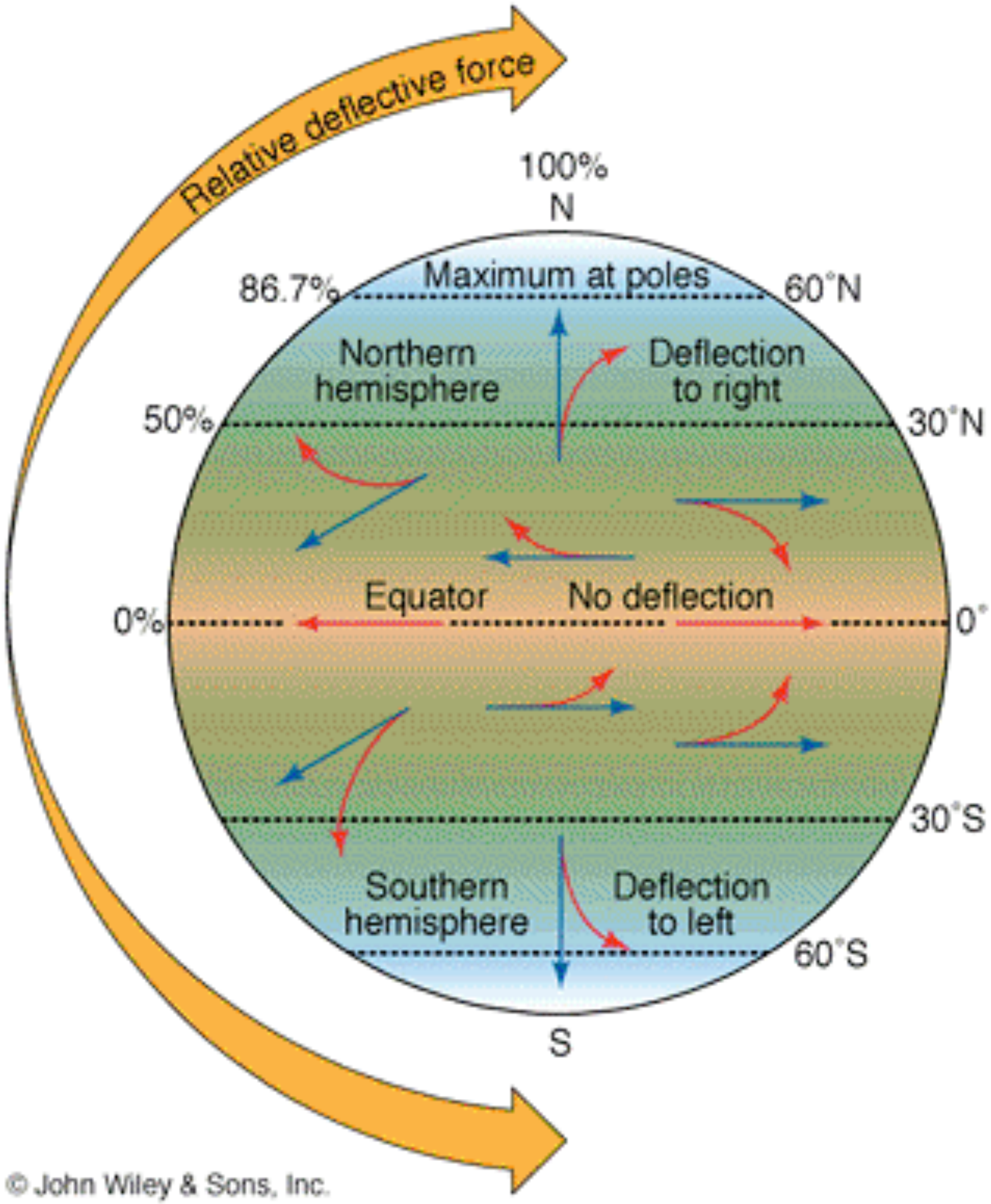

H
P
L
Detail of above map
Isobar
Isobar
P
High pressure
Coriolis effect
Pressure gradient force
Low pressure
Geostrophic wind

Southern Hemisphere



Southern Hemisphere

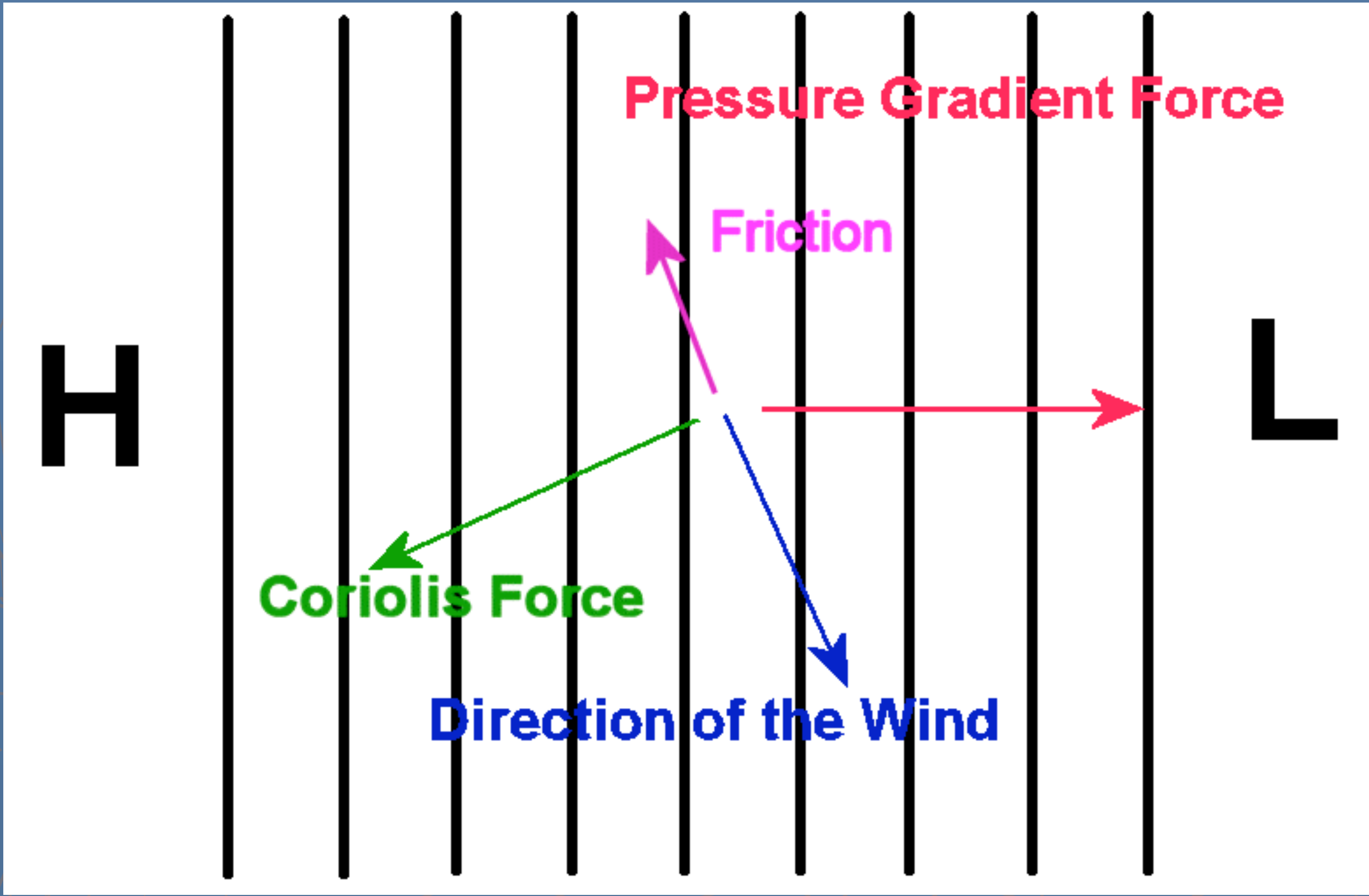



Relative deflective force
100%
N
86.7%
Maximum at poles
60°N
Northern hemisphere
Deflection to right
50%
30°N
0%
Equator
No deflection
0°
30°S
Southern hemisphere
Deflection to left
60°S
S

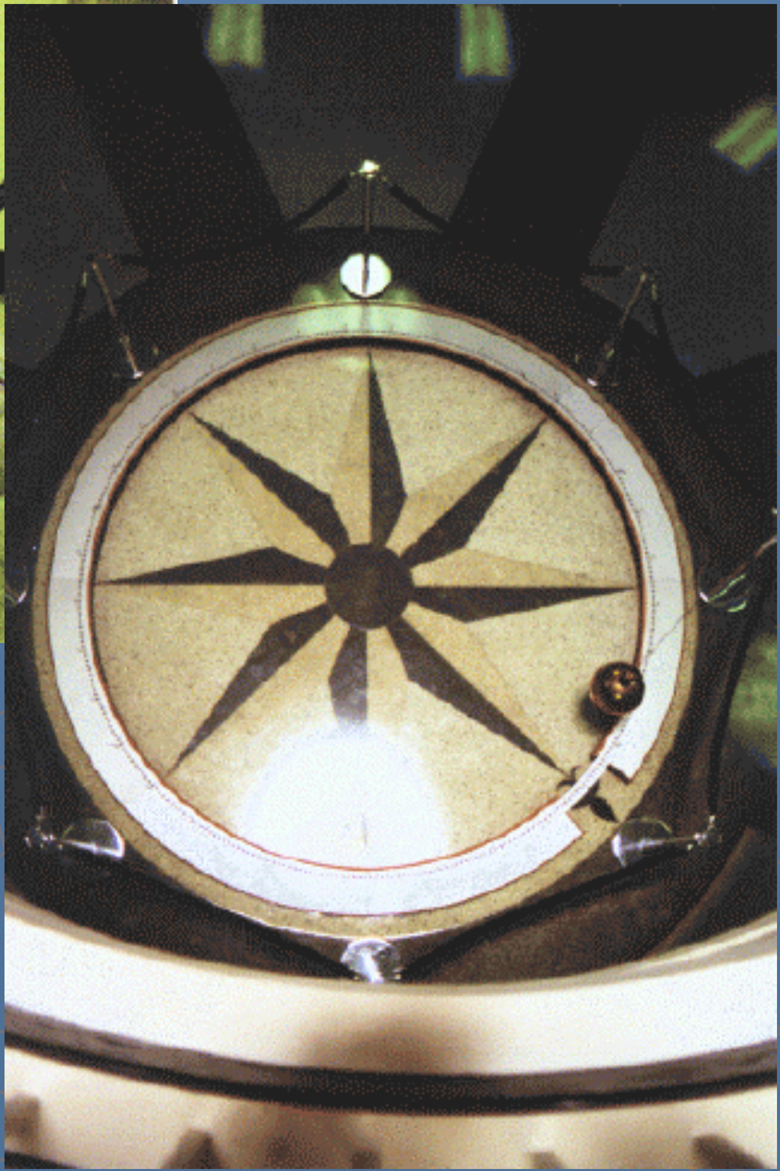
The Effect of Friction

- ***Friction*** is a drag force that inhibits forward movement
- Friction always works in the opposite direction of motion
- Thus, friction will cause the wind to cross the isobars, but not at a perpendicular angle
- Low friction – shallow angle
- High friction – steeper angle

Northern Hemisphere



http://www.astro.louisville.edu/foucault/

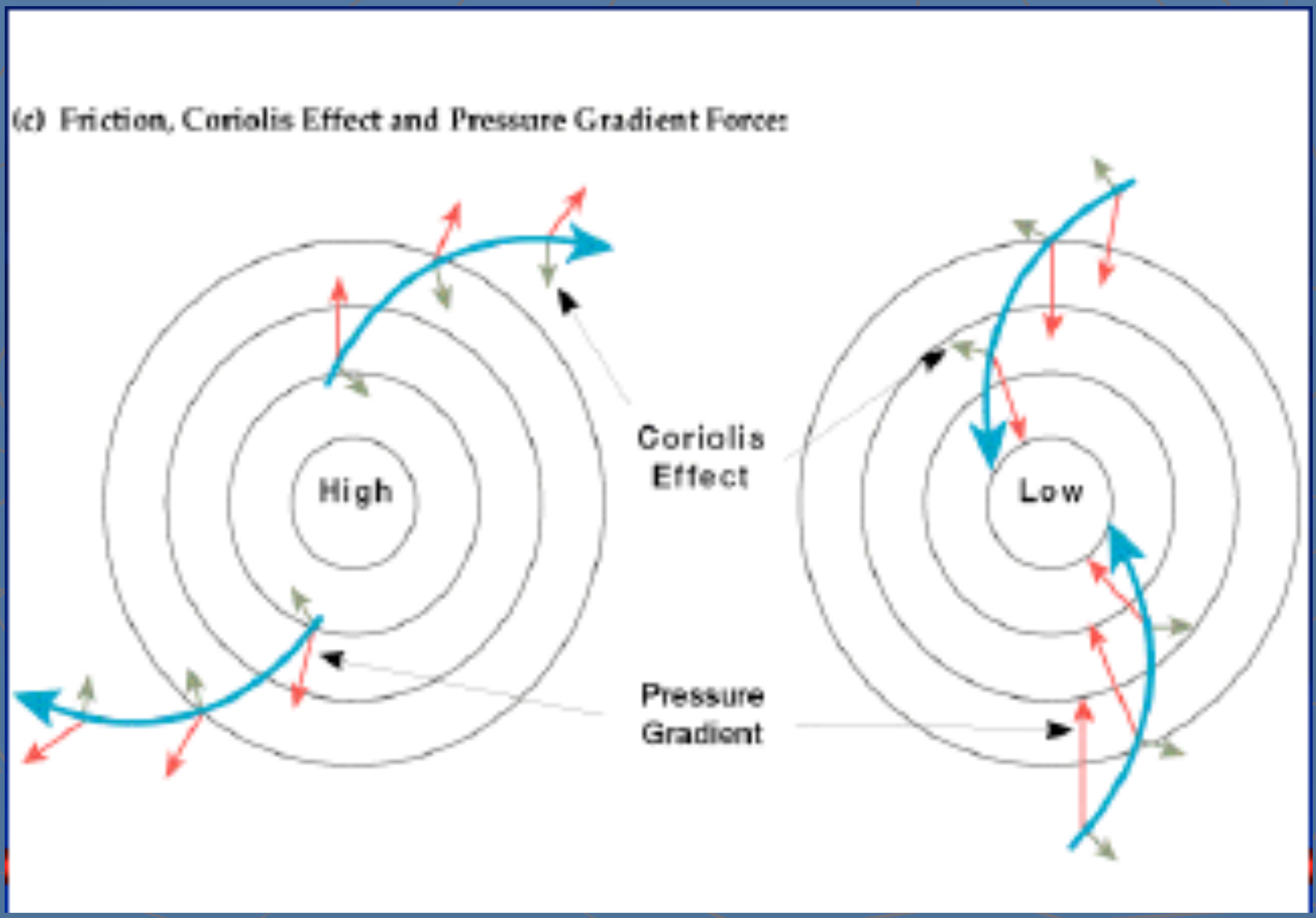


Foucault Pendulum


60°
N
40°
N
Chicago
New
York
74°W
Rotation

Frictional Force

- Friction will cause the wind to cross the isobars at an angle



Circulation around Highs and Lows

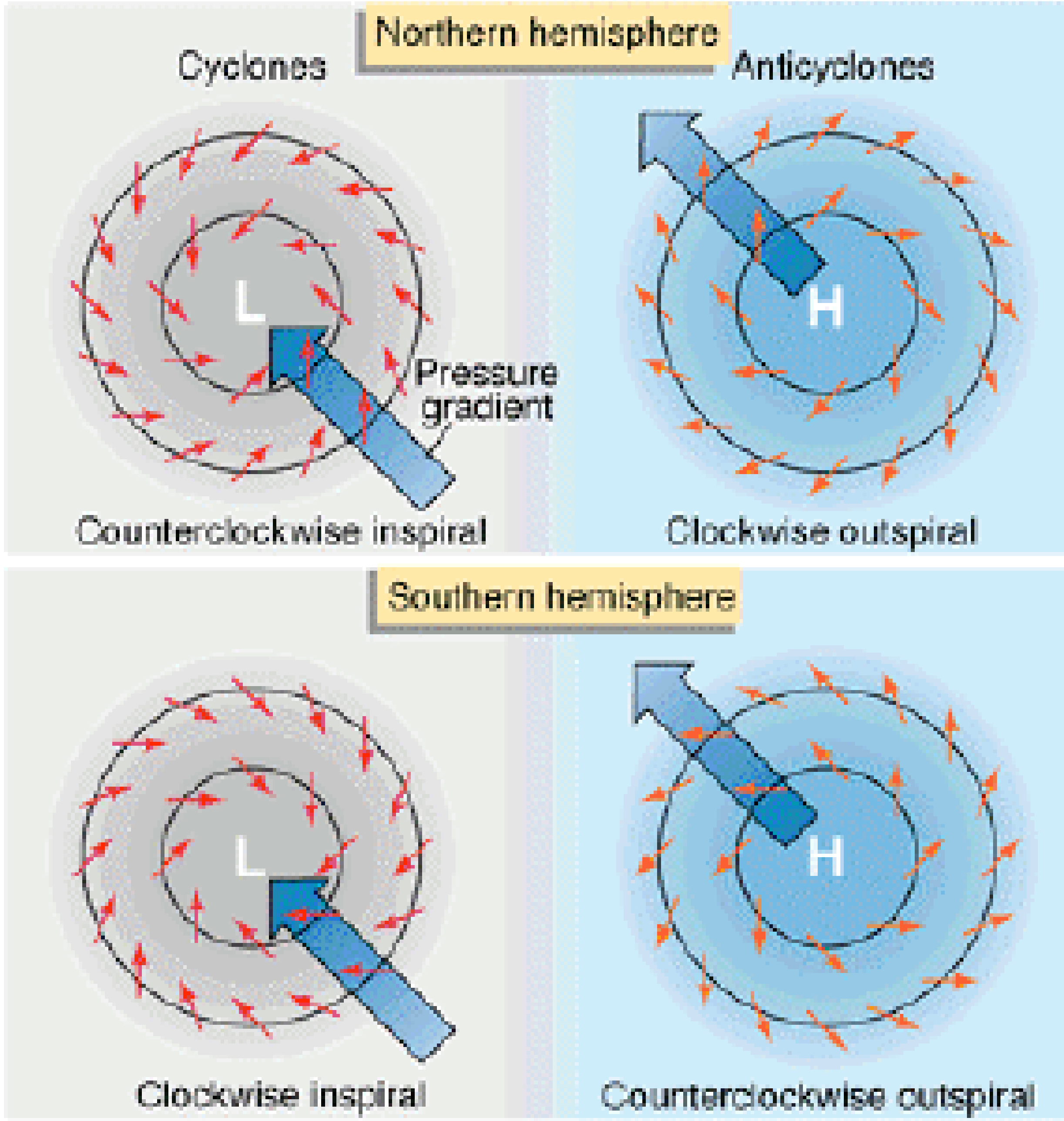
Low Pressure System = Cyclone

- Inward spiral of air (pressure gradient force)
- Rising air in center of cyclone (convergence)
- Counter-clockwise spiral in NH
- Clockwise spiral in SH
- Usually small systems and strong winds

Circulation around Highs and Lows

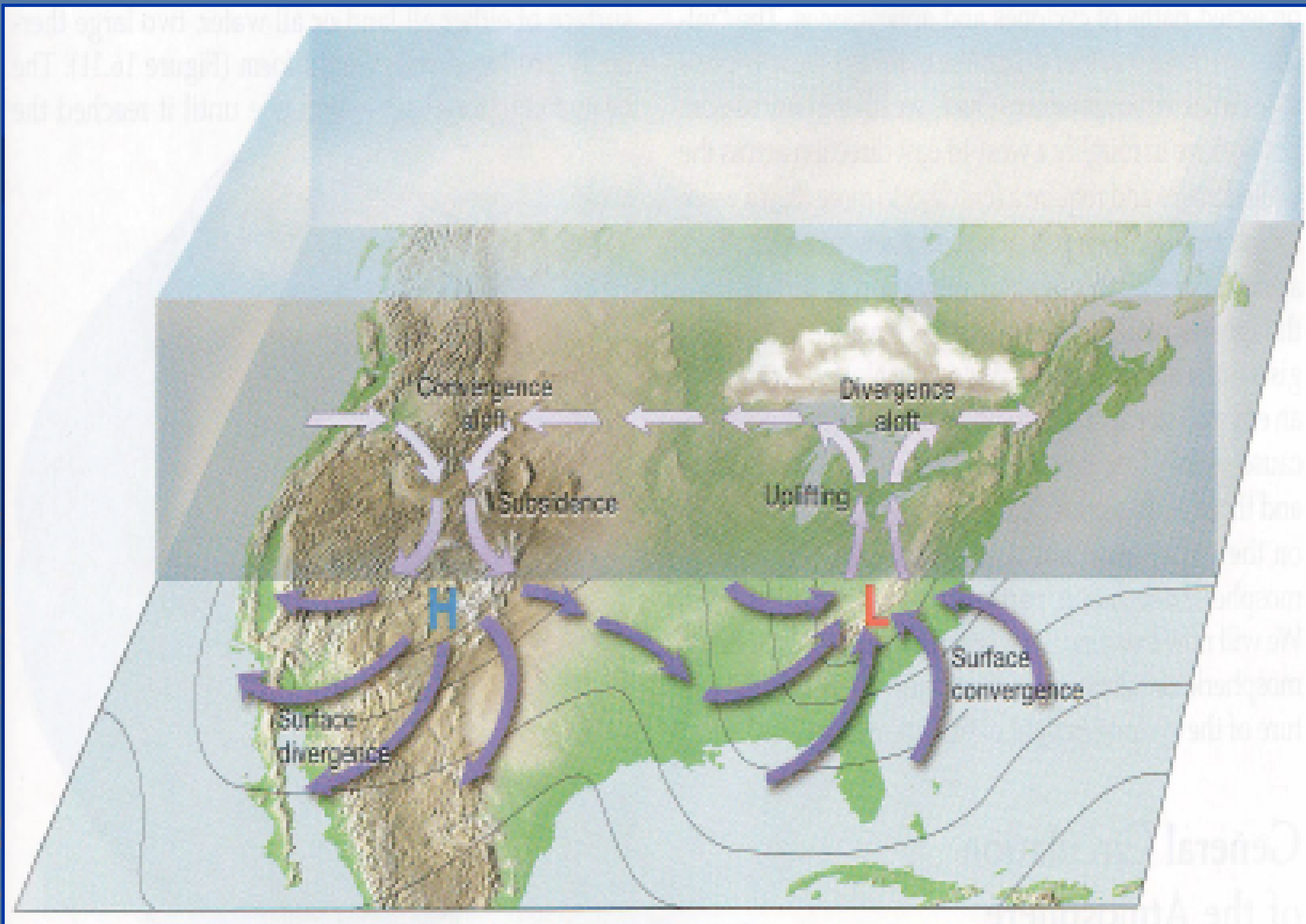
High Pressure System = Anticyclone

- outward spiral of air (pressure gradient force)
- Descending air in center of cyclone (divergence)
- clockwise spiral in NH
- Counter-clockwise spiral in SH
- Usually large systems and light winds

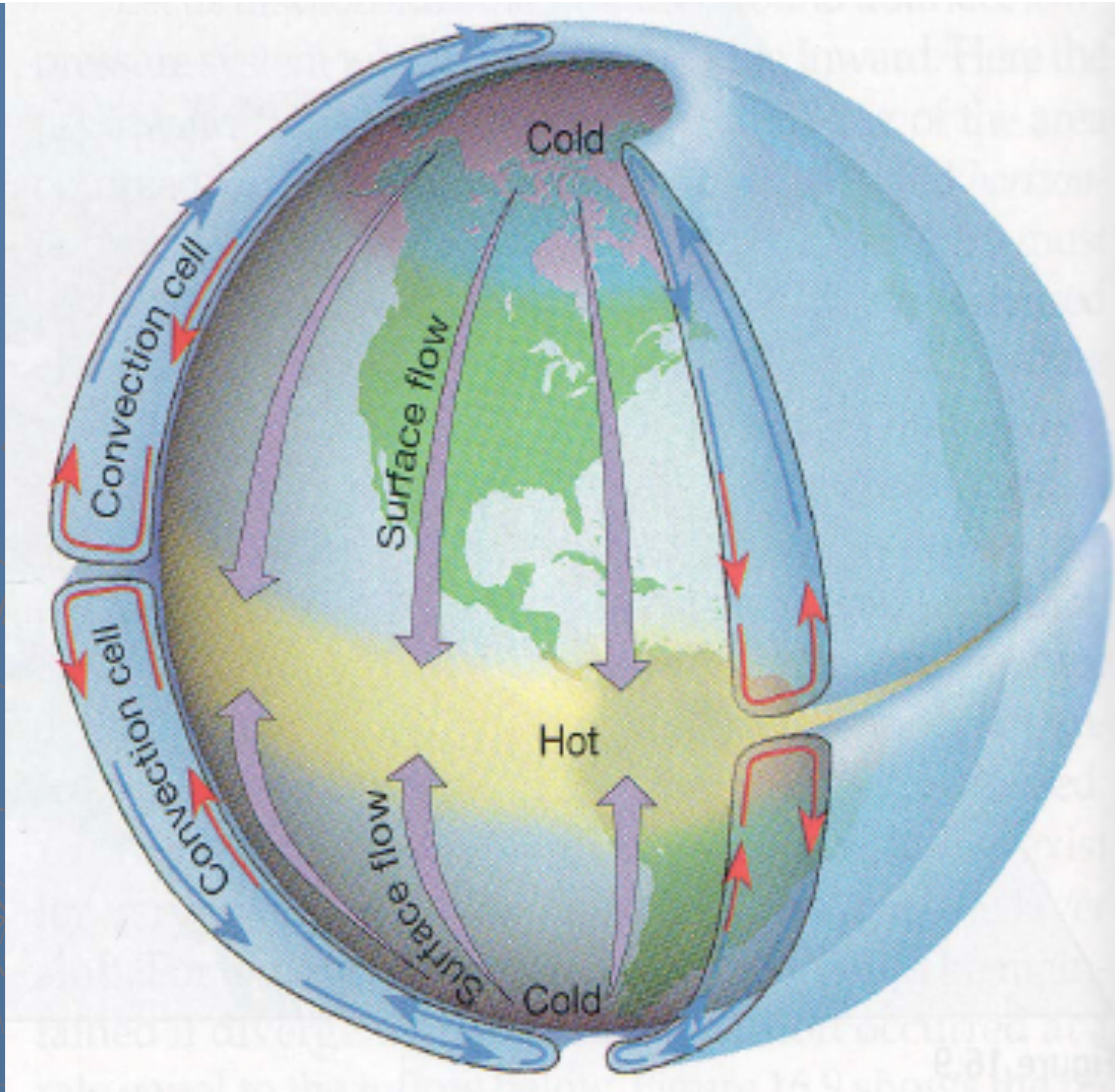


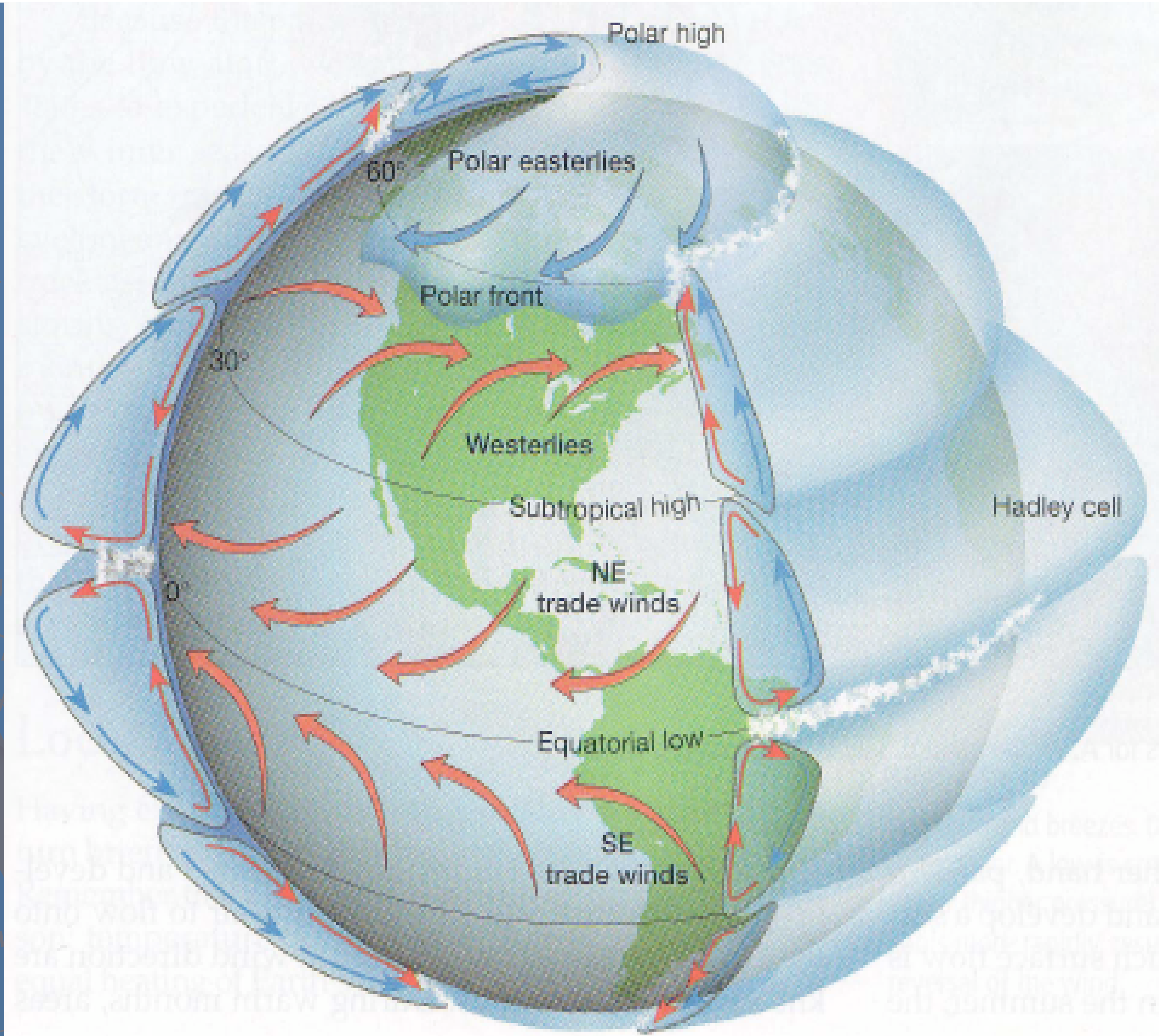
Northern hemisphere
Cyclones
Anticyclones
L
H
Pressure gradient
Counterclockwise inspiral
Clockwise outspiral
Southern hemisphere
L
H
Clockwise inspiral
Counterclockwise outspiral

- Cyclones and anticyclones are about 1000 kilometers (approx. 600 mi) across, or more.
- They can remain in one location or they can move rapidly, to create weather disturbances.


Convergence aloft
Divergence aloft
Subsidence
Uplifting
H
L
Surface divergence
Surface convergence

Winds and Global Circulation


Cold
Convection cell
Surface flow
Convection cell
Hot
Surface flow
Cold

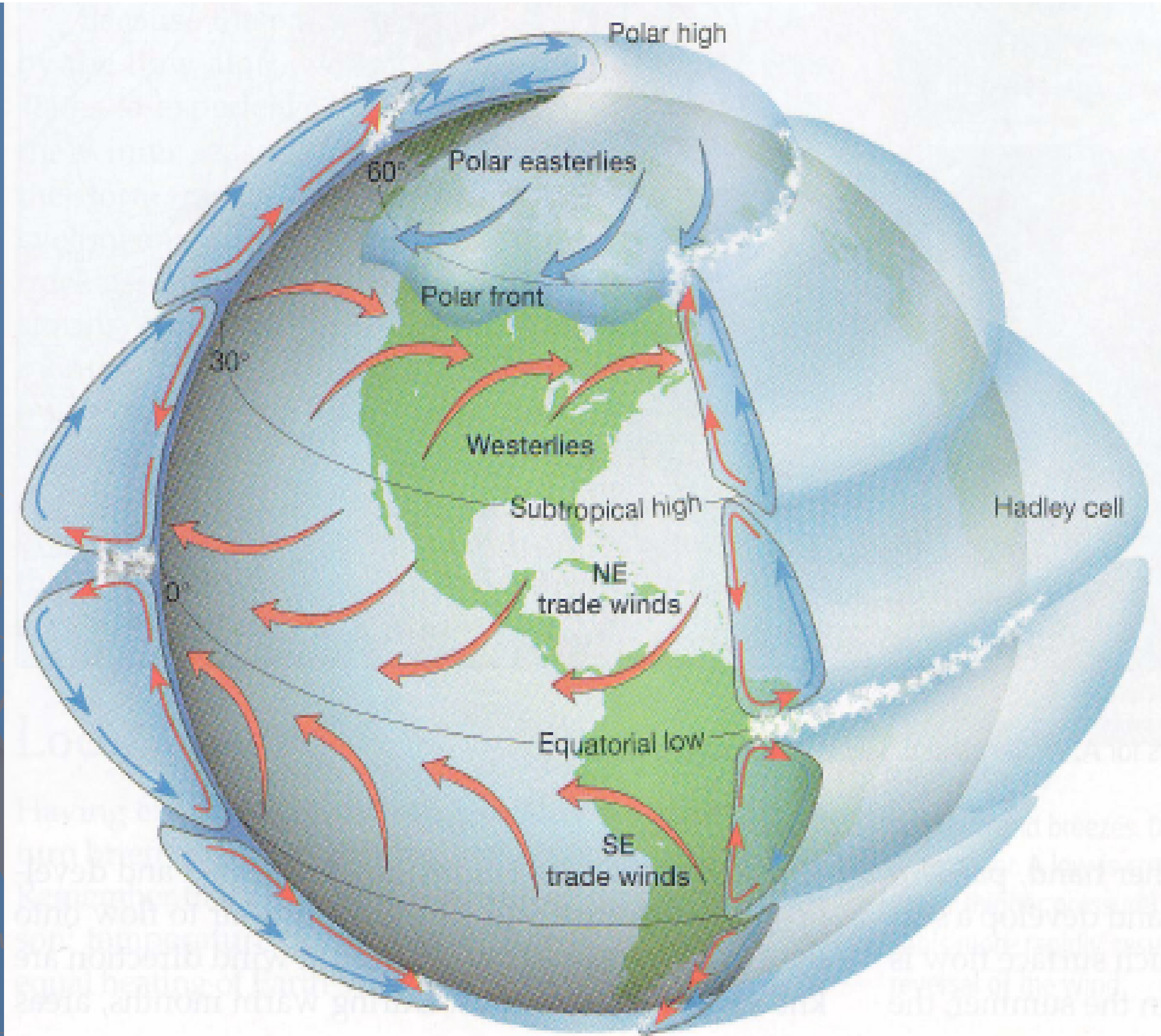


Polar high
60°
Polar easterlies
Polar front
30°
Westerlies
Subtropical high
Hadley cell
NE
trade winds
0°
Equatorial low
SE
trade winds

Surface Winds on an Ideal Earth

- Hadley cell – air rises over the equator, flows poleward, and descends at about 30 degrees latitude

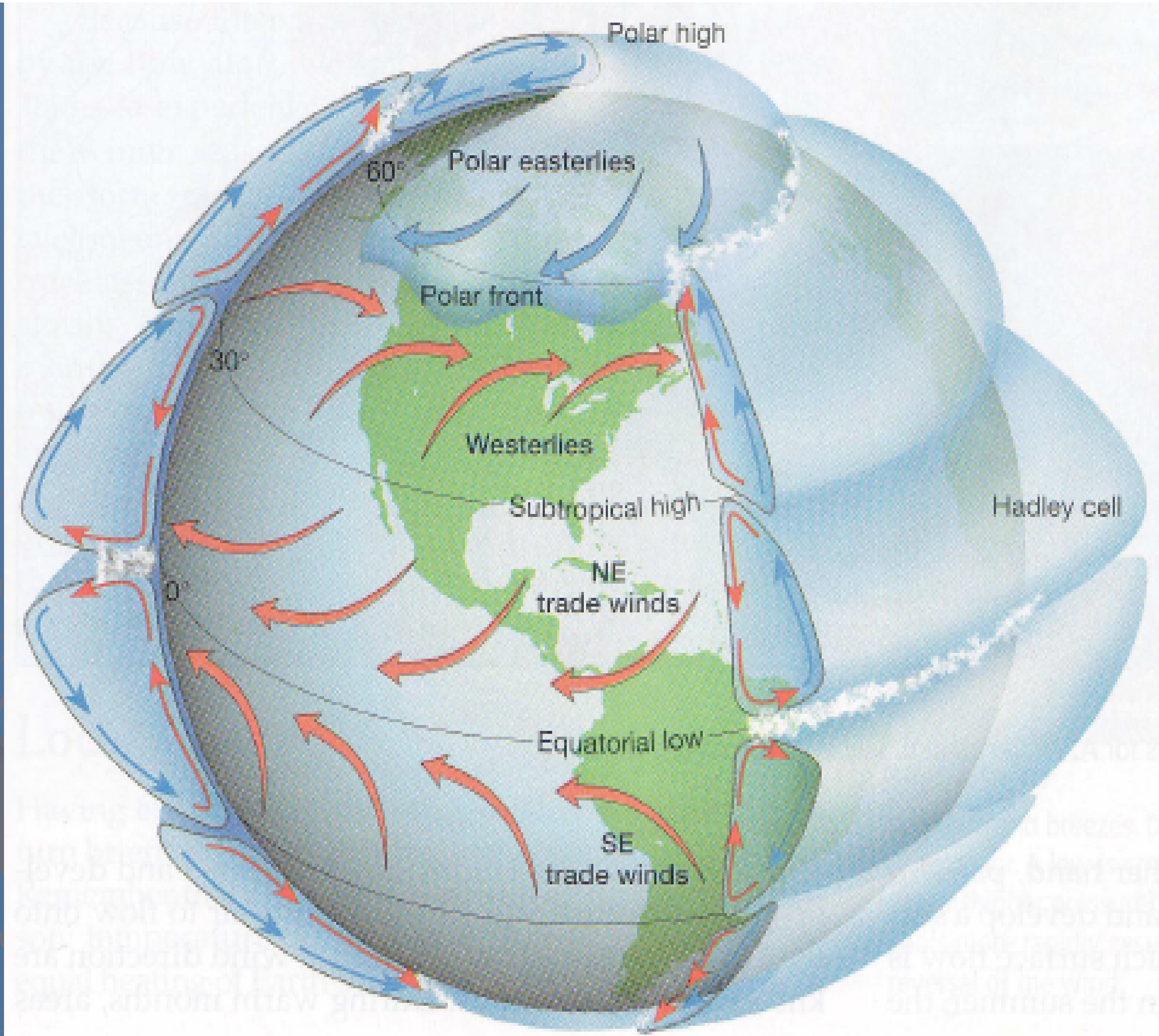
- Air converges toward the equator to replace the air that is moving aloft (Intertropical Convergence Zone)



Polar high
60°
Polar easterlies
Polar front
30°
Westerlies
Subtropical high
Hadley cell
NE
trade winds
0°
Equatorial low
SE
trade winds

Surface Winds on an Ideal Earth

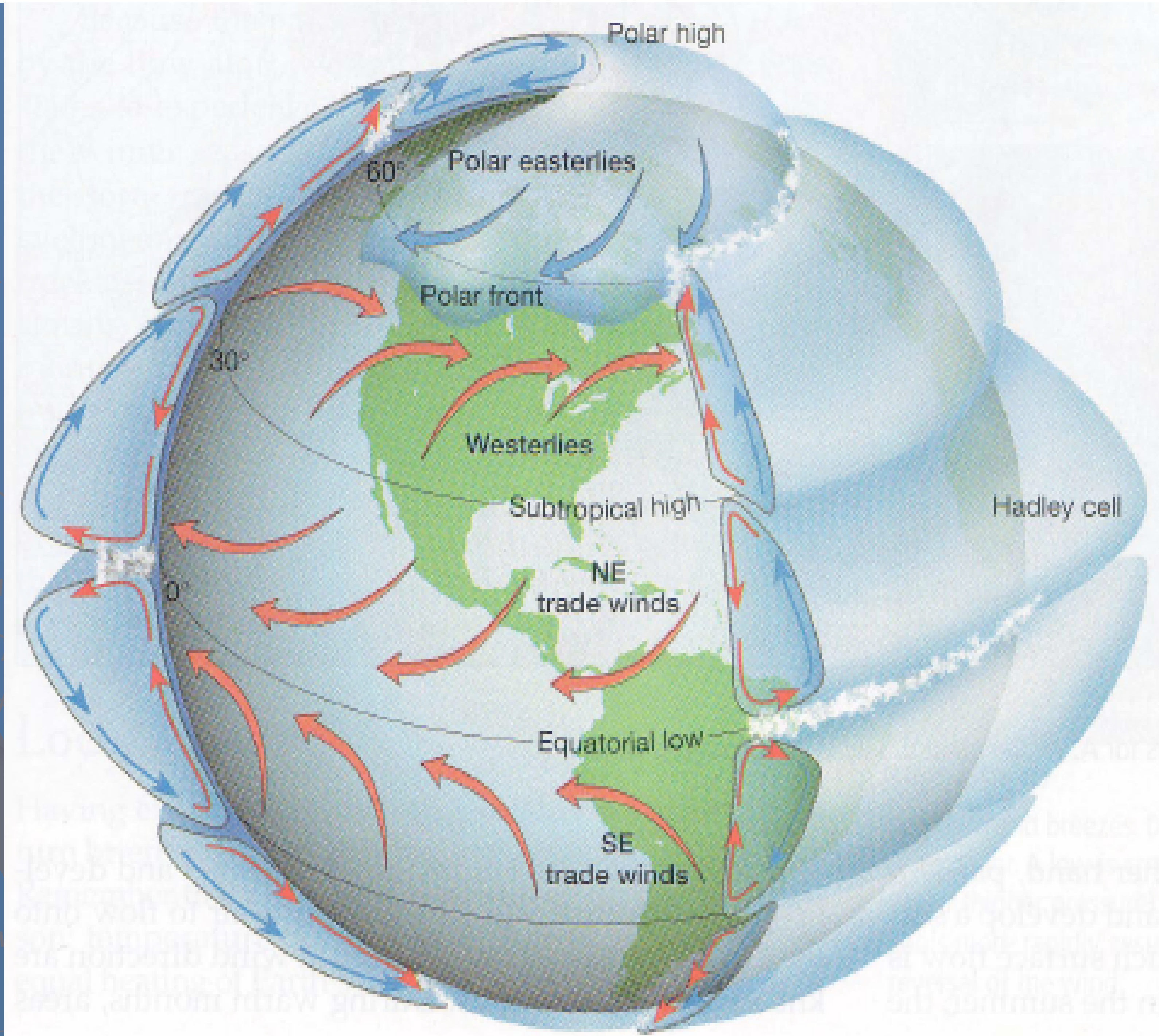
- Subtropical High Pressure Belts – poleward of the Hadley cell, air descends and surface pressures are high (at about 30 degrees latitude)
  - A number of large surface anticyclones are formed
  - Winds are weak at the center of these anticyclones
- Trade Winds – winds around the subtropical highs that are spiraling out
  - The winds moving equatorward are the strong and dependable trade winds
  - Northeast trades (NH), southeast (SH)



Polar high
Polar easterlies
60°
Polar front
30°
Westerlies
Subtropical high
Hadley cell
NE
trade winds
0°
Equatorial low
SE
trade winds

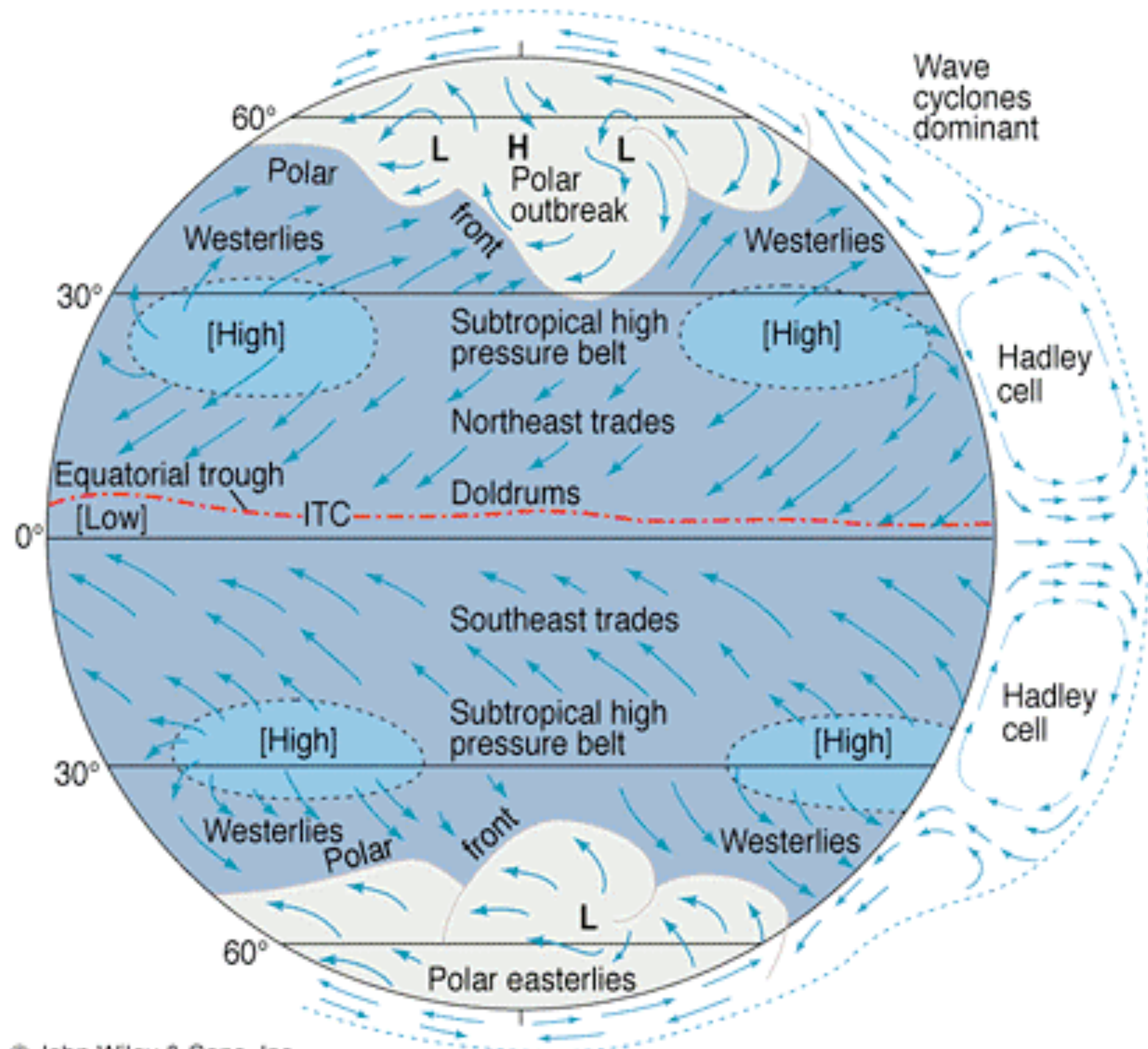
Surface Winds on an Ideal Earth

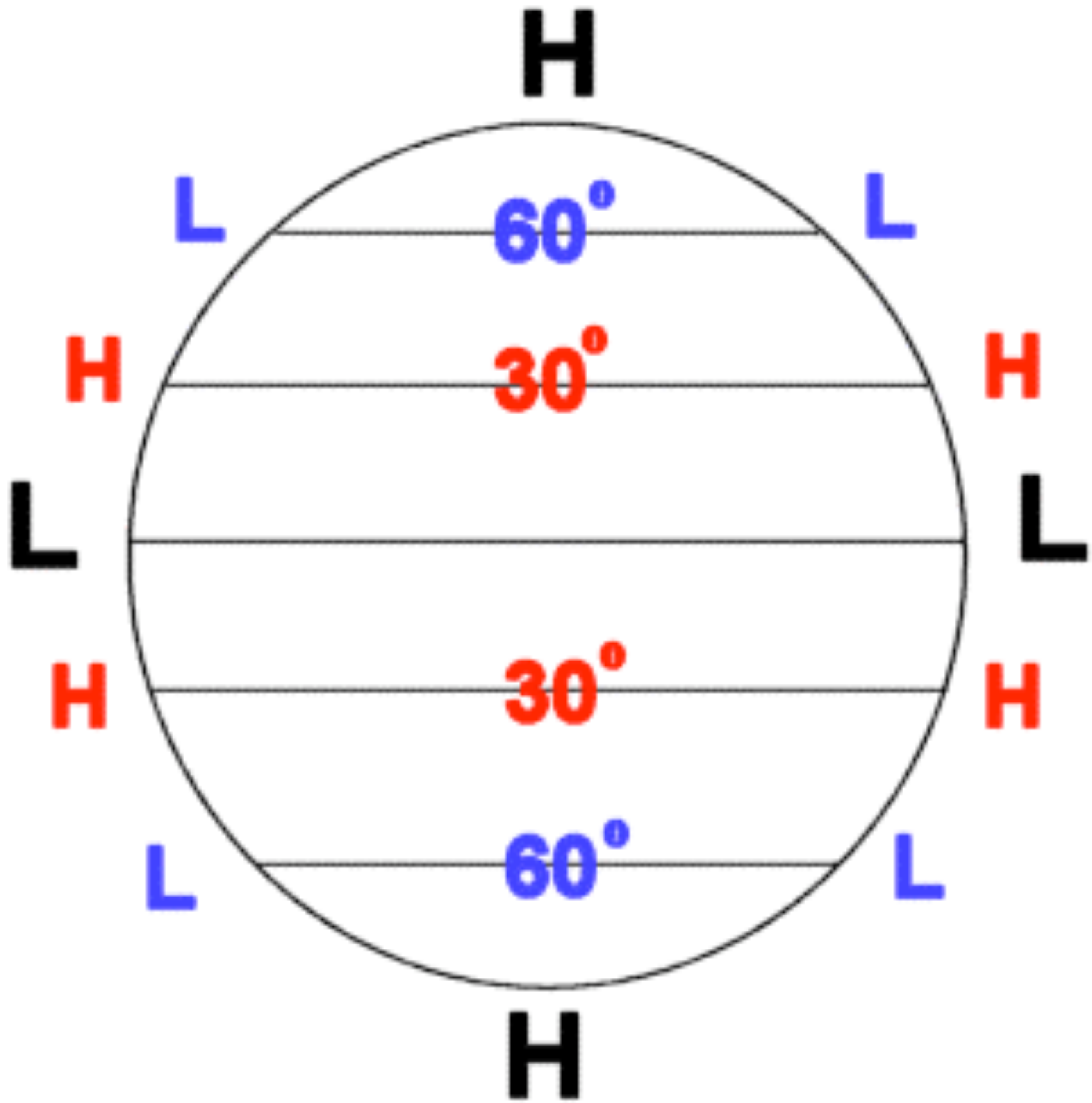
- Westerlies – poleward of the subtropical anticyclones, air spiraling outward produces the "westerlies"
  - Pressure and wind patterns are more complex in the mid-latitudes…. On average, winds are more often from the west
  - This latitudinal belt is a zone of conflict between air bodies with different characteristics… cool, dry air move into the region, from the pole (polar outbreaks)
  - The border is known as the polar front


Polar high
60°
Polar easterlies
Polar front
30°
Westerlies
Subtropical high
Hadley cell
NE
trade winds
0°
Equatorial low
SE
trade winds

Surface Winds on an Ideal Earth

- Polar Easterlies– at the poles, the air is intensely cold causing high pressure
  - Outspiraling of winds around a polar anticyclone should create polar easterlies


Wave cyclones dominant
60°
L
H
L
Polar
Polar outbreak
front
Westerlies
Westerlies
30°
[High]
Subtropical high pressure belt
[High]
Hadley cell
Northeast trades
Equatorial trough
Doldrums
[Low]
ITC
0°
Southeast trades
Hadley cell
[High]
Subtropical high pressure belt
[High]
30°
Westerlies
Polar
front
Westerlies
L
60°
Polar easterlies


H
L
60°
L
H
30°
H
L
L
H
30°
H
L
60°
L
H

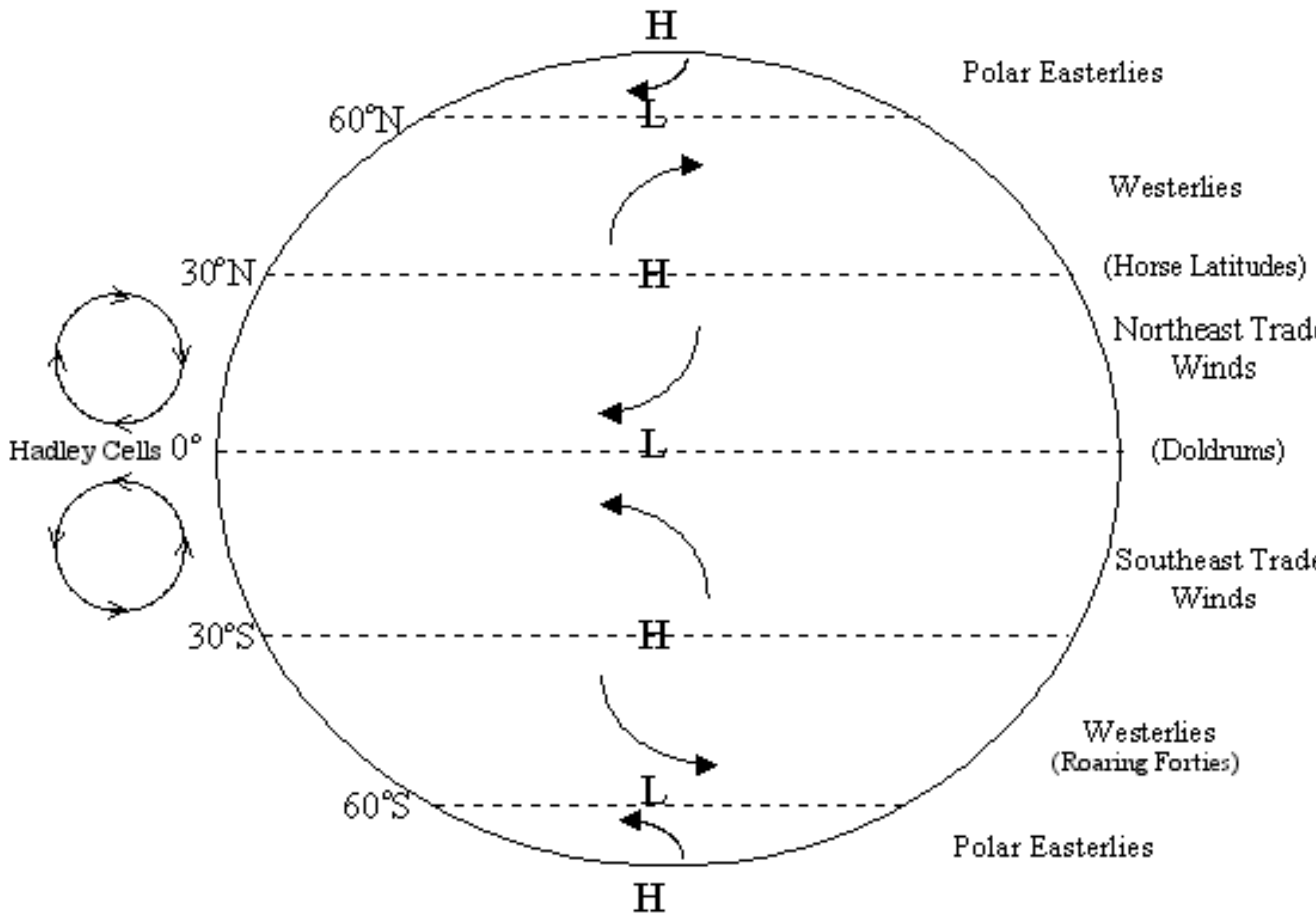


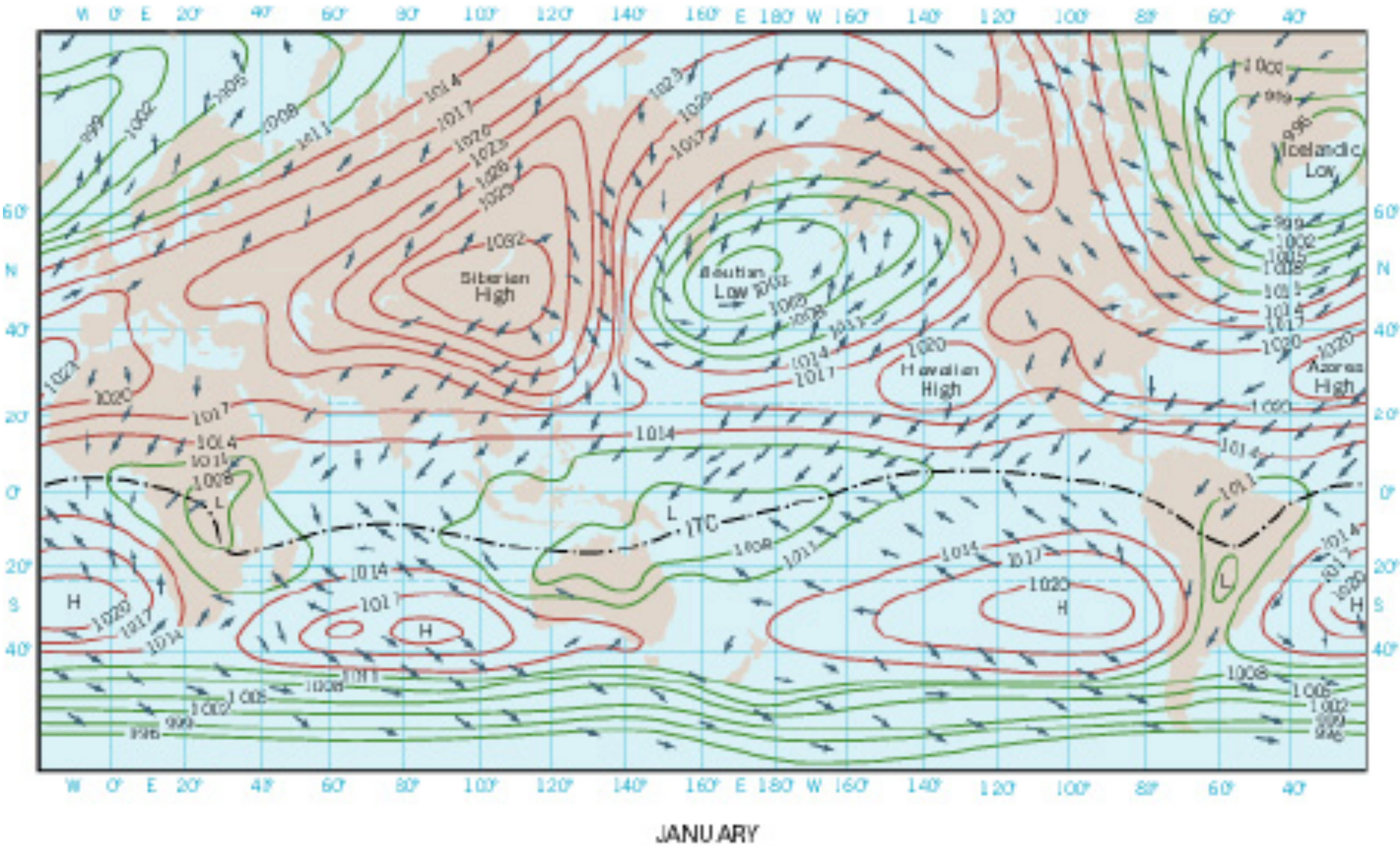
Figure 5-2: Winds for a homogeneous, rotating earth. Note that the Hadley Cells extend vertically in the troposphere whereas the other winds are surface winds.

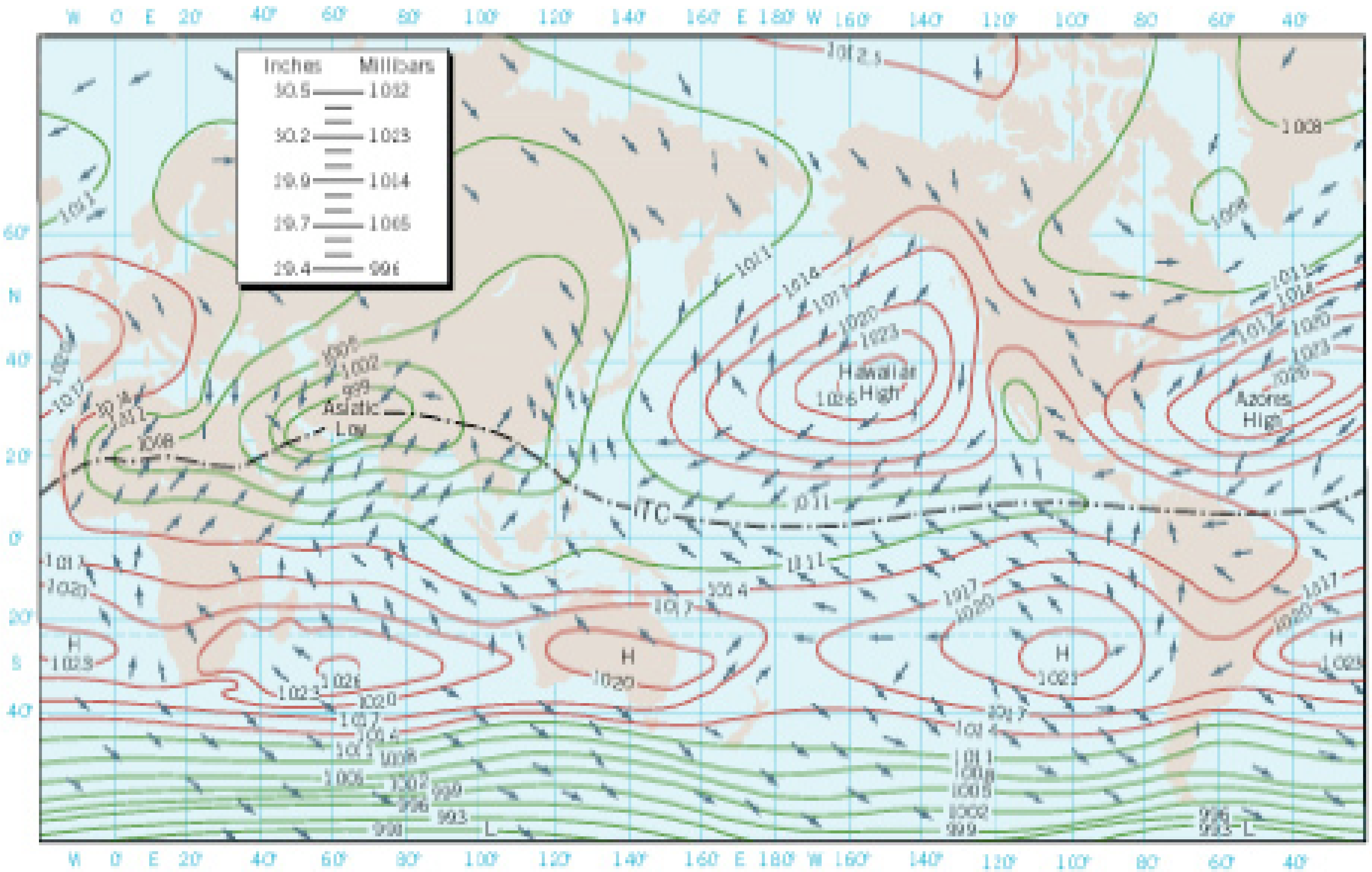
Winds and Global Circulation

This is the wind pattern on an idealized earth….

(no seasons, and no land/water contrasts)

On the real earth, we see more complex wind patterns that vary seasonally


Siberian High
Aleutian Low
Icelandic Low
Hawaiian High
Azores High
ITC
JANUARY

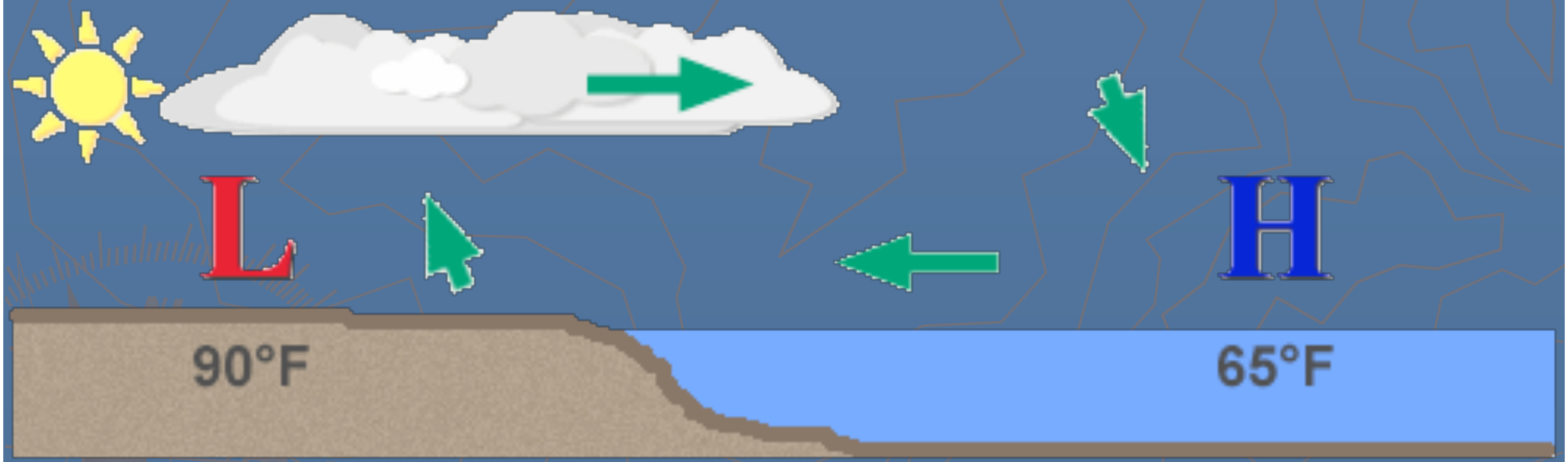


Inches Millibars
30.5 1032
30.2 1023
29.9 1014
29.7 1005
29.4 996
Asiatic Low
Hawaiian High
Azores High
ITC
H
L

JULY

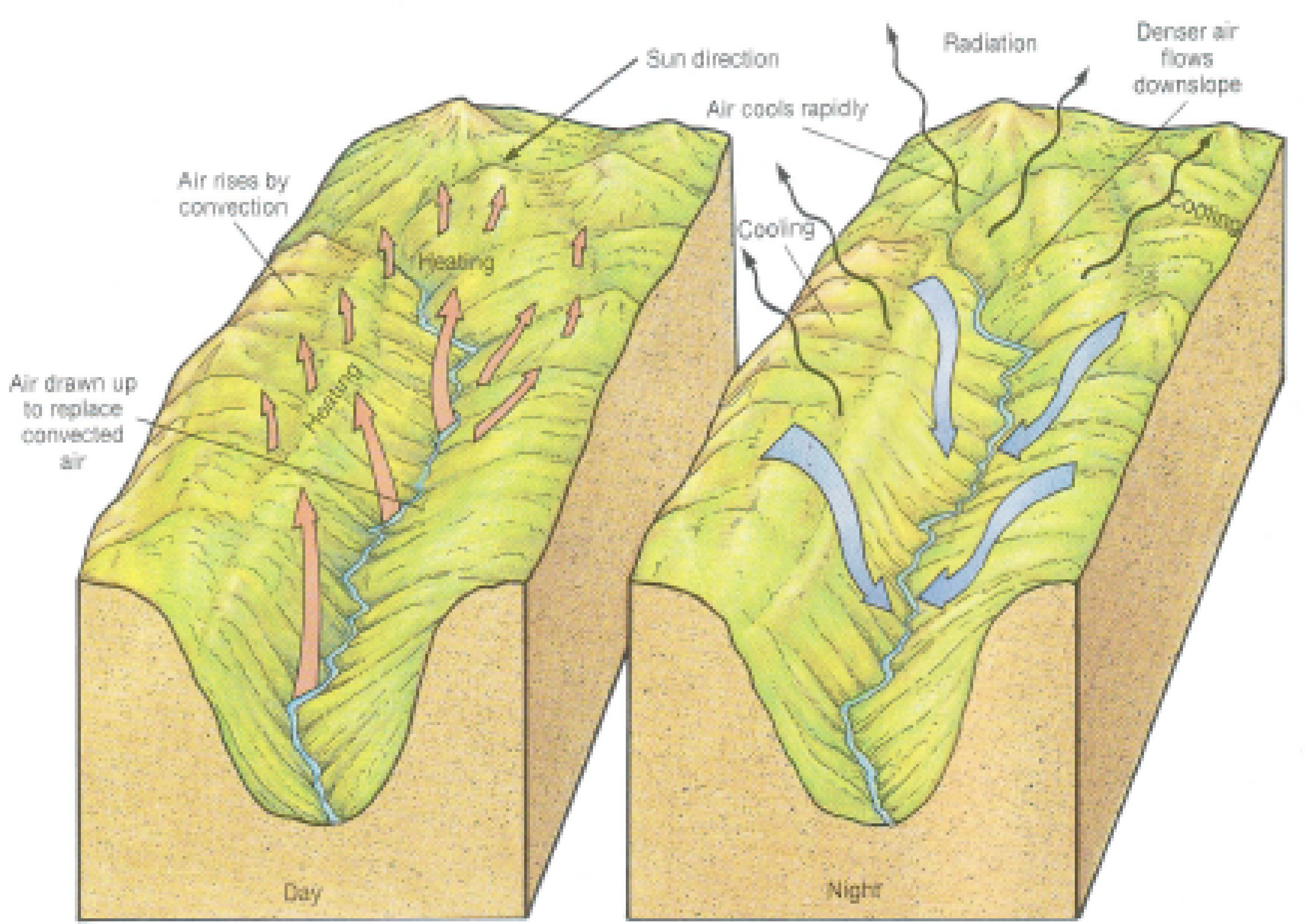
Local Winds

A Sea Breeze



A Land Breeze

Mountain and Valley Winds



Mountain and Valley Winds

- Local winds that alternate in direction like the land and sea breezes

Mountain Winds – during the day, mountain side is heated intensely by the sun, causing air to rise. This causes wind to blow from the plains below, up the mountain slopes

Valley Winds – At night, the mountain cools rapidly. The cooler, denser hill slope air then flows down the valley to the plains below

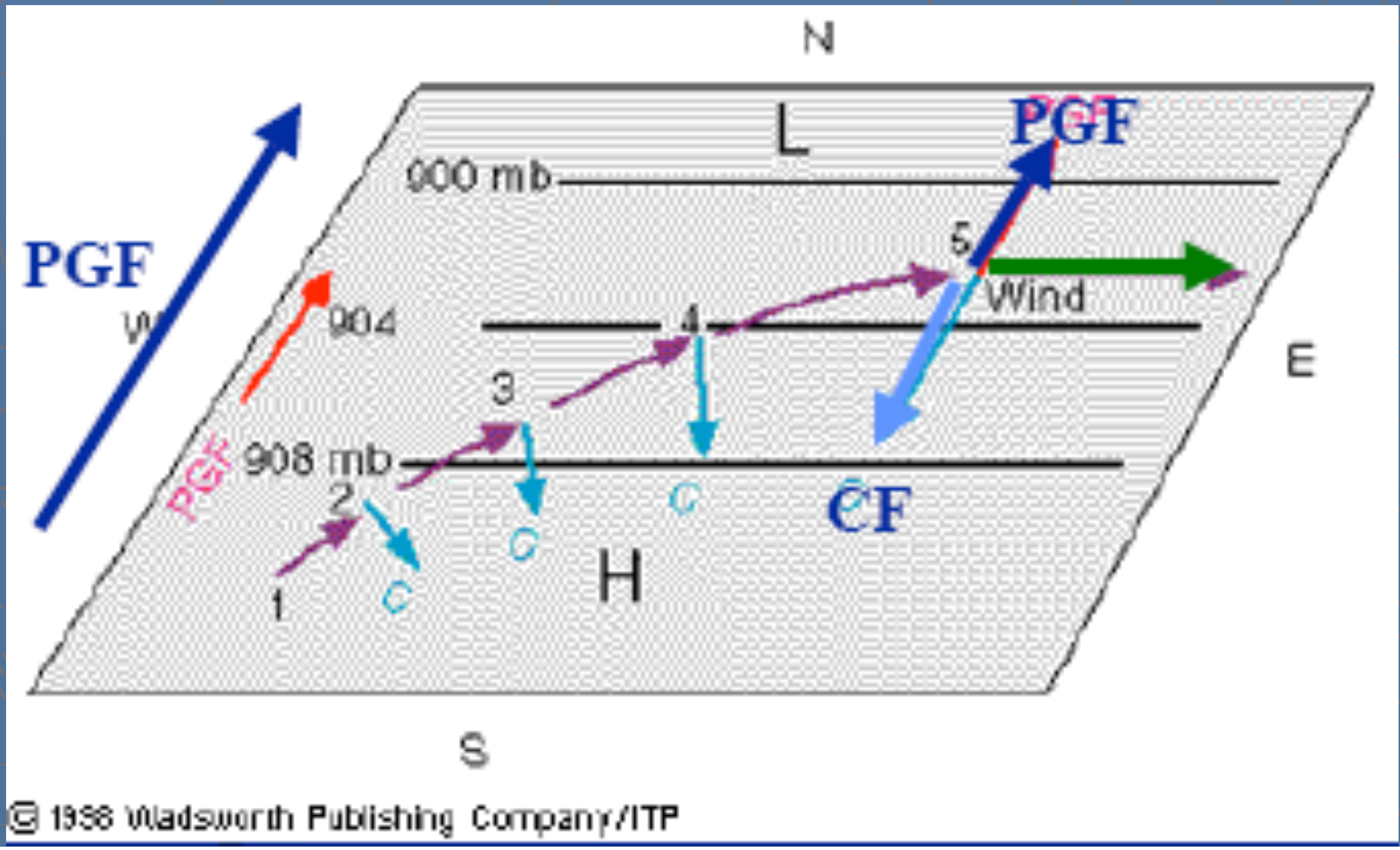
Upper Level Winds

Geostrophic Winds: are influenced by pgf and coriolis

- Winds flow perpendicular to the pressure gradient
- These winds are often called "jet streams"

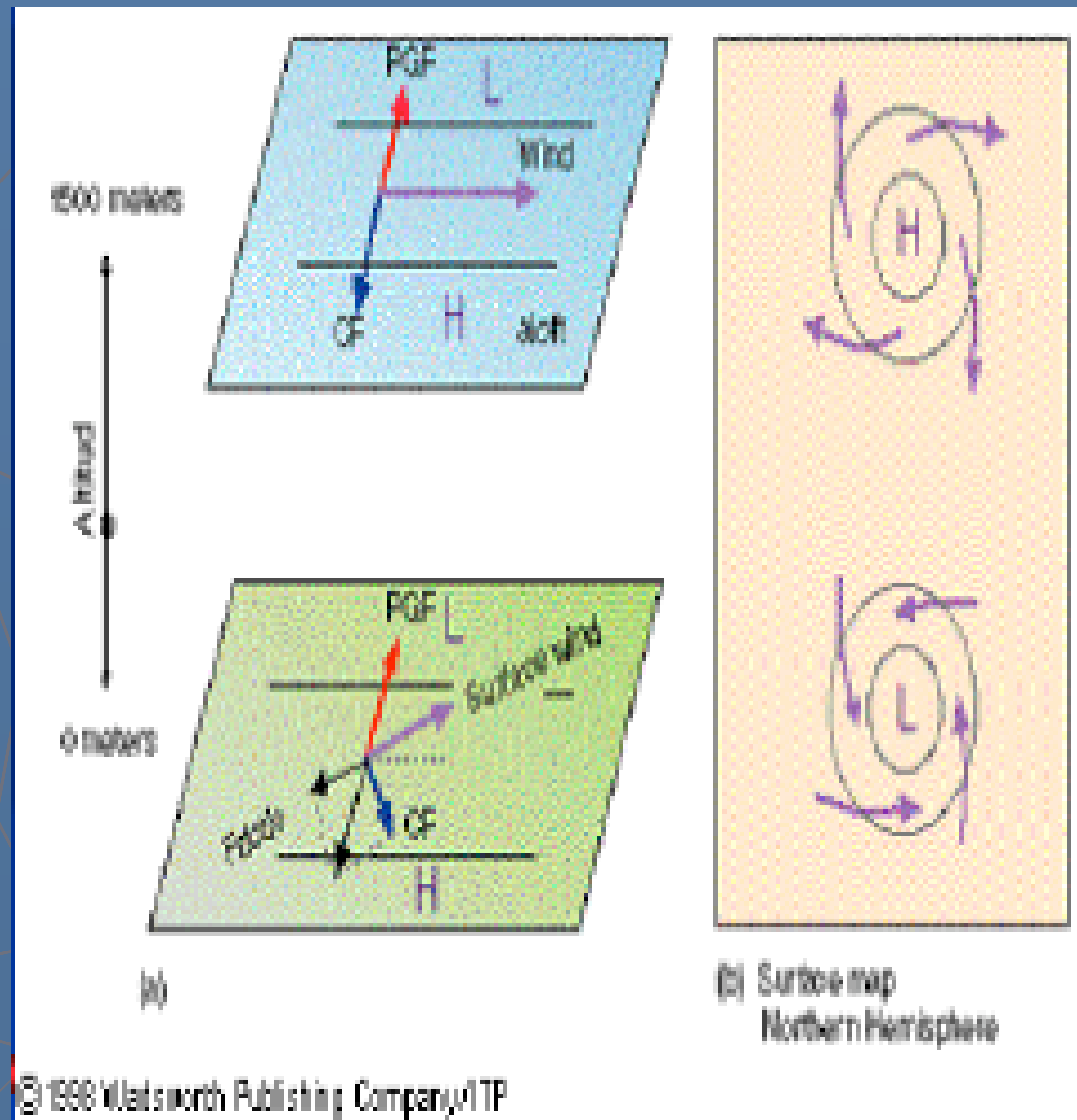
Upper Level Winds

Geostrophic Winds: occurs in the upper atmosphere (no friction)



Surface Winds

- Friction reduces the wind velocity which reduces the coriolis f
- Coriolis f no longer balances the PGF, so wind blows across the isobars toward the Low



Upper Level Winds

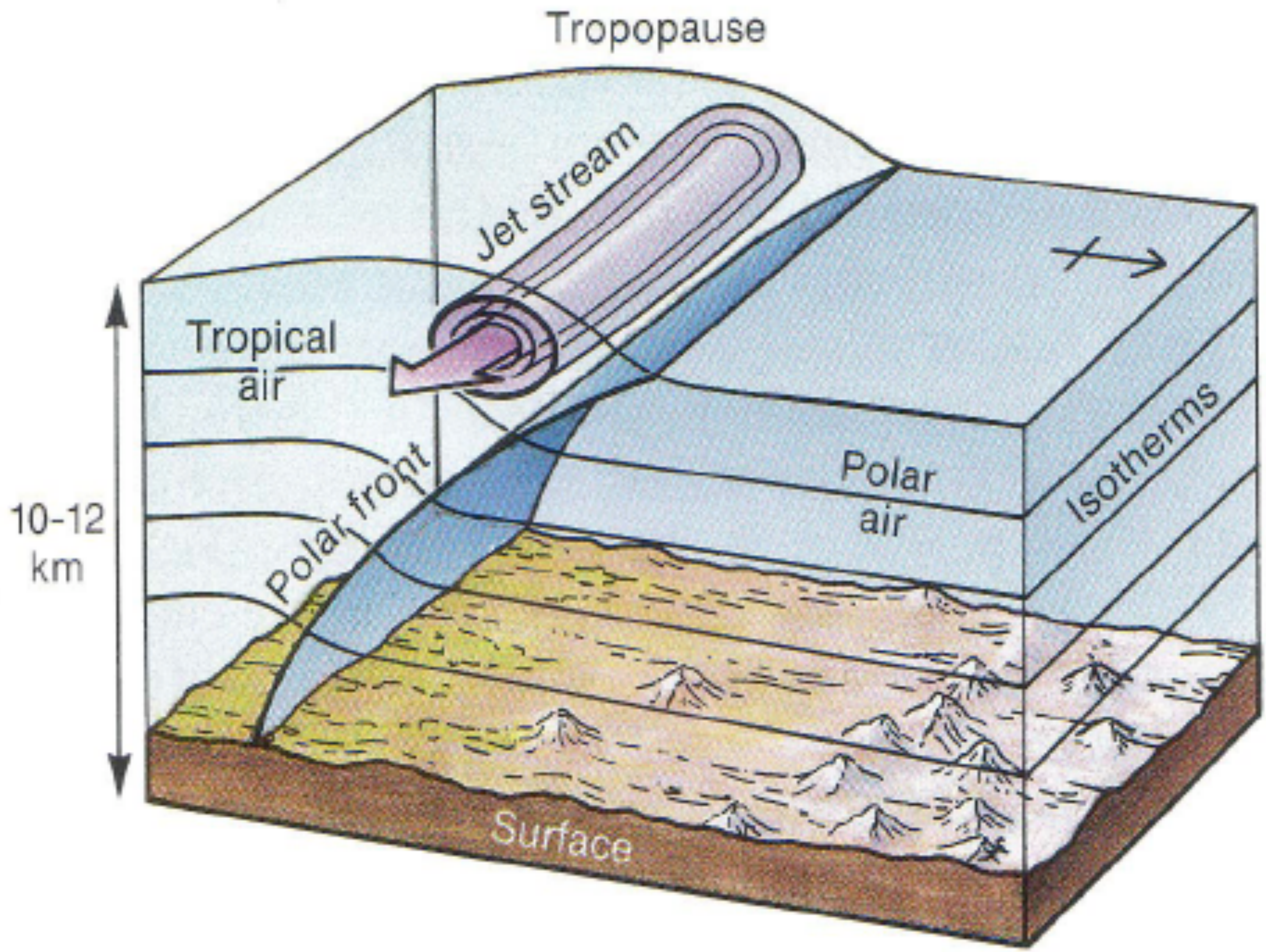
Jet Streams = narrow zones of very fast winds at a high altitude (top of the troposphere, lower part of the stratosphere)

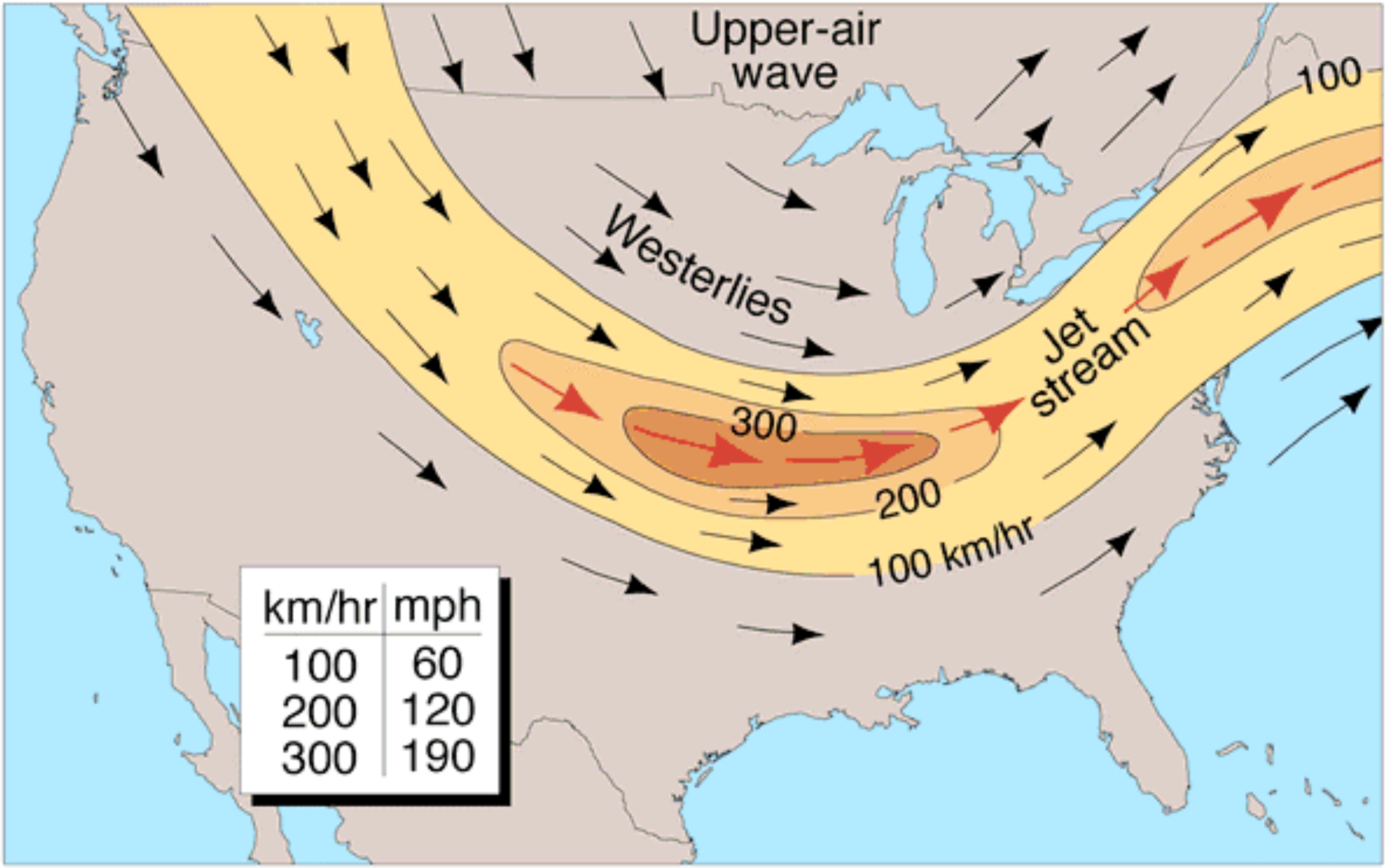
Polar-Front Jet Stream: located along the polar front (fluctuating boundary between cold polar air and warmer tropical air)

windspeeds of ~ 400km/hr (225 mph)

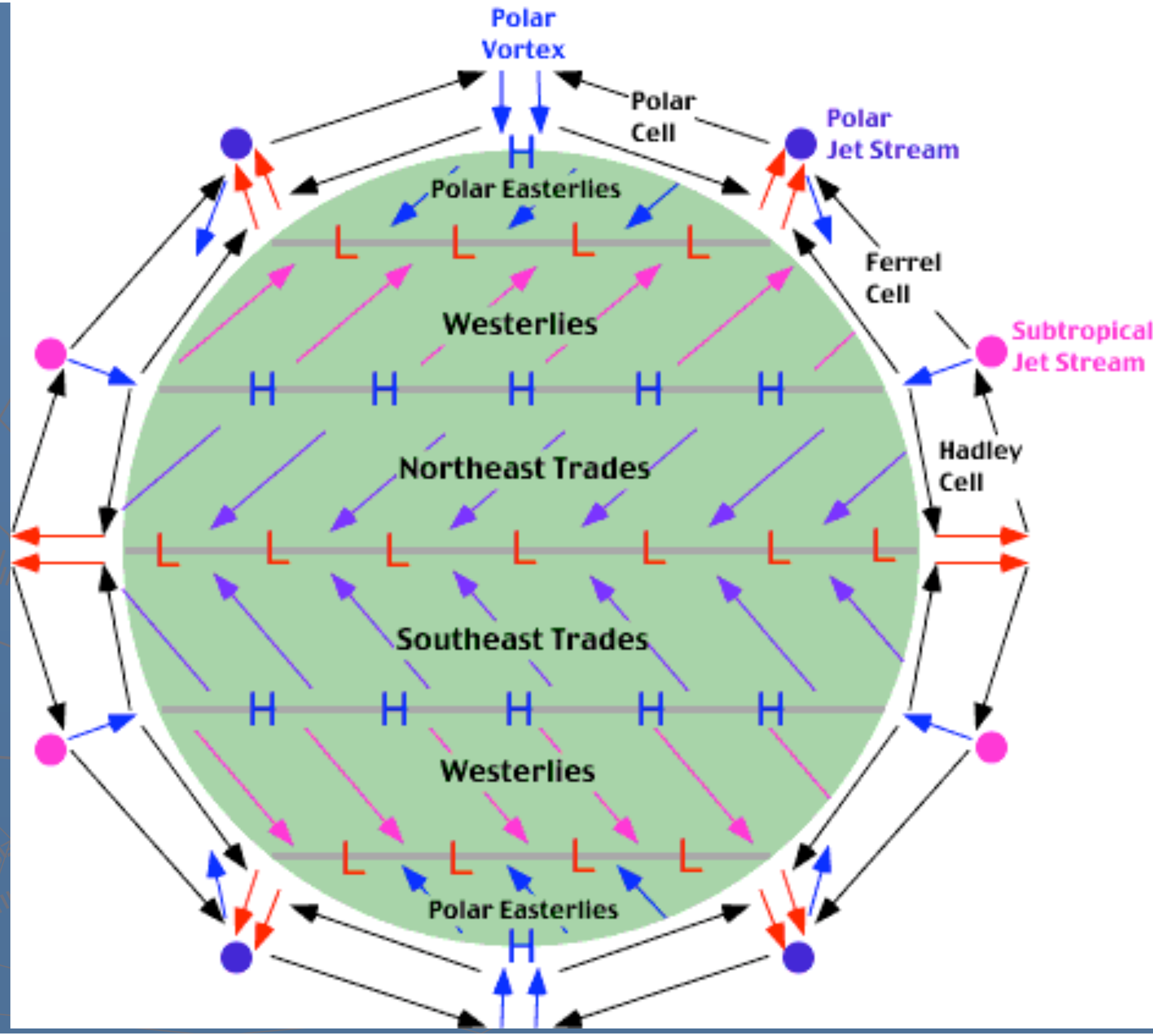
Subtropical Jet Stream: located in the subtropics at the tropopause just above the Hadley cell

windspeeds of ~ 350 km/hr (200 mph)


Tropopause
Jet stream
Tropical
air
10-12
km
Polar front
Polar
air
Isotherms
Surface



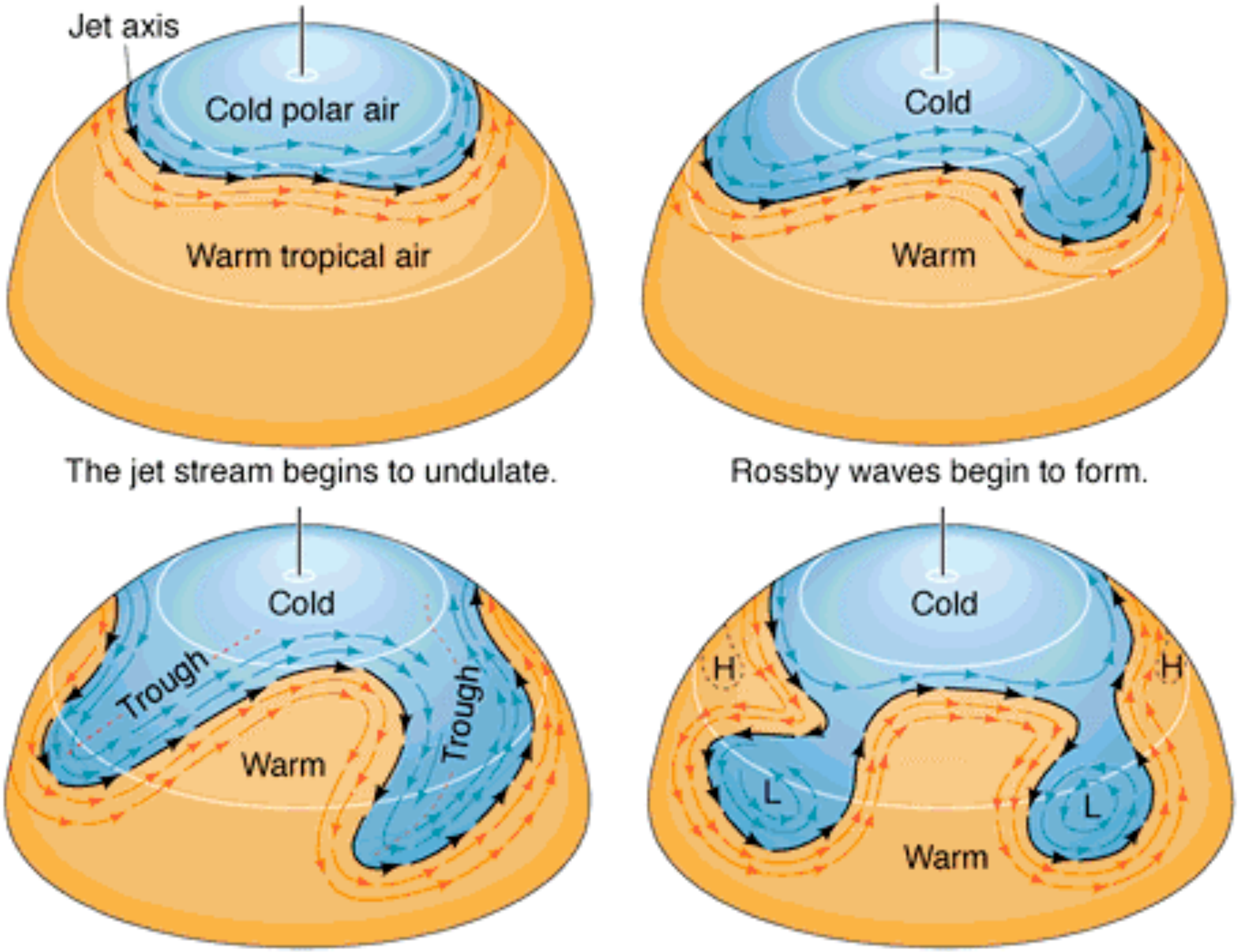
National Weather Service.


Polar Vortex
Polar Cell
Polar Jet Stream
Polar Easterlies
Ferrel Cell
Westerlies
Subtropical Jet Stream
Hadley Cell
Northeast Trades
Southeast Trades
Westerlies
Polar Easterlies

Rossby Waves

Rossby Waves = undulations in the polar jet streams

- The waves arise in a zone of contact between cold polar air and warm tropical air
- As a result, warm air pushes north and cold air is brought south
- Eventually, the air mass intrusions are cut off, leaving a pool of cold air at a latitude far south of its normal location



The jet stream begins to undulate.

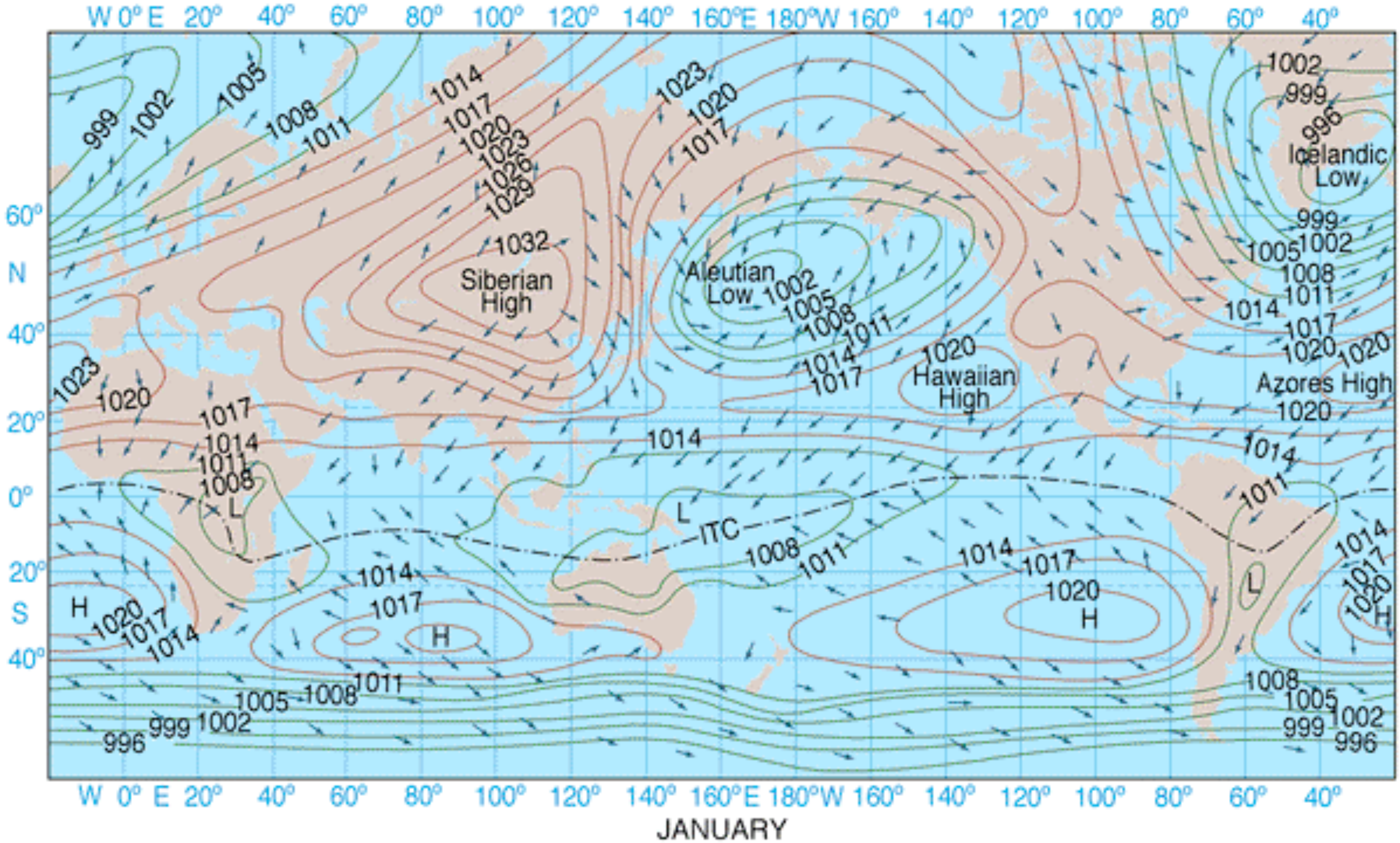
Rossby waves begin to form.

Waves are strongly developed. The cold air occupies troughs of low pressure.

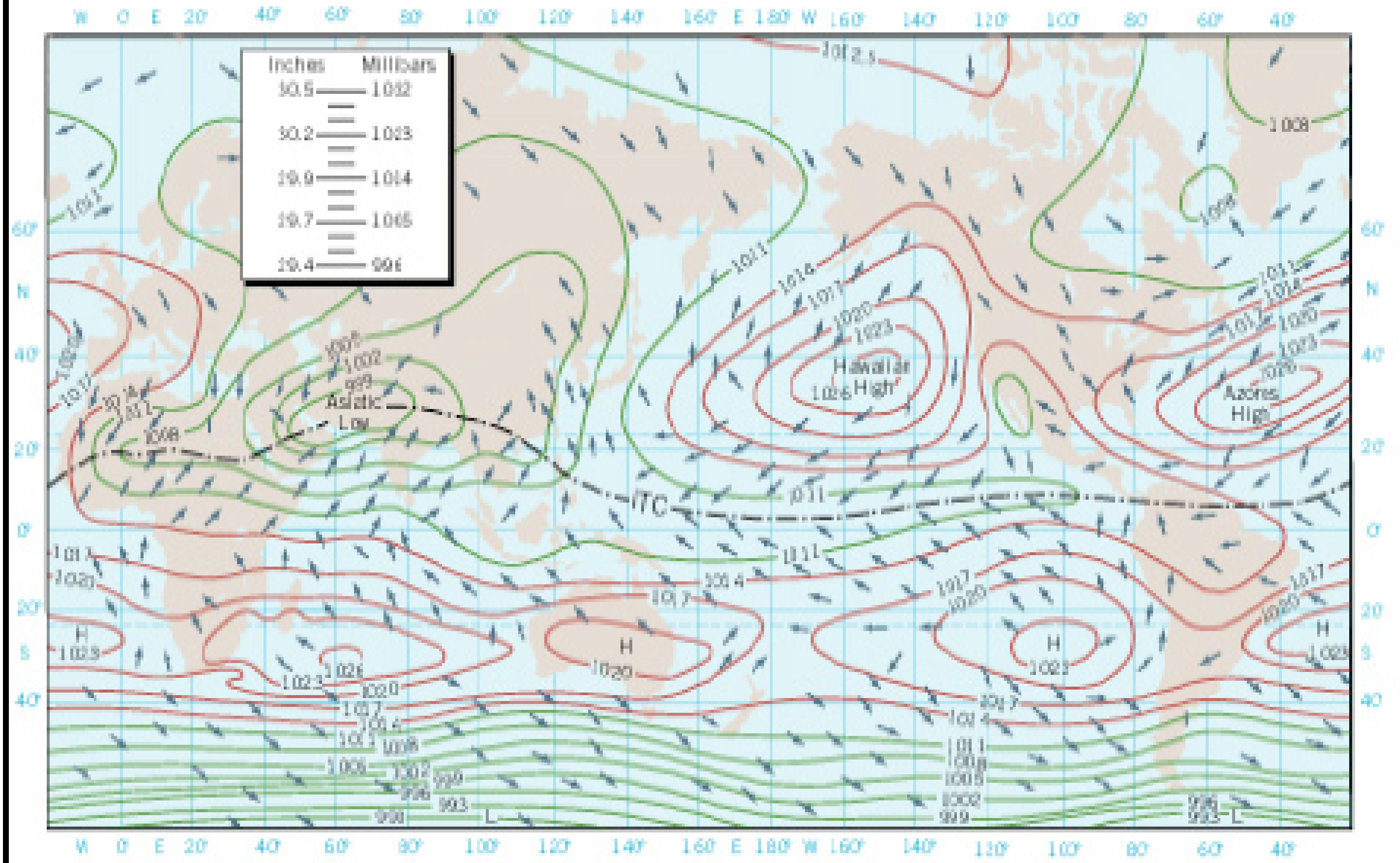
When the waves are pinched off, they form cyclones of cold air.

Heterogeneous, Rotating Earth

- Land/Water differences in pressure systems
- In Winter, differences are pronounced at about 60° latitude
  - Highs over land, Lows over water
- In Summer, differences are pronounced at about 30° latitude
  - Lows over land, Highs over water



Data compiled by John E. Oliver.


Inches Millibars
30.5 1032
30.2 1023
29.9 1014
29.7 1005
29.4 996
Asiatic Low
Hawaiian High
Azores High
ITC

JULY

Summary of the Forces

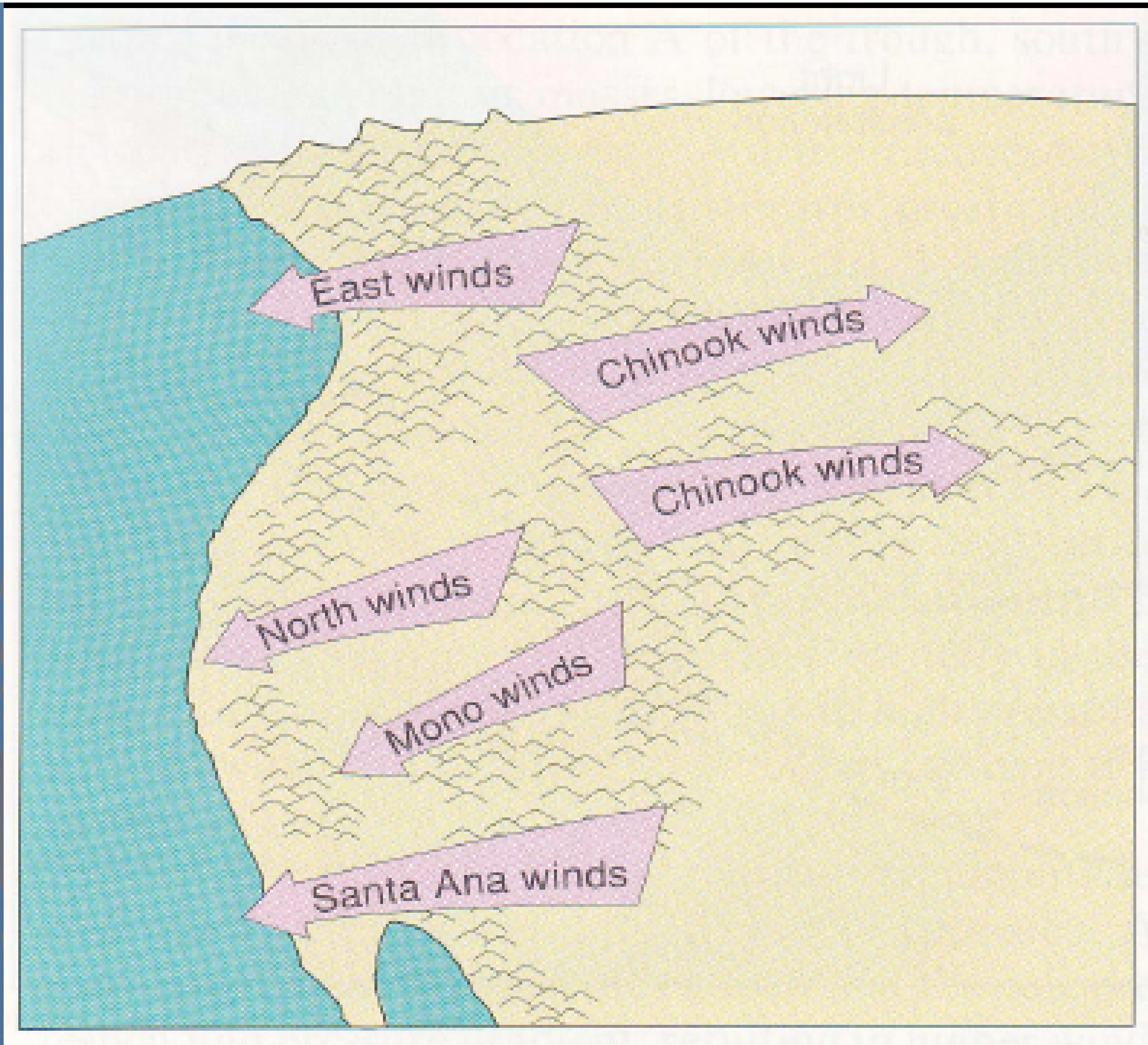
- A parcel of air in motion near the surface is subjected to *three influences*:
  I. Pressure Gradient Force
  II. Coriolis Force
  III. Friction

- Therefore, air will move away from high to low pressure at an angle to the pressure gradient

Local Winds

- Drainage Winds – occur when cold, dense air flows under the influence of gravity from higher to lower regions (occurs around mountains and ice sheets)

- Chinook Winds – occur on the leeward side of mountains. The descending air is heated and dried thus producing hot and dry winds


East winds
Chinook winds
Chinook winds
North winds
Mono winds
Santa Ana winds

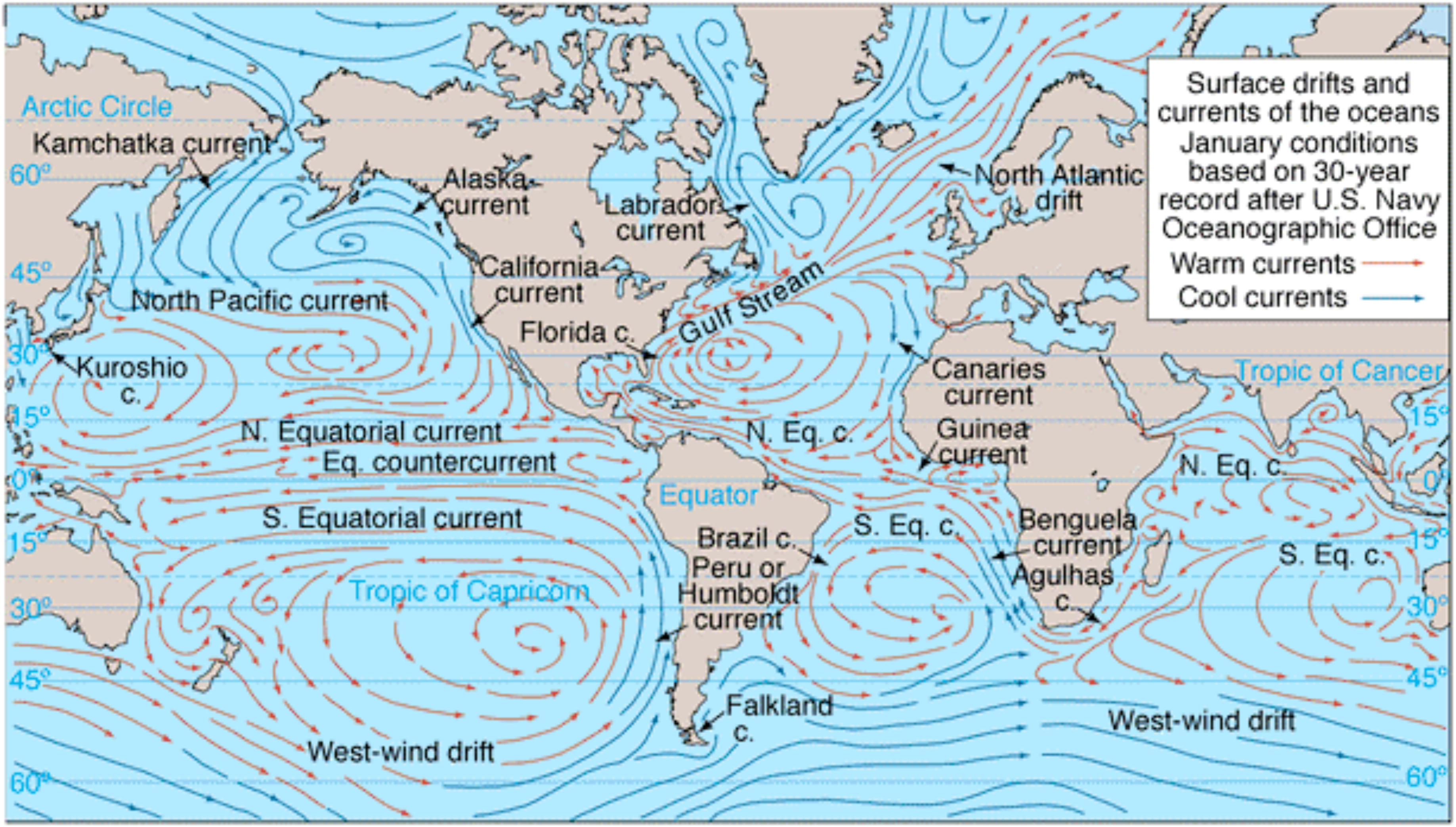
Oceanic Circulation

- Circulation of the Oceanic Mixed Layer

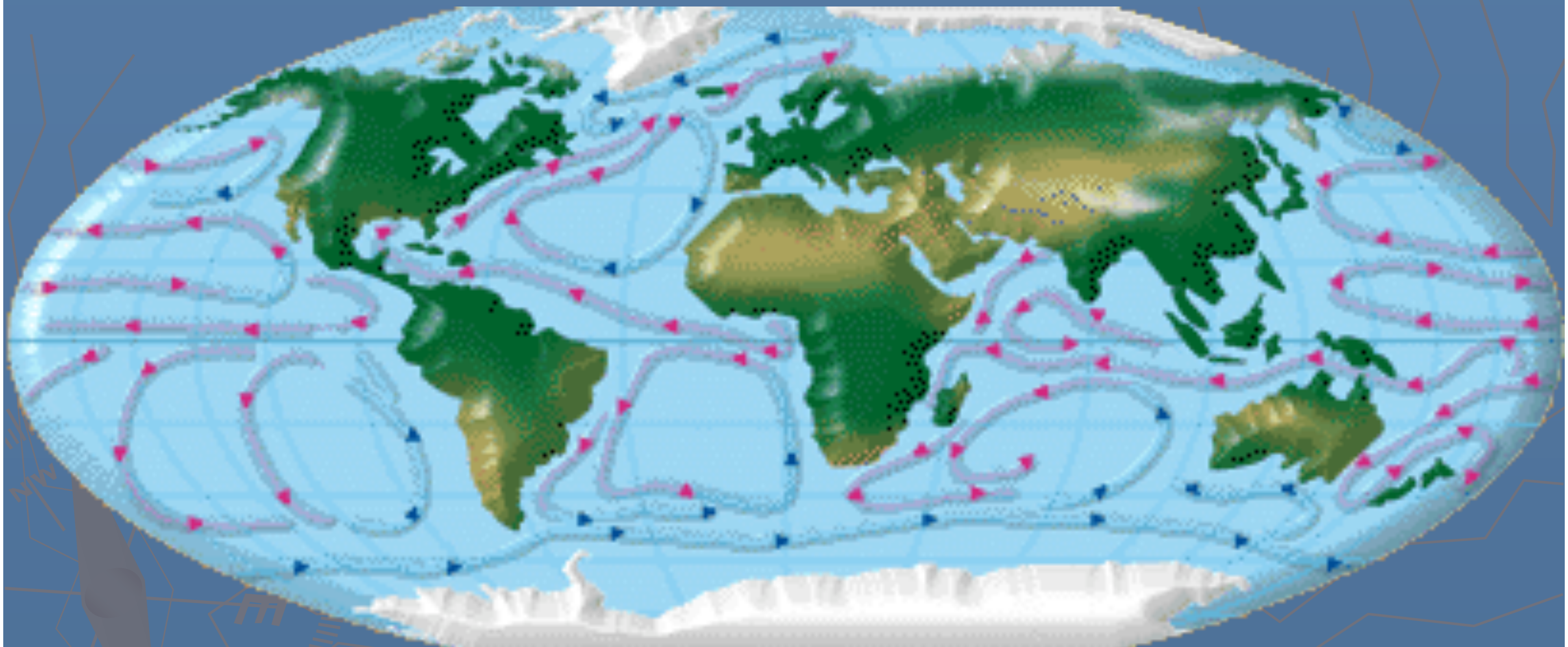
- Wind-driven
  - "The Wind Sets the Ocean in Motion"

- Since the ocean is a bounded basin, oceanic flow will be in a circular motion – ***Gyres***

- Unlike winds, ocean currents are defined in the direction ***to*** which they flow
  - *e.g.*, a flow from south to north in the Northern Hemisphere is called either a northerly current or a warm current

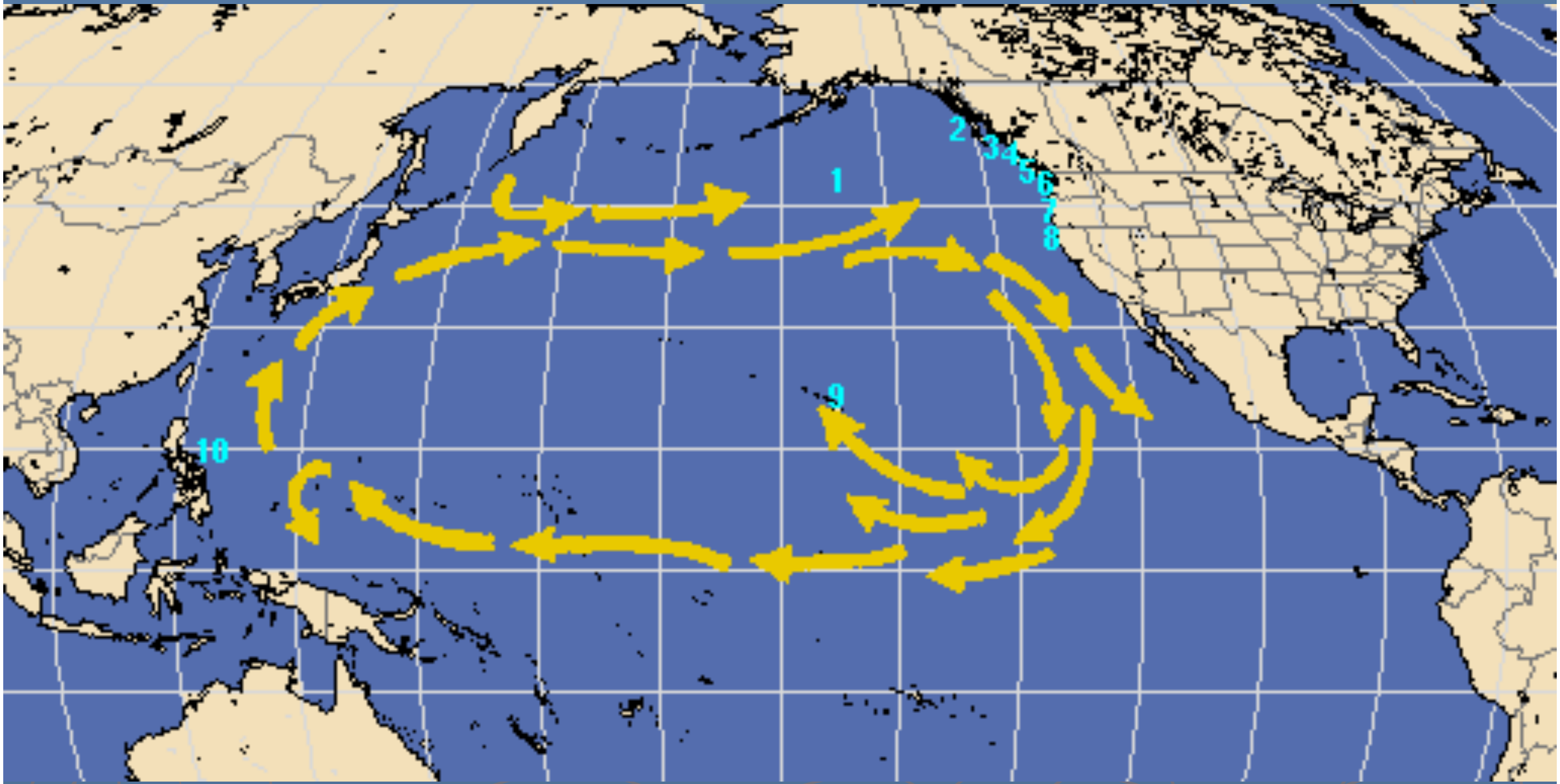


Based on data from U.S. Navy Oceanographic Office. Redrawn and revised by A.N. Strahler.



Several of the 60,000 Nike shoes spilled in May 1990

Nike Shoe Spill – May 27, 1990



Courtesy: Ocean Planet, The Smithsonian Institute