ATOC 3500: Air Chemistry & Pollution

Guest Lecture: Atmospheric Circulation

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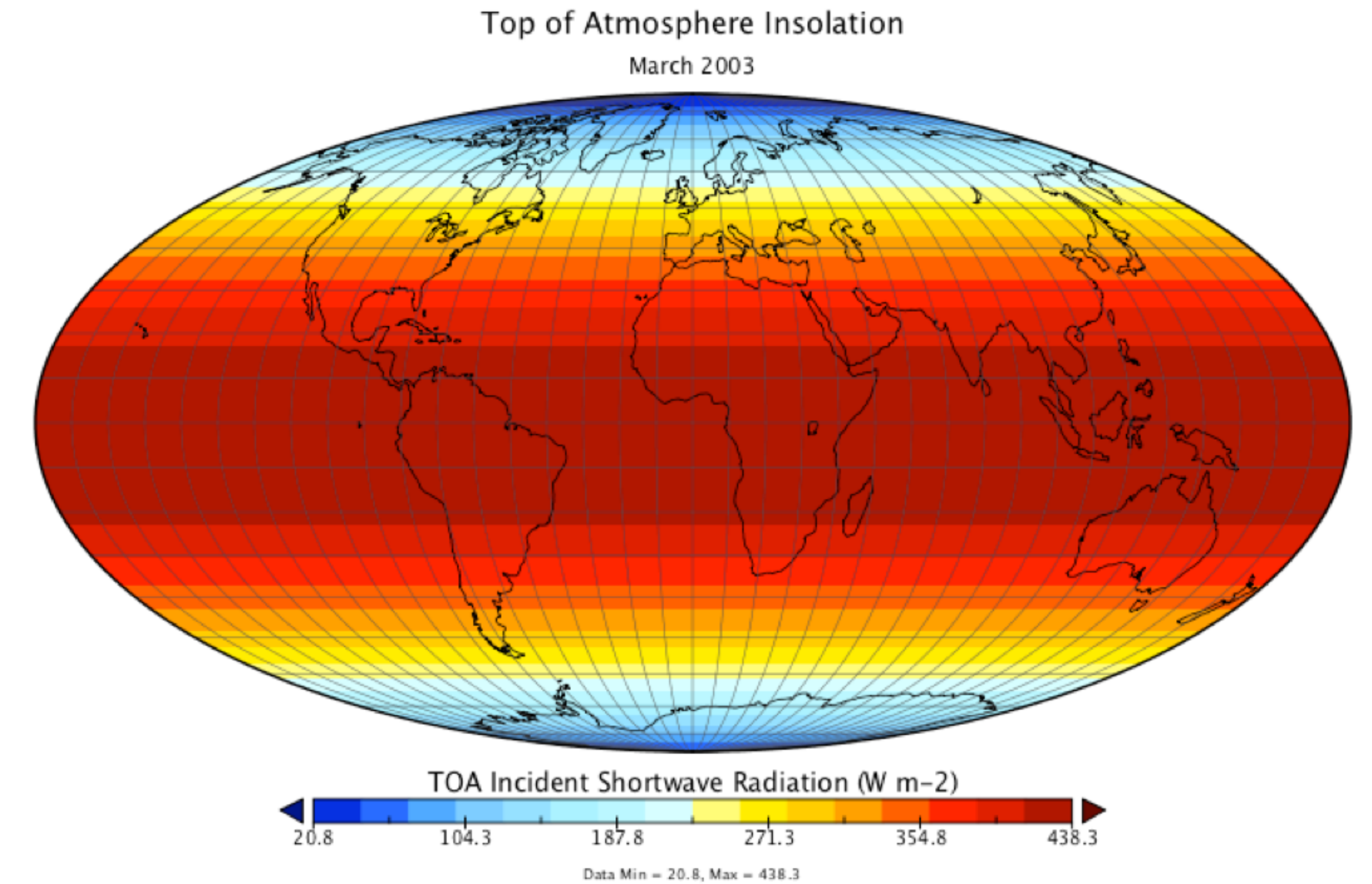
Learning outcomes for today

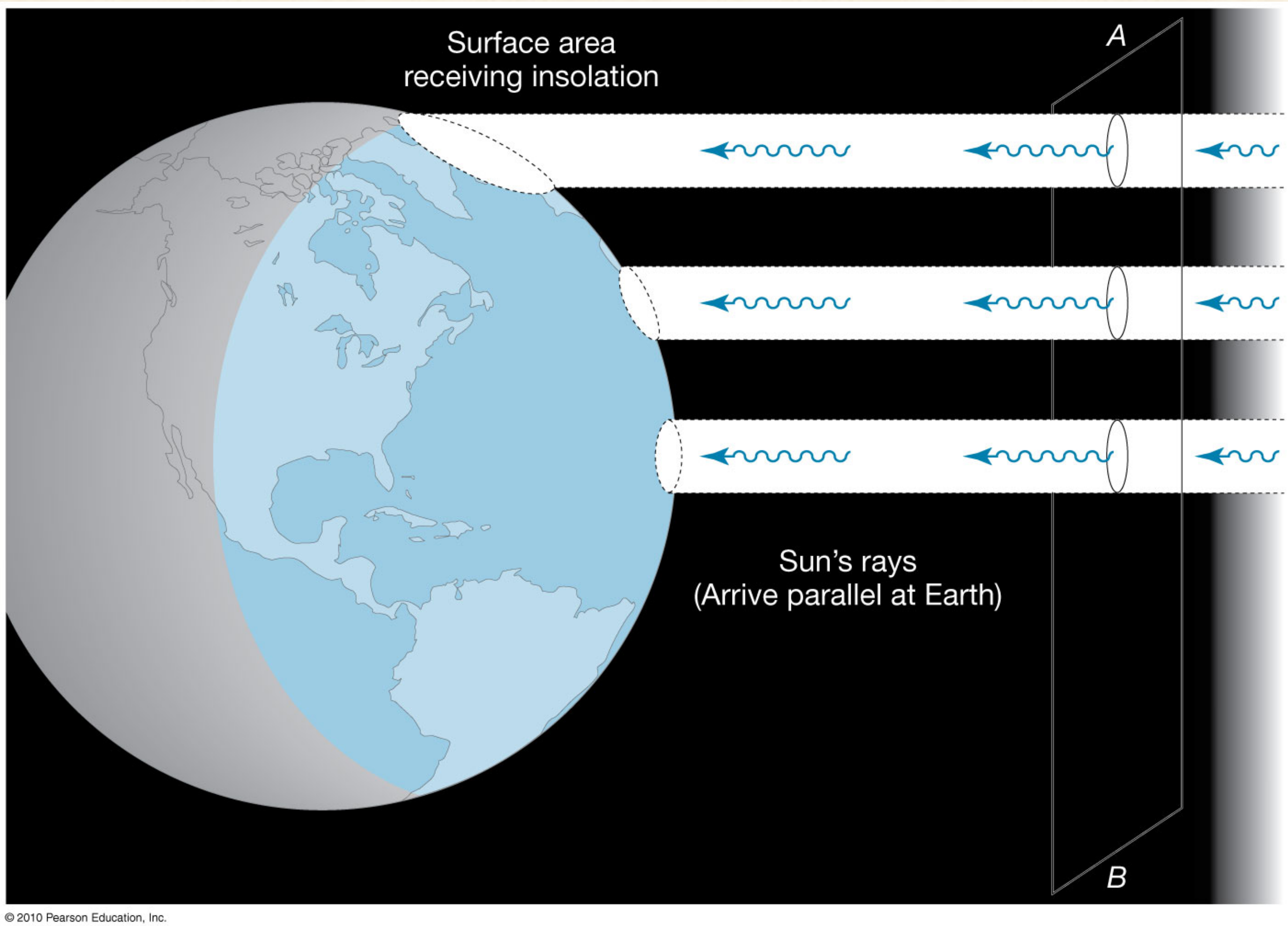
- Understand why air rises and sinks and moves horizontally in the atmosphere
- Discuss how advection and convection transport heat from the tropics to the poles
- Understand the Coriolis effect and its effect on air circulation
- Understand how atmospheric circulation cells affect climate on Earth's surface (e.g., deserts, rain bands)
- Understand regional circulation impacts on pollution mixing and dispersal

Incoming radiation at the top of the atmosphere

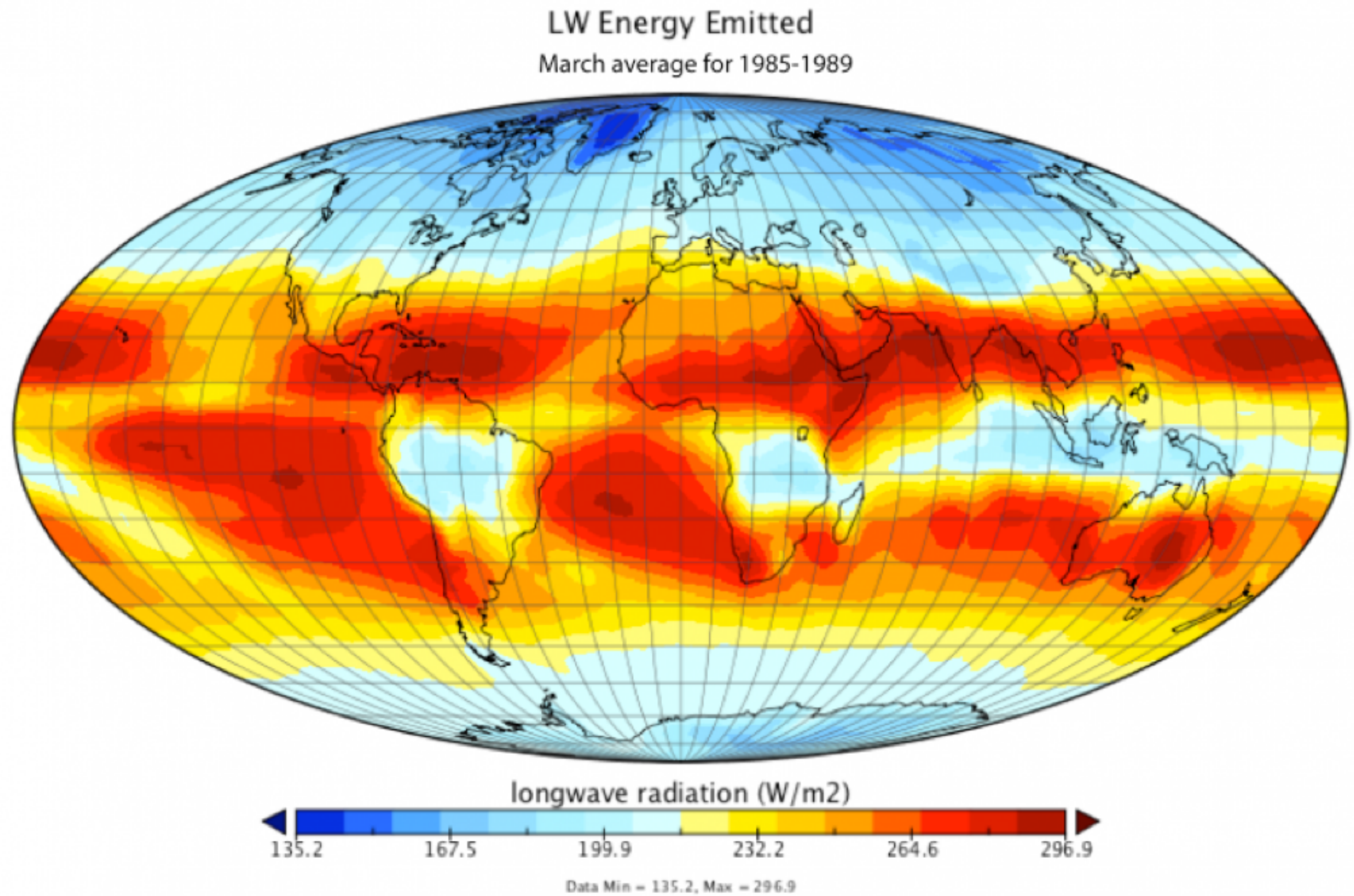


Review: Why are the tropics warmer than the poles?

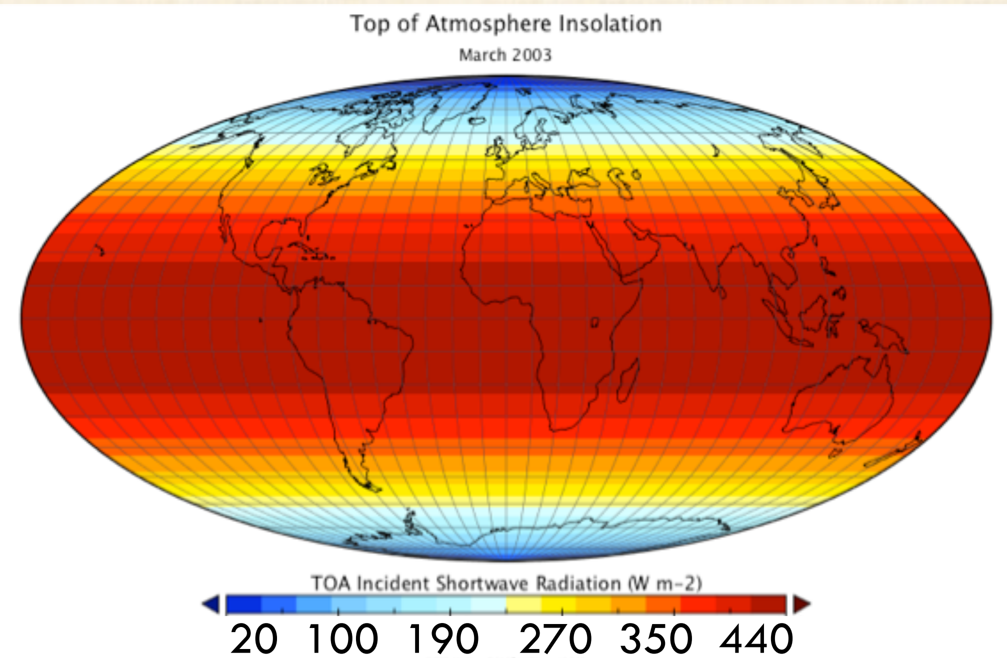
The tropics get more overhead sun than the poles

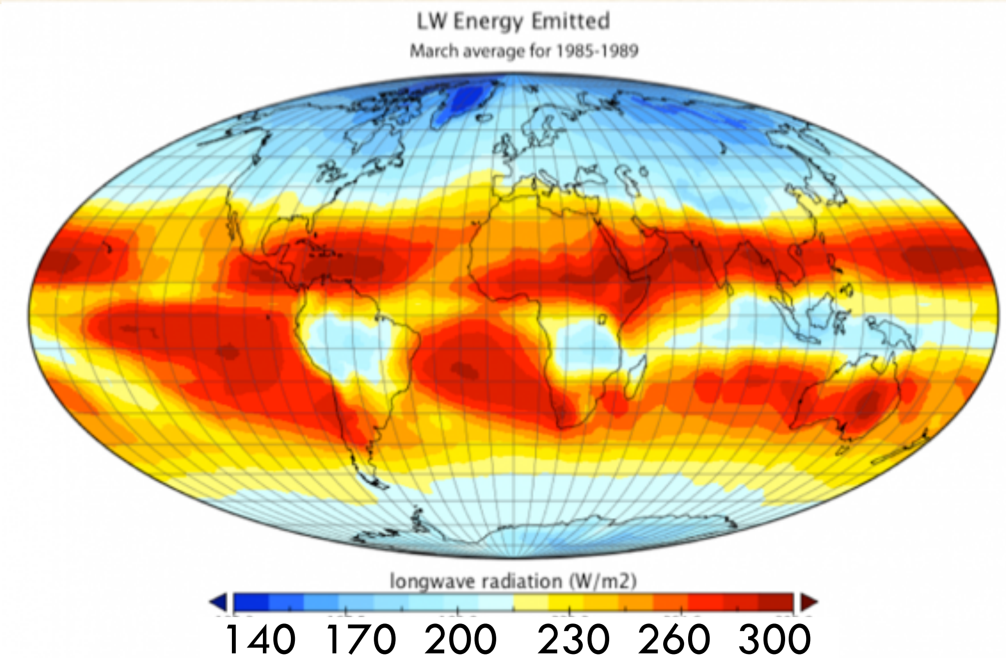


Outgoing radiation at the top of the atmosphere



The balance of radiation at TOA





Which region loses energy at TOA on average?

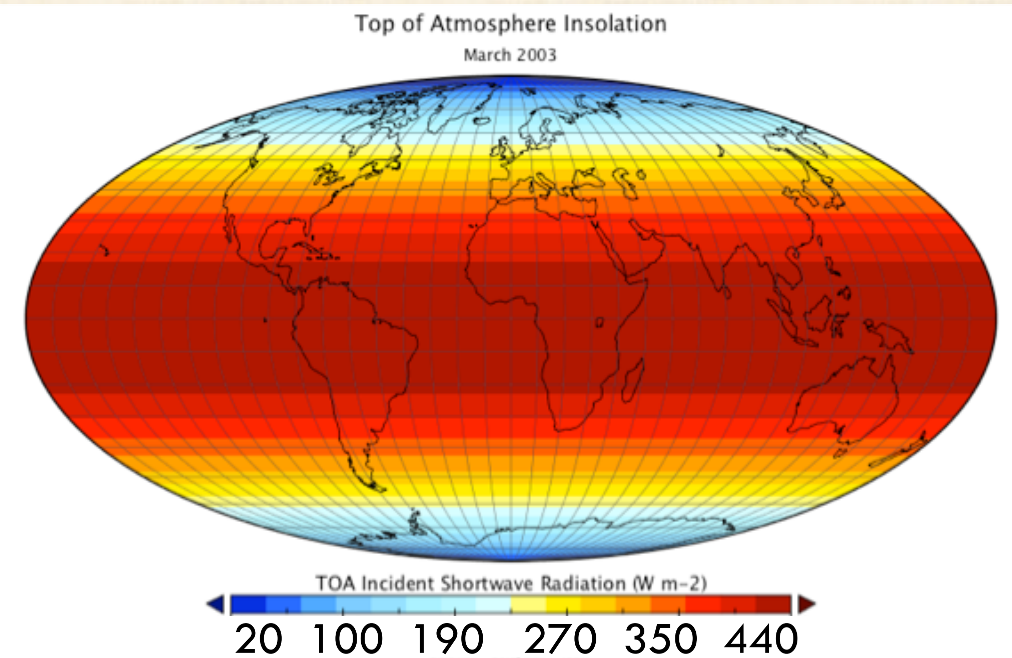
A. The tropics

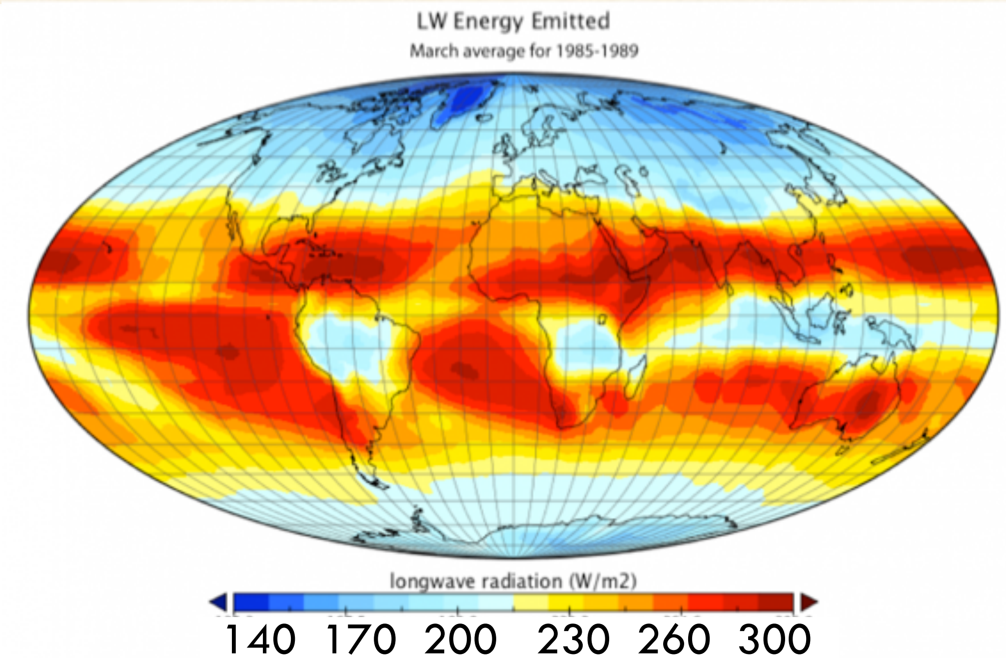
B. The polar regions

C. Both

D. Neither

The balance of radiation at TOA





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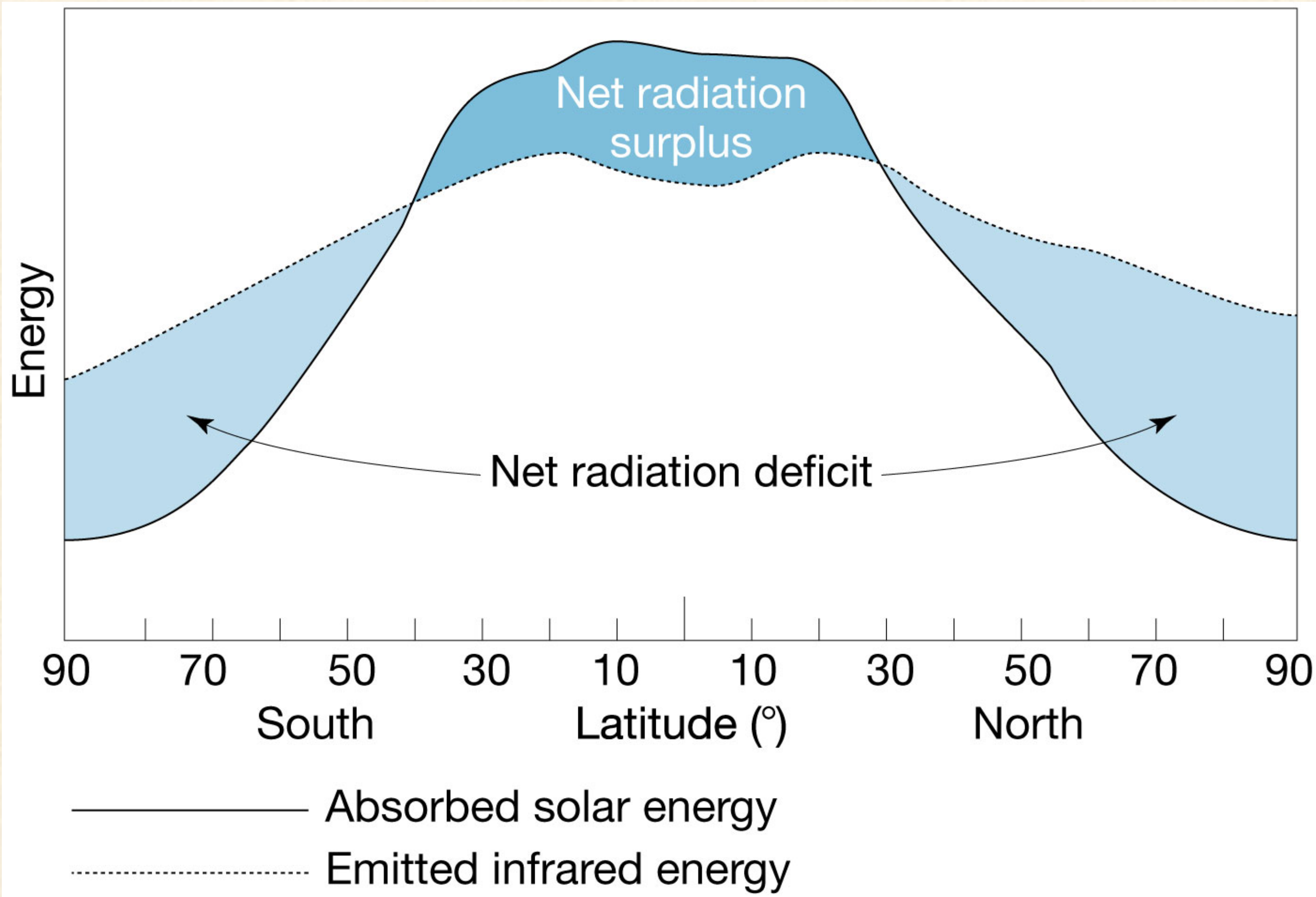
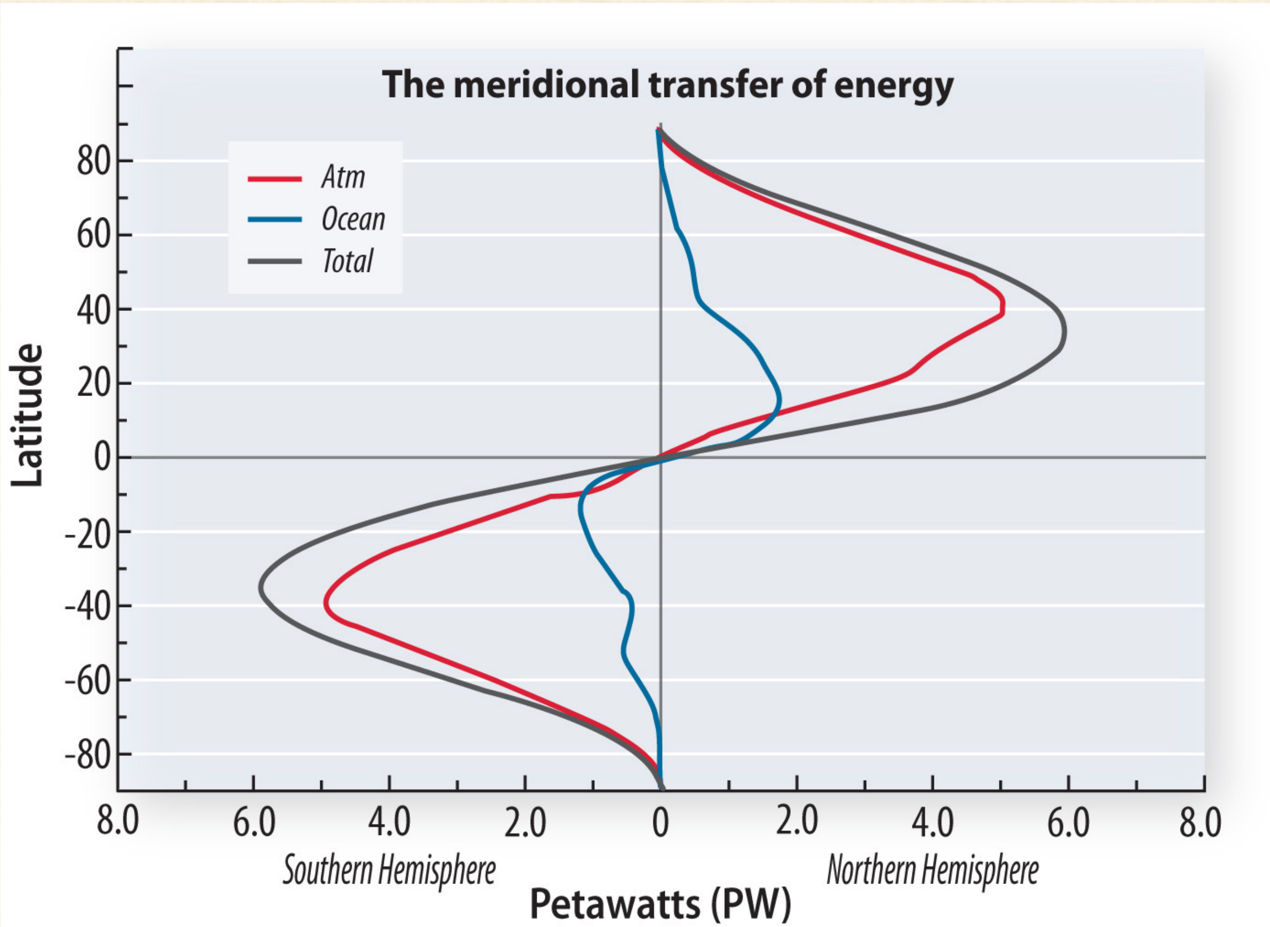
Net radiation by latitude

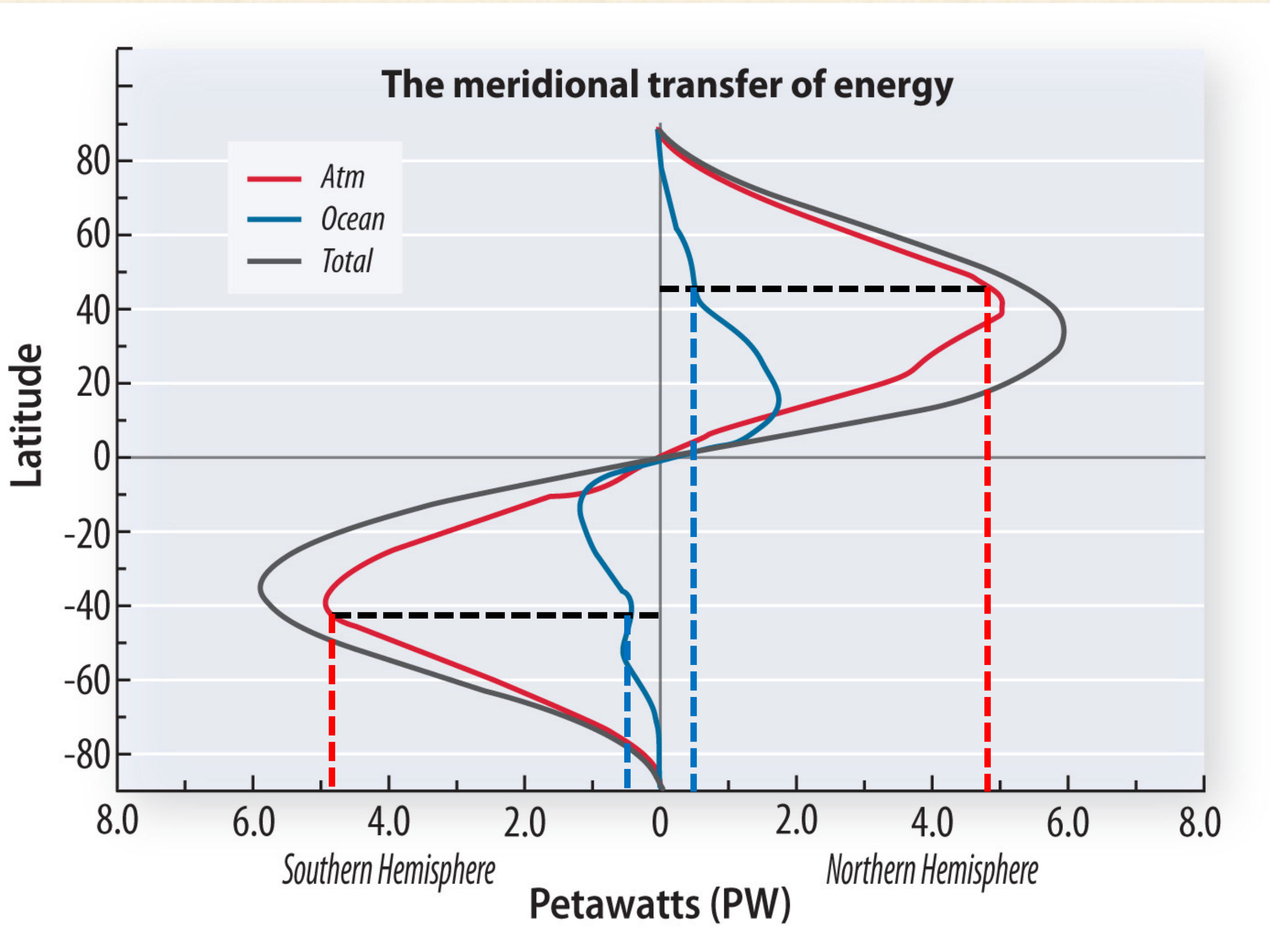


Heat transfer



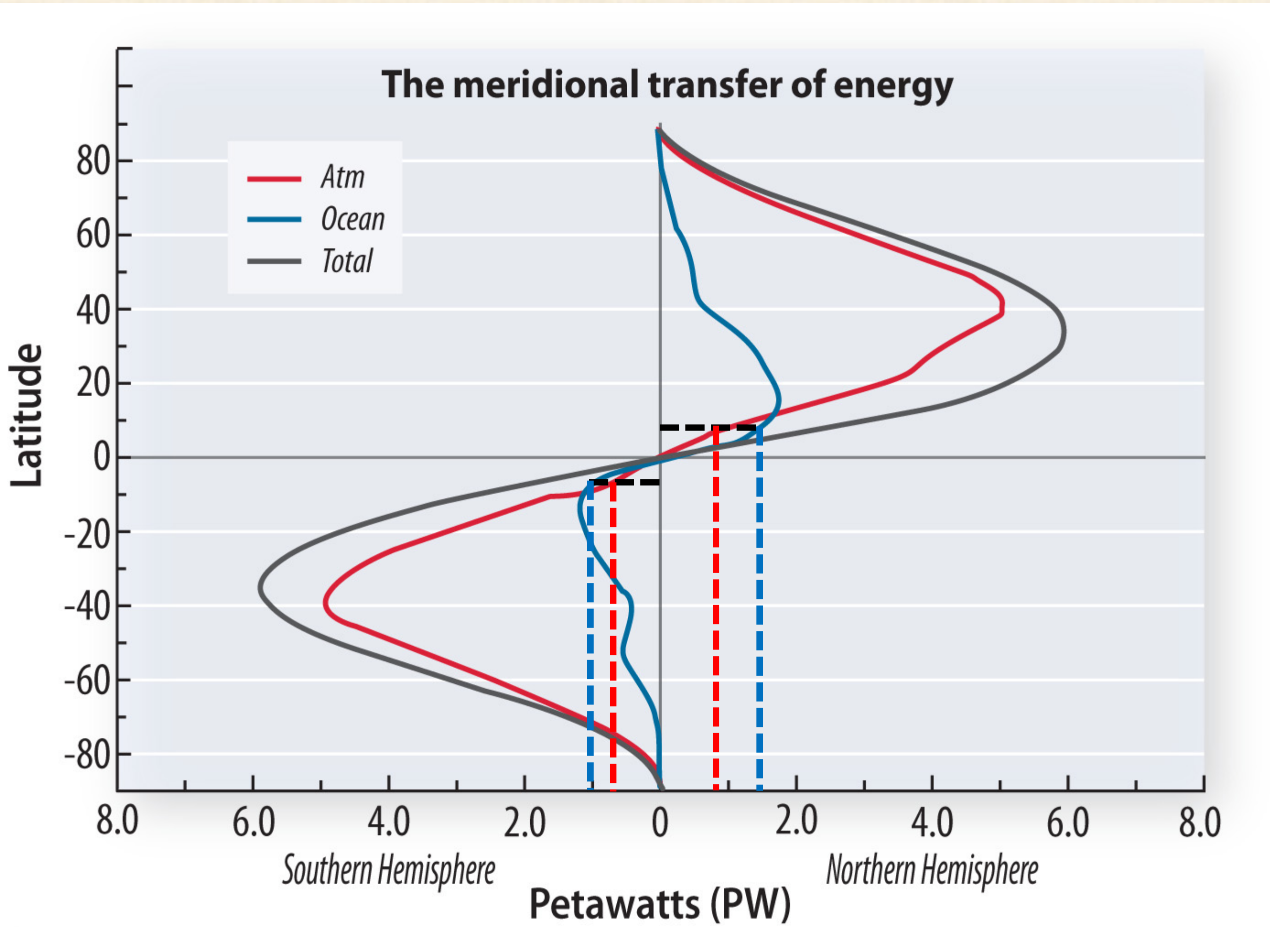
- Due to the uneven distribution of energy, heat is transferred from the equator toward the poles to reach equilibrium (balance).
- Most of the heat transfer happens in the atmosphere (~75%)

Heat transfer – a closer look



More transport by the atmosphere at higher latitudes

Heat transfer – a closer look



More transport by the oceans at lower latitudes

Why does an air parcel rise or sink?

- **Density differences.** When air parcels are warmer or cooler than their surrounding environments, **they rise or fall.** The buoyancy of an air parcel is controlled by the temperature of an air parcel.
- Vertical motion can also occur mechanically, such as when winds run into mountains and are forced to rise (e.g., lenticular clouds)

Ideal Gas Law

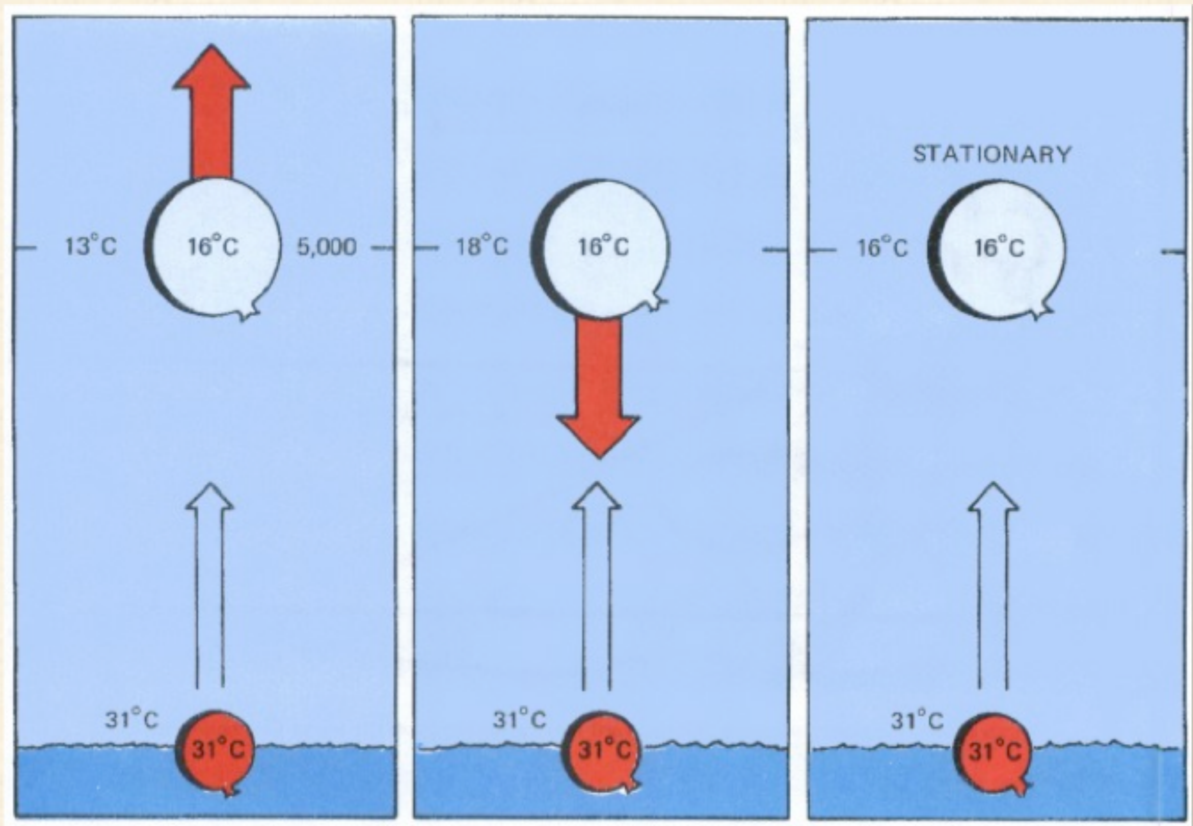
$$P=\rho R^{*}T$$

P = Pressure (Pa)
ρ = Density (kg/m^3)
T = Temperature (K)
R^{*} = Gas constant for dry air 287 $JK^{-1}kg^{-1}$

The Ideal Gas Law relates Pressure, Temperature and Density.

In atmosphere, air cools as it rises (while hot air in balloon is constantly heated)

- As warm air rises in the atmosphere, it expands, and the energy needed to expand decreases the temperature of the air ***(dry adiabatic cooling)***
- If air contains moisture, it eventually cools enough so that water vapor condenses, releasing (latent) energy into the rising air (=making it warmer, leading to more rising) (***moist adiabatic cooling***)



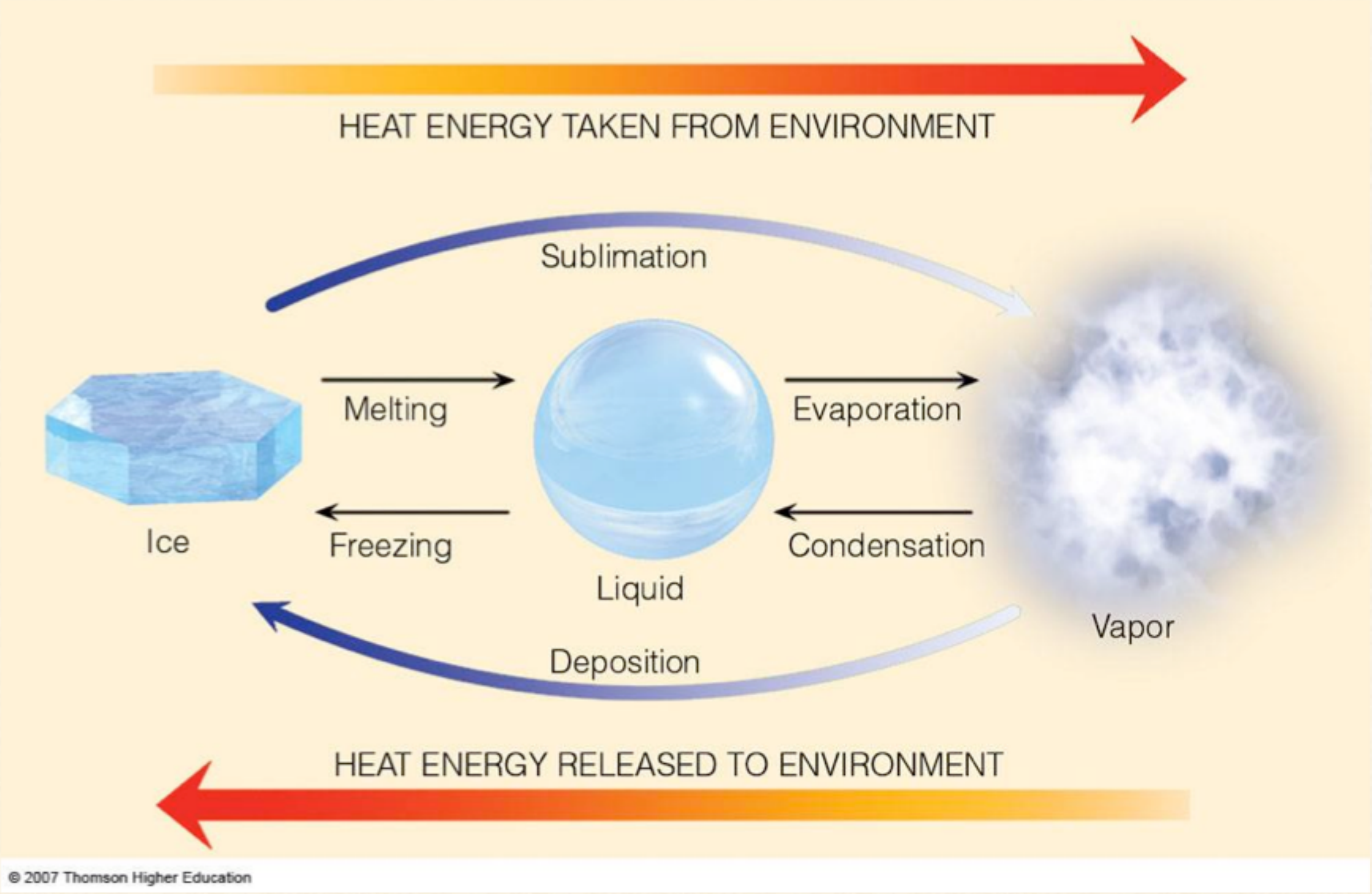
Sensible and latent heat

Sensible heat can be measured (sensed) with a thermometer

Latent heat cannot be measured with a thermometer ("latere"= hidden)

- If adding/removing heat from a substance changes its temperature, it is called sensible heat
- If adding/removing heat results only in a phase change (ice-water-vapor), it is called latent heat

Latent heat during phase changes

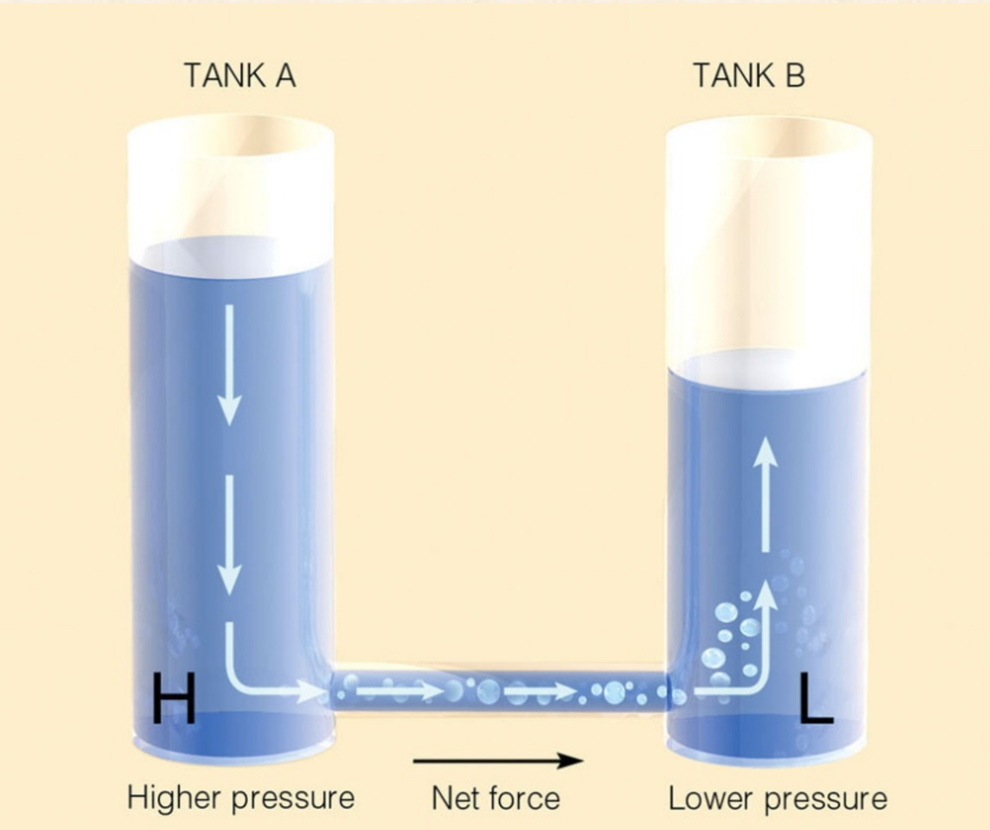


Lapse rate

The Lapse rate is the cooling of air as air rises:

- **Dry adiabatic lapse rate: 9.8 °C/km**
- **Moist adiabatic lapse rate: variable depending on moisture content, but around ~5 °C/km (and always lower than the dry adiabatic lapse rate)**
- When air sinks, air warms at the same lapse rate (just add a minus to the above lapse rates)
- Why is moist adiabatic lapse rate less than dry adiabatic lapse rate?

The Movement of Air: Horizontal Movement



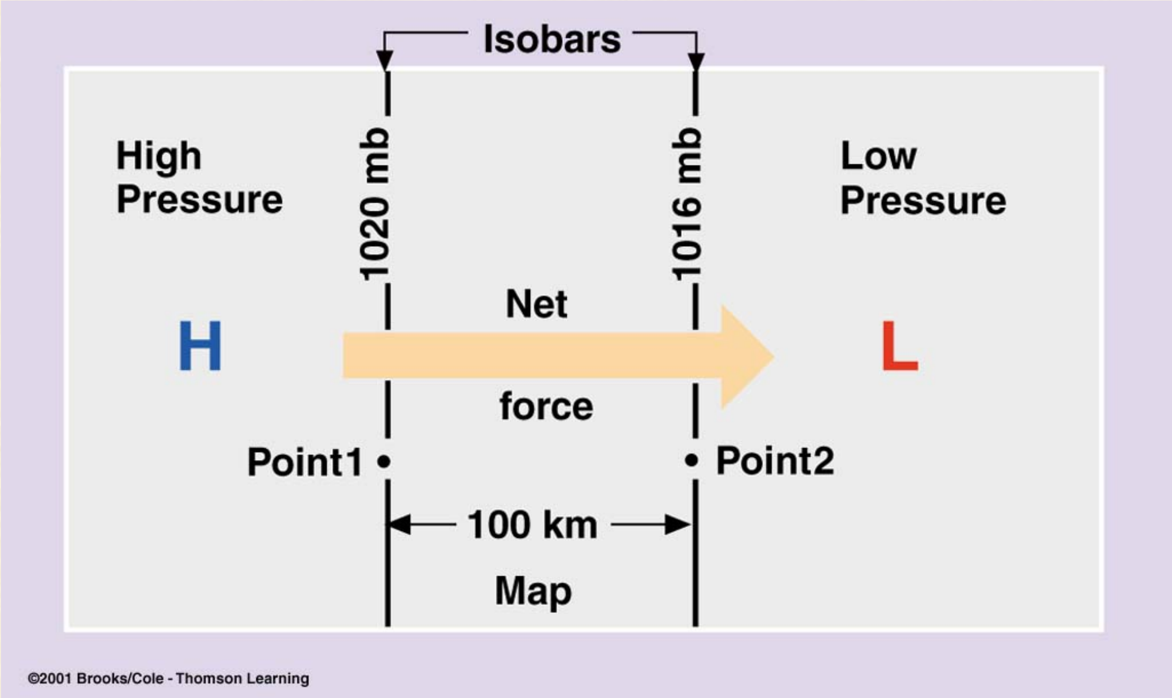
High pressure (lots of mass above surface)	Low pressure (less mass above surface)

- Air moves from high to low pressure
- Tank A has a higher pressure than Tank B, so water moves into Tank B.

The Movement of Air: Horizontal Movement

Why does the wind blow?

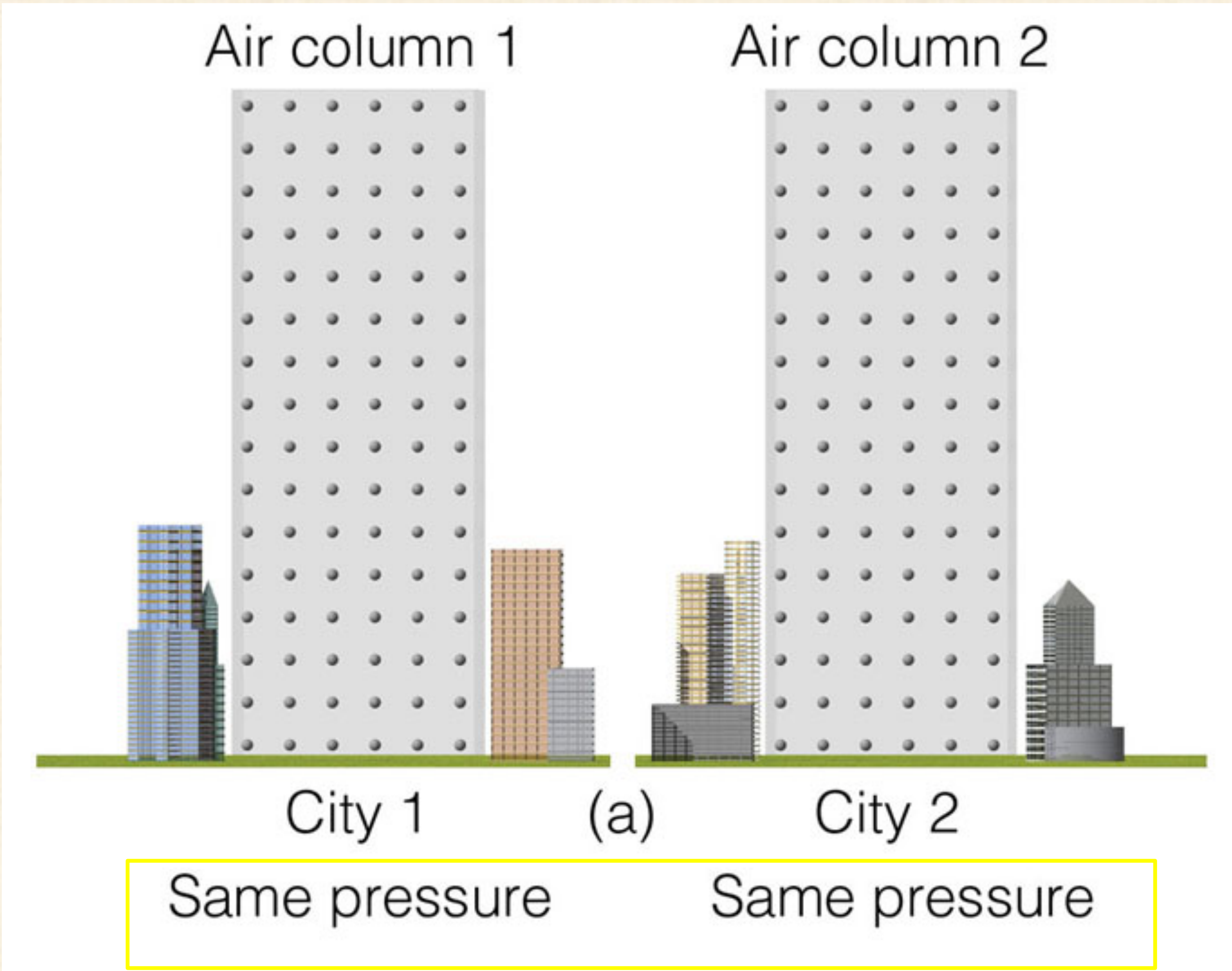
The pressure gradient force!



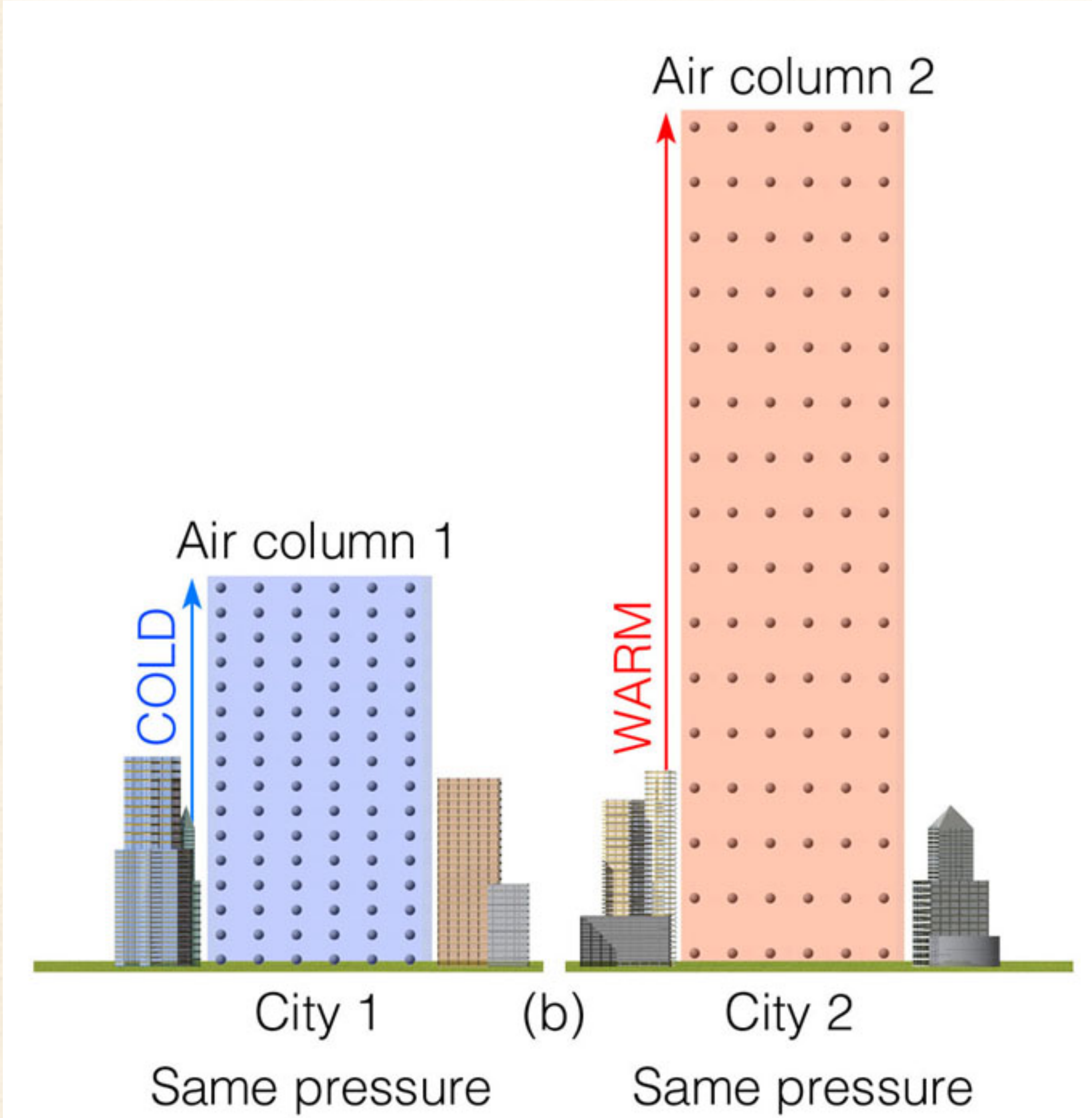
The pressure gradient between point 1 and 2 is 4 mb per 100 km.

The net force directed from higher toward lower pressure is called the ***pressure gradient force***.

Let's consider two air columns that contain equal numbers of molecules and that are initially at the same temperature

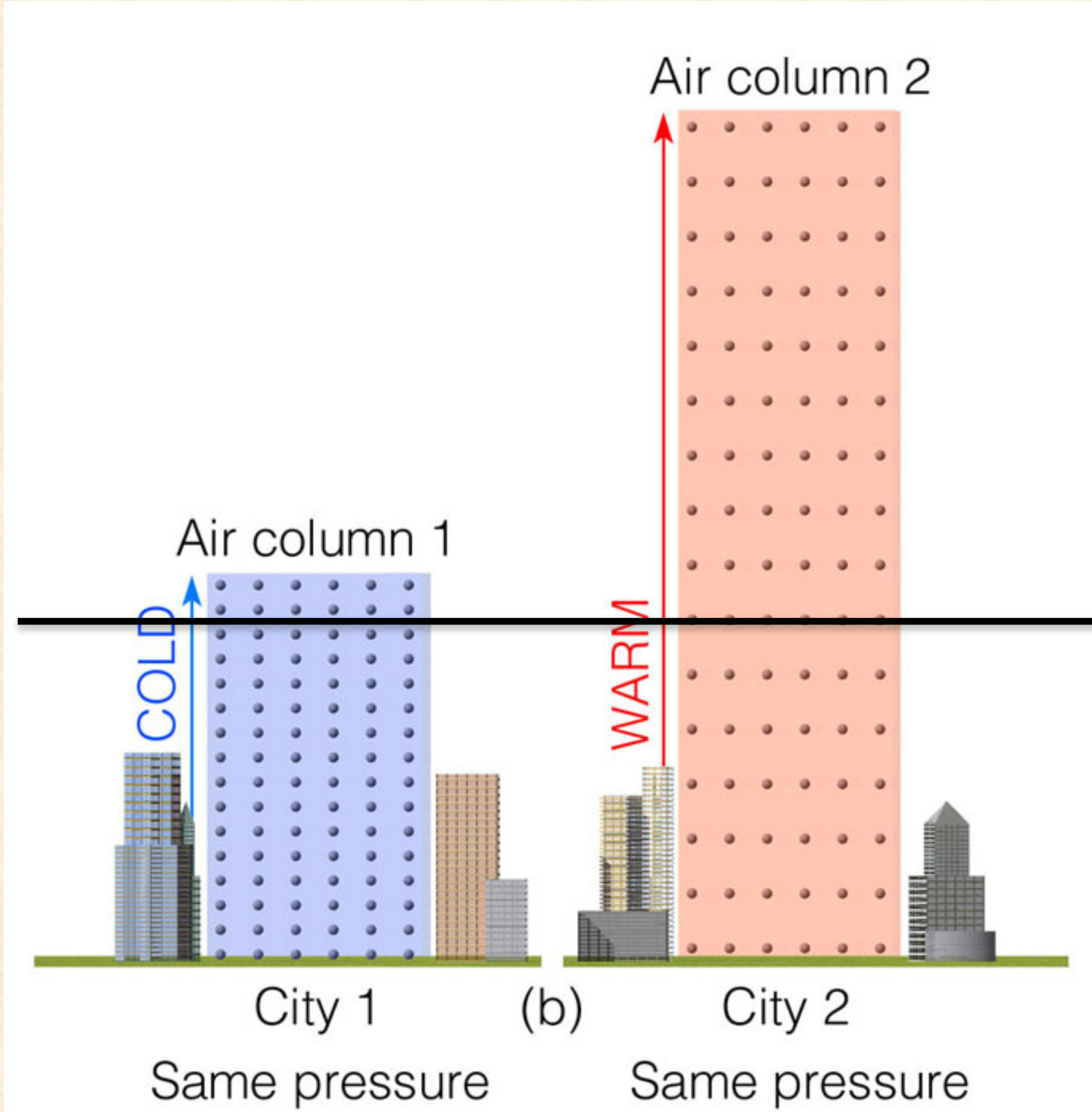


- Warm one column of air
- Keep the surface pressure the same (both still have the same number of molecules)
- This causes the warm column to take up more volume and be less dense



Which column has a higher pressure at the black line? In other words - which has more molecules sitting on top of it?

A. Column 1
B. Column 2



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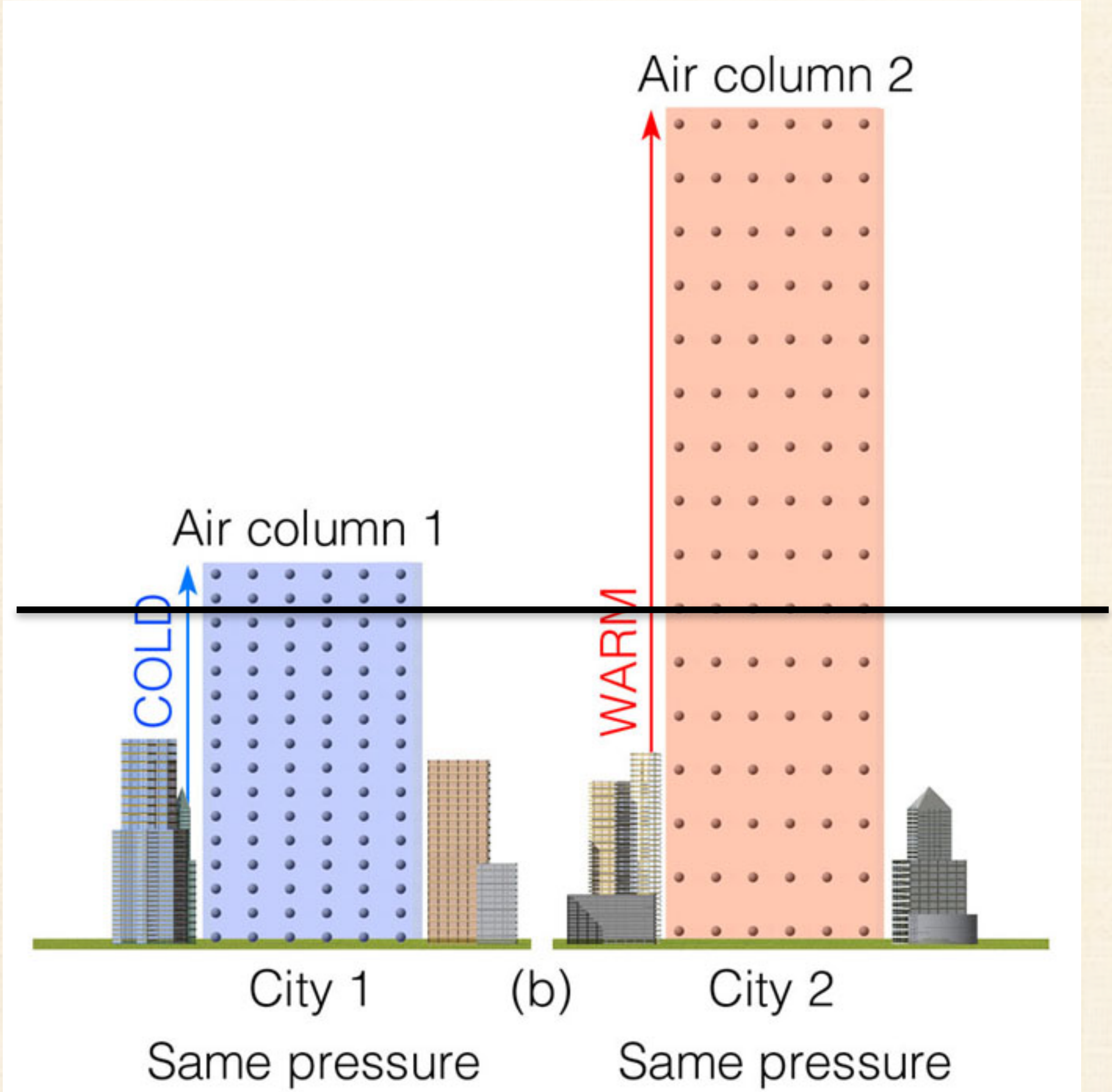

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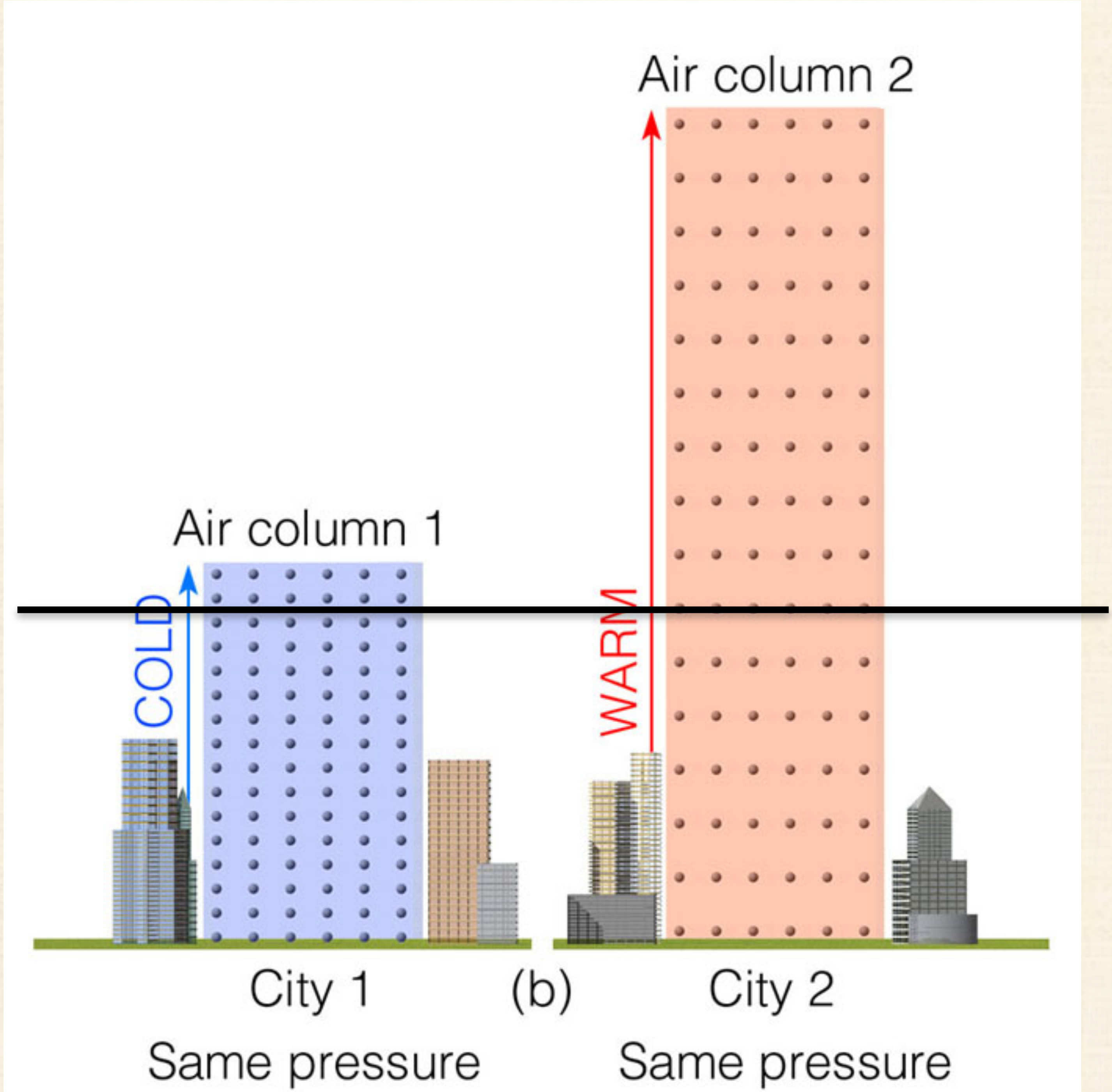
A. Column 1
B. Column 2

At the level of the black line, which way will air flow?

A. From column 2 to column 1
B. From column 1 to column 2



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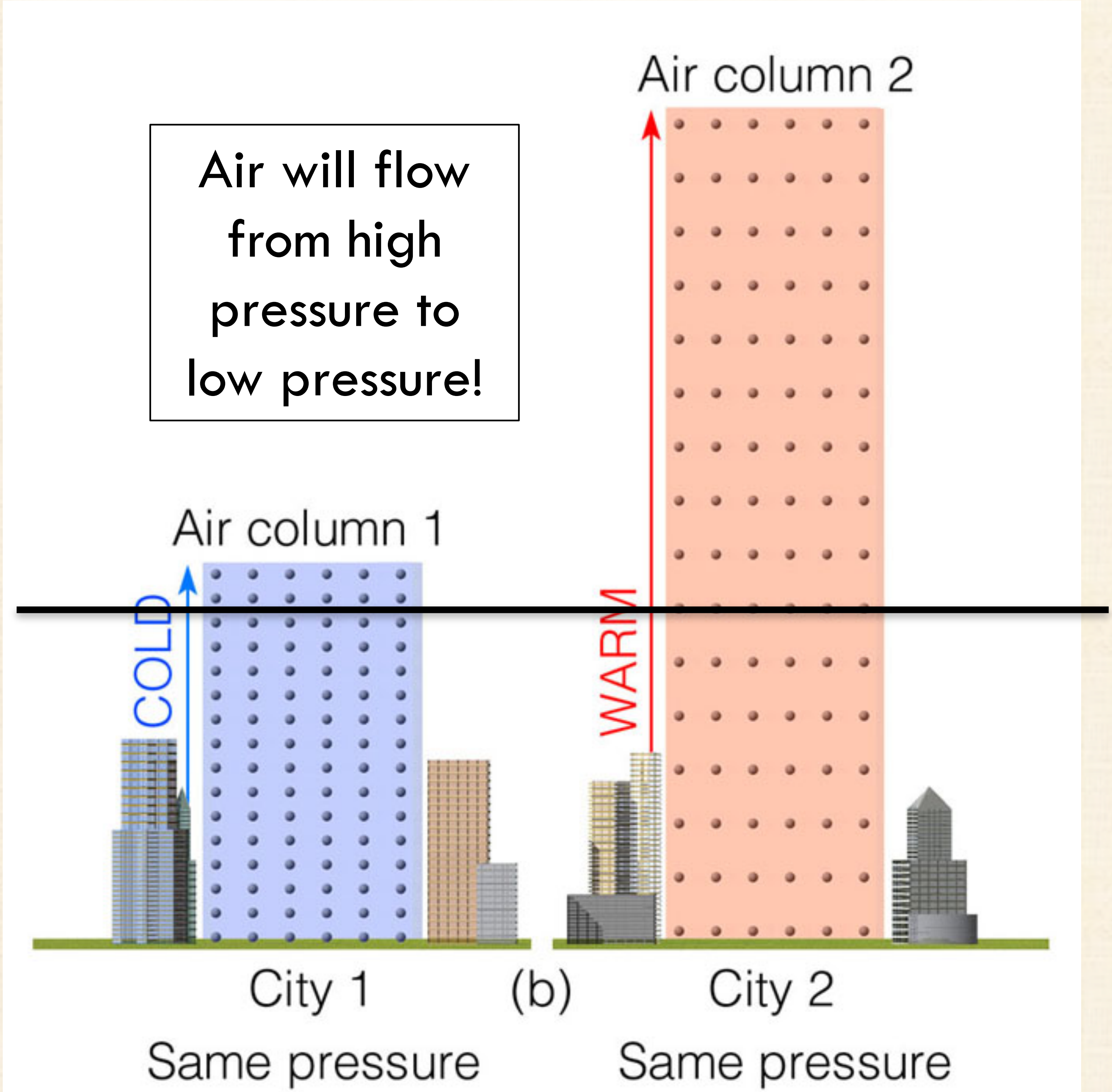
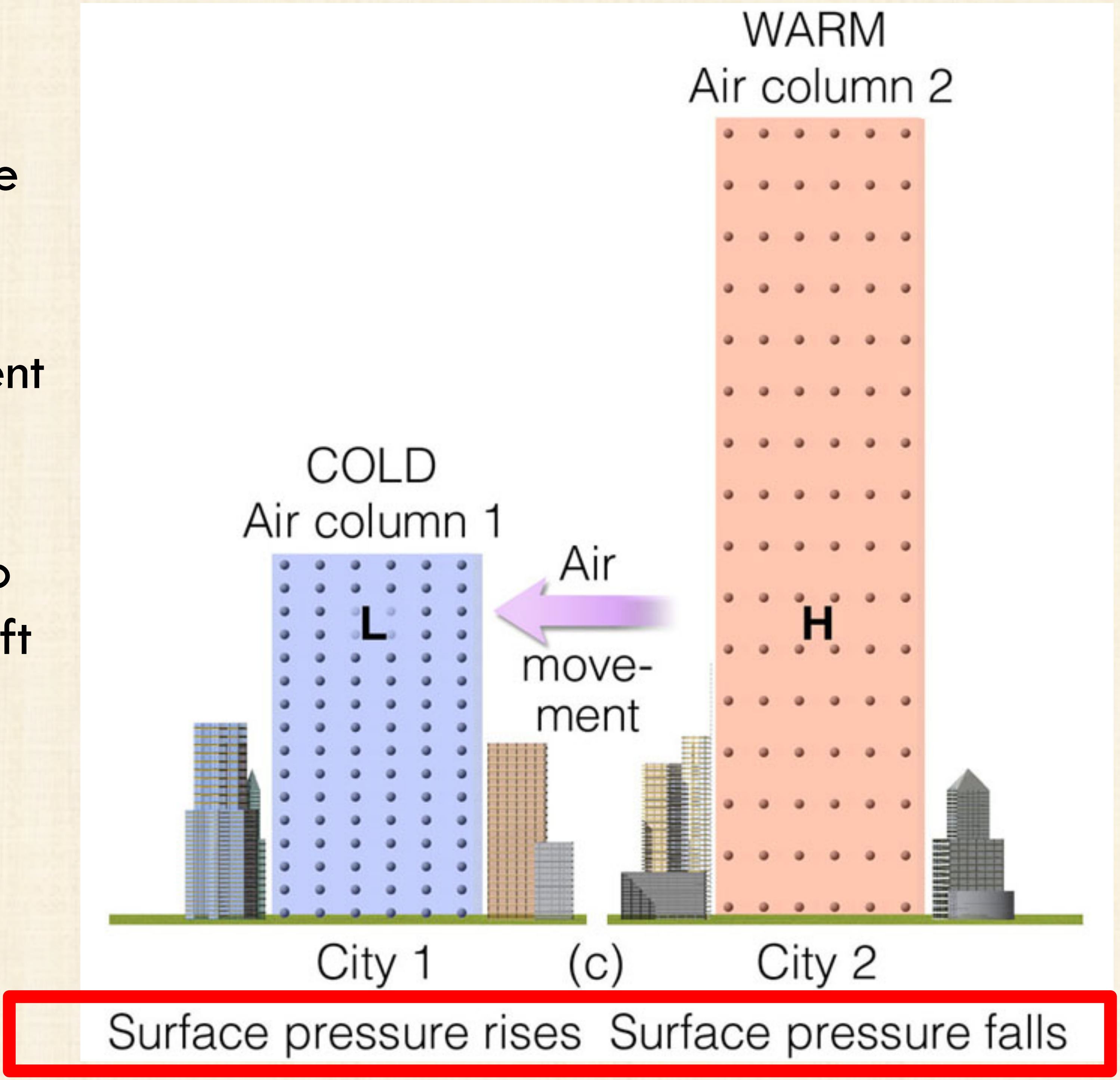
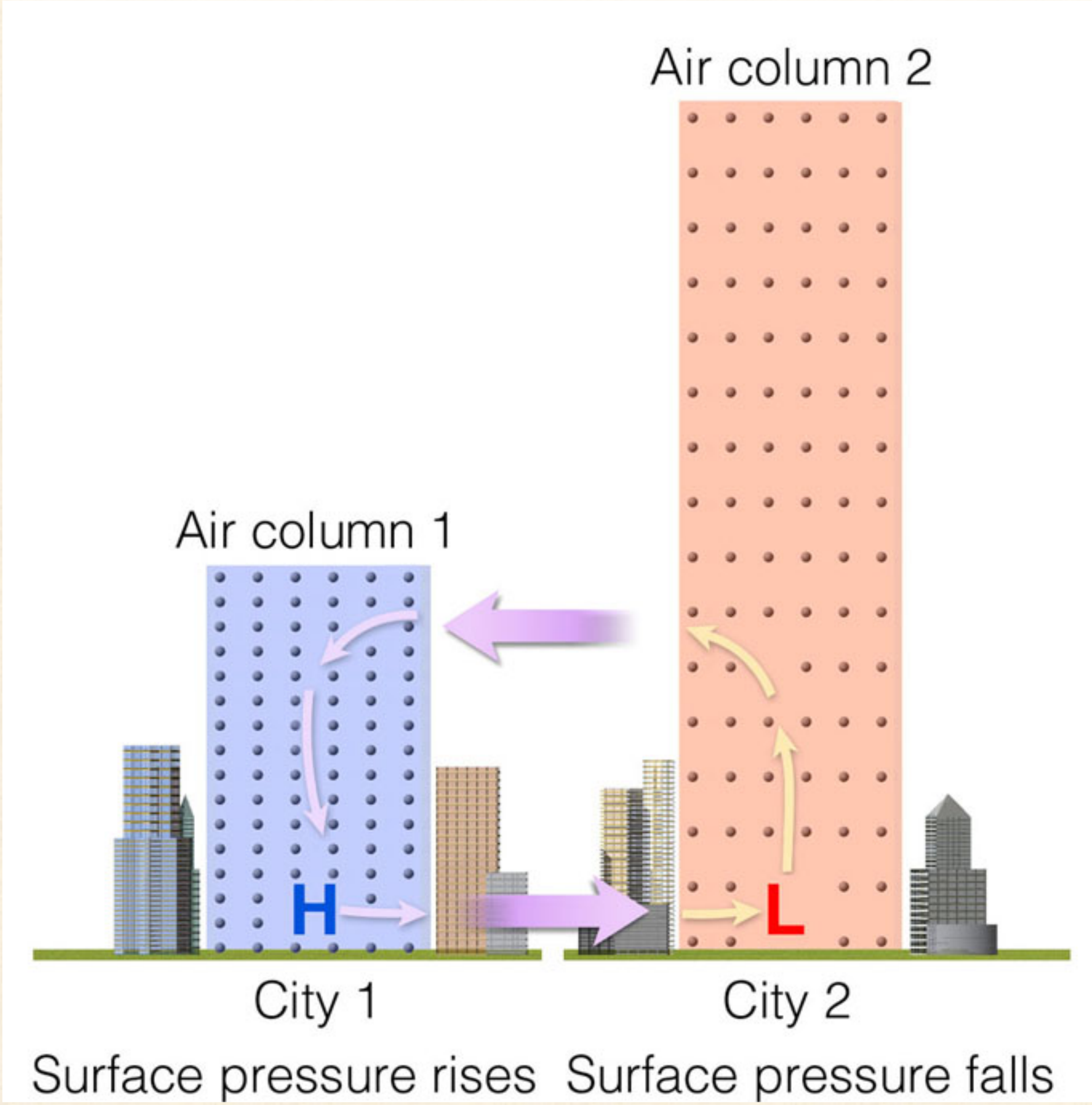
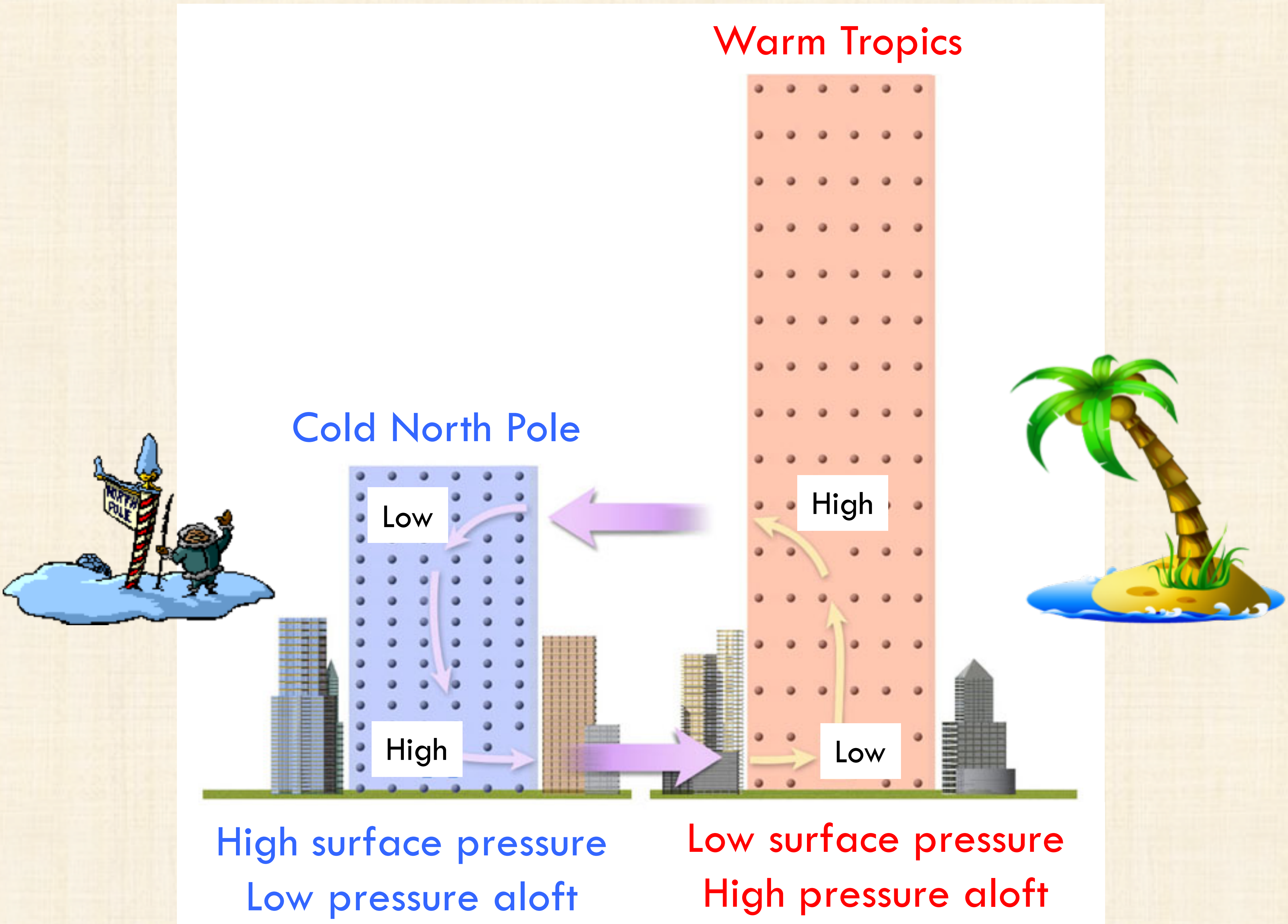


If air is moving from the right column (2) to the left column (1) due to the pressure gradient force, air molecules are going to start to pile up in the left column



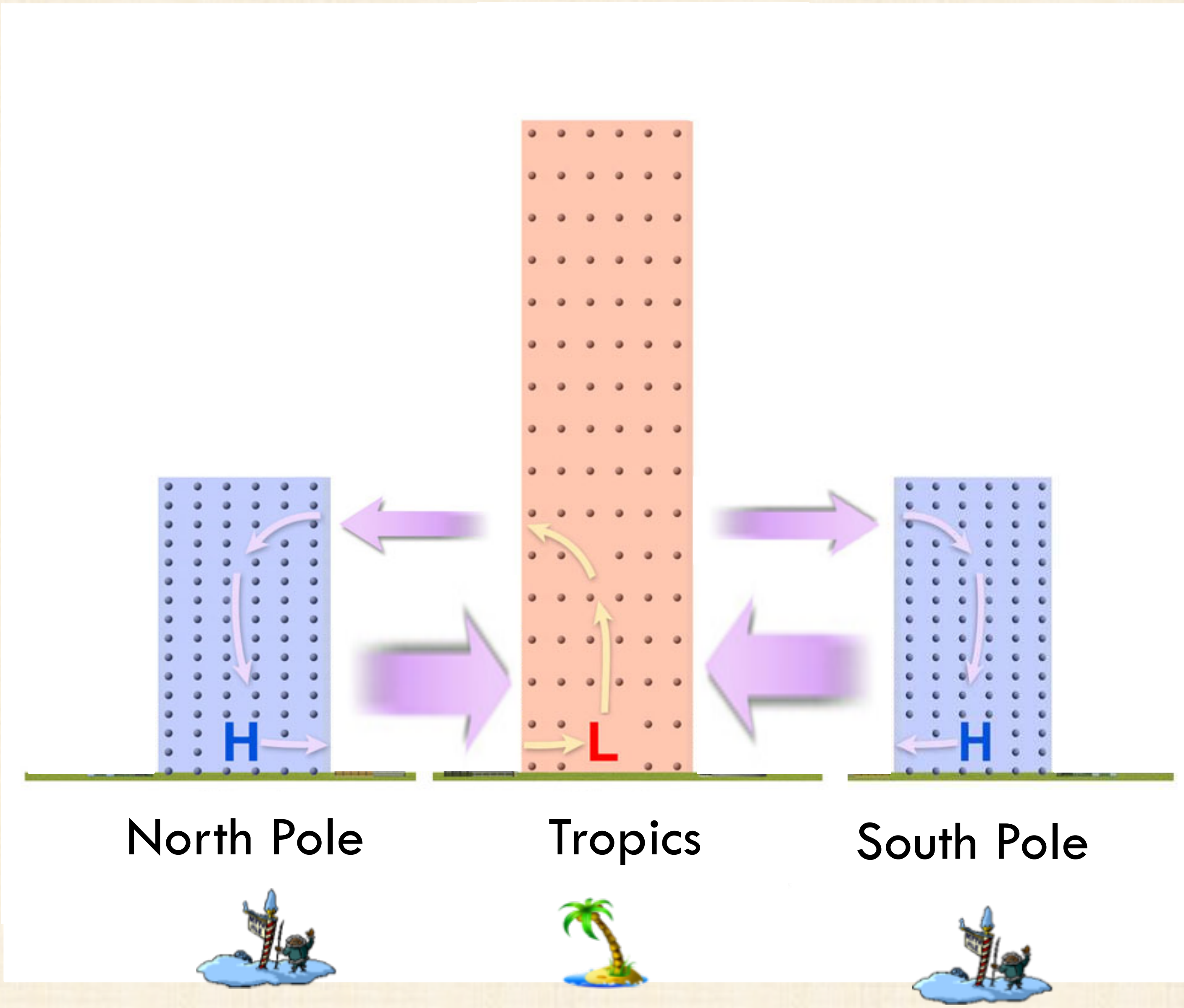
- Molecules start to pile up on the left side, making the surface pressure higher. Molecules leave the right side, making the surface pressure lower.
- The pressure gradient force kicks in again and air moves from high to low pressure at the surface.
- This is a thermally direct circulation (hot air rising, cold air sinking).



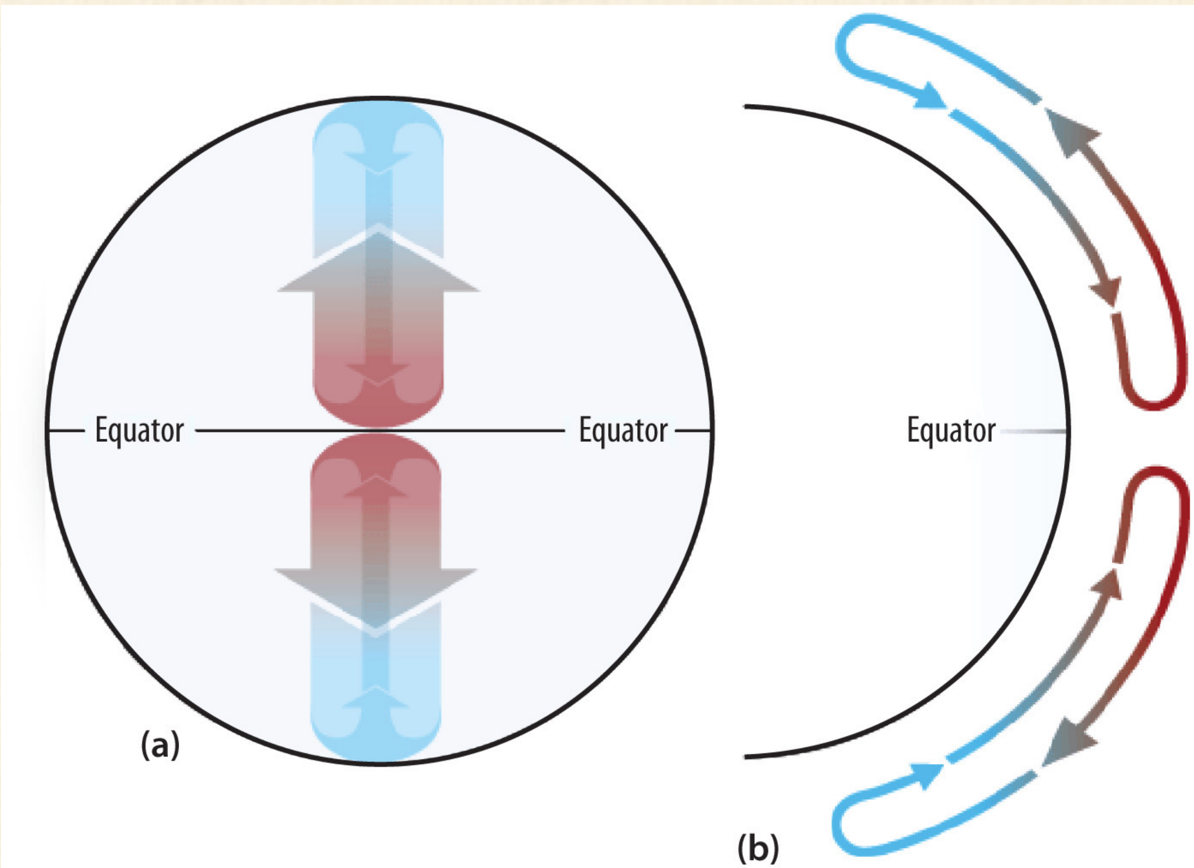


Warm Tropics
Cold North Pole
Low
High
High
Low
High surface pressure
Low pressure aloft
Low surface pressure
High pressure aloft

Back to Horizontal Movement of air… let's add in both poles → Completing the analogy for Earth



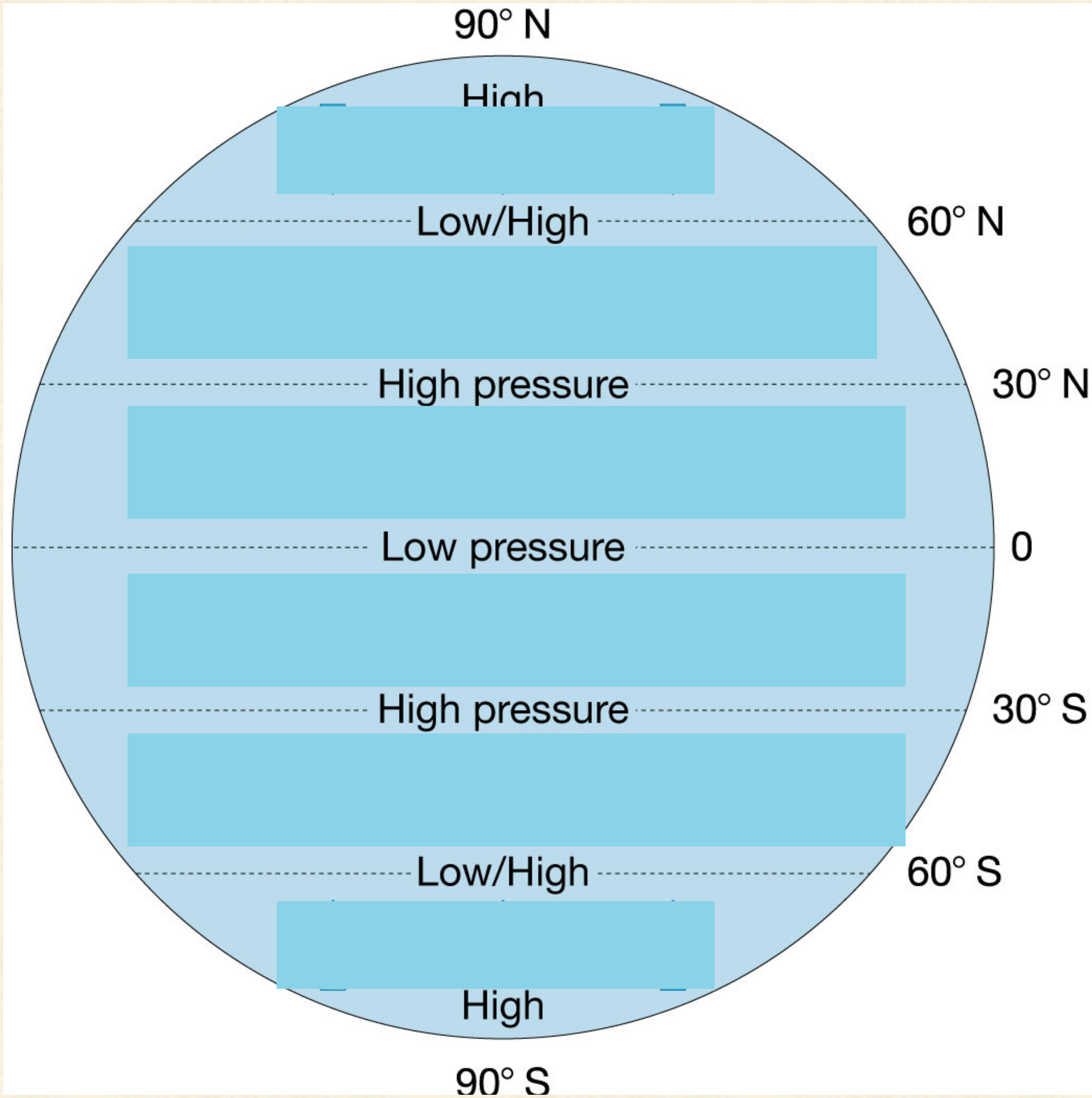
Circulation for a non-rotating, uniform planet



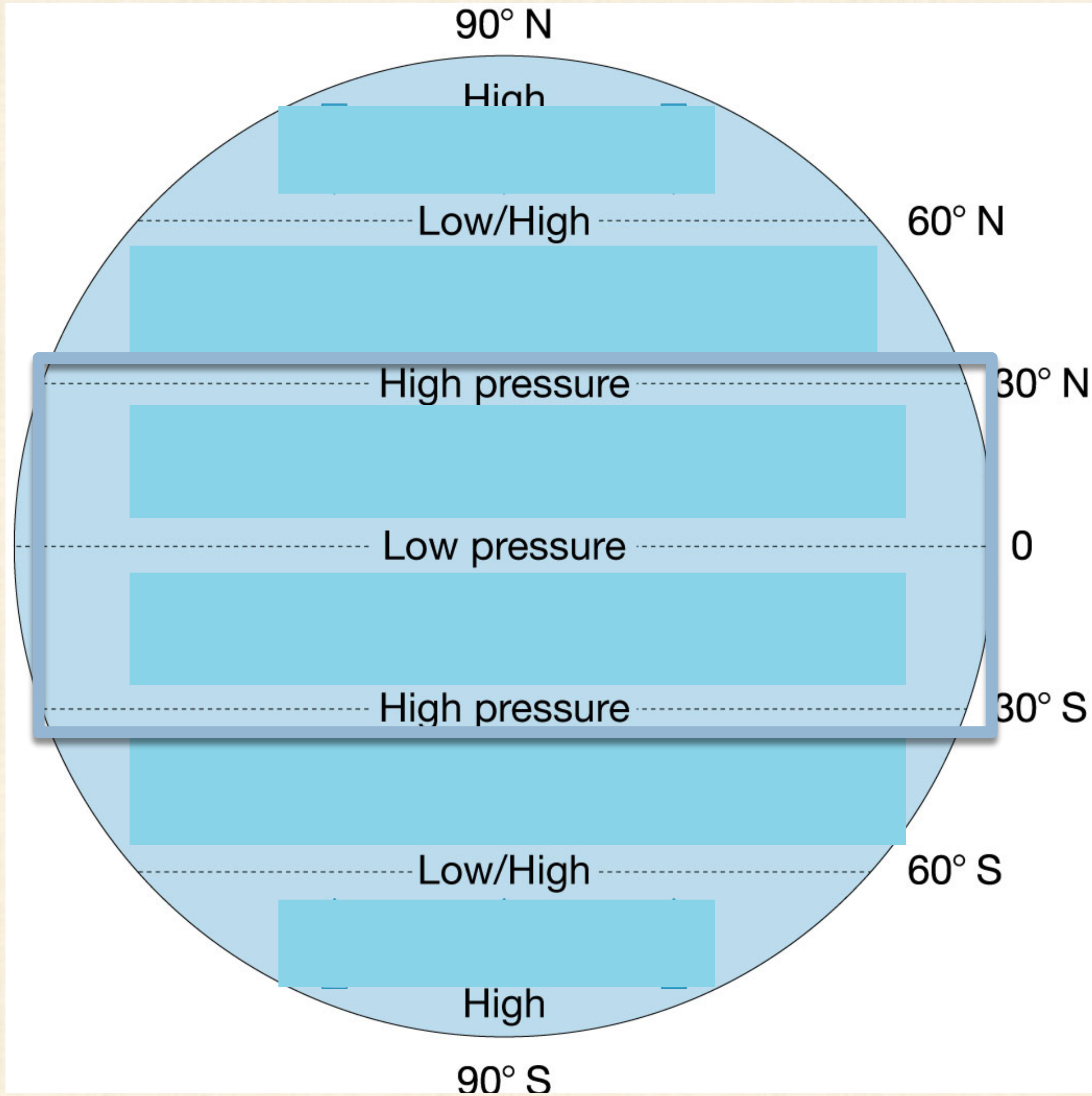
- Without rotation on a smooth planet, warm air would rise at the equator, move towards the poles, sink, and move back towards the equator

  But earth rotates, which leads to more cells

Predict the surface winds based on the surface pressure



Predict the surface winds based on the surface pressure and what we've learned so far



In the highlighted region,

A. Air moves towards the equator

B. Air moves towards the poles

C. Air does not move

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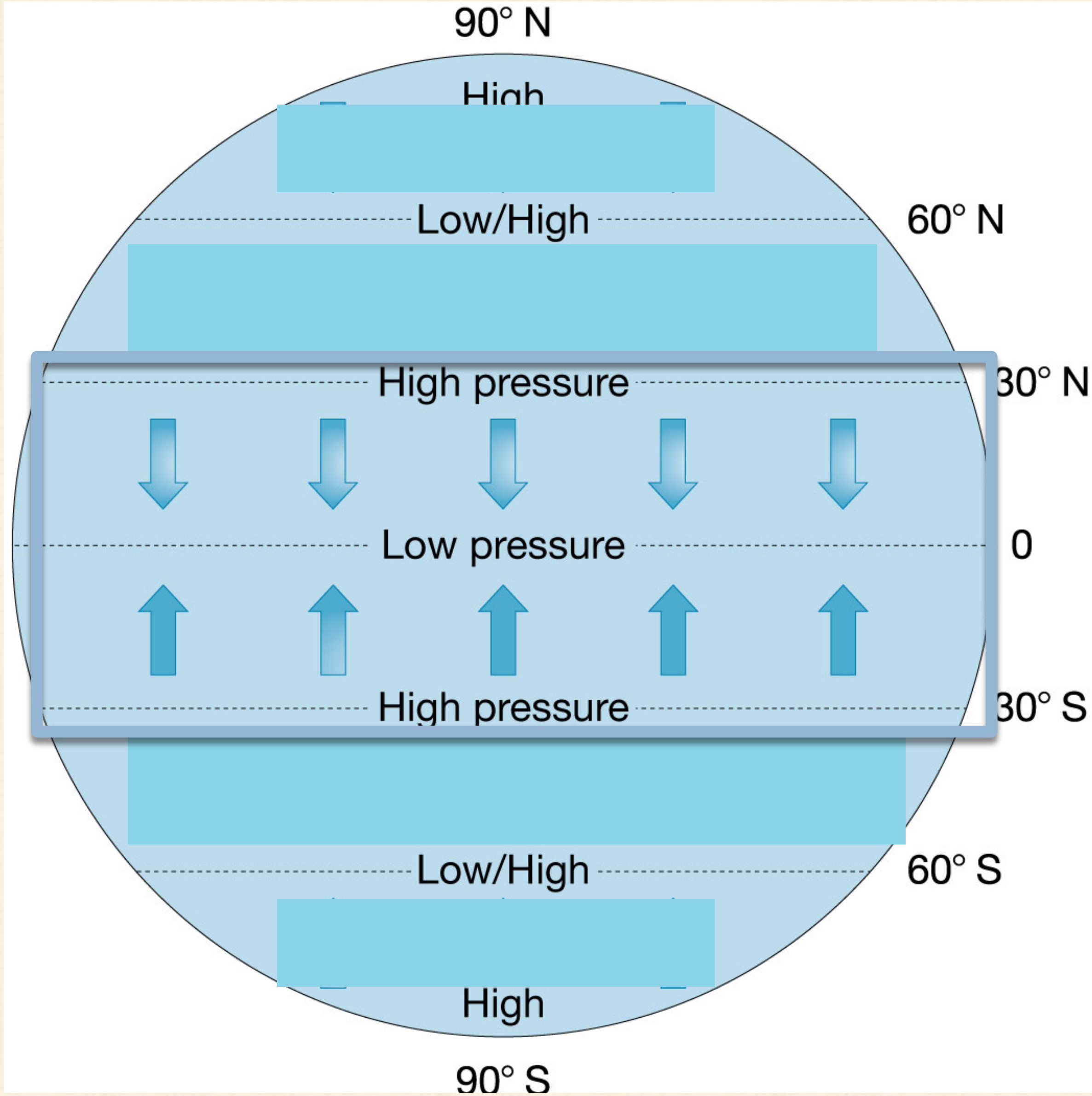

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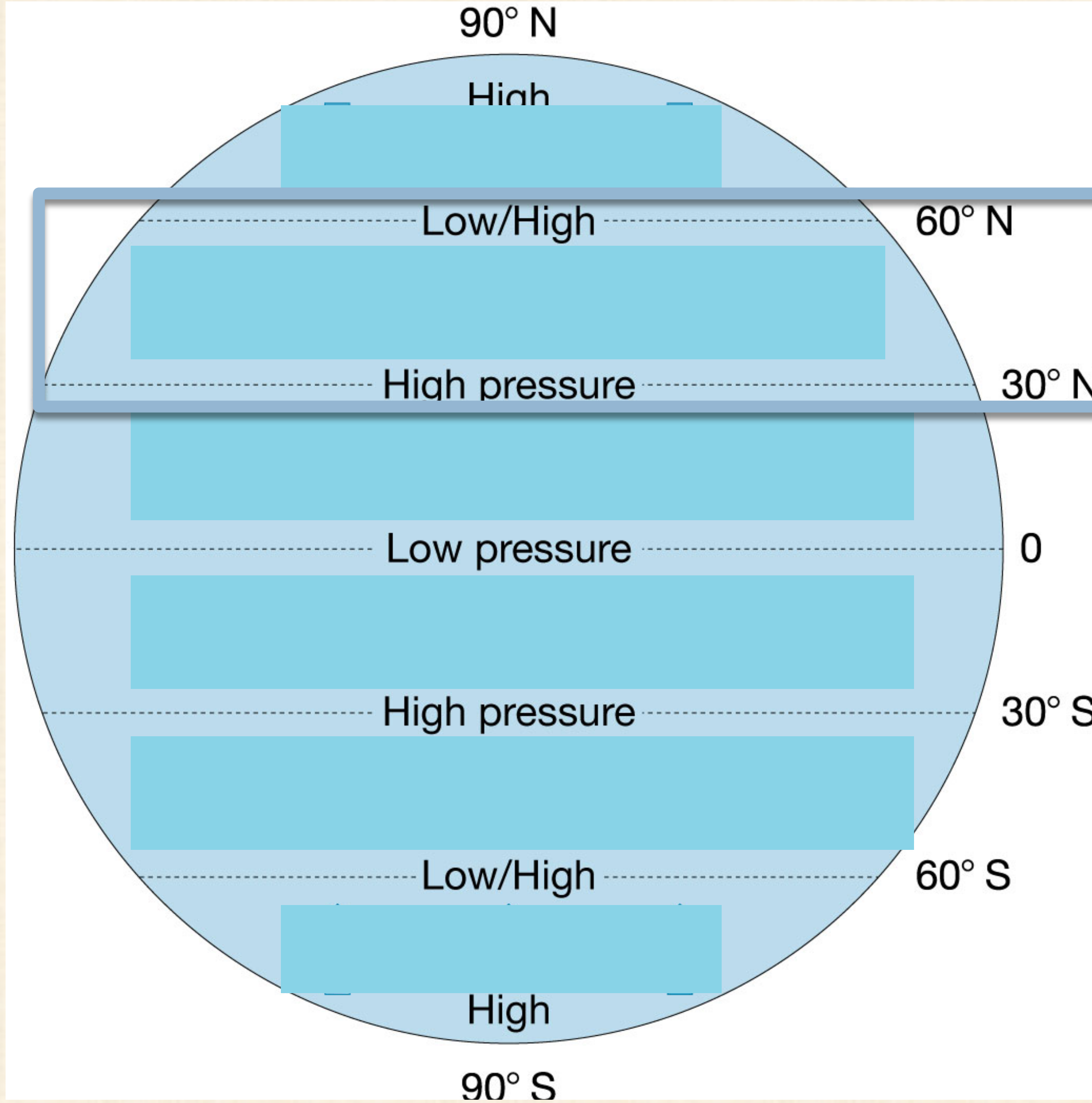

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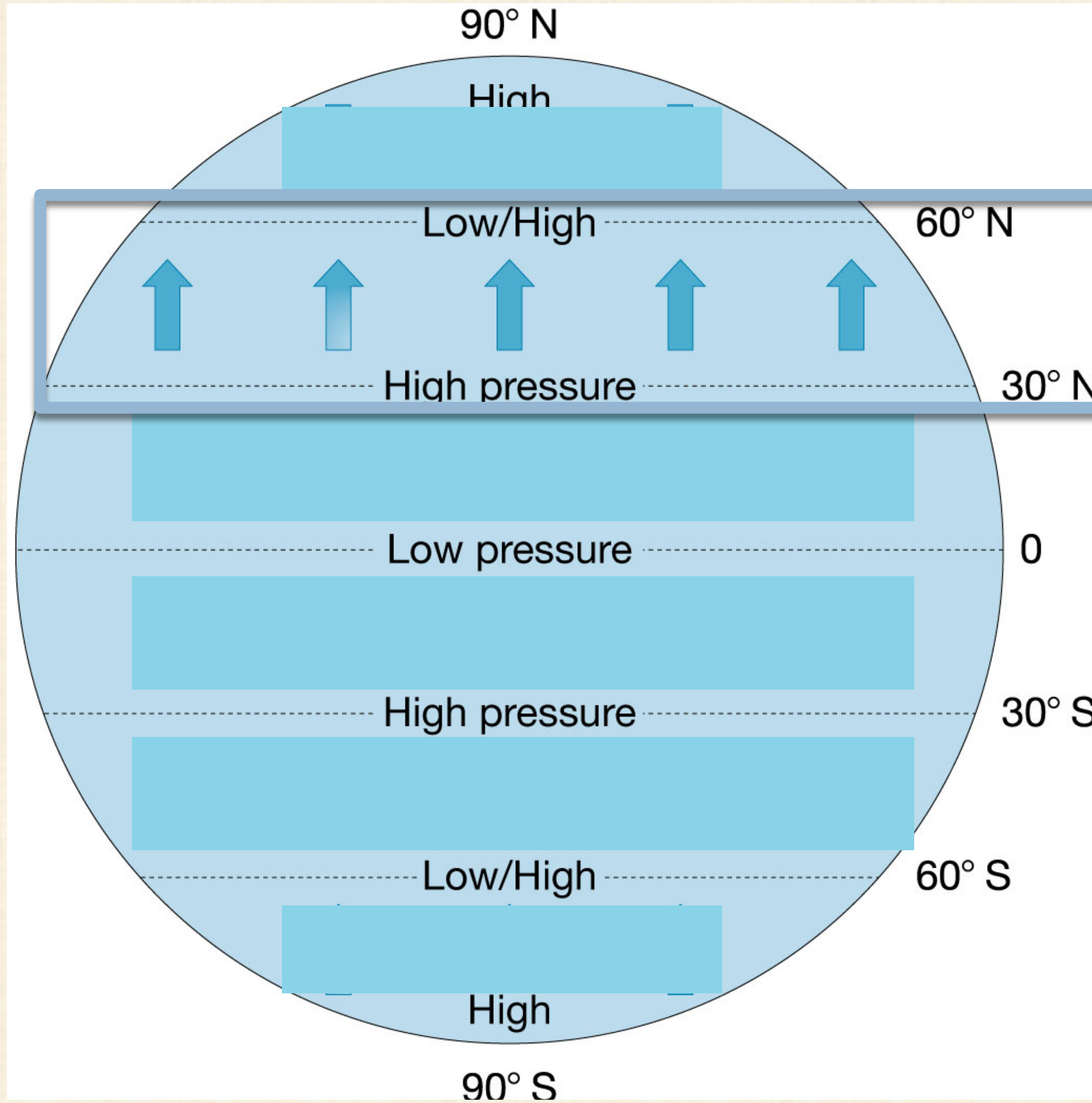

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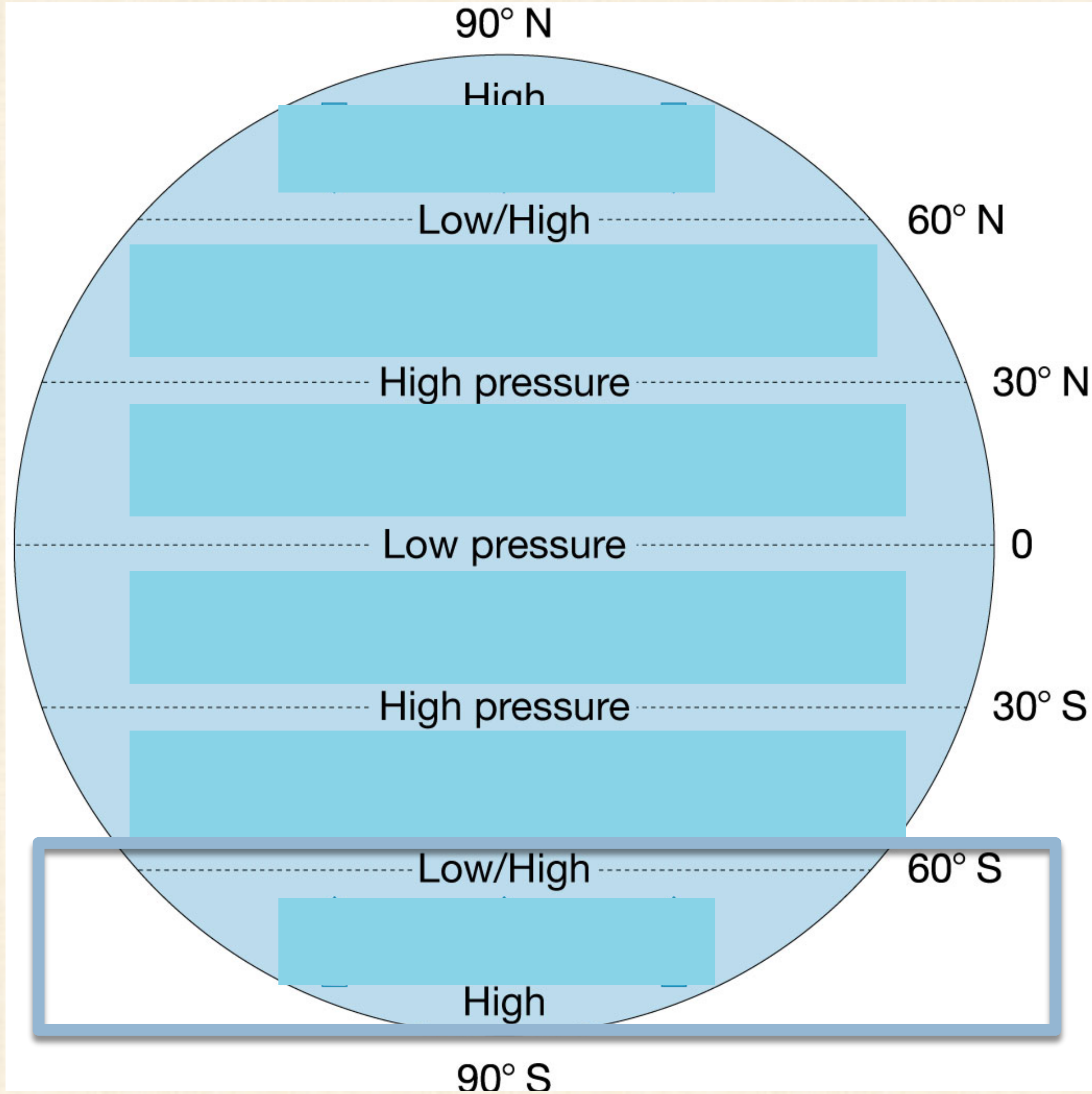

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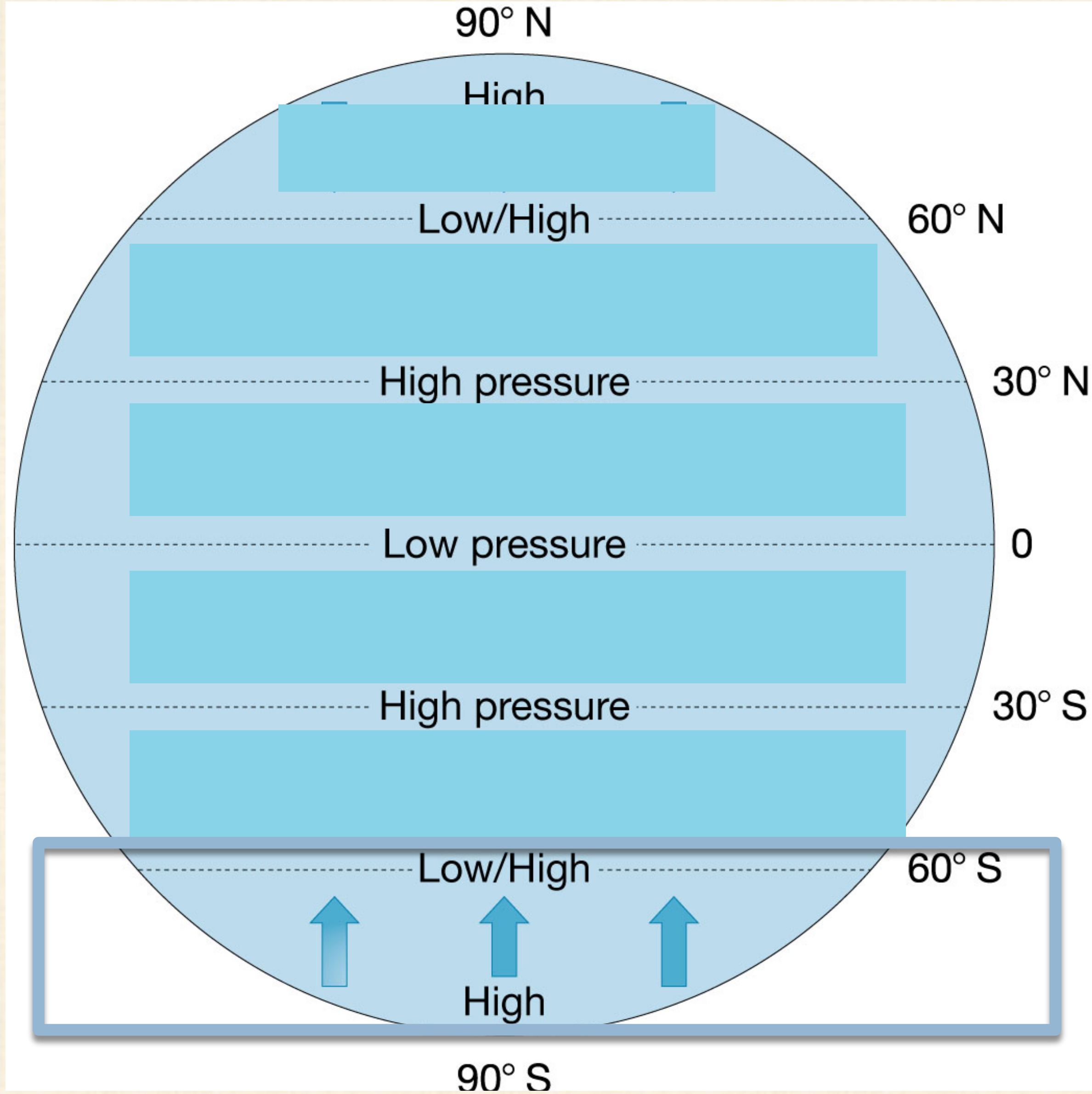
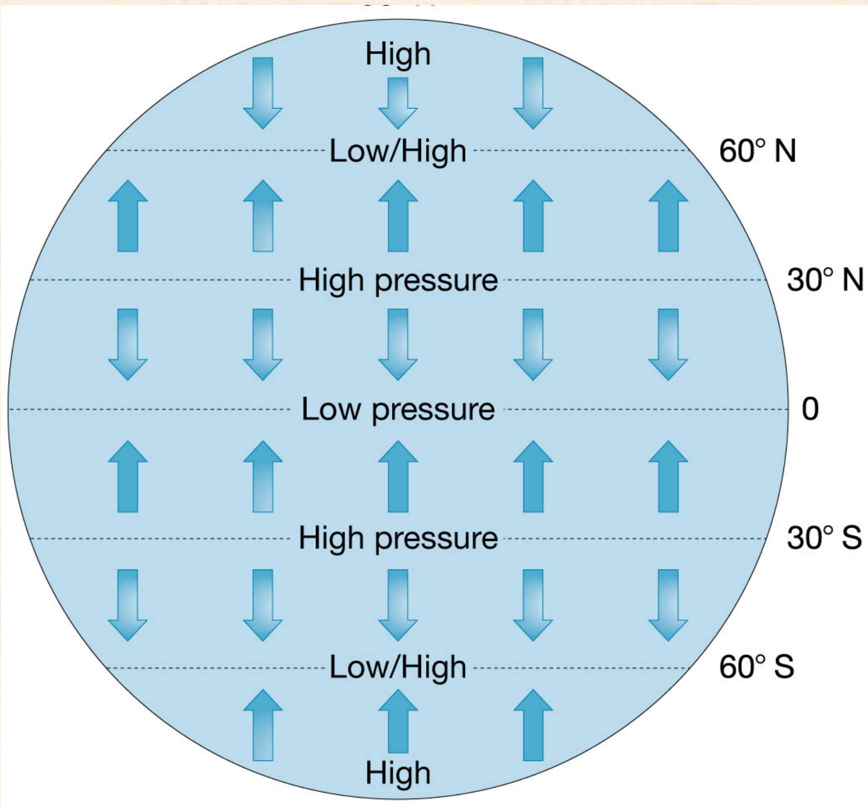
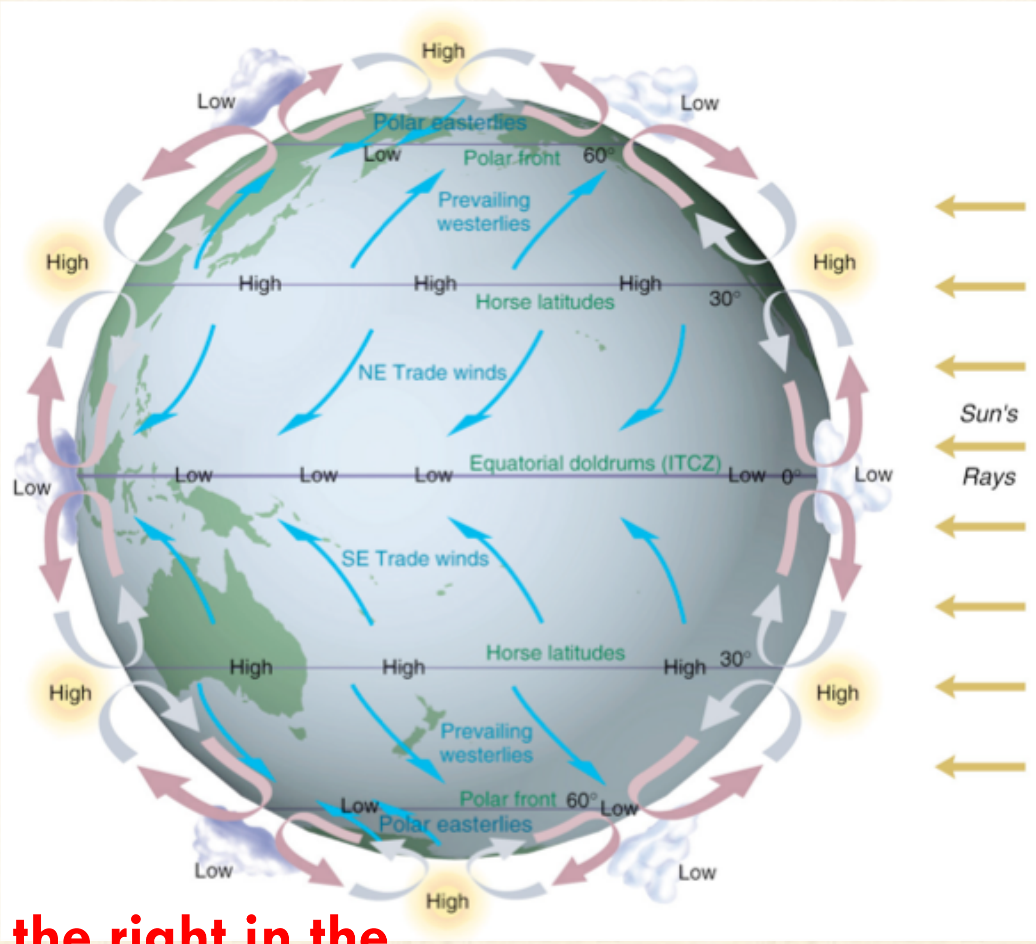


Surface winds based on pressure gradient force compared to observed winds: What do you notice?

Predicted based on pressure gradient force



Observed

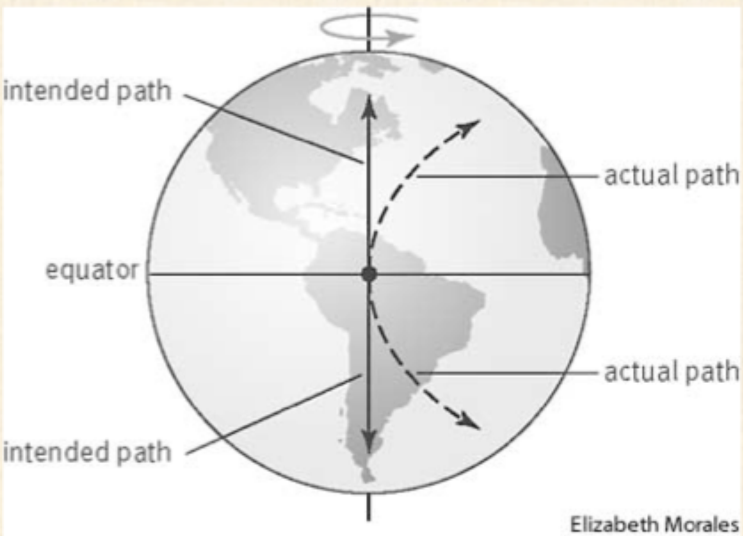


Why are the winds deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere?

Due to the Coriolis effect

What is the Coriolis Effect?

The Earth's counter-clockwise rotation causes air to be deflected from a straight path in our frame of reference.



Movie about the Coriolis Force
https://www.youtube.com/watch?v=i2mec3vgeal

Scales of the Coriolis Force effect

Does the Coriolis force influence large atmospheric motions (synoptic scale)?

A. Yes
B. No

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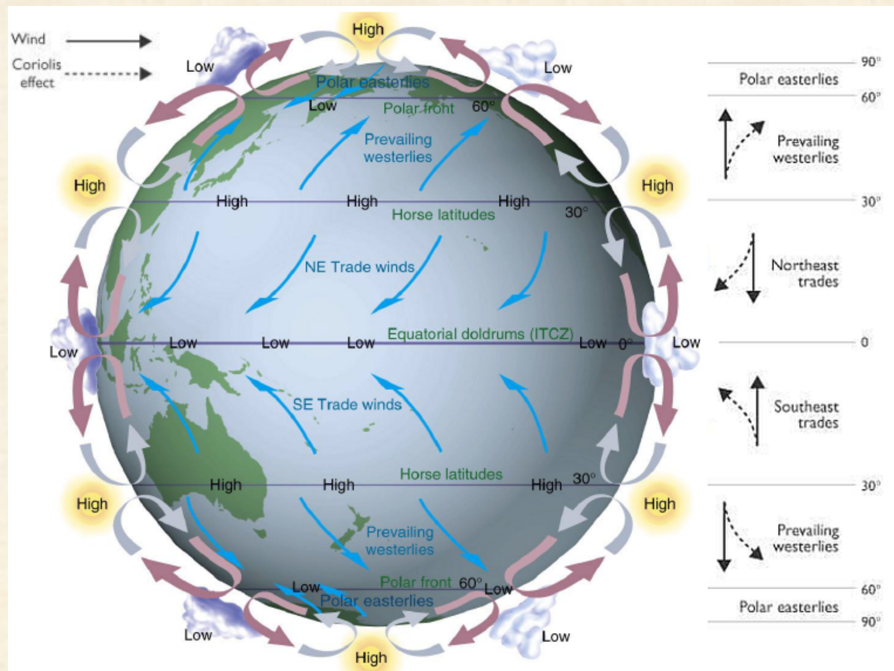

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Does the Coriolis force influence mesoscale atmospheric features (i.e. Hurricanes, frontal systems)?

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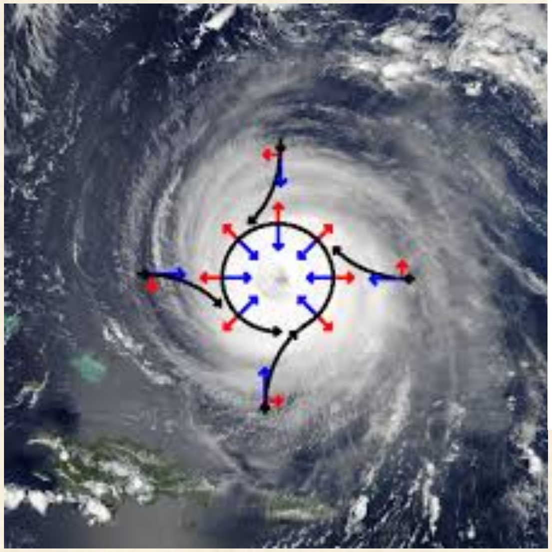
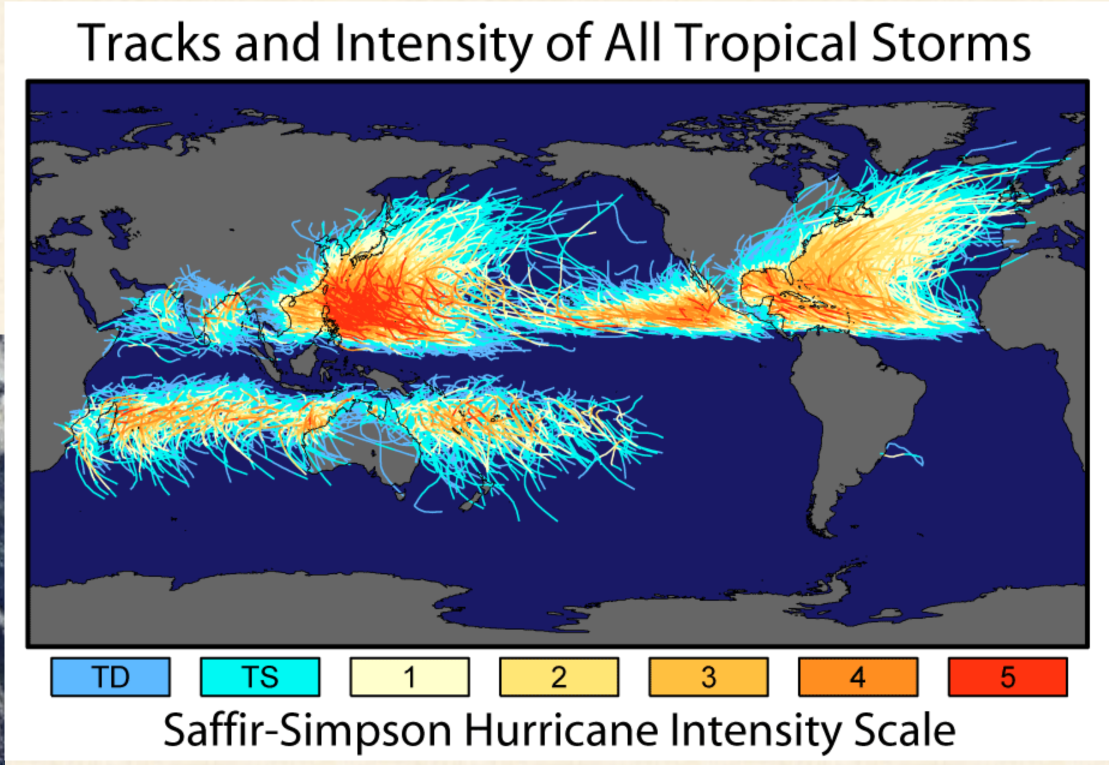




Scales of the Coriolis Force effect

Does the Coriolis force influence the spin of tornados?

A. Yes

B. No

Scales of the Coriolis Force effect

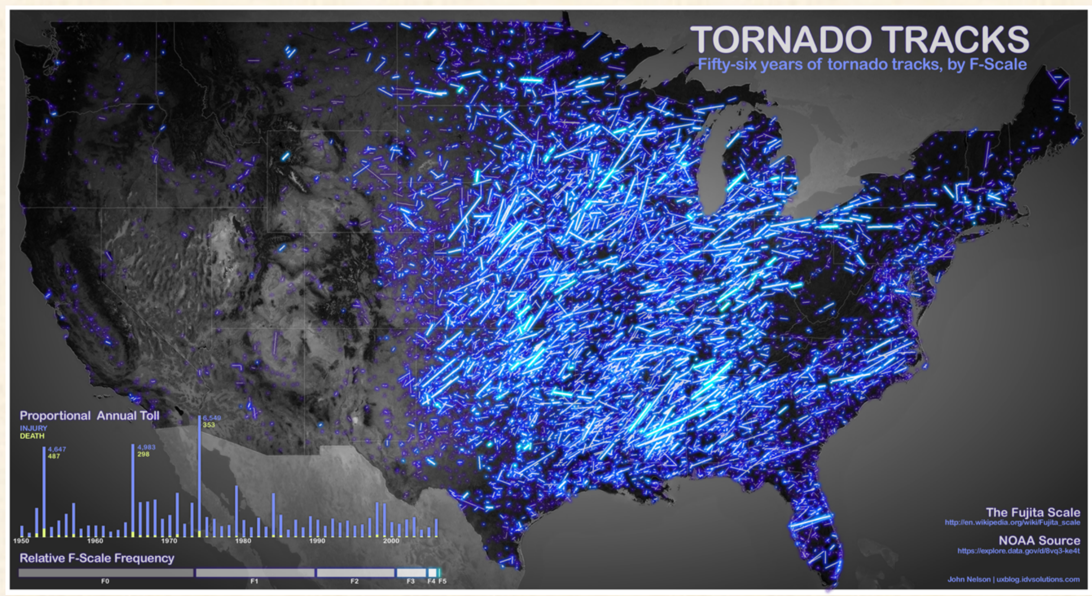
Does the Coriolis force influence the spin of tornados?

A. Yes

B. No

No influence on tornado rotation

However, Coriolis effect DOES Influence tornado tracks



Scales of the Coriolis Force effect

Does the Coriolis force influence your motion of water in your toilet?

A. Yes
B. No

Scales of the Coriolis Force effect

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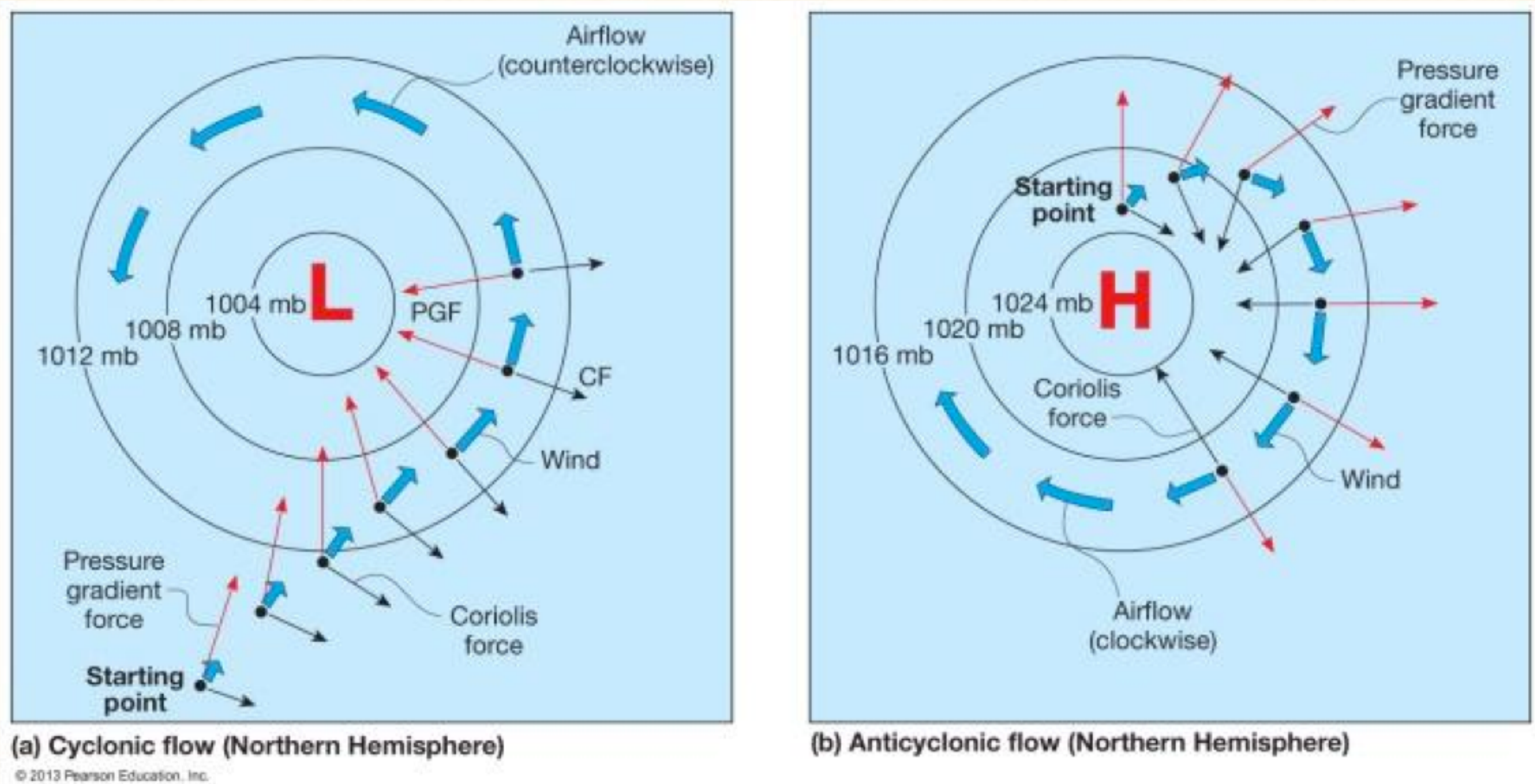
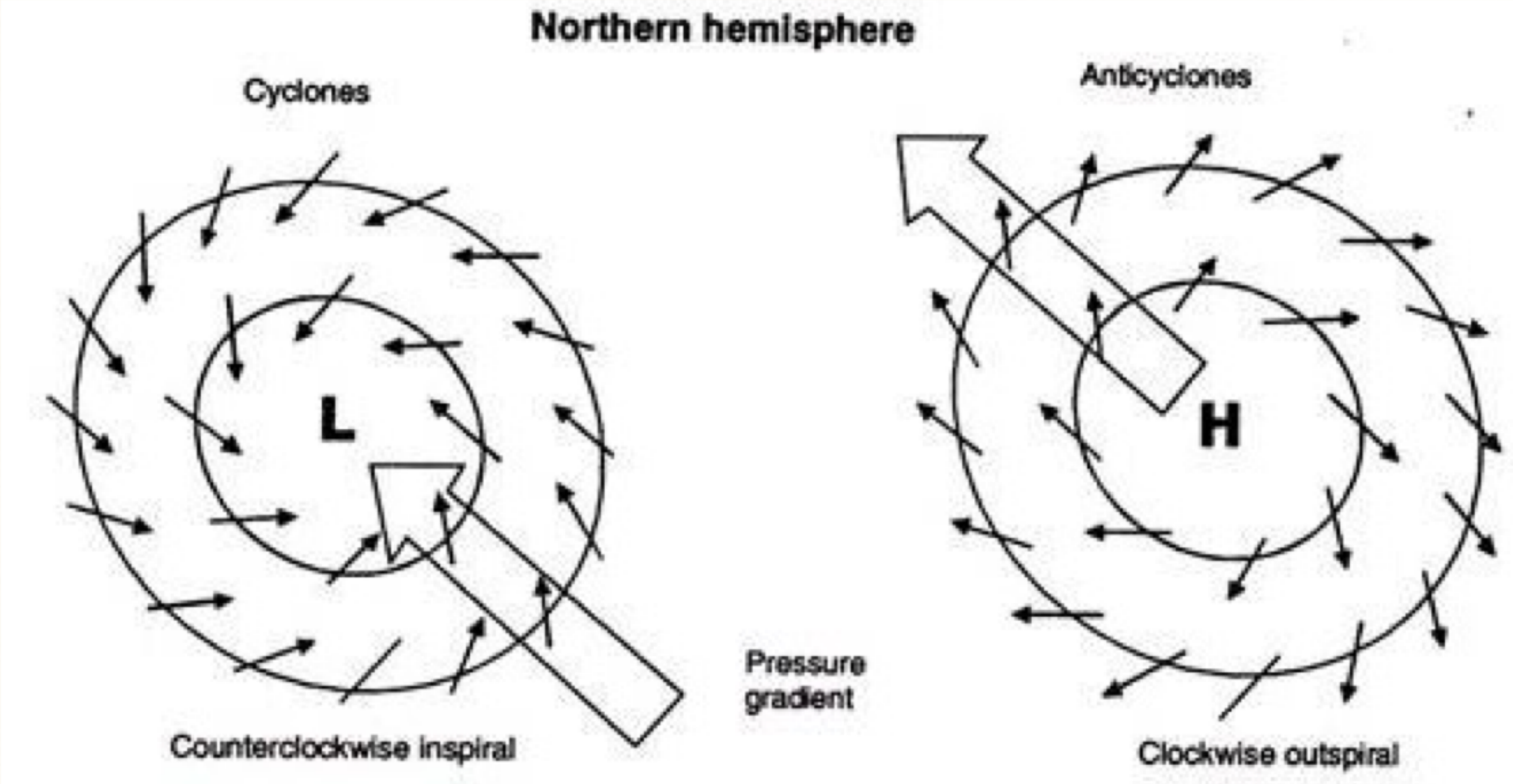
A. Yes
B. No

Geostrophic Wind

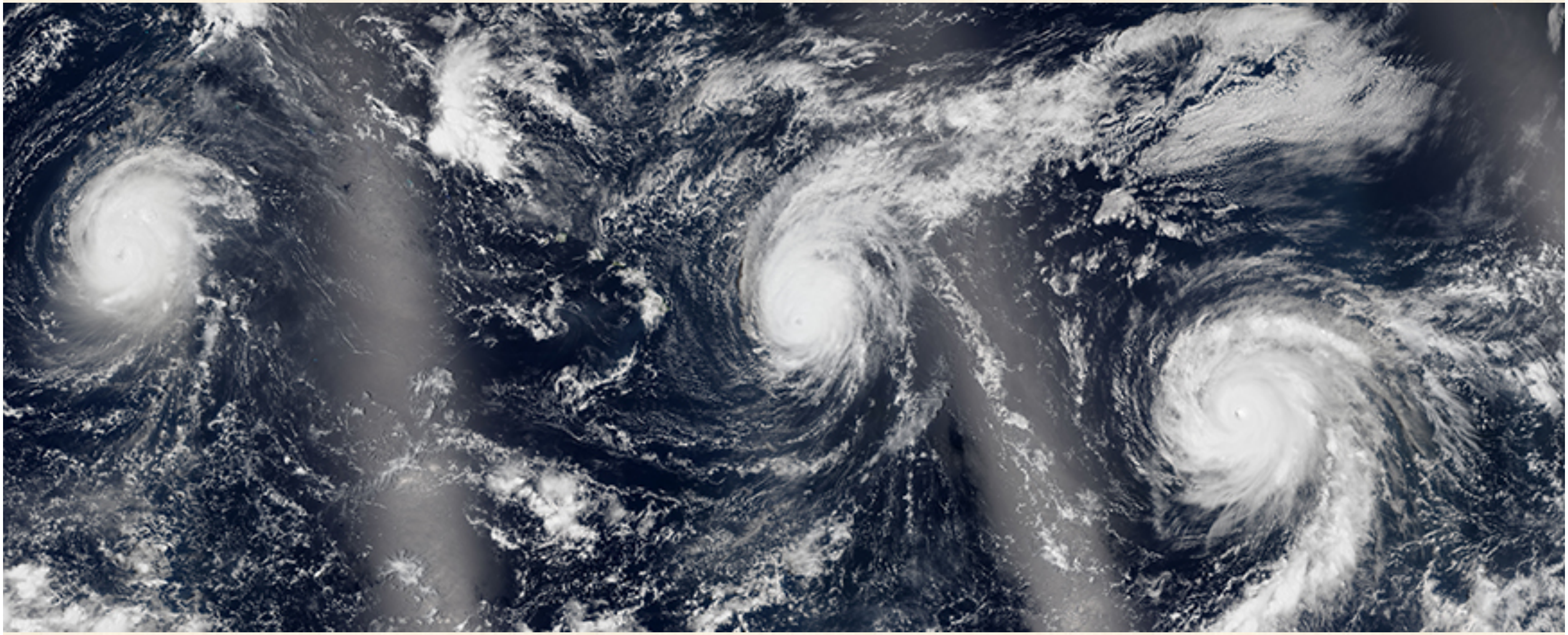
Geostrophic wind is the combined effect of both the Coriolis force and the Pressure Gradient Force





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

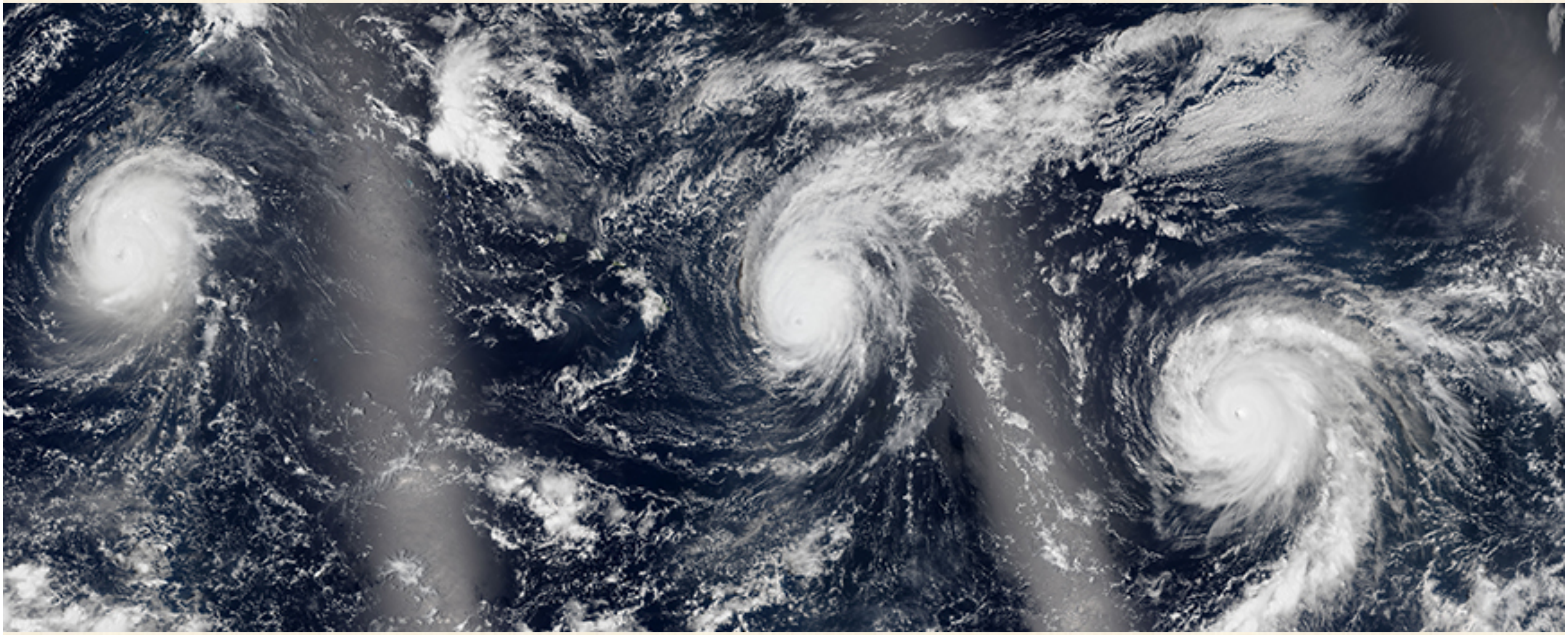
Which hemisphere is this picture from?



A. Northern hemisphere

B. Southern hemisphere

NH Pacific Ocean, Aug 30 2015



A.Northern hemisphere B. Southern hemisphere

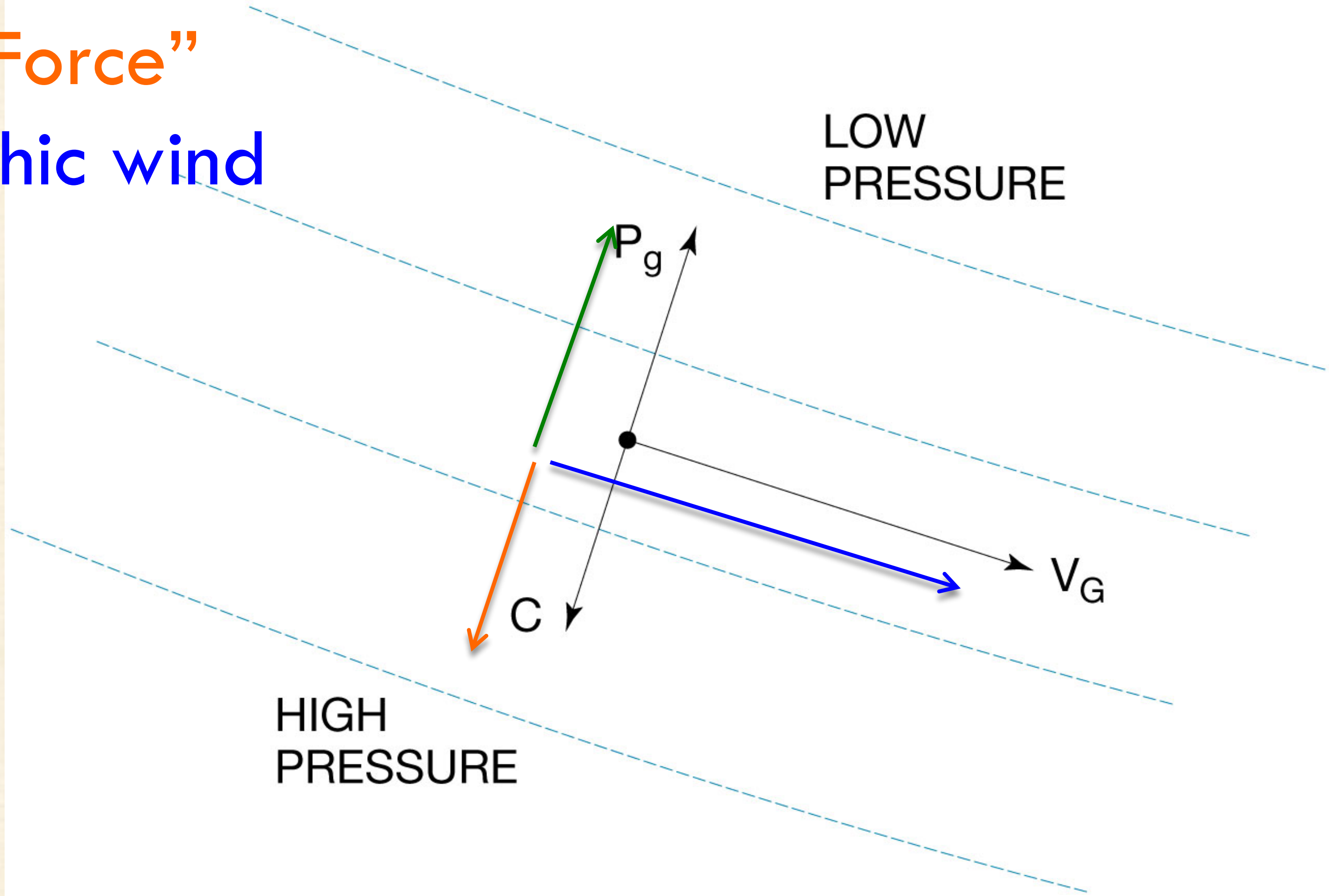
Geostrophic Balance:

On Northern Hemisphere

Pressure Gradient Force

Coriolis “Force”

Geostrophic wind



Wind flows along isobars

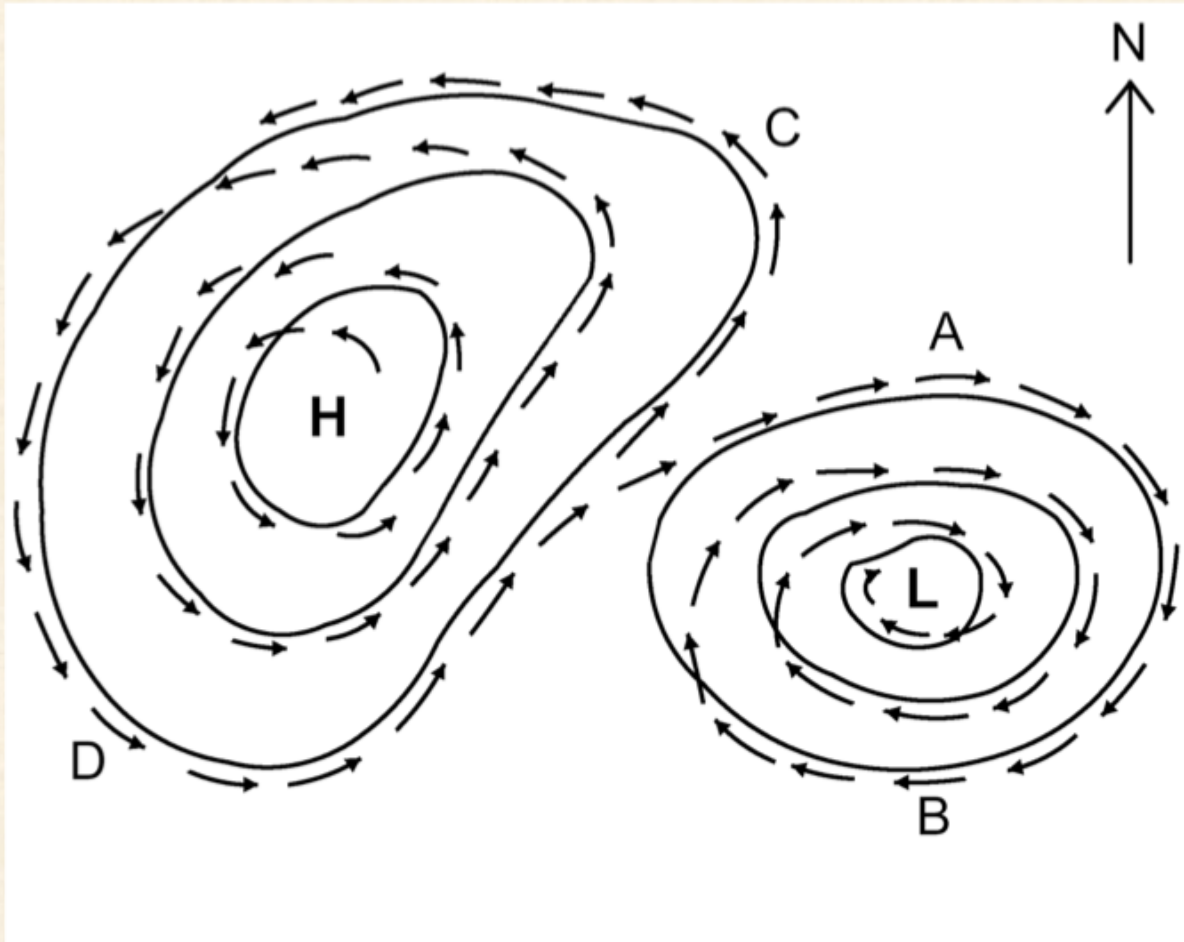
(isobars=lines of constant pressure)

P_g = Pressure Gradient Force
C = Coriolis Force
V_G = Geostrophic Wind

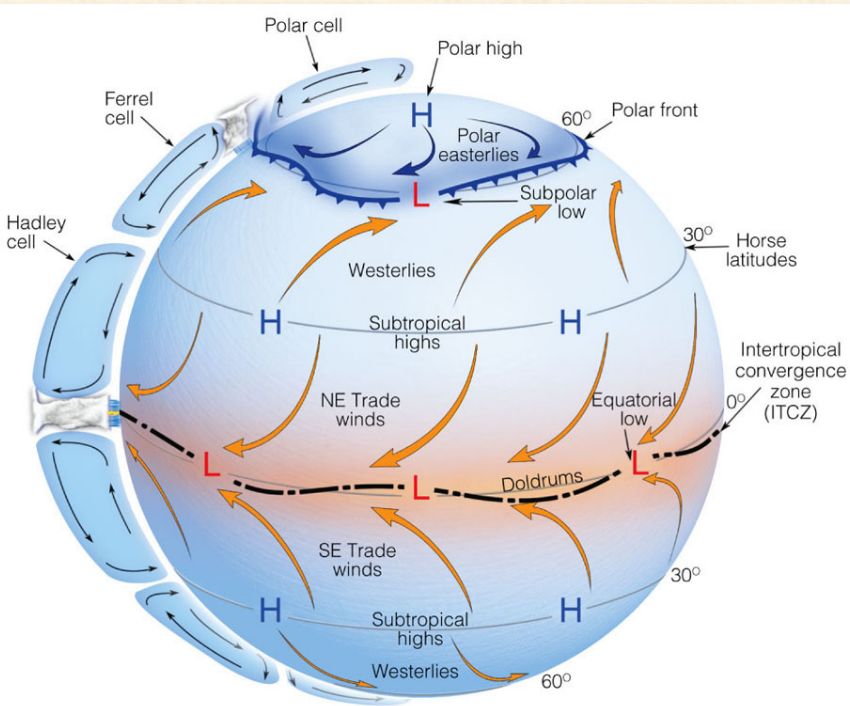
Geostrophic Balance: Wind flows along isobars around highs and lows

- **In the Southern hemisphere:** high-pressure systems rotate counterclockwise and low-pressure systems rotate clockwise due to the Coriolis force
- **In the Northern Hemisphere:** high-pressure systems rotate clockwise and low-pressure systems rotate counter clockwise due to the Coriolis force

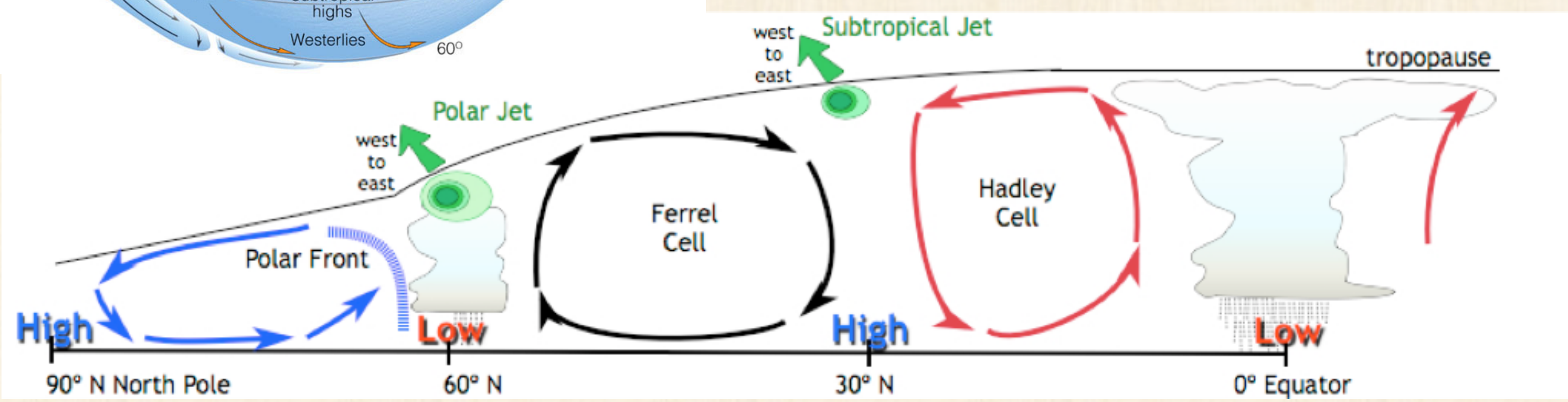
Southern Hemisphere example



Important atmospheric circulation cells



- Hadley Cell
- Ferrell Cell
- Polar Cell



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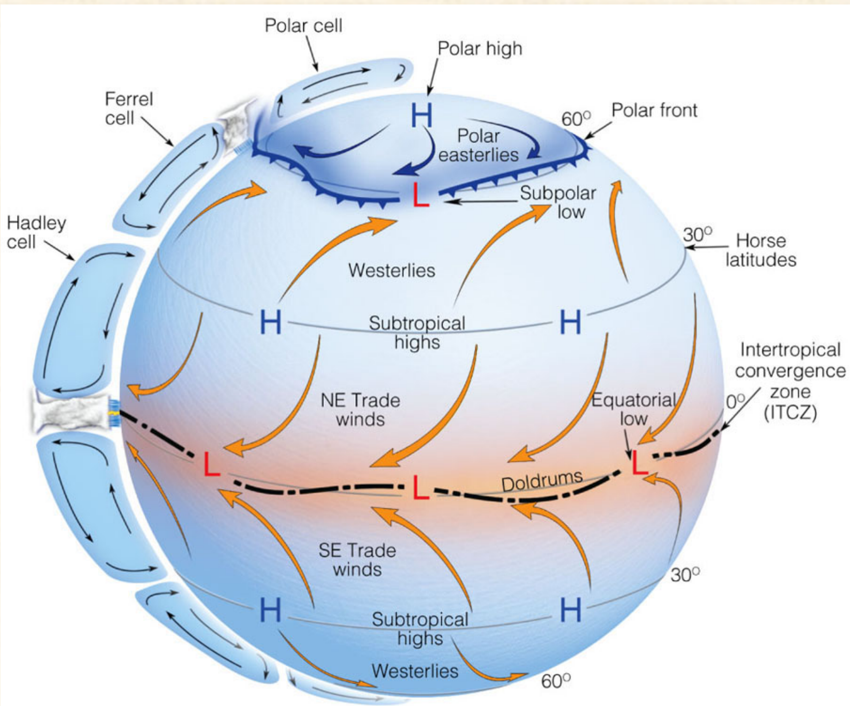
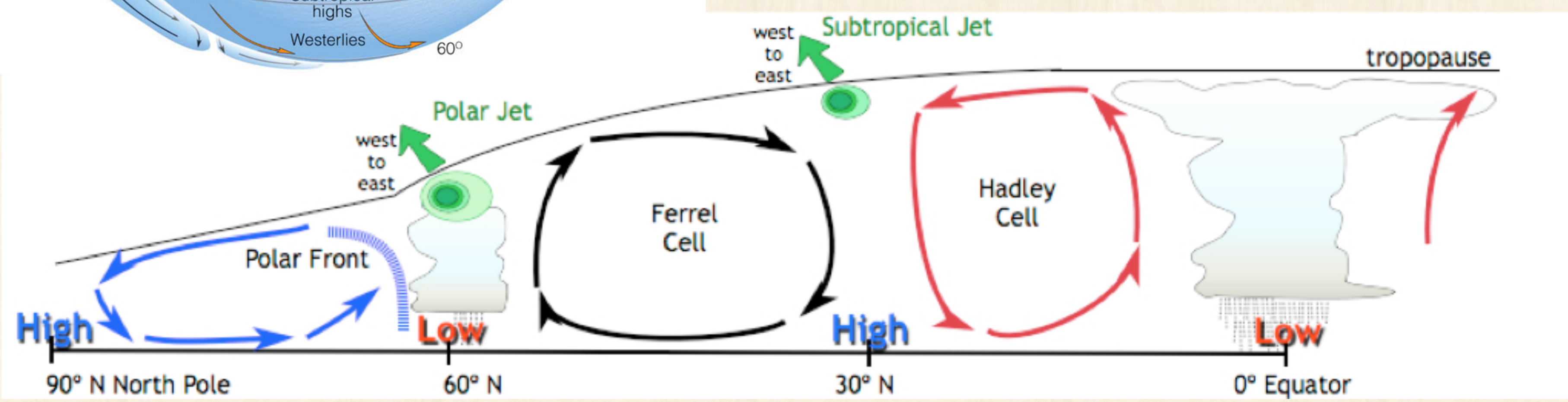


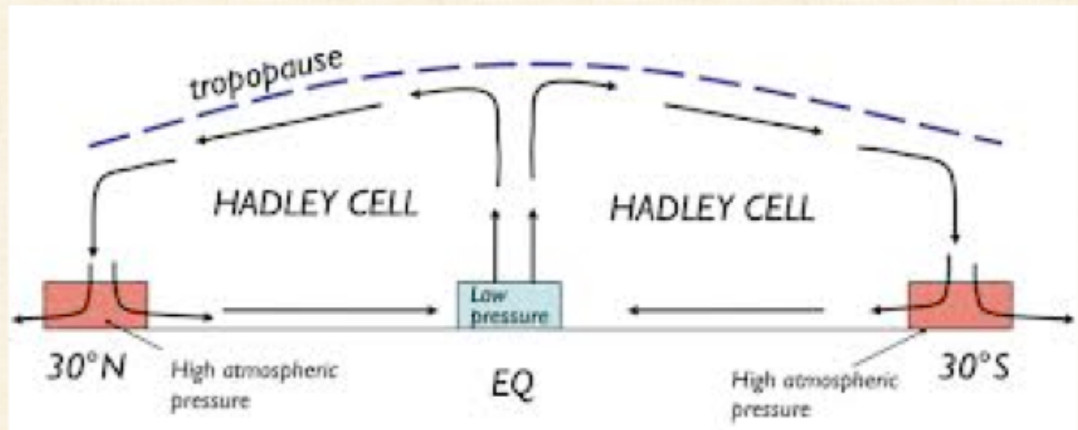
- Hadley Cell
- Ferrell Cell
- Polar Cell

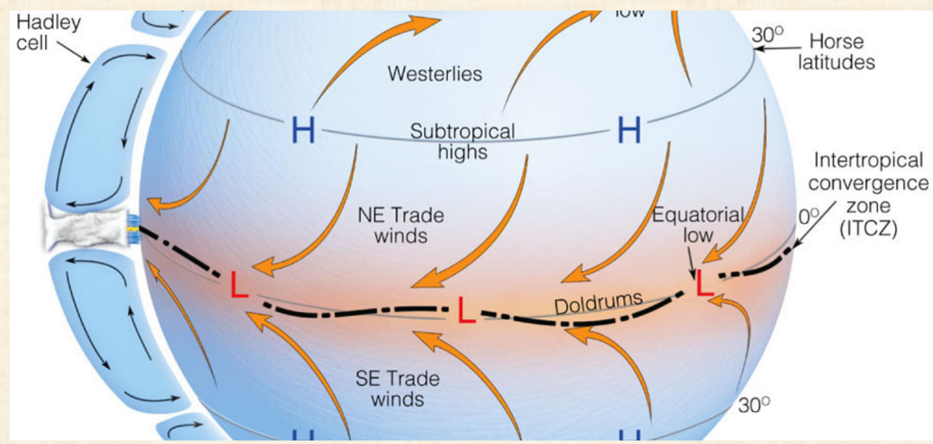
→ Together they move heat from the tropics to the poles



Hadley Cell

- ***What happens in the Hadley Cell?***
- **Equator/Tropics –** ascending air, low pressure at the ground, surface convergence, lots of clouds and rainfall, easterly winds, Intertropical Convergence Zone
- **Subtropics –** descending air, high pressure at the surface, few clouds, low rainfall



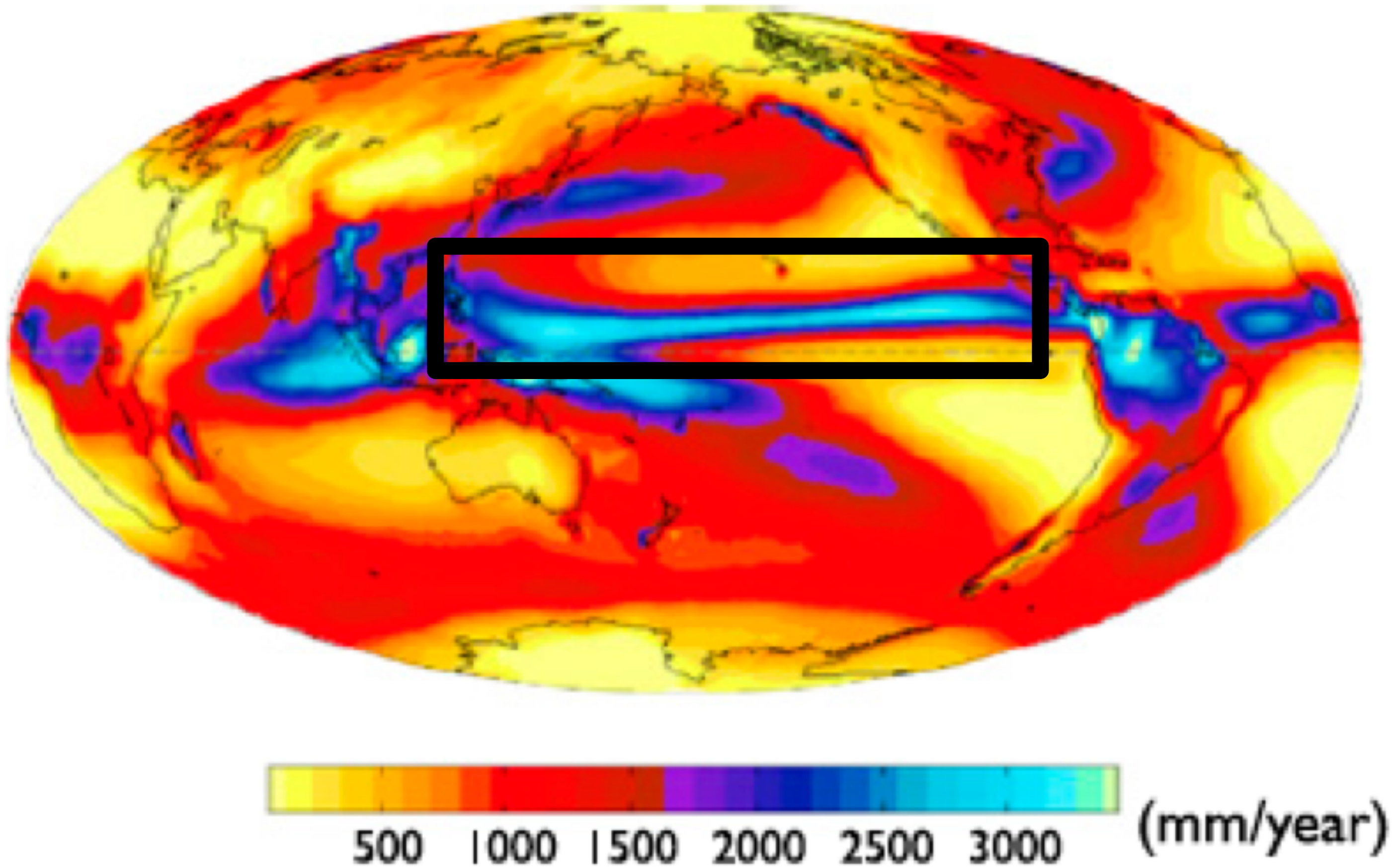


Hadley circulation helps explain tropical precipitation

InterTropical Convergence Zone (ITCZ) = Equatorial Rain Belt.

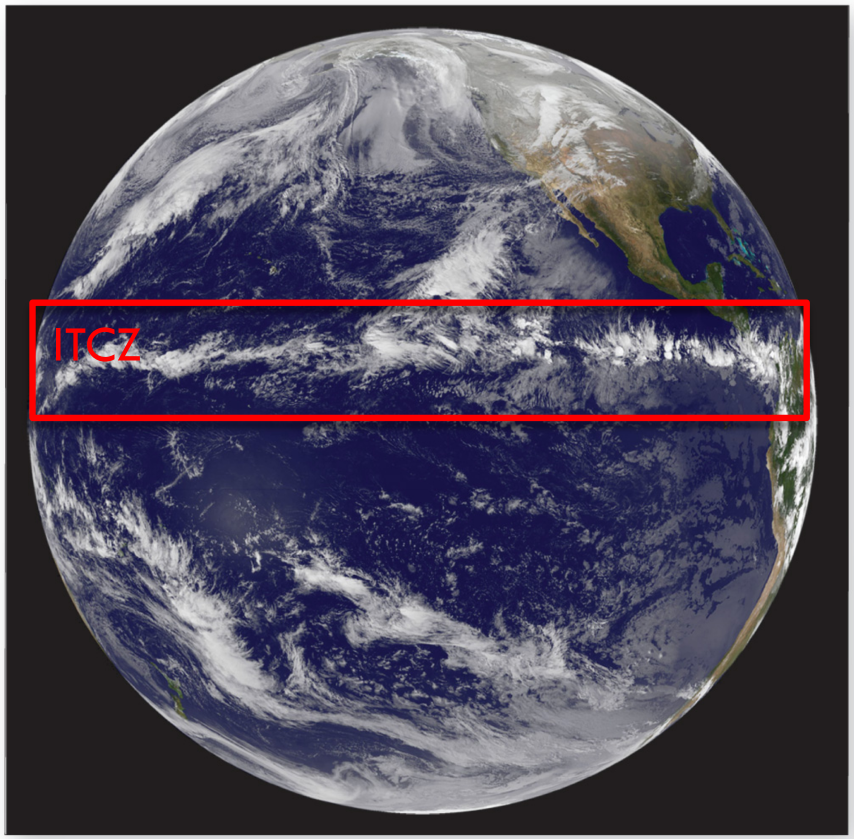
Rain near the equator where warm air rises; Latent heat release enhances rising!

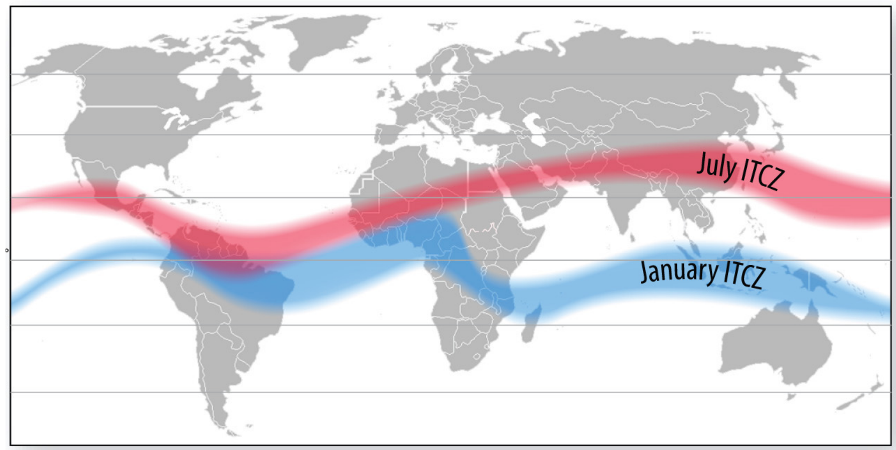
The ITCZ is most obvious over Pacific Ocean.



Observed annual mean precipitation from 1985-2004

ITCZ = InterTropical Convergence Zone





ITCZ moves north- and southwards with the seasons, marks the region of maximum solar radiation

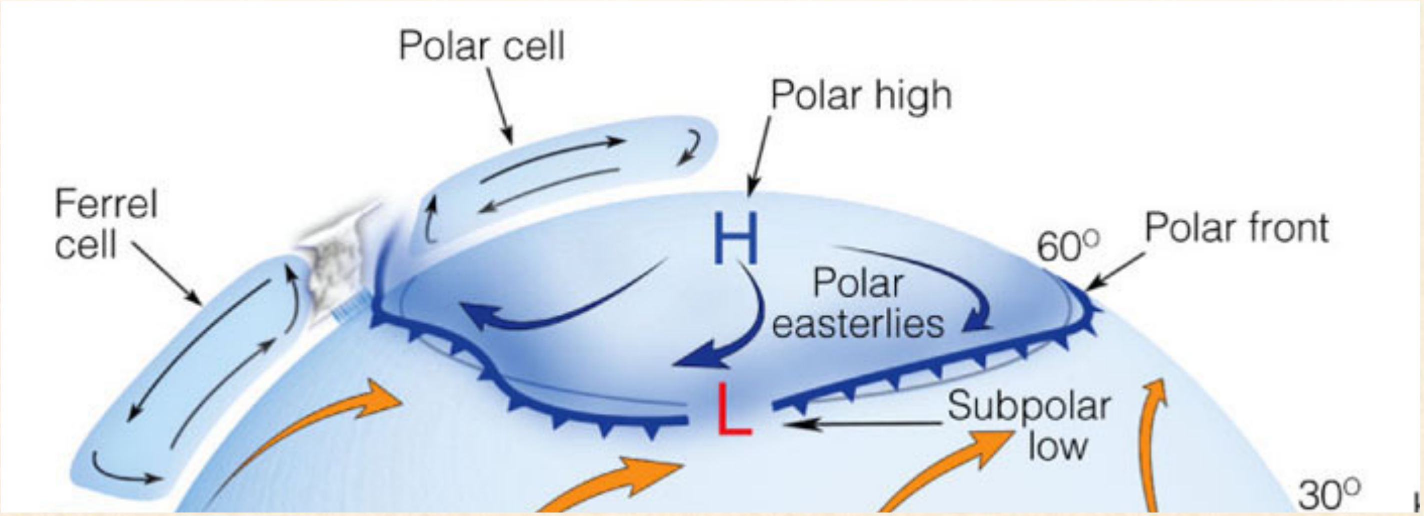
Mid-latitude deserts

Hadley circulation helps explain location of large Deserts.

Deserts in sub-tropics where warm air sinks

Sinking motion (=warming air) destroys clouds!

Polar cell



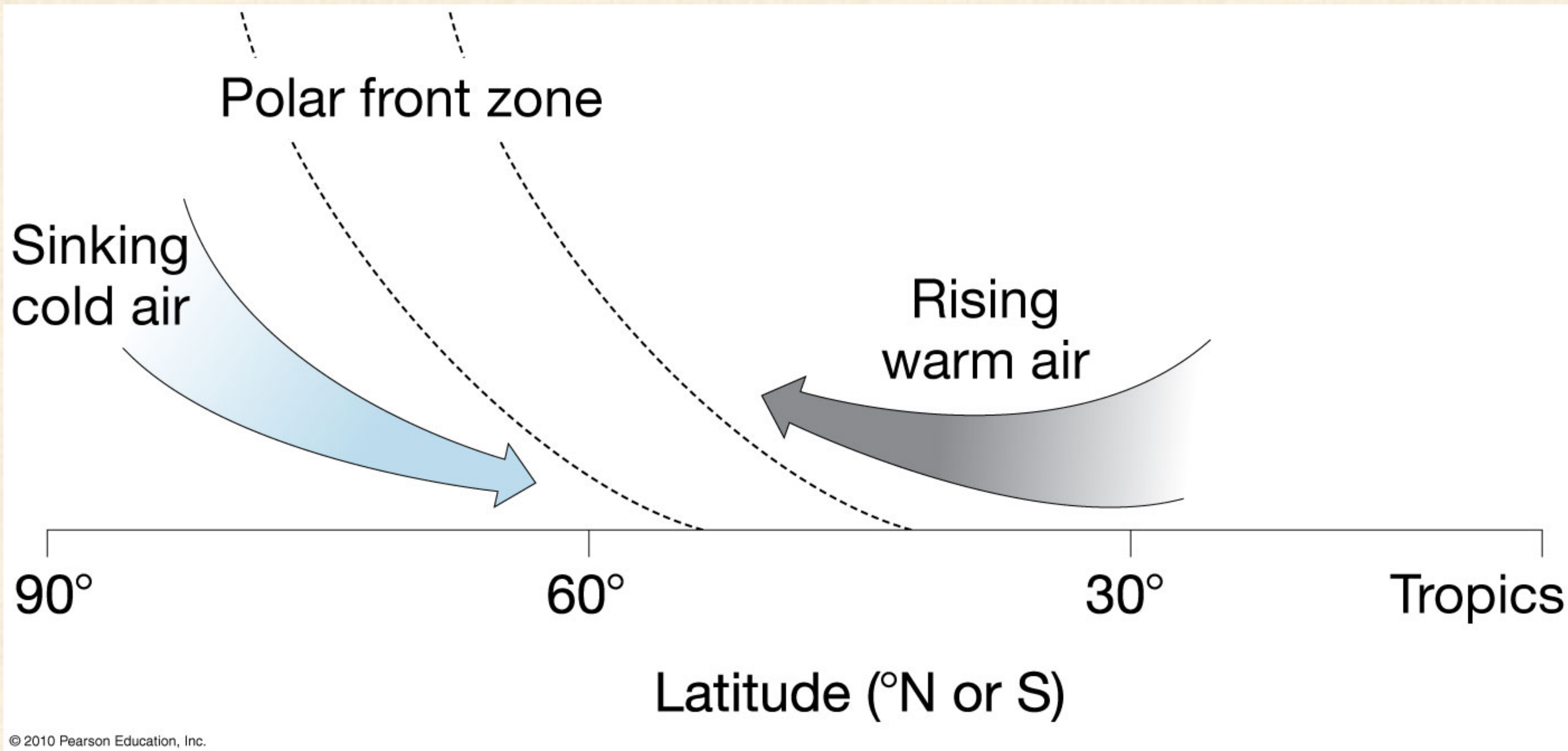
What happens in the Polar Cell?

Polar regions – High pressure at the ground, Cold air sinking, flow towards mid-latitudes at the ground, Weak easterly wind

In the “Polar Front Zone” at mid-latitudes:

Cold air from the Poles sinks and moves equatorward.

Hot air from the Tropics rises and moves poleward.



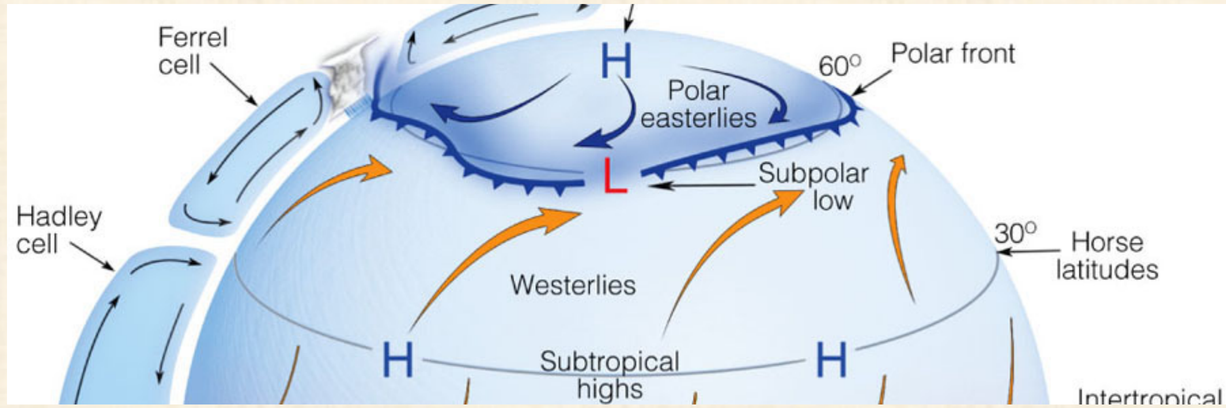
Hot and cold air do not mix easily – forming storms.

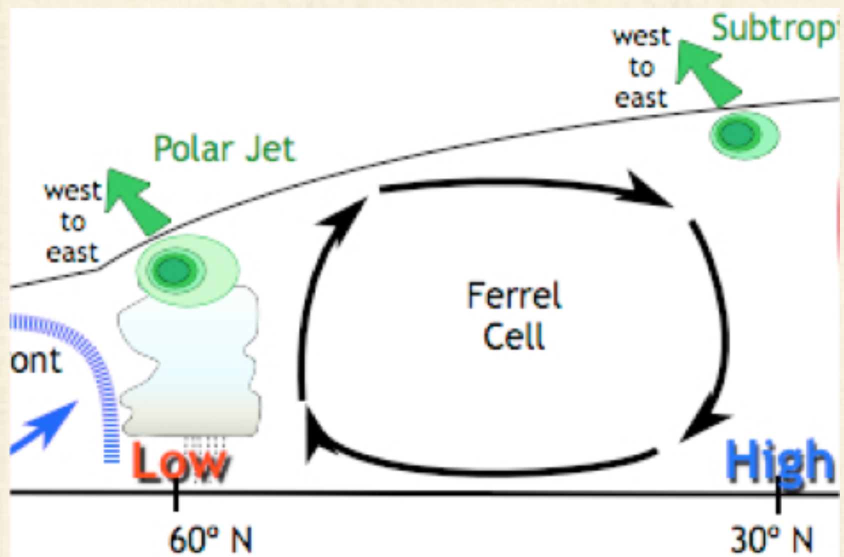
The Polar frontal zone forms a wave-like structure around the hemisphere

Ferrell cell

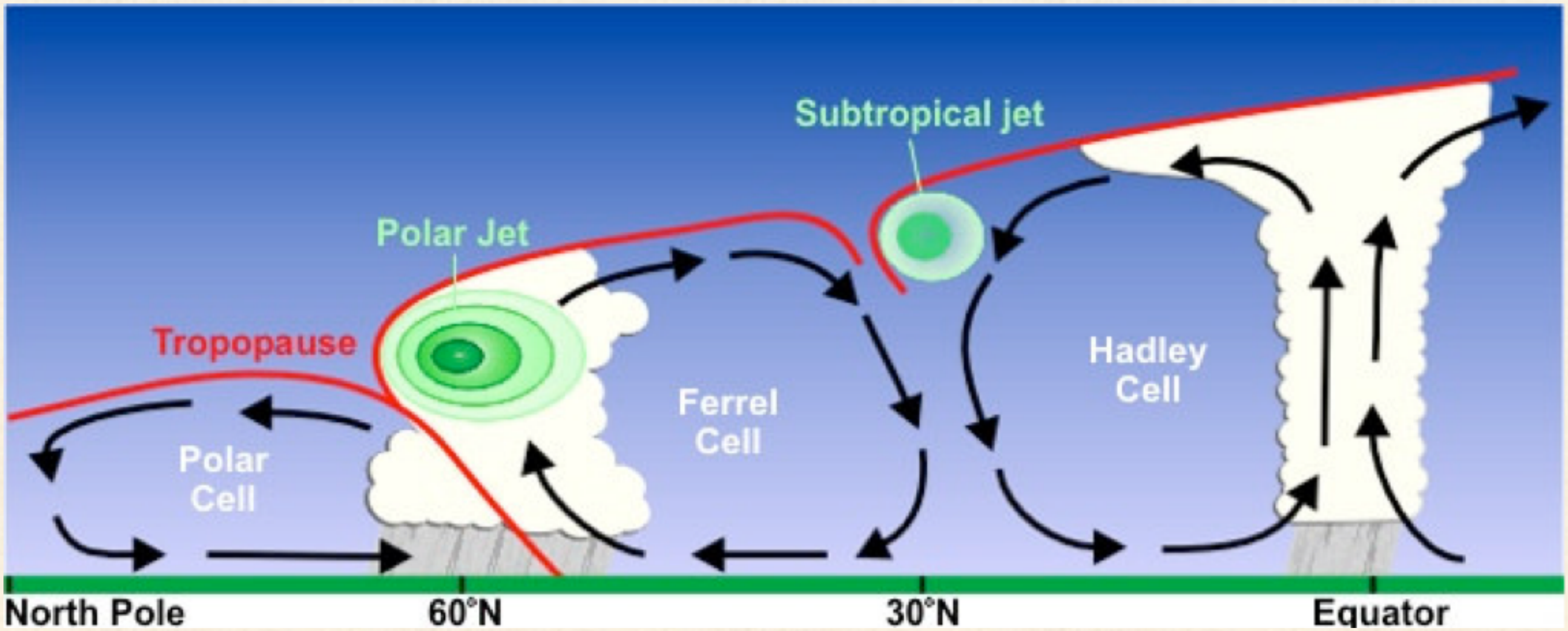
What happens in the Ferrel Cell?

- a parade of short-lived high and low pressure systems between 30N and 60 N (and 30S and 60S)
- moves heat and moisture poleward near the surface, and moves cold, dry air equatorward.





Jet streams



- Jet streams exist at the boundaries between the circulation cells
- Jet streams are fast flowing, relatively narrow air currents

Regional circulation features

Boundary layer meteorology

- Dispersion relates to horizontal winds and advection

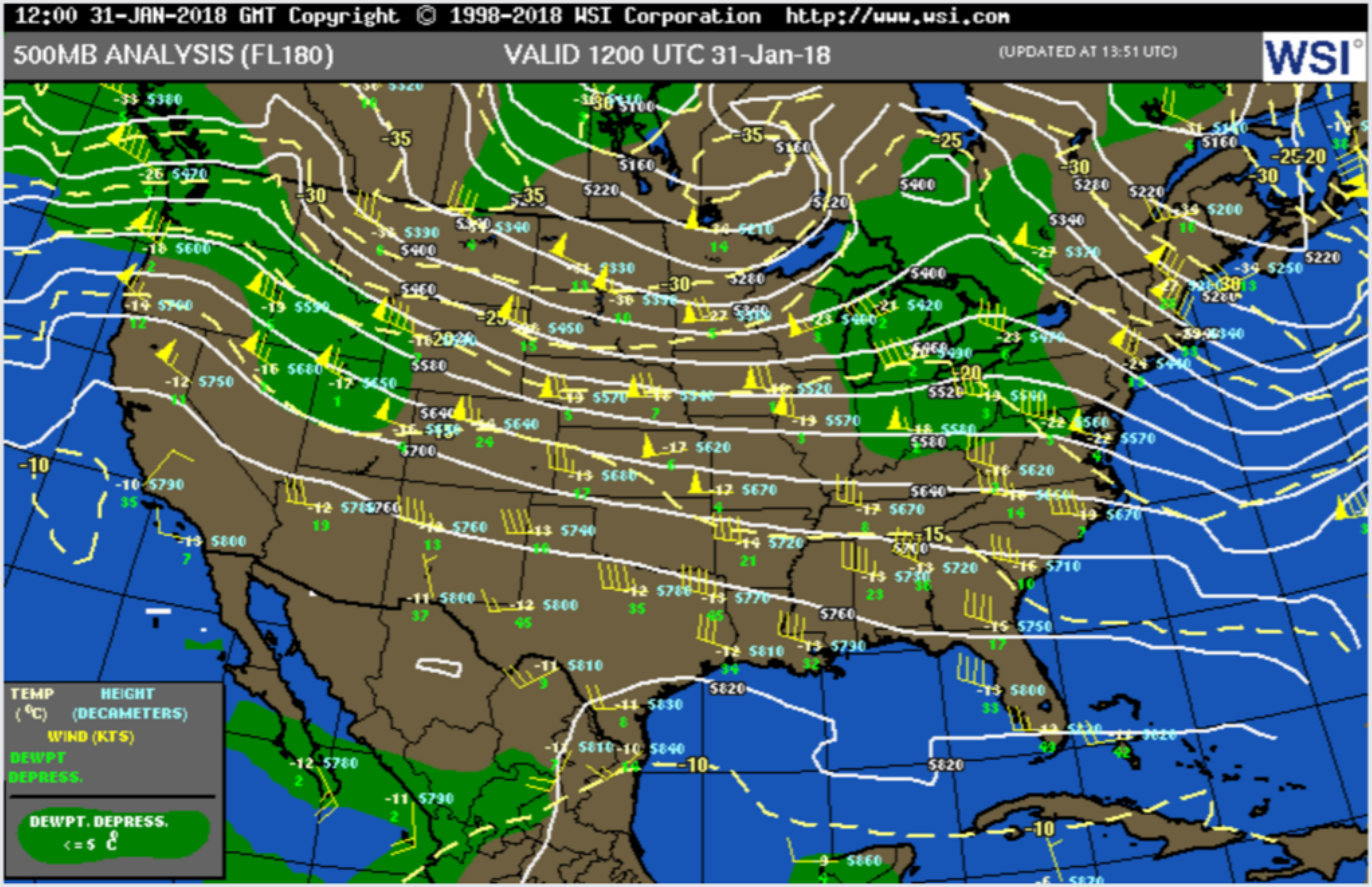
- Mixing from the ground up depends on vertical wind structure

Let's watch a cool NASA video

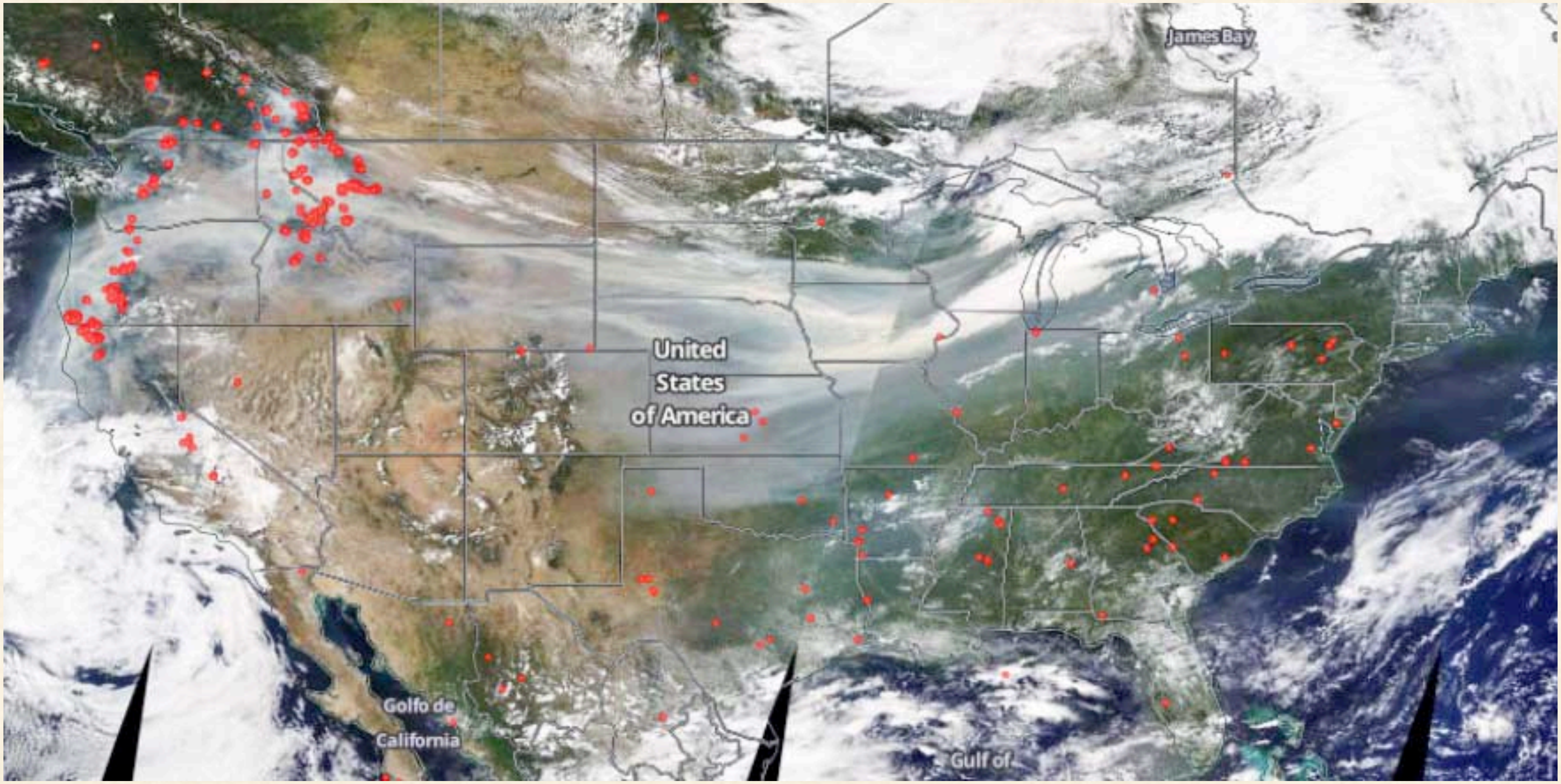
This video shows patterns of smoke, sea salt and dust across the planet:

https://www.youtube.com/watch?v=h1eRp0EGOmE&feature=youtu.be

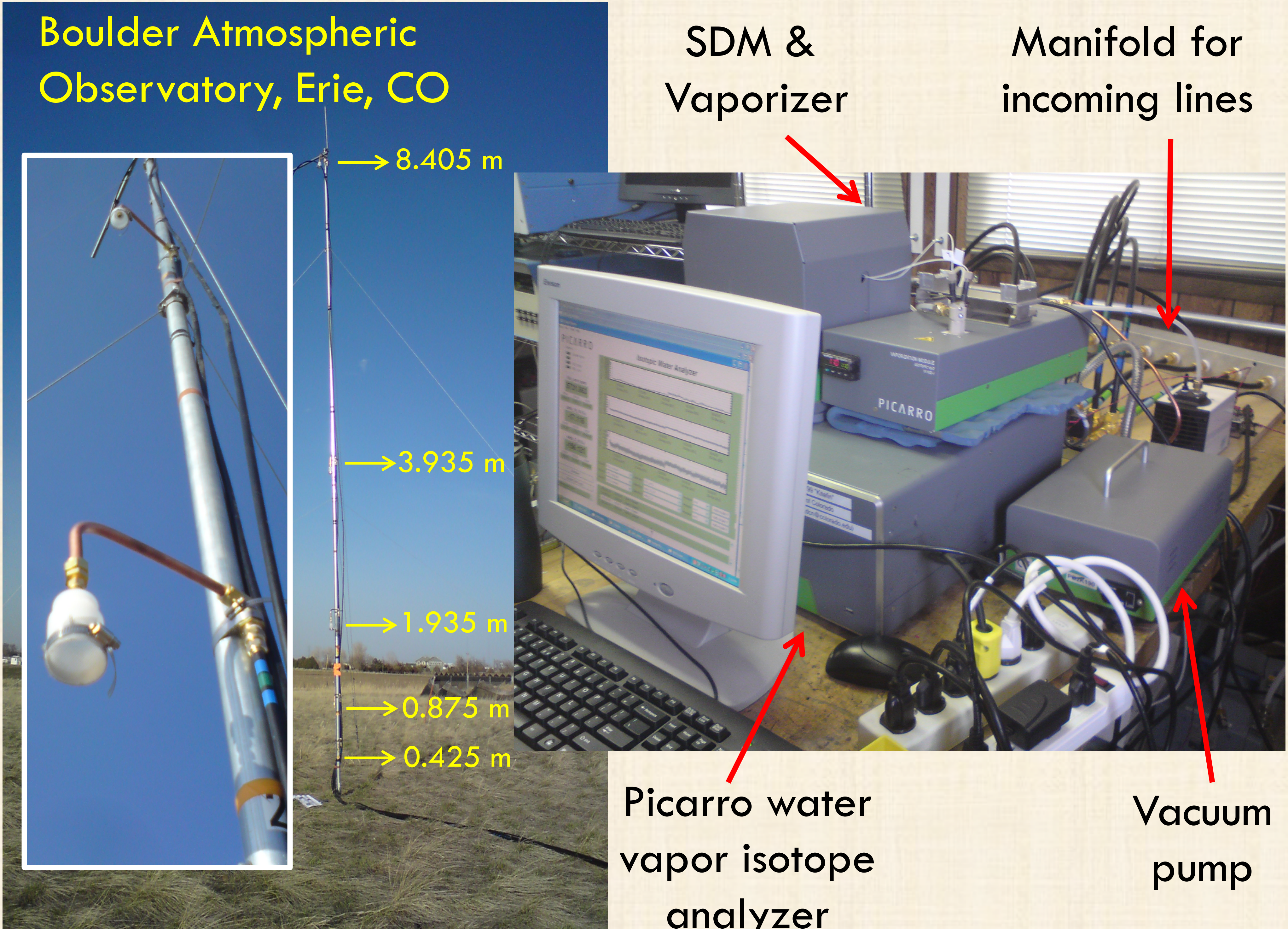
Circulation closer to home



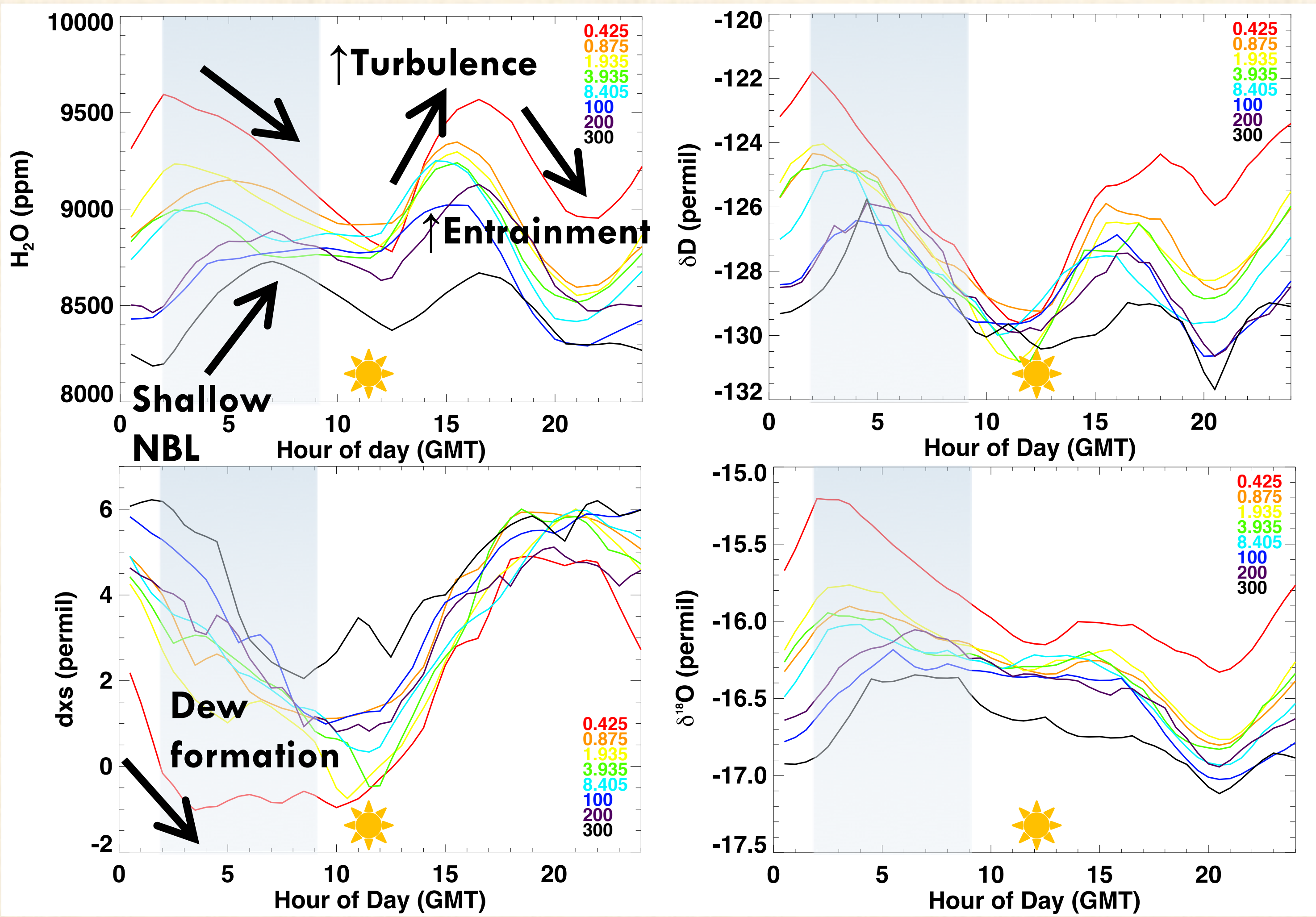
September 4, 2017



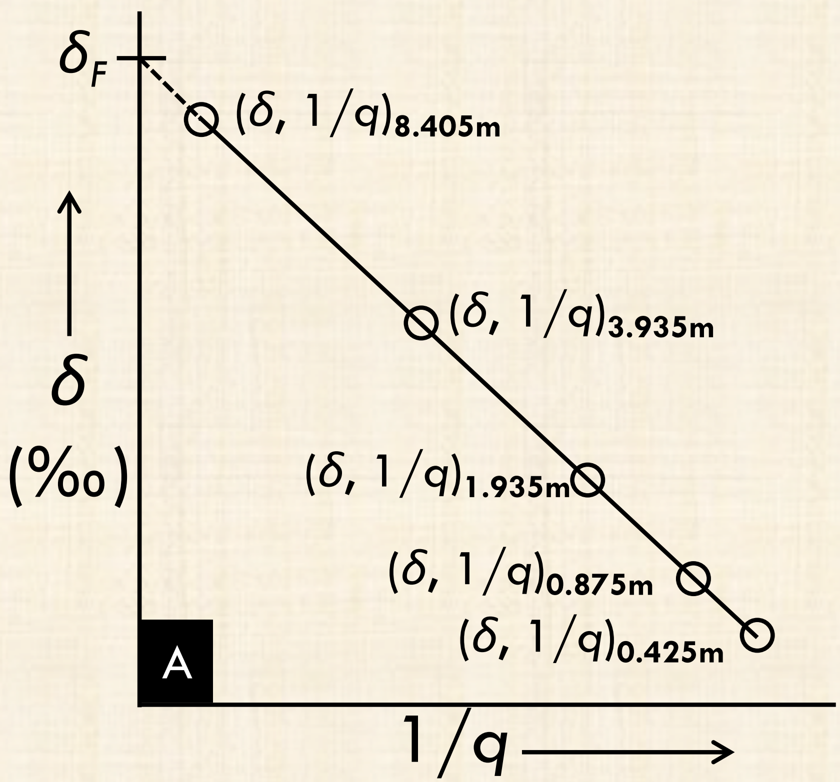
Even more regional: tower-based


Boulder Atmospheric Observatory, Erie, CO
8.405 m
3.935 m
1.935 m
0.875 m
0.425 m
SDM & Vaporizer
Manifold for incoming lines
PICARRO
Picarro water vapor isotope analyzer
Vacuum pump

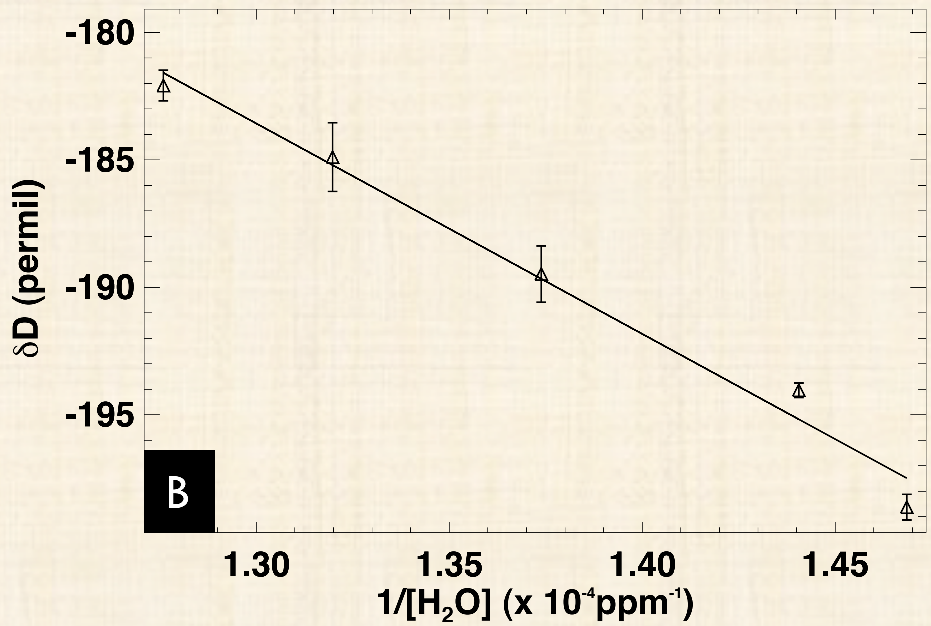
Water vapor isotopes JJA diurnal cycle

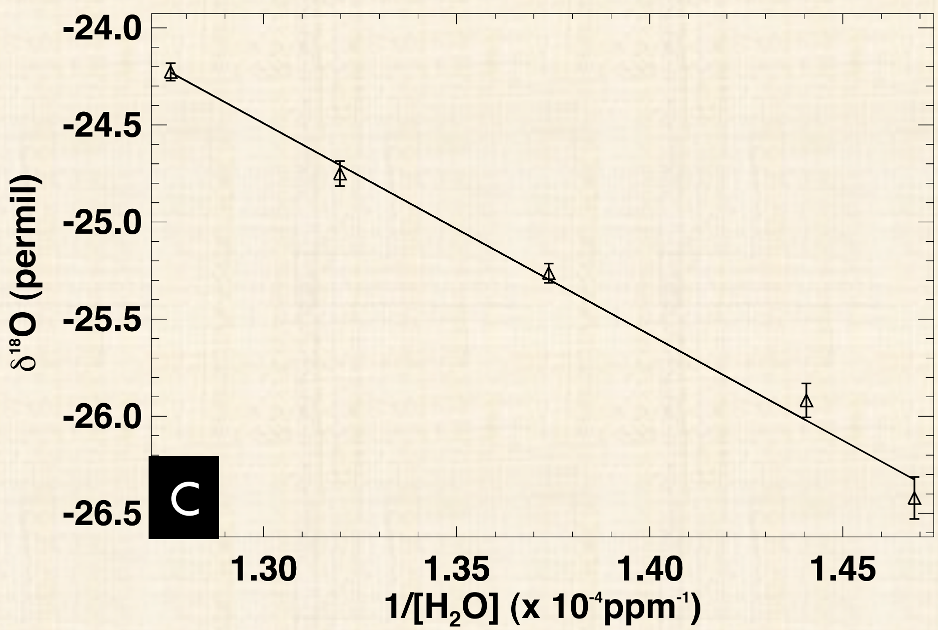


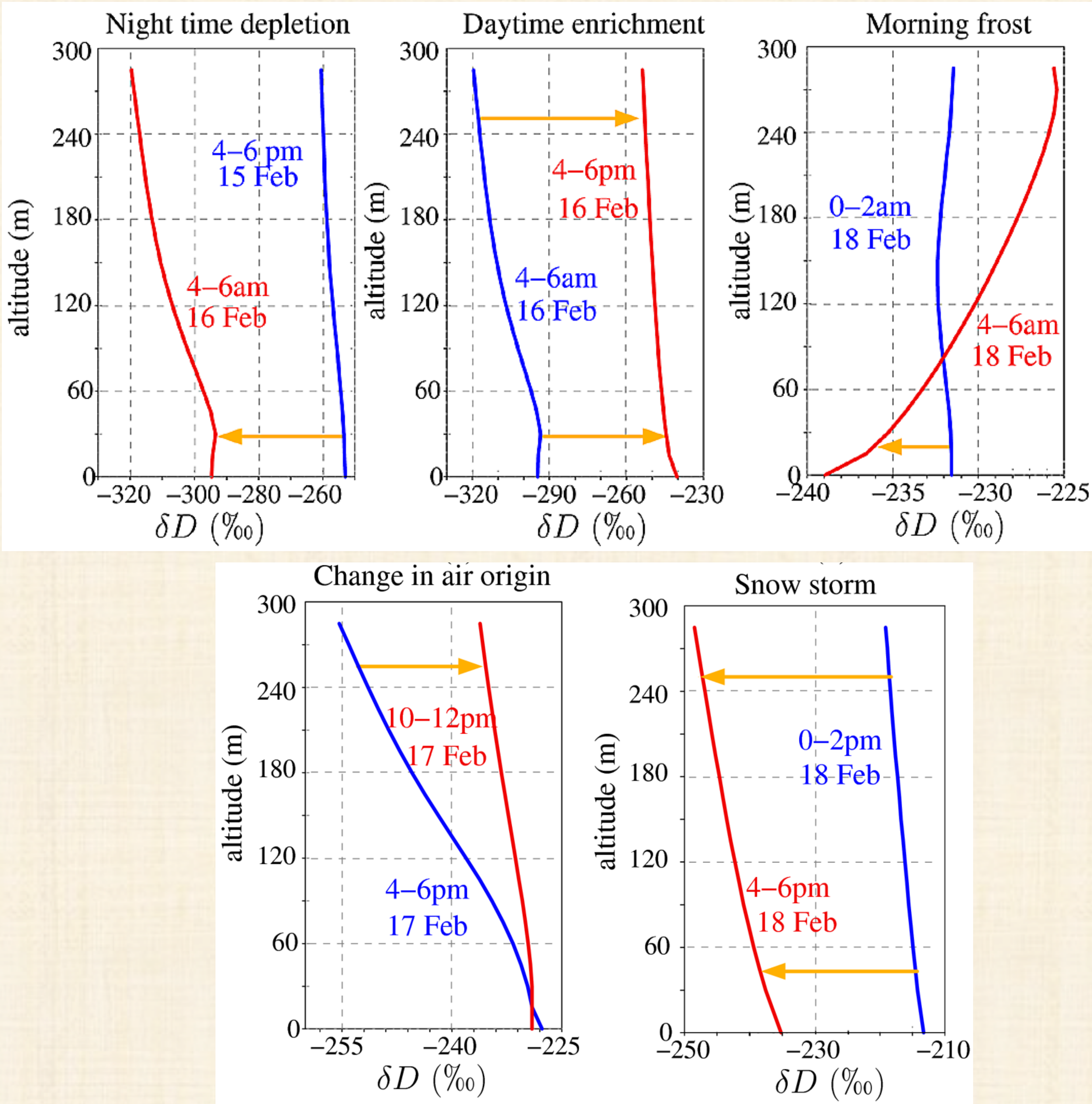
Theoretical Keeling plot: Use surface vapor profiles to extrapolate evaporative flux

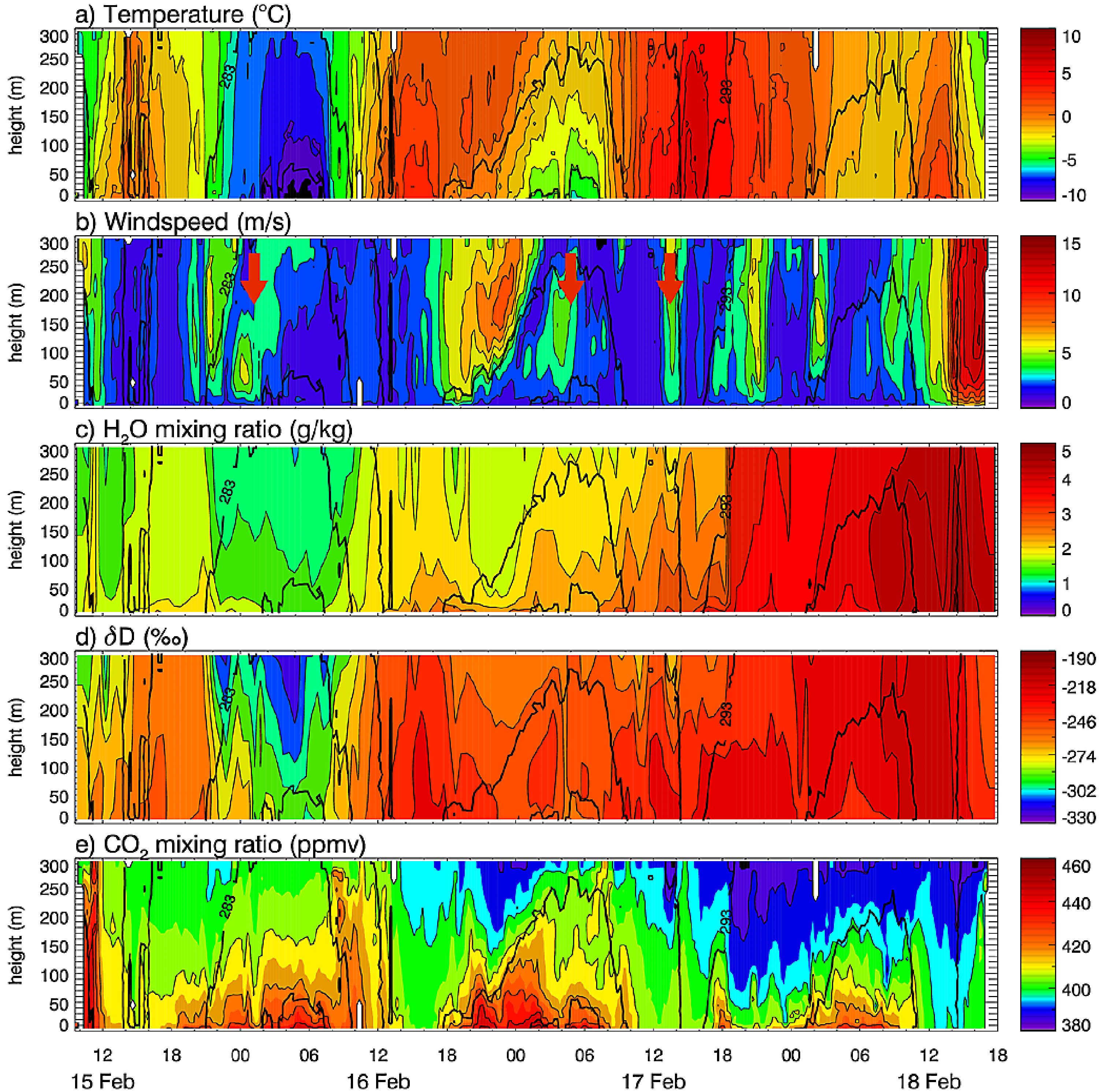


Examples from field data






Night time depletion
Daytime enrichment
Morning frost
Change in air origin
Snow storm
altitude (m)
δD (‰)
4–6 pm
15 Feb
4–6am
16 Feb
4–6pm
16 Feb
4–6am
16 Feb
0–2am
18 Feb
4–6am
18 Feb
10–12pm
17 Feb
4–6pm
17 Feb
0–2pm
18 Feb
4–6pm
18 Feb



a) Temperature (°C)
b) Windspeed (m/s)
c) H_2O mixing ratio (g/kg)
d) δD (‰)
e) CO_2 mixing ratio (ppmv)
height (m)
283
293
12
18
00
06
15 Feb
16 Feb
17 Feb
18 Feb