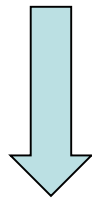


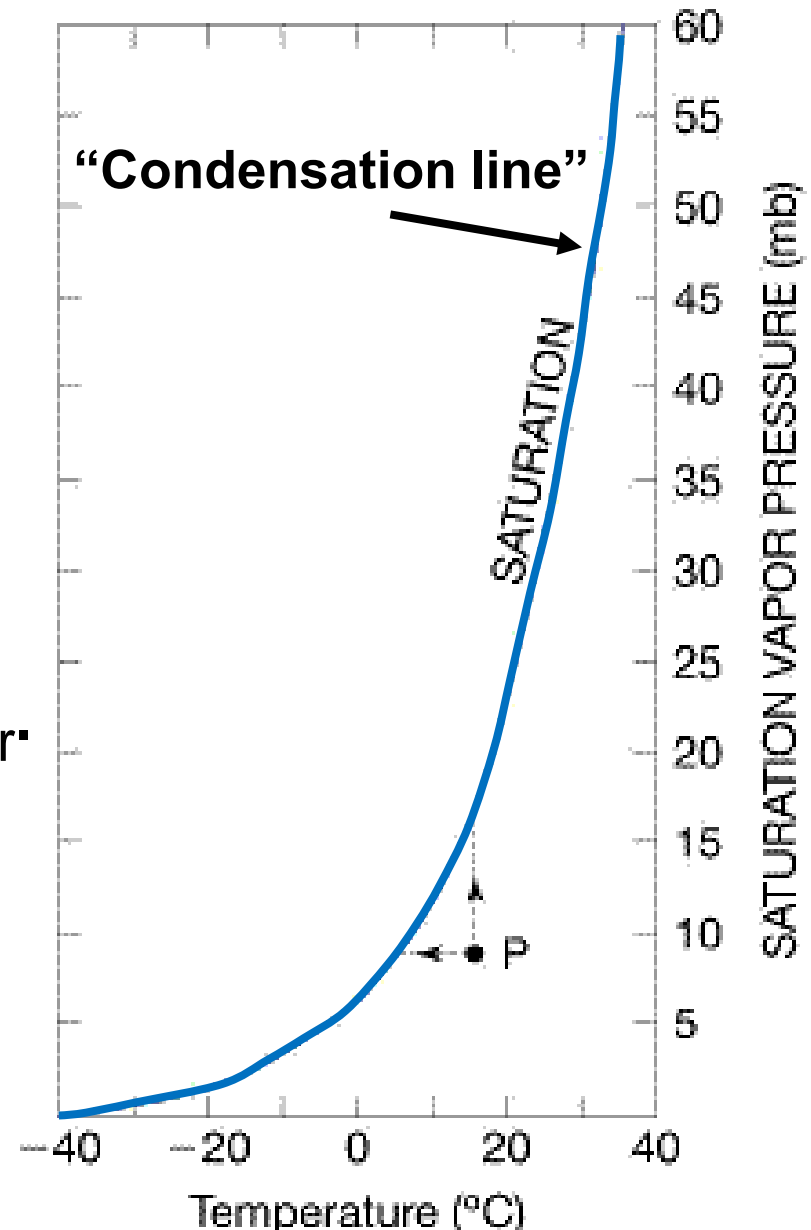
# Saturation Vapor Pressure of Water

The maximum amount of  $\text{H}_2\text{O}_{\text{vapor}}$  that “air can hold”

Warmer air can hold *exponentially more*  $\text{H}_2\text{O}_{\text{vapor}}$ .



**Implications for Greenhouse Effect And Climate Feedback**



# Vertical Motions Summary

- A warm planetary surface induces **buoyant forces**, which cause vertical motions, and thus **convection** in the atmosphere above it
- **Rising** air **expands** and therefore **cools**, while **sinking** air is **compressed** and therefore **warms** (1<sup>st</sup> Law  $E = Q + W$ )
- Vertical motions are coupled to phase transitions of water: **condensation** (precip) during **rising** motions; **evaporation** (drying) during **sinking** motions
- The above concepts explain the **average decrease** in temperature (T) with altitude (z) in the troposphere:

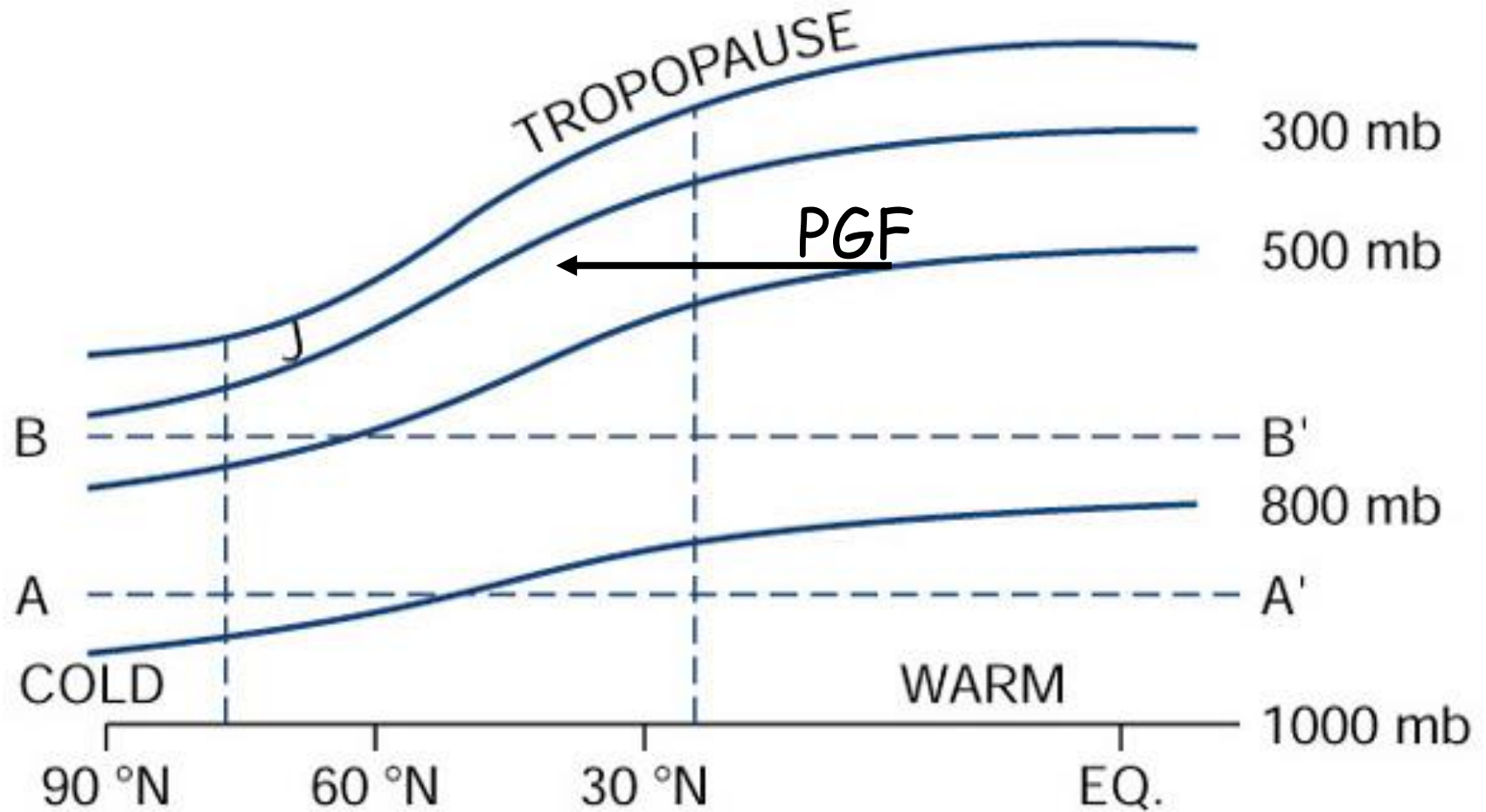
$$T(z) = T_{\text{surface}} - (6.5\text{K/km}) \cdot z$$

- A self-sustaining circulation (“Hadley Circulation”)
  - Wet tropics
  - Subtropical dry zones
  - Temperate, but stormy mid-latitudes
  - Cold/dry poles

# Vertical and Horizontal Motions Are Connected

- Warmer (less dense air) at one location  
→ less mass → lower pressure
- The “expansion” causes a horizontal pressure gradient → horizontal motions
- Result is a self-sustaining circulation of air (“circulation cells”)

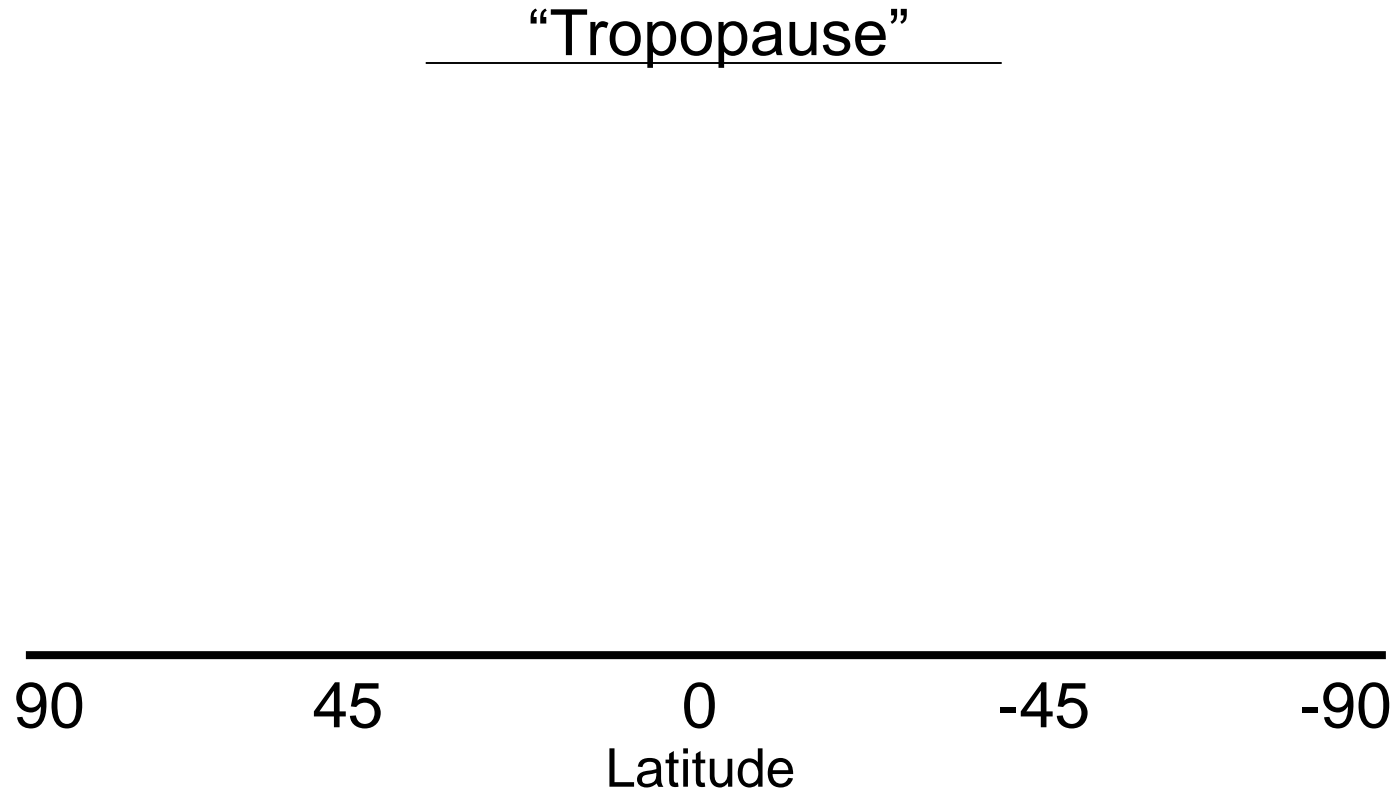
# Horizontal Pressure Gradients



**The picture is roughly symmetric for the Southern Hemisphere (SH)**

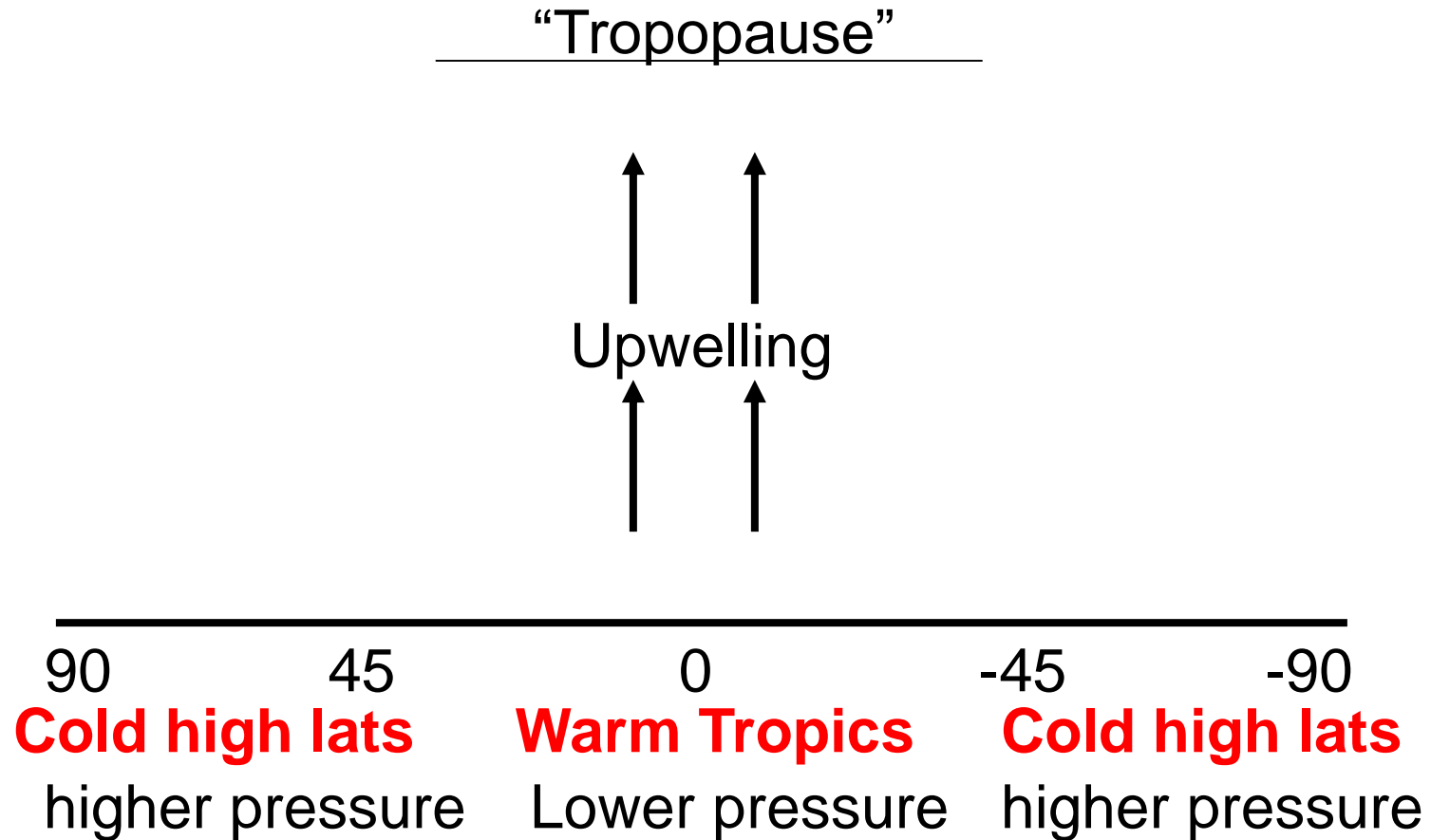
# Early Picture of General Circulation

Based on Hadley's 1735 paper:



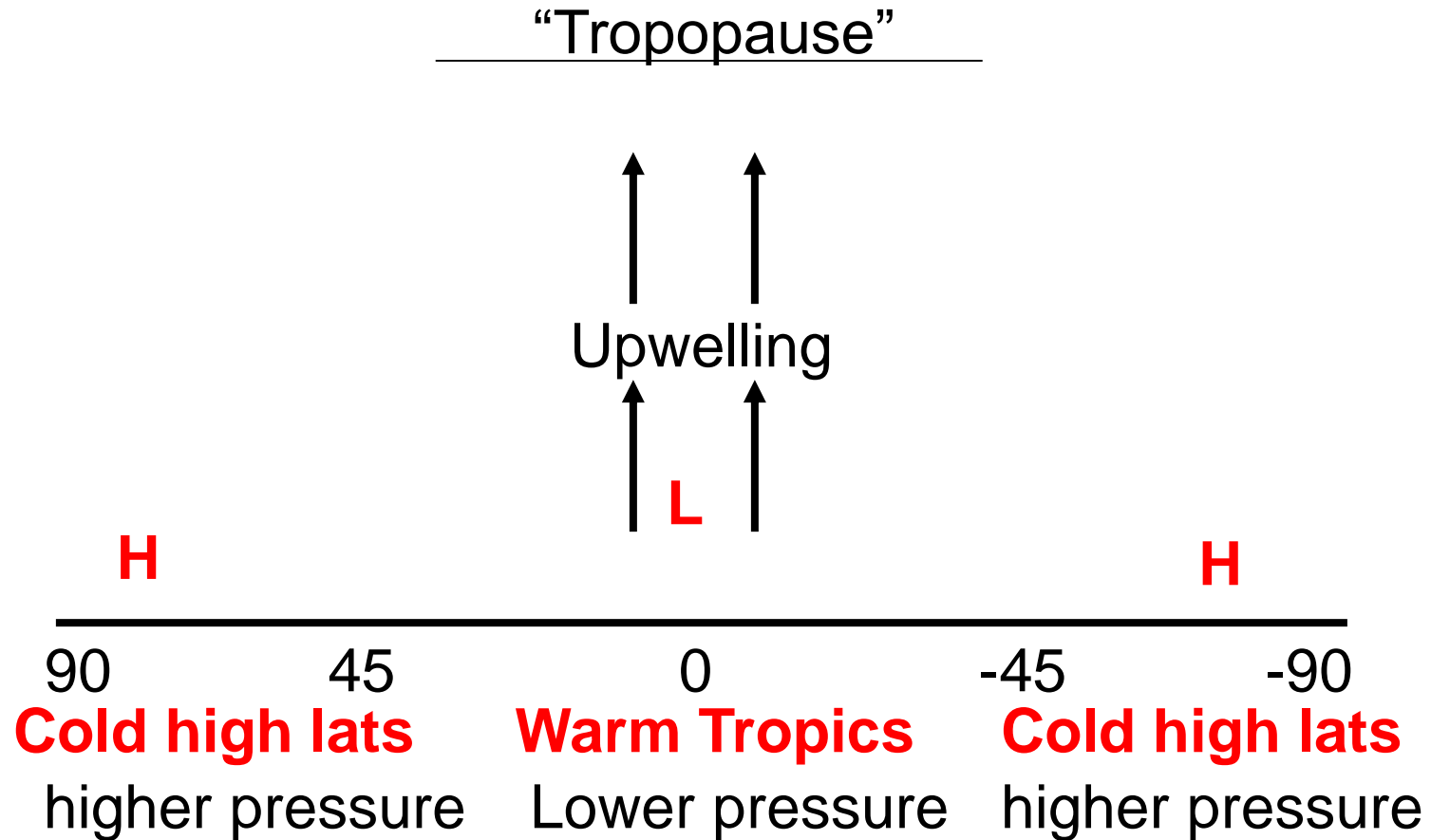
# Early Picture of General Circulation

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# Early Picture of General Circulation

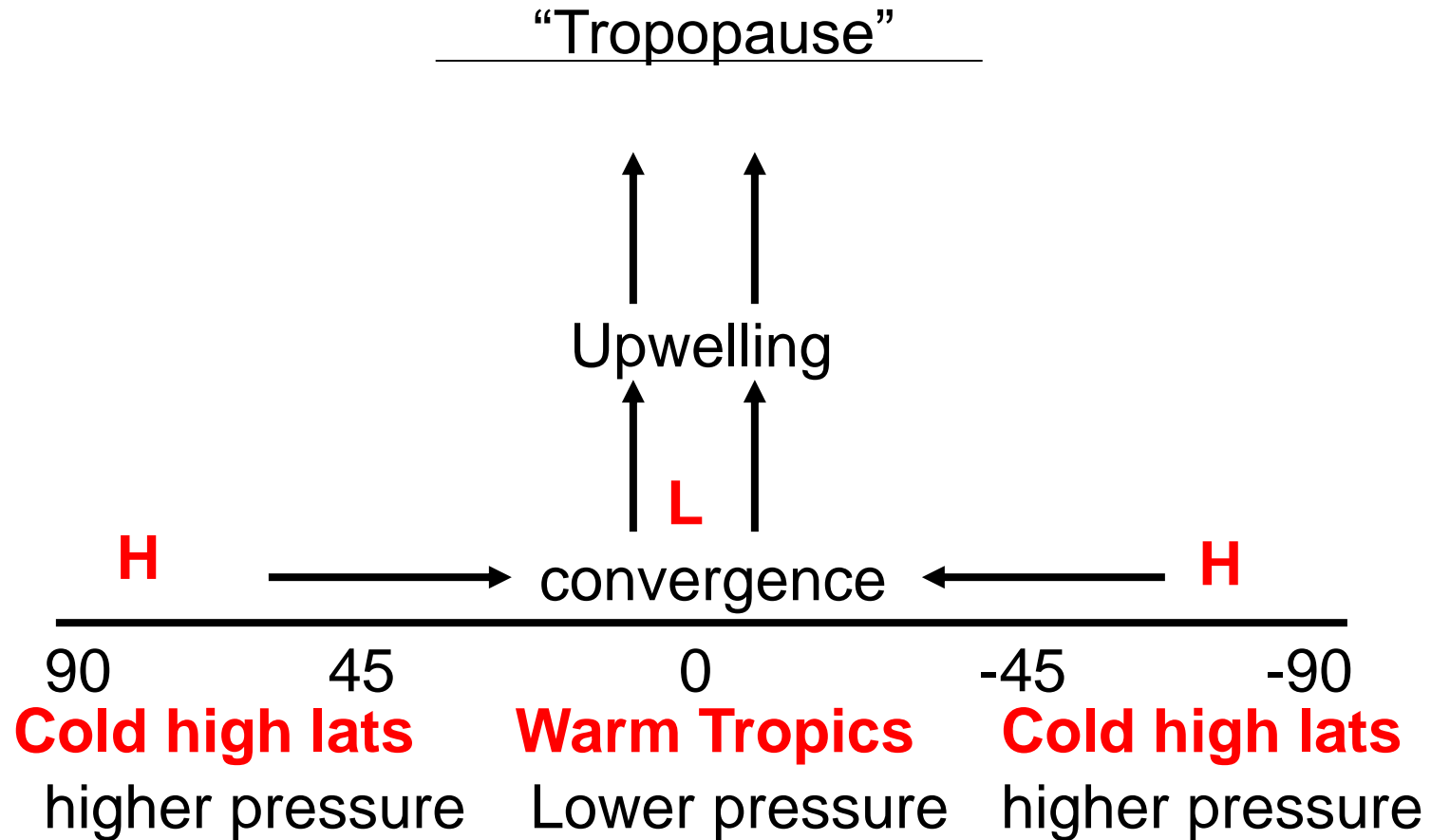
Based on Hadley's 1735 paper:





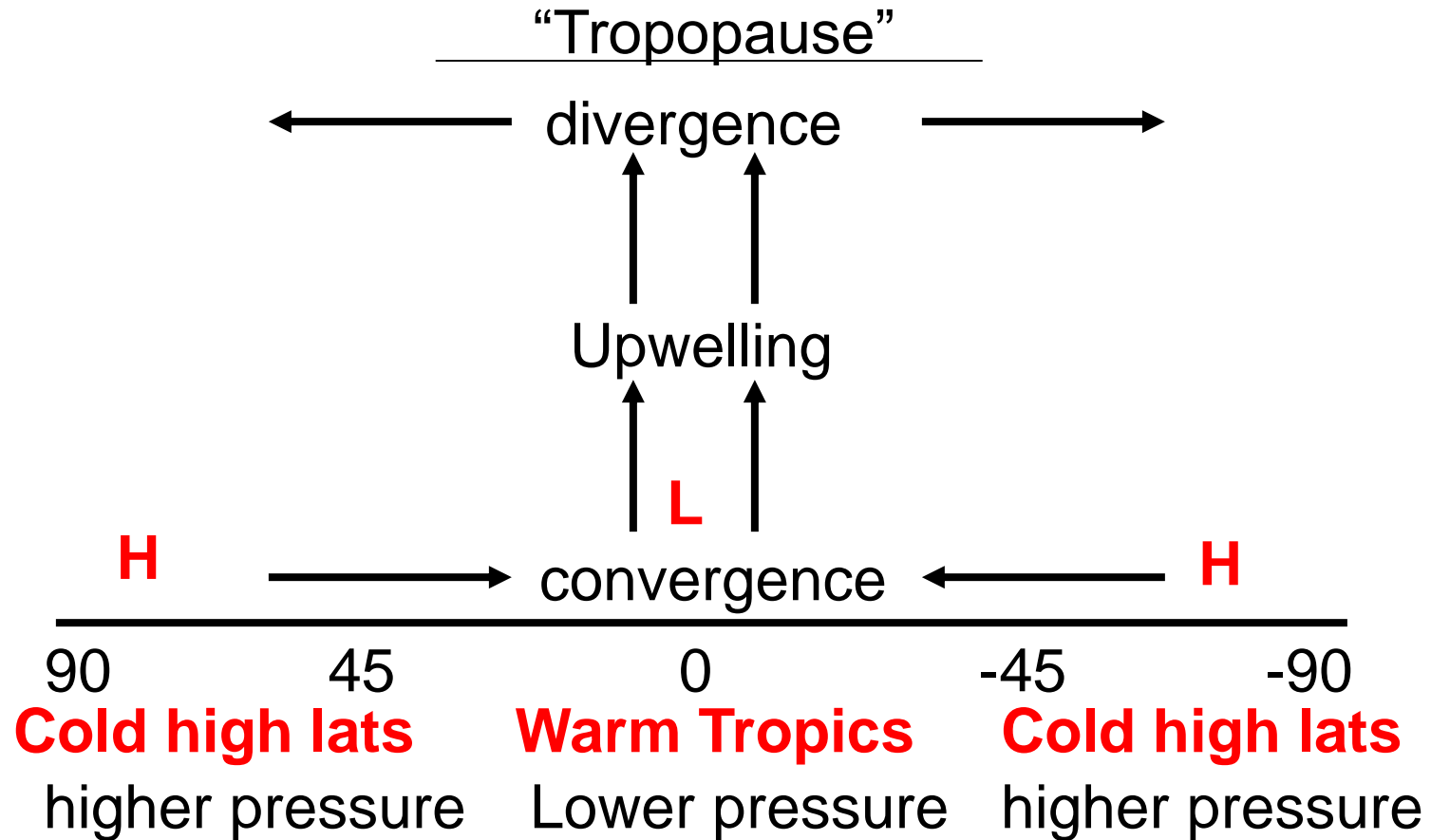
# Early Picture of General Circulation

Based on Hadley's 1735 paper:



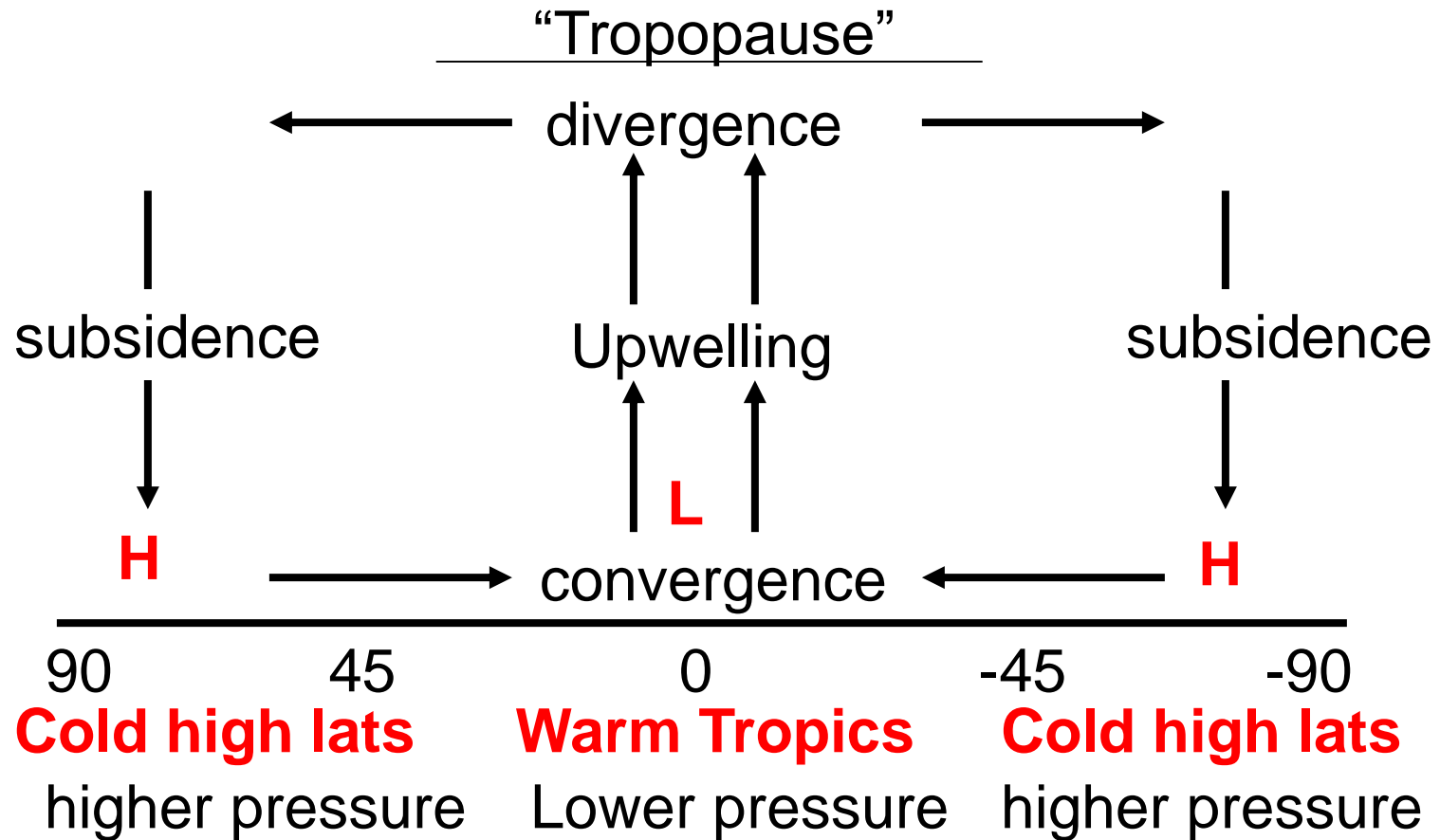
# Early Picture of General Circulation

Based on Hadley's 1735 paper:



# Early Picture of General Circulation

Based on Hadley's 1735 paper:

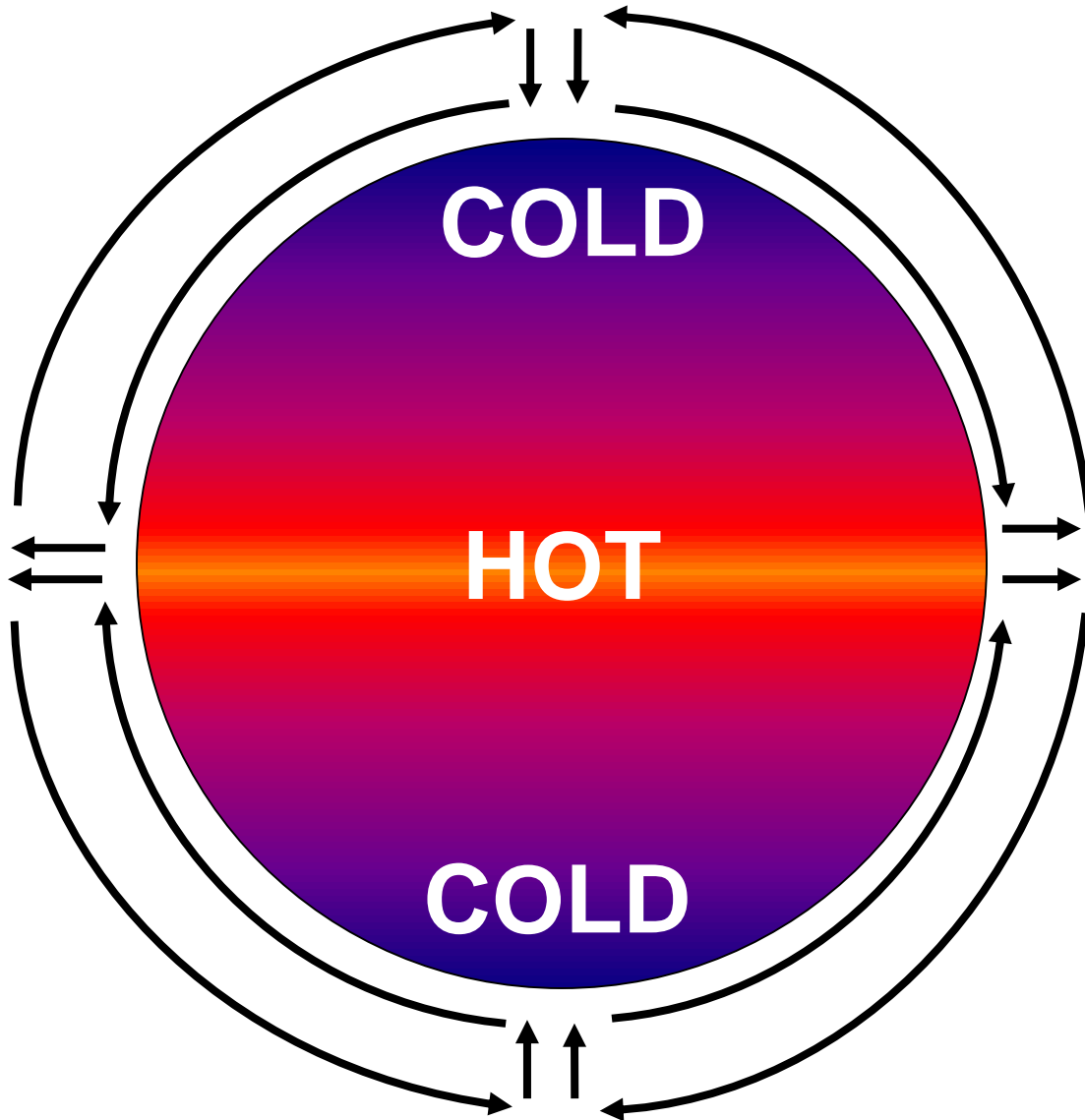


# Small-Scale Upwelling and Upper-Level Divergence

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# The (original) Hadley Circulation (1735)



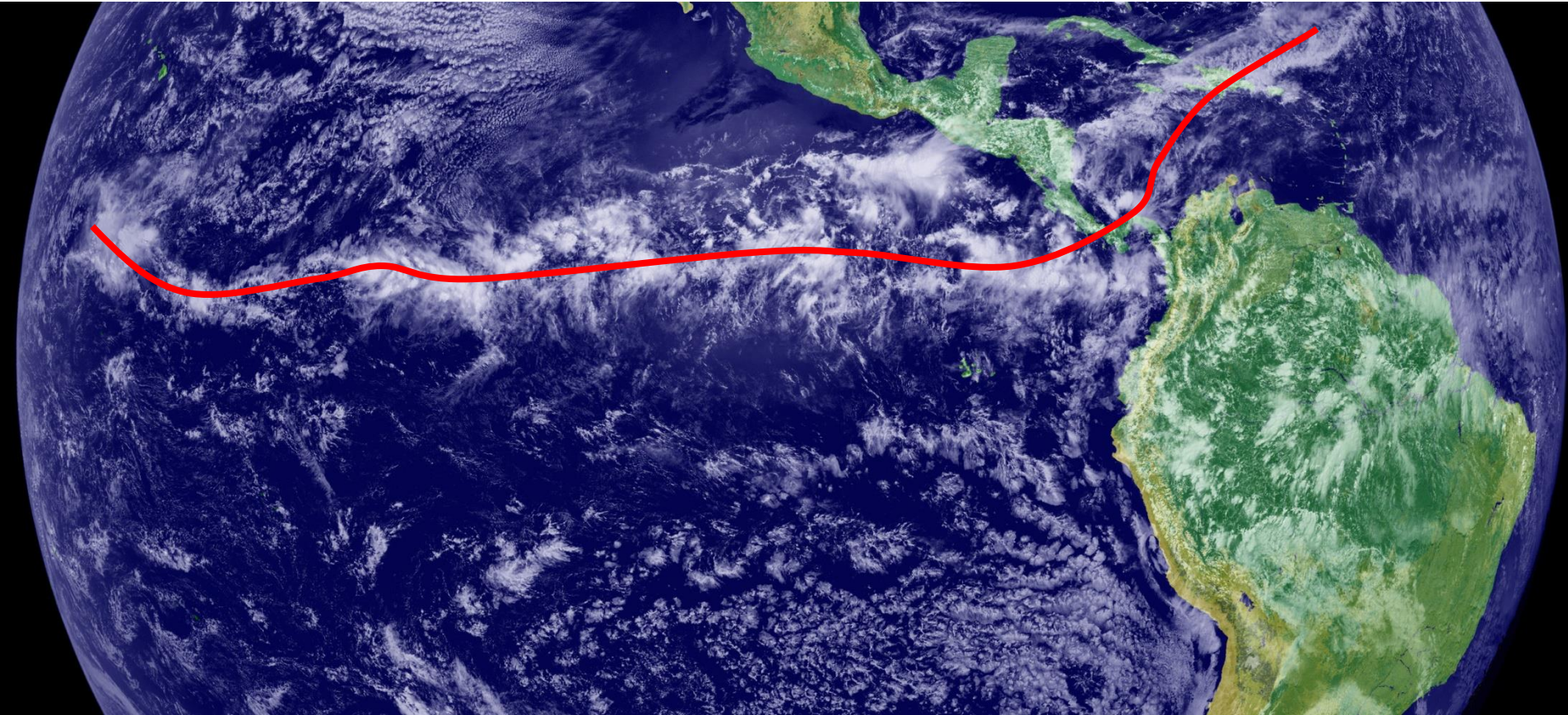
**Can Explain**  
Intertropical  
Convergence Zone  
(ITCZ)

Wet Tropics  
Dry Poles

But it has some  
problems...



# Intertropical Convergence Zone (ITCZ)

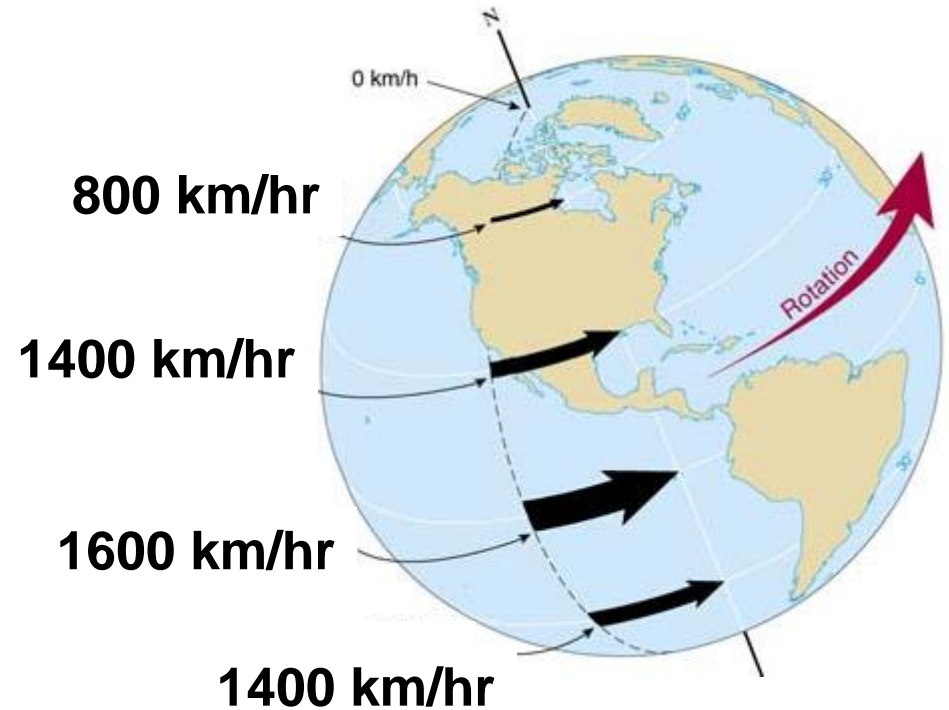


# Earth Rotates from West to East

**Circumference (distance around earth at a latitude) decreases equator to pole**

**Every spot on earth spins around one complete rotation in 1 day**

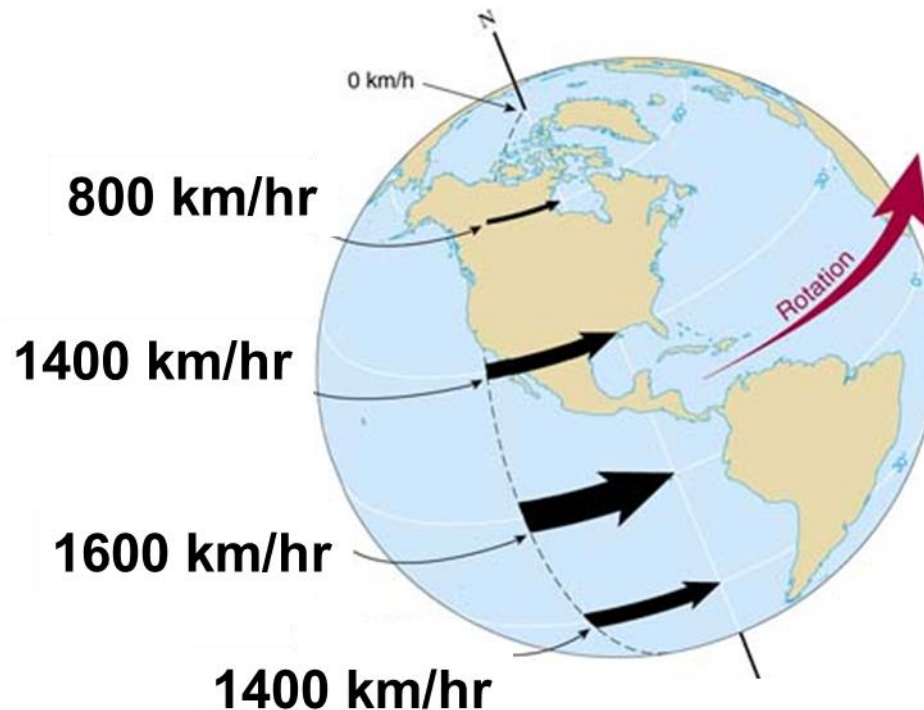
**This means equator rotating faster than higher latitudes**



# Coriolis Effect in Northern Hemisphere

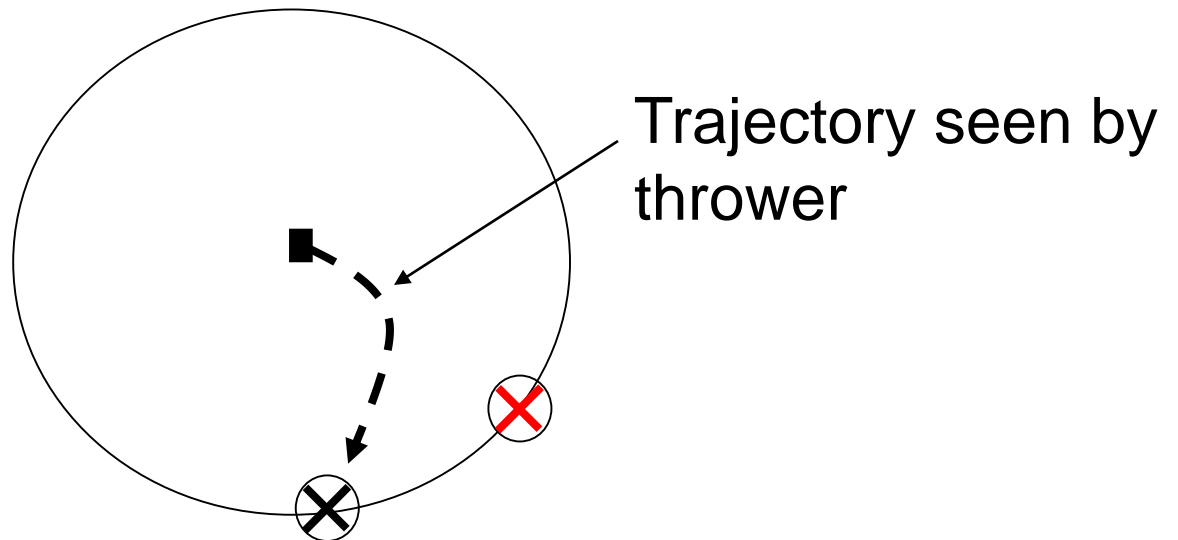
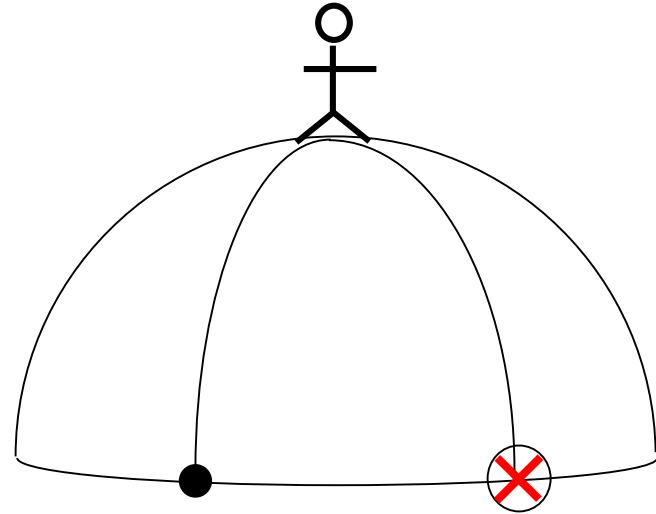
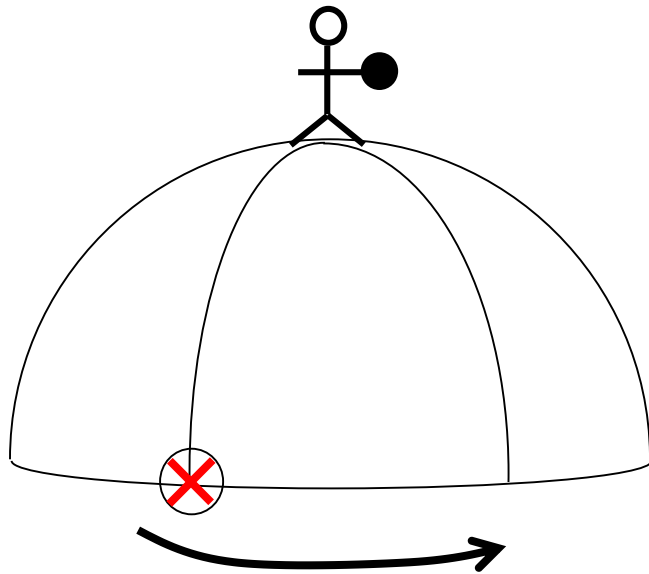
**Object moving North from equator has greater easterly velocity than surface at higher latitudes**

**→ “curves to right” of initial forward direction**






# Coriolis Cartoon



# Poll Question

**W** An object moving south from the equator curves to the \_\_\_\_\_ of its initial forward direction

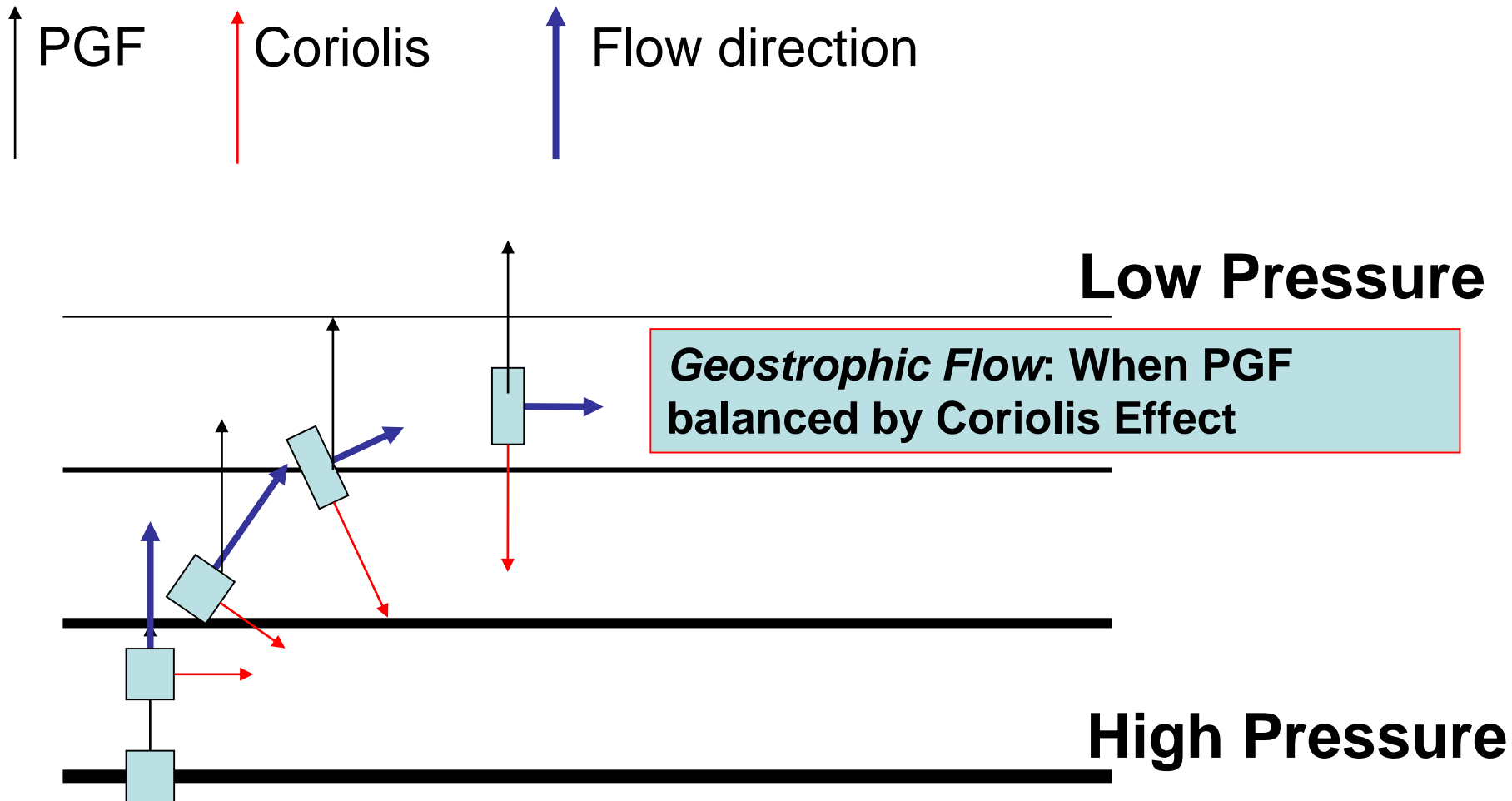
 When poll is active, respond at **PollEv.com/joelathornto254**  Text **JOELATHORNT0254** to **22333** once to join

Left

Right

Total Results: 0

# High Altitude Flow Tends to be *Geostrophic*



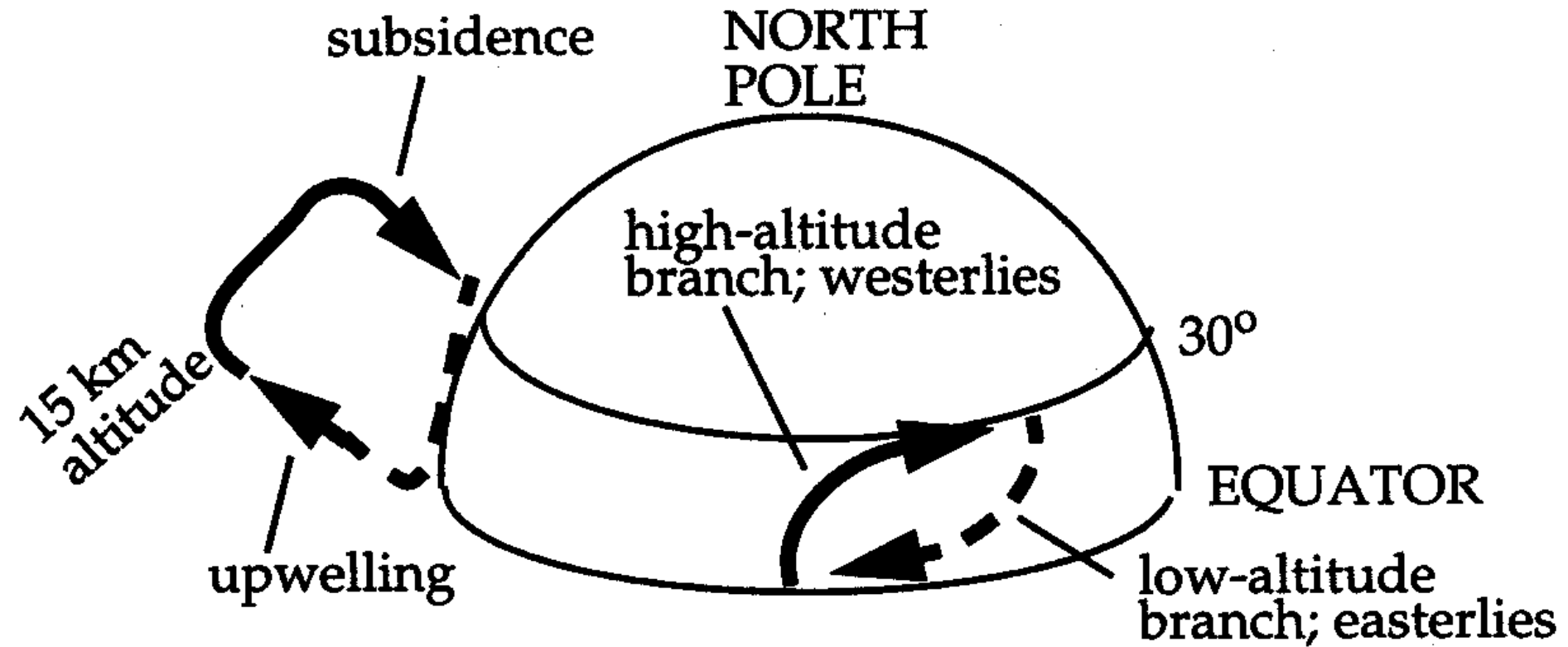
# Coriolis/Centrifugal Effect Summary

**Coriolis Effect applies to objects moving North or South relative to Earth's surface**

**A similar effect occurs for objects traveling in E-W directions (*centrifugal force*)**

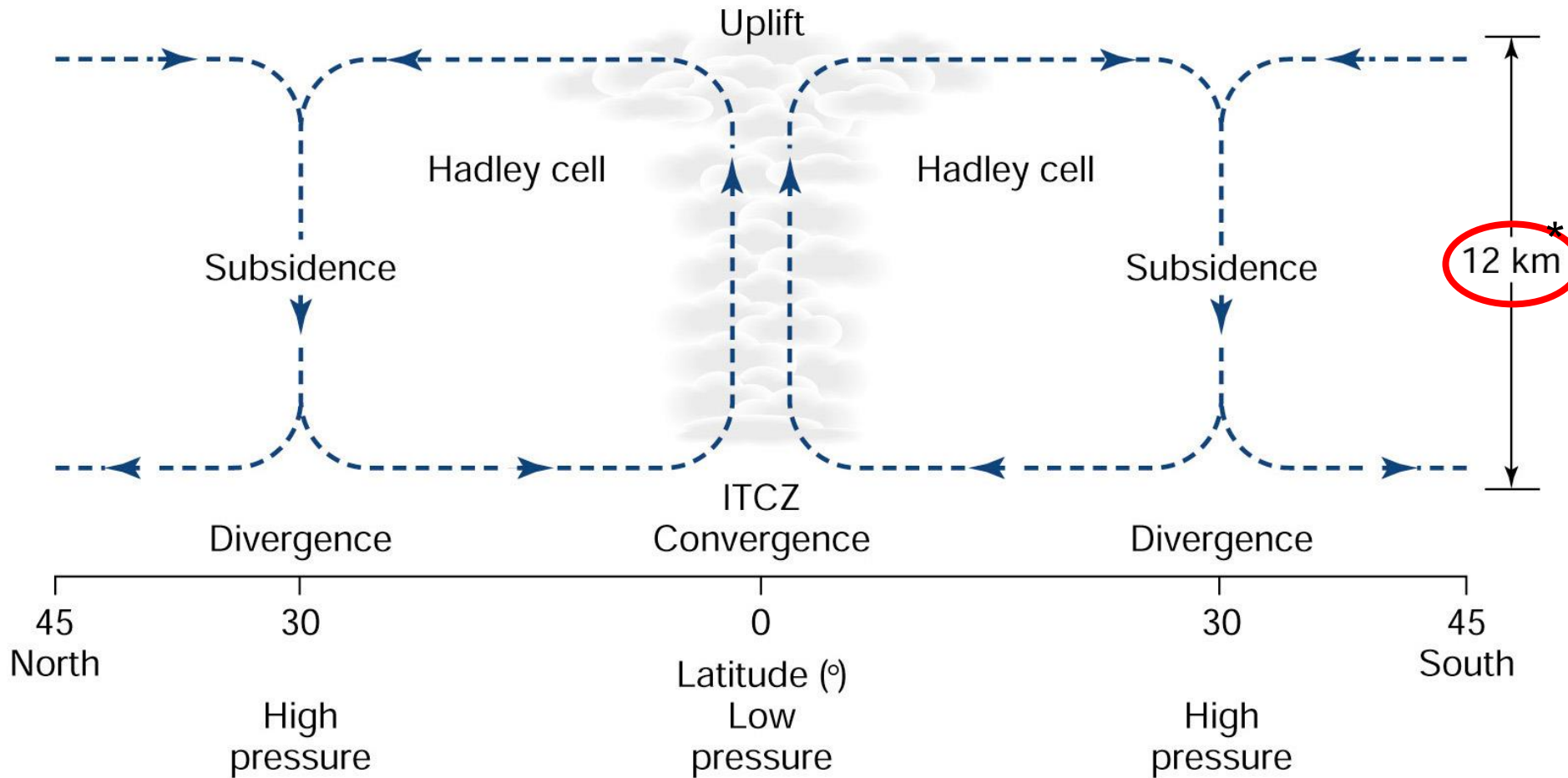
**NET RESULT: objects (air or water, e.g.) moving in the NH will curve to the *right* of their forward direction, while in the SH they curve to the *left* of their forward direction.**

# Coriolis Effect Modifies Hadley Circulation



**Fig. 4-11** Northern hemisphere Hadley cell.

# Modified Hadley Circulation



## Horizontal motions

**convergence: coming together**

**divergence: spreading apart**

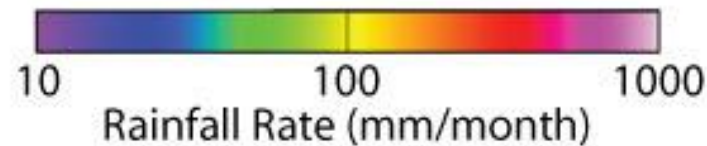
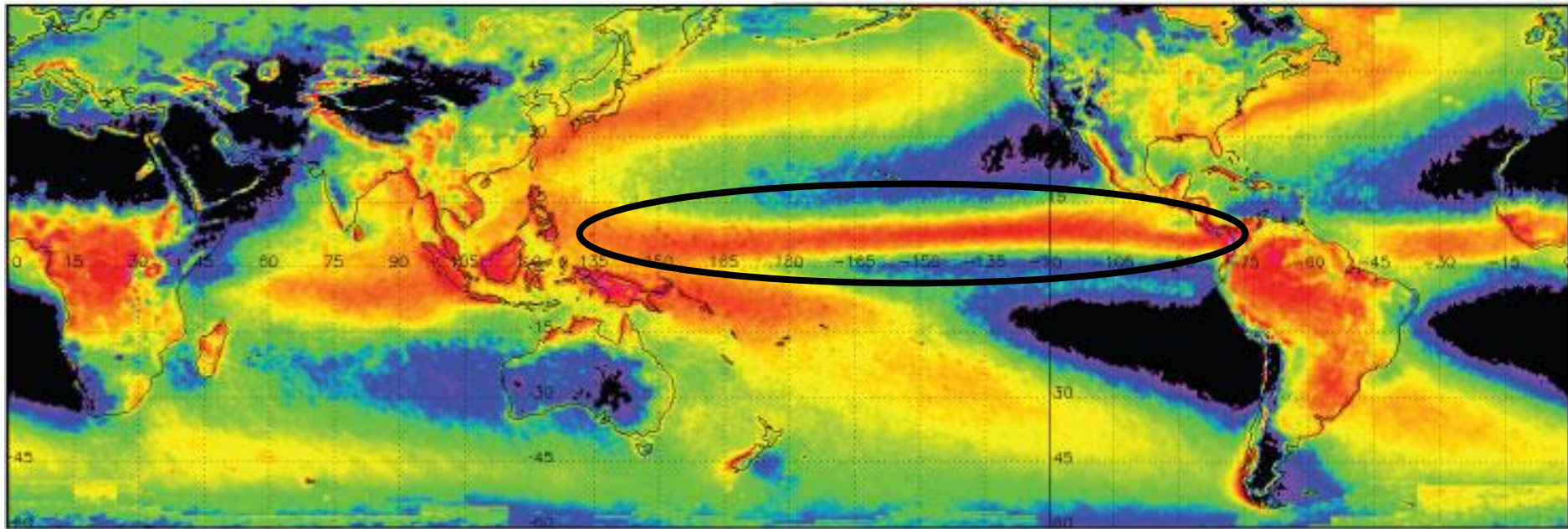
## Vertical motions

**upwelling: rising air**

**subsidence: sinking air**

# Seeing Hadley Circulation in Precipitation

Global Rainfall Rate

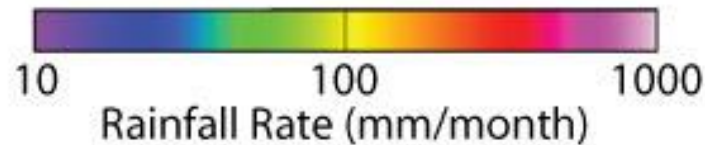
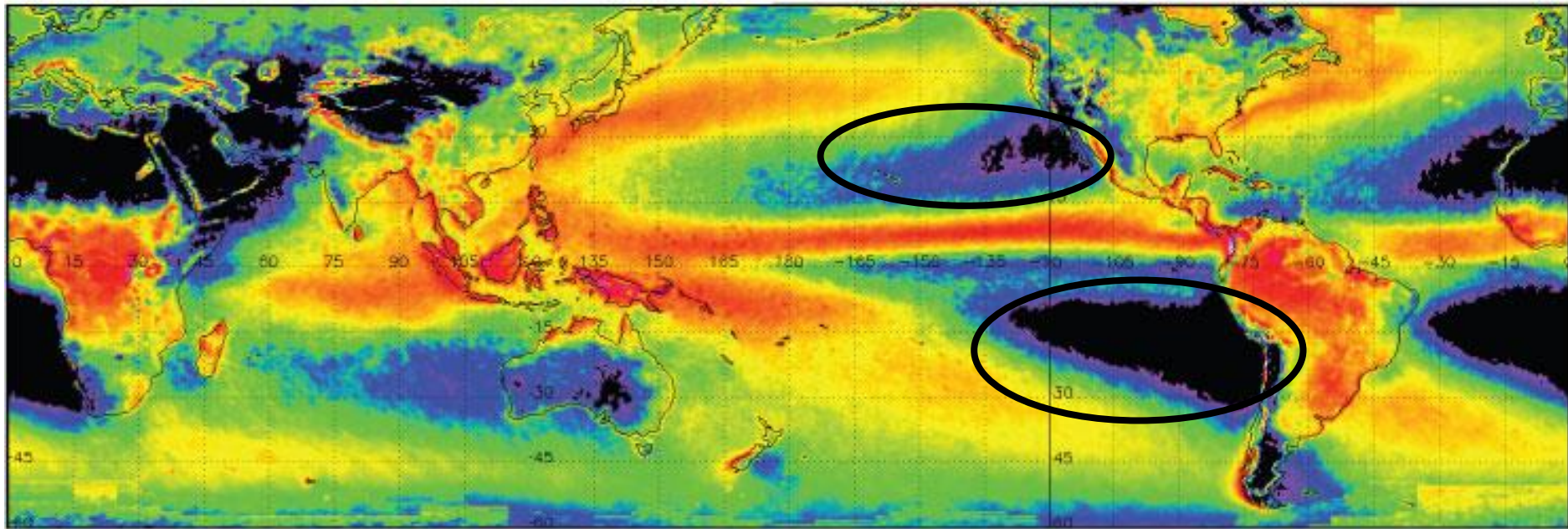


Nagri (2004)



# Seeing Hadley Circulation in Precipitation

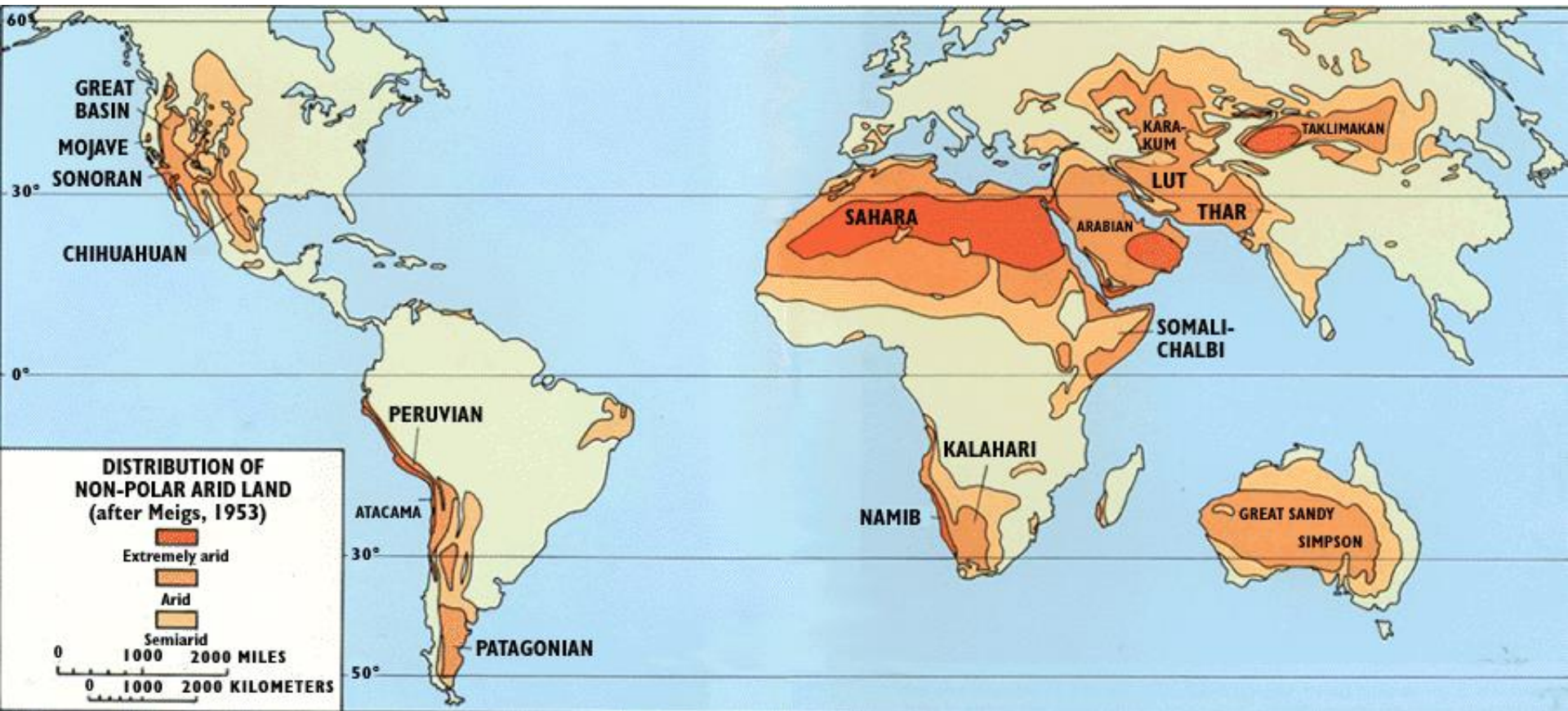
Global Rainfall Rate



Nagri (2004)



# World's Deserts



Not shown: Polar Regions (also deserts)

# Some deserts at 30°N/S



**Namib (Africa)**



**Great Sandy (AUS)**



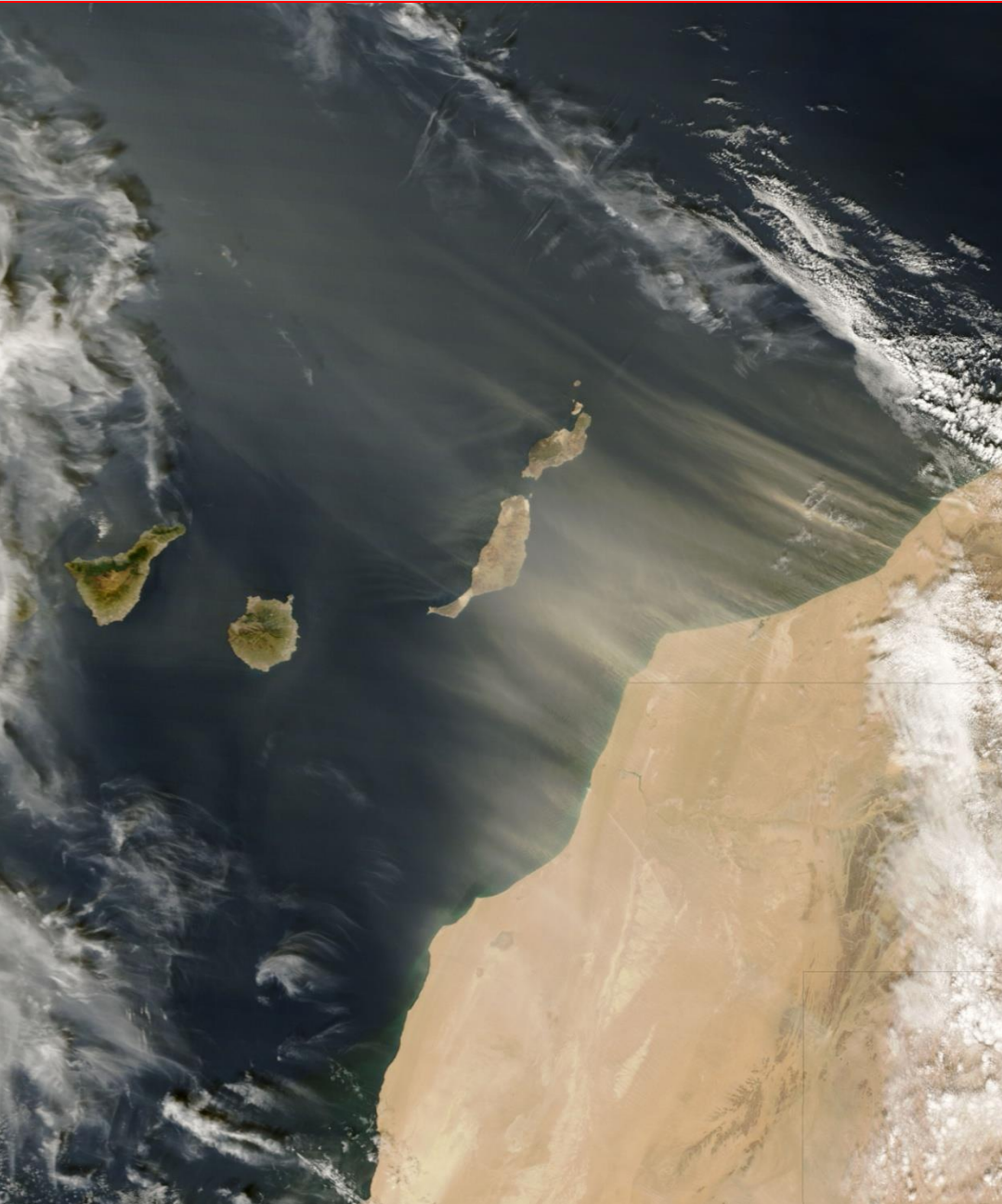
**Thar (India/Pakistan)**

**Sahara  
(N. Africa)**





# World's Deserts



**Desert dust blows from W. Sahara and N. Morocco over Canary Islands (in picture).**

**Desert dust is a source of nutrients to ocean and land biota (often  $\frac{1}{2}$  a world away).**

# Shifting ITCZ?

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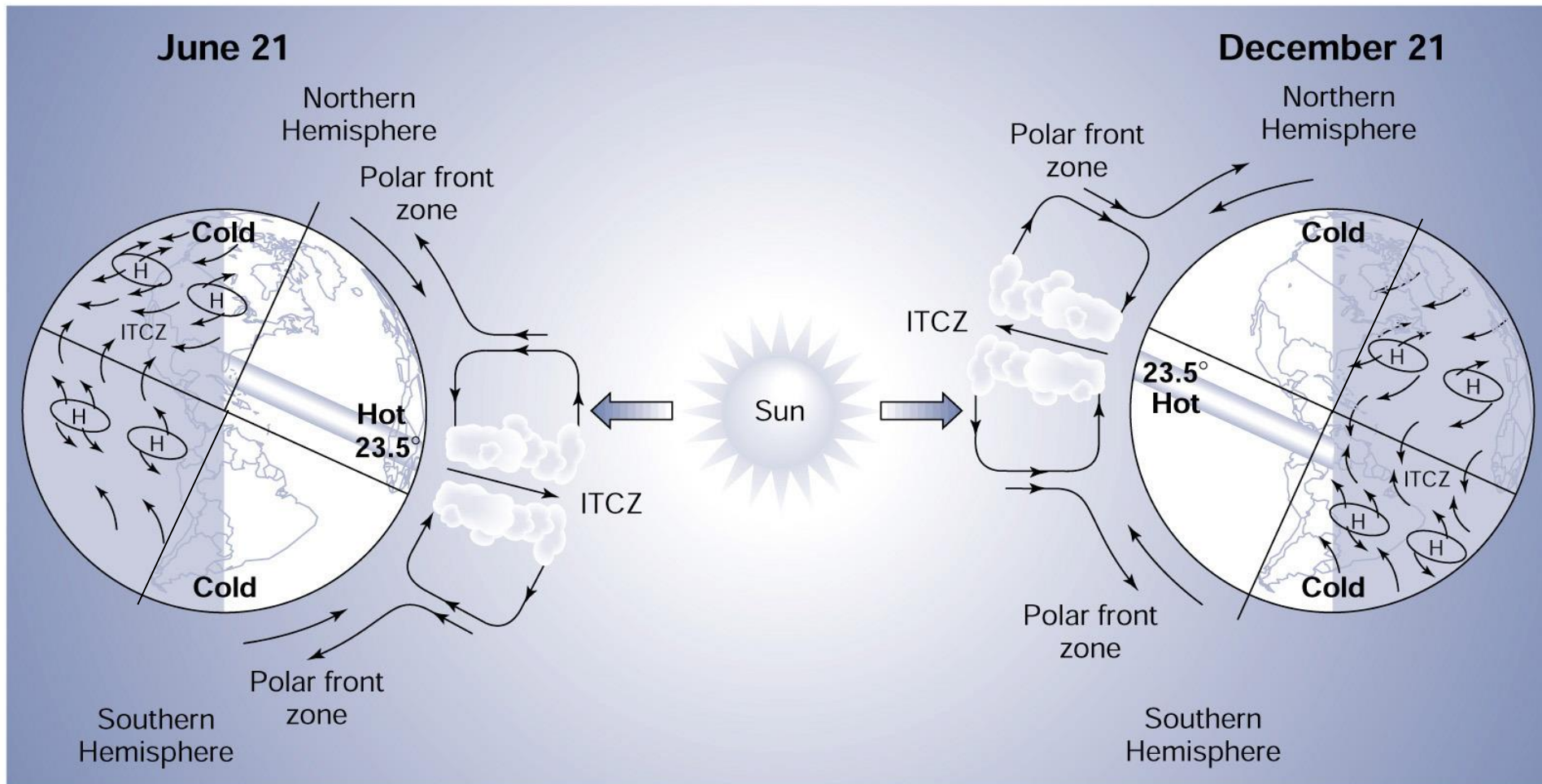
[TRIMM Rainfall](#)

<https://svs.gsfc.nasa.gov/3461>

<https://svs.gsfc.nasa.gov/3584>

<https://imgur.com/gallery/tUCJN3H>

# Seasonal Shift in Hadley Circulation




ITCZ location shifts N-S depending on season.  
Leads to wet and dry seasons in the tropics.

# Poll Question

**W** Suppose you wanted to the take February vacation in the sunny and warm tropics. Because you want sunny dry weather you choose



When poll is active, respond at [PollEv.com/joelathornto254](https://PollEv.com/joelathornto254)  Text **JOELATHORNT0254** to **22333** once to join

Costa Rica (NH)

Amazonia (SH)

Total Results: 0

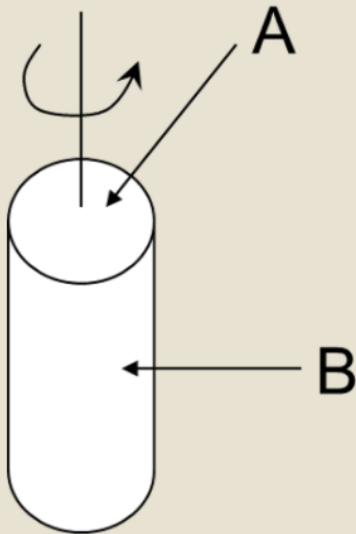
# Hadley Circulation Summary

- Intertropical convergence zone (ITCZ) varies north and south of equator with season
- ITCZ: rainy!
- High ***altitude*** flow is southwesterly to westerly in NH, northwesterly to westerly in SH
- Low-level flow is northeasterly to easterly in NH and southeasterly to easterly in SH → **TRADE WINDS**
- Subsiding branches located around 30° N and 30° S → **MAJOR DESERTS**

# Poll Question

**W** Suppose Earth were a cylinder. Where would there be a Coriolis Effect?

When poll is active, respond at [PollEv.com/joelathornto254](https://poll-ev.com/joelathornto254) Text **JOELATHORNTO254** to **22333** once to join



A

B

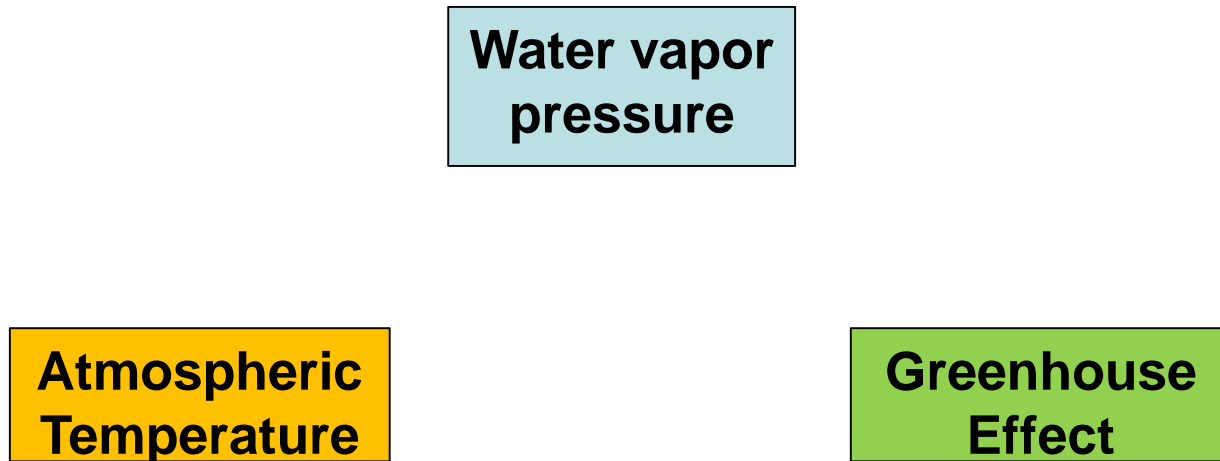
Both A and B

Neither A nor B

Total Results: 0

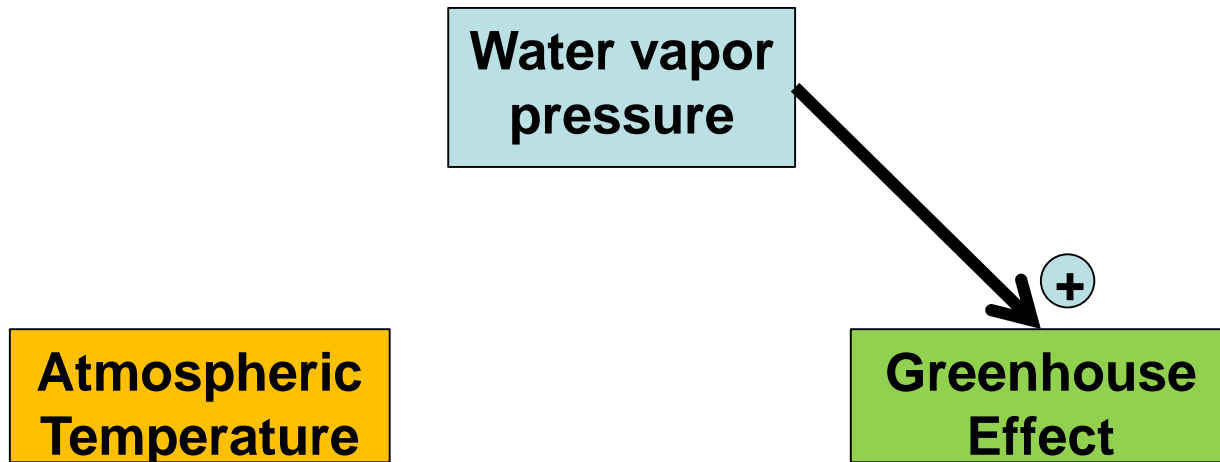


# Water Vapor Feedback



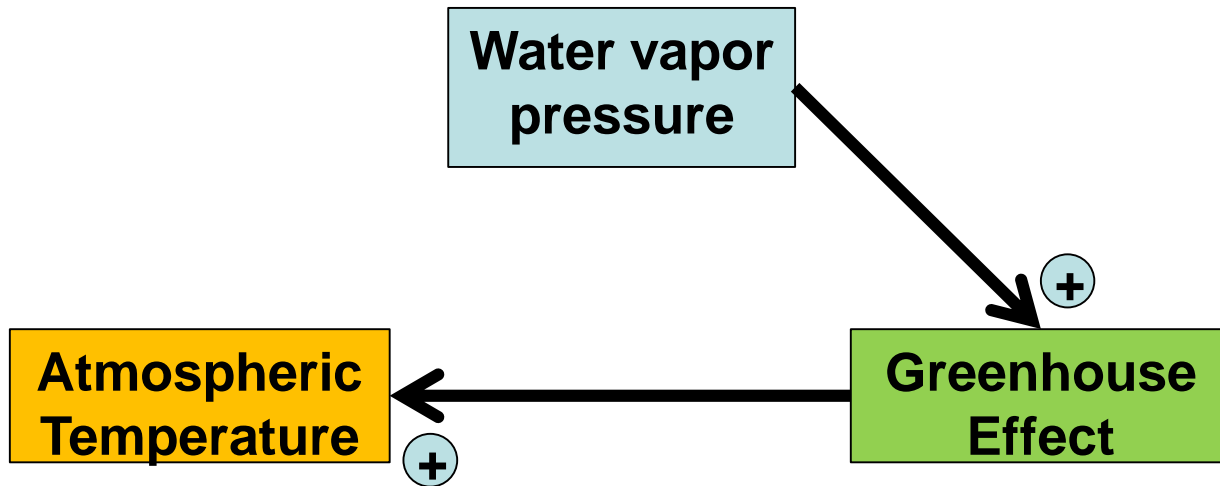
The average amount of water vapor in the atmosphere is a *response to the climate*

# Water Vapor Feedback



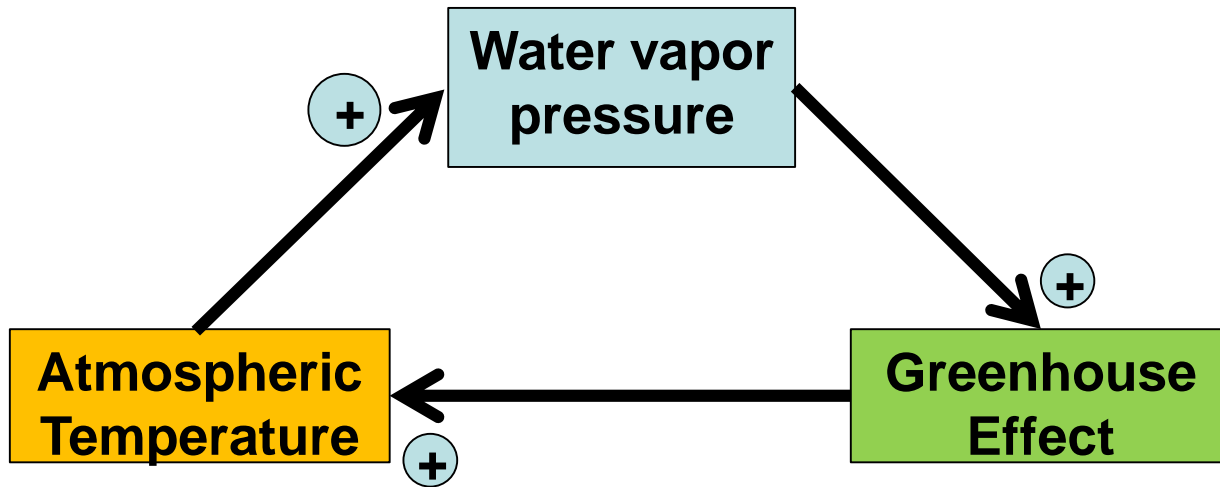
The amount of water vapor in the atmosphere is a *response to the climate*

# Water Vapor Feedback



The amount of water vapor in the atmosphere is a *response to the climate*

# Water Vapor Feedback



The amount of water vapor in the atmosphere is a *response to the climate*