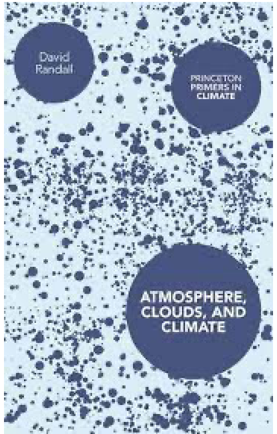
Energy Transfer and Feedbacks

Princeton Primers
Atmosphere, Clouds, and Climate Ch. 4-5

680 - Maddie Seiler



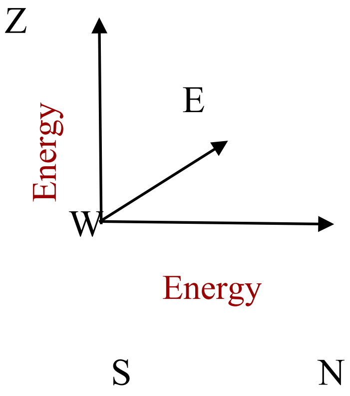
Over the Next Hour..

- Dive into **large scale circulation** and **energy transport** over the globe
- Discuss **primitive concepts** and **equations** that govern **the flow of weather patterns**
- Achieve a comprehensive understanding of the **forcing and response of feedbacks** in the atmosphere
- Gain a new and more thorough **respect for meteorological phenomena** that happens around the world daily.

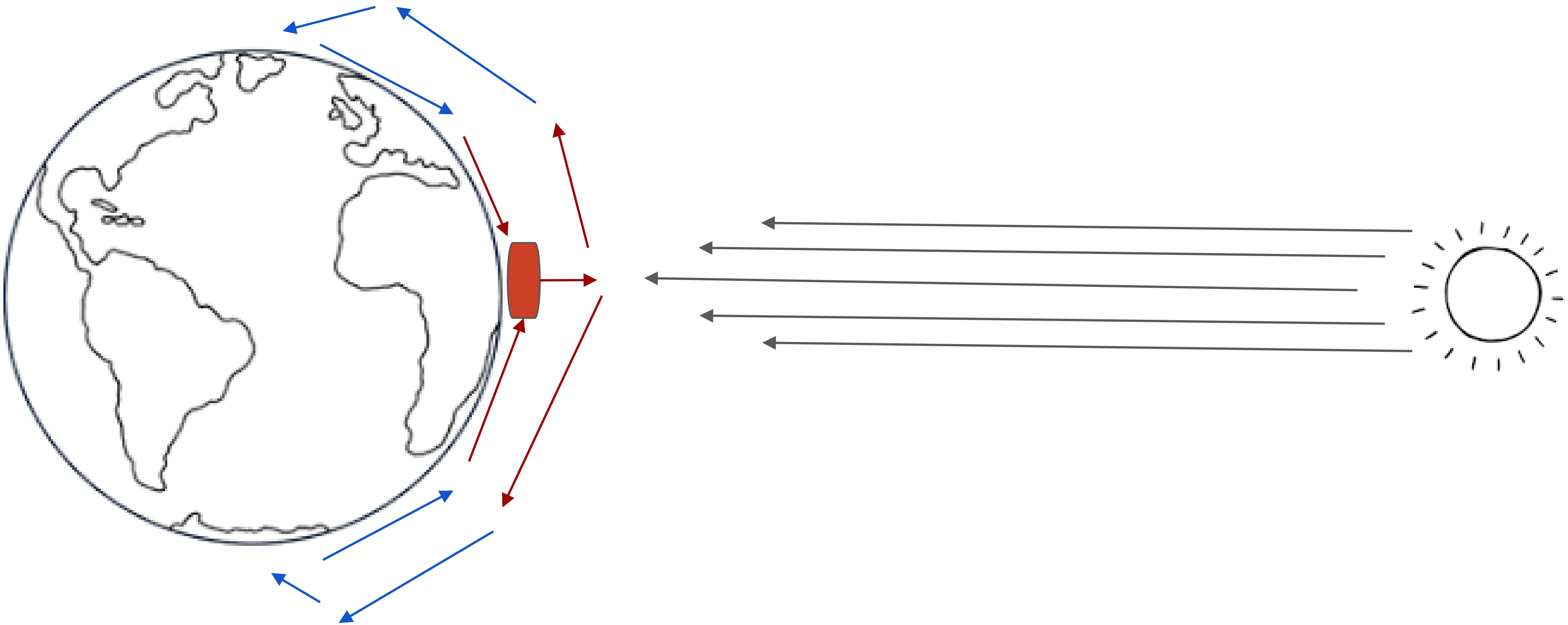
What drives weather and global circulations?

→ The uneven distribution of heat in our atmosphere

This redistribution is completed through the transfer of energy from the equator to the poles via wind.



“Big Loop Theory”



MMC: Mean Meridional Circulation

- The Hadley Cell resides primarily in the Winter Hemisphere.

- Upon seasonal change, the meridional component of wind changes.

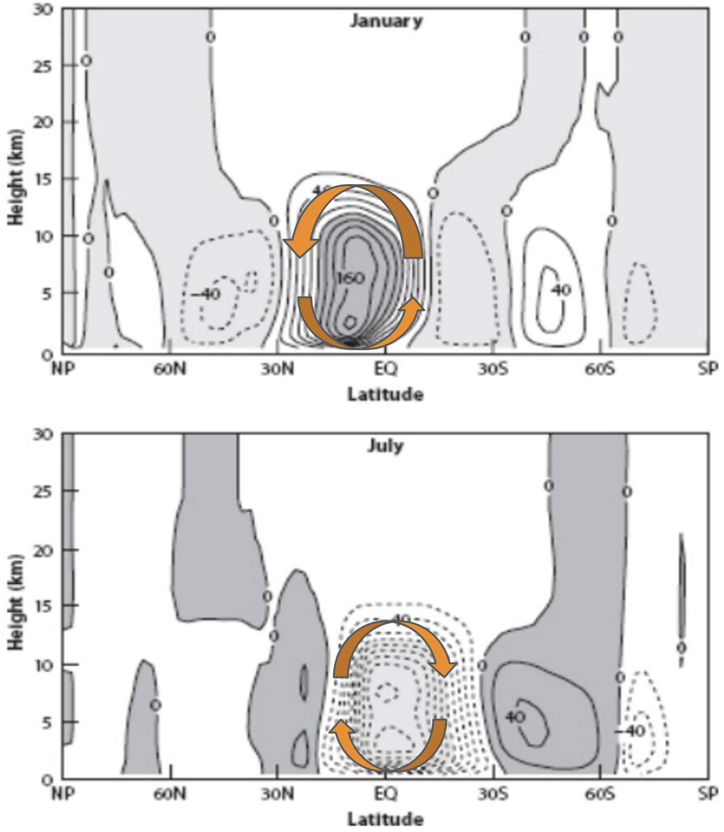
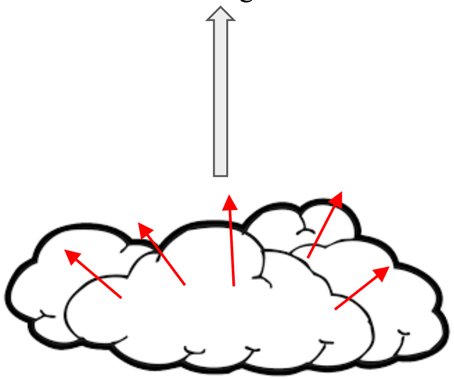


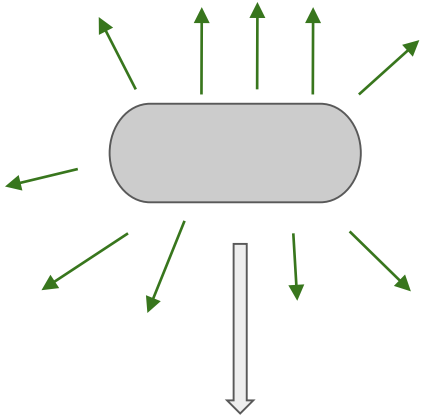
Figure 4.1. The streamfunction of the mean meridional circulation, plotted as a function of height and latitude.

Positive values, denoted by solid contours, represent counterclockwise circulations, while negative values, with dashed contours, represent clockwise circulations. Strong positive values are darkly shaded, and strong negative values are lightly shaded. The units are 10^{12} g s^{-1}.

Drivers of the Hadley Cell



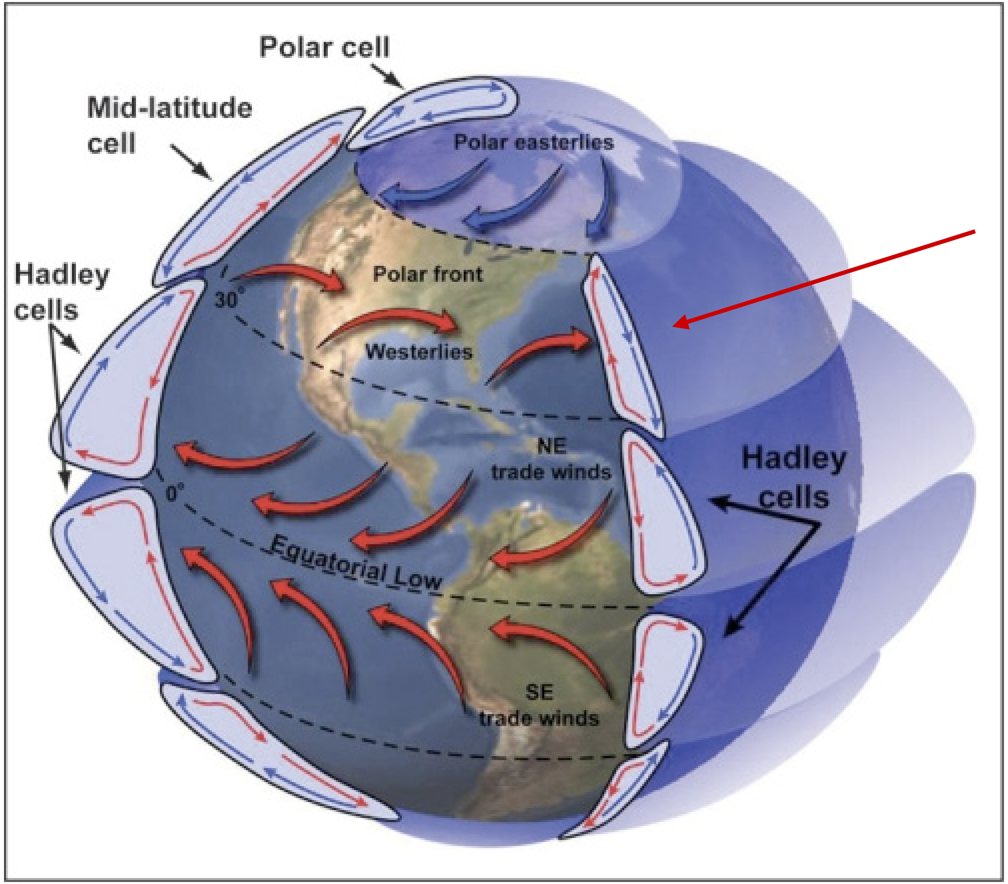
The upward motion of these cells are buoyancy driven and obtain kinetic energy through conversion of gravitational potential energy



What process adds heat to the system near the equator that aids to the buoyancy/rise of air?

What process takes away heat from the system away from the equator that aids to the subsidence/sinking of air?

The main difference between the actual Global Circulation and the "Big Loop Theory"



Ferrel Cells are driven by?

"Big Loop Theory" stretched from equator to pole, while the Hadley Cell reaches 30ºLat.

https://groups.seas.harvard.edu/climate/eli/research/equable/hadley.html

The Winds in the Hadley Cell actually travel a distance greater than 30º. Why?

In order to conserve angular momentum of the parcel

Angular Momentum is denoted by: M

$M = (\Omega\, a \cos(\varphi) + u) a \cos(\varphi))$

There are two torques that can change angular momentum. What are they?

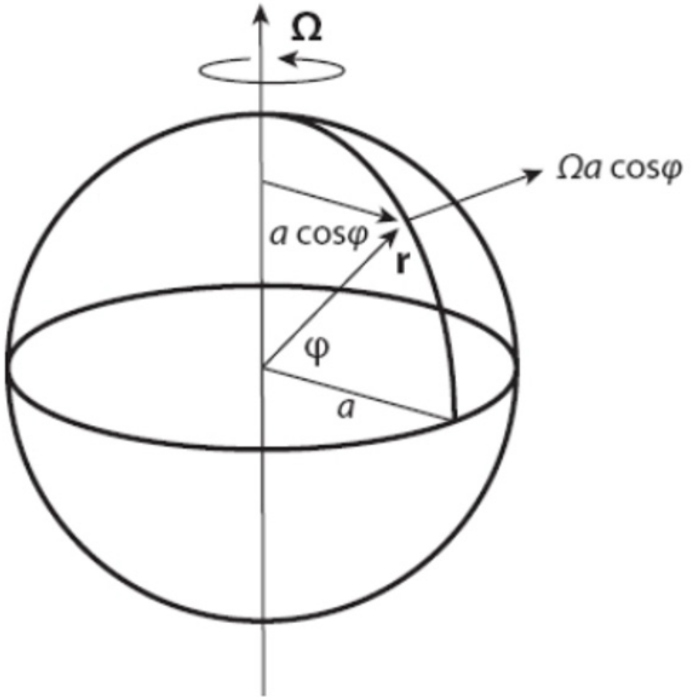
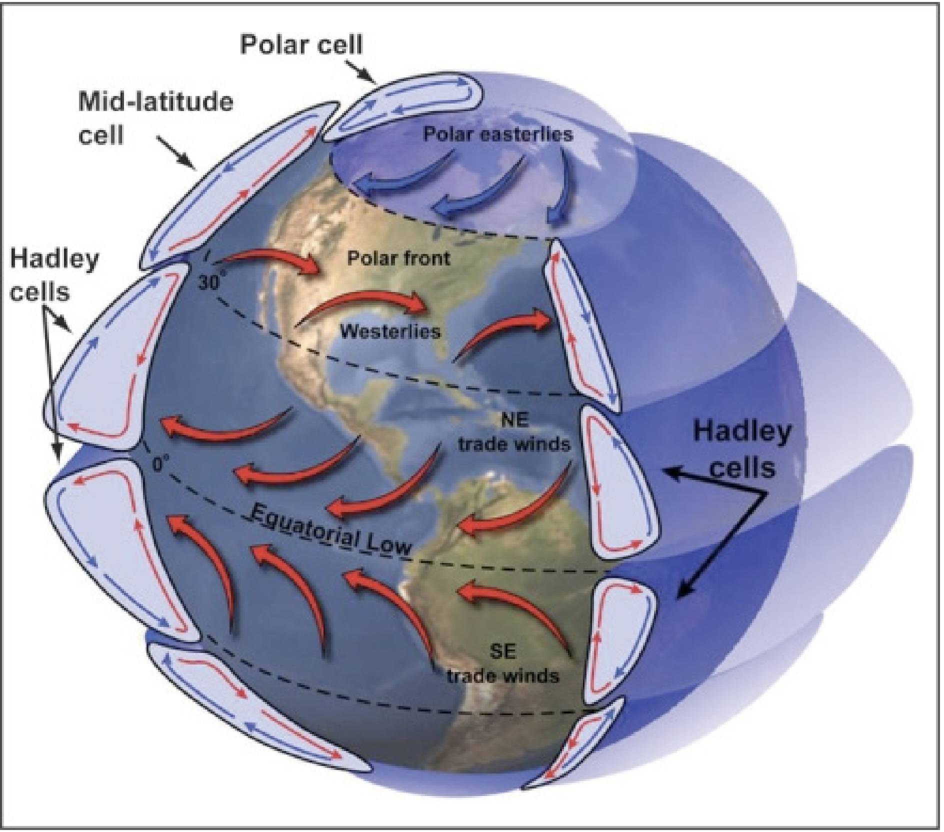


Figure 4.2. Sketch illustrating the rotating Earth.
The Earth's rotation is indicated by the vector (boldface) pointing upward, that is, toward the North Star. The position of a point on the Earth is indicated by the position vector r. The point is moving toward the east at the speed $\Omega a \cos\varphi$.

Relating Angular Momentum to the Hadley Cell Motion



Angular Momentum is denoted by: M

$M = (\Omega\, a \cos(\varphi) + u)a \cos(\varphi))$

Any change in φ must be compensated by a change in the zonal wind u.

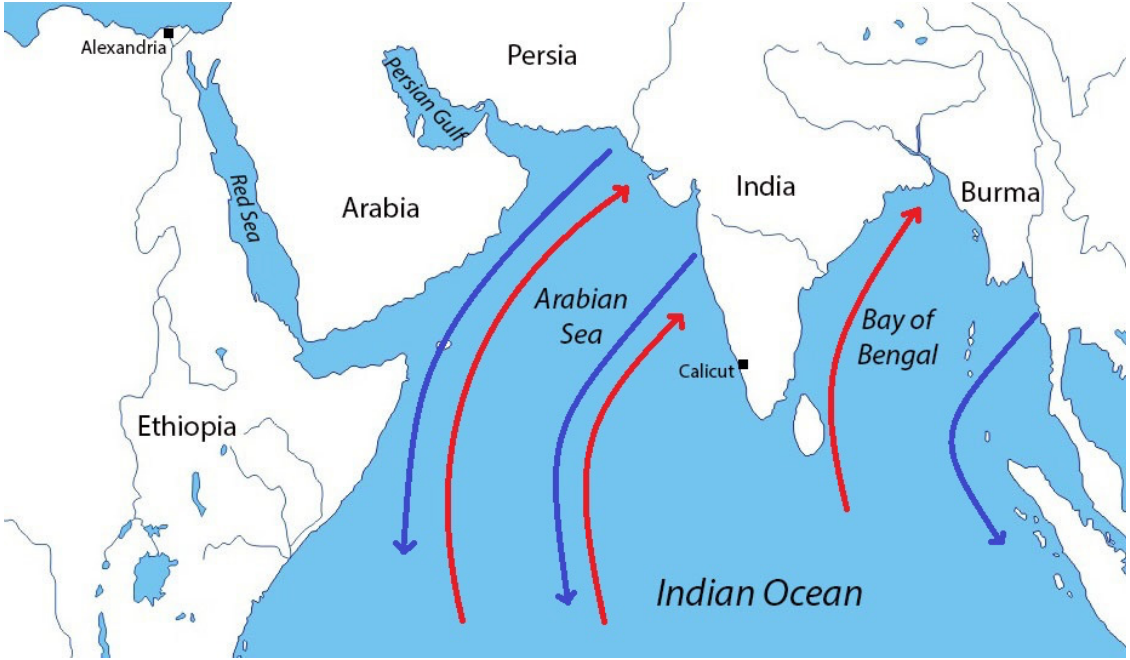
Some φ

Eq.

Hadley Cells on a “smaller scale”

Hadley Circulation - Winds are brought about due to temperature contrasts based on latitude

Monsoons- Winds are brought about due to temperature contrasts between ocean and land



https://byzantinemporia.com/monsoon-trade-system/

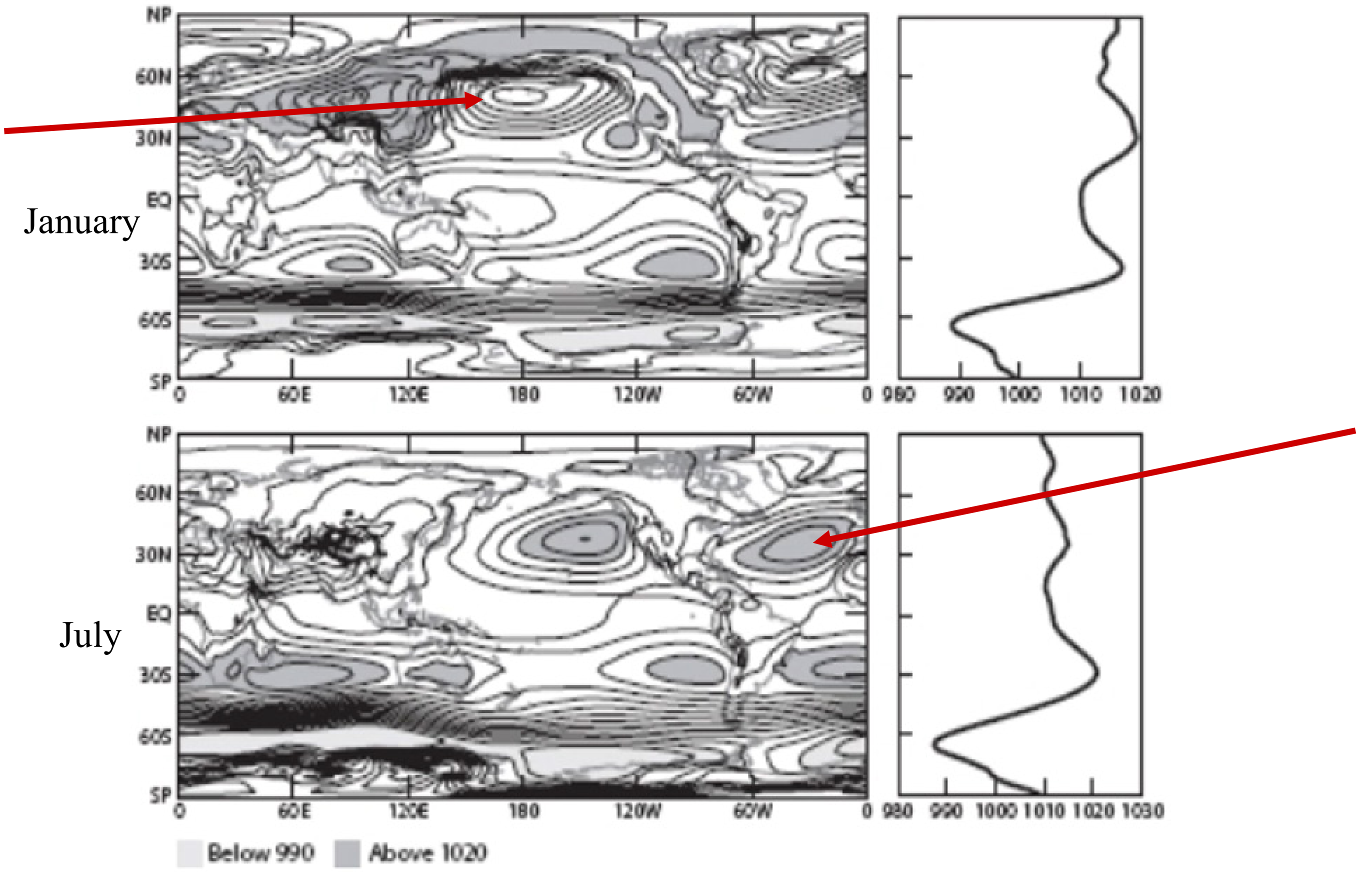


Figure 4.4. Sea level pressure maps for January (top) and July (bottom).
The units are hundreds of pascals, abbreviated hPa. The contour interval is 3 hPa. Values higher than 1,020 hPa have dark shading, and those lower than 990 hPa have light shading. The zonal averages are shown on the right.

Simple Scale Analysis - For Synoptic and Large Scale Motions

HORIZONTAL MOMENTUM

What balance is this?

$\frac{\partial u}{\partial t}$	$+ u\frac{\partial u}{\partial x}$	$+ v\frac{\partial u}{\partial y}$	$+ w\frac{\partial u}{\partial z}$	$= -\frac{1}{\rho}\frac{\partial p}{\partial x}$	$+ fv$	$- 2\Omega w cos(\phi)$
$\frac{U}{\tau}$	$\frac{U^2}{L}$	$\frac{U^2}{L}$	$\frac{WU}{H}$	$\frac{\Delta_h p}{\rho L}$	fU	fW
$\frac{10}{10^5}$	$\frac{10^2}{10^6}$	$\frac{10^2}{10^6}$	$\frac{10^{-2} \cdot 10}{10^4}$	$\frac{10^3}{1 \cdot 10^6}$	$10^{-4} \cdot 10$	$10^{-4} \cdot 10^{-2}$
10^{-4}	10^{-4}	10^{-4}	10^{-5}	10^{-3}	10^{-3}	10^{-6}

$$\Longrightarrow 0 = -\frac{1}{\rho}\frac{\partial p}{\partial x} + fv.$$

Going through the same steps for the $\hat{j}$ direction results in

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial y} - fu.$$

Simple Scale Analysis - For Synoptic and Large Scale Motions

VERTICAL MOMENTUM

$$\frac{\partial w}{\partial t} + \boldsymbol{u}\frac{\partial w}{\partial x} + \boldsymbol{v}\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - 2\Omega u cos(\phi) - g.$$

$$\frac{W}{\tau} \quad \frac{UW}{L} \quad \frac{UW}{L} \quad \frac{W^2}{H} \quad \frac{\Delta_z p}{\rho H} \quad fU \quad g$$

What balance is this?

$$\frac{10^{-2}}{10^5} \quad \frac{10\cdot 10^{-2}}{10^6} \quad \frac{10\cdot 10^{-2}}{10^6} \quad \frac{10^{-4}}{10^4} \quad \frac{10^5}{1\cdot 10^4} \quad 10^{-4}\cdot 10 \quad 10$$

$$10^{-4} \quad 10^{-6} \quad 10^{-6} \quad 10^{-5} \quad 10 \quad 10^{-3} \quad 10$$

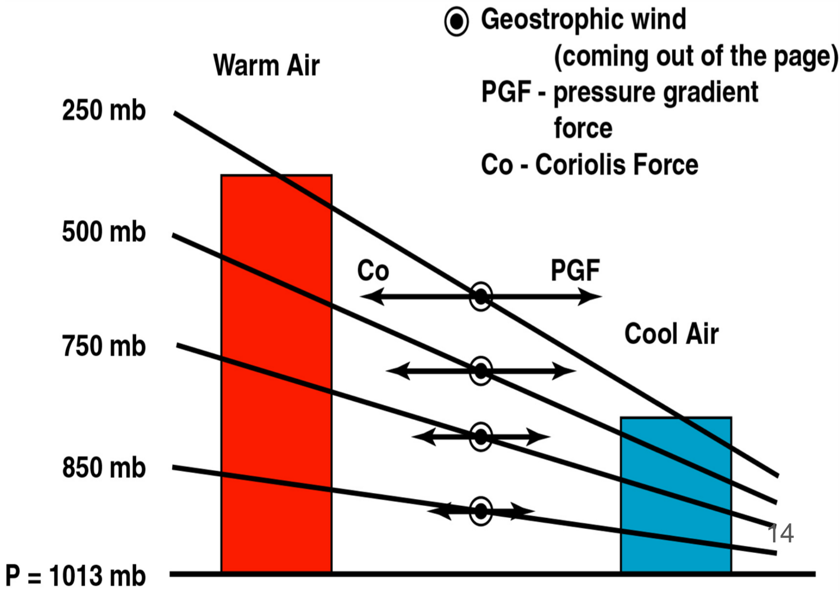
$$\Longrightarrow 0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g.$$

Thermal Wind

Again, another wind that is induced by temperature variation.

Horizontal changes in temperature lead to the horizontal pressure differences changing rapidly with height.

In relation to global circulation: The zonal wind increases when the temperature decreases toward the poles.



If a baroclinic structure is one that has temperature change rapidly in the horizontal and wind changes strongly with height, which is more baroclinic?

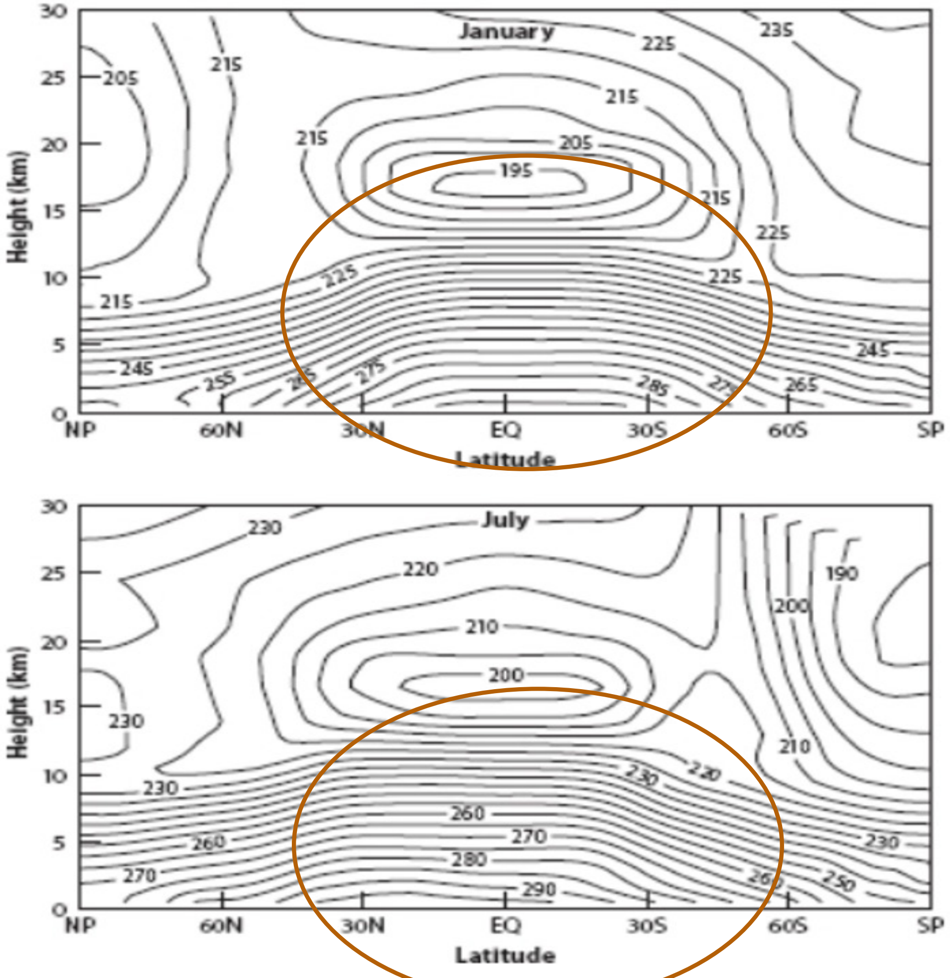
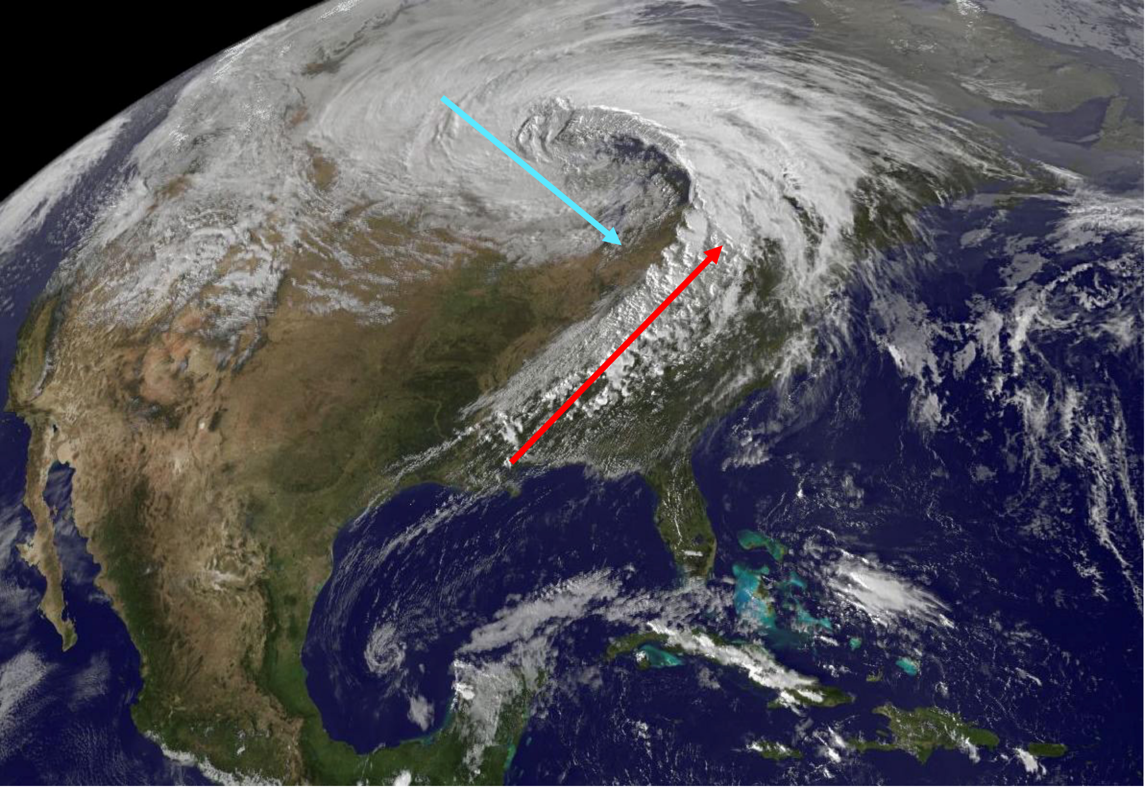
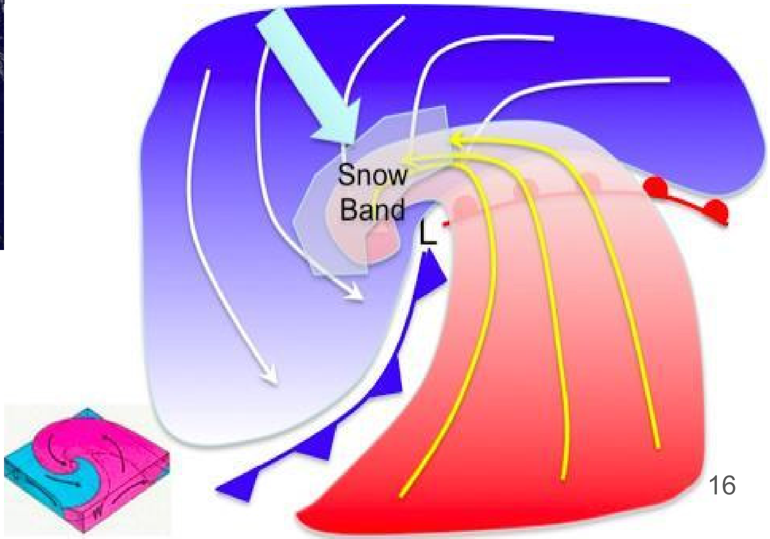


Figure 4.5. Latitude-height cross sections of temperature, for January and July. The contour interval is 5 K.



Source:
https://www.weather.gov/images/grb/events/102610/satellite_large_2132z.JPG

https://www.atmos.illinois.edu/~nriemer/education/blizzard_module.pdf



Formation of Baroclinic Waves

Difference between the Hadley Cell and Baroclinic Waves

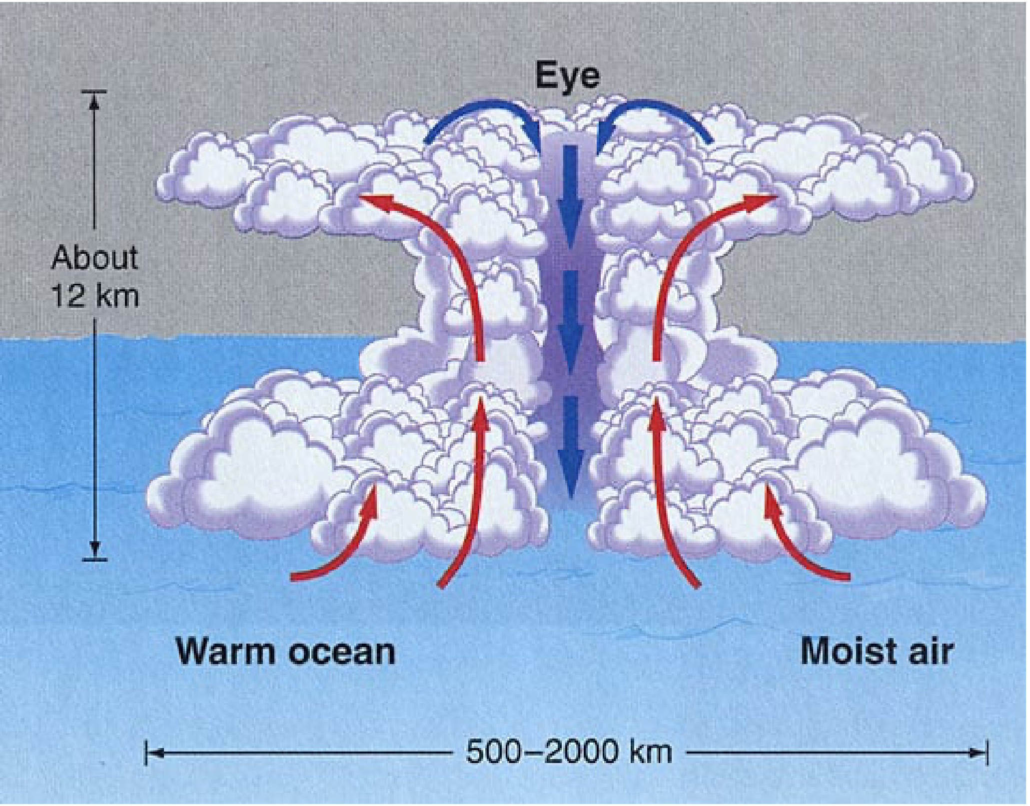
Hadley Cells do not penetrate into the midlatitudes → Baroclinic waves do not penetrate into the tropics.

Why?

Hadley → 

→ Baroclinic Waves

Tropical Cyclones and Typhoons



https://www.whoi.edu/multimedia/hurricane-cross-section/

Tropical Cyclones are an integral part of Earth's Energy Balance.

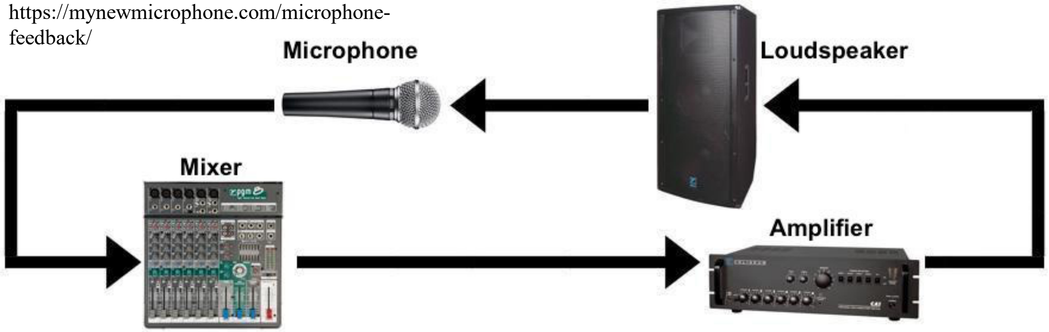
Tropical Cyclones are responsible for cooling the oceans through evaporation and deep upwelling.
The energy extracted from these processes is transported to the upper troposphere and eventually leaked to space.

Feedbacks

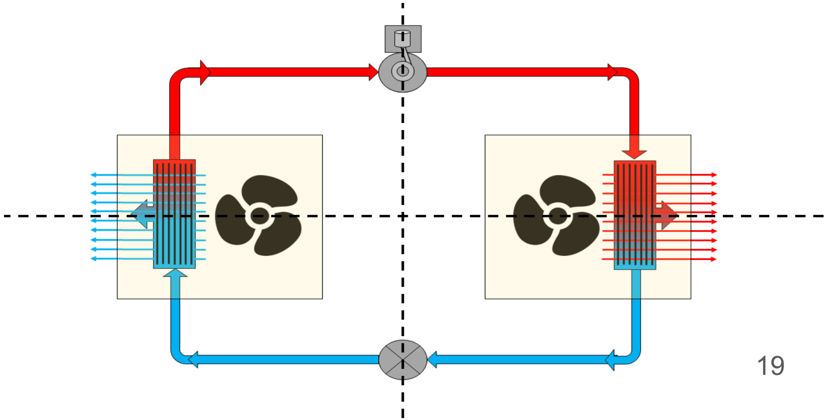
Positive Feedback → Amplify a perturbation or the response to an event
Negative Feedback → Dampens a perturbation or the response to an event

What is an example of each?

https://mynewmicrophone.com/microphone-feedback/



https://www.torr-engineering.com/the-refrigeration-cycle/#gallery-1

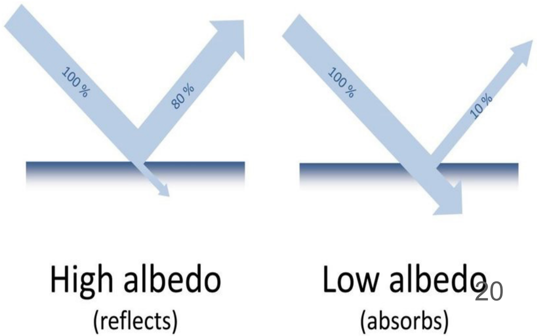


Relating Feedbacks to Climate

There are two processes that can induce a feedback. External and Internal

External → This process is unaffected by the state of the system. Example:

Internal → This process occurs within the system and occurs as a response to a change. Example:



Our climate is “forced” by External Processes

A change in an external process
will induce a change in forcing

Change in forcing can be shown by:

$$\left(\frac{\Delta T_S}{T_0}\right) \cong \left(\frac{\Delta S}{S_0}\right) - 16\left(\frac{\Delta \alpha}{1-\alpha_0}\right) - 4\frac{\Delta \varepsilon}{\varepsilon_0} \qquad (5.1)$$

Table 5.1
Classification of the changes that appear in Equation (5.1).

Quantity	*Meaning*	*Classification*
ΔS	Change in solar output	External
$\Delta \alpha$	Change in planetary albedo	Partly internal and partly external
ΔT_S	Change in surface temperature	Internal; this is the “response” of the system
$\Delta \varepsilon$	Change in bulk emissivity	Partly internal and partly external

Snow - Ice Albedo Feedback Arctic Amplification

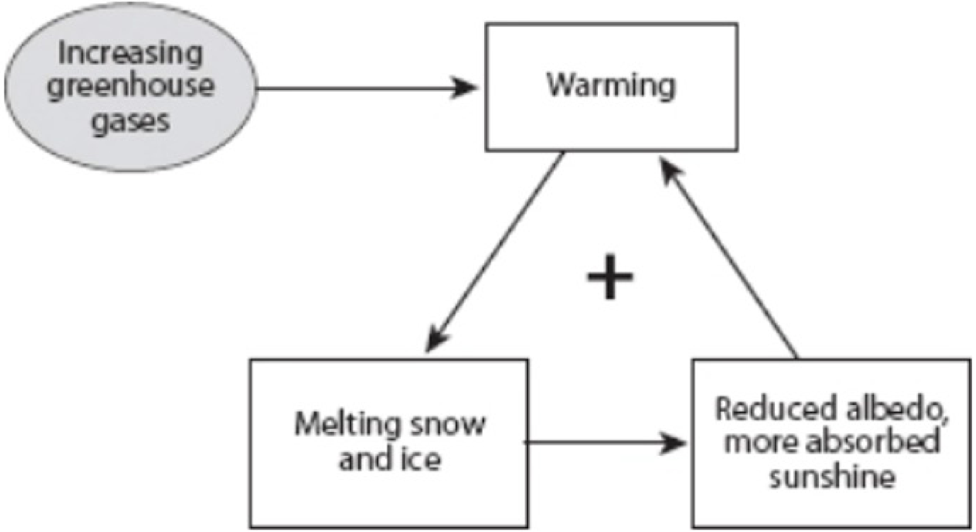


Figure 5.1. The positive feedback loop due to the dependence of snow and ice cover on temperature.

Here we show the feedback resulting from an external perturbation, that is, an increase in greenhouse gases. In this case, the positive feedback leads to increased warming. It is also possible, however, for the same physical mechanism to amplify a cooling, which might be externally forced, for example, by a decrease in the Sun's energy output.

From this process, a change in albedo can be written as:

$$\Delta\alpha = \left(\frac{\delta\alpha}{\delta T_s} \right)_{ice} \Delta T_s$$

Note: δ is for partial derivative

From this process a resulting change in temperature would be given as :

$$\left(\frac{\Delta T_S}{T_0}\right) \cong \frac{\left(\frac{\Delta S}{S_0}\right) - 4\frac{\Delta \varepsilon}{\varepsilon_0}}{1 + \left(\frac{16T_0}{1-\alpha_0}\right)\left(\frac{\partial \alpha}{\partial T_S}\right)_{ice}}$$

The numerator is showing:

The denominator is showing:

Water Vapor Feedback

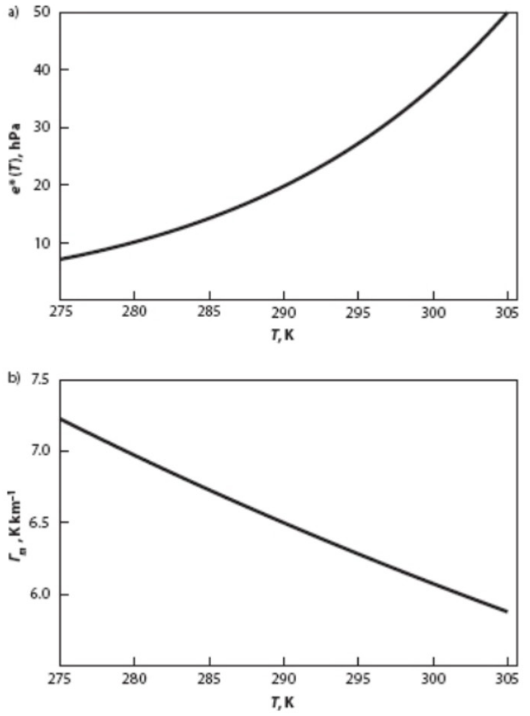


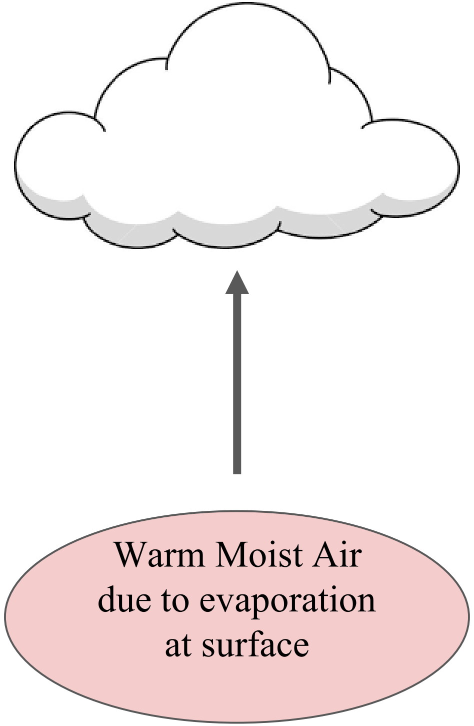
Figure 3.4. The upper panel shows the saturation vapor pressure, e^*, as a function of temperature. The units are hPa, which stands for "hectopascals."

This figure from Ch. 3 showcases this feedback very well

An increase in the atmospheric water vapor content causes an increase in the downwelling of infrared radiation at the surface.

Would this be a positive or negative feedback?

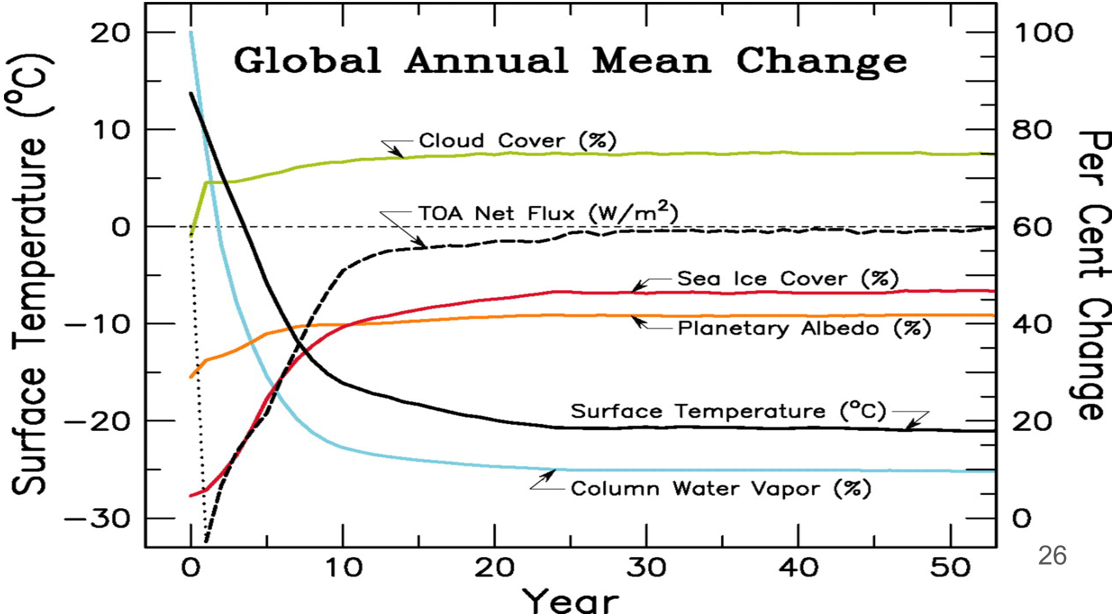
This Feedback also leads to..



Cumulus Convection!

Greenhouse Gases and Feedbacks

Even though the concentration of water vapor greatly exceeds that of Carbon Dioxide, why does Carbon Dioxide play a controlling role in the greenhouse effect?



Combination of Multiple Feedbacks

First, Bulk Emissivity is due to the effects of: Carbon Dioxide, Water Vapor, GHGs, and clouds.

$$\left(\frac{\Delta T_S}{T_0}\right) \cong \frac{\left(\frac{\Delta S}{S_0}\right) - 4\frac{(\Delta\varepsilon)_{CO2}}{\varepsilon_0}}{1 + \left(\frac{16T_0}{1-\alpha_0}\right)\left(\frac{\partial\alpha}{\partial T_S}\right)_{Ice} + \left(\frac{4T}{\varepsilon_0}\right)\frac{\partial\varepsilon_{H2O}}{\partial T_S}} \quad (5.5)$$

Simply put, the addition of more feedbacks will just add another partial derivative to the denominator.

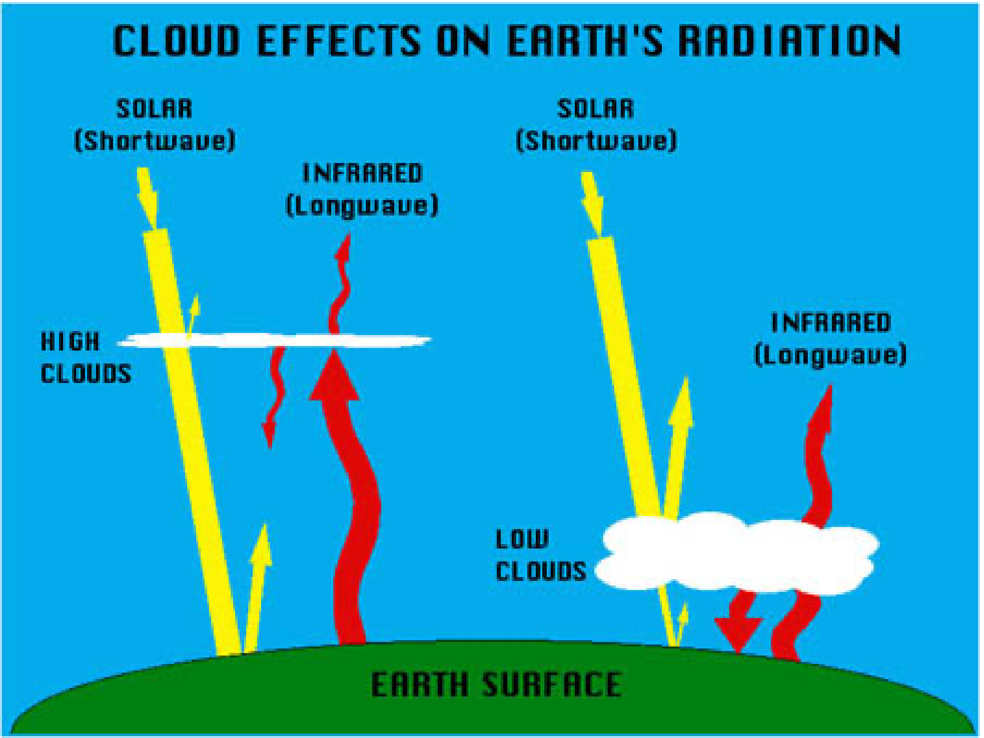
Cloud Feedbacks

It has been discussed in this class, and multiple others that clouds are…complicated!

1. Microphysical Processes
2. Dynamical Processes
3. Radiative Processes
4. Turbulence Processes
5. Chemical Processes

Spatial scale of these processes ranging microns to kilometers!

Low Cloud vs High Cloud Feedback



https://www.nasa.gov/audience/forstudents/5-8/features/F_The_Role_of_Clouds.html

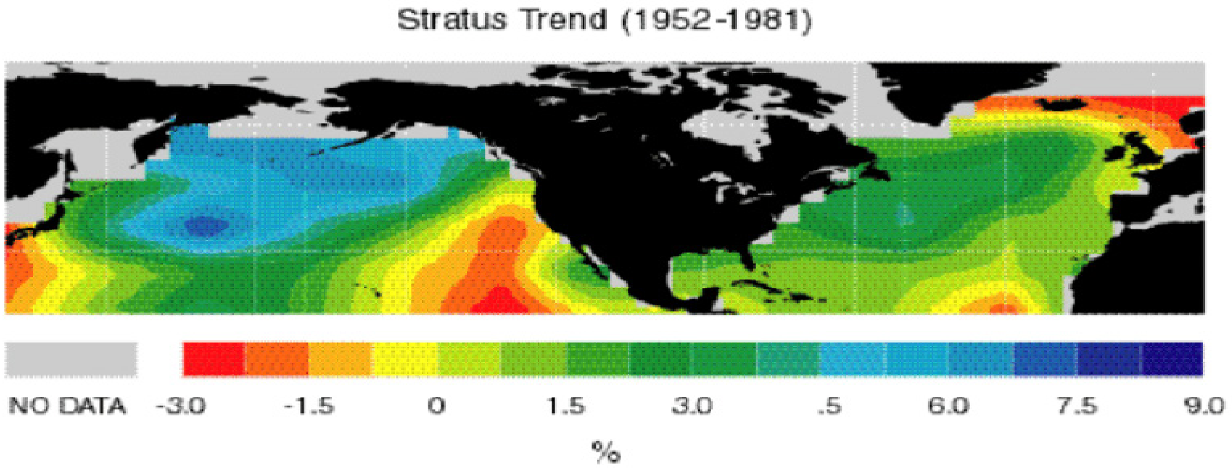
Low Clouds: Very Bright and have great reflectivity properties. Cooling Agent.

High Clouds: Somewhat transparent and are not good reflectors. Efficiently absorb LW radiation. Warming Agent.

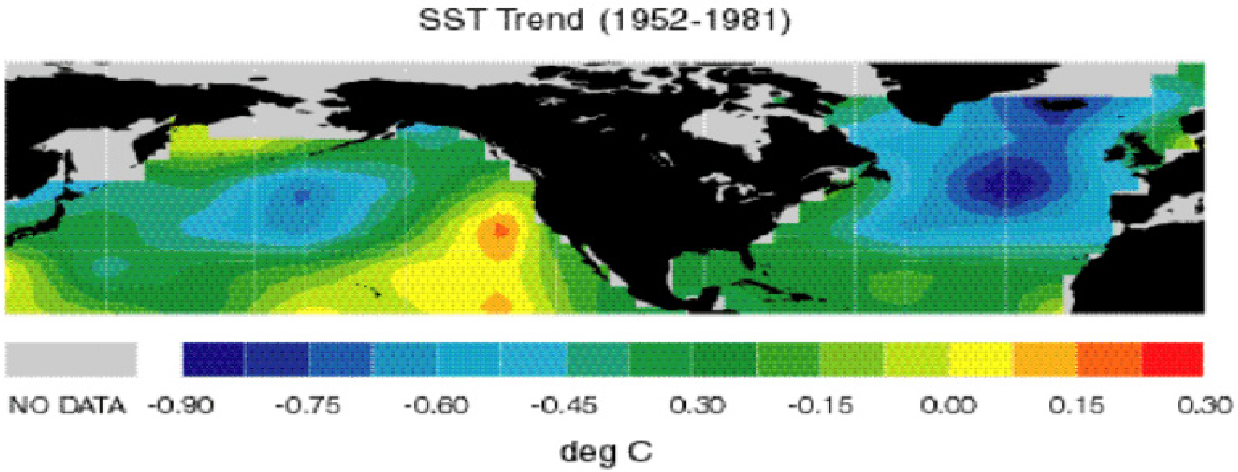
Low Cloud amount tends to be greater when the SST is cooler than the average SST at that latitude.

Low Cloud Abundance

What can be inferred from these two plots?



Downward trends in SST are collocated with upward trends in statocumulus amounts.



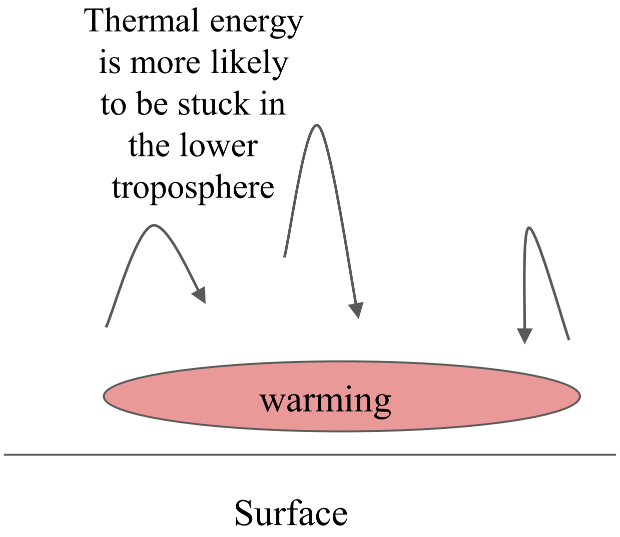
Cooling → Increase in low-cloud amount

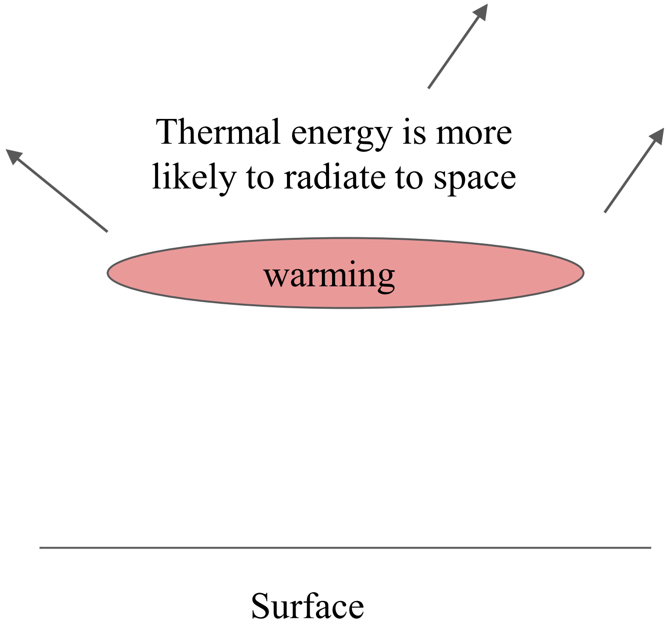
Increase in low-cloud amount → Cooling

Lapse Rate Feedback

A Lapse rate is the change in temperature with respect to change in height

If warming is increasing with height then the lapse rate is decreasing.





Overall:

- Feedbacks on a climate scale can be observed over extended periods of time, while some can be observed on the daily.
- When it comes to how much the climate is affected by these feedbacks, it is important to know that only the ‘net’ feedback matters.