Energy Flows and Climate Feedback

ATMOSPHERE, CLOUDS, AND CLIMATE BY DAVID RANDALL

CHAPTERS 4 & 5

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Background

WHAT DO WE KNOW SO FAR ABOUT ENERGY FLOWS IN THE ATMOSPHERE?

Chapter 2: Radiative Energy Flows

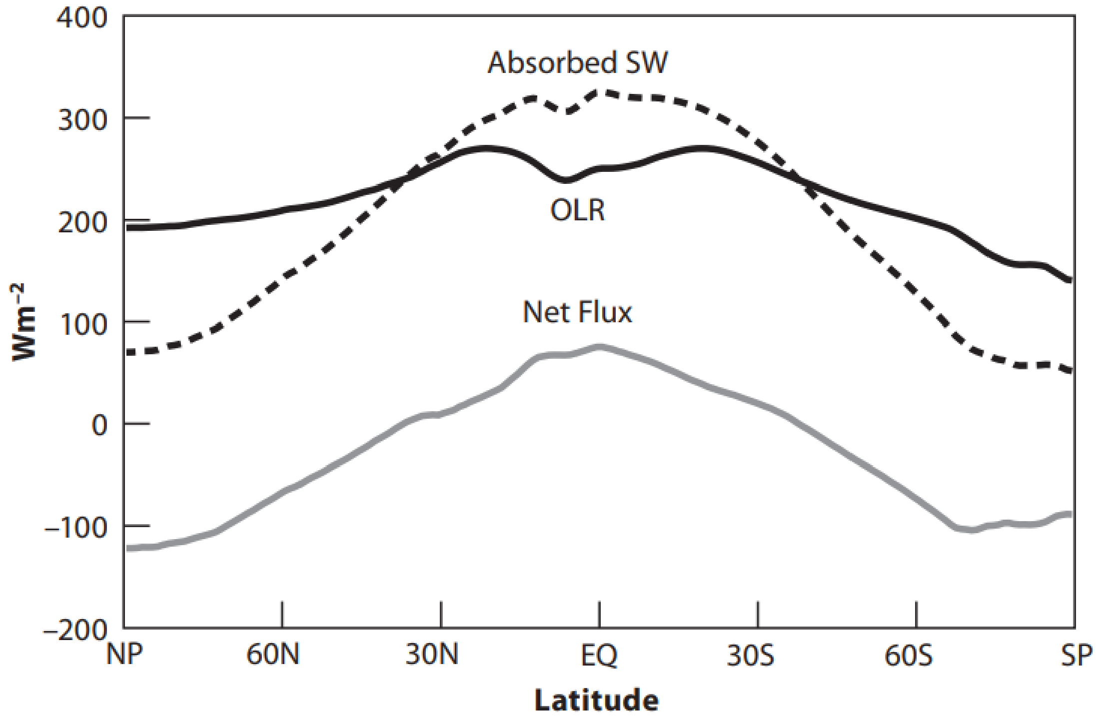

Figure 2.5. The zonally and annually averaged absorbed solar radiation (dashed), outgoing longwave radiation (solid black), and net radiation at the top of the atmosphere (gray), as observed from satellites. The data are discussed by Wielicki et al. (1996).

Which region absorbs more than it emits?

Which region emits more than it absorbs?

What does this tell us about energy transport of the *internal* system?

(Randall, 2012, p. 50-51)

Chapter 3: How Turbulence and Cumulus Clouds Carry Energy Upward

Most of the solar and infrared energy input to the oceans and land surface is used to evaporate water.

p. 56

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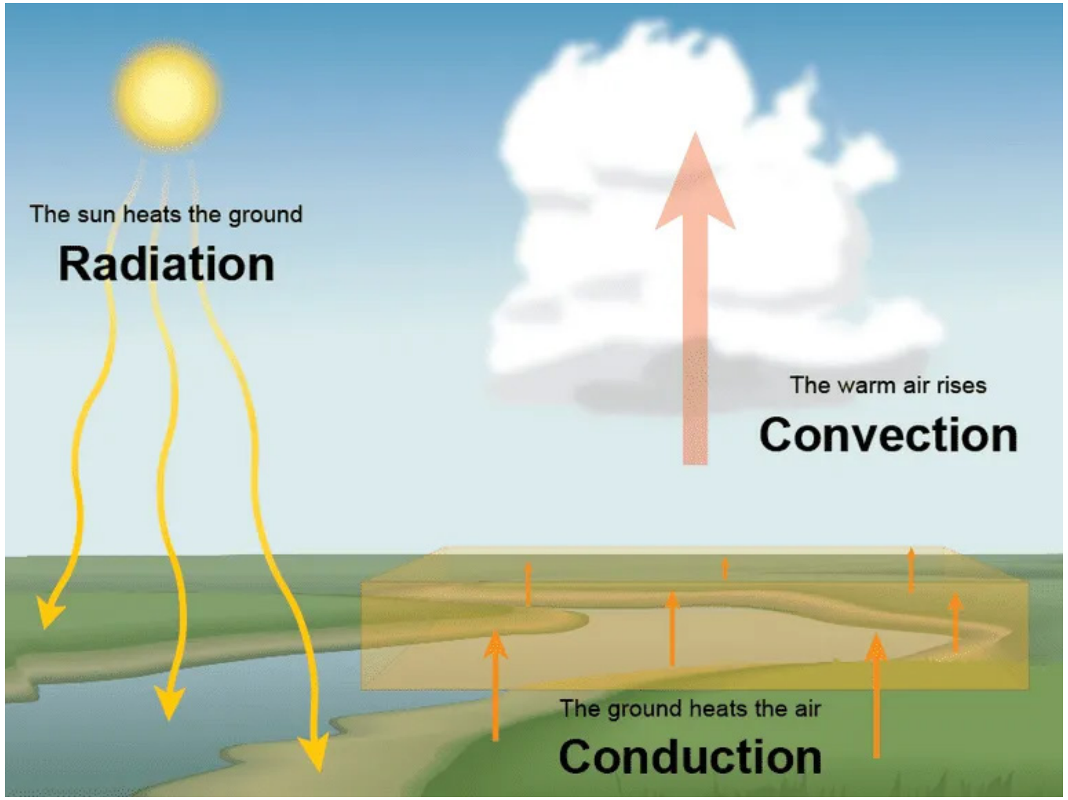
cloudy rising air is warmer than its environment, and it also contains more water vapor. Because the rising air has a high moist static energy and the surrounding, sinking clear air has a smaller value, *the net effect is that moist static energy is carried upward*. Cumulus clouds therefore produce an upward energy transport.

p. 82



https://scied.ucar.edu/learning-zone/earth-system/conduction

Chapter 4: How Energy Travels from the Tropics to the Poles

UNDERSTAND HOW ENERGY IS TRANSPORTED UPWARDS/POLEWARDS AND HOW THIS ACTS TO BALANCE THE SYSTEM

The Winds

Solar absorption dominates in the tropics while infrared loss to space dominates at the poles

- Energy must be balanced
- This is done by winds

How does the strength of wind vary?

- Strongest winds are in stratosphere while near-surface winds are weaker
- Vertical winds are slower than horizontal winds

(Randall, 2012, p. 103-104)

The Hadley Cells

Mean meridional circulation shows distinct cells near tropics

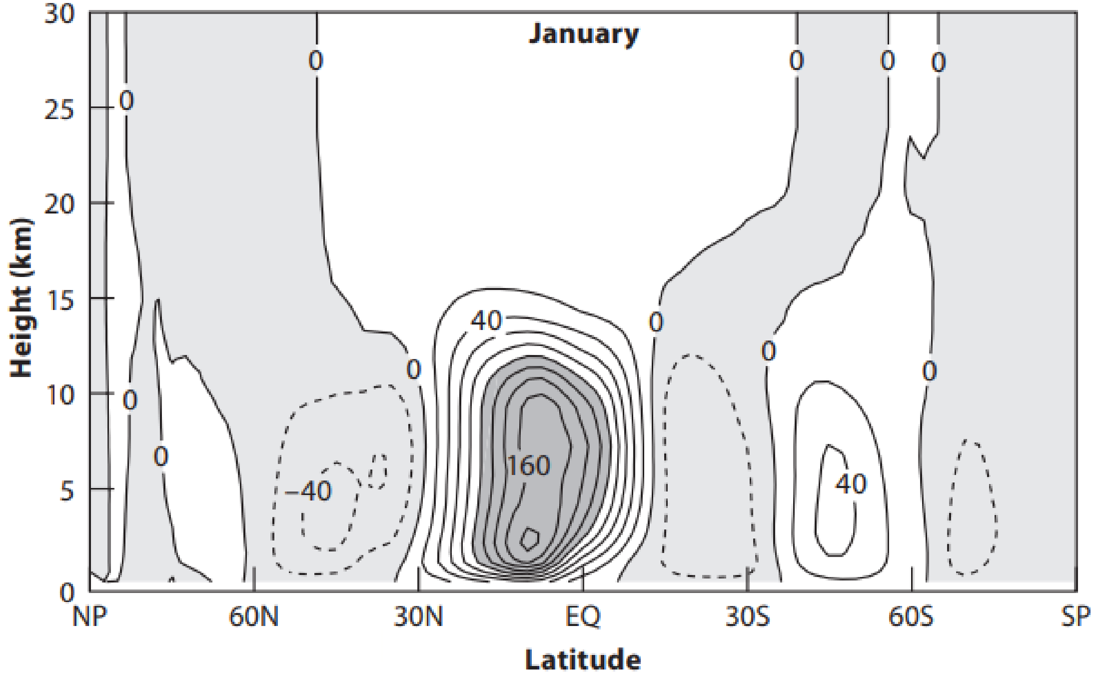
- The Hadley cells have rising branches and sinking branches
- There are two processes that allow air to move through the branches

The rotation of the planet plays a role in atmospheric circulation

- Leads to special circulation structures
- Conservation of some property determines westerlies and easterlies

(Randall, 2012, p. 106-114)

Mean Meridional Circulation (MMC)



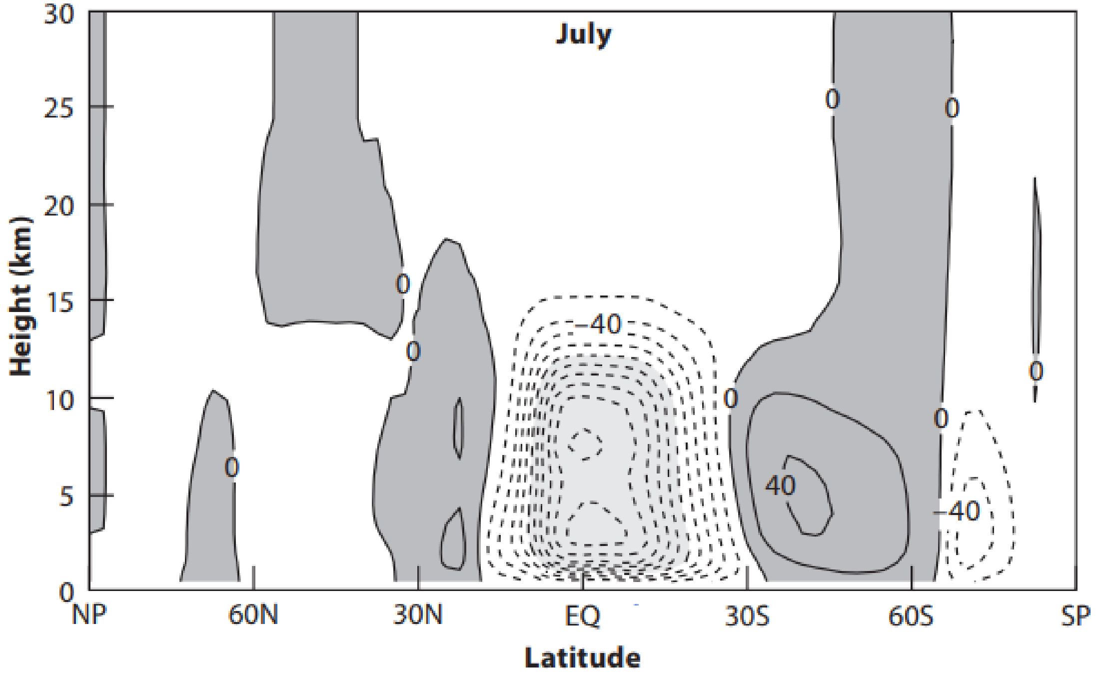


Figure 4.1. The streamfunction of the mean meridional circulation, plotted as a function of height and latitude.

Positive values, denoted by solid contours, represent counter-clockwise 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}.

Monsoons

Monsoons are an intense weather phenomenon caused by the temperature difference between land and ocean

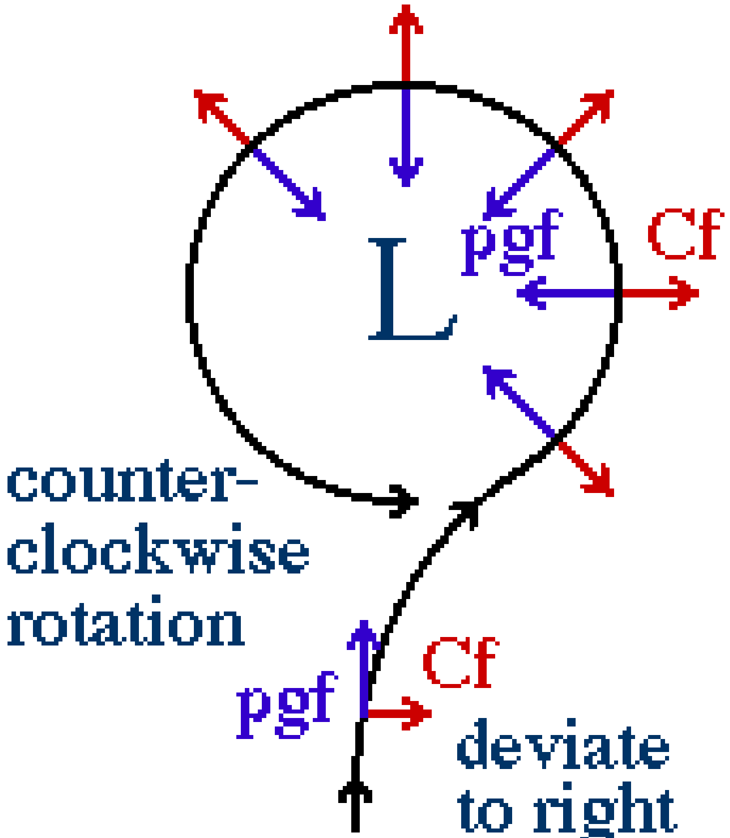
- Land is warmer than the ocean during the summer due to differing heat capacities
- This temperature contrast drives moist wind onshore

(Randall, 2012, p. 115-116)

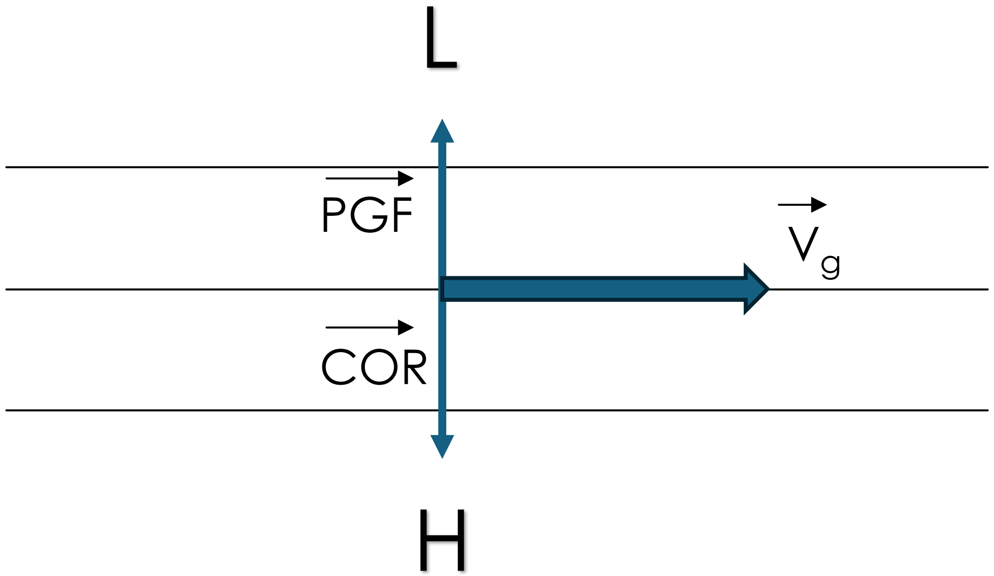
How the Earth's Rotation Affects the Wind, Temperature, and Pressure

The rotation of the Earth causes the Coriolis effect, an apparent force that results from being in a rotating reference frame

- Coriolis deflects parcels to the right (left) in the NH (SH)
- Air rotates CCW around lows and CW around highs in NH; opposite for SH



(Randall, 2012, p. 116-124)



$$-fv = -\frac{1}{\rho}\left(\frac{\partial p}{\partial x}\right), \text{ and } fu = -\frac{1}{\rho}\left(\frac{\partial p}{\partial y}\right)$$

Equation 4.2

Geostrophic balance is a good approximation where the Coriolis effect is strong

- Large scales and away from the equator

The Thermal Wind

Temperature variation in the horizontal direction

- Temperature is almost horizontally uniform throughout the tropics
- Midlatitude temperature can change rapidly in the horizontal direction

Thermal wind relationship demonstrates that rapid horizontal temperature changes result in rapid wind changes with height

- Referred to as “baroclinic” structure

(Randall, 2012, p. 125-127)

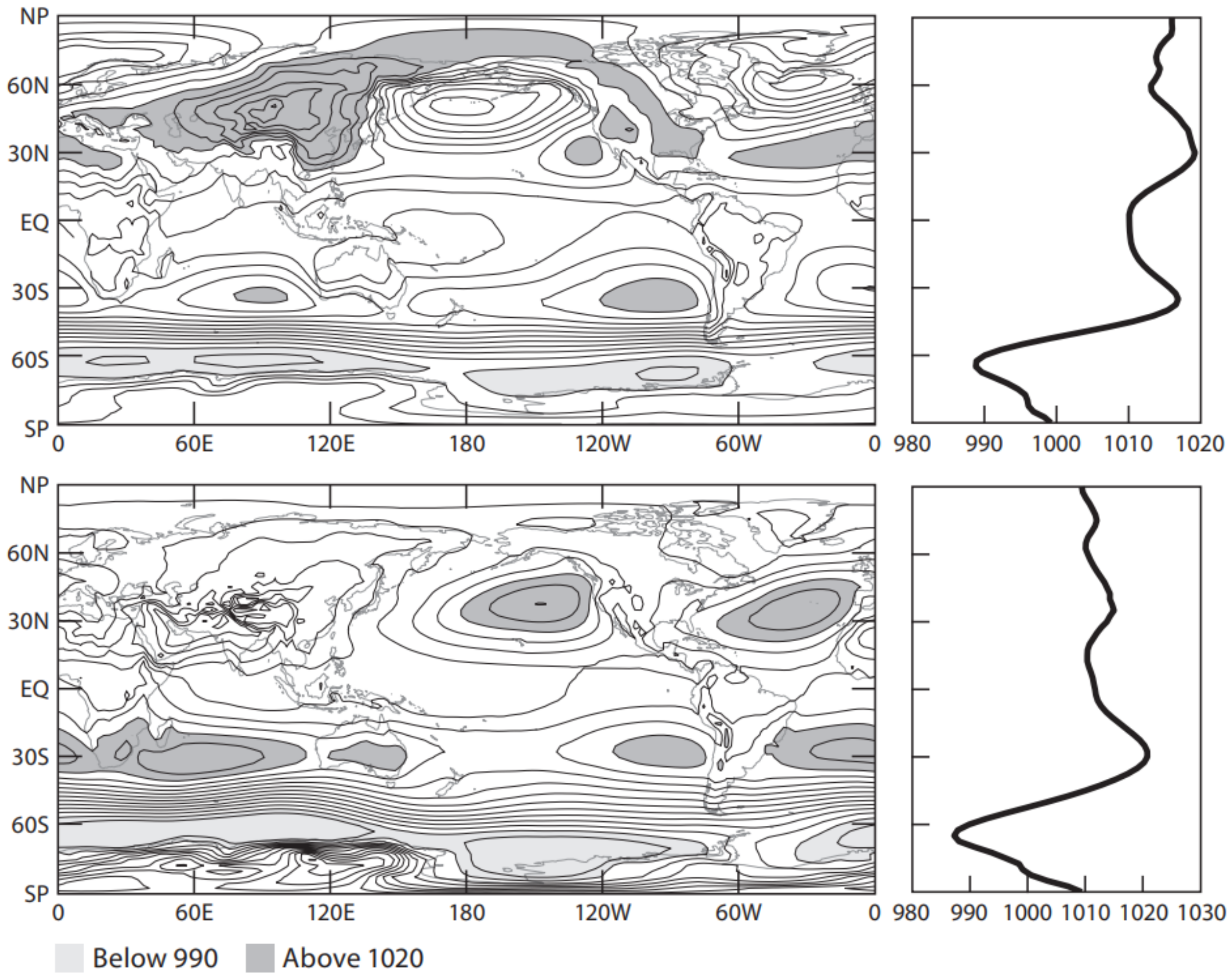


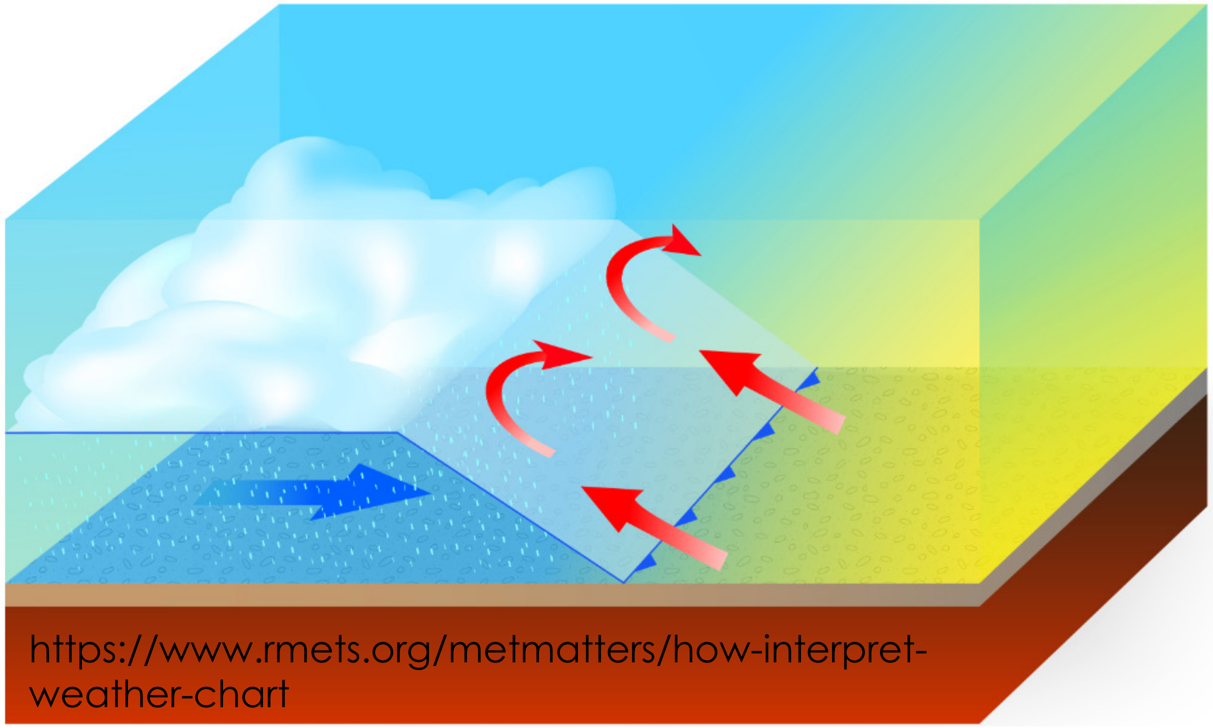
Figure 4.4. Sea level pressure maps for January (top) and July (bottom).

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.

Winter Storms

Baroclinic instability leads to winter storms

- Cold air moves downward from the poles and warm air moves upward from the equator, thus transporting energy poleward
- Cold air sinks and warm air rises, transporting thermal energy upward



(Randall, 2012, p. 127-131)

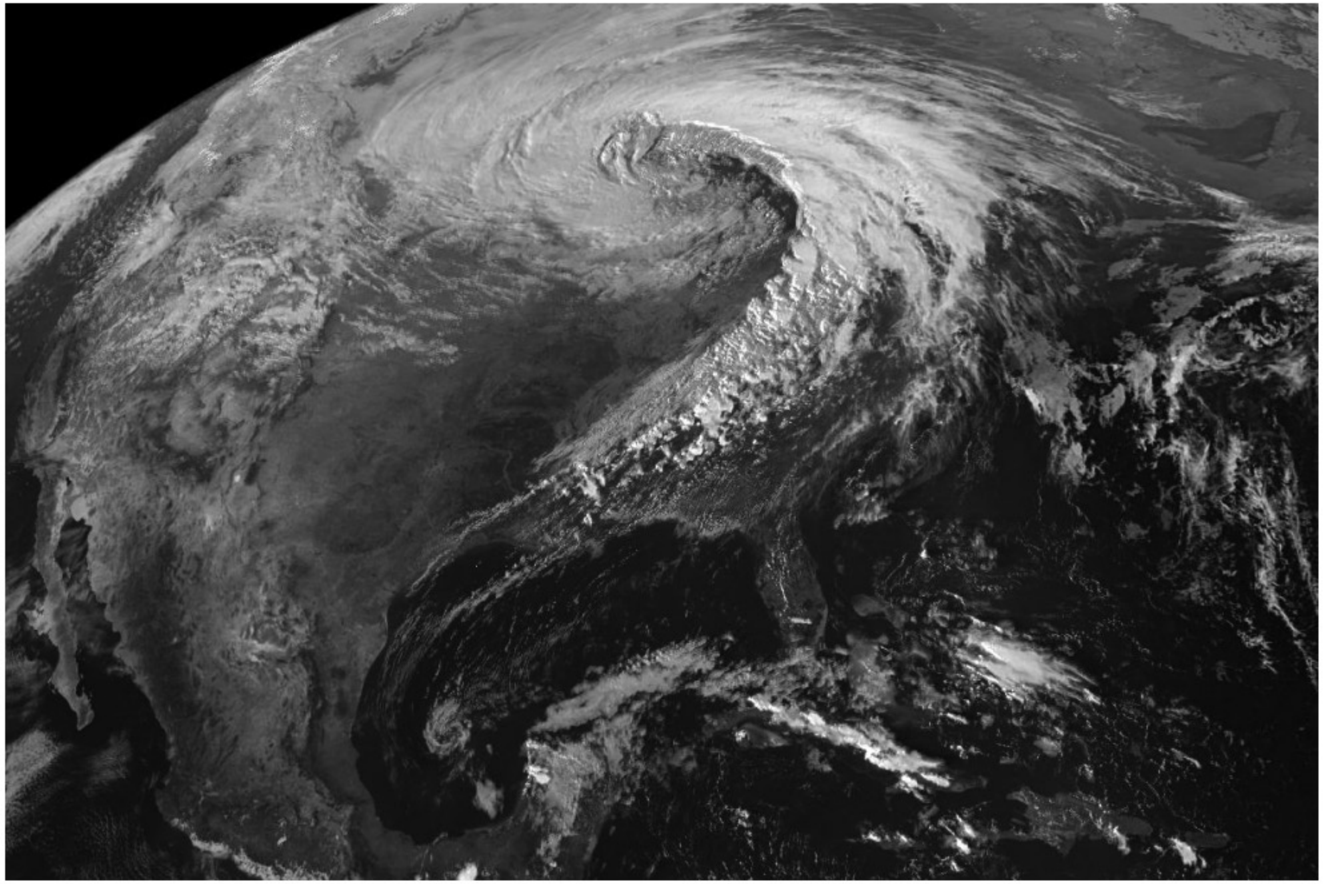


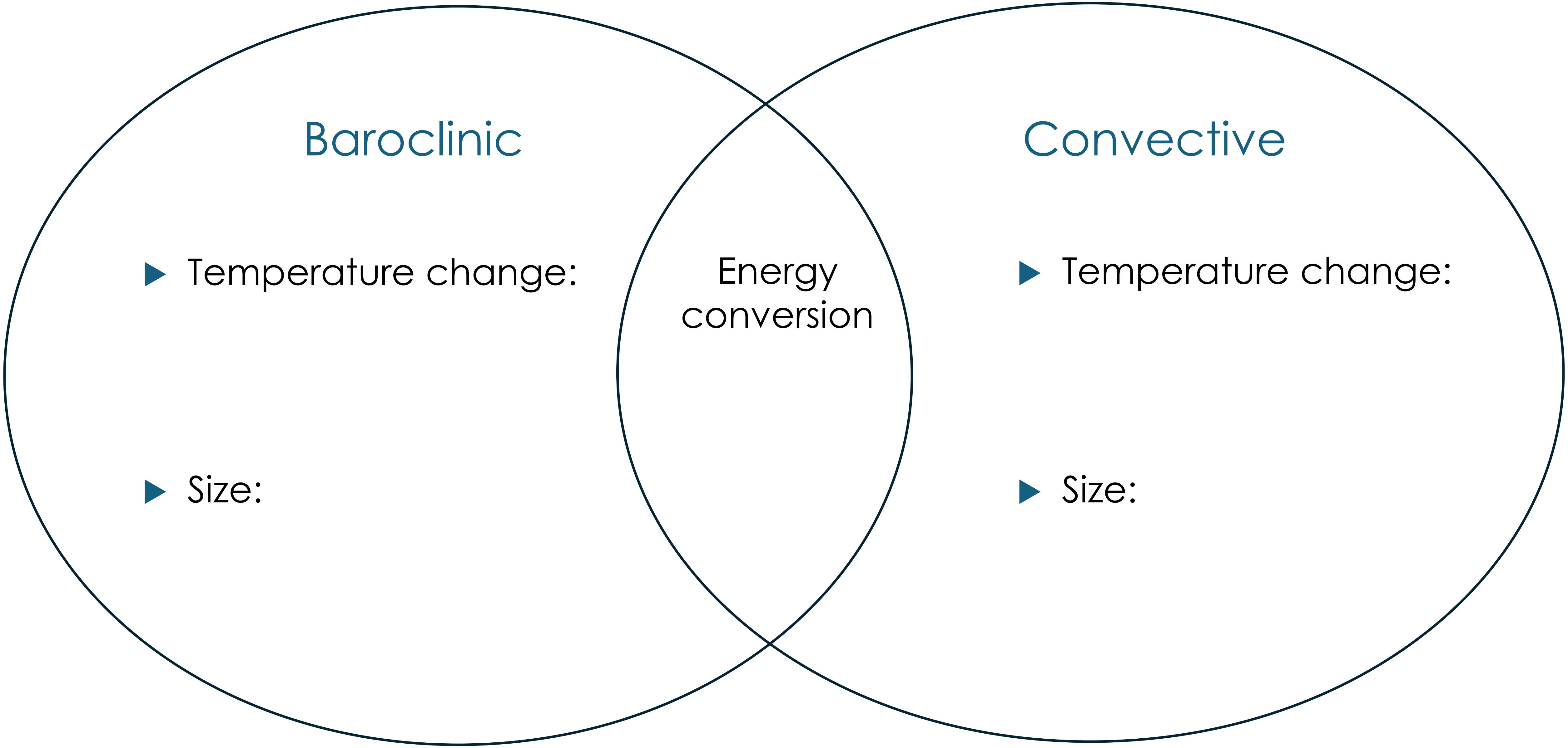
Figure 4.6. A winter storm over North America on October 26, 2010.

The core of the storm is in the upper Midwest, near the top center of the image. South and east of the center, warm, humid air is flowing poleward. North and west of the center, cool and relatively dry air is flowing equatorward.

Source: http://www.crh.noaa.gov/images/dlh/StormSummaries/2010/october26/satellite_large_2132z.JPG.

(Randall, 2012, p. 127-131)

Baroclinic Instability vs Convective Instability

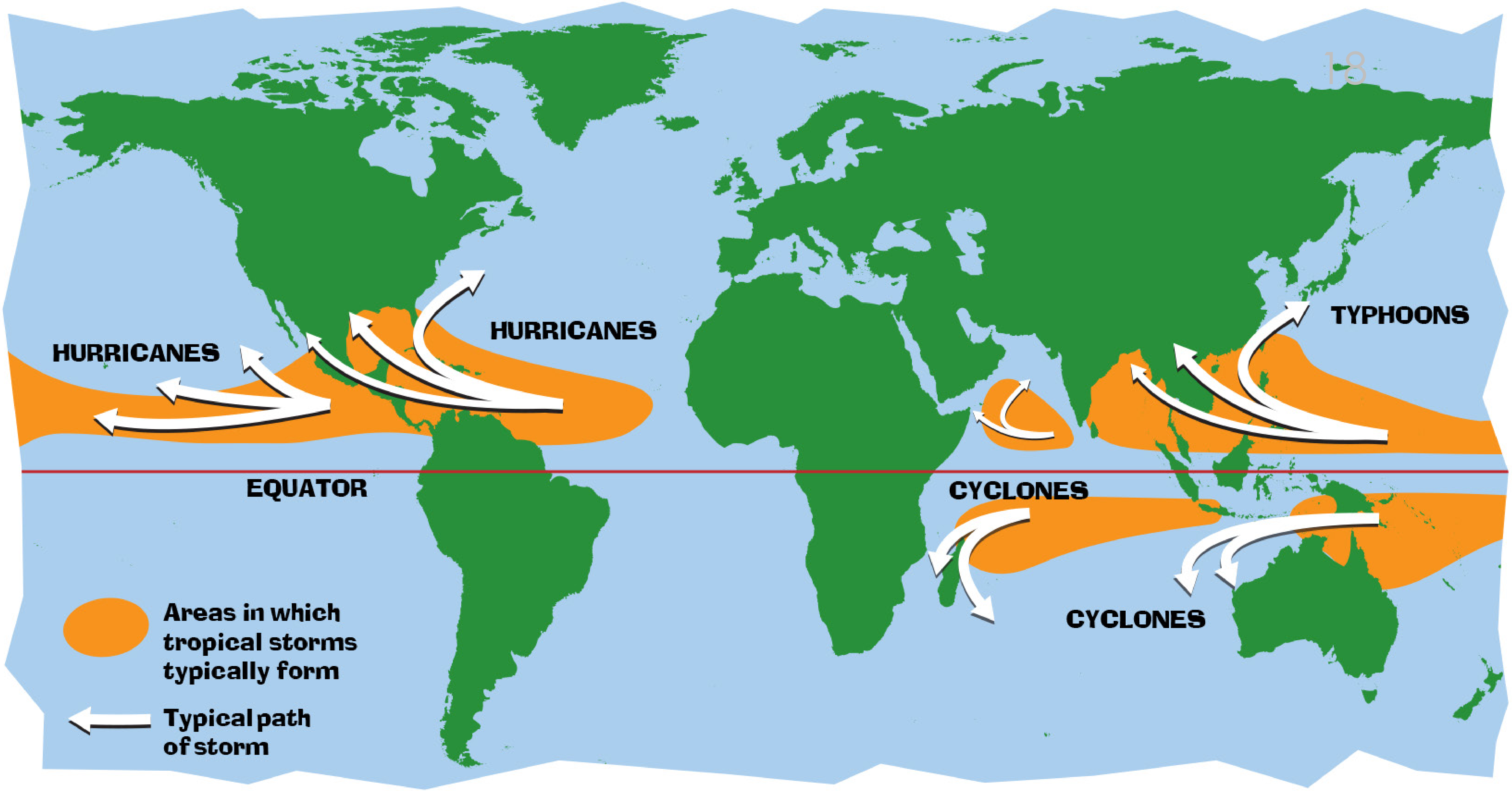


Tropical Storms

Energy fluxes from the warm tropical oceans into the atmosphere lead to tropical storms

- Three key functions in the climate system
- Weakening occurs

(Randall, 2012, p. 131-133)



https://scijinks.gov/hurricane/

Checkpoint in Atmosphere, Clouds, and Climate

CHAPTERS 2-4 PRESENTED ENERGY FLOW MECHANISMS

CHAPTERS 5 AND BEYOND PRESENT OTHER INFORMATION

Temperature differences arise when:	Balanced by:	Results in:
Net radiation is positive in the tropics and negative at the poles		
Energy from sun absorbed by Earth's surface (tropics)		
Heat transferred from surface to atmosphere (mid-lat)		
Latent heat release occurs from cloud formation and precipitation		

Chapter 5: Climate Feedbacks

UNDERSTAND HOW CHANGING PROCESSES LEAD TO FORCING OF THE SYSTEM

Forcing and Response

Positive (negative) feedbacks amplify (damp) and increase (reduce) variability in the climate system

(Randall, 2012, p. 140-143)

The Snow and Ice Albedo Feedback

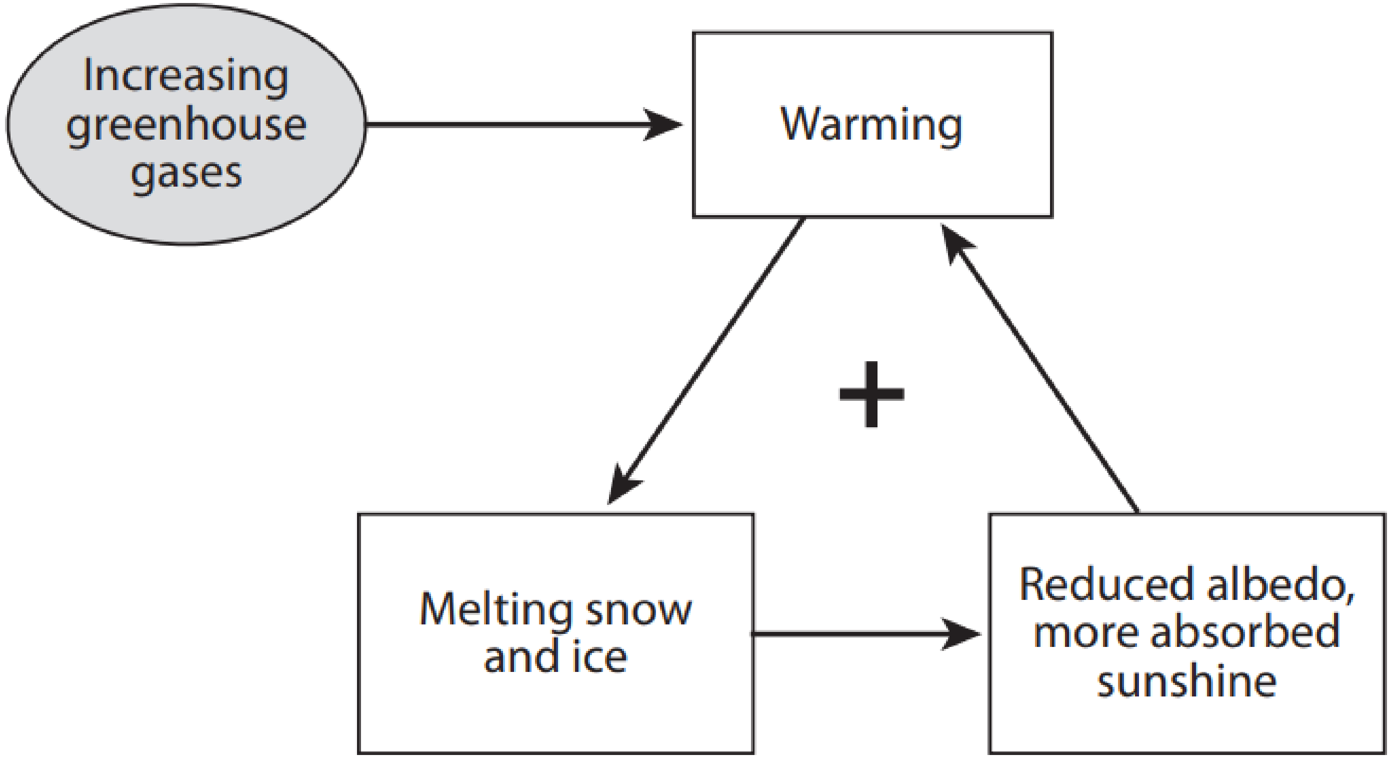


Figure 5.1. The positive feedback loop due to the dependence of snow and ice cover on temperature.

(Randall, 2012, p. 143-146)

The Water Vapor Feedback

Most important feedback in the atmosphere!

- Saturation vapor pressure of water increases (exponentially) with temperature
- As temperature increases, more water vapor will be in the atmosphere acting as a greenhouse gas; water vapor content increases %7 per K
- More greenhouse gas will lead to further warming at the surface, thus amplifying the original perturbation

(Randall, 2012, p. 146-150)

How Multiple Feedbacks Combine

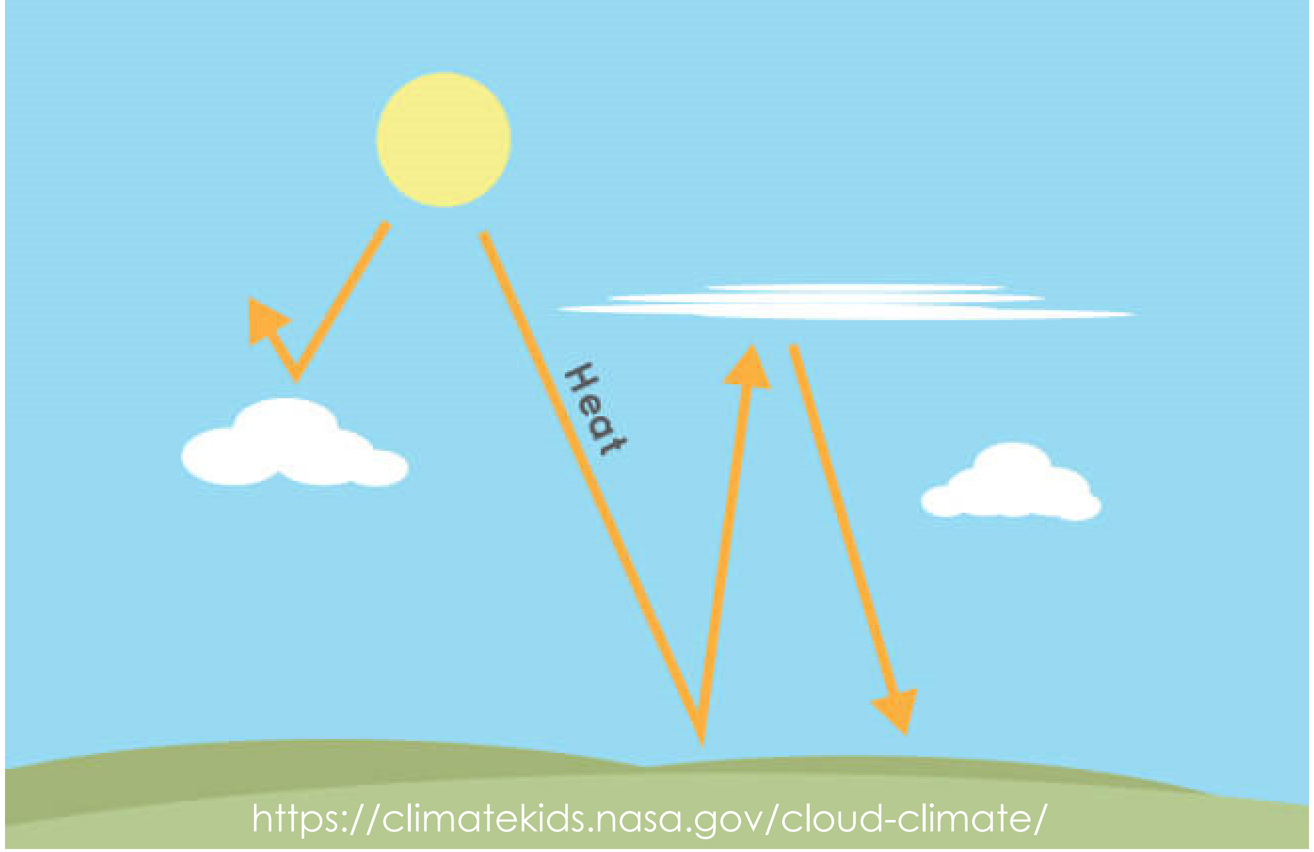
The combined effect of feedbacks is represented by the bulk emissivity of the atmosphere

How temperature responds to forcing from multiple feedbacks:

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

(Randall, 2012, p. 150-151)

Cloud Feedbacks



High clouds

Low clouds

(Randall, 2012, p. 151-157)

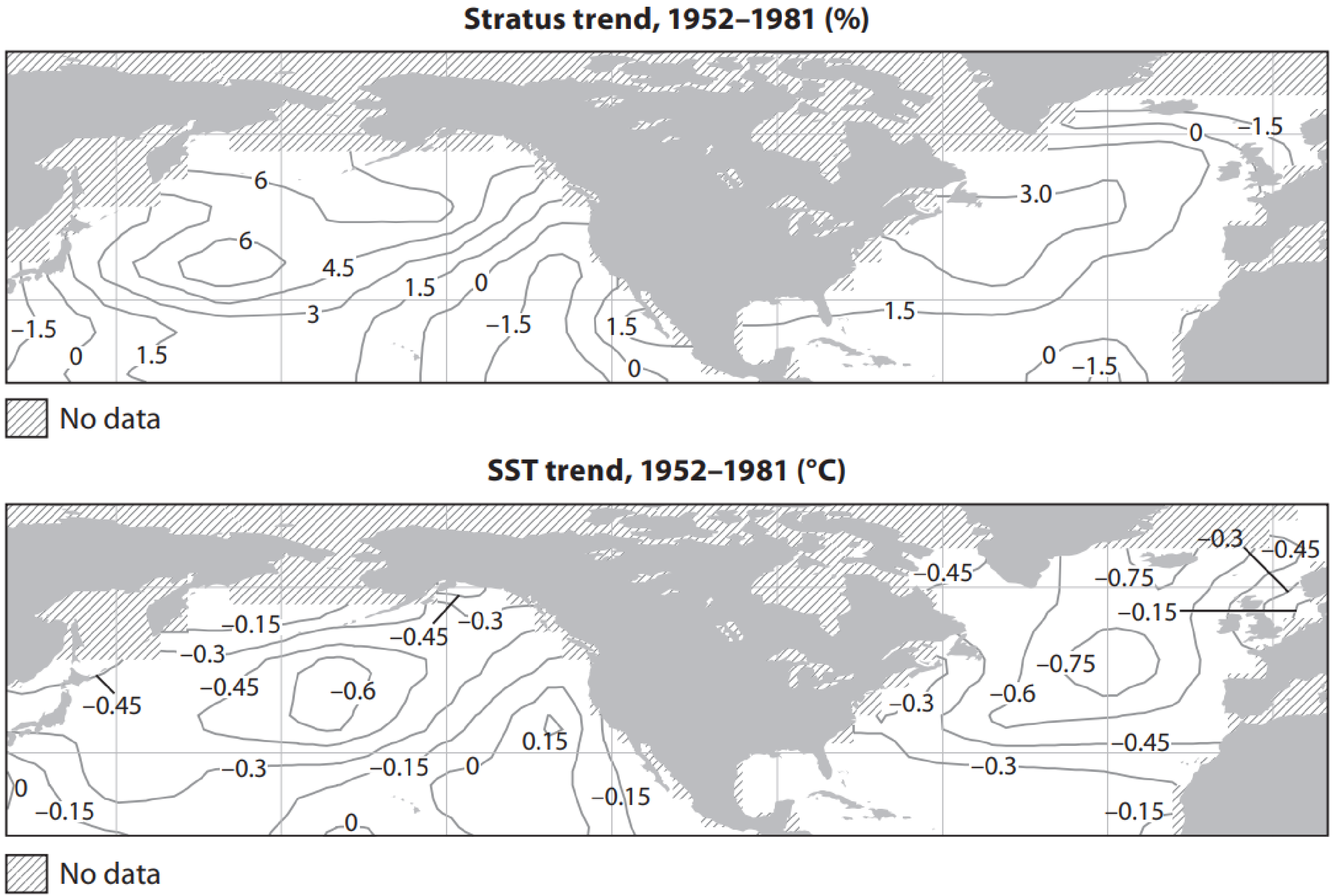
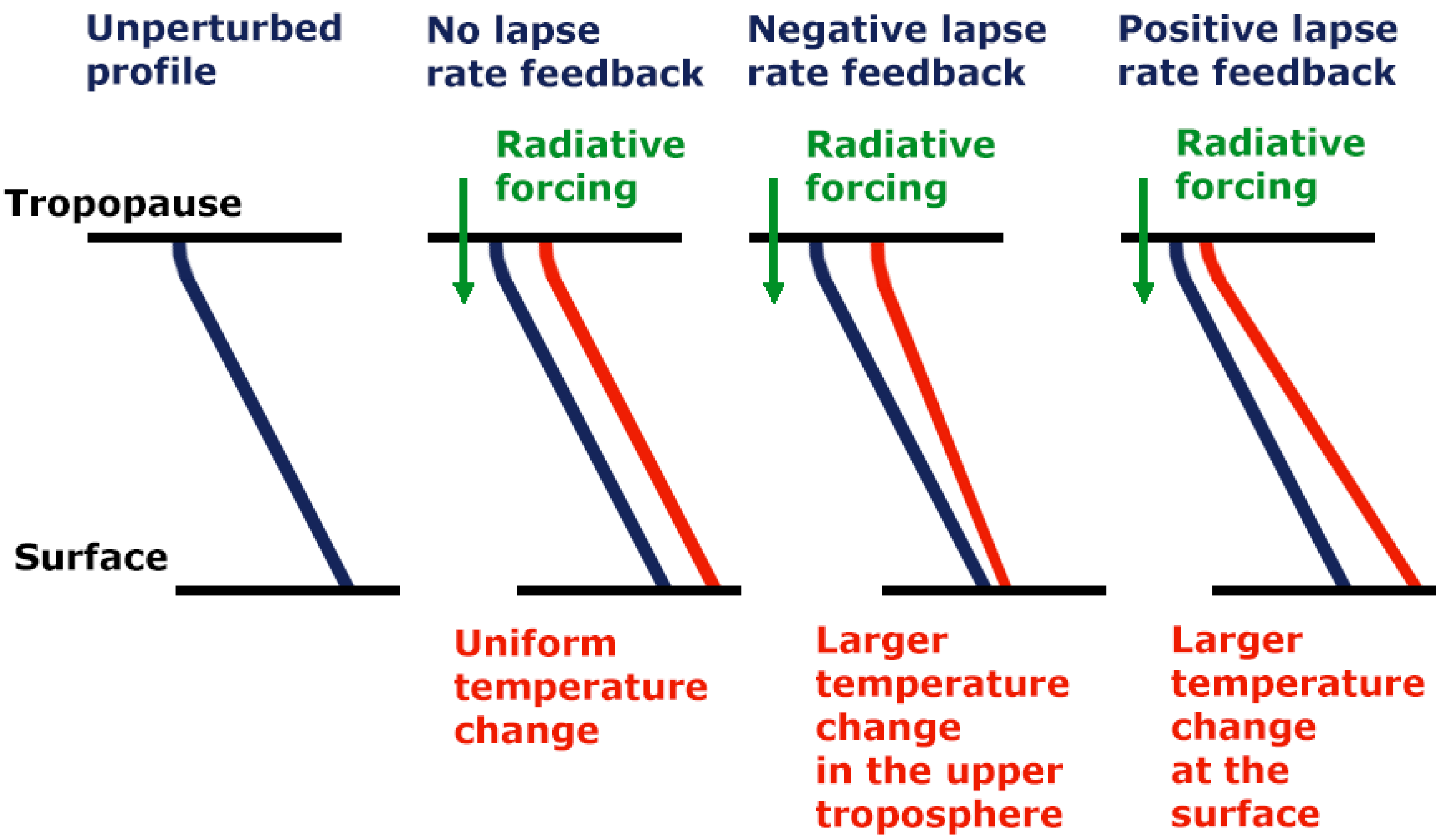


Figure 5.3. Observed trends of stratus cloud amount (top) and sea surface temperature (bottom), for the period 1952–81.

Source: The figure was provided by Joel Norris. It is based on work published by Norris and Leovy (1994).

The Lapse-Rate Feedback



(Randall, 2012, p. 157-158)

Observing Feedbacks in the Climate System

Additional feedbacks

- Large-scale atmospheric circulation, ocean circulation, vegetation, ice sheets, etc.

Feedbacks are measured by the variability that they induce in the climate system

- Observe changes in internal variables (ice and snow, water vapor, cloudiness, etc.) and compare over time

(Randall, 2012, p. 158-159)

Summary

"FOLLOW THE ENERGY" AND REMEMBER THAT THE ATMOSPHERE CLIMATE SYSTEM WILL

1) SEEK ENERGY BALANCE
2) RESPOND TO FORCINGS

Key Takeaways

Temperature differences result in atmospheric changes which act to balance the system

- Poleward and/or upward energy transport is achieved by meridional winds, monsoons, winter storms, and tropical storms

Perturbations to atmospheric processes lead to changes in the climate system

- Climate forcing is changed through ice-albedo, water vapor, low-cloud and high-cloud, and lapse-rate feedbacks