## Lecture 9: Climate Sensitivity and Feedback Mechanisms

- ❑ Basic radiative feedbacks (Plank, Water Vapor, Lapse-Rate Feedbacks)
- ❑ Ice–albedo & Vegetation-Climate feedback
- ❑ Cloud feedback
- ❑ Biogeochemical feedbacks (skipped)
- ❑ Dynamical feedbacks and meridional energy transport (skipped)
- ❑ Longwave and evaporation feedbacks in the surface energy balance (skipped)

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# Definition and Mathematic Form

direct impact

$$\frac{dT_s}{dS_0} = \frac{\partial T_s}{\partial S_0} + \sum_{j=1}^{N} \frac{\partial T_s}{\partial y_j}\frac{dy_j}{dS_0}$$

- ❑ Climate Sensitivity: the relationship between the measure of forcing and the magnitude of the climate change response.
- ❑ Climate Forcing ($S_0$): Climate forcing is a change to the climate system that can be expected to change the climate.
- ❑ Feedback Mechanism: a process that changes the sensitivity of the climate response.

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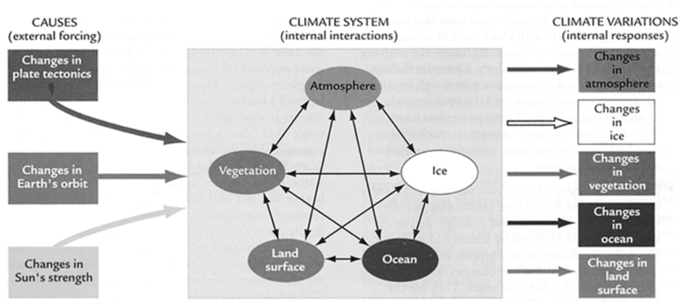
# Climate Sensitivity and Feedback




(from *Earth's Climate: Past and Future*)

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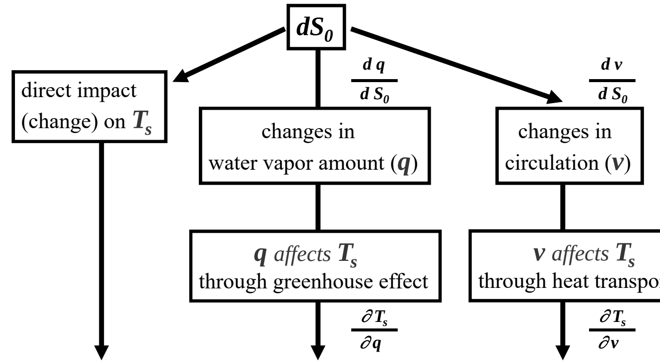
# Direct Impact and Feedback Process




$$\frac{dT_s}{dS_0} = \frac{\partial T_s}{\partial S_0} + \frac{\partial T_s}{\partial q} \times \frac{dq}{dS_0} + \frac{\partial T_s}{\partial v} \times \frac{dv}{dS_0}$$

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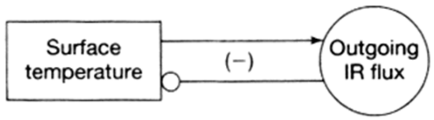
# Longwave Radiation (Plank) Feedback

$$E = \sigma T^4$$




- ❑ The outgoing longwave radiation emitted by the Earth depends on surface temperature, due to the Stefan-Boltzmann Law: $F = \sigma(T_s)^4$.

  ➔ warmer the global temperature
  ➔ larger outgoing longwave radiation been emitted by the Earth
  ➔ reduces net energy heating to the Earth system
  ➔ cools down the global temperature
  ➔ a negative feedback

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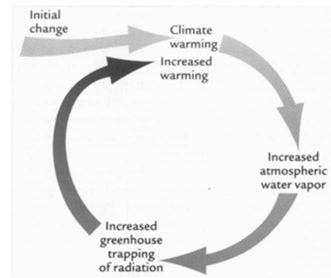
# Water Vapor Feedback




- ❑ **Mixing Ratio** = the dimensionless ratio of the mass of water vapor to the mass of dry air.
- ❑ **Saturated Mixing Ratio** tells you the maximum amount of water vapor an air parcel can carry.
- ❑ The saturated mixing ratio is a function of air temperature: the warmer the temperature the larger the saturated mixing ration.

  ➔ a warmer atmosphere can carry more water vapor
  ➔ stronger greenhouse effect
  ➔ amplify the initial warming
  ➔ one of the most powerful positive feedback

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# Stefan-Boltzmann Law

$$E = \sigma T^4$$

E = radiation emitted in W/m$^2$
σ= 5.67 x 10$^{-8}$ W/m$^2$ * K *sec
T = temperate (K ← ***Kelvin degree***)

- ❑ The single factor that determines how much energy is emitted by a blackbody is its temperature.
- ❑ The intensity of energy radiated by a blackbody increases according to the fourth power of its absolute temperature.
- ❑ This relationship is called the Stefan-Boltzmann Law.

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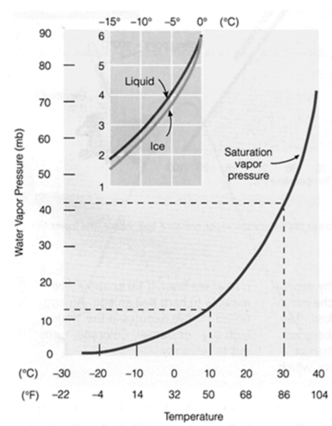
# Clausius–Clapeyron Relationship




- ❑ Saturation vapor pressure describes how much water vapor is needed to make the air saturated at any given temperature.
- ❑ Saturation vapor pressure depends primarily on the air temperature in the following way:

$$\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}$$

**The Clausius-Clapeyron Equation**

$$➔ \quad e_s \cong 6.11 \bullet \exp\left\{\frac{L}{R_v}\left(\frac{1}{273} - \frac{1}{T}\right)\right\}$$

- ❑ Saturation pressure increases exponentially with air temperature.

L: latent heat of evaporation; α: specific volume of vapor and liquid

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# Water Vapor Feedback

$$\frac{de_s}{dT} = \frac{L}{T(\alpha_v - \alpha_l)}$$

$$\frac{dq^*}{q^*} = \frac{de_s}{e_s} = \left(\frac{L}{R_v T}\right)\frac{dT}{T}$$

(20%) = (20) × (1%)

- A 1% change in temperature (about 3˚C) is associated with about a 20% change in saturation specific humidity
  - ➔1 ˚C change in temperature corresponds to a 7% change in saturation specific humidity.
- It is observed that the relative humidity of the atmosphere, which is the ratio of the actual to the saturation humidity, tends to remain constant, even when the air temperature goes through large seasonal variations in middle to high latitudes.
- In this case, we find that the terrestrial radiation emitted from the planet increases much less rapidly with temperature than would be indicated by the Stefan–Boltzmann relationship.
- An assumption that the relative humidity remains approximately constant when the climate warms or cools has generally been shown to be an excellent approximation.

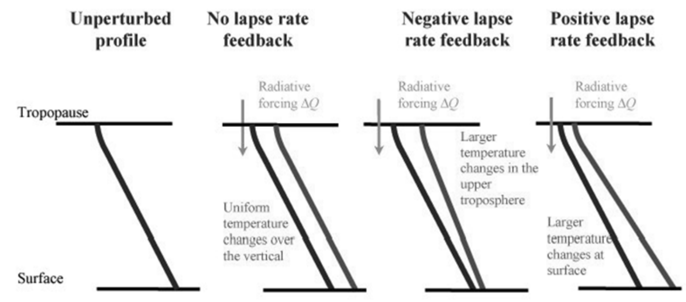


Figure 4.10: Schematic representation of positive and negative lapse-rate feedbacks.

http://www.climate.be/textbook/chapter4_node7.html

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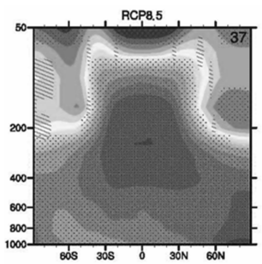
# Lapse-Rate Feedback




Global warming
➔ Decrease lapse rate
➔ Warm up middle troposphere
➔ Stronger terrestrial radiation
➔ Cooling climate
➔ A negative feedback

- In the tropics, the lapse rate is expected to decrease in response to the enhanced greenhouse effect, amplifying the warming in the upper troposphere and suppressing it at the surface.
- **This suppression causes a negative feedback on surface temperature.** Toward the poles, the reverse happens (a positive feedback), but the tropics tend to dominate, producing an overall negative feedback.
- Greenhouse gases and clouds cause the emission of thermal infrared radiation by Earth to originate in the middle troposphere, which is cooler than the surface.
- If we weaken the lapse rate, the surface and the emission temperatures become closer together, the greenhouse effect is weakened, and we should expect the surface temperature to cool.
- So if the lapse rate decreases with increasing surface temperature, that would be a negative feedback.

# Temperature Changes due to Anthropogenic Warming

associated with a decline in the moist adiabatic lapse rate of temperature in the tropics as the climate warms

1. enhanced warming in tropical troposphere

Warming in the troposphere and cooling in the stratosphere

➔ due to the absorption of longwave radiation by $CO_2$ in the troposphere such that it is no longer available to the stratosphere.

colder stratosphere ➔ increases PSC ➔ deplete ozone

associated with polar ozone depletion

2. enhanced cooling in polar stratosphere

associated with snow-ice-albedo feedback in the Arctic

3. enhanced warming at polar surface

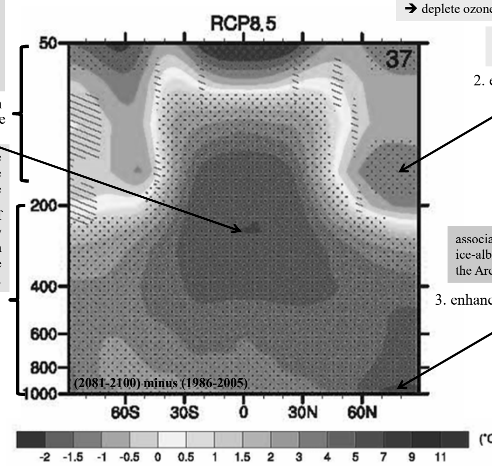



Figure 12.12 | CMIP5 multi-model changes in annual mean zonal mean temperature in the atmosphere and ocean relative to 1986–2005 for 2081–2100 under the RCP2.6 (left), RCP4.5 (centre) and RCP8.5 (right) forcing scenarios. Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model change mean is greater than two standard deviations of internal variability and where at least 90% of the models agree on the sign of change (see Box 12.1).

(from IPCC AR5)

# Snow/Ice Albedo Feedback

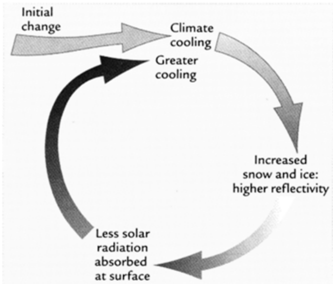



TABLE 2-1 Average Albedo Range of Earth's Surfaces

| Surface | Albedo range (percent) |
|---|---|
| Fresh snow or ice | 60–90% |
| Old, melting snow | 40–70 |
| Clouds | 40–90 |
| Desert sand | 30–50 |
| Soil | 5–30 |
| Tundra | 15–35 |
| Grasslands | 18–25 |
| Forest | 5–20 |
| Water | 5–10 |

*Adapted from W. D. Sellers,* Physical Climatology *(Chicago: University of Chicago Press, 1965), and from R. G. Barry and R. J. Chorley,* Atmosphere, Weather, and Climate, *4th ed. (New York: Methuen, 1982).*

- The snow/ice albedo feedback is associated with the higher albedo of ice and snow than all other surface covering.
- This positive feedback has often been offered as one possible explanation for how the very different conditions of the ice ages could have been maintained.

(from *Earth's Climate: Past and Future*)

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# Cloud Feedback

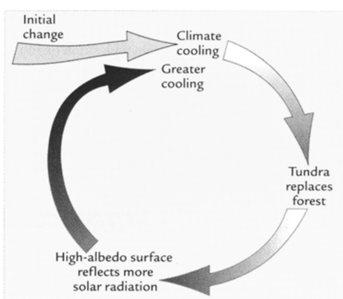
Cloud Radiative Forcing as Estimated from Satellite Measurements

| | Average | Cloud-free | Cloud forcing |
|---|---|---|---|
| OLR | 234 | 266 | +31 |
| Absorbed solar radiation | 239 | 288 | −48 |
| Net radiation | +5 | +22 | −17 |
| Albedo | 30% | 15% | +15% |

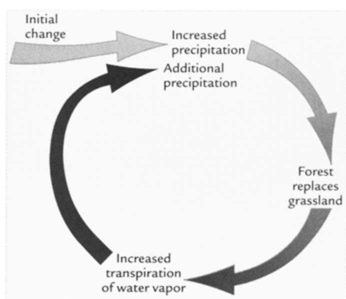
Radiative flux densities are given in W $m^{-2}$ and albedo in percent. [From Harrison *et al.* (1990), © American Geophysical Union.]

- Clouds affect both solar radiation and terrestrial (longwave) radiation.
- Typically, clouds increase albedo ➔ a cooling effect (negative feedback)
  clouds reduce outgoing longwave radiation ➔ a heating effect (positive feedback)
- The net effect of clouds on climate depends cloud types and their optical properties, the insolation, and the characteristics of the underlying surface.
- In general, high clouds tend to produce a heating (positive) feedback. Low clouds tend to produce a cooling (negative) feedback.
- Clouds double the albedo of Earth from 15% to 30% and reduce the longwave emission by about 30 W $m^{-2}$.
- The effect of clouds on the global net radiative energy flux into the planet is a reduction of about 20 W $m^{-2}$.

# Vegetation-Climate Feedbacks




A Vegetation–albedo feedback




B Vegetation–precipitation feedback

(from *Earth' Climate: Past and Future*)

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