Ch 6: Forcing, Feedbacks, and Climate Sensitivity

March ~~9 &~~ 11, 2026

6.3.2. Fast Feedbacks

Feedbacks = set of processes that do not act to initiate change, but act to either amplify or reduce initial change:

Start with initial warming (e.g., brightening Sun, decreasing albedo, GHG added to atmosphere).

Ice melts at 0 degrees C (273.15 K), so initial warming reduces ice on Earth (Fig. 2.6-2.7).

6.3. Climate Sensitivity (feedback)

6.3.2. Fast Feedbacks

Initial warming:

1) Ice melts exposing darker land/water surfa
2) Albedo decreases due to lower reflectivity
3) Energy-in increases due to higher absorption.
4) More warming (T increases) – back to (1).

Process amplifies over time becoming a self-sustaining, feedback loop (**Fig. 6.8**).

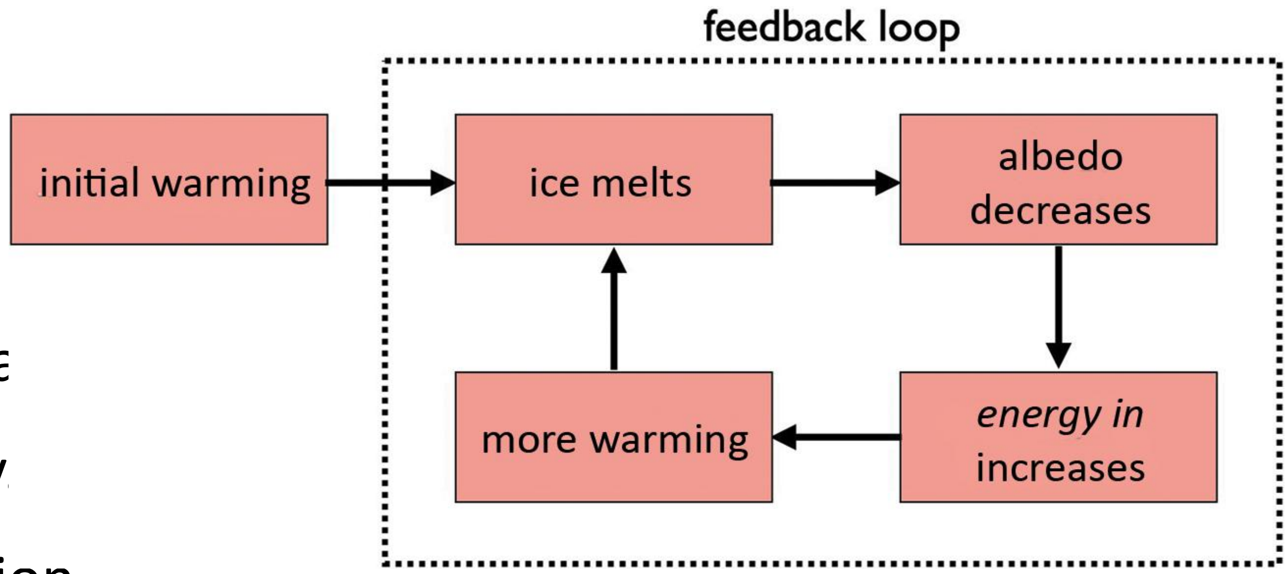

Fig. 6.8: Ice-albedo feedback loop.

Positive Feedback = feedback loop that acts to amplify initial change.

6.3.2. Fast Feedbacks

Initial warming:

1) Warming reduced grassland cover but increase bare ground).
2) Albedo increases due to the high reflectivity.
3) Energy-in increases due to higher albedo.
4) Less warming (T decreases) – back to (1).

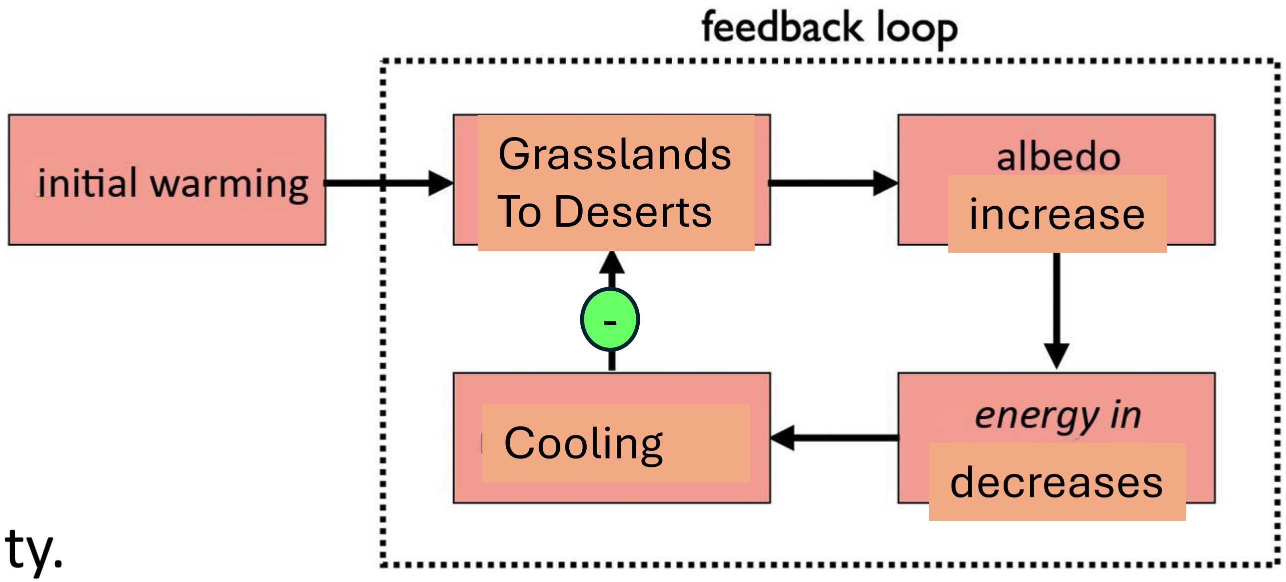

Fig. 6.8: Ice-albedo feedback loop.

Negative Feedback = feedback loop that acts to reduce initial change.
a.k.a. Lapse-Rate Feedback

6.3.2. Fast Feedbacks

Four important “fast” feedbacks in climate system:

1) **Ice-albedo Feedback** = positive feedback
2) **Water-vapor Feedback** = positive feedback
3) **Lapse-rate Feedback** = negative feedback
4) **Cloud Feedback** = net effect still under debate

6.3.3. Impact of the Fast Feedbacks

To quantify feedbacks, we can express feedback strength = g.

> *Additional fractional warming produced by one trip through feedback loop per degree of initial warming.*

In response to initial warming (ΔT_i), first trip through loop produces additional warming ($g \times \Delta T_i$),

but feedback also operates on this additional warming ($g \times \Delta T_i$), producing additional warming of $g \times (g \times \Delta T_i) = g^2 \times \Delta T_i$.

6.3.3. Impact of the Fast Feedbacks

Subsequent feedback operates on additional warming too, leading to g^3 x ΔTi.

Process continues forever, resulting in final warming (ΔTf) in Eqn. 6.2:

$$\Delta T_\mathrm{f} = \Delta T_\mathrm{i} + g\Delta T_\mathrm{i} + g^2\Delta T_\mathrm{i} + g^3\Delta T_\mathrm{i} + g^4\Delta T_\mathrm{i} + \ldots$$

Infinite series can be rewritten as summation into Eqn. 6.3:

$$\Delta T_\mathrm{f} = \sum_{k=0}^{\infty} g^k \Delta T_\mathrm{i}$$

6.3. Climate Sensitivity

Alternatively, **Eqn. 6.4**:

$$\Delta T_f = \frac{\Delta T_i}{(1-g)}$$

- If $g = 0$, then no feedback and $\Delta T_f = \Delta T_i$.
- If $0 < g < 1$, then $\Delta T_f > \Delta T_i$ = positive feedback.
- If $g < 0$, then $\Delta T_f < \Delta T_i$ = negative feedback.
- Strong positive feedbacks generate “runaway greenhouse effect,” where ΔT_i leads to very large ΔT_f.
- With multiple feedbacks g is sum of individual fast feedbacks.

6.3. Climate Sensitivity

Eqn. 6.5: $$g = g_{\mathrm{ia}} + g_{\mathrm{wv}} + g_{\mathrm{cloud}} + g_{\mathrm{lr}}$$

Where:

- g_{ia} = *ice-albedo feedback =* *+0.15.*
- g_{wv} = *water-vapor feedback = +0.6 (enough to double* ΔT_i*).*
- g_{cloud} = *cloud feedbacks = 0.0 to +0.25.*
- g_{lr} = *lapse-rate feedback = -0.25.*

Summing values gives, g = +0.5 to +0.75.

6.3. Climate Sensitivity

Plugging g into **Eqn. 6.4** gives $\Delta T_f = (2 \text{ to } 4) \times \Delta T_i$.

Thus, 50-75 % of warming we experience comes from feedbacks rather than GHG directly!

Climate sensitivity calculation for Earth without atmosphere:

1.0 K per CO_2 doubling.

Simulations for Earth with atmosphere suggest 1.2 K per CO_2 doubling without feedbacks.

6.3. Climate Sensitivity

Using ΔT_i = 1.2 K in **Eqn. 6.4** gives ΔT_f = 2.4 to 4.8 K.

Simulations with atmosphere and feedbacks conclude climate sensitivity likely 2.5 to 4.0 K, with best estimate = 3.0 K.

Given CO_2 doubling RF = +4 W/m^2, can express sensitivity as warming per unit of RF = 0.63 to 1.0 K per (W/m^2), with best estimate = (0.75 K) / (W/m^2).

6.4. Slow Feedbacks

Slow Feedbacks = respond slowly to initial change and require long periods to alter either E_{in} or E_{out}.

Greenland/Antarctic ice sheets require millennia to completely respond to ΔT:

- Ice-albedo in terms of entire ice sheets = “slow”
- Permafrost thaw could release C from dead organic matter to atmosphere as CO_2 and CH_4
- Changes in vegetation can affect climate
- Chemical weathering thermostat

6.4. Slow Feedbacks

In general, slow feedbacks less certain than fast feedbacks because simply not enough data to observe, understand, and quantify them.

Evidence suggests slow feedbacks will be net positive over coming millennia.

Many worst-case scenarios involve net positive slow feedbacks and their long-term warming.

Summary of this chapter

- We focus on Forcing & Feedbacks
- Two major warming species (GHG and aerosols)
  how do they affect climate!
  Spatial dependent
- Calculations of RF and temperature changes
- 4 Major fast feedbacks (how they work)
- Uncertainty for slow feedbacks

Chapter 7: Why Is The Climate Changing?

March 16 & 18, 2026

7.1. Context of the Recent Warming

Quiz 3 on March 16

7.2. The First Suspect: Plate Tectonics

7.3. The Sun

7.4. The Earth’s Orbit

7.5. Unforced Variability

7.6. Greenhouse Gases

7.7. Putting It Together

Terms

Problems