GE510 properties of complex systems: stability, instability, metastability, and feedback

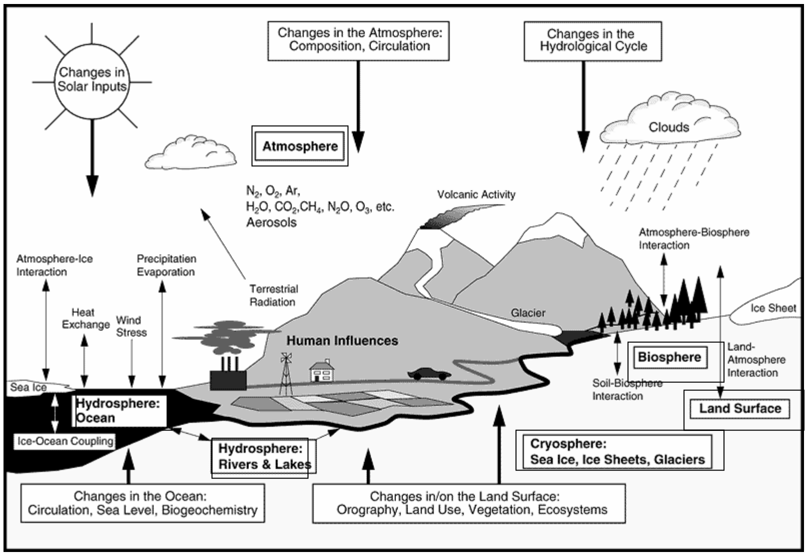
•The earth system
•General properties of systems relevent to this course
•Stability, instability, metastability in relation to the earth system

Etymology and definition

Greek:
'Sys' – together
'histanai' – to cause to stand

"a set of objects together with relationships between objects and their attributes"
"a set of interdependent elements forming a collective entity"

IPCC: Five interacting sub-systems of the climate system



Evidence of balanced stoichiometry between elements exchanged amonth atmosphere, biosphere, hydrosphere, and geosphere

General properties of systems

- Open vs. closed systems
- Boundaries of systems
- Emergent properties
- State variables
- feedback

Open vs. closed systems

- Two major types of systems:

Closed systems do not exchange mass, energy, and/or information with surroundings

Open systems exchange mass, energy, and/or information with surroundings

Mass	Energy	Example
Closed	Closed	Chem rxn in insulated flask
Closed	Open	Earth, ecosystem in a bottle
Open	Closed	Frictionless pipe
Open	Open	Animals, ecosystems

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Boundaries of systems

- Arbitrary, depends on focus of investigator, may be physical or virtual
- Environmental systems are often *nested* or *hierarchical* (e.g. organs in organisms in ecosystems in biomes in earth)

General properties of systems

- Open vs. closed systems
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Emergent properties

- A system may be ‘more than the sum of its parts’
- Whole system behavior can’t be inferred from properties of constituent elements

(e.g. snowflakes from h2o, group behavior)

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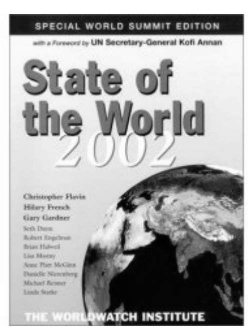

“system” implies equations or variables of state

e.g., state variables of the carbon cycle system

1. **Gross Primary Production (GPP): Total amount of Carbon fixed in photosynthesis (‘gross salary’)**
2. **Net Primary Production (NPP) : GPP - plant respiration (also ANPP = above ground NPP) (‘gross salary – state taxes’)**
3. **Net Ecosystem Production (NEP) – also Net Ecosystem Exchange (NEE): NPP – animal respiration (‘gross salary – state – fed taxes’)**
4. **Net Biome Production (NBP): NEP – fires, disease, harvest, other disturbances (‘Net salary – stock market losses’)**

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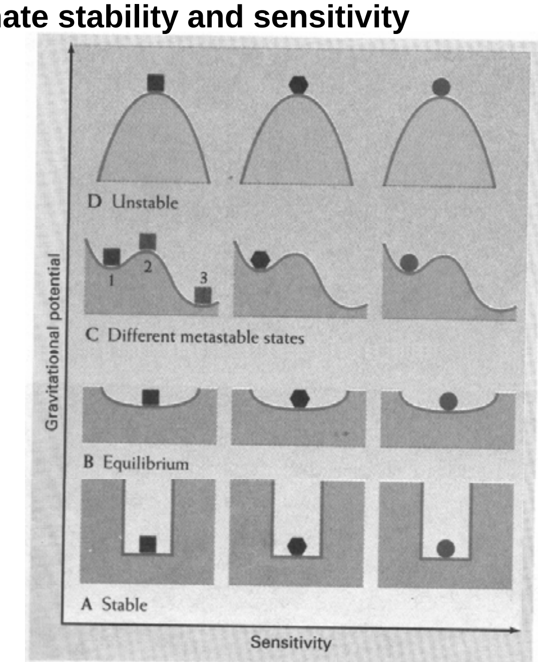
Feedback

- Output from a system influences future inputs
- Positive feedback: promotes system instability (examples)
- Negative feedback: promotes system stability (examples)
- Feedback is central to ideas of stability, instability, and metastability

General concepts of climate stability and sensitivity

Degrees of stability and the concept of sensitivity

What about our planet?



Lovelock and Gaia: Negative feedback and earth system stability

- Lovelock proposed an earth system that evolves negative feedback to stabilize climate favorable to continued life.
- Took a systems viewpoint, looking for state variables and system behavior for life on other planets, rather than searching for specific elements of life as we know it (e.g. organic molecules)

Three major lines of evidence for earth homeostasis

- Historical global temperature stability in spite of variable solar output
- Atmospheric oxygen level maintained at extreme disequilibrium
- Earth's atmosphere is much different from 'dead' mars or venus

Global temperature stability

In the beginning 21

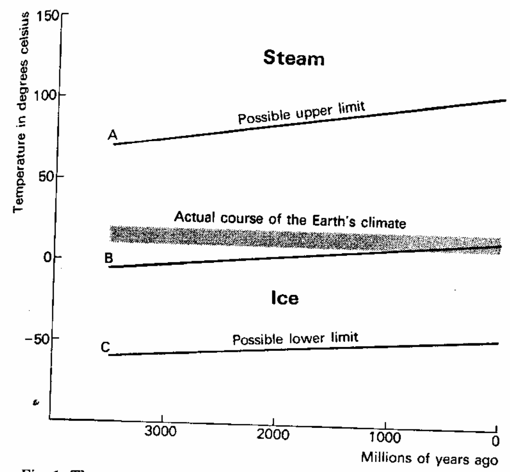


Fig. 1. The course of the Earth's average temperature since the beginning of life 3.5 aeons ago is all within the narrow bounds of the horizontal lines between 10° and 20°C. If our planetary temperature depended only on the abiological constraints set by the sun's output and the heat balance of the Earth's atmosphere and surface, then the conditions of either the upper or lower extremes, marked by the lines A and C, could have been reached. Had this happened, or even if a middle course were followed, line B, which passively goes with the sun's heat output, all life would have been eliminated.

Oxygen content poised at 21%

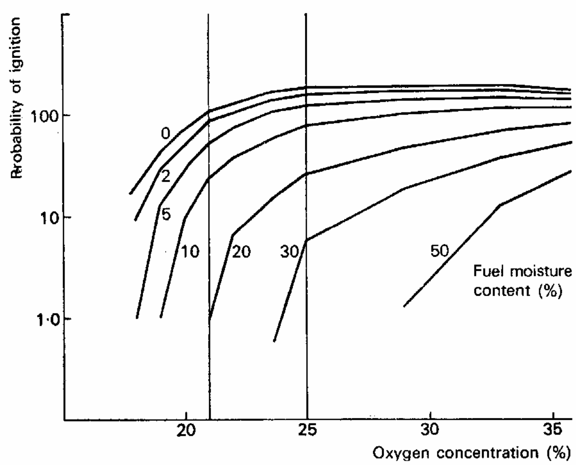


Fig. 5. The probability of grass or forest fires in atmospheres of different oxygen enrichment. Natural fires are started by lightning strokes or by spontaneous combustion; their probability is greatly dependent upon the moisture content of the natural fossil fuels. Each line corresponds to a different moisture level going from completely dry (0%) to visibly wet (45%). At the present oxygen content (21%) fires do not start at more than 15% moisture content. At 25% oxygen even the damp twigs and grass of a rain forest would ignite.

Living earth vs. dead(?) mars/venus

Table 2

Gas	Planet			
	Venus	Earth without life	Mars	Earth as it is
Carbon dioxide	98%	98%	95%	0.03%
Nitrogen	1.9%	1.9	2.7%	79%
Oxygen	trace	trace	0.13%	21%
Argon	0.1%	0.1%	2%	1%
Surface temperatures °C	477	290±50	−53	13
Total pressure bars	90	60	0064	1.0

Daisyworld

- Background and setting
- Planetary temperature regulation

Daisyworld – temperature regulation

6
Gaia: An Overview

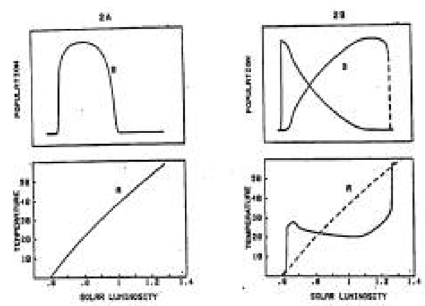


Figure 1.2 Models of the evolution of Daisyworld according to conventional wisdom (A) and to geophysiology (B). The upper panels illustrate daisy populations in arbitrary units; the lower panels, temperatures in degrees Celsius. Going from left to right along the horizontal axis, the star's luminosity increases from 60% to 140% of that of our own Sun. *A* illustrates how the physicists and the biologists in complete isolation calculate their view of the evolution of the planet. According to this conventional wisdom, the daisies can only respond or adapt to changes in temperature. When it becomes too hot for comfort, they will die. But in the Gaian Daisyworld (*B*), the ecosystem can respond by the competitive growth of the dark and light daisies and regulates the temperature over a wide range of solar luminosity. The dashed line in the lower panel in *B* shows how the temperature would rise on a lifeless Daisyworld.

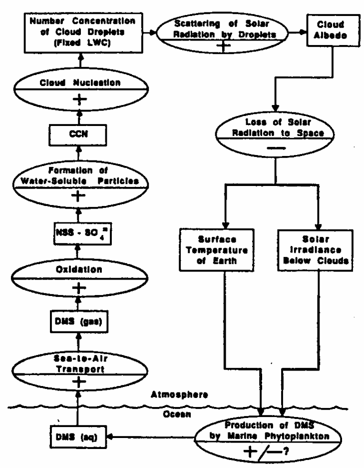


Figure 17.5 Hypothetical feedback loop. The rectangles are measurable quantities and the ovals are processes linking the boxes. The sign (+/−) in the oval indicates the effect of a positive change of the quantity in the preceding box on that in the succeeding one. The most uncertain link is the effect of cloud albedo on DMS emission; its sign would have to be positive in order to provide a degree of thermostasis. Of course, the +/− could be zero as well.

Nytimes & james lovelock

- Q. What's your perception of where we're headed with even conservative predictions for growth of both populations and energy use?
- A. I think we're headed straight back to the Earth's *second stable state*, which is a hot state that it's been in many times before in the past. It's about 14 degrees warmer than it is in these parts of the world now.

Multiple equilibria: IPCC WGI 7.7

There is no clear definition of "rapid climate change". In general, this notion is used to describe climate changes that are of significant magnitude (relative to the natural variability) and occur as a shift in the mean or variability from one level to another. In order to distinguish such changes from "extreme events", a certain persistence of the change is required. Among the classical cases are spontaneous transitions from one preferred mode to another or transitions triggered by slowly varying forcing. This occurs in non-linear systems which have multiple equilibria (Lorenz, 1993). Evidence for the possibility of such transitions can be found in palaeoclimatic records (see Chapter 2, Section 2.4; and Stocker, 2000), in observations of changes in large-scale circulation patterns from the instrumental record (see Section 7.6.5.1), and contemporary observations of regional weather patterns (e.g., Corti *et al.*, 1999).

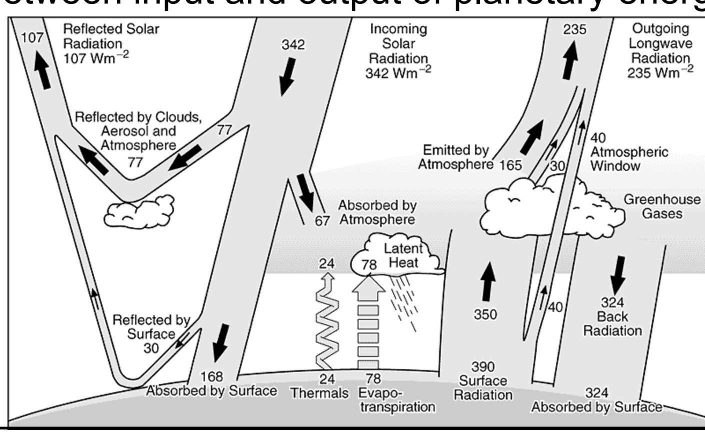
A simple (simplistic, really) model of the global climate illustrates the possibility of metastable climate states (ice age vs. 'warm')

-**No atmosphere**

-**Surface can be bare (soil), liquid water, or ice, depending on temperature**

Simplified planetary energy balance shows possibility of multiple metastable states

- Planetary energy budget equals the difference between input and output of planetary energy



Simplified planetary energy balance

$C\, dT/dt = Q(1-\alpha(T)) - \varepsilon\sigma T^4$

C = heat capacity of Earth's surface (J/K m^2)
T = planetary surface temperature (K)
t = time
Q = Solar energy impinging on earth's surface (W/m^2)
α = planetary albedo (linear decrease with T increase, until all ice covered or all melted, then flat)
σ = Stefan-Boltzmann constant (W/m^2K^4)
ε = emissivity (unitless – ratio of radiation emitted by a real object to that emitted by an ideal blackbody)

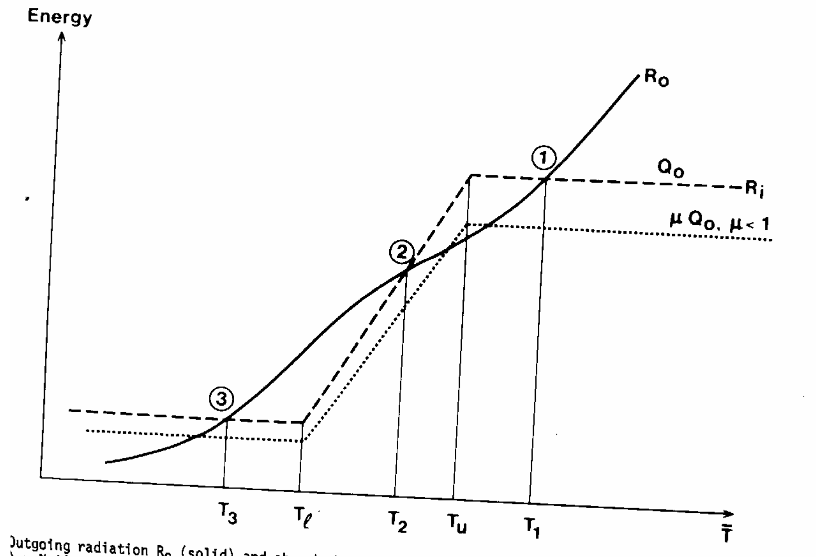
Let's say the planet is in energy balance

$C\, dT/dt = 0 = Q(1-\alpha(T)) - \varepsilon\sigma T^4$

i.e. there is no change in T with t
Thus,

$Q(1-\alpha(T)) = \varepsilon\sigma T^4$

This is not an easy equation to solve!



T1 ~ 25 °C, T2 ~ 7°C, T3 ~ -100°C

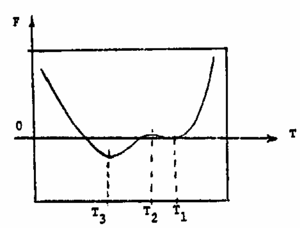


Fig. 10.7. The pseudo-potential F(T) for an EBM with three e
libria (courtesy of C. Nicolis).

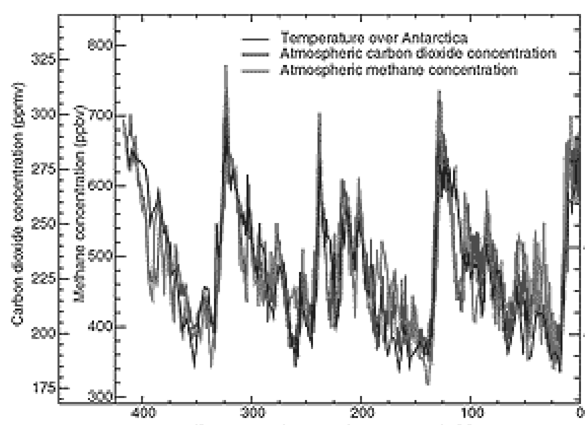
2. Evidence and Causes of Rapid Climate Change

Climate has certainly changed abruptly over the last million years.

Much of this variation can be explained by orbital geometry.

Much can't (see high frequencies)

Greenhouse gas changes in parallel, but hard to resolve which is leading and which lagging



The younger dryas constitute one of our best resolved examples of extremely rapid climate change

7°C cooling in perhaps 50 years!

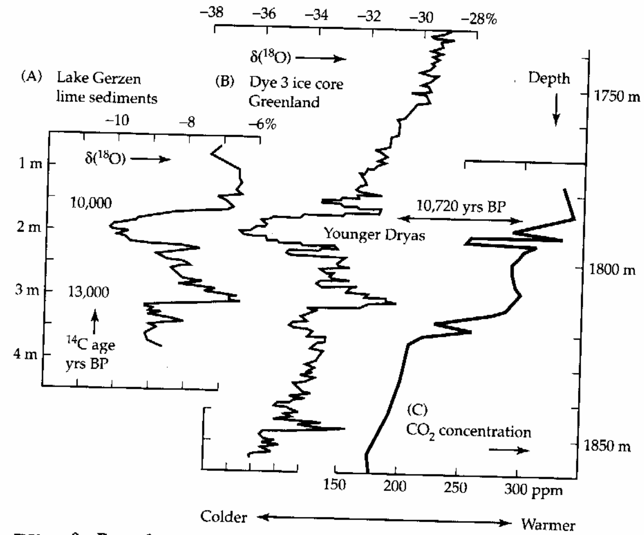
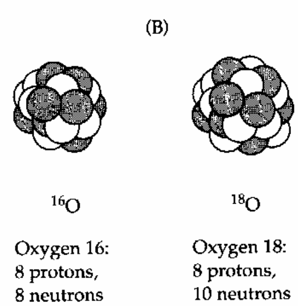
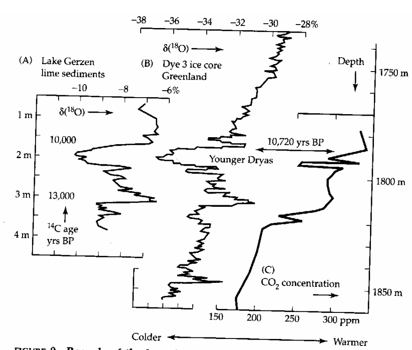


FIGURE 9 **Records of the late glacial transition and the Younger Dryas cold event. (A) $\delta^{18}O$ measurements from Lake Gerzen, Switzerland. (B) $\delta^{18}O$ along a 120-meter core from Dye 3, Greenland. (C) Atmospheric CO_2 concentration from gas trapped in polar ice. (After Dansgaard et al., 1989.)**

An aside: how are oxygen isotopes a paleothermometer?

The lighter isotope (^{16}O) evaporates increasingly more readily then ^{18}O as temperature increases. The water left behind is relatively more enriched with 18O at higher temperatures, and Tiny marine organisms incorporate this into their skeletons.





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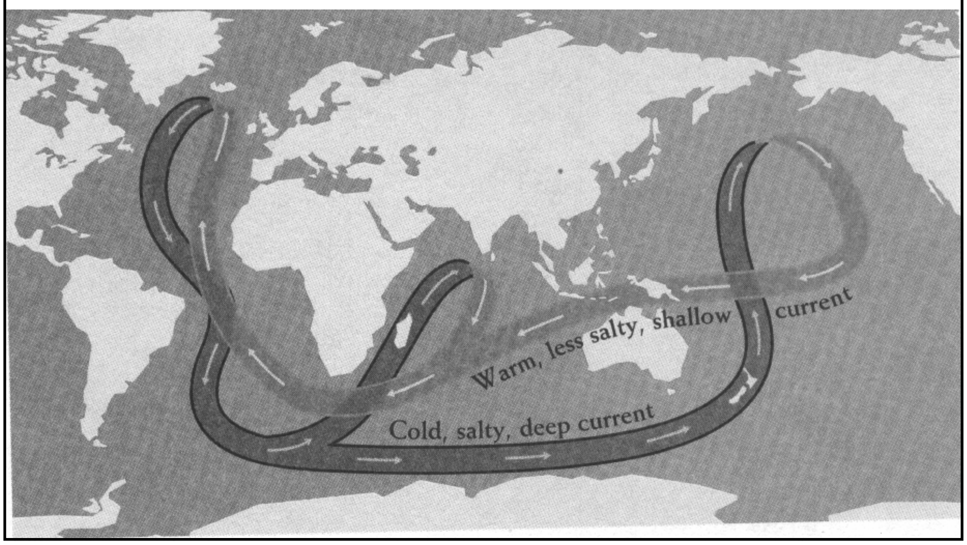
Younger dryas was likely caused by a weakening or collapse of the thermohaline circulation – basis of "Day After Tomorrow"



How can humans cause a collapse of the thermohaline circ?

1. Global warming leads to increased arctic/polar melting
2. This freshens seawater
3. Fresh seawater is more bouyant than salty water
4. Disrupts the sinking loop in the N. Atlantic
5. Shifts loop to the far south
6. N. America and Europe cools drastically – as in Younger Dryas.

This rapid alteration of the ocean circulation illustrates a more fundamental property of the climate system:

The possibility of multiple, distinct, metastable climate states

Kind of like quantum mechanics.