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


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

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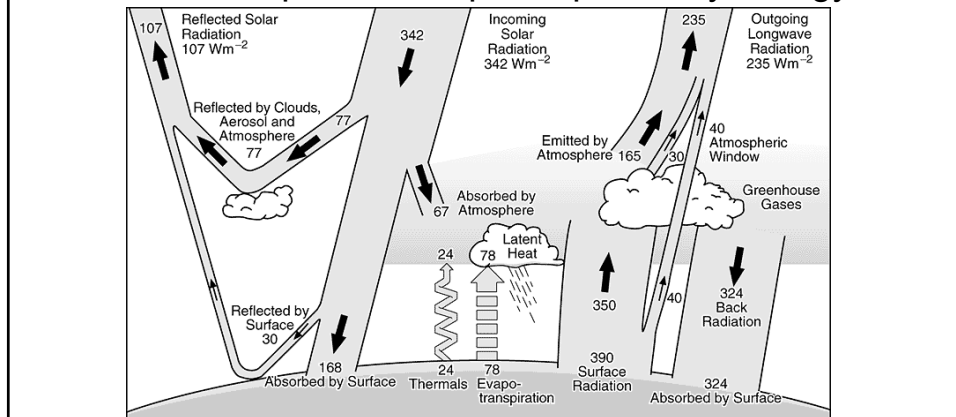
Simplified planetary energy balance

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

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^{2}K^4)

ε = emissivity (unitless – ratio of radiation emitted by a real object to that emitted by an ideal blackbody)

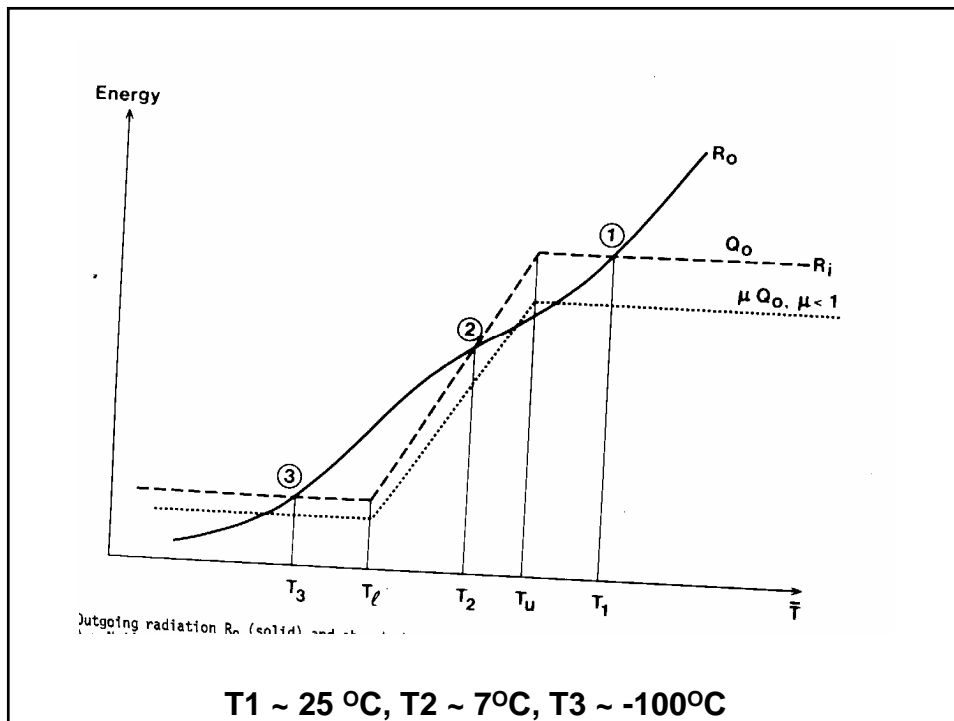## Let's say the planet is in energy balance

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

i.e. there is no change in T with t
Thus,
$Q(1-\alpha(T)) = \varepsilon\sigma T^4$
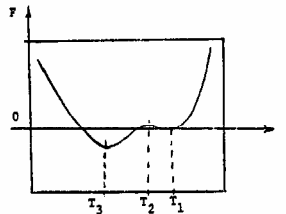
This is not an easy equation to solve!

T1 ~ 25 ºC, T2 ~ 7ºC, T3 ~ -100ºC

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

Chaos in the climate system:

Lorenz 1963 "Deterministic Nonperiodic Flow", J. Atmos. Science.

A.K.A. the "butterfly effect"

Other examples: taffy mixers, leaky faucets, wallets on ski slopes, toys, pendulums.
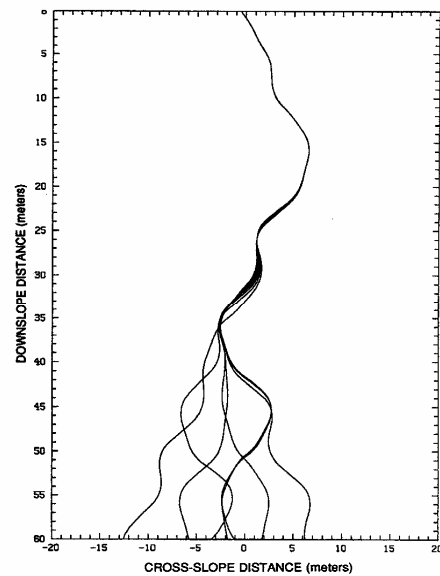
Figure 2.2 The paths of seven wallets, starting with identical velocities from points spaced at intervals of 1 mm along a west-east line. From Lorenz (1993).

Figure 2.1 Moguls on a ski slope. A skier is barely discernible in the upper part of the figure. From Lorenz (1993).

Chaos can be generated from Mathematically EXACT (deterministic) and very simple processes.

It is the inexact initial conditions that creates chaotic behavior in mathematically deterministic processes.

Laplace's Demon: "if we knew the position and movement of all particles in the universe at some point in time, that would give us all the information needed to predict the future with total certainty"   Chaos says 'not so'.

One further example of chaos generated very simply:

Robert May 1976. "Simple math models with very complicated dynamics" Nature 261:459

•**Population fluctuations, but concept applies to climate as well.**

•$X_{i+1} = aX_i - aX_i^2$

Where X_i = population size at time i
    a = some species specific constant (intrinsic fertility rate)

Note squared term indicates non-linearity – an essential ingredient of chaos. What are examples of non-linear processes in the climate?

The negative squared term represents resource scarcity.

Sigmaplot code I wrote last night… try it in excel!
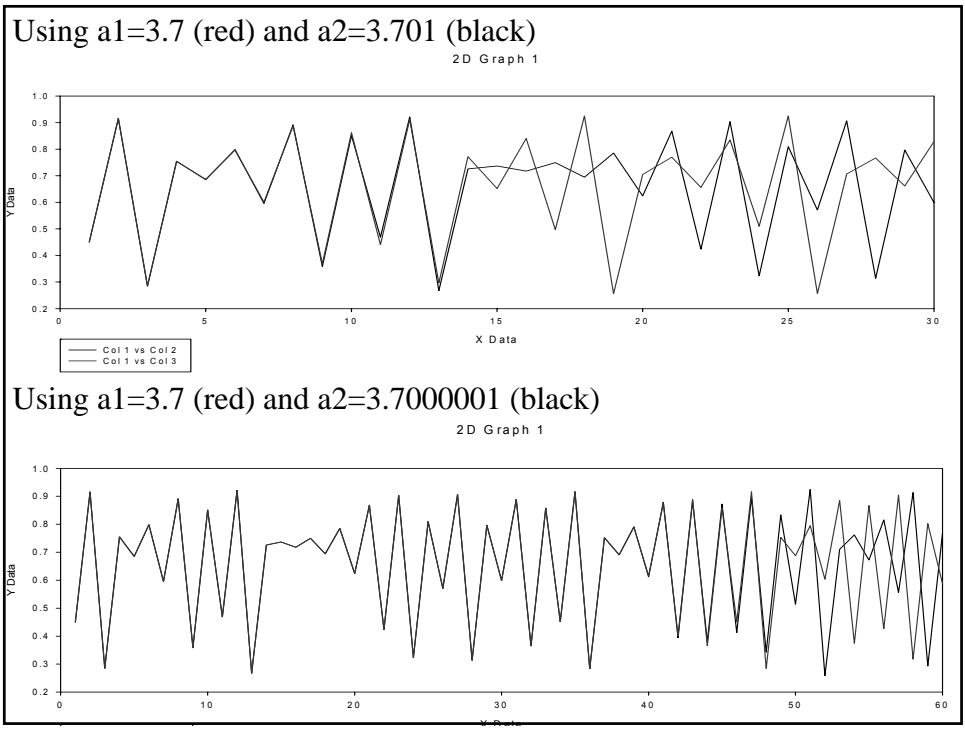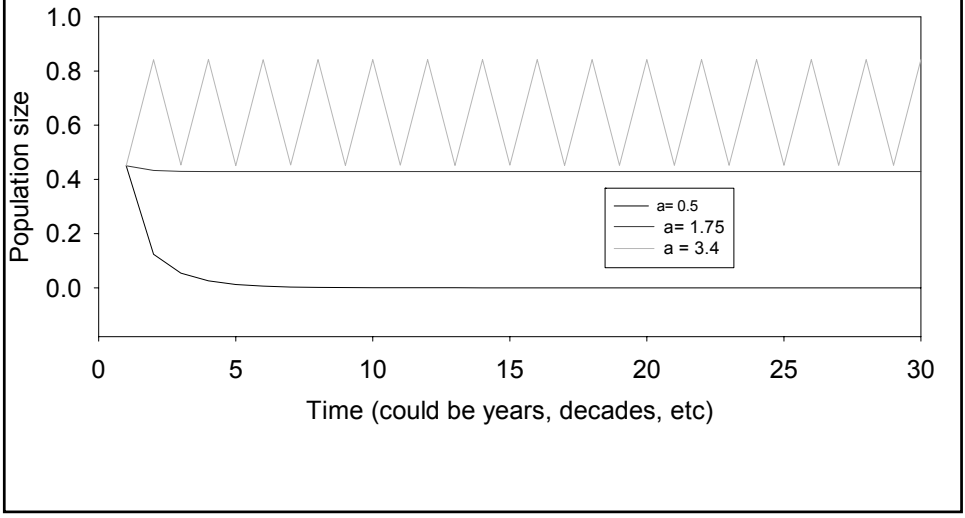
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a1=0.5

a2=1.75

a3=3.4

for x = 1 to 150 do

col(2,x+1)=a1*col(2,x)*(1-col(2,x))

col(3,x+1)=a2*col(3,x)*(1-col(3,x))

col(4,x+1)=a3*col(4,x)*(1-col(4,x))

end for
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Natural systems (including climate) are not always chaotic and can be predictable (albeit boring)

Using a1=3.7 (red) and a2=3.701 (black)

Using a1=3.7 (red) and a2=3.7000001 (black)

Why is Chaos in the climate system important?

•It means that there is not only a practical limit to predictability of climate, but some level of *inherent, fundamental* unpredictability.

•Climate models may never be able to predict actual temporal trajectories of climate variability, no matter how powerful our supercomputers become.
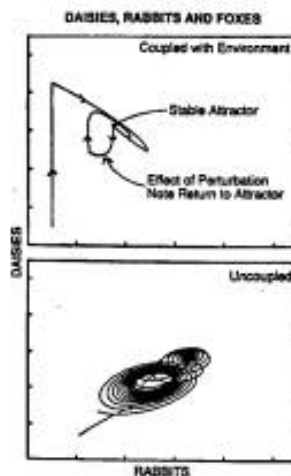
•Extreme events, short range weather forecasts

Figure 1.5 Comparison of the stability of a Daisyworld that included rabbits to eat the daisies and foxes to cull the rabbits (upper panel) with the instability of a population biology model of daisies, rabbits, and foxes (lower panel). The model in the upper diagram included environmental feedback; that in the lower diagram did not.

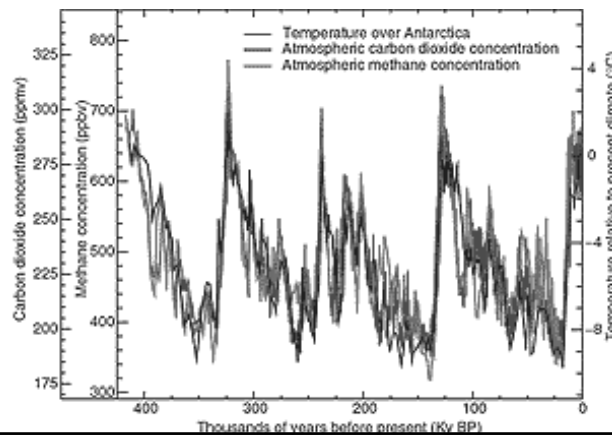## 2. Evidence and Causes of Rapid Climate Change

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!

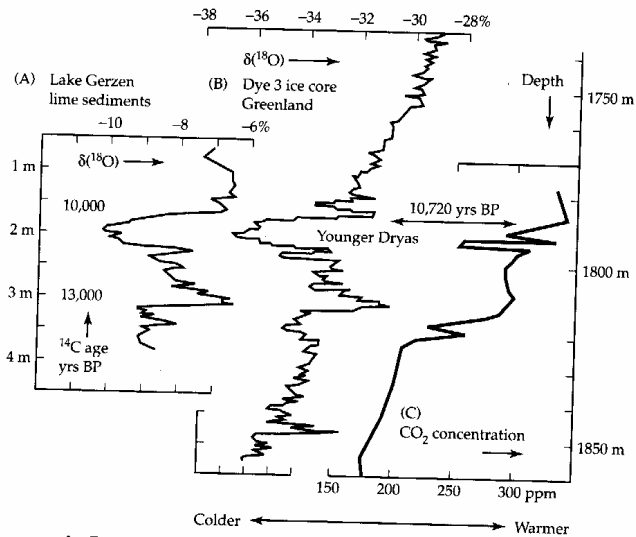
FIGURE 9 Records of the late glacial transition and the Younger Dryas cold event. (A) $\delta^{18}O$ measurements from Lake Gerzen, Switzerland. (B) $\delta^{18}O$ along a 120-meter core from Dye 3, Greenland. (C) Atmospheric CO_2 concentration from gas trapped in polar ice. (After Dansgaard et al.,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

(B)

^{16}O ^{18}O

Oxygen 16:   Oxygen 18:
8 protons,   8 protons,
8 neutrons   10 neutrons

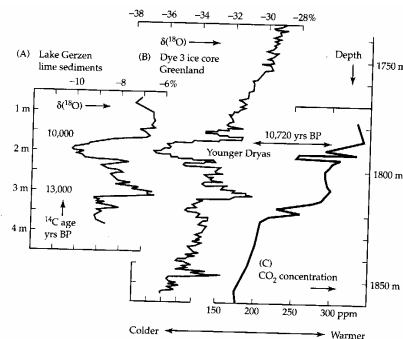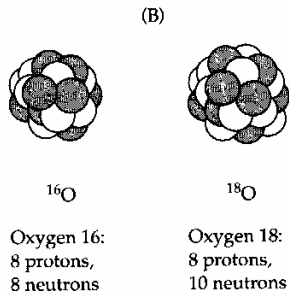
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Younger dryas was likely caused by a weakening or collapse of the thermohaline circulation – basis of "Day After Tomorrow"
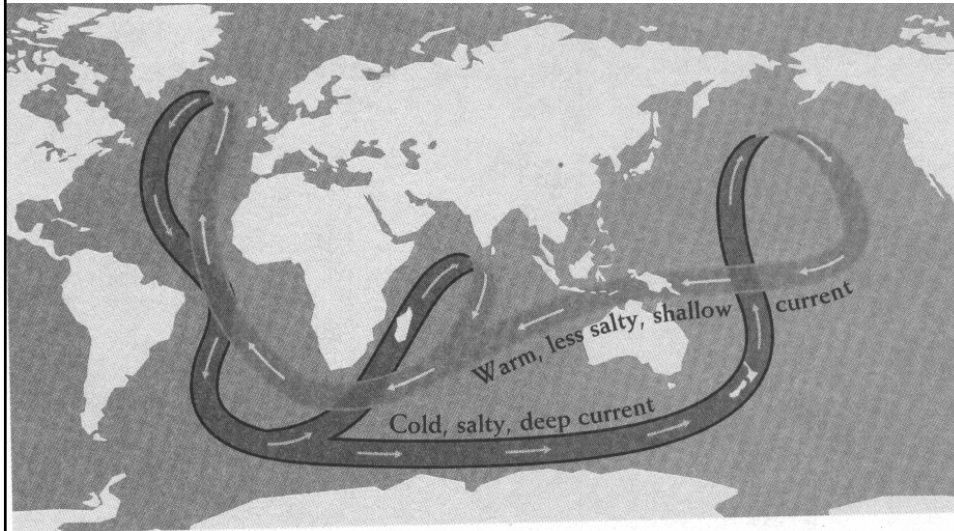
How can humans cause a collapse of the thermohaline circ?

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.