Earthlike Planets

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The earth (and other terrestrial planets) formed with no atmosphere

The current atmospheres were either

- bound chemically into solids or
- bound as radioactive isotopes, e.g. $^{40}K \rightarrow {}^{40}Ar$ or

  $^{238}U \rightarrow {}^{234}Th + {}^{4}He$
- resulted from late accretion events

The gases now found on the terrestrial planets either

- were baked out of minerals by the interior heat of the planet (volcanoes), or
- were delivered by impacts of late arriving volatile rich planetesimals, I.e., comets

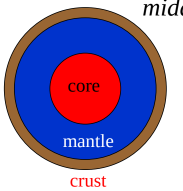
But volcanoes and impacts spew out mostly CO_2 and H_2O plus traces of N_2 & ^{40}Ar

So the atmosphere must evolve

- Earth formed out of volatile poor planetesimals
- Late infall of volatile rich planetesimals scattered in from the outer solar system
- At some point the inner earth melts
  - ❑Energy from impacts
  - ❑Energy from radioactivity

❑It then *differentiates*

Dense easily melted stuff (Fe, Ni, etc) sinks to the middle.

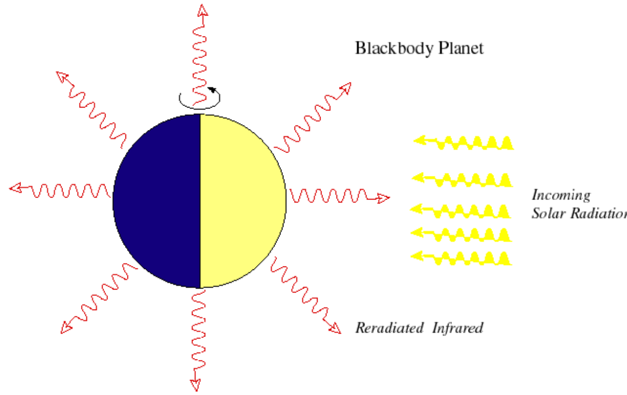


Escaping heat drives circulation which continues after the mantle and crust solidify.

Blackbody planets

A first approximation to temperature of a planet is to consider it to be a perfect black body.

A perfect black body absorbs all radiation falling on it. In addition to being a perfect absorber a black body is the most efficient possible emitter of radiation.



The amount of energy radiated by a blackbody increases as (radiation per unit area increases as T^4)

So if a planet is exposed to the energy of a star heats up until

energy output via IR = energy input from sunlight

But planets with clouds are not very good blackbody absorbers.

Astronomers call the fraction of the incoming sunlight which is reflected the *albedo*

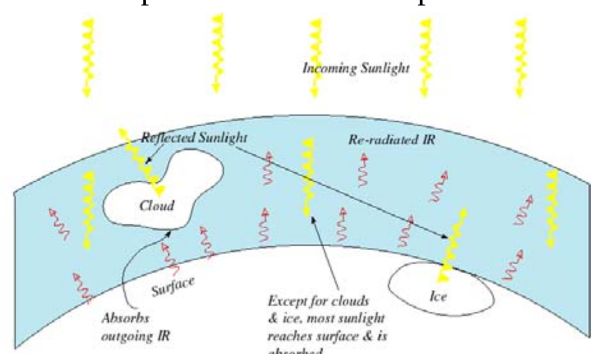
So energy input to a planet with "clouds" is:

(1 – albedo) × amount of sunlight striking the planet

First Guess at Temperatures of Terrestrial Planets

Planet	Distance from Sun	albedo	$T_{\text{blackbody}}$	T_{CloudyBB}
Mercury	0.39AU	0.06	450K	440K
Venus	0.72	0.76	330	230
Earth	1.00	0.3	280	250
Earth *all clouds*	1.00	0.76	280	240
Mars	1.52	0.16	230	220

A planet with an atmosphere



With an atmosphere, a planet may have clouds and/or ice.

Clouds and ice have very high albedo; rocks, dirt, and oceans have a rather low albedo

Except for fraction that hits the clouds and ice, most incoming sunlight reaches the surface and is absorbed.

The surface heats up an reradiates the incoming energy as IR

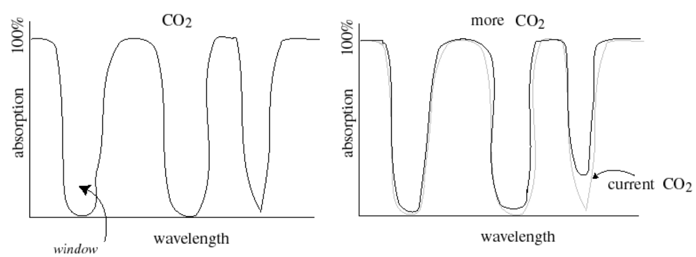
However the atmosphere is not transparent to the escaping IR; it is absorbed mostly by the CO_2 and H_2O vapor. The escaping IR has to diffuse through the atmosphere which thus acts as a blanket.

This situation where the incoming energy flows freely inward but the energy trying to escape is trapped is called the *Greenhouse Effect.*

Note that clouds also contribute to trapping the IR, thus they both cool by increasing the albedo and warm by trapping IR.

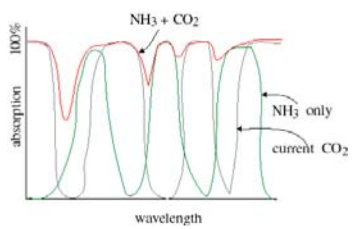
Current Terrestrial Greenhouse

Greenhouse agent	% of atmosphere	Contribution to Greenhouse
H_2O water	1—4%	36—70%
CO_2 carbon dioxide	0.04%	9—26%
CH_4 methane	0.0002%	4—9%
O_3 ozone		3—7%

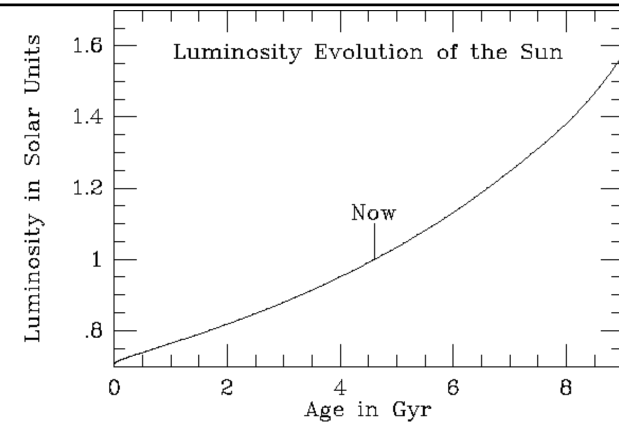


There must have been a better greenhouse

There are two ways to build a better greenhouse

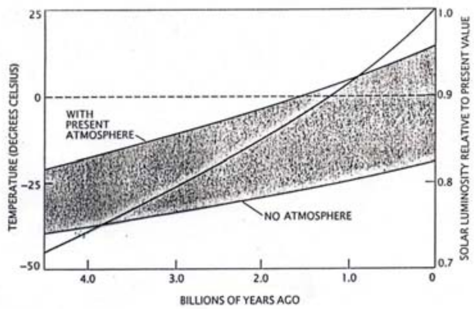


- More of current greenhouse components---basically more CO_2
- Adding different greenhouse components, e.g. NH_3 or CH_4



In the 4.6 Gyr since the Sun formed its luminosity has increased by 25%. This has important consequences for the Earth.

The Faint Young Sun Problem



Because young sun was 25-30% fainter than now, the early atmosphere must have had compensating changes.

Absorption by CO_2 is nearly saturated: CO_2 absorbs some wavelengths of IR very well and others hardly at all. Where it absorbs well it already absorbs all the radiation. There are wavelength ranges, windows, where the atmosphere is still fairly transparent.

Adding more CO_2 doesn't change the situation at wavelengths where everything is already blocked. It mostly affects things at the boundaries of the windows.

To compensate for the faint young Sun requires a huge amount of CO_2.

On the other hand some compounds, particularly NH_3 and CH_4, have IR absorption characteristics that complement those of CO_2.

Even small amounts can effectively plug the windows and compensate for the faint young Sun.

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THE GOLDILOCKS PROBLEM: Climatic Evolution and Long-Term Habitability of Terrestrial Planets

Michael R. Rampino

Department of Earth System Science, New York University, New York, New York 10003

Ken Caldeira

Global Climate Research Division, Lawrence Livermore National Laboratory, Livermore, California 94551

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INTRODUCTION

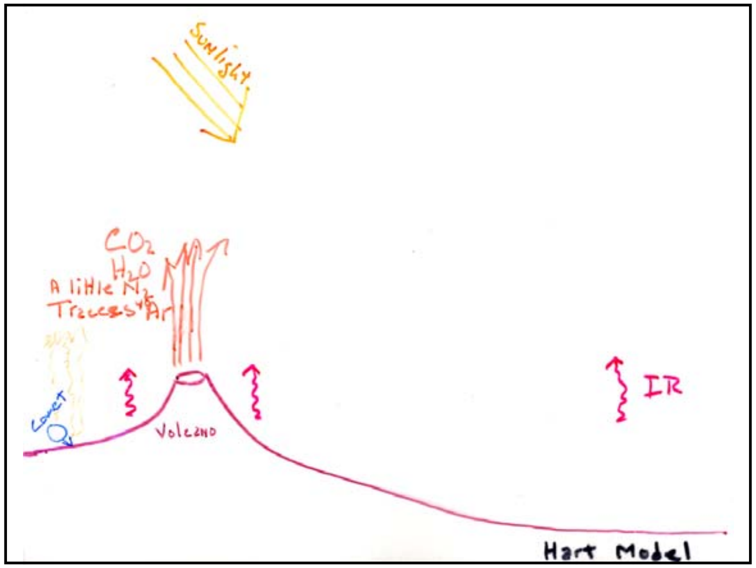
Why is Venus too hot, Mars too cold, and Earth "just right" for life? (The allusion to the fairy tale involves the three bowls of porridge belonging to Papa Bear, Mama Bear, and Baby Bear—one too hot, one too cold, and one just right—tested by a hungry Goldilocks.) A simplistic answer might be that a planet's surface temperature is to a large extent a function of its distance from the Sun, and Earth just happens to be at the "right" distance for comfortable temperatures and liquid water. However, this is far from the whole story.

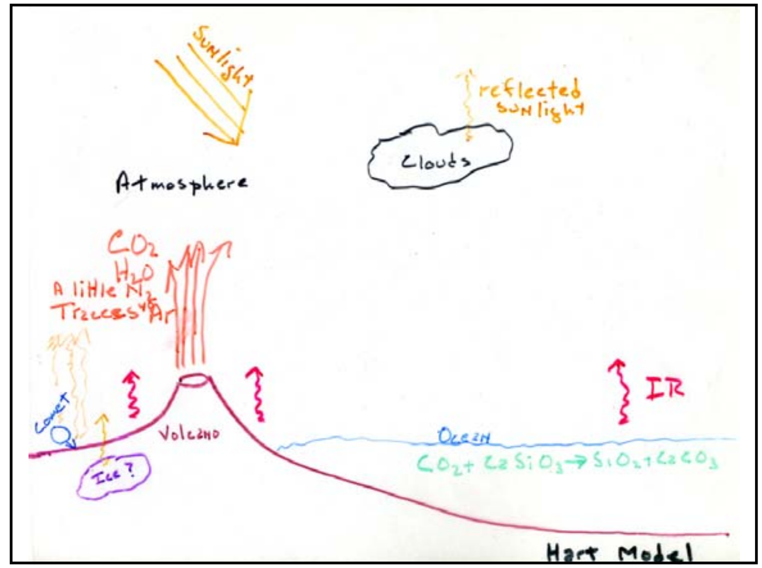
The Goldilocks Problem involves the early history of the planets and the evolution of their atmospheres. Its solution must also take into consideration the long-term evolution of the Sun, and hence the so-called faint young Sun problem, that is, the fact that the early Earth was apparently warm enough for liquid water despite the 25–30% lower luminosity of the early Sun (Newman & Rood 1977; Gough 1981). Had Earth been too cold initially for liquid water

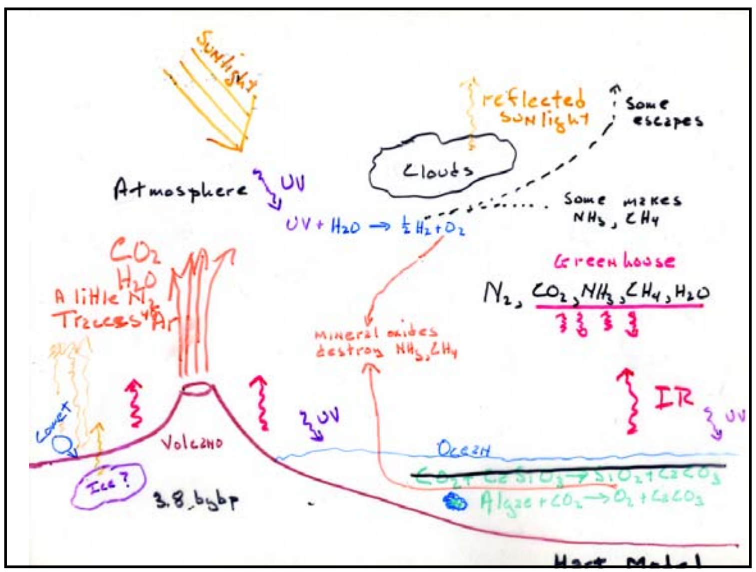
The Hart Model

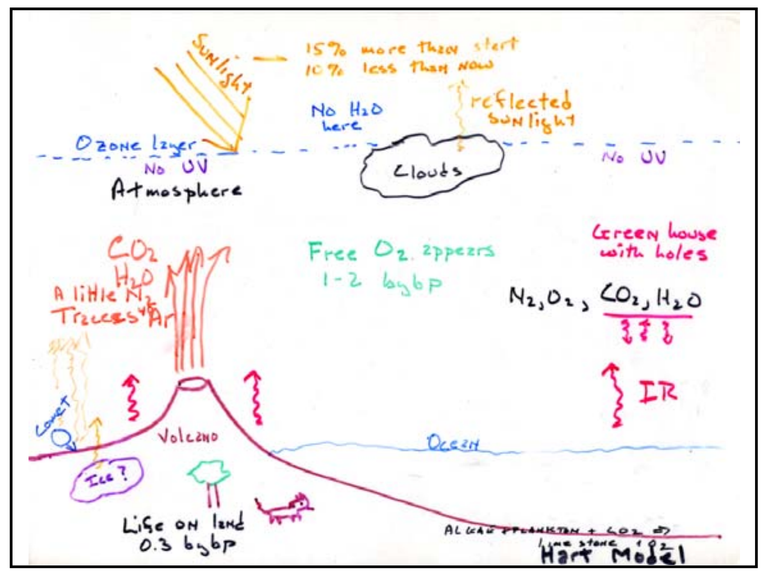
The first detailed attempt to model the evolution of the Earth's climate and atmosphere was done by Michael Hart in 1978

At that time it was thought that the atmosphere was highly (chemically) reducing. While that is now not thought to be so, the Hart model introduces several important ideas so we begin with it.


Sunlight
CO2
H2O
A little N2
Traces Ar
Comet
Volcano
IR
Hart Model


Sunlight
reflected sunlight
Clouds
Atmosphere
CO2
H2O
A little N2
Traces Ar
Comet
Ice?
Volcano
IR
Ocean
CO2 + CaSiO3 → SiO2 + CaCO3
Hart Model


Sunlight
reflected sunlight
Some escapes
Clouds
Atmosphere
UV
UV + H2O → ½ H2 + O2
Some makes NH3, CH4
Greenhouse
N2, CO2, NH3, CH4, H2O
CO2
H2O
A little N2
Traces Ar
Mineral oxides destroy NH3, CH4
Comet
Ice?
Volcano
3.8 bybp
UV
IR
UV
Ocean
CO2 + CaSiO3 → SiO2 + CaCO3
Algae + CO2 → O2 + CaCO3
Hart Model


Sunlight
15% more than start
10% less than now
No H2O here
reflected sunlight
Ozone layer
No UV
Atmosphere
Clouds
No UV
CO2
H2O
A little N2
Traces Ar
Free O2 appears
1-2 bybp
Green house with holes
N2, O2, CO2, H2O
IR
Comet
Ice?
Volcano
Ocean
Life on land
0.3 bybp
Hart Model

Hart found that his models contained *Positive feedback loops* which made them unstable. These instabilities could lead to climatic catastrophes.

1. More solar input (e.g. closer to sun)
2. ⇒ Higher T
3. ⇒ CO_2 absorption not as efficient
4. ⇒ CO_2 builds up
5. ⇒ Better greenhouse
6. ⇒ go to 2

Once liquid H_2O is gone all CO_2 stays in atmosphere.

This is called a *Runaway greenhouse*

Hart found a runaway greenhouse if earth 5% closer to sun

A variant of this happened on Venus

•The Venereal atmosphere is mostly CO_2 (~ 100 times pressure of Earth)

•About the same CO_2 in Venus' atmosphere as limestone on Earth Surface

•Surface T ~ 750K (Pb melts at 600K)

•Atmosphere while only 1—2% N_2, it has ~ same total N_2 as Earth

•H_2O gets to upper atmosphere where solar UV + $H_2O \rightarrow H_2 + O$

•The H_2 escapes. On ⊕ the H_2O freezes in lower atmosphere and is protected from UV

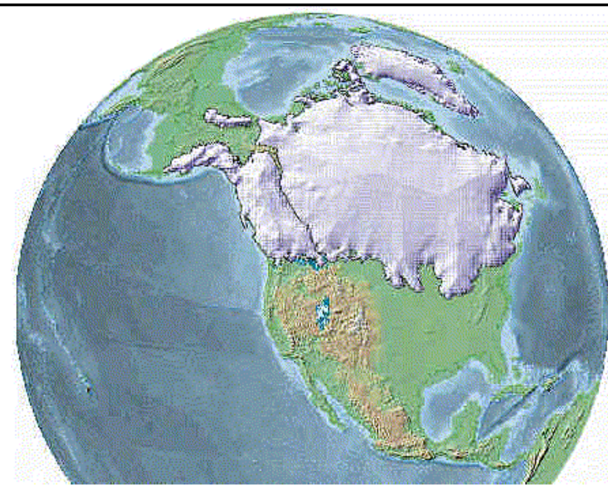
•On Venus most of the H has escaped; since $^2H = D$ = deuterium escapes less easily than H the D/H ratio on Venus has ⇑. About 100 $(D/H)_\oplus$

Another positive feedback loop

Suppose that T is low enough that ice can exist near the poles all year long.

1. Something increases ice cover
2. ⇒ More solar energy reflected into space
3. ⇒ Cooler earth
4. ⇒ go to 1

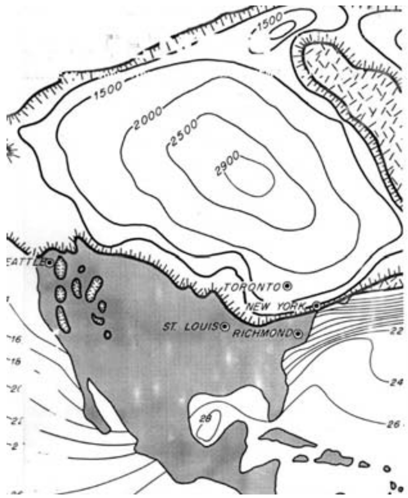
This is called a "Runaway glaciation" and produces a snowball earth.

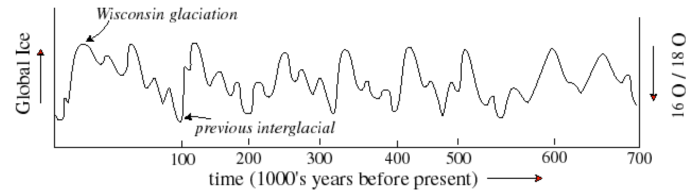


An example of a runaway glaciation is the recent Earth

The peak of the Wisconsin glaciation 18,000 years ago

Sea level was 100m lower





Global ice cover in the past million years can be determined by measuring the $^{16}O/^{18}O$ ratio in ocean sediments.

Ice starts to advance when the various wobbles of the Earth lead to the mildest late summers in the Northern Hemisphere, I.e. all of the observed wiggles are induced with rather small changes. The recent Earth has been flirting with runaway glaciation.

The Earth doesn't completely glaciate because precipitation turns off

Potential runaway glaciation when atmosphere becomes oxidizing 1—2 Gyr ago

If early greenhouse is partially due to CH_4 and/or NH_3 which vanish when the atmosphere becomes oxidizing and the greenhouse becomes leaky.

Hart found this if was more than 1% further from sun.

Other climate models also tend toward runaway glaciation at this time.

The geological record shows that there were major glaciations at about this time.

What about Mars?

Mars had liquid water at early stage. Eroded channels, and sinuous channels. Most dramatic features were probably due to flash floods. A few features show evidence for sedimentation and longer standing H_2O.

Liquid H_2O cannot exist in a atmosphere with pressure as low as Mars' is now (about 1% Earth) The early liquid H_2O suggests that Mars must have had more atmosphere than present.

One Scenario:

Initial outgassing $\Rightarrow$ CO_2 atmosphere and liquid H_2O.

Because Mars has less mass than the Earth (only $\sim 1/10 M_{\oplus}$) the internal heat is less and outgassing was limited and stopped some time ago.

The evidence shows that the tectonic activity was limited

CO_2 was absorbed and not replenished $\Rightarrow$ cold planet with almost no atmosphere

Inside some critical planet-sun distance the planets underwent a runaway greenhouse or lost their water

Outside some critical planet-sun distance the planets became snowballs.

The area between these critical distances is called the *continuously habitable zone* or CHZ.

A New View of the CHZ

In addition to geological evidence that the early atmosphere was not very reducing, calculations show that CH_4 and NH_3 would be destroyed by solar UV.

Thus the only option for an enhanced greenhouse lots of CO_2.

Current atmosphere contains 0.0003 bar of CO_2. (1 bar = pressure of current total atmosphere on)

There is enough in carbonate rocks to make an atmosphere of 60 bars of CO_2.

Current release rate via outgassing would give 1 bar of CO_2 in 20 million years

1 bar CO_2 $\Rightarrow$ 50C greenhouse

Any greenhouse must turn off as the solar *L* increases.

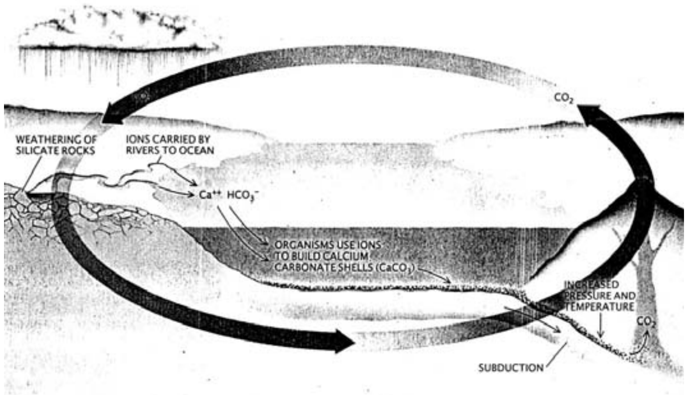
Current CO_2 is 0.0004 bar

Outgassing releases this amount in only 8,000 years

$\Longrightarrow$ Tuned balance between input and absorption

Kasting, Toon, & Pollack suggested how this might happen in an article in the Feb. 1988, Scientific American

They invoked the carbonate-silicate geochemical cycle



The current carbon cycle is:

1. CO_2 enters the atmosphere from volcanoes
2. CO_2 dissolves in rain making carbonic acid (H_2CO_3)
3. Acid rain weathers rock producing calcium ions (Ca^{++}) and bicarbonate ions (HCO_3^-)
4. the Ca^{++} and HCO_3^- wash into the ocean
5. Plankton make calcium carbonate shells
6. dead plankton make limestone
7. limestone is subducted at plate boundaries where it is heated contributing to volcanic gasses
8. go to 1

The carbon cycle has negative feedback---(stable)

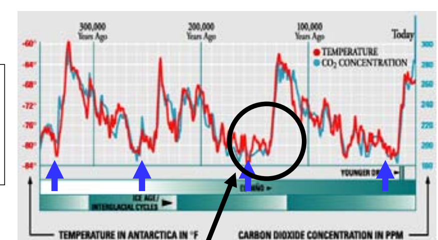
Suppose $T \Downarrow$

1. Less evaporation $\Rightarrow$
2. Less rain $\Rightarrow$
3. CO_2 not removed as rapidly while volcanism constant $\Rightarrow$
4. CO_2 builds up $\Rightarrow$
5. Better greenhouse $\Rightarrow$
6. T $\Uparrow$, i.e. back toward equilibrium

Bubbles of gas trapped in layers of ice give a measure of temperature and carbon dioxide

350,000 years of Surface Temperature and Carbon Dioxide (CO_2) at Vostok, Antarctica ice cores

This has been extended back to > 700,000 years



- **This is one of the points of controversy.**
- **There is a lag between CO2 and T turn around.**

Having CO_2 increase as T increases is exactly the opposite that one would expect if the carbon silicate cycle was providing negative feed back!

Supposedly the carbon silicate cycle works slowly—time scale of several 10^5 years

Then how can it stabilize climate which can have major changes in 1000's of years or less???

The return of CH_4

•Early CO_2 greenhouse would require at least 0.2 bar

•We should see evidence for this in minerals

E.g., iron carbonate ($FeCO_3$) or siderite but there is no siderite in old minerals

•Maybe CH_4 could survive solar UV if a photochemical smog forms

•Problems with the snowball earth instability when the atmosphere becomes oxidizing.

Conclusions

This is all very, very, complicated

The details of how certain things are modeled are important -

for example, cloud feedback:

•increased clouds $\Rightarrow$ increased albedo (cooling)

•increased clouds $\Rightarrow$ increased IR trapping (heating)

Even the sign of the feedback is debated!

Important considerations impossible to include:

•location of continents

•burying the CO_2 - -(now mostly coastal rock)

A current problem:

The origin of the Earth's Oceans

- Vulcanism, I.e. outgassing does not seem capable of providing enough water.
- Perhaps late accretion of objects from outer solar system
  - Comets?
    - × Ratio of D_2O/H_2O measure in 3 comets is a factor of 2 too high
  - Inner belt asteroids have correct D_2O/H_2O (as inferred from carbonaceous chondrites) but not enough H_2O

- Outer belt asteroids have correct D_2O/H_2O (as inferred from carbonaceous chondrites) and enough H_2O
    - Delivery of H_2O to Earth depends critically on Jupiter
- Mars size impacter, enough H_2O but heat from the impact may lead to loss of much of the H_2O