Looking back on the future of climate change

Brian Rose and Daniel Enderton

IAP 2008

Looking back on the future of climate change

Part 1: The early years of greenhouse theory. A tale of ice ages and carbon dioxide

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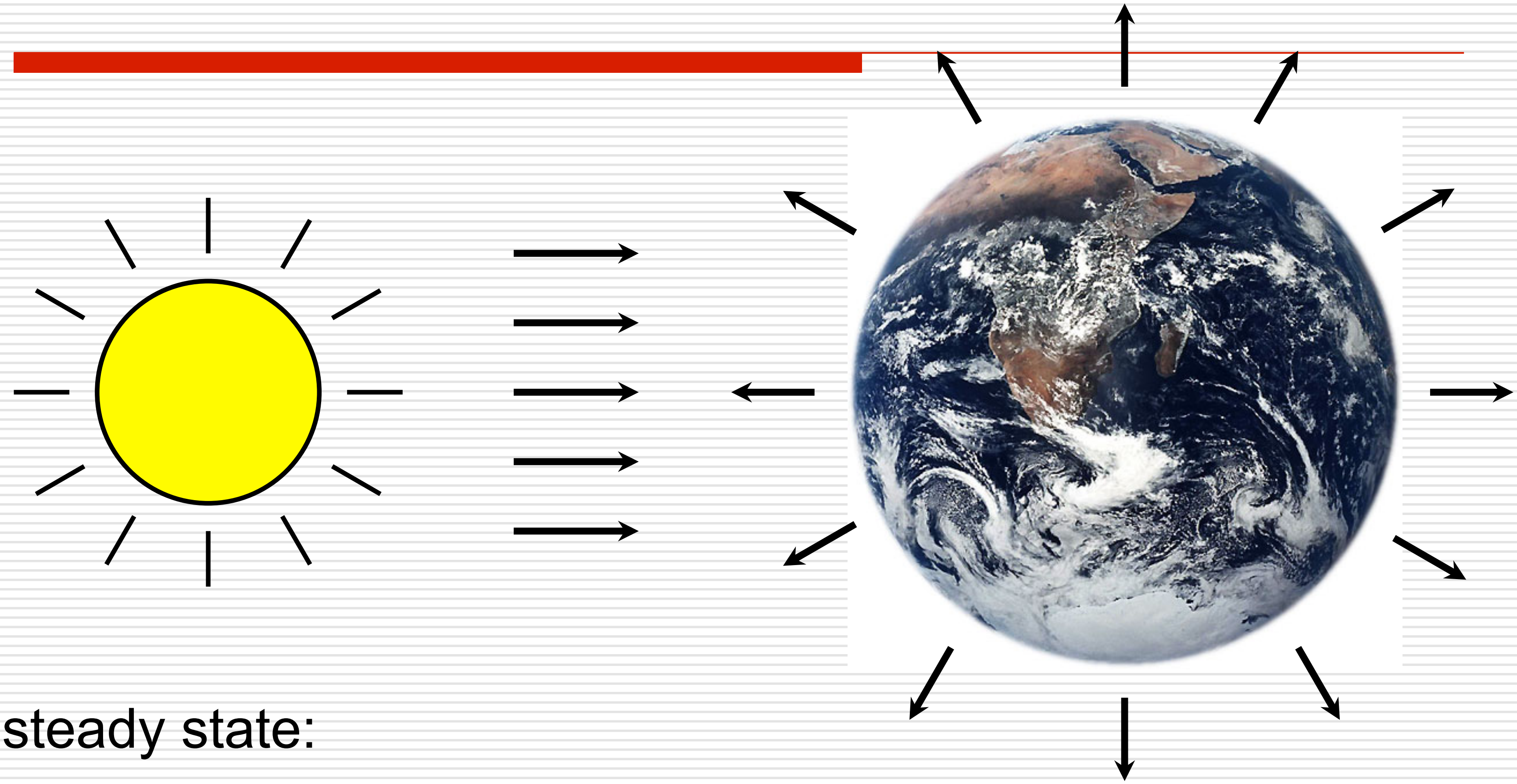
In the beginning…

- There was an energy balance model

Global Energy Balance Model



In steady state:

Energy IN = Energy OUT,   Solve for surface temperature …

Incoming Solar Radiation

Solar energy ⊥ to rays:

$$S_0 \approx 1367\ W/m^2$$

Average incident solar energy:

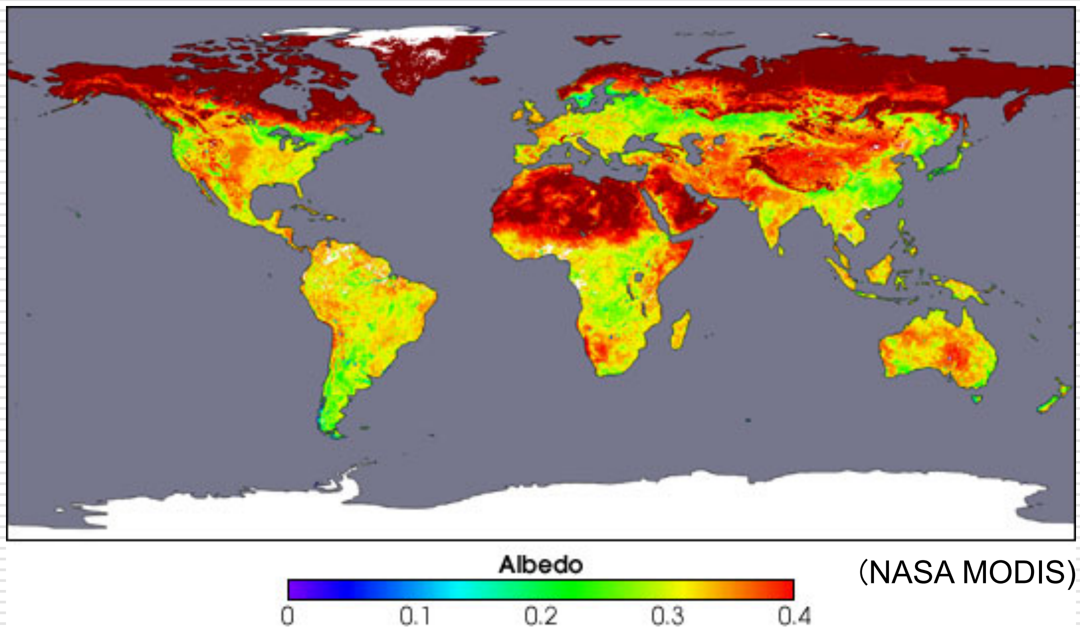
$$S_0 / 4 \approx 342\ W/m^2$$

Albedo

Albedo (α) = fraction of incoming solar radiation reflected

Type of surface	Albedo (%)
Ocean	2 – 10
Forest	6 – 18
Grass	7 – 25
Soil	10 – 20
Desert (sand)	35 – 45
Ice	20 – 70
Snow (fresh)	70 – 80

(Marshall, 2007)



(NASA MODIS)

Global mean albedo: $\alpha \approx 30\%$

includes effect of clouds

Incoming Solar Radiation

Energy IN

= absorbed solar radiation

= $(1 - \alpha)\, S_0 / 4$

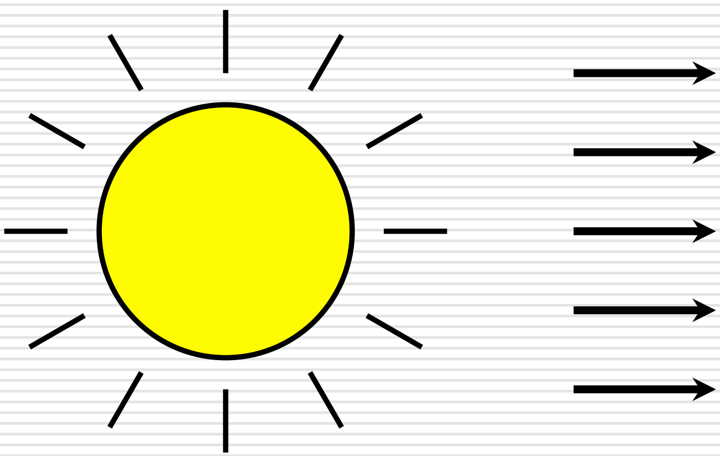
Energy OUT …

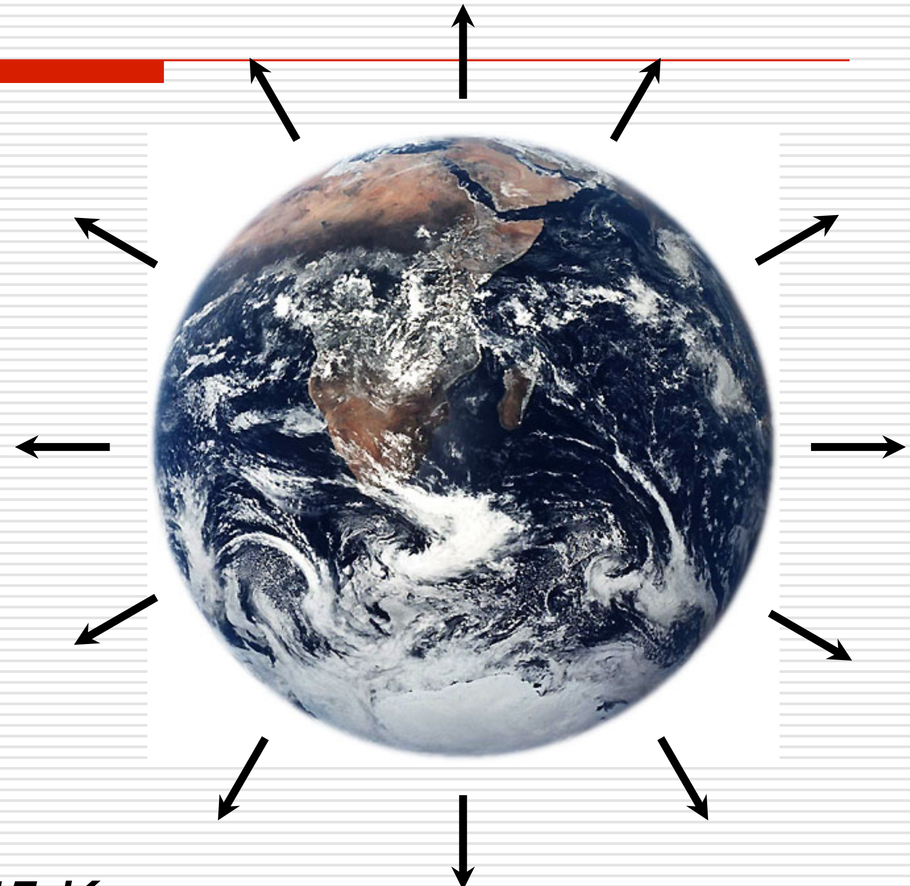
Outgoing Terrestrial Radiation

Stefan's law for blackbody radiation:

Energy OUT = σT_e^4

Global Energy Balance Model





Energy IN = Energy OUT $\Rightarrow$

$$T_e = \left[\frac{S_0(1-\alpha_p)}{4\sigma}\right]^{\frac{1}{4}}$$

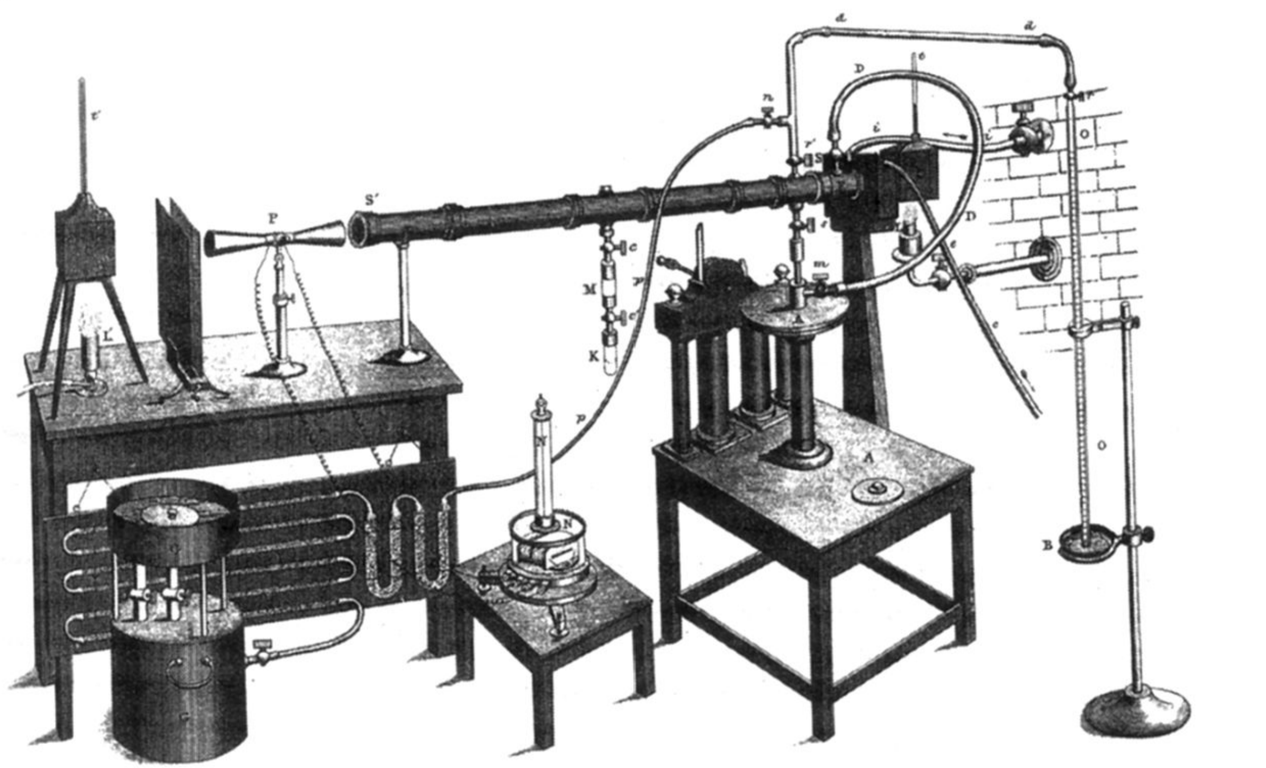
T_e = 255 K

[Actual: T_s = 288 K]

Joseph Fourier (1768-1830)

- First to recognize the concept of planetary energy balance (though infrared radiation had not yet been discovered)
- Calculated a radiative equilibrium temperature much too cold
- Inferred that the atmosphere interferes with the transmission of outgoing terrestrial heat
- This is what eventually came to be called the *greenhouse effect*

John Tyndall (1820-1893)



John Tyndall (1820-1893)

- Conducted laboratory experiments, showed that several atmospheric gases absorb heat, notably H_2O and CO_2
- Recognized the important implications for the energy balance of the earth:

  "*As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth's surface.*" Tyndall, 1862

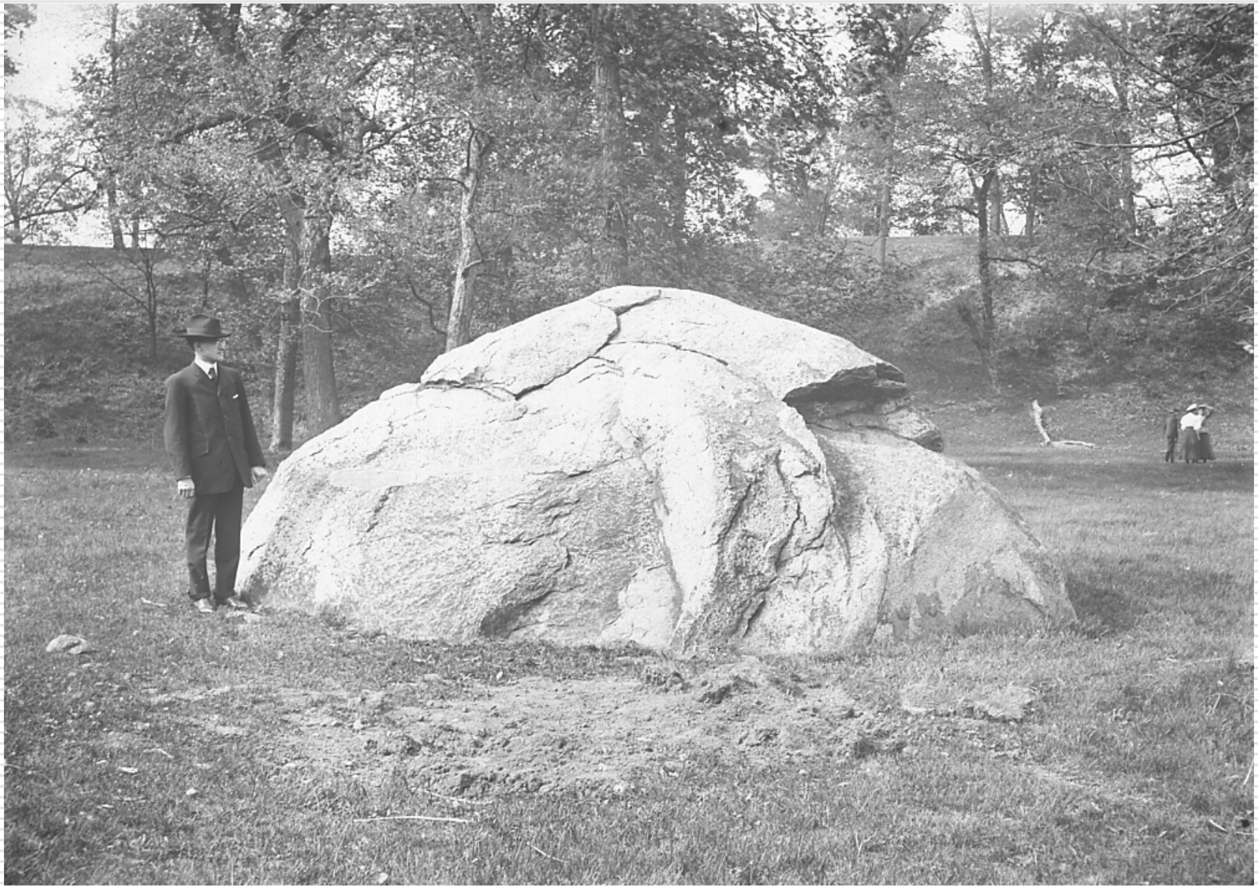
John Tyndall (1820-1893)

Water vapor "is a blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapour from the air… and the sun would rise upon an island held fast in the iron grip of frost." Tyndall, 1863

Tyndall’s motivation

- An avid alpinist with first-hand knowledge of glaciers, he had become convinced by the evidence that all of northern Europe had once been covered by a colossal ice sheet
- He was looking for mechanisms to explain how the climate could change so radically!

Erratic boulders



Source: The Jesse Earl Hyde Collection, Case Western Reserve University (CWRU) Department of Geological Sciences, http://geology.cwru.edu/~huwig/catalog/slides/167.A.1.jpg

Louis Agassiz (1807-1873)

- Argued to the Swiss Society of Natural Sciences in 1837 that an *immense polar ice sheet* had once blanketed the nearby Jura mountains, as well as all of northern Europe.
- A long dispute among geologists followed…
- 30 years later, the existence of the ice age was generally accepted.

Terminal moraines

Source: The Jesse Earl Hyde Collection, Case Western Reserve University (CWRU) Department of Geological Sciences, http://geology.cwru.edu/~huwig/catalog/slides/169.A.1.jpg

Figure 10. Professor T.C. Chamberlin's map was the first attempt to picture North America during the last ice age. (From J. Geikie, 1894.)

Source: Imbrie & Imbrie, "Ice Ages: Solving the Mystery", Harvard University Press, 1986, p. 50

Not one ice age, but several!

But why and how did it happen?

- By the end of the 19th century, geologists had amassed a great deal of information about the ice ages.
- Multiple ice ages suggested that the climate had fluctuated enormously over time
- Explaining the ice ages became the "holy grail" of climate studies (and still is!)

Svante Arrhenius (1859-1927)

- Swedish chemist, also interested in the ice age problem
- First attempt to calculate the temperature change resulting from adding or removing CO_2 from the atmosphere (what we now call *climate sensitivity*)

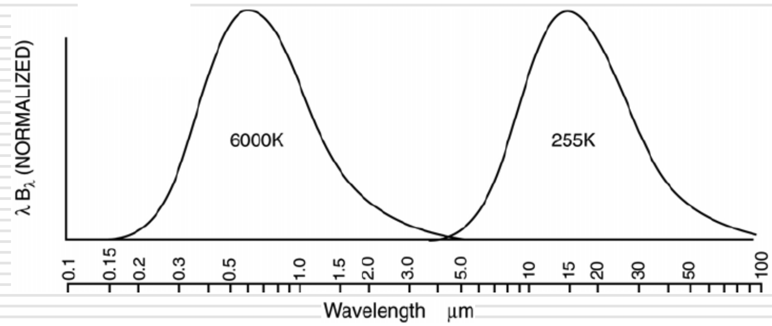
Calculating the greenhouse effect

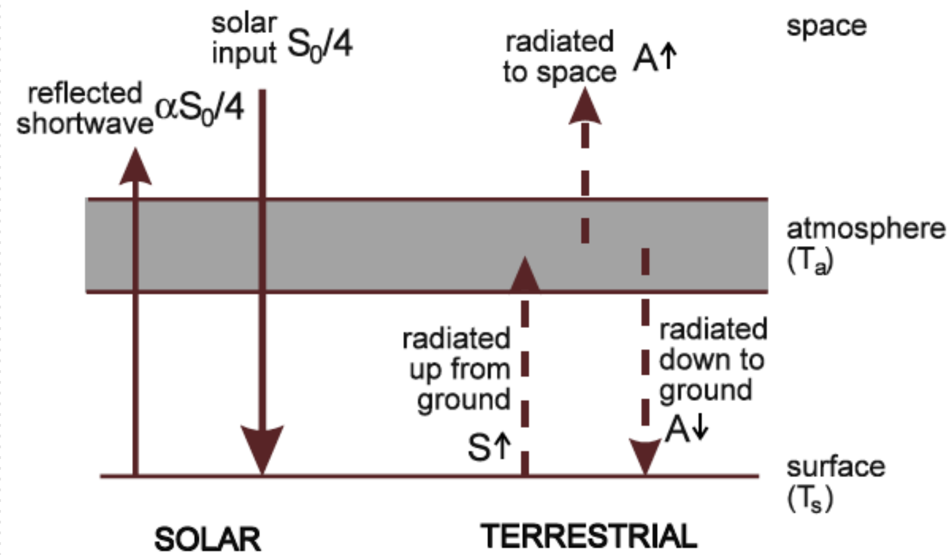
- Atmosphere:
    - Does not absorb solar radiation
    - Absorbs terrestrial radiation
- Re-radiates energy in both directions
- 2 equations:
    - Top of atmosphere
    - Surface
- 2 unknowns (T_e , T_s)

$$T_s = 2^{\frac{1}{4}} T_e$$

$$T_s = 303\ K$$

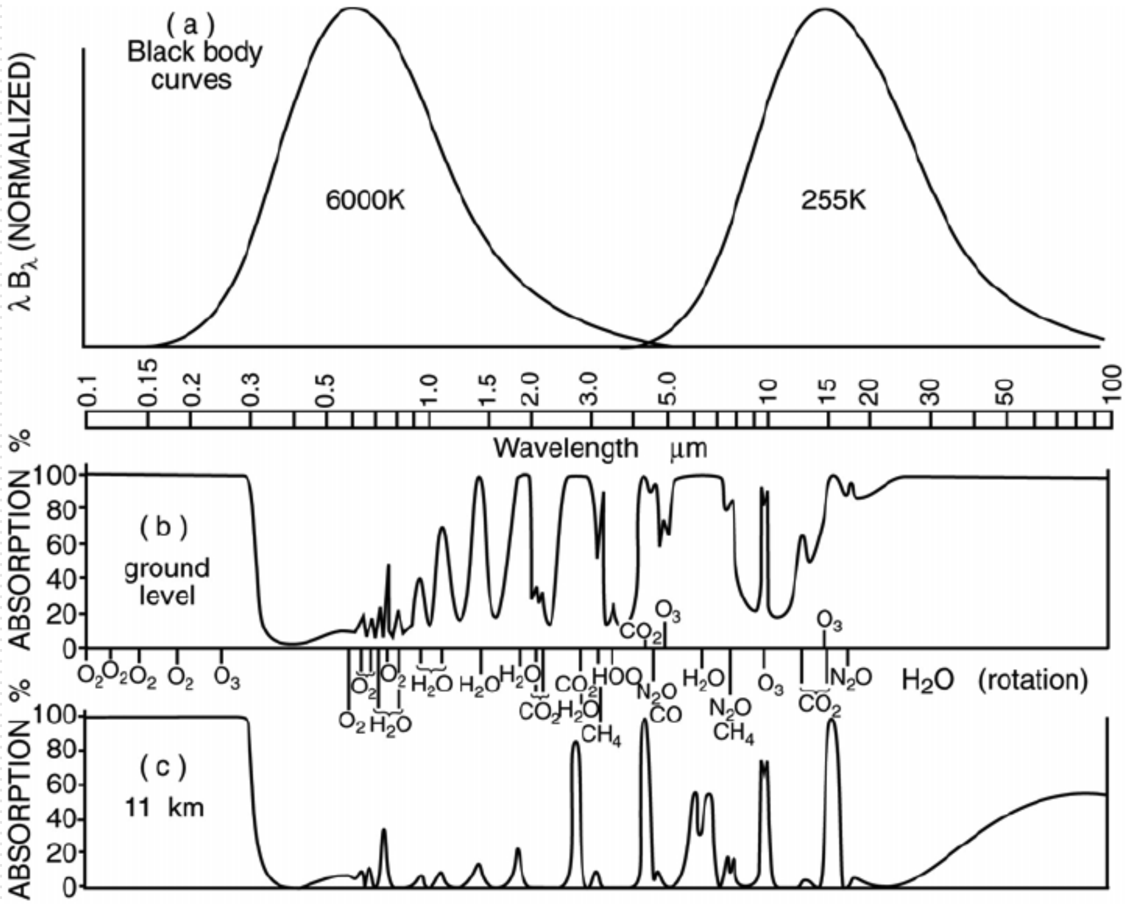
[Actual: $T_s = 288\ K$]





Source: Marshall 2007

A "leaky" greenhouse



Source: Goody and Young, 1989

Water vapor feedback

- Tyndall's work had shown that H_2O is the dominant greenhouse gas in the atmosphere (was and still is much more abundant that CO_2).
- Warmer air can hold more water vapor
- Warmer ---> more H_2O ---> more greenhouse warming
- A positive feedback!
- Arrhenius recognized the crucial importance of this feedback and included it in his calculations

After months of pencil work…

- Arrhenius concluded that *halving* the atmospheric CO_2 would lead to a cooling of 4-5°C in Europe -- enough for an ice age!

"I should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them." Arrhenius, 1896

Could CO_2 vary that much?

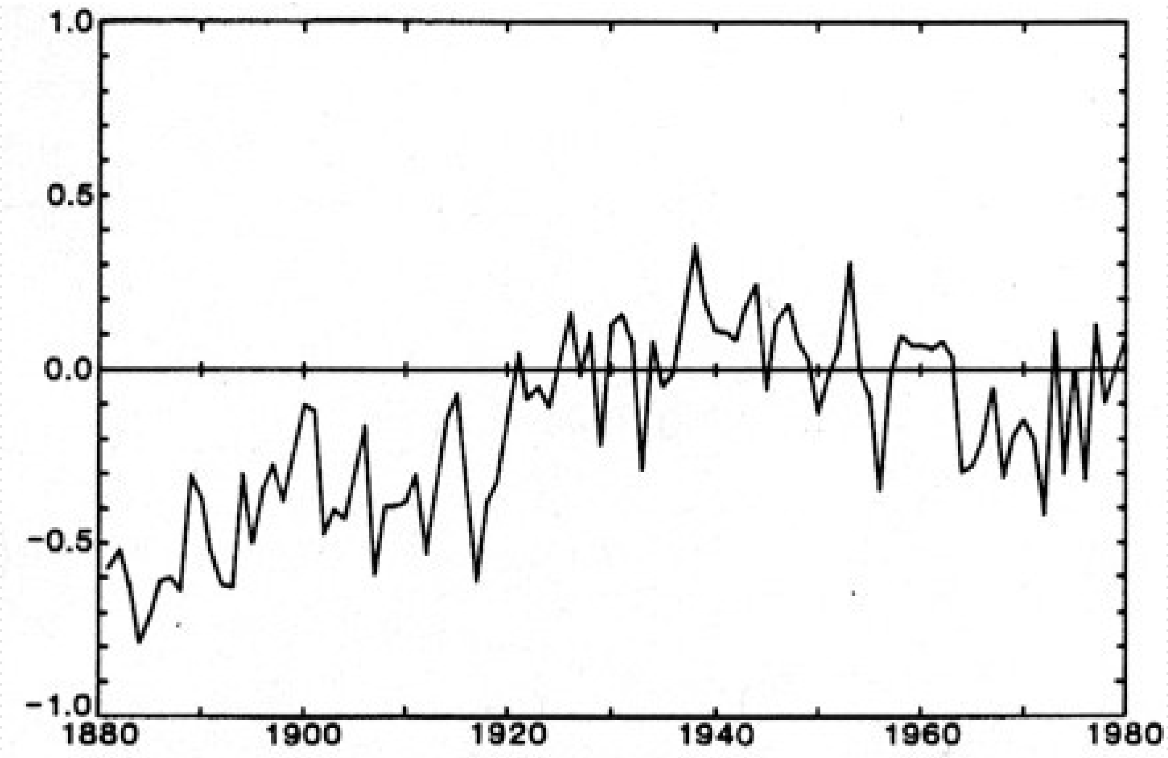
- Arrhenius turned to a colleague named Arvid Högbom who was studying how CO_2 cycles through natural geochemical processes (e.g. volcanoes, oceans)
- Högbom found something remarkable: industrial sources were emitting CO_2 at a rate comparable to geochemical sources!
- They realized that given enough time there was a possibility for artificial warming of the climate.

So Arrhenius did another calculation

- Now curious about the warming question, he calculated the effect of *doubling* the CO_2 in atmosphere.
- Answer: 5-6°C warming
- With the rate of coal consumption in 1896, this doubling would take 3000 years (revised in 1908 to hundreds of years)
- Arrhenius had demonstrated anthropogenic global warming… as a curious theoretical concept.

Meanwhile, the climate was warming…

Northern hemisphere surface temperature (expressed as deviation from 1946-1960 mean in °C)



P.D. Jones et al (1982), MWR 110, p.67

TIME
IN PARTNERSHIP WITH CNN

Monday, Jan. 02, 1939

Warmer World

During the cold winter of 1717, snow fell steadily for five days in New England, lay five or six feet deep in Boston for a long time. In March 1741, people sleighed from Stratford, Conn. to Long Island across the solidly frozen Sound. In 1779-80, according to Thomas Jefferson, "the Chesapeake Bay was frozen solid from its head to the mouth of the Potomac. At Annapolis the ice was five to seven inches in thickness, quite across. . . ."

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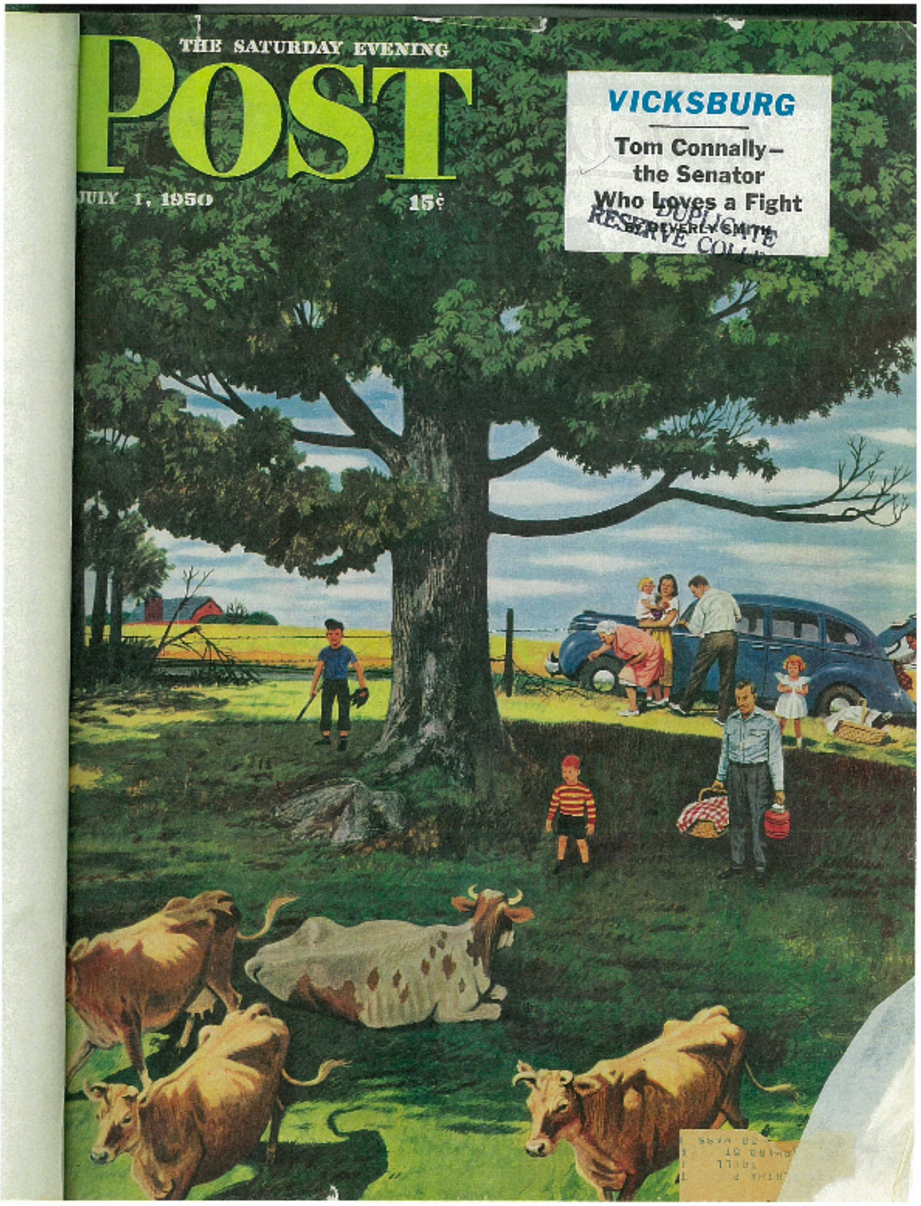
"The Northern Hemisphere is still recovering from the last great glaciation of the Ice Age, though for chronological purposes this period is considered to have ended some 20,000 years ago. The continental ice sheet which once covered the northern United States still exists in Greenland where it is still retreating. Despite various speculations, the reason for such climate changes is obscure.

In 1932 the U.S. Weather Bureau assembled all available records covering a century or more, found that they showed a trend towards warmth."

In 1932 the U. S. Weather Bureau assembled all available records covering a century or more, found that they showed a trend towards warmth. In Manhattan, white-thatched James Henry Kimball, famed weather adviser of transatlantic fliers, found that in his territory average annual temperatures rose 2.1° from 1831 to 1900, 1.4° more from 1900 to 1938. Meteorologists do not know whether the present warm trend is likely to last 20 years or 20,000 years.

Time Magazine, Jan. 2 1939




Greenland is now a major breeding ground for North Atlantic icebergs. Is it on the way to becoming as torrid as South Carolina?

Is the World Getting Warmer?

By ALBERT ABARBANEL and THORP McCLUSKY

Was this past mild winter just part of a natural cycle? Will the old-fashioned blizzard someday disappear? Here are the startling facts revealed by world-wide weather surveys now going on

Climatologist Hans Ahlmann asserts that the earth is undergoing a change toward greater warmth.

FOR the past three winters a colony of Penobscot Indians who live on an island in the Penobscot River, near Old Town, Maine, have been plagued by unseasonable thaws. Since time immemorial, the tribe has used the ice as a bridge to the mainland from November until April, walking back and forth and even driving trucks and automobiles on sawdust laid across the slippery surface. Until recently the ice had never gone out in January, as the memories of older tribesmen and the results of annual betting pools on the day and hour of the spring breakup attested.

But since 1948 there has been a January thaw every year—to the astonishment of Indians and Old Towners alike. In 1949 the ice went out so suddenly that 610 Indians were marooned on their island for three days. Now the state of Maine has decided to build a bridge across the river to the island. "It has really been good to us," says Mrs. Bruce Poolaw, wife of the chief. "If it hadn't changed like this, we'd never have had the new bridge."

Last August sixth various New Jersey fishermen reported that they had seen schools of "rare tropical fish" and "tropical flying fish" swarming off the coasts. There was even considerable conjecture that the Gulf Stream might have changed its course.

That mysterious changes are happening in the world's climate many persons are beginning to suspect, and a few scientists know. Speaking before the Royal Geographical Society, in London on ...

Saturday Evening Post, July 1 1950

Guy Stewart Callendar (1898-1964)

- English steam engineer, dabbled in meteorology as a hobby
- Curious about the apparent warming trend
- Also interested in Arrhenius' CO_2 warming theory
- Compiled many old temperature observations, found a warming
- Compiled available data on atmospheric CO2 concentration, and found it was increasing
- Used an energy balance argument to calculate the effect of the CO_2 increase on temperature, found it consistent with observations
- Stood before the Royal Meteorological Society in London in 1938 and delivered his paper "The Artificial Production of Carbon Dioxide and its Influence on Temperature"

Image source: http://www.aip.org/history/climate/

Guy Stewart Callendar

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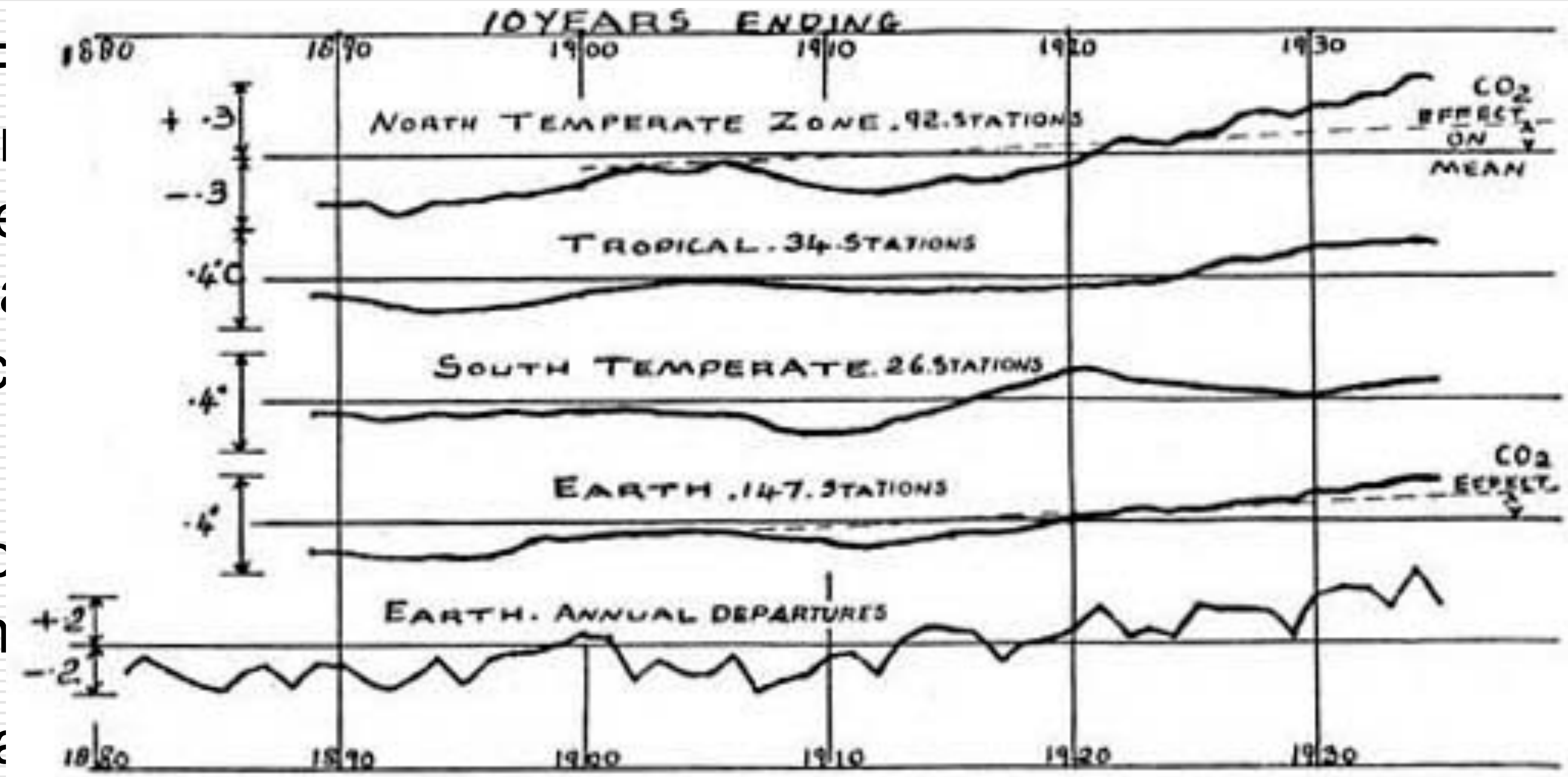


Callendar (1968), QJRMS 64, p. 233

Guy Stewart Callendar

"In conclusion it may be said that the combustion of fossil fuel, whether it be peat from the surface or oil from 10,000 feet below, is likely to prove beneficial for mankind in several ways, besides the provision of heat and power. For instance the above mentioned small increases of mean temperature would be important at the northern margin of cultivation… In any case the return of the deadly glaciers should be delayed indefinitely."

Callendar, 1938

Guy Stewart Callendar

- Continued to argue for the next 20 years that CO_2-induced greenhouse warming was occurring.
- Sometimes called the "Callendar Effect"
- However, few people were convinced at the time.

A few persistent arguments against CO_2 greenhouse warming

- Lab results showed CO_2 absorption already saturated
- Oceans are a huge carbon sink, probably taking up excess emissions
- Simple calculations by Arrhenius, Callendar and others completely neglected many important meteorological processes, including changes in cloud cover

Whither the carbon?

- As late as 1950's, reliable measurements of atmospheric CO_2 were lacking. Were emissions accumulating in the atmosphere, or being quickly taken up by the oceans?
- Meanwhile, radiometric ^{14}C dating was invented.
- In 1955 Hans Suess was measuring carbon isotopes in tree rings to better calibrate ^{14}C dates.
- He found "old" carbon in recent growth rings.

Whither the carbon?

- Some saw in Suess's discovery a great new opportunity to study the circulation of the ocean and the gas exchange with the atmosphere.
- Suess collaborated with Roger Revelle at the Scripps Institution of Oceanography
- They calculated an average lifetime of 10 years for a molecule of CO_2 in the atmosphere
- Along the way, Revelle discovered a peculiar buffering mechanism in seawater: to equilibrate with a given increase in atmospheric CO_2, the amount of dissolved carbon need only increase by about 1/10th as much.

Roger Revelle (1909-1991)

- Oceanographer, Al Gore's hero
- Instrumental in setting up the International Geophysical Year, 1957
- Many important contributions as researcher, teacher and administrator
- Was aware of Callendar's arguments, and became personally interested in the fate of fossil carbon emissions.
- His demonstration of the "Revelle factor" suggested that the oceans were probably not taking up carbon at a sufficient rate to prevent a build-up in the atmosphere.
- It was clear that *better measurements were needed*.

Image source: http://www.aip.org/history/climate/

Roger Revelle

"Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."

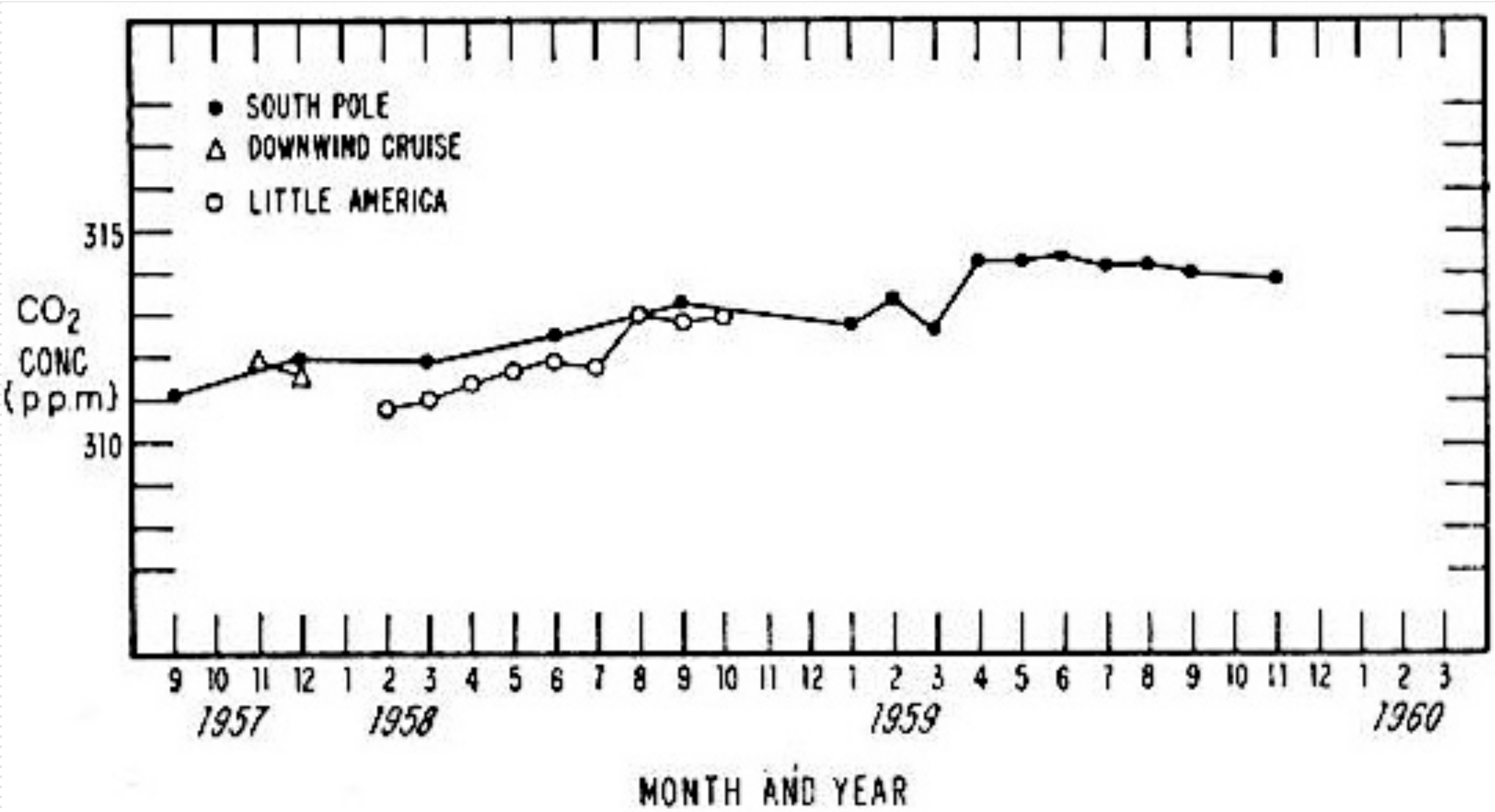
Revelle and Suess, 1957

C. David Keeling (1928-2005)

- Geochemist, became interested in atmospheric CO_2 as a post-doc at CalTech (1954-1956)
- First to develop reliable instruments and techniques to measure the baseline atmospheric CO_2 concentration
- Measurements motivated in part by the CO_2-greenhouse theory of climate change
- With IGY funds, Revelle hired Keeling to conduct a short-term global CO_2 survey

Image source: http://sio.ucsd.edu/keeling/

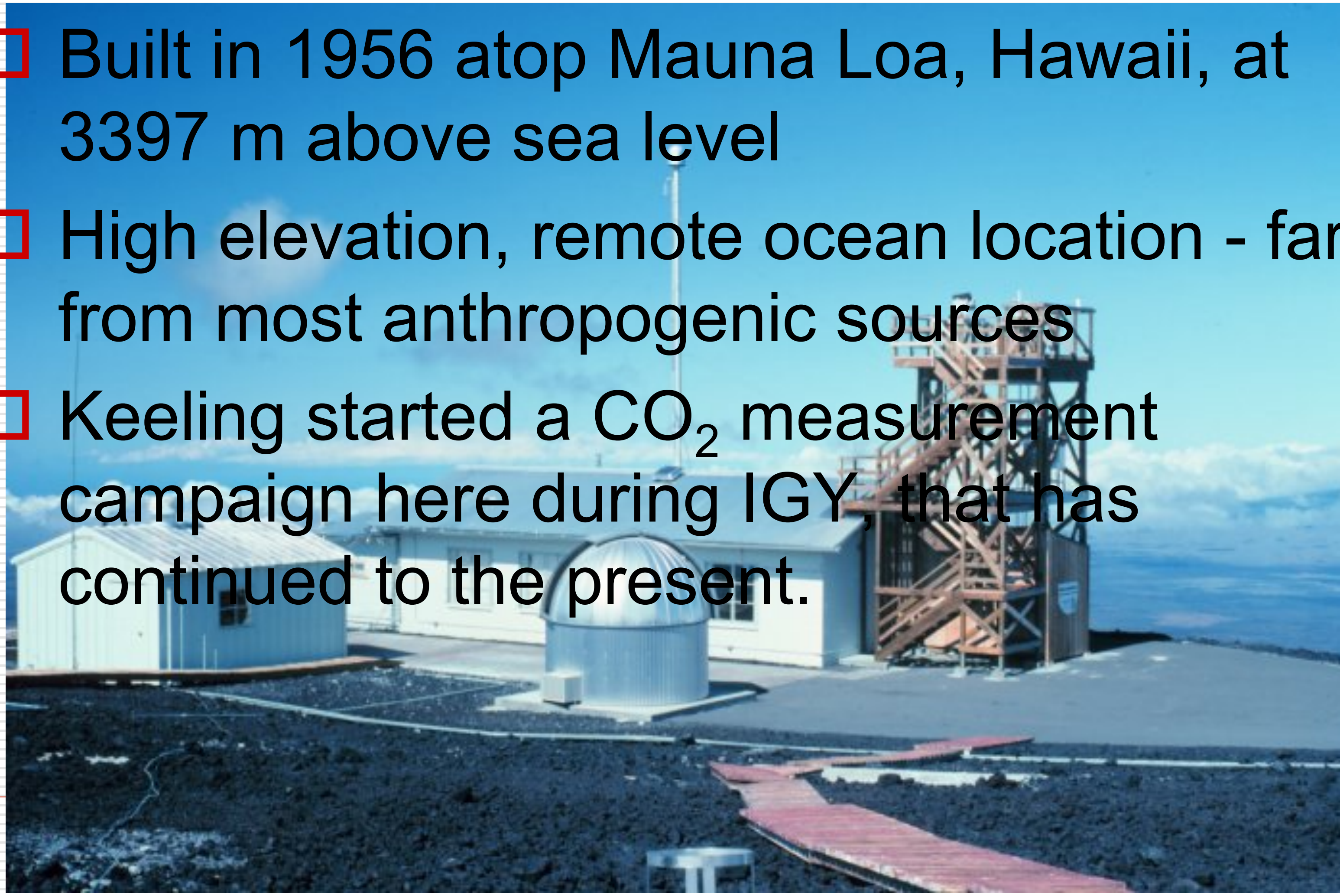
Keeling’s Antarctic measurements



C. D. Keeling, Tellus 12, (1960), p. 200

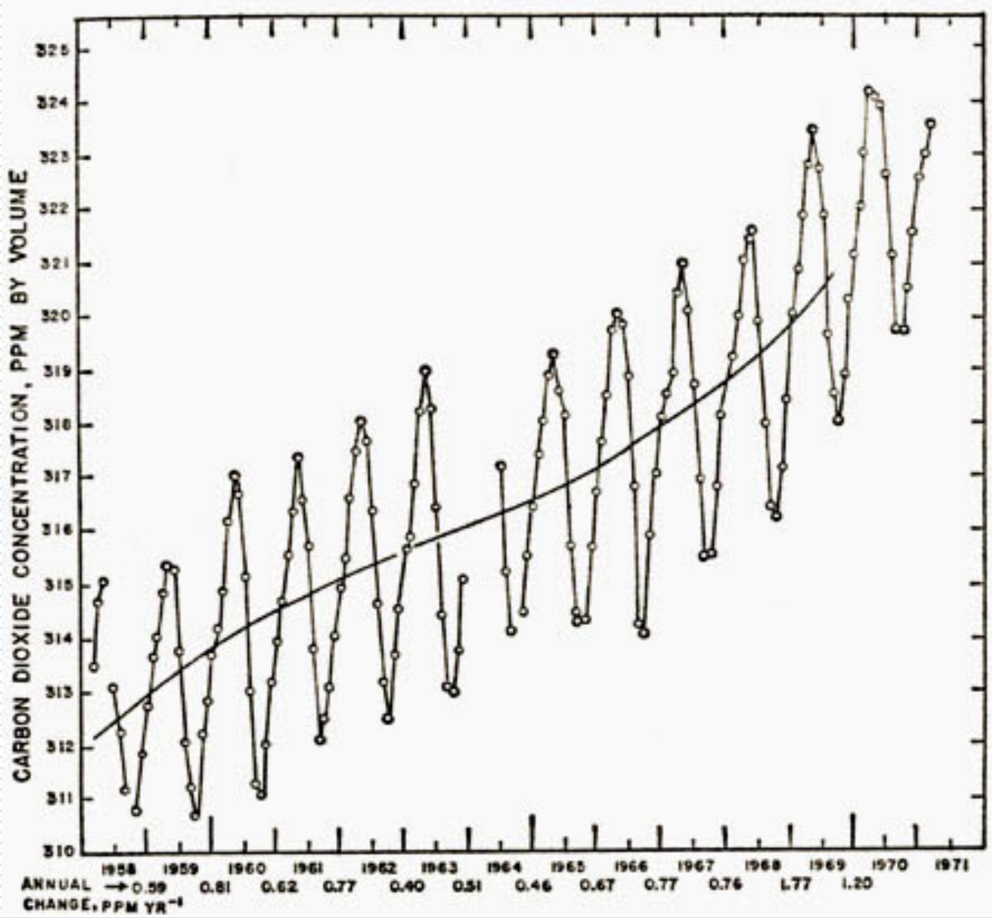
Image source: NOAA Photo Library, http://www.photolib.noaa.gov/

The Mauna Loa observatory



- Built in 1956 atop Mauna Loa, Hawaii, at 3397 m above sea level
- High elevation, remote ocean location - far from most anthropogenic sources
- Keeling started a CO_2 measurement campaign here during IGY, that has continued to the present.

The Keeling Curve (1971)

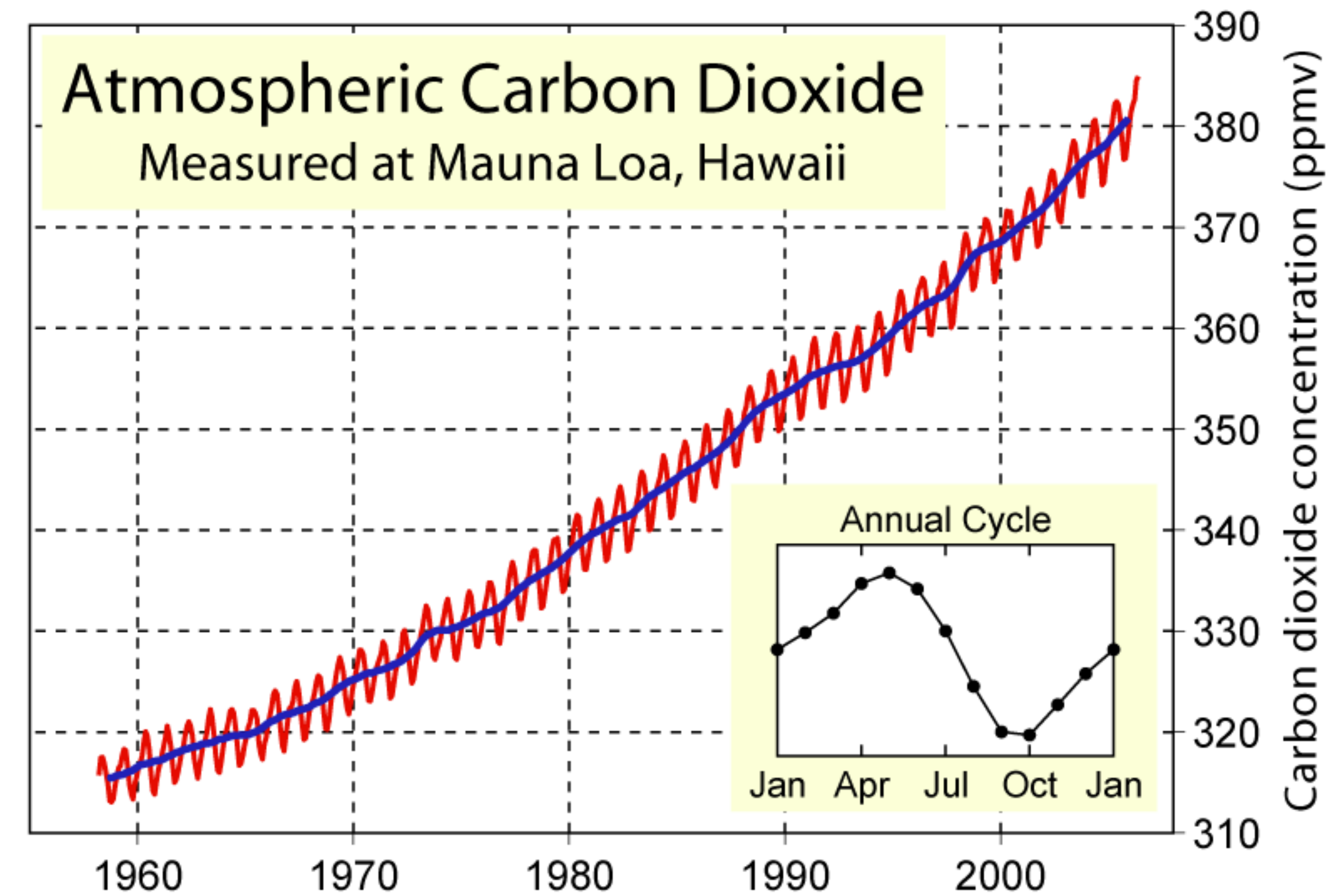


Reproduced from The Discovery of Global Warming at http://www.aip.org/history/climate/xKeeling71.htm

Original source: *Inadvertent Climate Modification*. Report of Conference, *Study of Man's Impact on Climate (SMIC)*, Stockholm, edited by Carroll L.Wilson and William H. Matthews , p. 234, copyright MIT Press, 1971.

Source: Global Warming Art, http://www.globalwarmingart.com/wiki/Image:Mauna_Loa_Carbon_Dioxide_png

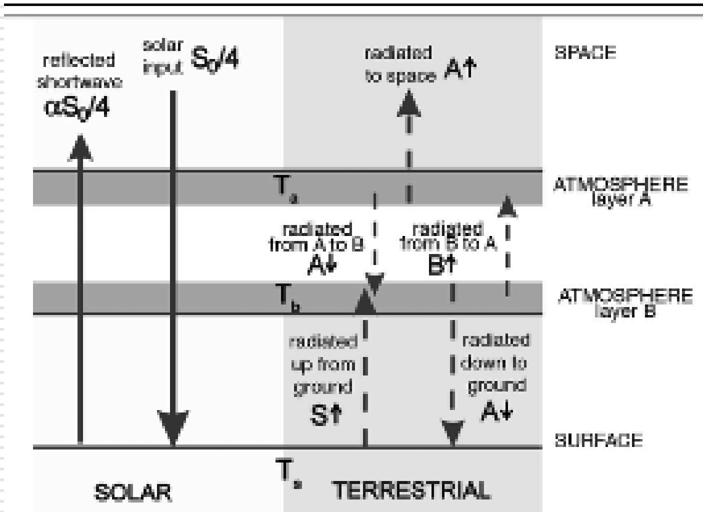
The Keeling Curve (now)

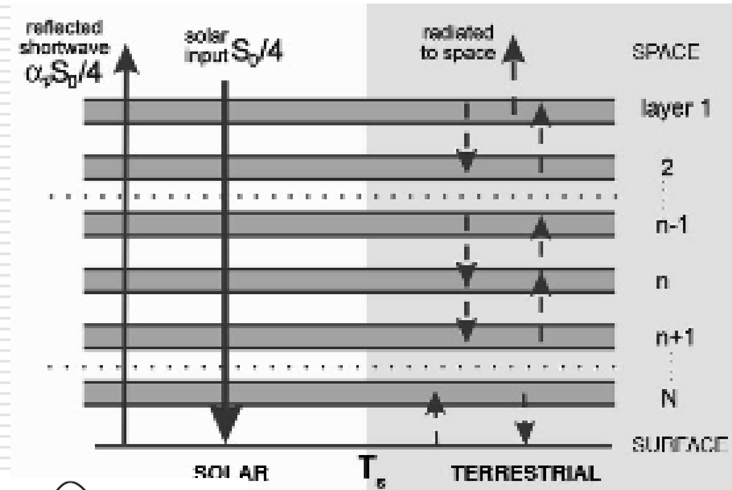


So now we know

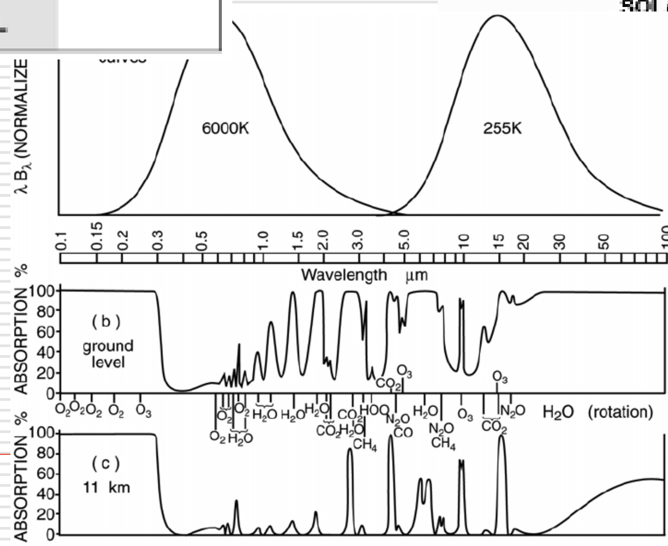
- As Keeling's measurements continued, there could no longer be any doubt that anthropogenic CO_2 was accumulating in the atmosphere.
- The possibility of a greenhouse warming had to be taken seriously
- Meanwhile, progress was being made on the theoretical side, helped tremendously by the invention of computers

Why is the energy balance calculation so difficult?





Source: Marshall 2007



Source: Goody and Young, 1989

Why is the energy balance calculation so difficult?

- Details of absorption spectra depended on quantum mechanics; not worked out until WWII era.
  - 1956: Gilbert Plass made the first accurate calculation of vertical radiative transfer; CO_2 shown to have warming effect
- Need to know vertical distribution of absorbing gases, which depends on temperature (water vapor feedback)
  - 1963: Fritz Möller publishes a similar calculation, but taking account of the water vapor feedback; model is extremely sensitive to CO_2

Why is the energy balance calculation so difficult?

- Radiative equilibrium temperature profile is unstable to vertical motion
  - 1967: Manabe and Wetherald publish an energy balance calculation with both water vapor feedback and vertical redistribution of heat through convection
  - Doubling CO_2 --> about 2°C warming
  - Considered by many to be the first convincing demonstration that CO_2 greenhouse warming was a real possibility.

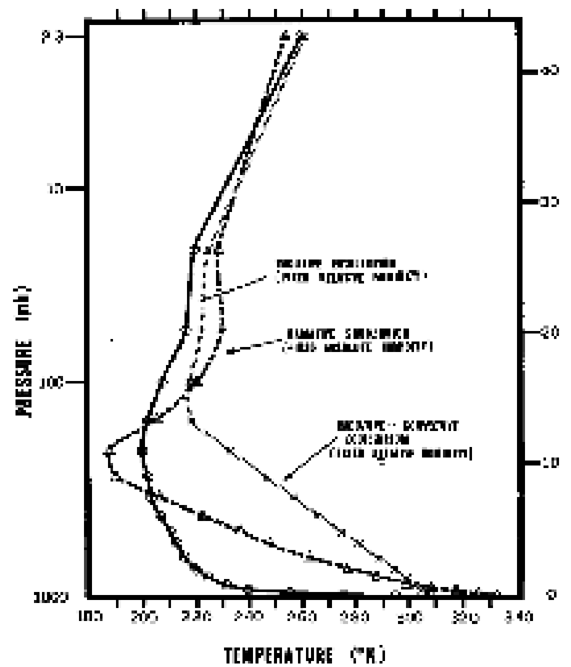


FIG. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given distribution of relative humidity.

Manabe & Wetherald (1967), JAS 24 p. 244

The story so far, circa 1967

- Most of the technical details of the greenhouse effec … ntury after
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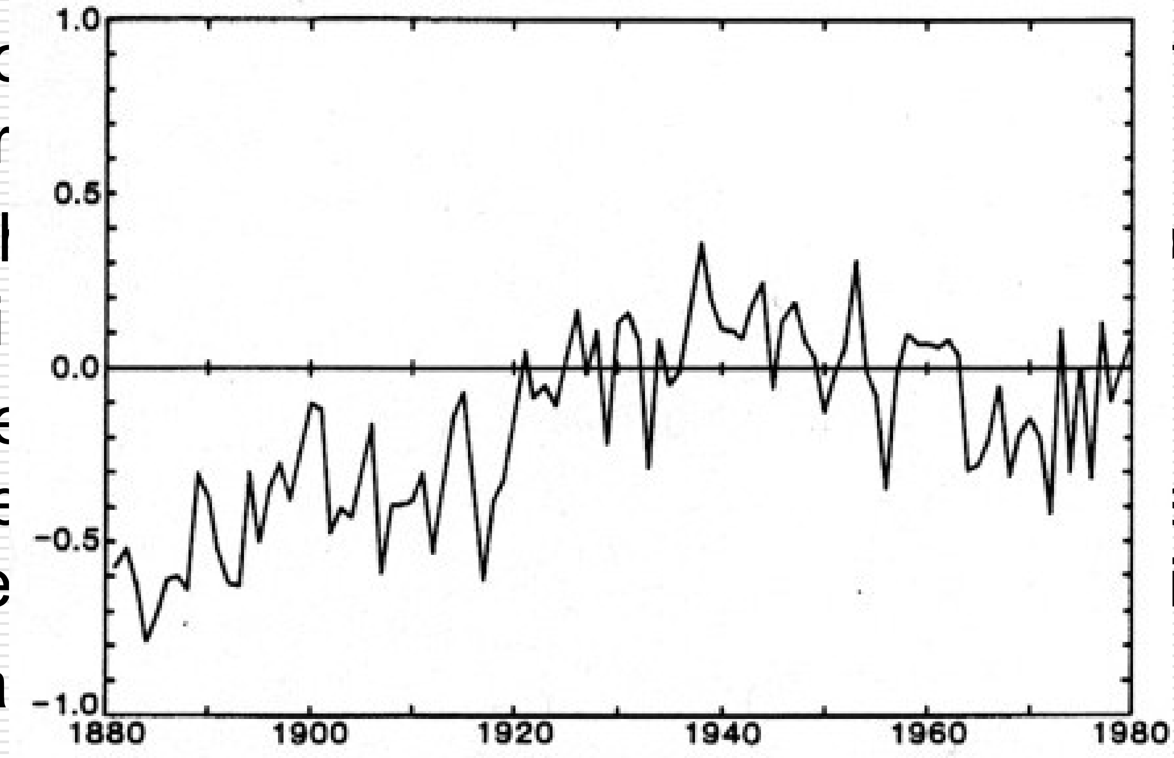
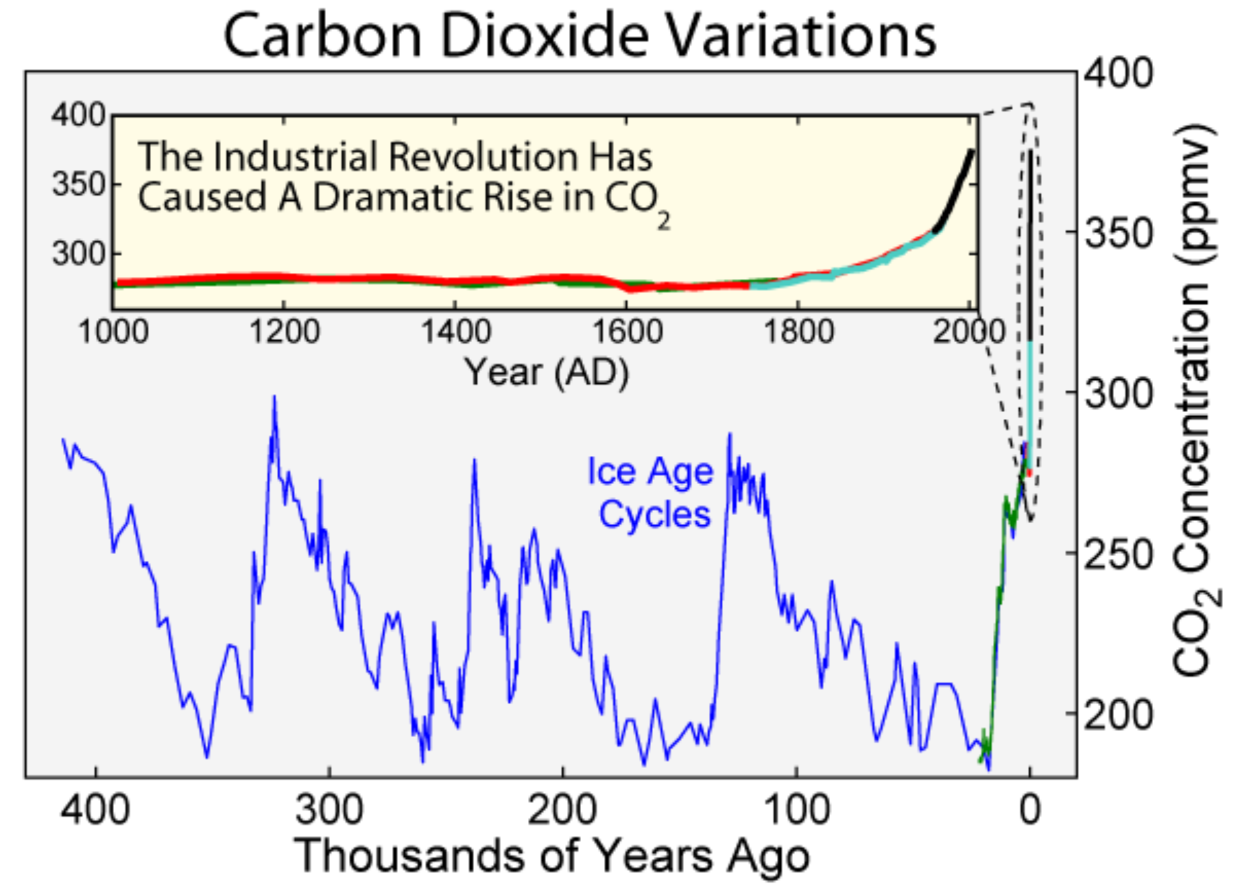


P.D. Jones et al (1982), MWR 110, p.67

CO_2 and the ice age story

- In 1897, inspired by Arrhenius's calculation, T.C. Chamberlin publishes a theory of the ice ages as a self-oscillating cycle driven by CO_2 feedbacks (involving, among other things, the temperature dependence of the chemical weathering of rocks and the increased solubility of CO_2 in cold oceans)
- This sort of CO_2 ice age theory was pitted against the astronomical theory championed first by James Croll in the 1860s, and later by Milutin Milankovic in the early 20th century.
- In more recent times, ice cores and ocean sediment cores have given us a very detailed picture of the ice ages.
- The debate has not gone away: CO_2 and orbital changes both seem to be involved in ice age cycles.

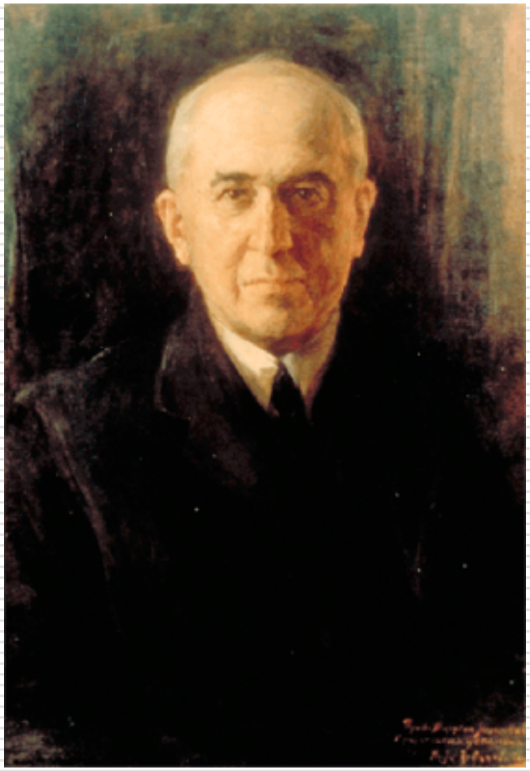
CO_2 and the ice age story



Source: Global Warming Art, http://www.globalwarmingart.com

James Croll (1821-1890) and Milutin Milankovic (1879-1958)

Figure 20. Photograph of James Croll. (From J.C. Irons, 1896).



Source: Imbrie & Imbrie, “Ice Ages: Solving the Mystery”, Harvard University Press, 1986, p.87

Painting by Paja Jovanovic, 1943. Source: http://en.wikipedia.org/wiki/Image:280px-MilutinMilankovic.png

For more information

- “The discovery of global warming” by Spencer R. Weart, Harvard University Press, 2003
- Weart’s excellent website http://www.aip.org/history/climate/
- “Ice Ages: Solving the Mystery” by Imbrie and Imbrie, Harvard University Press, 1986

Please join us tomorrow for Part 2

Daniel Enderton will talk about the observations of climate change, and what can and can't say about the role of greenhouse warming in those changes.

1 pm, E40-298