

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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Program in Atmospheres, Oceans and Climate

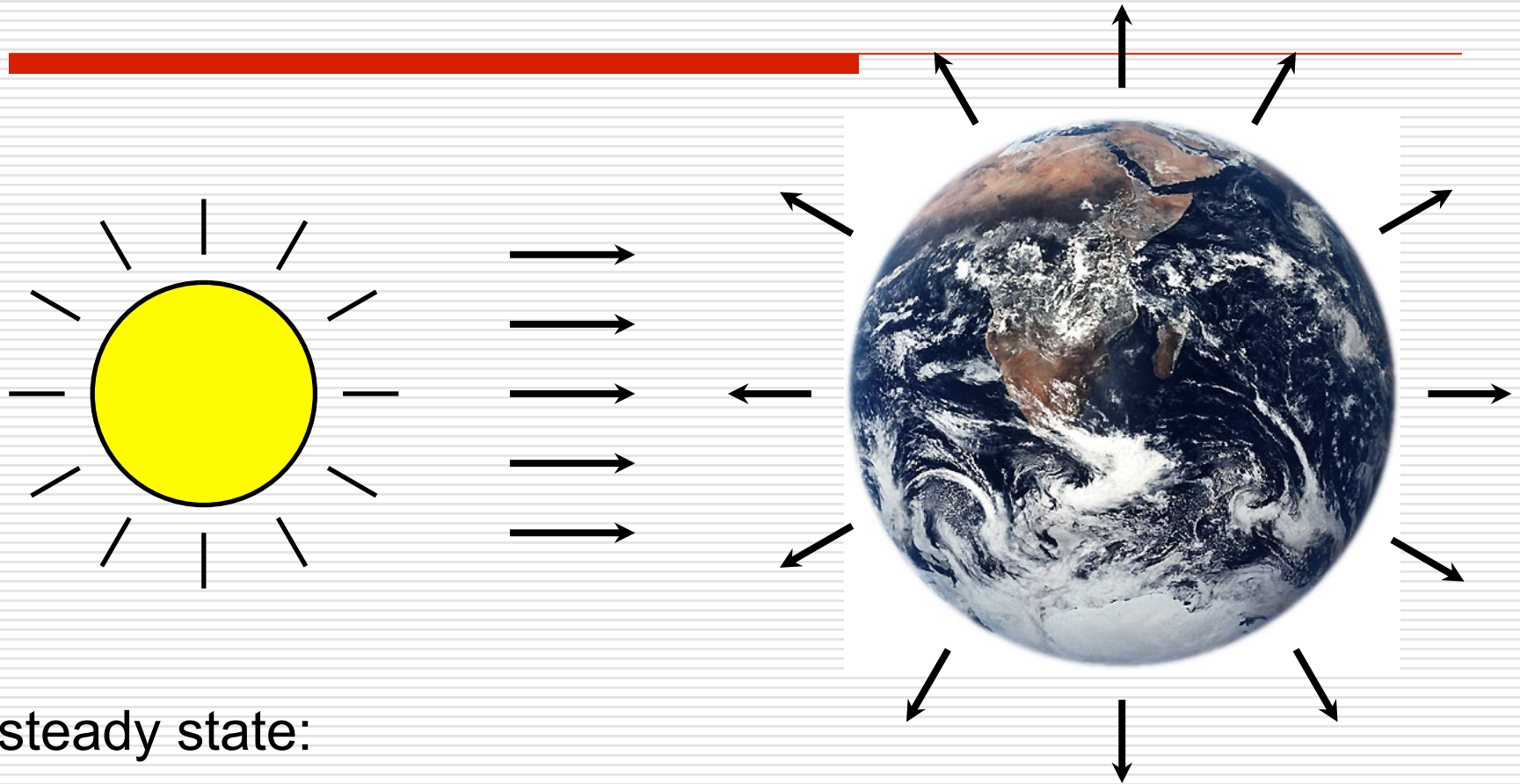
MIT

January 14, 2008

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 \perp to rays:

$$S_0 \approx 1367 \text{ W/m}^2$$

Average incident solar energy:

$$S_0 / 4 \approx 342 \text{ W/m}^2$$

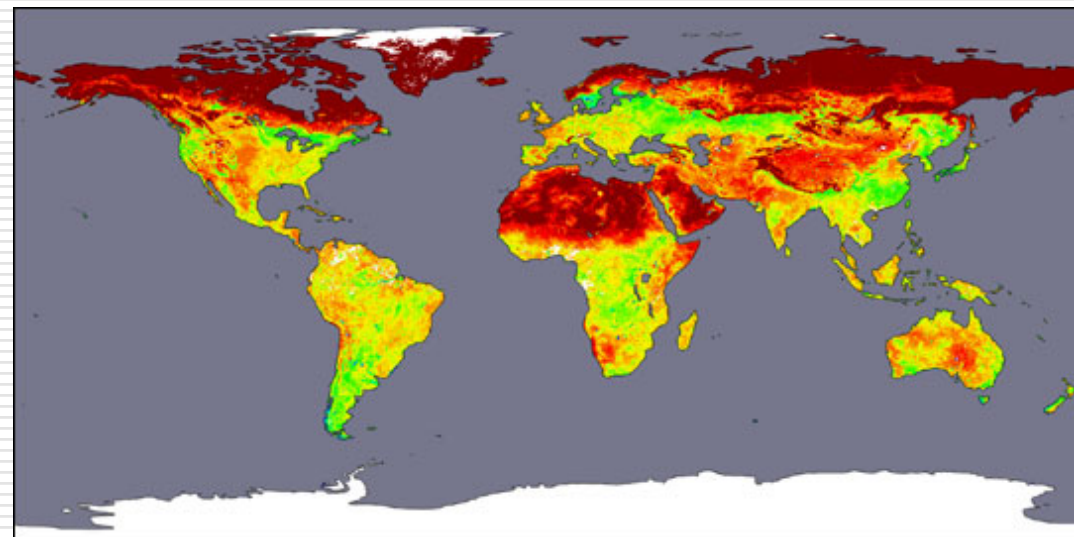


Albedo

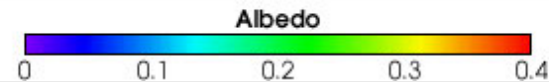
Albedo (α) = fraction of incoming solar radiation reflected

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 ...



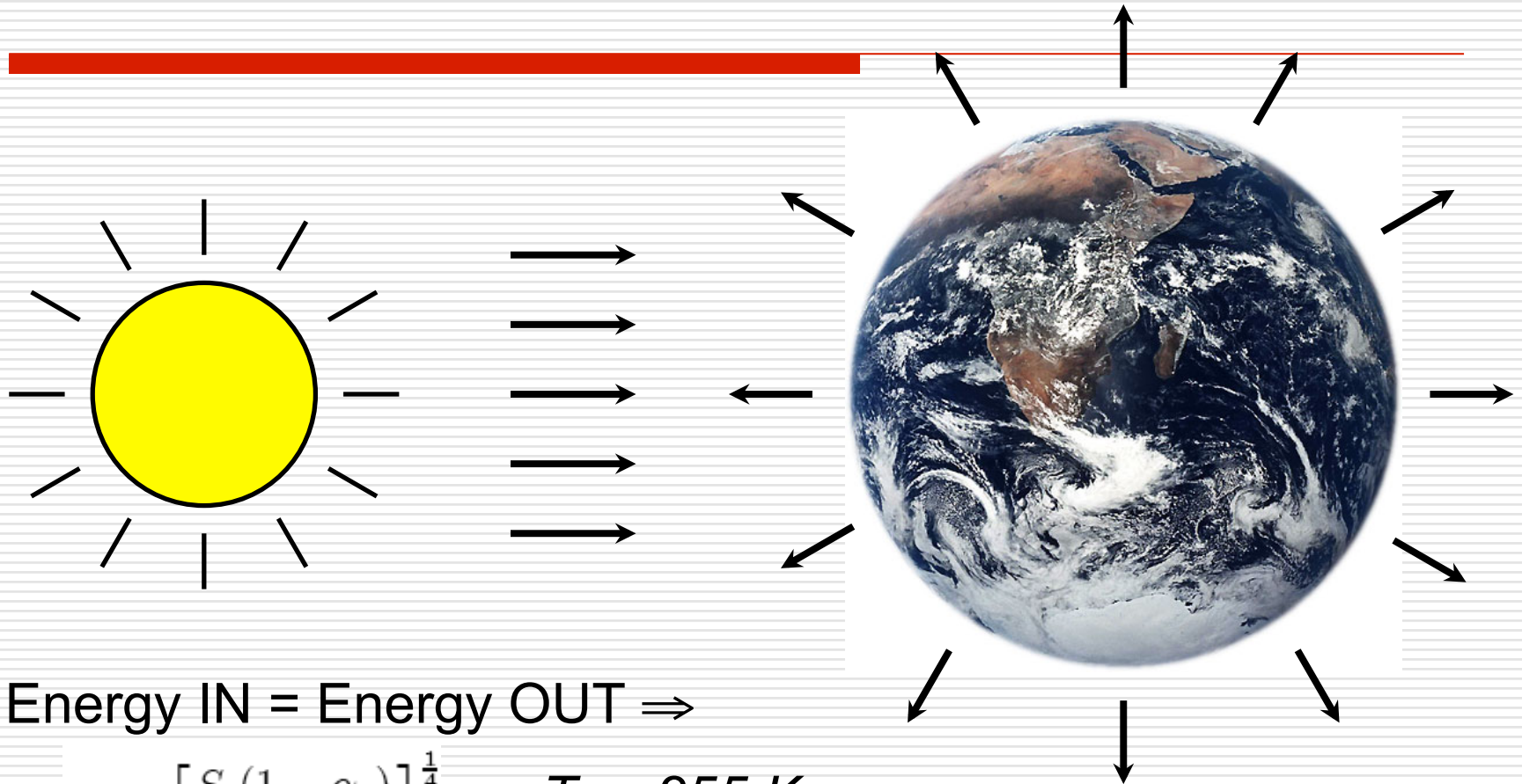
Outgoing Terrestrial Radiation

Stefan's law for blackbody radiation:

$$\text{Energy OUT} = \sigma T_e^4$$



Global Energy Balance Model



Energy IN = Energy OUT \Rightarrow

$$T_e = \left[\frac{S_0(1 - \alpha_p)}{4\sigma} \right]^{\frac{1}{4}} \quad T_e = 255 \text{ K}$$

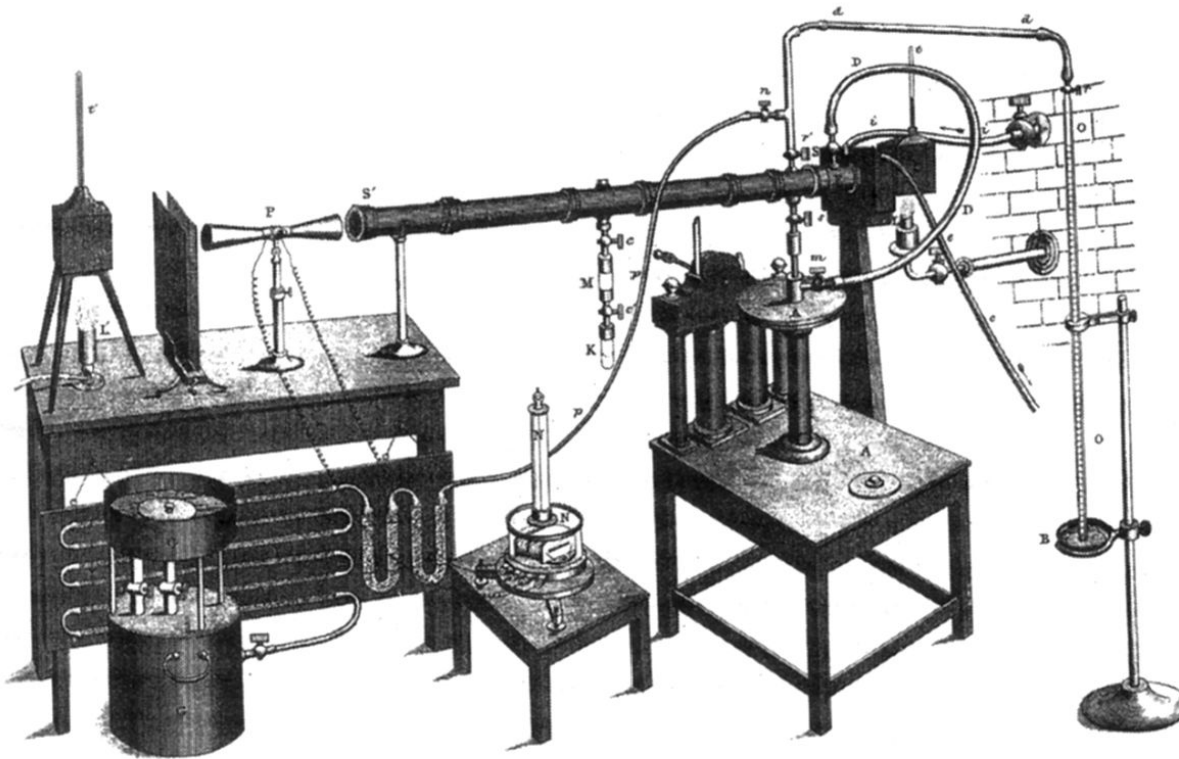
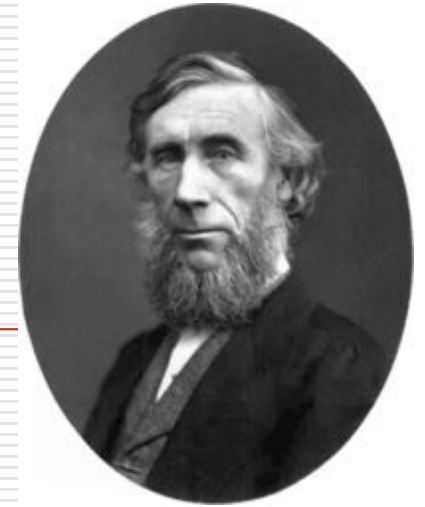
[Actual: $T_s = 288 \text{ K}$]

Joseph Fourier (1768-1830)

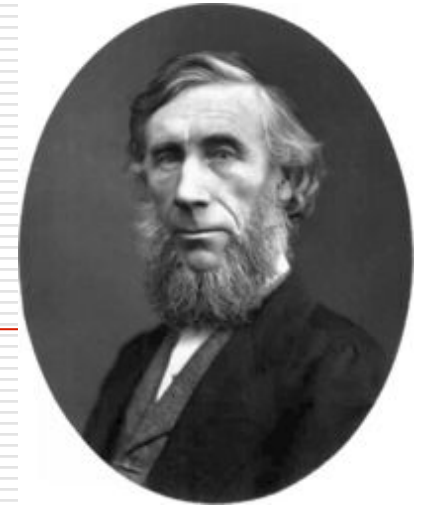


- ❑ First to recognize the concept of planetary energy balance (though infrared radiation had not yet been discovered)
 - ❑ Calculated a radiative equilibrium temperature much too cold
 - ❑ Inferred that the atmosphere interferes with the transmission of outgoing terrestrial heat
 - ❑ This is what eventually came to be called the *greenhouse effect*
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John Tyndall (1820-1893)



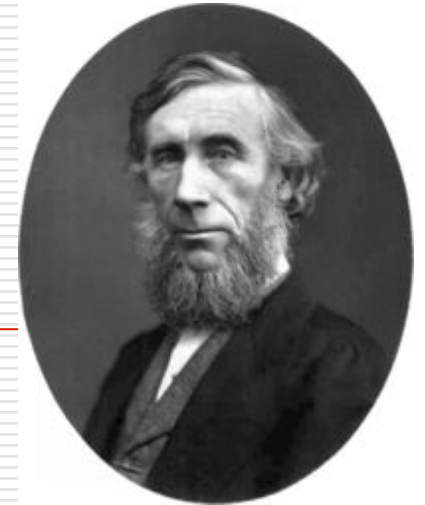
John Tyndall (1820-1893)



- Conducted laboratory experiments, showed that several atmospheric gases absorb heat, notably H₂O and CO₂
- 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)

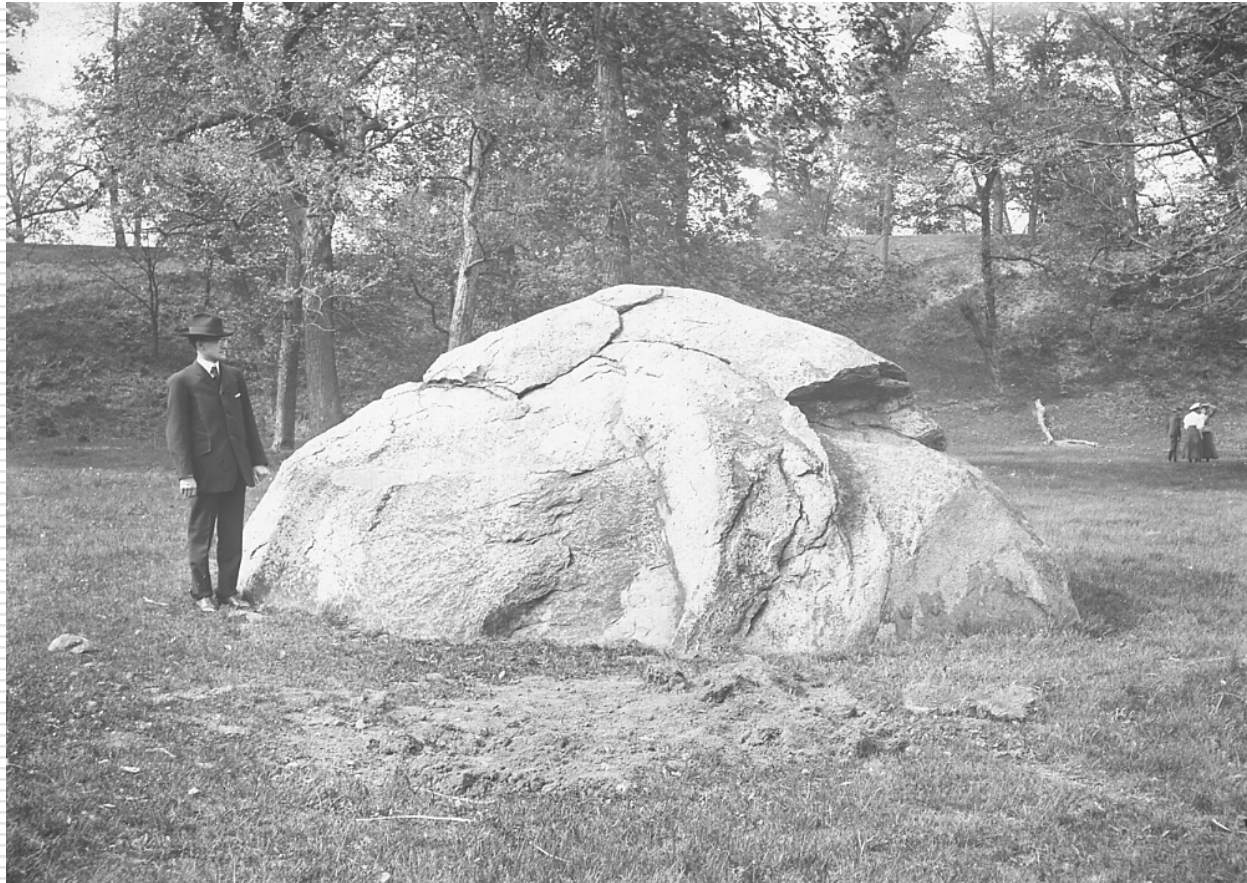


Water vapor “is a blanket more necessary to the vegetable life of England than clothing is to man. Remove for a single summer-night the aqueous vapour from the air... and the sun would rise upon an island held fast in the iron grip of frost.” Tyndall, 1863

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.cwr.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.cwr.edu/~huwig/catalog/slides/169.A.1.jpg>



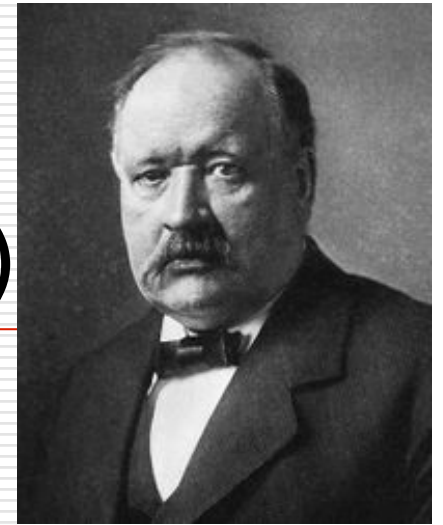
Figure 10. Professor T.C. Chamberlin's map was the first attempt to picture North America during the last ice age. (From J. Geikie, 1894.)

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*)
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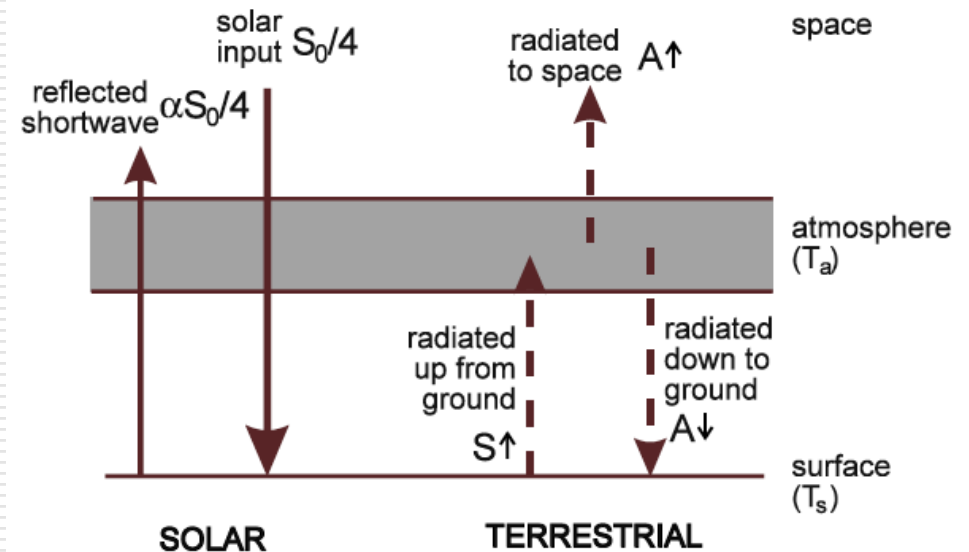
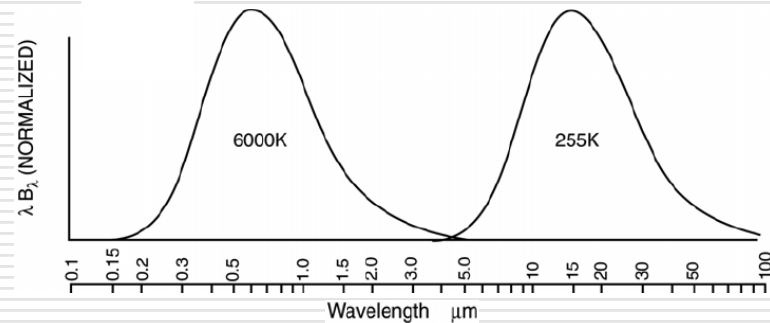
Calculating the greenhouse effect

- 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)

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

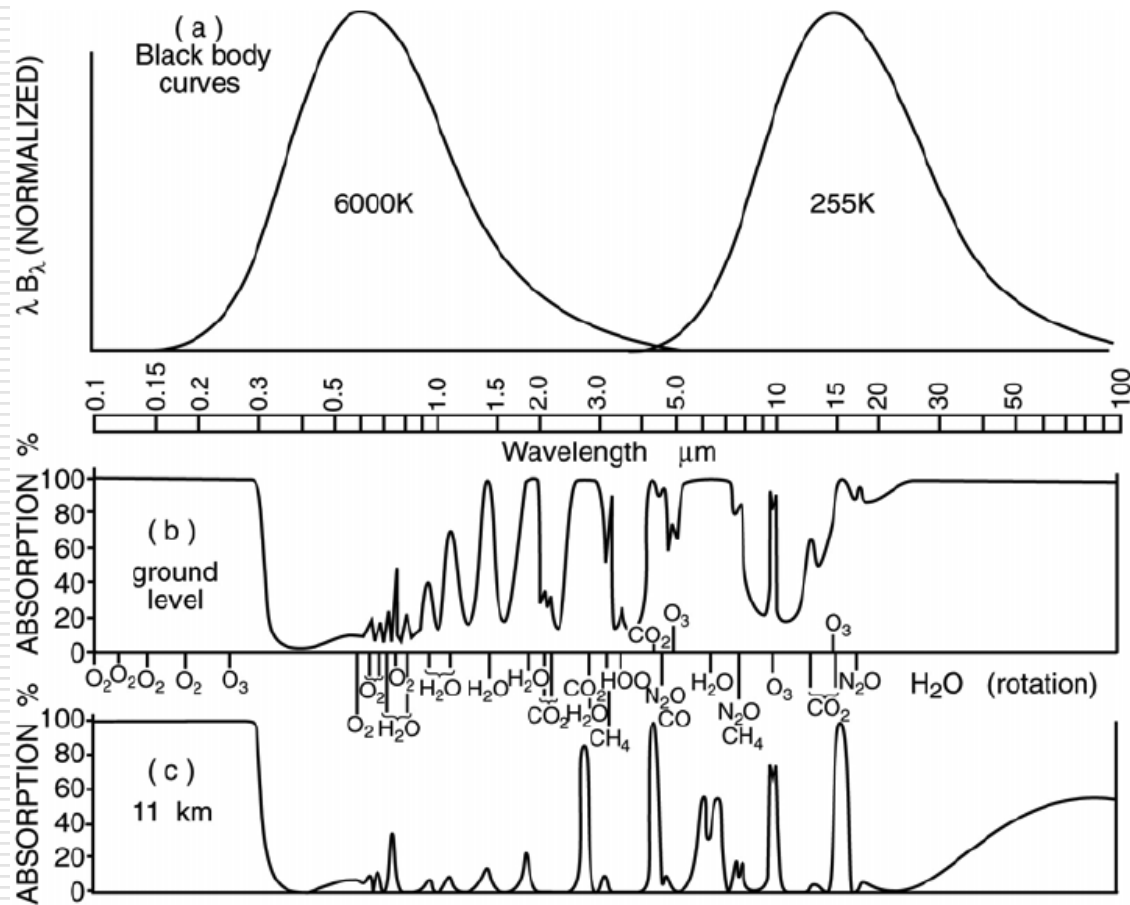
$$T_s = 303 \text{ K}$$

[Actual: $T_s = 288 \text{ K}$]



Source: Marshall 2007

A “leaky” greenhouse



Source: Goody and Young, 1989

Water vapor feedback

- ❑ Tyndall's work had shown that H₂O is the dominant greenhouse gas in the atmosphere (was and still is much more abundant than CO₂).
 - ❑ Warmer air can hold more water vapor
 - ❑ Warmer ---> more H₂O ---> 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 CO₂ 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 CO₂ vary that much?

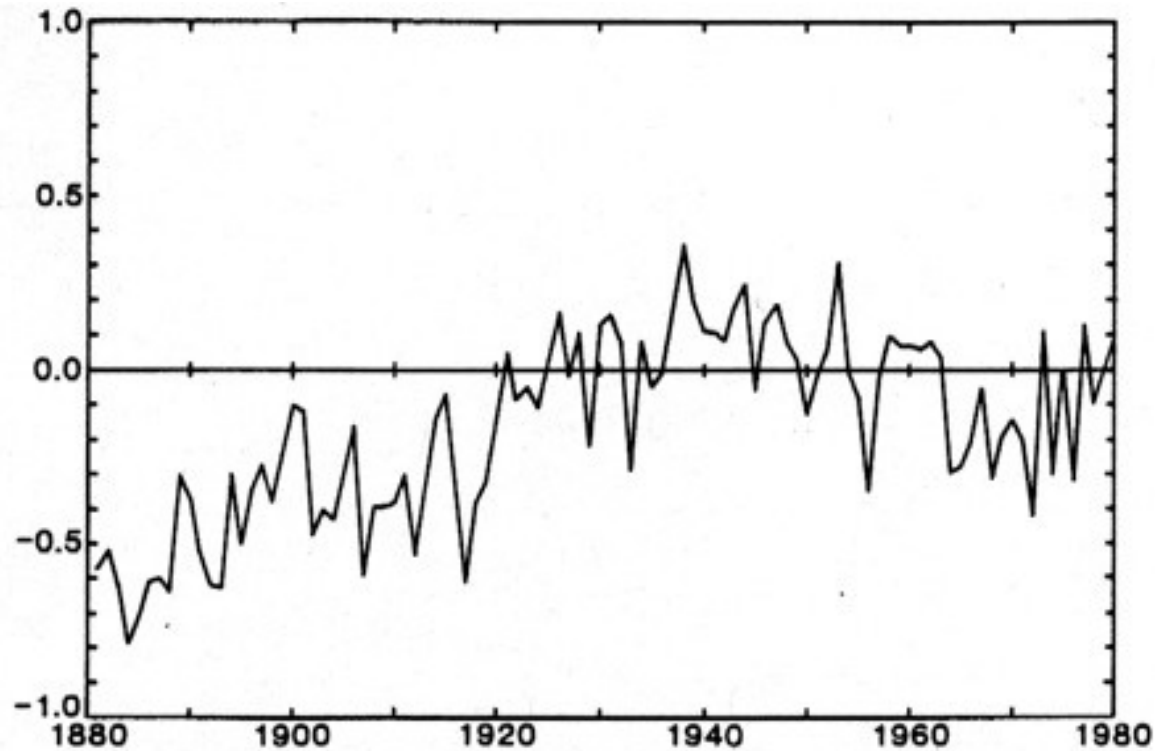
- ❑ Arrhenius turned to a colleague named Arvid Högbom who was studying how CO₂ cycles through natural geochemical processes (e.g. volcanoes, oceans)
 - ❑ Högbom found something remarkable: industrial sources were emitting CO₂ at a rate comparable to geochemical sources!
 - ❑ They realized that given 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 CO₂ 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)





Monday, Jan. 02, 1939

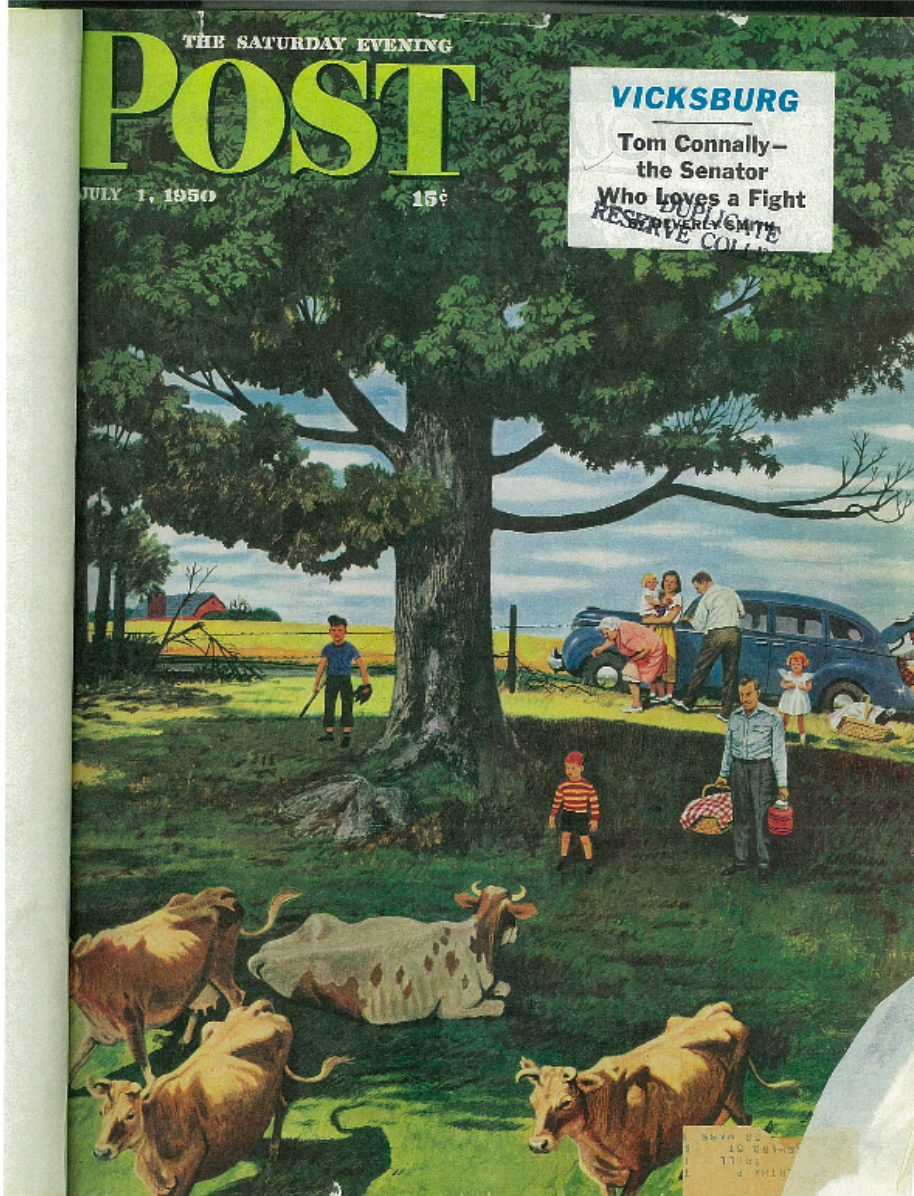
Warmer World

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. . . ."

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

great | In 1932 the U.S. Weather Bureau assembled all available records covering a 20,00 | century or more, found that they showed a trend towards warmth." Greer | obscu |

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.



Crewland to run a major icebergs. Is it on the way to becoming as terror as South Carolina?



Climatologist H. H. Ahlstrom asserts that the earth is undergoing a change toward greater warmth.

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

FOR the past three winters a colony of French and Indian who live on an island in the Deschamps River, near Old Town, Maine, have been plagued by unseasonable frosts. Since time immemorial, the tribe has used the ice as a bridge to the mainland from November until April, walking back and forth on sleds, driving tracks and automobiles on a usual late, across the slippery surface. Until recently, the ice had never gone out in January, so the members of the tribe seem and the results of annual heating tests on the day and hour of the spring break-up outside.

But since 1948, there has been a January thaw every year—in the neighborhood of Trenton and Old Townville alike. In 1949 the ice was out on an ordinary day 610 Trentons were maximum on their trip the same three days. Now the state of Maine has a winter. Doctor Ahlstrom really has good to us," says Mrs. Fredo Haddock, a climate of the chief. "It has had a changed character, we would never have had the new bridge."

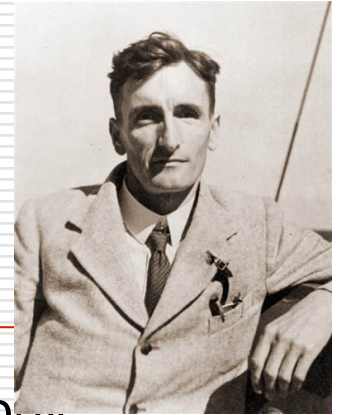
Last August sixth, without New Jersey industrialists in reported that they had been robbed of "the climate was in fact," and "local figure" covering the old, common sense. There was even possible side effect, explain.

The Gulf Stream might have changed its course. Doctor Ahlstrom's mysterious changes are happening in the super-heat, and a few scientists know. Franking, who has been a Royal Geographical Society, in London on the record was a

1948, Dr. Hans Geographical at Stockholm. Many people as has happened to is of great interest say that they in winters in their. Even more remarkable observation, average on all social life. Full possession, land climatic in natural and exotic change in south, and in f weather and was. In the Arctic records which h years indicate of and draw. Both the measurement refer you to situ annual growth. Lake, the ice of the volume, and nearly doubled "Okla" now is difference said. Drive from the tropical border England in the. If there is still a fresh flow of Atlantic states. Yorkers as the snow fell and it long been.

Just What PEOPLE are actually doing "ask someone?" course? Is the a getting ready for a matter of a twelve-mile or Bill's home p rhaps of a clim in previous a uminary's stud atomic experime (ness, perhaps) in a atmosphere side of merely. The picture is questions in past world's most e gress. A full, le was and frost in years of its side the ice rivets of finally, with geologists, in from all over the mosaic of 1975. This picture of their; the, ending of the v atmosphere can measure, parts

Guy Stewart Callendar (1898-1964)

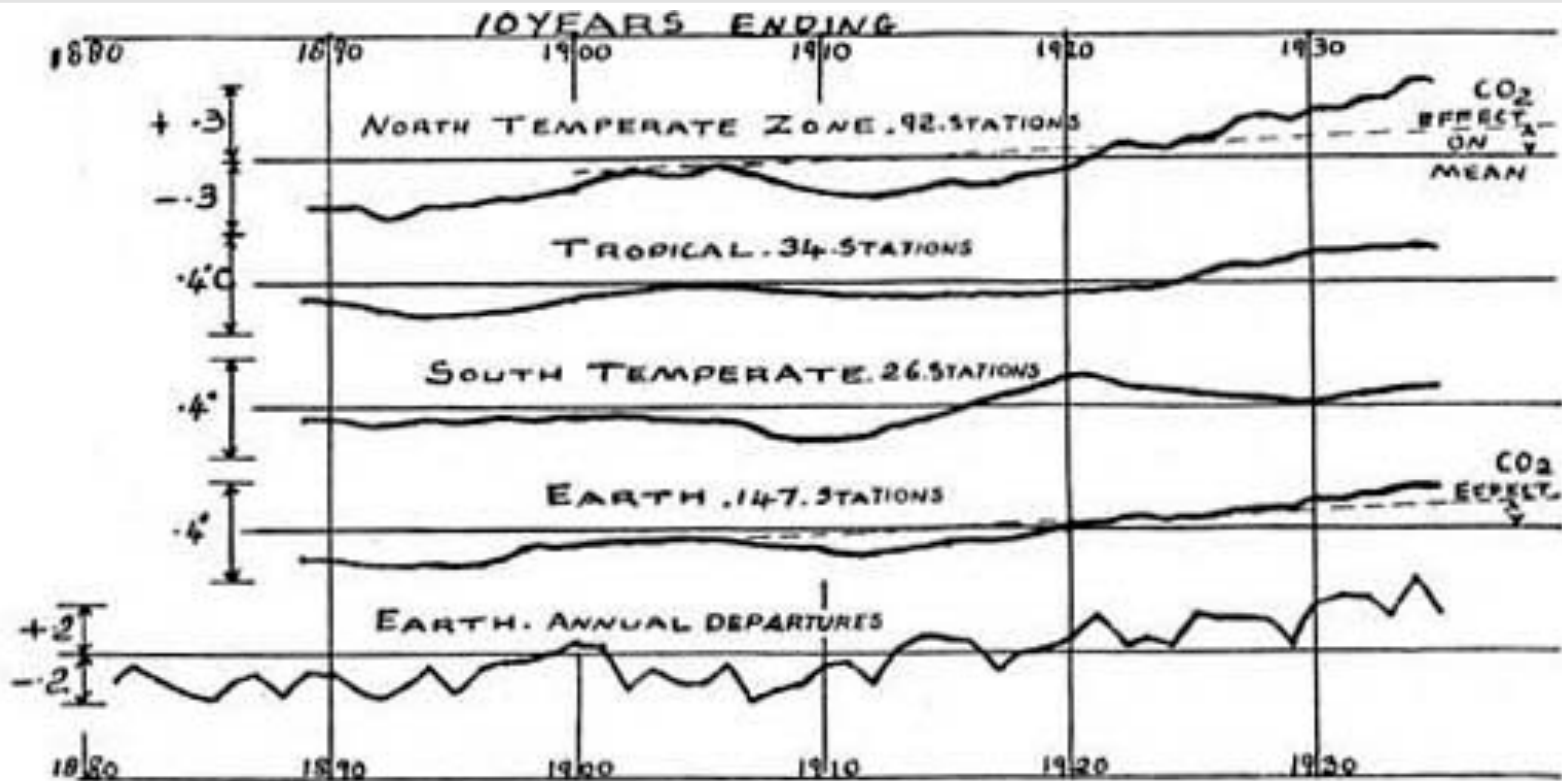


- ❑ English steam engineer, dabbled in meteorology as a hobby
- ❑ Curious about the apparent warming trend
- ❑ Also interested in Arrhenius' CO₂ warming theory
- ❑ Compiled many old temperature observations, found a warming
- ❑ Compiled available data on atmospheric CO₂ concentration, and found it was increasing
- ❑ Used an energy balance argument to calculate the effect of the CO₂ 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"

Guy Stewart Callendar



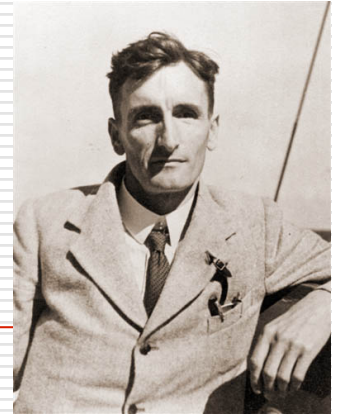
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Callendar (1968), QJRMS 64, p. 233

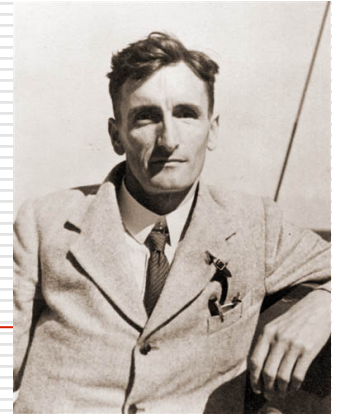
Guy Stewart Callendar



“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 CO₂-induced greenhouse warming was occurring.
 - ❑ Sometimes called the “Callendar Effect”
 - ❑ However, few people were convinced at the time.
-

A few persistent arguments against CO₂ greenhouse warming

- ❑ Lab results showed CO₂ 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 CO₂ were lacking. Were emissions accumulating in the atmosphere, or being quickly taken up by the oceans?
 - ❑ Meanwhile, radiometric ¹⁴C dating was invented.
 - ❑ In 1955 Hans Suess was measuring carbon isotopes in tree rings to better calibrate ¹⁴C 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 CO₂ in the atmosphere
 - ❑ Along the way, Revelle discovered a peculiar buffering mechanism in seawater: to equilibrate with a given increase in atmospheric CO₂, 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*.

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.”

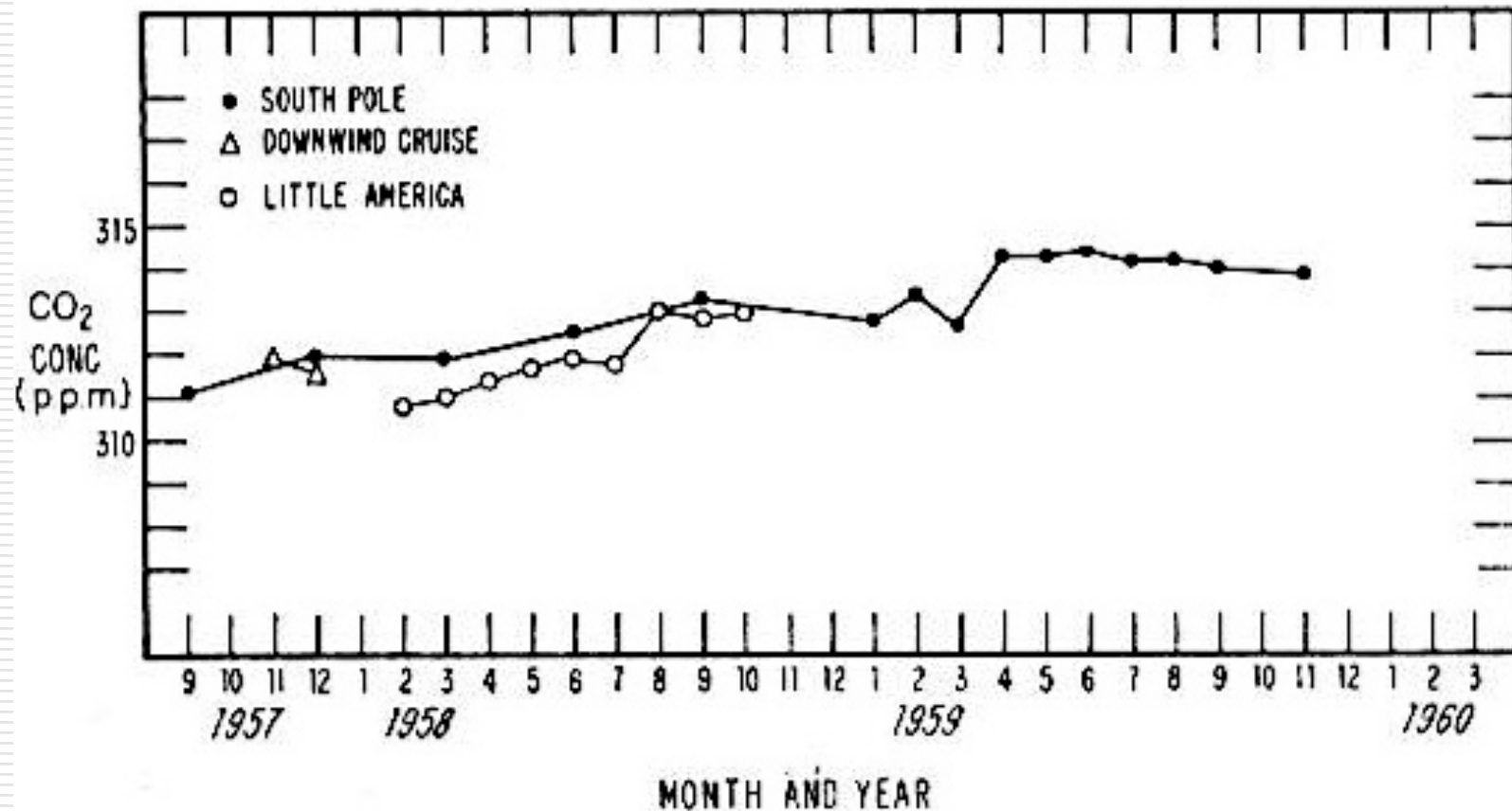
Revelle and Suess, 1957

C. David Keeling (1928-2005)



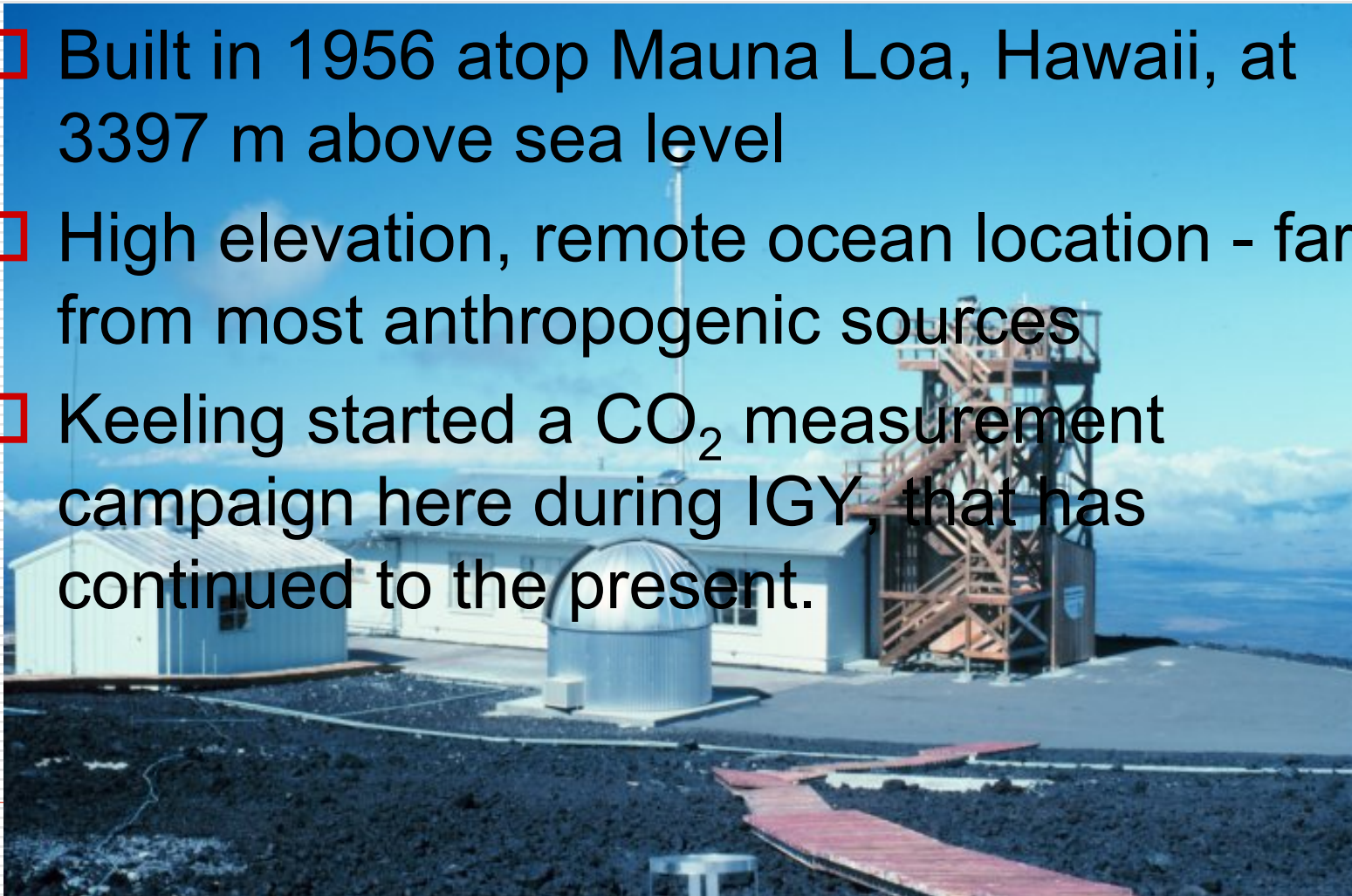
- ❑ Geochemist, became interested in atmospheric CO₂ as a post-doc at CalTech (1954-1956)
- ❑ First to develop reliable instruments and techniques to measure the baseline atmospheric CO₂ concentration
- ❑ Measurements motivated in part by the CO₂-greenhouse theory of climate change
- ❑ With IGY funds, Revelle hired Keeling to conduct a short-term global CO₂ survey

Keeling's Antarctic measurements

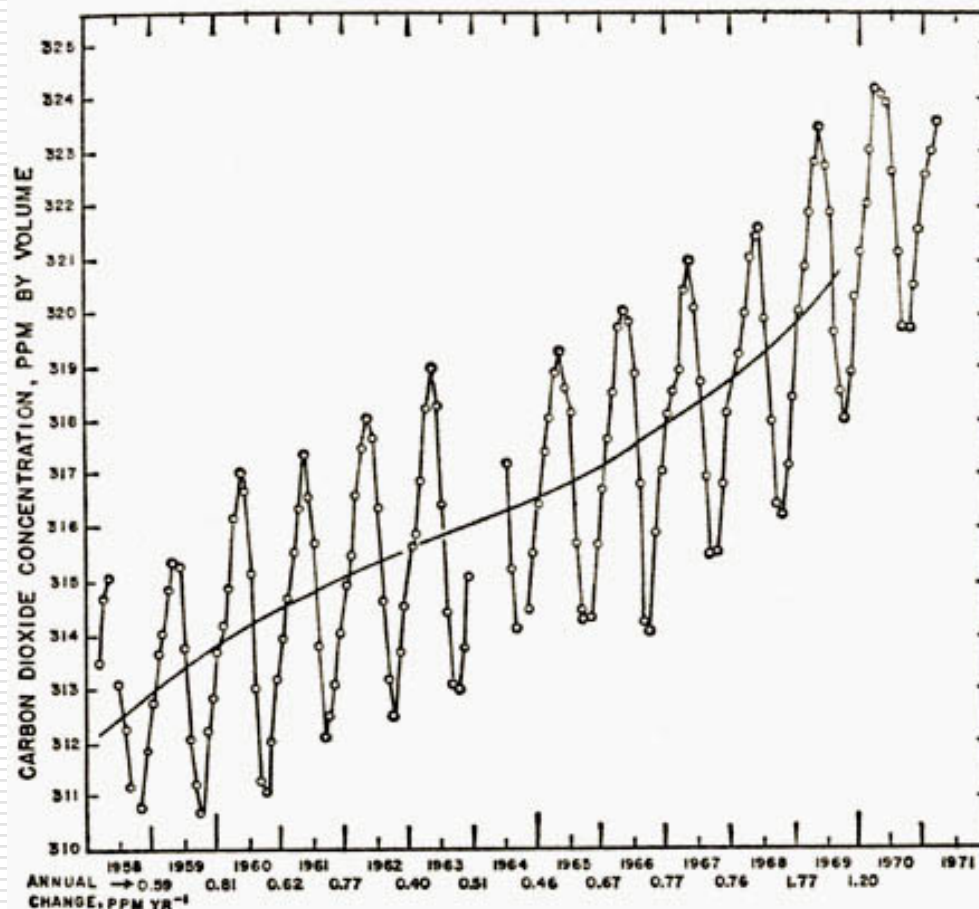


The Mauna Loa observatory

- ❑ 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 CO₂ measurement campaign here during IGY, that has continued to the present.



The Keeling Curve (1971)

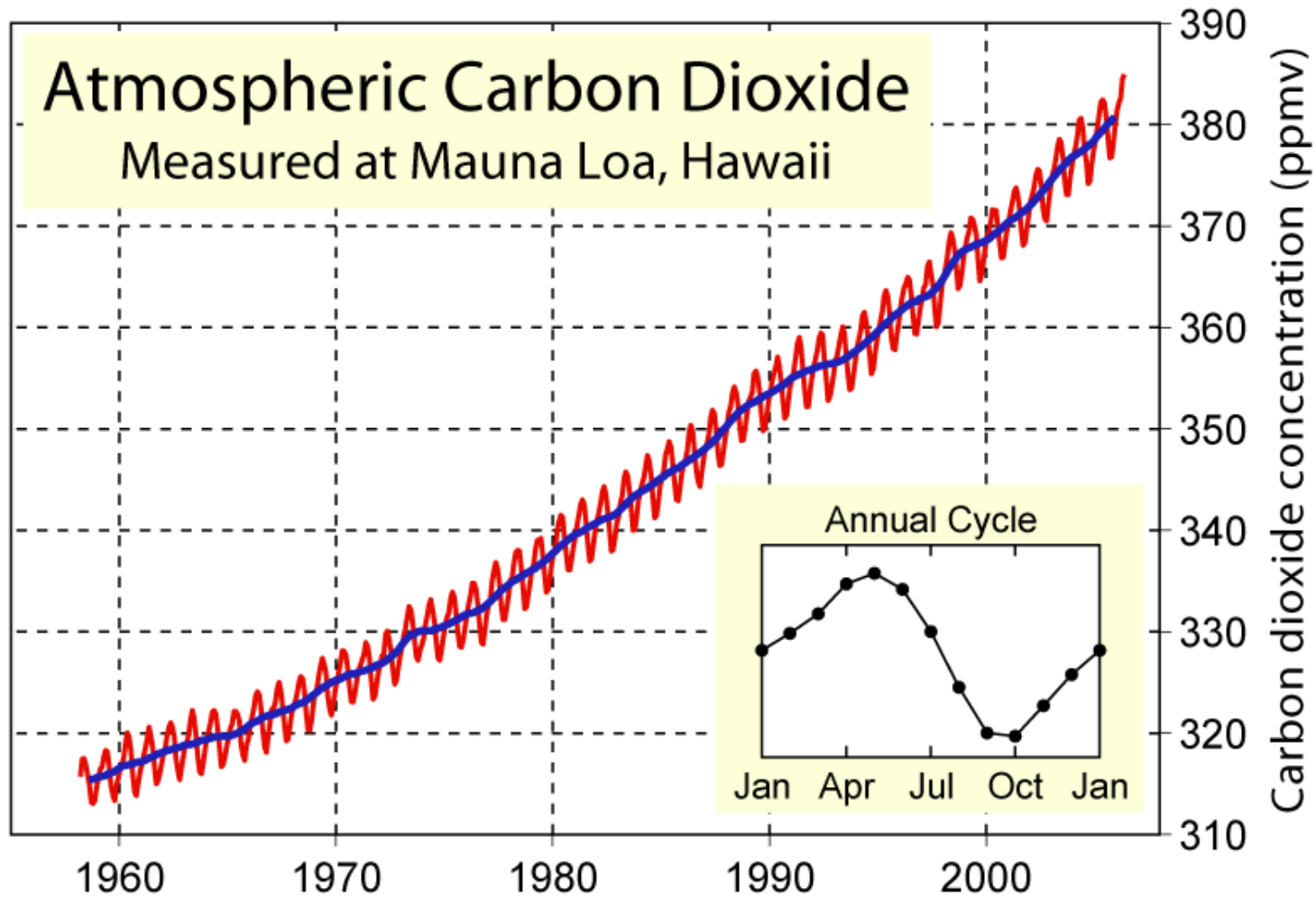


Reproduced from The Discovery of Global Warming at <http://www.aip.org/history/climate/xKeeling71.htm>

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

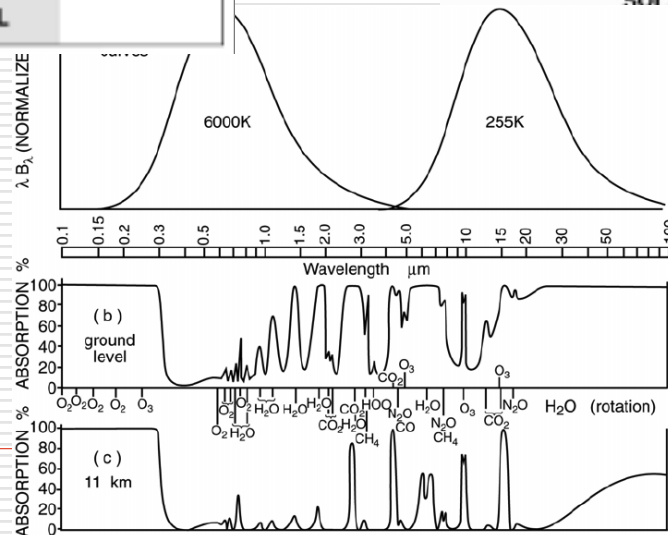
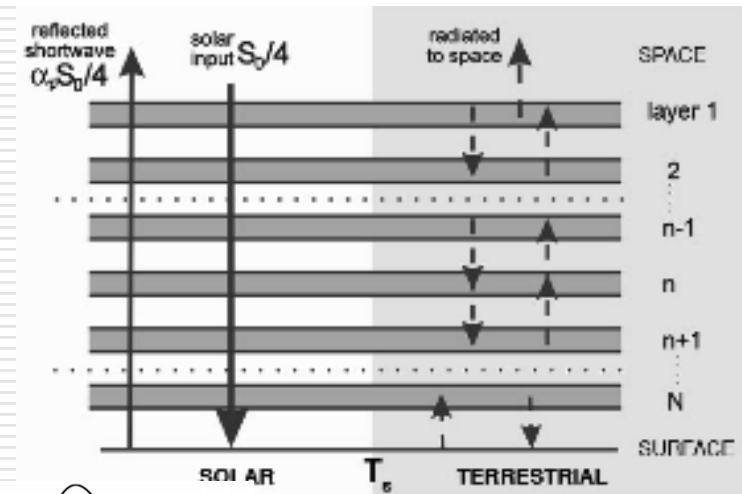
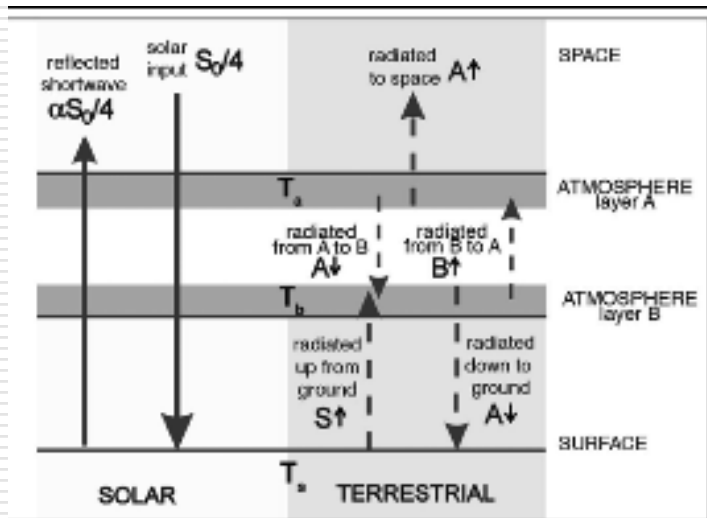
The Keeling Curve (now)



So now we know

- ❑ As Keeling's measurements continued, there could no longer be any doubt that anthropogenic CO₂ 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; CO₂ 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 CO₂
-

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.

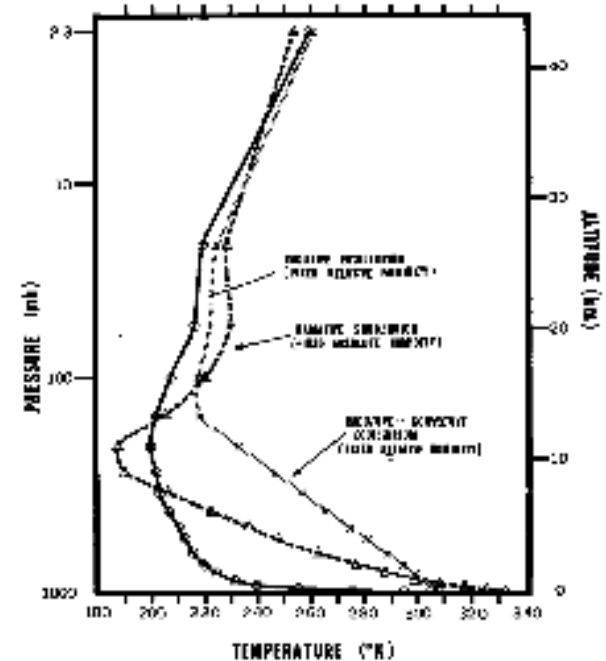
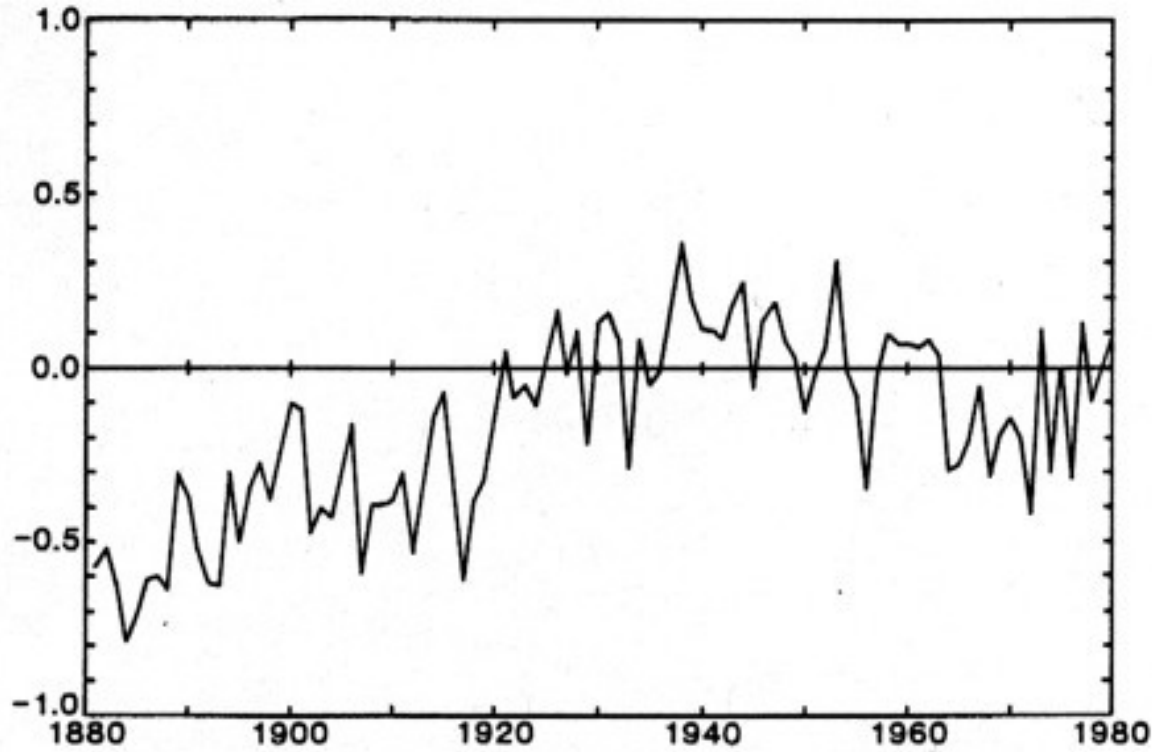


FIG. 5. Solid line, radiative equilibrium of the clear atmosphere with the given distribution of relative humidity; dashed line, radiative equilibrium of the clear atmosphere with the given distribution of absolute humidity; dotted line, radiative convective equilibrium of the atmosphere with the given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

The story so far, circa 1967

- Most of the technical details of the greenhouse effect were worked out after World War II.
- We had a long history of original research on the greenhouse effect.
- Increases in atmospheric CO₂ were measured in the late 1950s and early 1960s.
- Measurements of the greenhouse effect were made in the late 1950s and early 1960s.

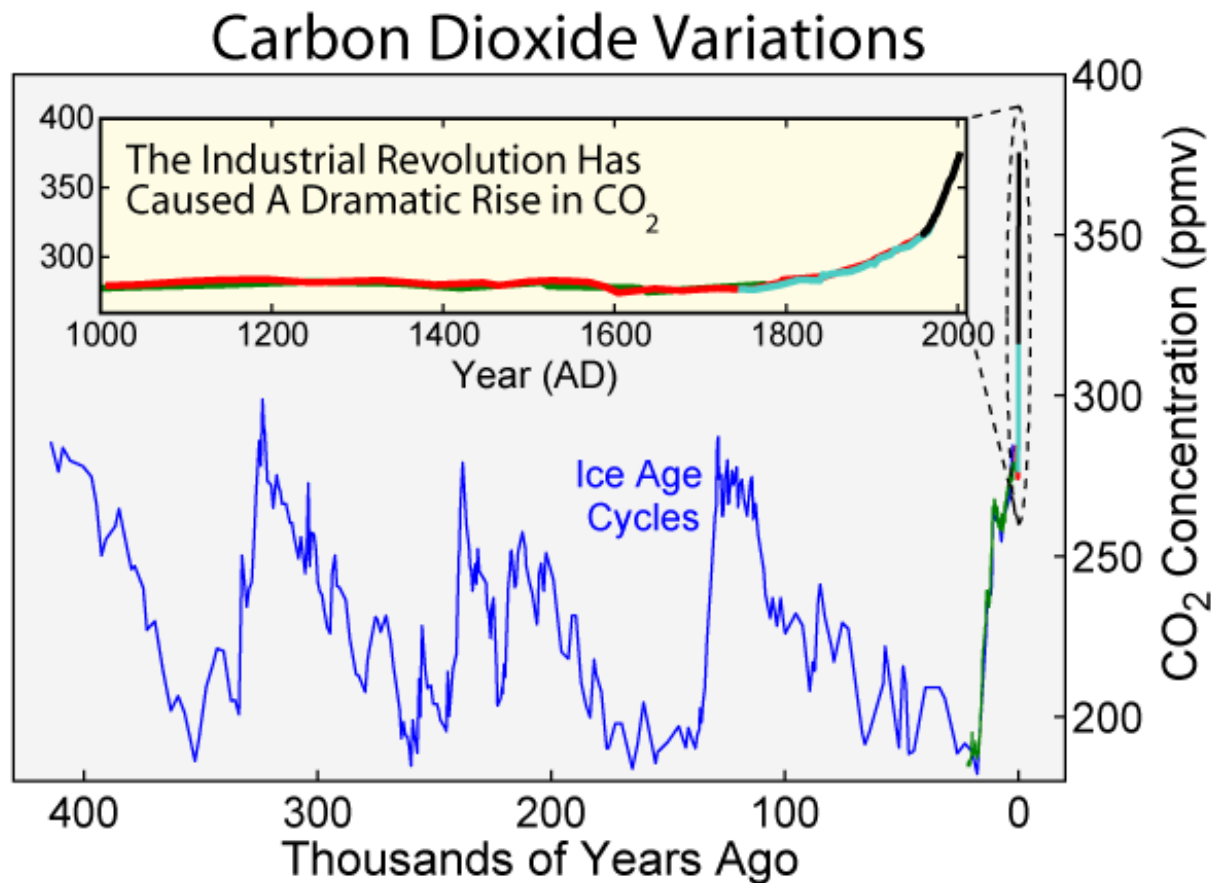


P.D. Jones et al (1982), MWR 110, p.67

CO₂ 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 CO₂ feedbacks (involving, among other things, the temperature dependence of the chemical weathering of rocks and the increased solubility of CO₂ in cold oceans)
 - ❑ This sort of CO₂ 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: CO₂ and orbital changes both seem to be involved in ice age cycles.
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CO₂ and the ice age story

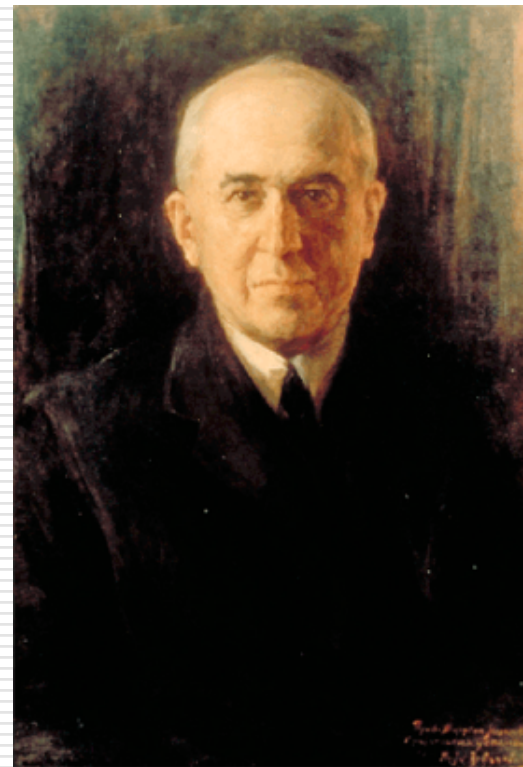


Source: Global Warming Art, <http://www.globalwarmingart.com>

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
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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
