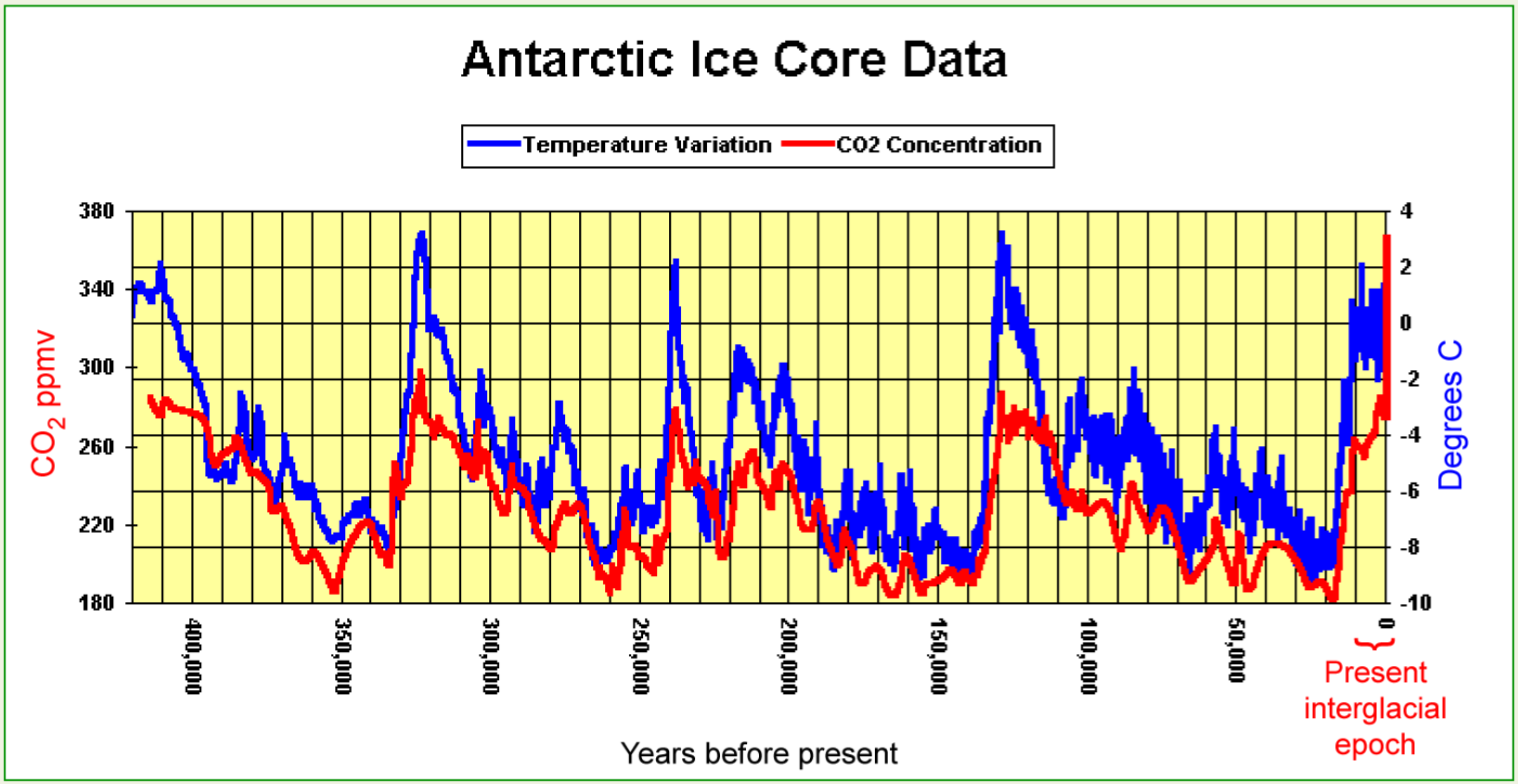
"Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere?"
- Svante Arrhenius (1896)



- From **Petit et al.**, *Nature*, 1997

The science behind projections of forced climate change:

Historical basis, open questions, and implications for policy makers

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For the seminar "Faith in the Future"
to be held at the Royal Palace, Stockholm
22 March 2012

Photo credit: "The Blue Marble"
http://visibleearth.nasa.gov/view_rec.php?id=2429

The science behind projections of forced climate change: Historical basis, open questions, and implications for policy makers

1. **History: highlights of research on climate and *forced* climate change**
2. **What is known with certitude; esp. chemistry**
3. **Conclusion: implications of these limitations to planning for the future climate**

1. History of the development of a scientific basis for understanding Earth's climate

Pre-19th century:

- **Boyle (1665); Newton (1700); Anders Celsius (1742);** Definition and measurement of temperature
- **An open question of the day:** What determines the Earth's temperature?

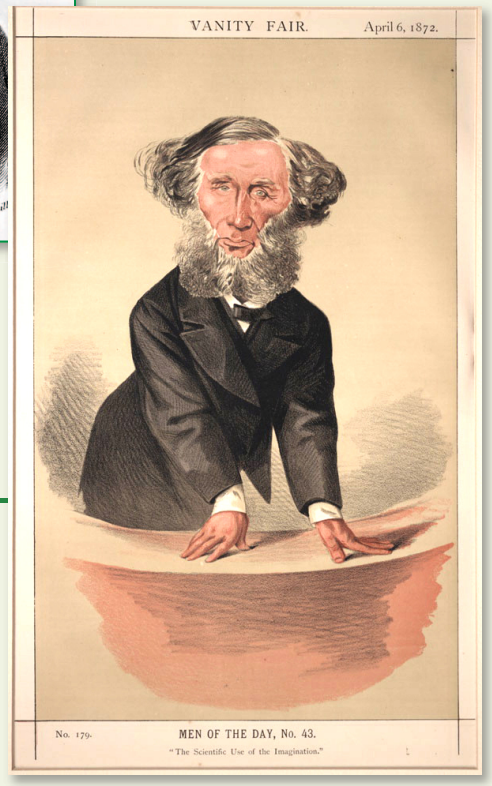
1. History, continued

19th century:

- **Fourier** (1827):

"Greenhouse effect"
"… light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat."

- **Agassiz** (1837):
  The Earth has been subjected to an ice age in the past.
- **Lord Kelvin (William Thomson)** (1848):
  Absolute temperature scale
- **Tyndall** (1860s):
  IR absorption and emission by CO_2 and water vapor
- **Stefan-Boltzmann** (1879-1880s):
  Radiative equilibrium and equilibrium temperature: Flux ~T^4



1. History, continued

19th century (cont.):

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

I. *Introduction : Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this : Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
§ *Comptes rendus*, t. vii. p. 41 (1838).

Phil. Mag. S. 5. Vol. 41. No. 251. *April* 1896. S

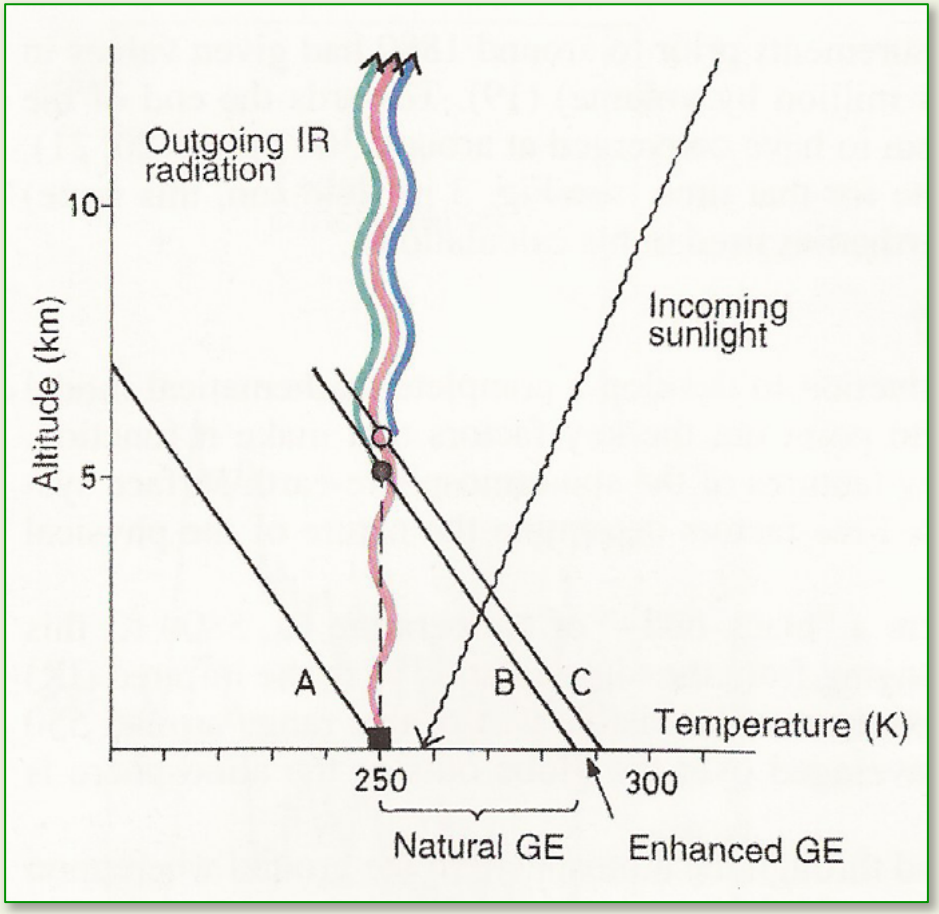
173

- **Langley** (1890): Infra-red absorption spectrum of Earth's atmosphere; temperature of Earth and moon (rock-salt prism; 21 bands)

- **Arrhenius** (1896): Earth's temperature and change of CO_2

1. History, continued

The fundamentals were all in place by 1900:



- From **Rodhe, Charlson, and Crawford**, *The Legacy of Svante Arrhenius* (KVA, 1998)

Figure 2. Schematic illustration of the natural and enhanced greenhouse effect. (See text for explanation.) Different effective altitudes for the IR emission are shown in color: Case A, no atmospheric IR absorption (red); Case B, natural greenhouse effect (green); and Case C, enhanced greenhouse effect (blue).

- Adding more CO_2 to the atmosphere would further warm the Earth's surface. Burning coal does that.

1. History, continued

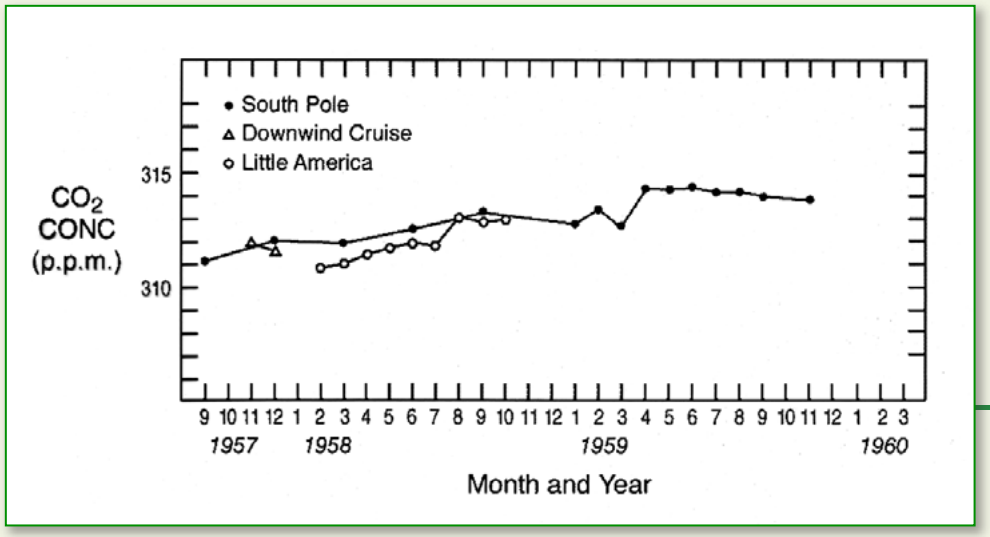
20th century:

- **Callendar** (1938):
  CO_2 has increased because of burning fossil fuels and is warming the Earth.
- **Rossby** (1939):
  Wave mechanics of atmosphere and oceans
- **Milanković** (1920, 1941):
  Cyclic wobbling of the Earth's orbit modulates timing of ice ages.
- **Suess** (1955): Pre-bomb increase of $^{12}C/^{14}C$ in tree rings proved anthropogenic source of increased CO_2.

1. History, continued

20th century (cont.):

- **Suess** (cont.): ^{14}C is produced naturally by cosmic rays and has a half-life of 5730 years; ^{12}C is stable and the main form in fossil-fuel CO_2
- **Revelle** (1956): Limited oceanic sink for anthropogenic CO_2; therefore, anthropogenic CO_2 will accumulate in the atmosphere. (He did not emphasize ocean acidification.)



- **Keeling**: First accurate measurements of increased CO_2 (Tellus XII, 1960)

- **Manabe and Weatherald** (1967): Beginnings of computer-based modeling of climate

1. History, continued

20th century (cont.):

- **McCormick and Ludwig** (1967); **Bryson** (1968); **Mitchell** (1970): Anthropogenic aerosols as a cause of the observed global cooling after 1940.

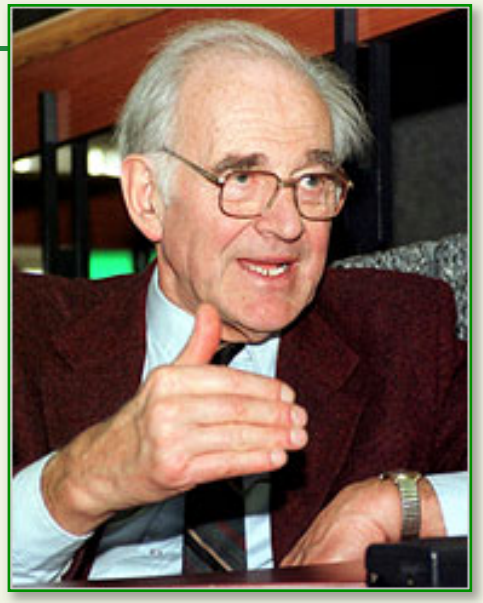
- **Rasool and Schneider** (1971): cooling by aerosols could "…be sufficient to trigger an ice age."

- **Charlson et al.** (1967-1982): Determination of scattering efficiency of industrial aerosols and its dependence on relative humidity; approx. Eastern U.S. molecular form: NH_4HSO_4; horizontal scale of haze blobs ~1000 km (matches synoptic/Rossby meteorological scale)

1. History, continued

20th century (cont.):

- **Twomey** (1971): Aerosol enhancement of cloud albedo (the so-called "indirect effect")



- **Bolin and Charlson** (1976): Regional scale cooling by anthropogenic sulphate aerosols; loss of several percent of incoming solar radiation (they missed the global box model calculation and global negative forcing!)

- **Junge** (1976): Articulated the terms *direct* and *indirect* cooling effects of aerosols

- **Ramanathan** (1985): Long-lived greenhouse gases (LLGHG) in addition to CO_2

1. History, continued

20th century (cont.):

- **Dickinson and Cicerone** (1986): Focus on the concept of climate *forcing* as being more certain than temperature response

Origins of emphasis on *forcing*
(as opposed to temperature
as the index of imposed climate change)

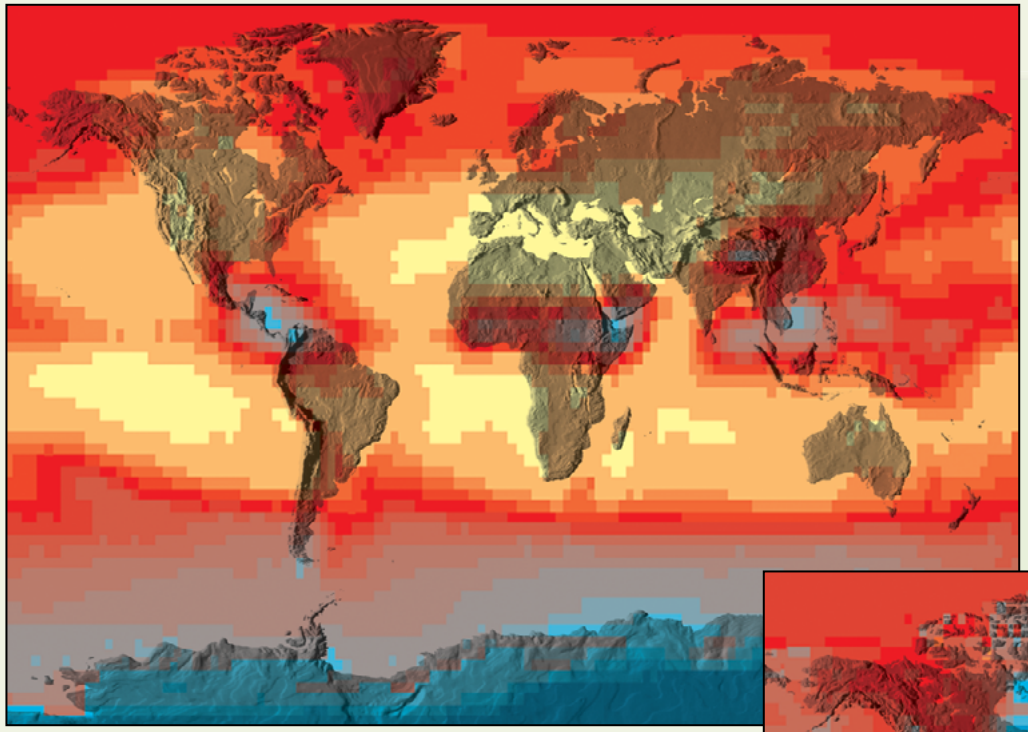
"…However, the implications of these details have not yet been satisfactorily resolved, and so our estimates of the climate change resulting from the various trace gases assume that the dependence of this climate change on external *forcing* can simply be represented by the global radiative trapping alone."

– Dickinson and Cicerone, *Nature*, **319,** 1986

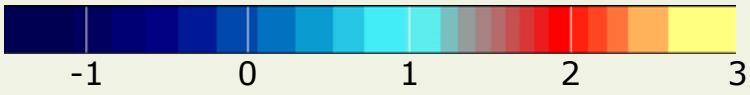
1. History, continued

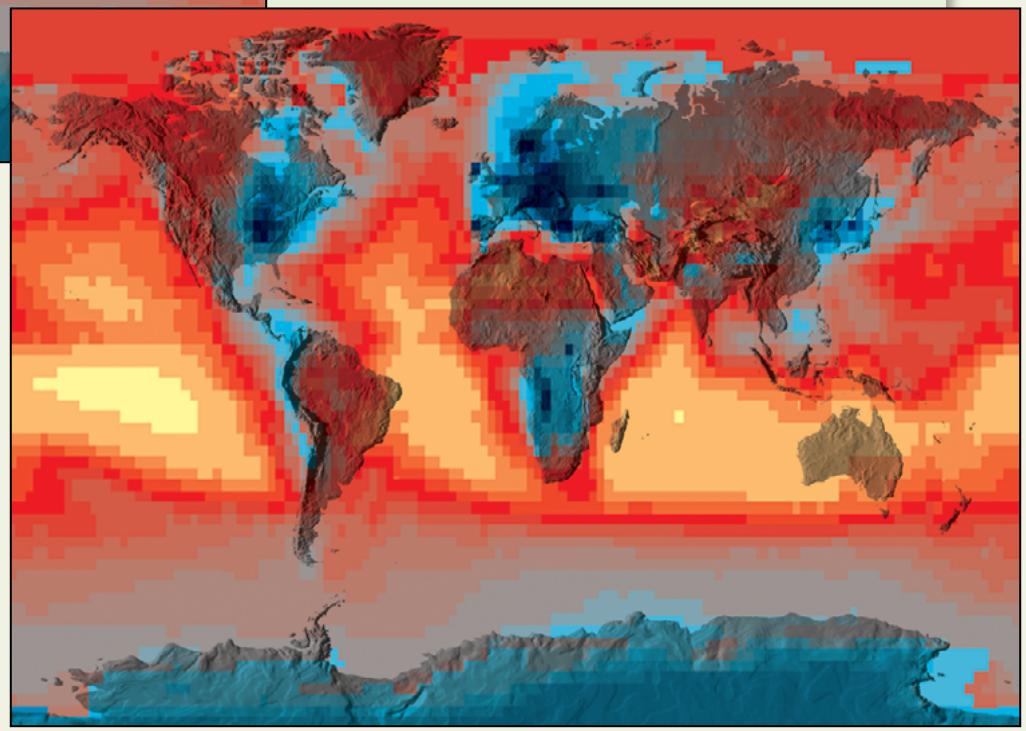
20th century (cont.):

- **Lorius et al.** (1987): Low CO_2 (280 ppm) during pre-industrial Holocene, lower still in ice ages (180 ppm)
- **Grassl** (1988): Existence of a large negative *forcing* by anthropogenic aerosols (e.g., $SO_4^=$) in mid-latitudes of the Northern Hemisphere
- **Charlson et al.** (1991): First global map of calculated direct *forcing* by $SO_4^=$ aerosol; *Negative forcing* comparable in magnitude to that of CO_2, but opposite in sign (-0.3 to -1 W/m^2, cf. +2.4 by man-made GHG)
- **Kiehl and Briegleb** (1993): *Forcings* by CO_2 *and* by aerosols are not geographically uniform



Results from Kiehl & Briegleb, as used in: **Charlson and Wigley,** *Scientific American,* 270 (1994)





Average heat gain (*forcing*), July 1993
(watts per square meter)

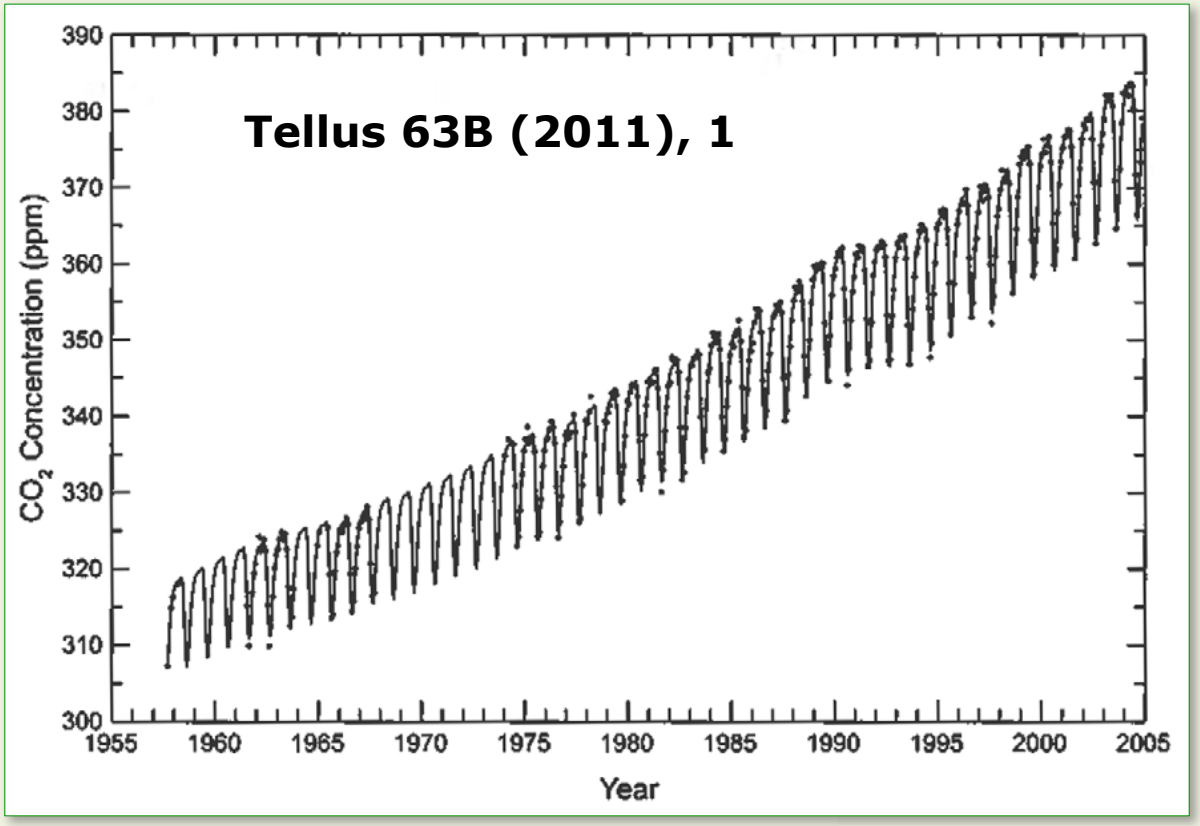
1. History, continued

… and on into the 21st century:

- **Weilicki et al.** (1998 onward): Attempts via satellites to measure Earth's changing radiation balance; unacceptably large uncertainty
- **Model calculations** of expected warming; large uncertainty in climate sensitivity (i.e., ΔT for doubled CO_2)
- **IPCC projections** of climate *forcing* and of climate change: (1990, '92, '94, '95, 2001, '03, '07…)
- Prediction and documentation of global **ocean acidification** by increased CO_2 (**Caldeira and Wickett**; 2003)
- **Keeling** and many others: Large amounts of CO_2 data
- Measured **increase of CO_2** to ~390 ppm

1. History, continued

C. D. Keeling et al., 2011 ◆ The last publication of the late Dave Keeling

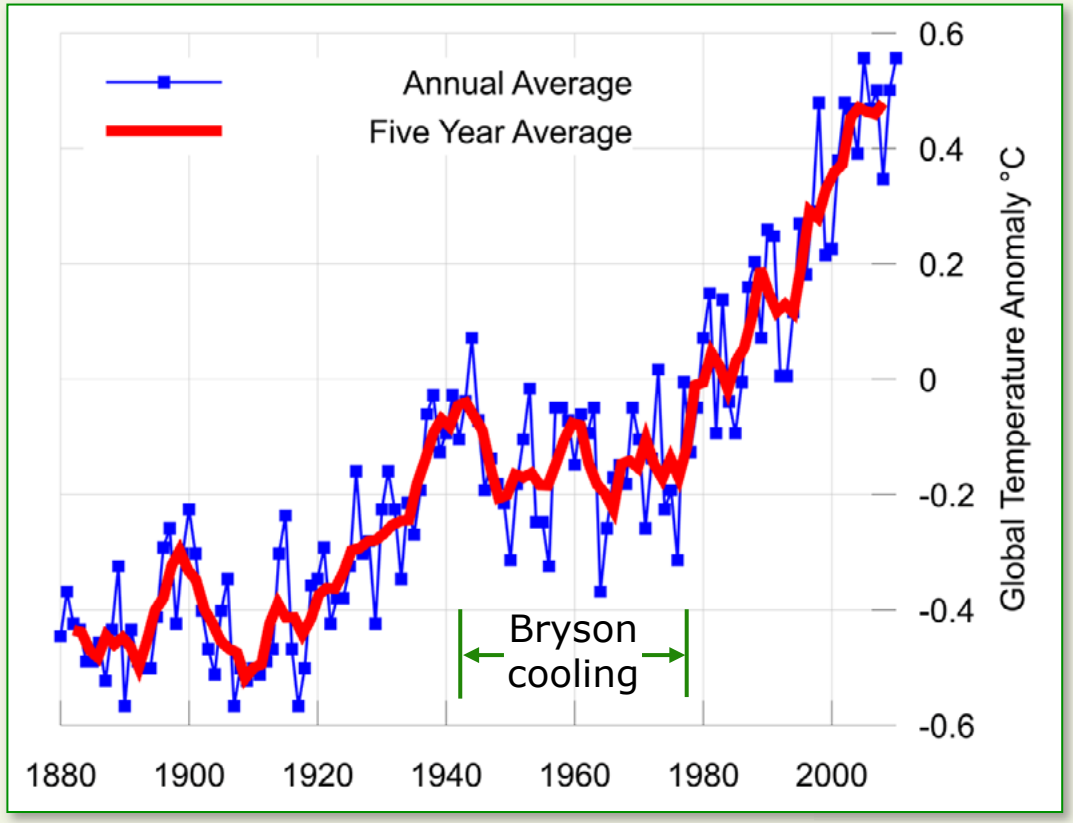


The CO_2 concentration, in ppm, versus time, from observations for Arctic ice floes, 1957-1958, and Point Barrow, Alaska, 1961- 1968 and 1974- 2003, shown as monthly averages (dots) and a spline fit combined with seasonal harmonics increasing in amplitude at an assumed constant rate (smooth curve).

1. History, continued

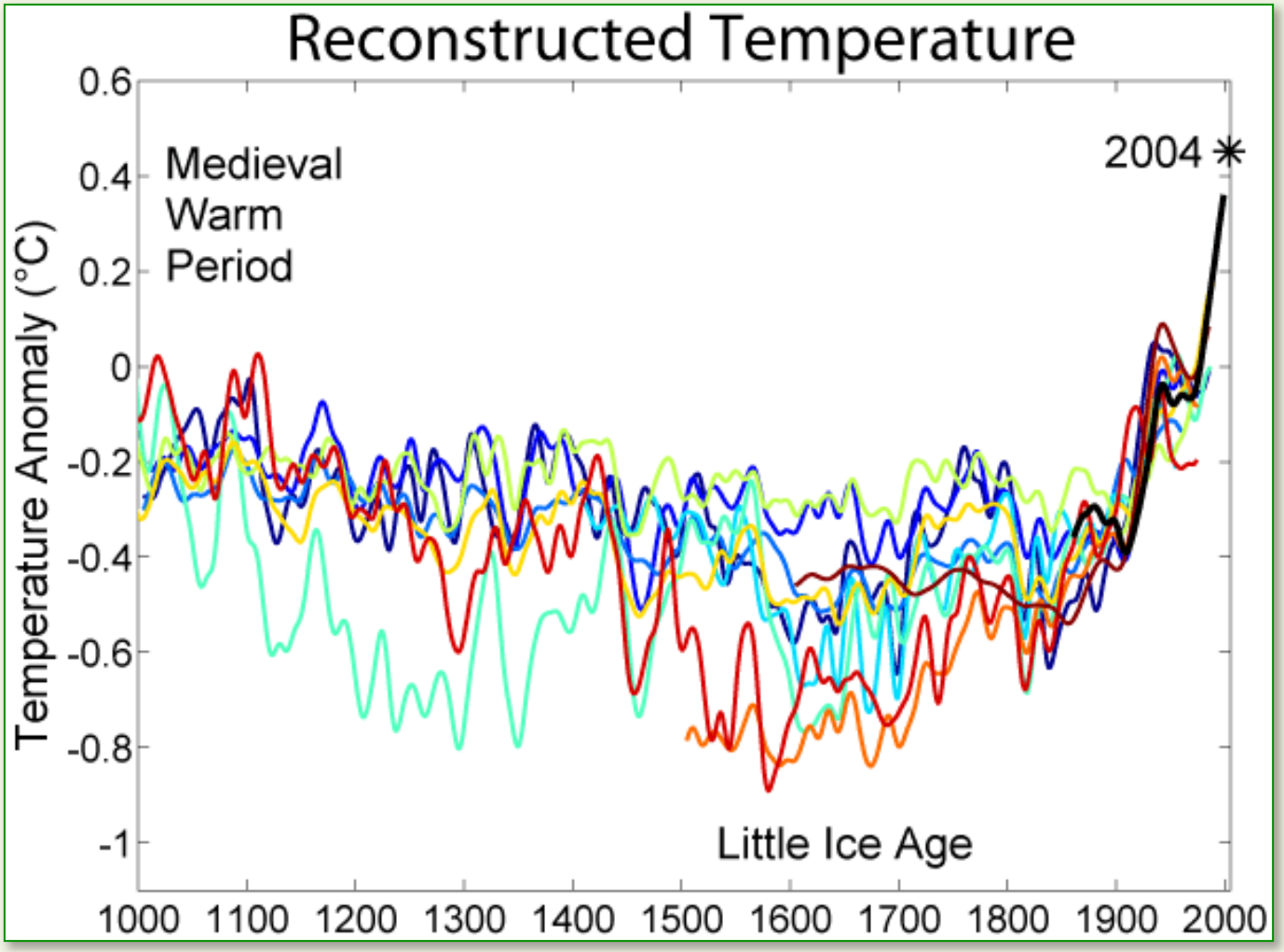
21st century:

- Measured increase of **global-mean surface temperature** (GMST), 1880-2010, of ~0.7 °C with large spatial and temporal variability



This traditional analysis by GISS using only meteorological station data is a line plot of global annual-mean surface air temperature change, with the base period 1951-1980, derived from the meteorological station network [This is an update of Figure 6b in Hansen et al. (2001).]

1. History, continued



Isotopic record from Wikipedia; instrumental record: black.
Reference period for temperature scale: 1950-1980

2. What is now known with certitude (in roughly chronological order)

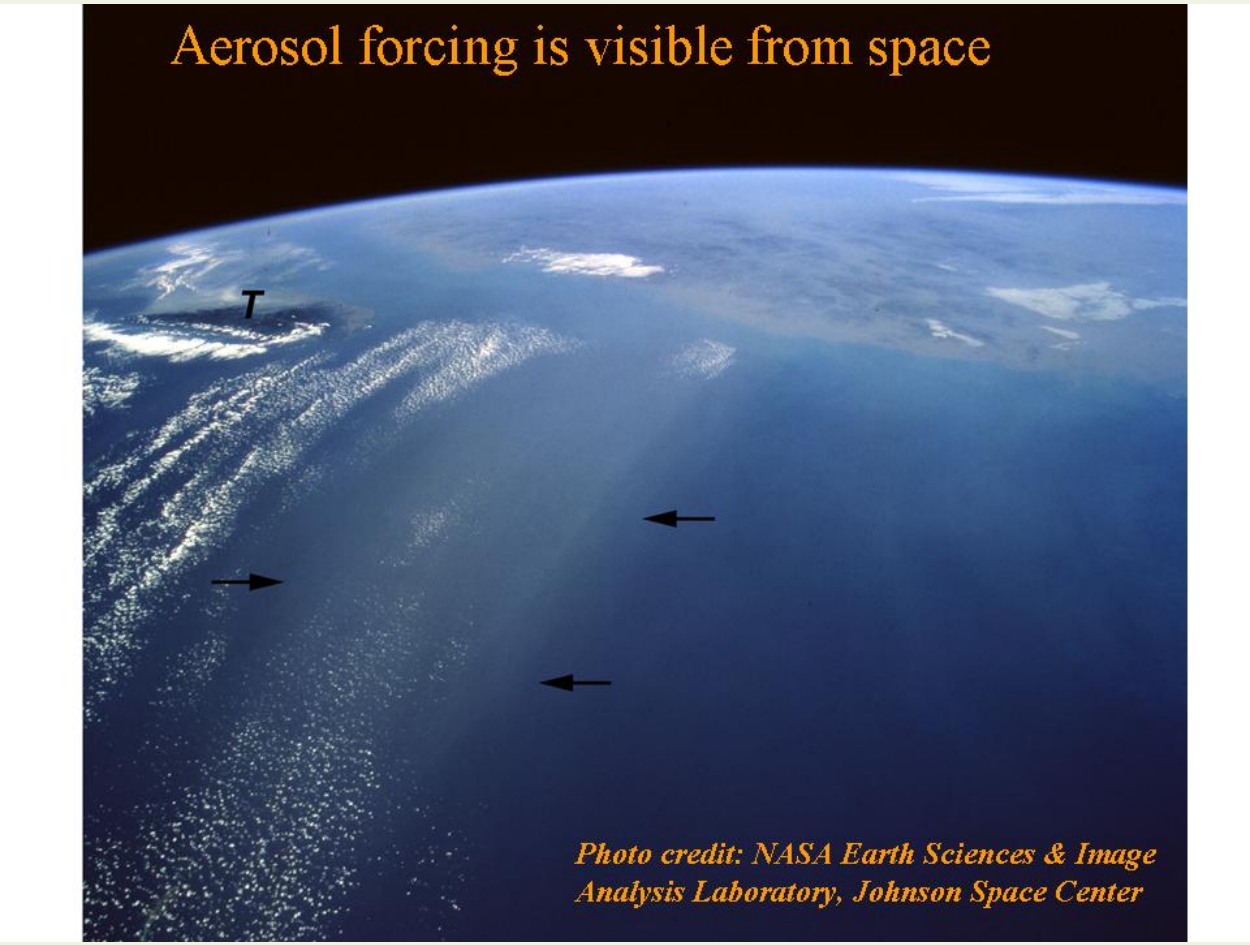
- Earth's GMST is ~33 °C above the emission temperature; the cause is the natural greenhouse effect of CO_2, water vapor and other LLGHG.
- Ice ages have existed in the past at roughly 100,000 year intervals, separated by short "interglacial" periods like the present one.
- CO_2 was at a concentration of ~180 ppm in the last ice age, 280 ppm in the pre-industrial period and CO_2 is now at ~390 ppm and rising more than 1 ppm/year.
- T_{sfc} is strongly correlated with CO_2 and, in polar regions, is assumed to follow GMST.

2. What is now known with certitude (cont.)

- The undeniable data regarding anthropogenic climate change are chemical: CO_2, CH_4, $SO_4^{=}$, infrared spectra, etc.
- CO_2, water vapor, and LLGHG in the atmosphere absorb some of the infrared light emitted by the Earth's surface.
- Of the increasing LLGHG, CO_2 is the dominant cause of increased absorption of IR.
- The main cause of the increase in CO_2 is combustion of fossil fuels (coal, oil, methane).

2. What is now known with certitude (cont.)

- Aerosols (haze) in the air cool the Earth *directly* by reflecting sunlight and *indirectly* by changing clouds. The result is geographically patchy cooling and warming in different regions. View is to the NW over Western Pacific Ocean; T = Taiwan.

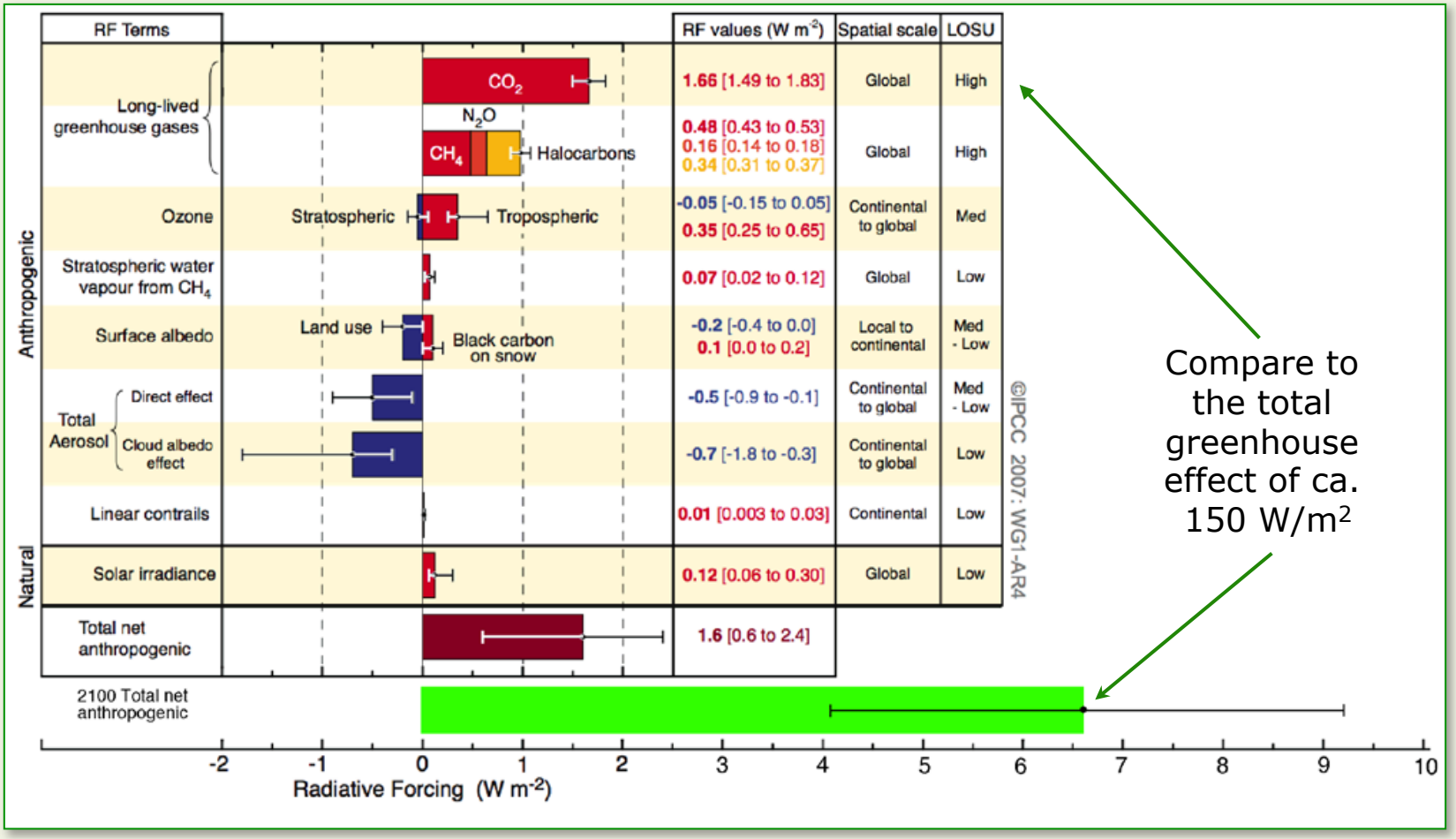


2. What is now known with certitude (cont.)

- Climate *forcing* at the present by LLGHG is known with an uncertainty of only ~10%; but aerosol *forcing* is known with an uncertainty of a little over a factor of two.

- By the year 2100, positive climate *forcing* by LLGHG will greatly dominate the negative *forcing* by anthropogenic aerosols because the aerosols have a lifetime of only a week or so and are not expected to increase, while the content of LLGHGs is cumulative because their lifetime in the atmosphere is very long (centuries).

2. What is now known with certitude (cont.)



Schwartz et al. (2007), *Nature Reports: Climate Change*, 1, 23-24; *forcing* projection to 2100 is from IPCC (2001).

3. Conclusions: Implications of these limitations to planning for the future climate

- The scientific fundamentals forming the extant basis of understanding of the greenhouse effect are old, well established and tested.
- GMST has increased over the past century, some of which is due to anthropogenic *forcing*.
- A further large increase is expected in *forcing.* GMST should also increase because of the expected rise in LLGHG as well as lags in the climate system. (IPCC sensitivity for 2x CO_2: 2-4.5 C. *Cf.* Arrhenius: ~5.5 C)
- Observations and the map of *forcing* indicate that temperature increases will not be geographically uniform or monotonic in time. Example: the Arctic.

3. Conclusions (cont.)

- It may seem ironic, but it is necessary to include climate forcing by aerosols in order to interpret the 20th century record of GMST; but by 2100, aerosols won't matter!
- **WHY?** LLGHG accumulate in the atmosphere, whereas aerosols do not.
- If LLGHG remain uncontrolled, deliberate acts by humans to try to cancel out the Greenhouse Effect ("geoengineering") with sea-spray or stratospheric aerosols would have to continuously increase, essentially forever.
- Geoengineering with aerosols might not work anyway because the *forcings* by aerosols and LLGHG are geographically and temporally so different (e.g., diurnal asymmetry).

3. Conclusions (cont.)

- The factors that are most uncertain are the very ones that matter to human habitability. Example, local precipitation amount, timing and form (rain vs. snow).
- In spite of these issues and because climate is already changing, it will be necessary to develop policies and proceed with controls on LLGHG, especially CO_2, without full scientific certitude. Doing nothing is itself a policy decision, and geoengineering seems unlikely to succeed.
- Continued research on *forced* climate change is required for the development of means for adaptation of human society to changing climatic factors; i.e., to learn how we must adapt to whatever climate we inflict upon ourselves.

Acknowledgements

Bert Bolin

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Prem Bhardawaja (SRP)

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Tami Bond (U. Illinois)

Sarah Doherty (UW)

Frida Bender (MISU)

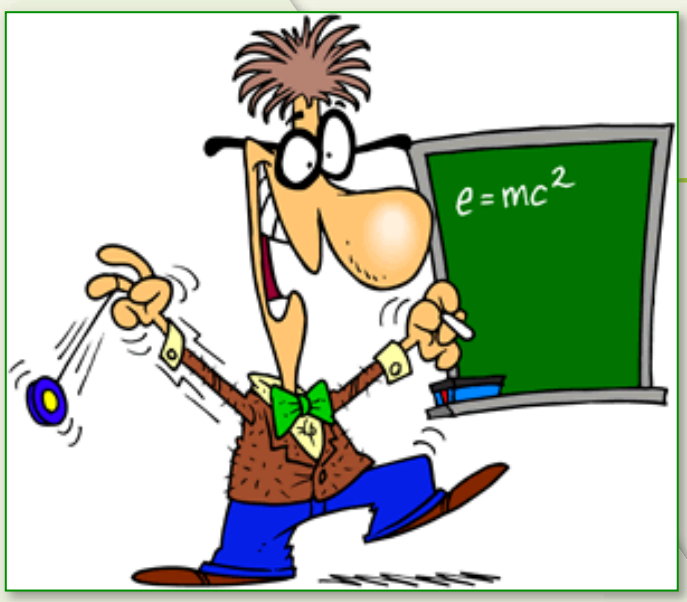
David Covert (UW)

Daniel Jaffe (UW)

Beth Tully, Presentation Design

Thank you very much.

BUT!

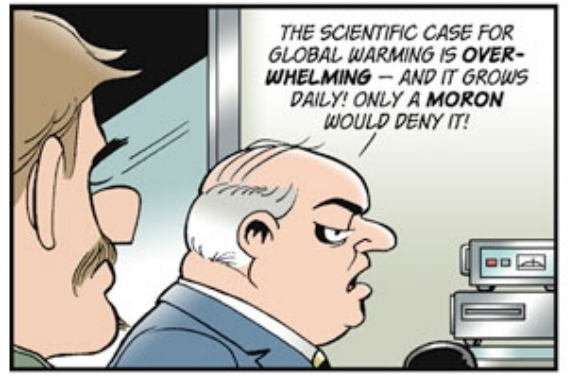


We are getting too serious …

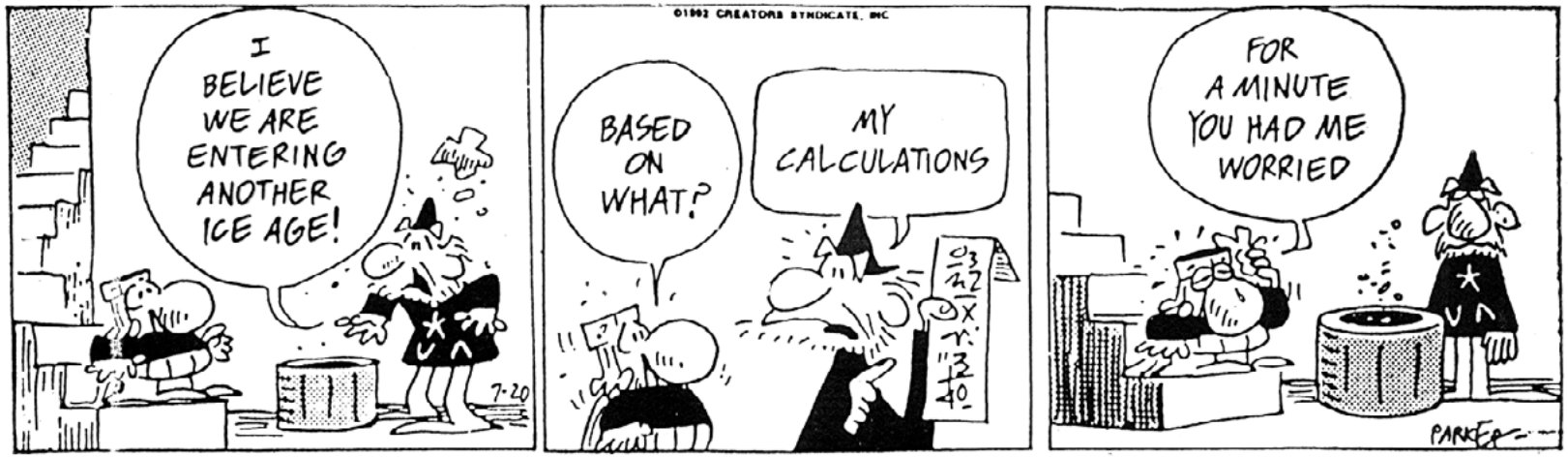
Doonesbury

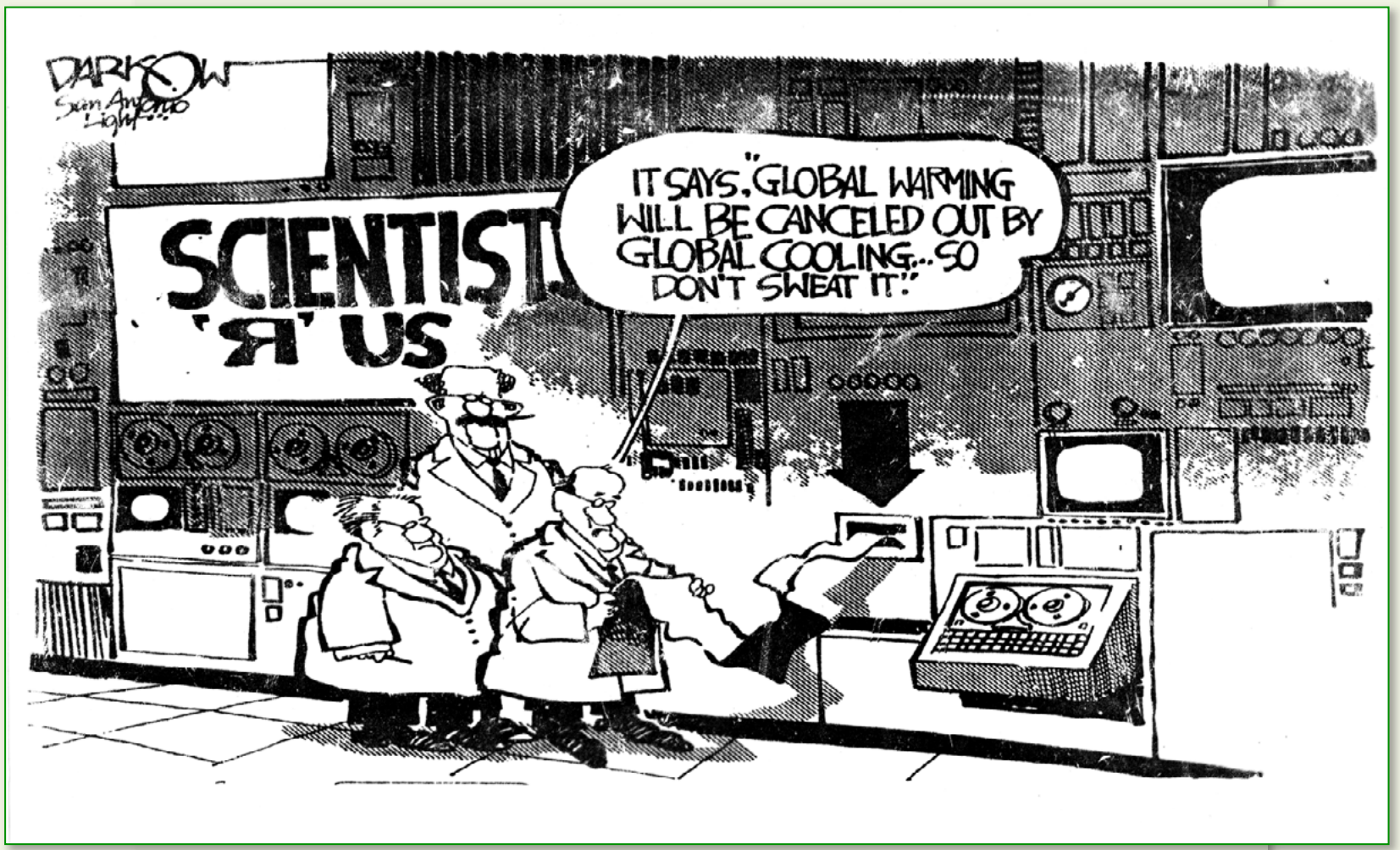
BY

G. B. TRUDEAU



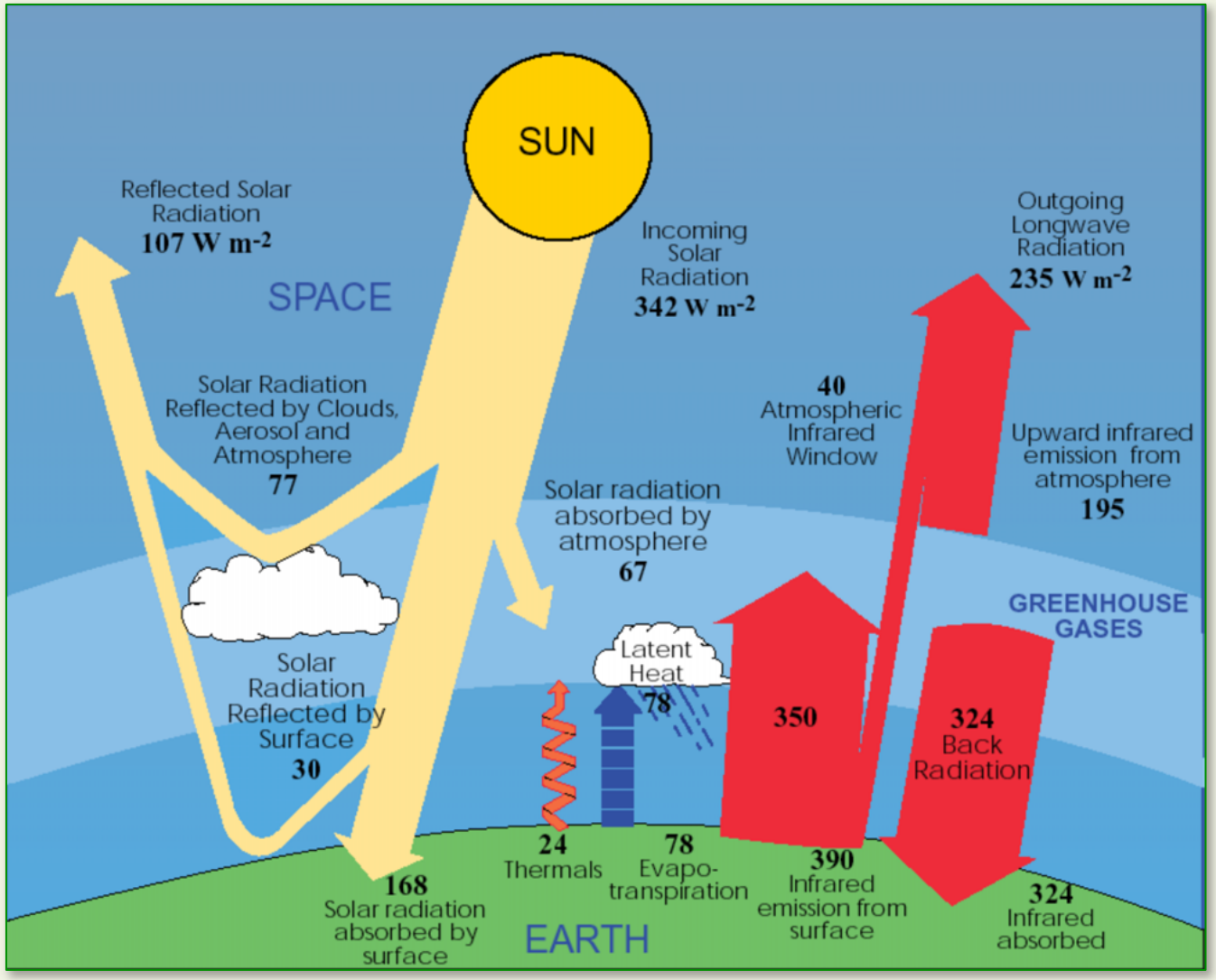
Wizard of Id / By Brant Parker and Johnny Hart




DARKOW
San Antonio Light
SCIENTIST 'R' US
IT SAYS, "GLOBAL WARMING WILL BE CANCELED OUT BY GLOBAL COOLING... SO DON'T SWEAT IT."

2. What is now known with certitude (cont.)

Energy fluxes in the climate system:



Hartmann, D. (2011); personal communication

“If we were clever enough to balance these two effects -- the reflectivity of particulate matter and the concentration of carbon dioxide -- the Earth’s temperature might stay constant.”

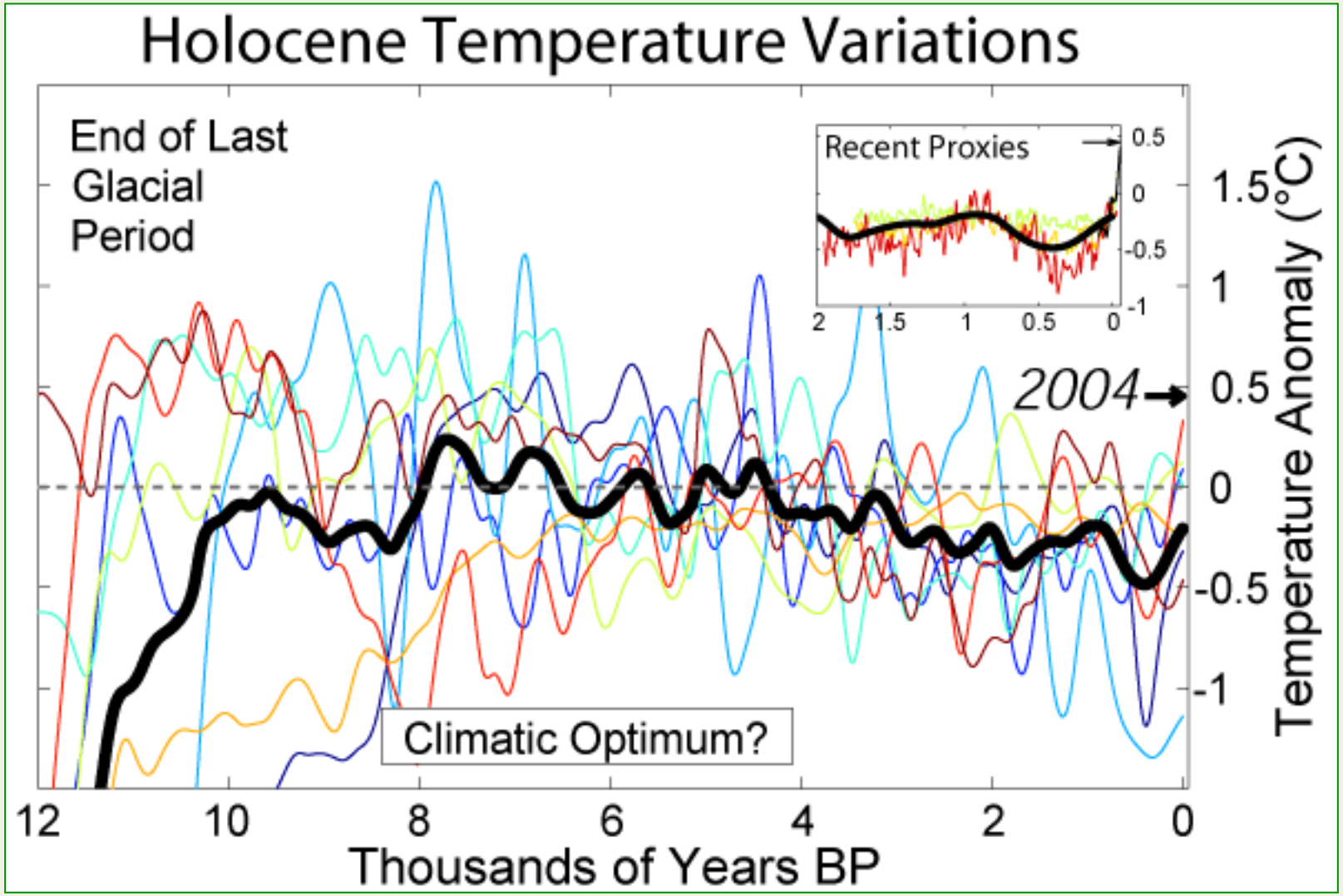
Dr. Lee Dubridge
Science Advisor to President Nixon
US News and World Report
January, 1970

CAVEAT:

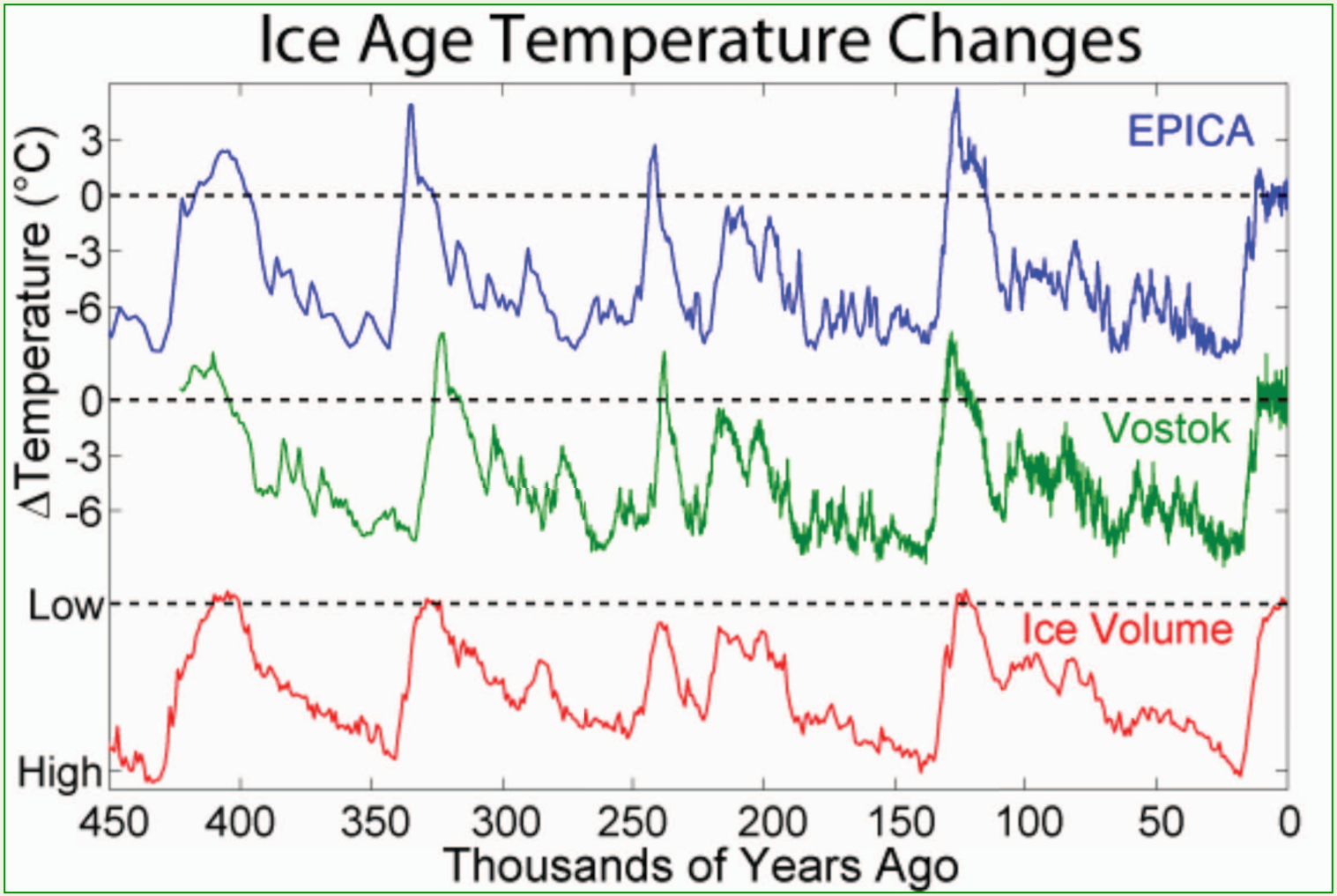
Aerosol effects and greenhouse gas effects cannot simply cancel each other out.

WHY?

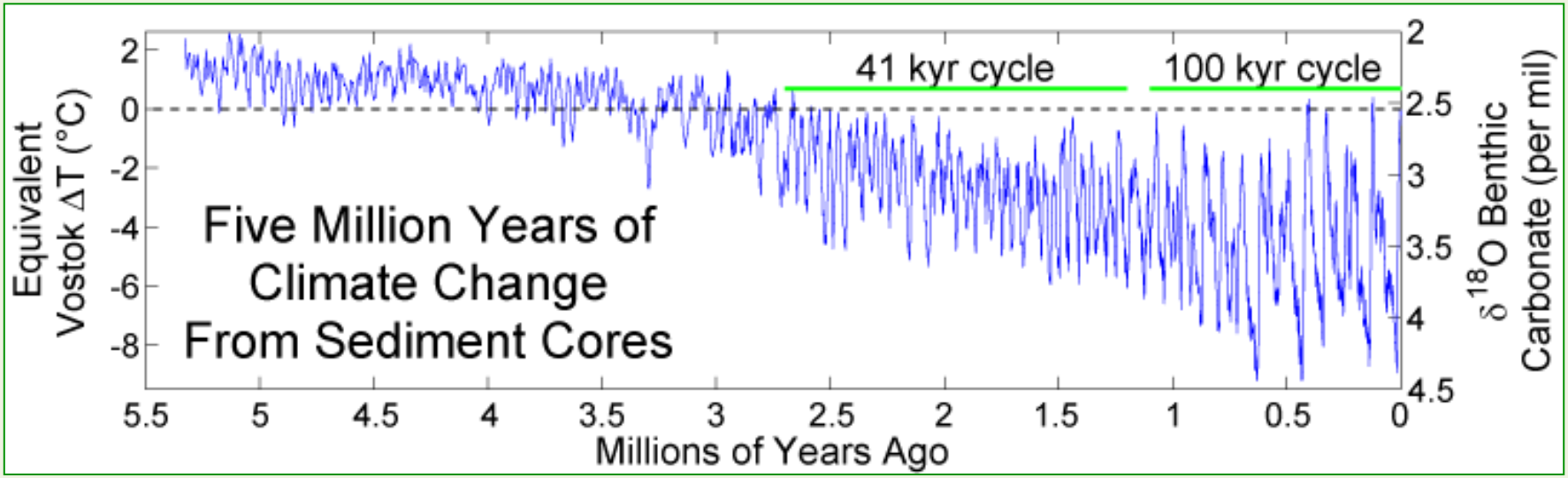
Because they occur at different places and times in the atmosphere.



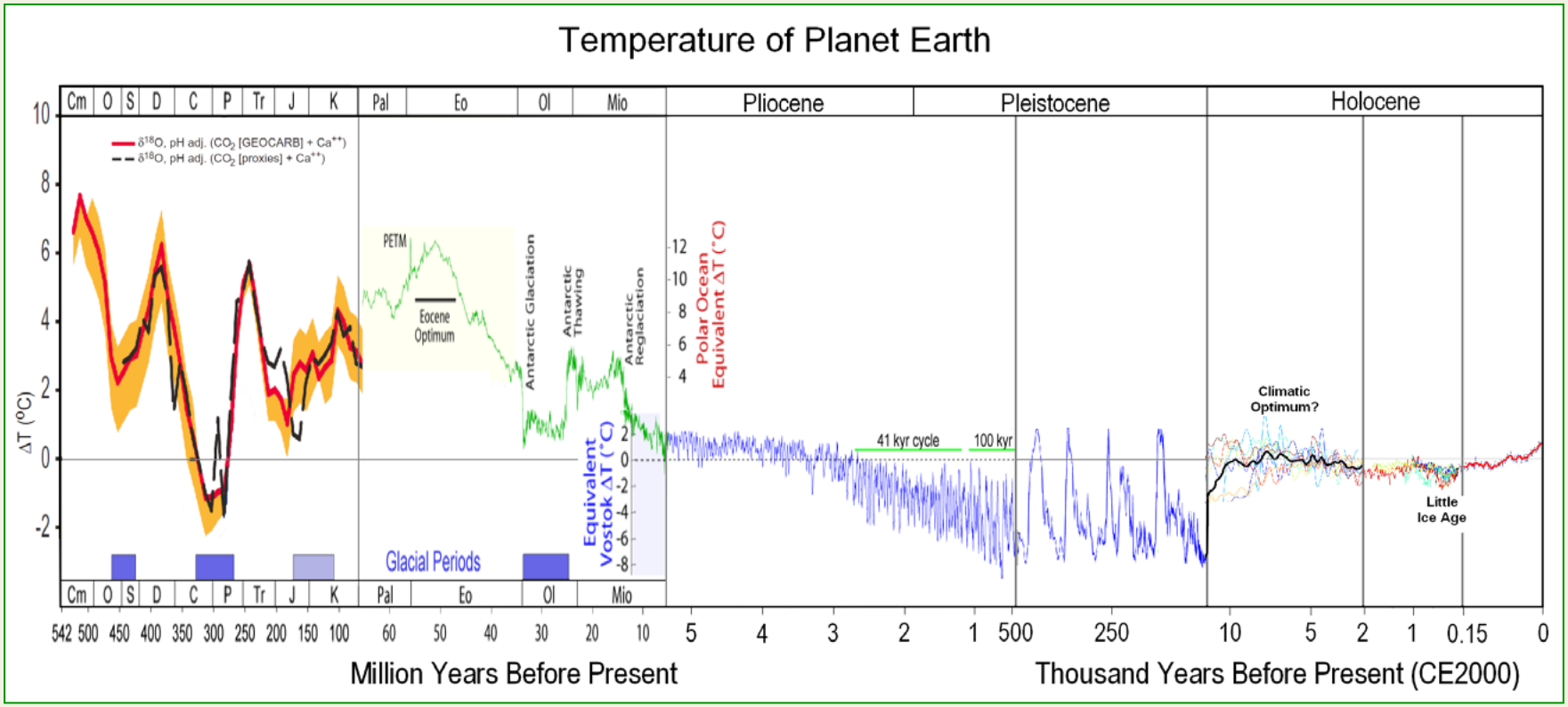
From Wikipedia.



From Wikipedia.



From Wikipedia.



From Wikipedia.

1. History, continued

20th century (cont.):

- 1965: White House document:

APPENDIX Y4

Atmospheric Carbon Dioxide

ROGER REVELLE, *Chairman*

WALLACE BROECKER
HARMON CRAIG
C. D. KEELING
J. SMAGORINSKY

RESTORING THE QUALITY
OF
OUR ENVIRONMENT

Report of The
Environmental Pollution Panel
President's Science Advisory Committee

THE WHITE HOUSE
NOVEMBER 1965

CONCLUSIONS AND FINDINGS

Through his worldwide industrial civilization, Man is unwittingly conducting a vast geophysical experiment. Within a few generations he is burning the fossil fuels that slowly accumulated in the earth over the past 500 million years. The CO_2 produced by this combustion is being injected into the atmosphere; about half of it remains there.

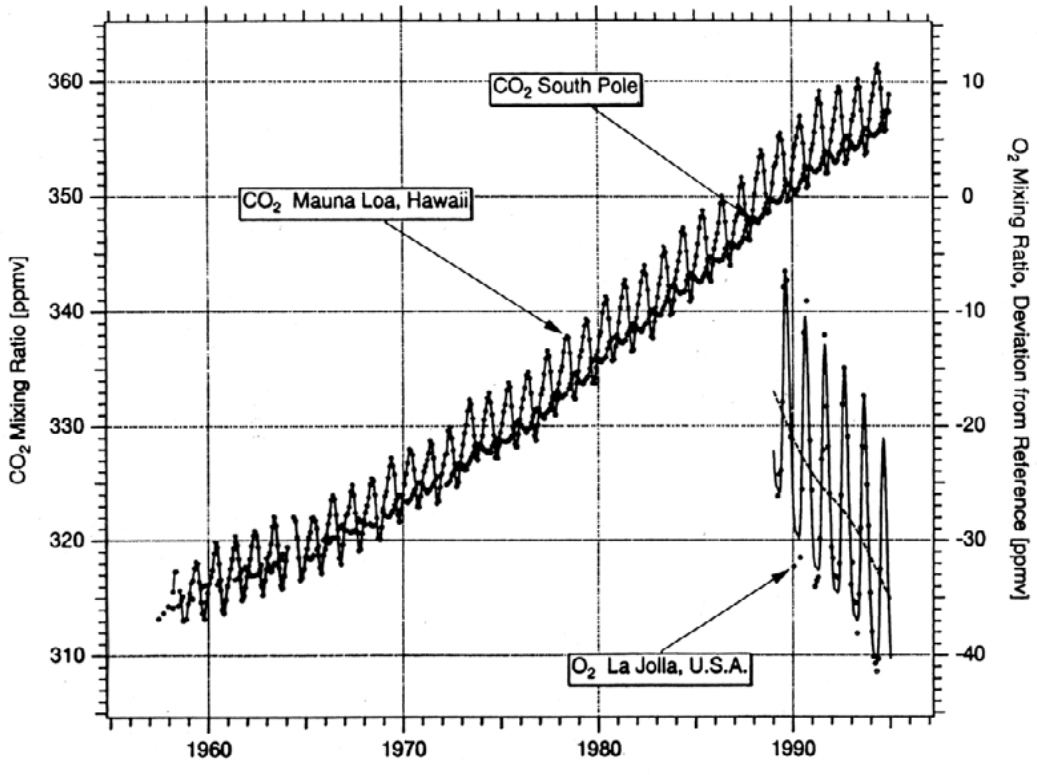
By the year 2000 the increase in atmospheric CO_2 will be close to 25%.

1. History, continued

21st century:

Keeling, R. (1996)

- CO_2 increase is linked to O_2 *decrease*



Direct atmospheric measurements of the CO_2 concentration at Mauna Loa (Hawaii) and the South Pole station together with the concurrently observed decrease in atmospheric oxygen content at the La Jolla station after 1989 (right-hand scale; the oxygen scale is relative to a standard which is approximately 209 500 ppmv), (R. F. Keeling, pers. comm).

2. What is now known with certitude (cont.)

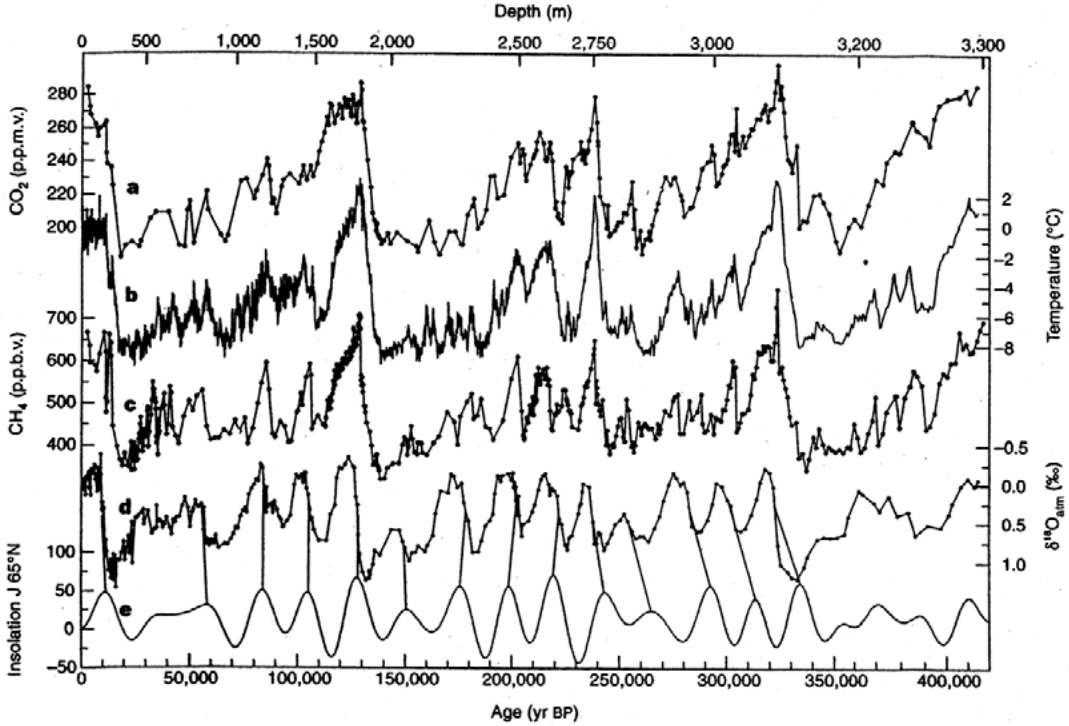


Figure 3 Vostok time series and insolation. Series with respect to time (GT4 timescale for ice on the lower axis, with indication of corresponding depths on the top axis) of: **a**, CO_2; **b**, isotopic temperature of the atmosphere (see text); **c**, CH_4; **d**, $\delta^{18}O_{atm}$; and **e**, mid-June insolation at 65° N (in $W m^{-2}$) (ref. 3). CO_2 and CH_4 measurements have been performed using the methods and analytical procedures previously described[5,9]. However, the CO_2 measuring system has been slightly modified in order to increase the sensitivity of the CO_2 detection. The thermal conductivity chromatographic detector has been replaced by a flame ionization detector which measures CO_2 after its transformation into CH_4. The mean resolution of the CO_2 (CH_4) profile is about 1,500 (950) years. It goes up to about 6,000 years for CO_2 in the fractured zones and in the bottom part of the record, whereas the CH_4 time resolution ranges between a few tens of years to 4,500 years. The overall accuracy for CH_4 and CO_2 measurements are ±20 p.p.b.v. and 2–3 p.p.m.v., respectively. No gravitational correction has been applied.

- This increase of concentration in CO_2 is about the same in magnitude as the increase in it at the end of an ice age.

5. Chemical data

- Atmospheric CO_2 concentration data have been available accurately, continuously, and globally since ~1957.
- At first they were controversial ***BUT NOT NOW.***
- They and the well-known IR absorption spectrum of CO_2 and the other LLGHG (long-lived greenhouse gases) are the BEST evidence for global warming
- The paleochemical data provide an accurate record of past climates.
- Chemists have a very large stake in this issue!
- Climate *forcing* in 2100 will approach +7 Wm^2; the Earth receives and absorbs only ~170 Wm^2. Therefore the climate forcing will go from about 1% now to several percent of Earth's energy balance. That would be comparable to the change in energy balance at the end of an ice age!
- Where's the controversy?