Global warming: the path to the future?

John Meriwether
Clemson University

Early on, 118 years ago, it was suspected that the Industrial Age was causing climate change!

This talk reviews the evidence
and presents several suggestions about what to do.

Climate change (global warming)

The issues:

1. Is the observed temperature increase of ~1.1 K just a typical fluctuation in global temperature or an abnormal increase?

2. If most of the temperature rise can be attributed to increases in anthropogenic CO_2 emissions, what are the likely consequences if no action is taken to curb these emissions?

3. What can we do if anything about this problem?

SCIENCE IN REVIEW
By WALDEMAR KAEMPFFERT
New York Times (1857-Current file); Oct 28, 1956; ProQuest Historical Newspapers The New York Times (1851 - 2003)
pg. 191

SCIENCE IN REVIEW

Warmer Climate on the Earth May Be Due To More Carbon Dioxide in the Air

By WALDEMAR KAEMPFFERT

The general warming of the climate that has occurred in the last sixty years has been variously explained. Among the explanations are fluctuations in the amount of energy received from the sun, changes in the amount of volcanic dust in the atmosphere and variations in the average elevation of the continents.

According to a theory which was held half a century ago, variation in the atmosphere's carbon dioxide can account for climatic change. The theory was generally dismissed as inadequate. Dr. Gilbert Plass re-examines it in a paper which he publishes in the American Scientist and in which he summarizes conclusions that he reached after a study made with the support of the Office of Naval Research. To him the carbon dioxide theory stands up, though it may take another century of observation and measurement of temperature to confirm starches) causes a large loss of carbon dioxide, but the balance is restored by processes of respiration and decay of plants and animals.

Despite nature's way of maintaining the balance of gases the amount of carbon dioxide in the atmosphere is being artificially increased as we burn coal, oil and wood for industrial purposes. This was first pointed out by Dr. G. S. Callendar about seven years ago. Dr. Plass develops the implications.

Generated by Man

Today more carbon dioxide is being generated by man's technological processes than by volcanoes, geysers and hot springs. Every century man is increasing the carbon dioxide content of the atmosphere by 30 per cent—that is, at the rate of 1.1° C. in a century. It may be a chance coincidence that the average temperature of the world since 1900 has risen by about this rate. But the possibility that man

New York Times article, 28 October 1956

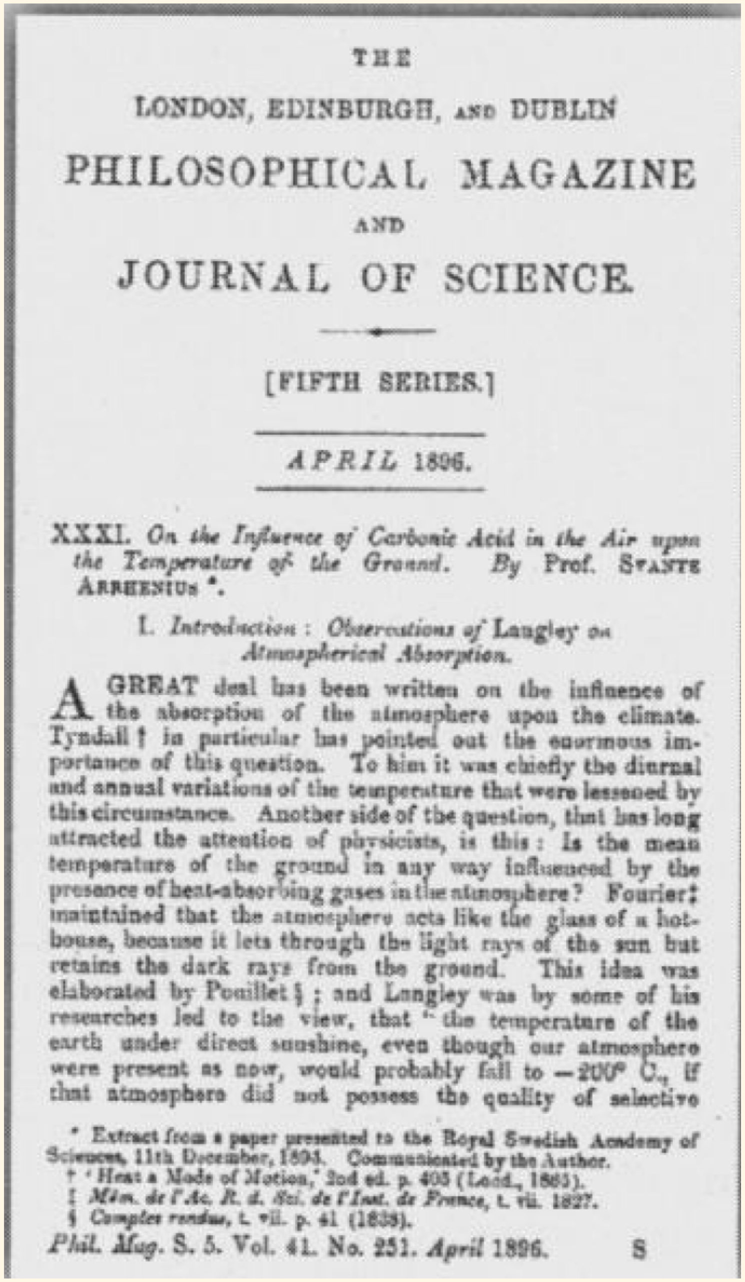
"Today more carbon dioxide is being generated by man's technological processes than by volcanoes, geysers and hot springs.

Every century man is increasing the carbon dioxide content of the atmosphere by 30% - that is, at the rate of 1.1 °C in a century"

At the time of this article CO_2 was at the level of 315 parts per million.

A year ago, this number passed the level of 400 parts per million, now about 405 ppm.

The Beginnings of Global Warming Science



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

Svante Arrhenius won the Nobel prize in chemistry in 1903 (for work on acid/base chemistry).

In 1896 he published a paper drawing on the work of Langley, Fourier, and Tyndall on atmospheric absorption and suggested that a doubling of CO_2 would be expected to warm the planet by about 5-6 C. He was interested in the ice ages and paleoclimates.

Arrhenius thought this would be a good thing:

Svante Arrhenius

We may hope to enjoy ages with more equable and better climates, ages when the Earth will bring forth much more abundant crops than at present...

—1908

A key early argument against any significant warming/fossil fuel CO_2 link was related to spectroscopy:

The bands of CO_2 were suggested to be saturated as well as overlapped with water vapor, so changes couldn't change climate

American Met Soc, Compendium of Meteorology, 1951:

The theory that carbon dioxide would change the climate "was never widely accepted - and was abandoned when it was found that all the long-wave radiation [that might be] absorbed by CO_2 is already absorbed by water vapor."

Rapid changes in views occurred from the 1950s on, as spectroscopy, ocean chemistry and transport, atmospheric measurements of CO_2 and other greenhouse gases, climate observations, computers and atmospheric modeling rapidly advanced.

Why does a 1° shift in climate matter?

Climate ("Averaged" weather) governs

Productivity of farms, forests, & fisheries

Geography of disease

Livability of cities in summer

Damages from storms, floods, wildfires

Property losses from sea-level rise

Expenditures on engineered environments

Distribution & abundance of species

Information at hand: Sources of Climate Data

Direct Measurements:

Observations of air & water temperature, precipitation amount, etc… have been made routinely with accurate instruments for about 150 years

Historical Records:

Clues left in written documents from the past

Paleoclimate:

Properties of the Earth and Atmosphere are determined from clues hidden in the Earth, a kind of forensic science.

Sources of paleoclimate information:

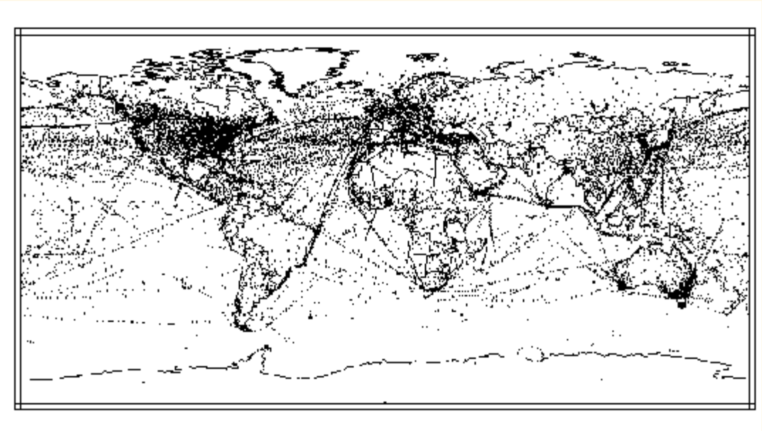
- Ice Cores
- Tree Rings
- Ocean Sediment

Surface Temperatures

Land: thermometers;   surface air T
Ocean: thermometers; sea surface T
Plus IR satellite patterns

Coverage:

Increases over time (poor 1800s, better after 1950)
Global after 1982 with satellite
No Antarctica pre-IGY (1957)
Poor southern oceans



Biases:

Changes in observing practices
Land use/urbanization effects

Advantages:

- Long record
- Many independent measurements
- Several independent analyses
- Many cross checks (NH vs SH; rural vs urban; global vs land-based vs SST vs Marine Air T)

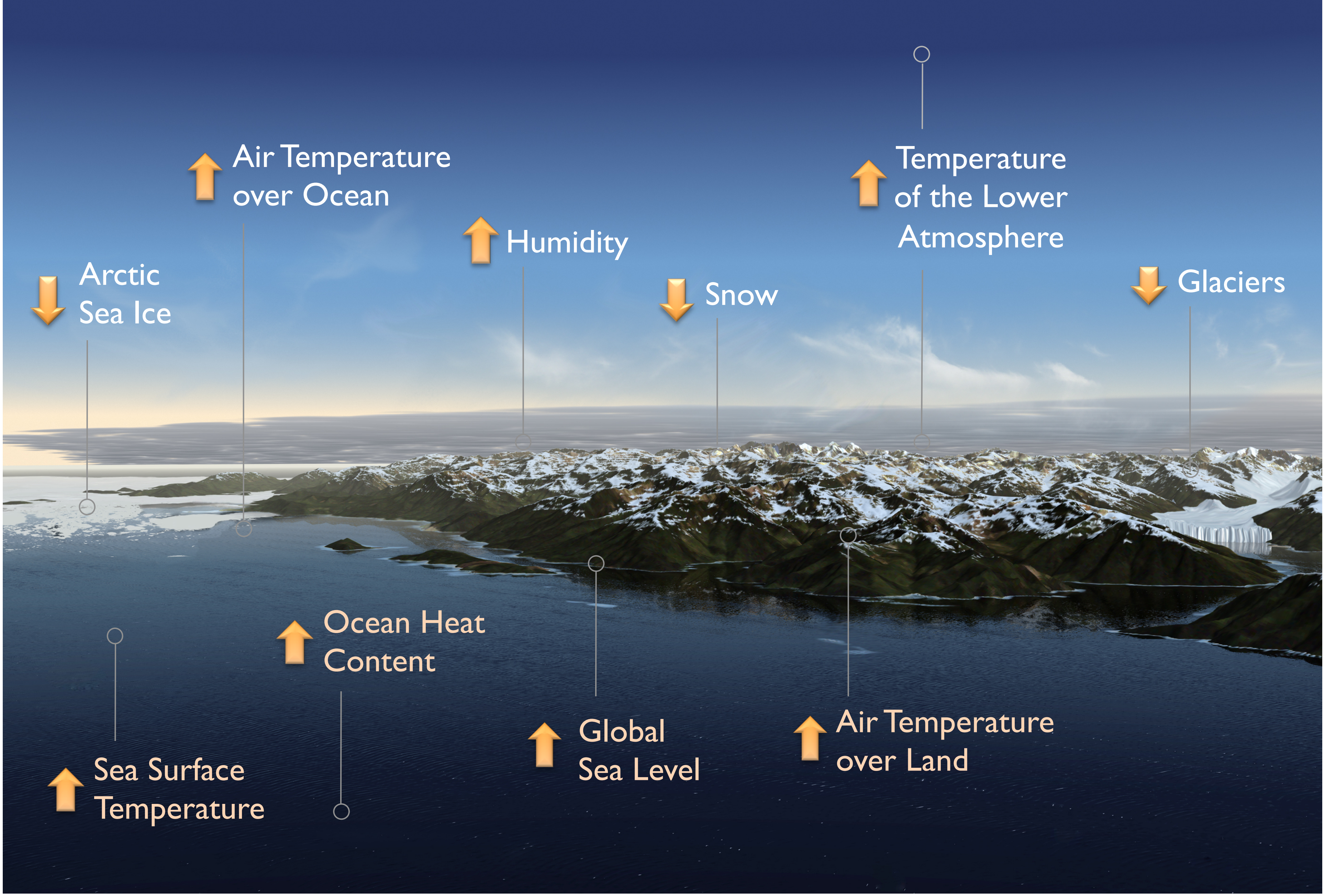
Disadvantages:

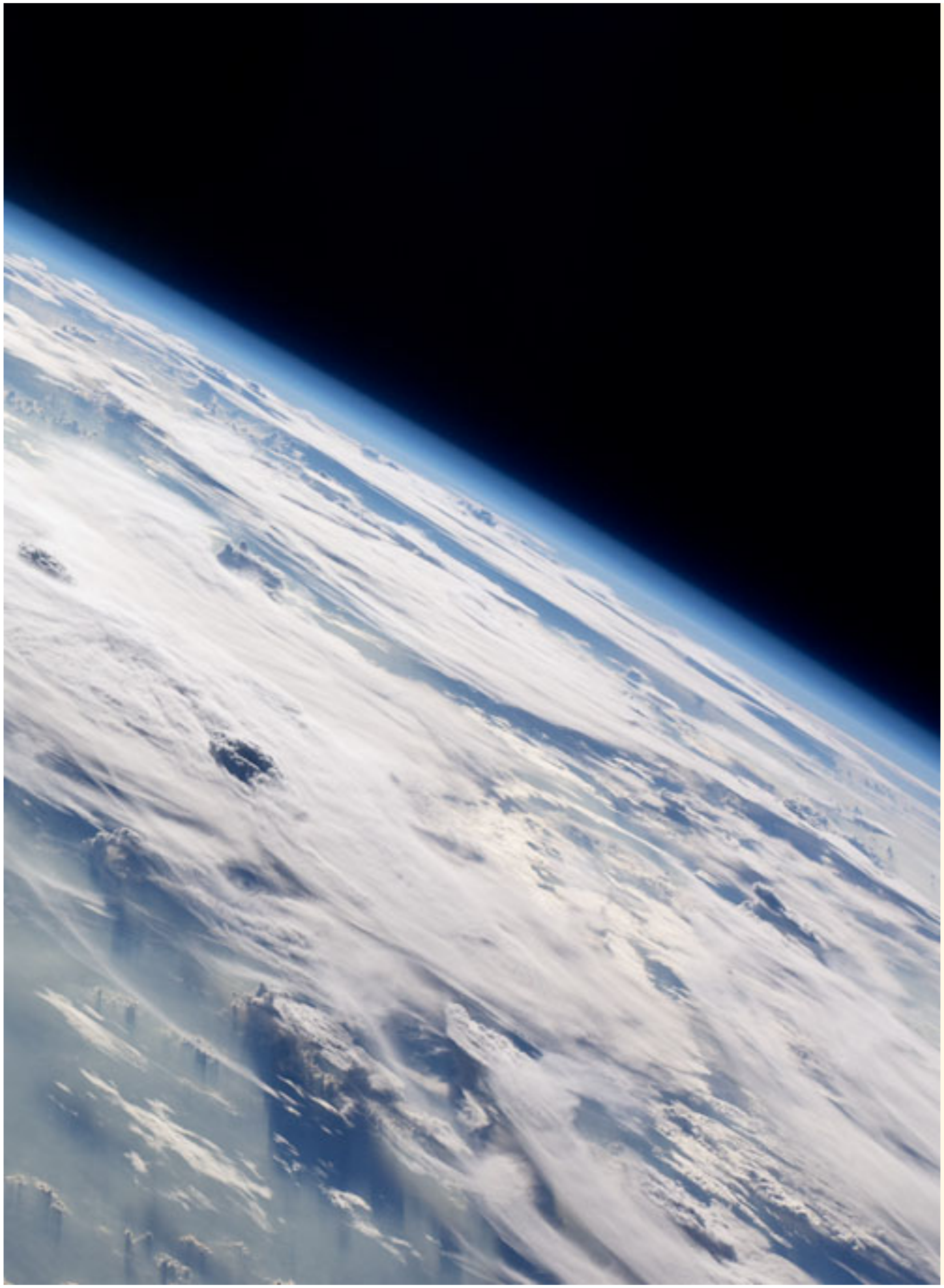
- Mostly less than global coverage
- Coverage changes with time

Assessment:

Trends robust; may be slightly underestimated owing to under-representation of southern oceans and Antarctica

How do we know the world is warming?

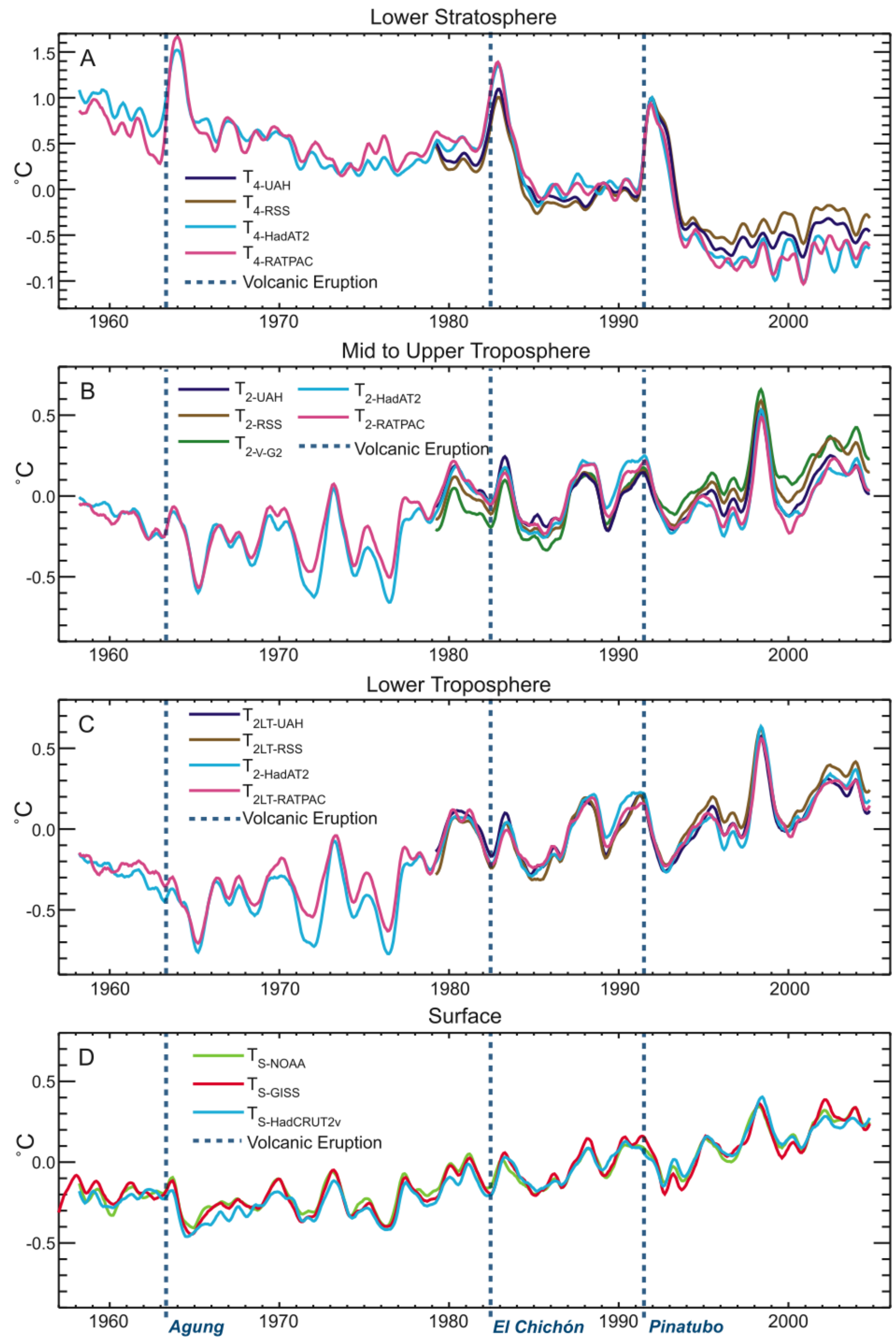




Temperature of the Lower Atmosphere

Measurements from satellites and weather balloons show that the lowest layer of the atmosphere—the layer where we live, airplanes fly, and weather occurs—is warming. Greenhouse gases are building up in this layer, trapping heat radiated from Earth's surface and raising the planet's temperature.

cooling

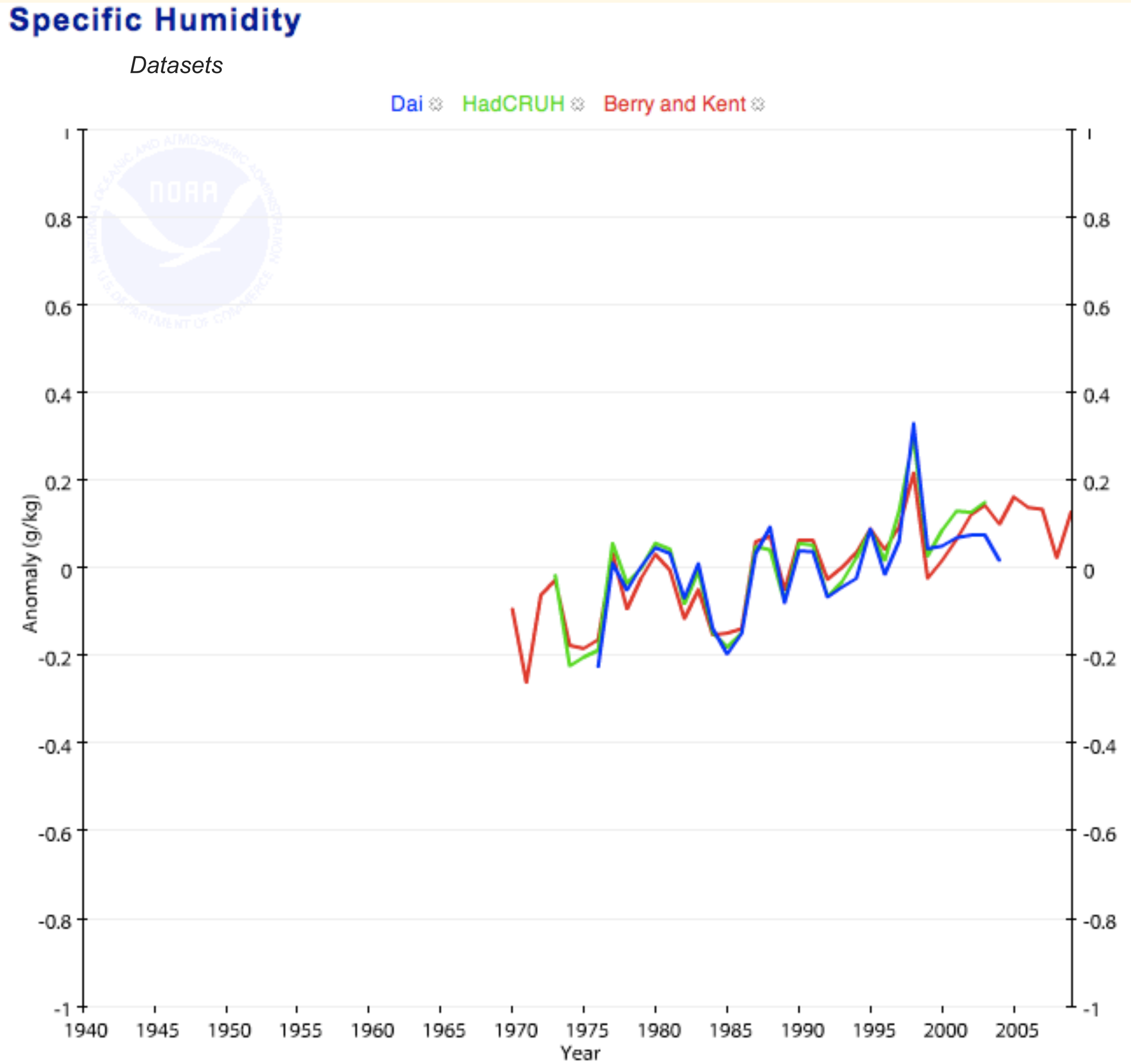


heating

Global temperature increase diminishes with altitude and reverses in stratosphere

⬆ Humidity

Measurements over land and water show more water vapor in the air. The air feels stickier when it's hot, and air conditioners have to work harder for us to feel comfortable.


Specific Humidity
Datasets
Dai
HadCRUH
Berry and Kent
Anomaly (g/kg)
Year
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

Glaciers

Historical paintings, photographs, and other long-term records show that most mountain glaciers are melting away.

People who depend on water from melting glaciers for their living needs, crops, and livestock are facing potential shortages.

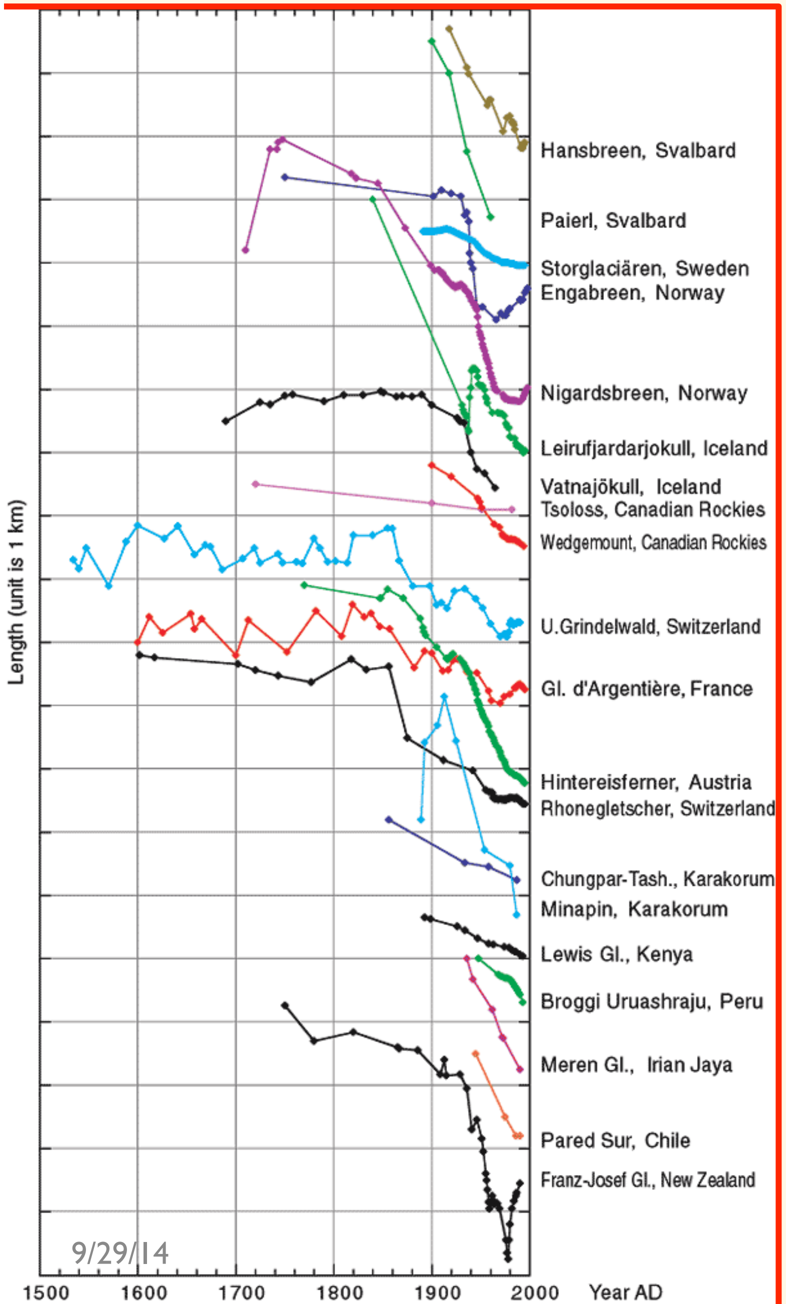
Glaciers are retreating globally

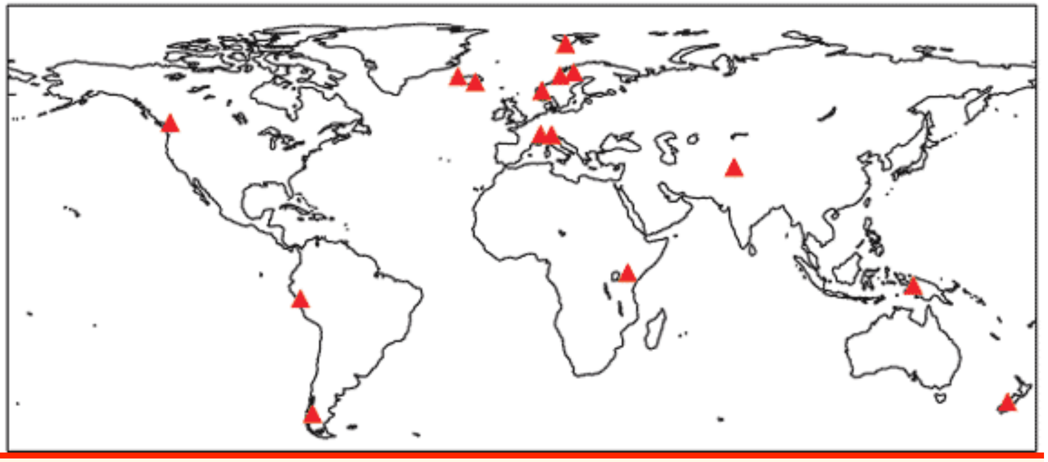
In Switzerland…

In Alaska…

from "Rhone-Glacier and its Ice Grotto" M. Carlen & Fotohaus Geiger

Mountain glaciers are melting



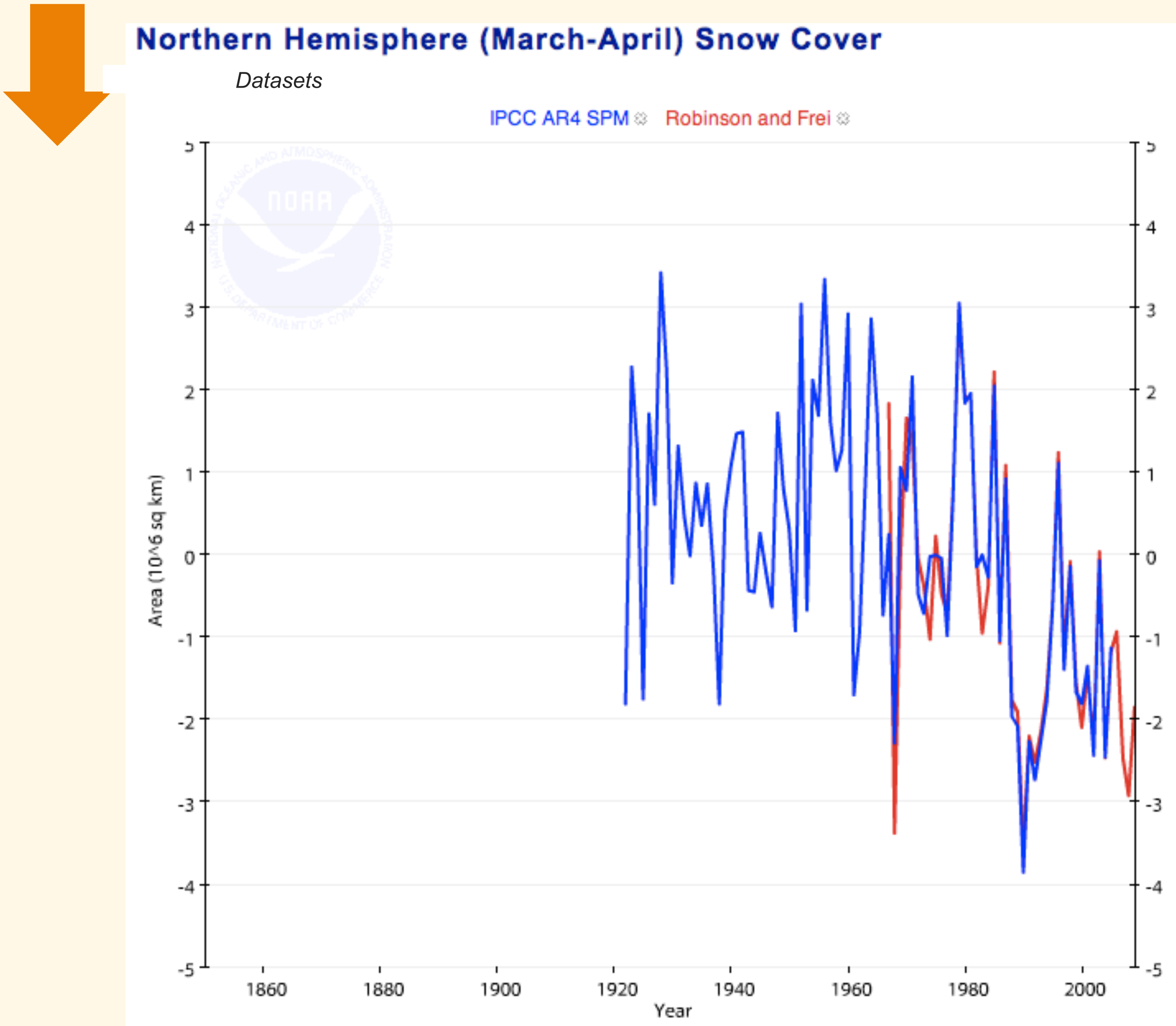


Mountain Glacier Trends

⬇ Snow

Satellite images show that the area of land covered by snow during spring in the Northern Hemisphere is getting smaller.

Snow is melting earlier, changing when and how much water is available for nature and people.

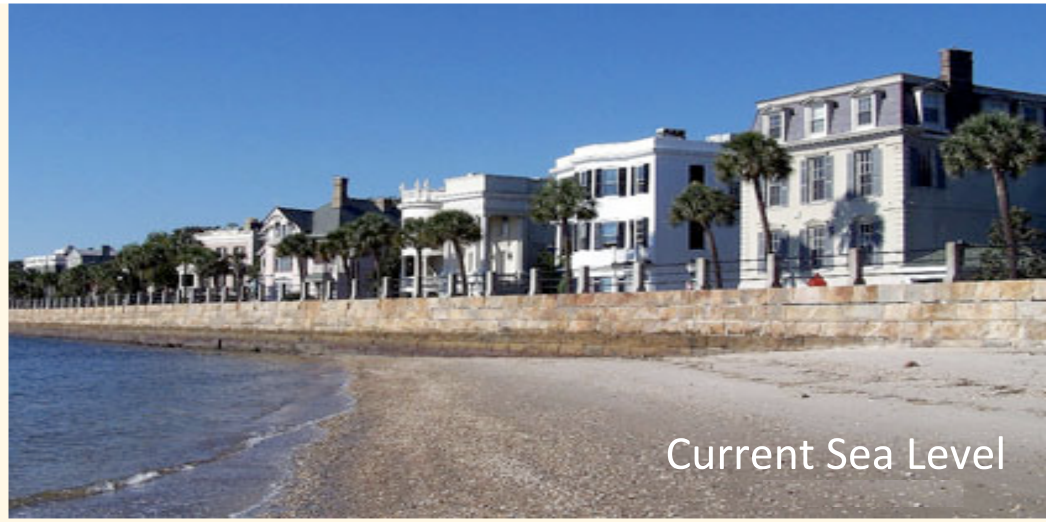


Northern Hemisphere (March-April) Snow Cover
Datasets
IPCC AR4 SPM
Robinson and Frei
Area (10^6 sq km)
Year
5
4
3
2
1
0
-1
-2
-3
-4
-5
1860
1880
1900
1920
1940
1960
1980
2000

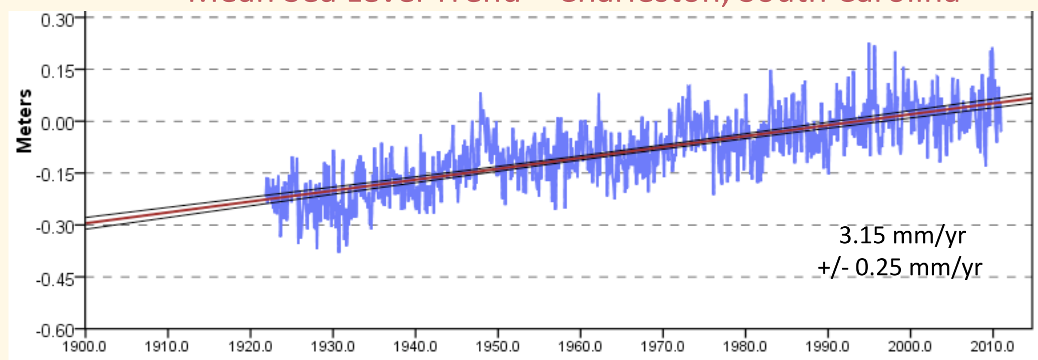
Global Sea Level

Tide gauges and satellites that measure the distance from their orbit to the ocean's surface both show that global sea level is getting higher.

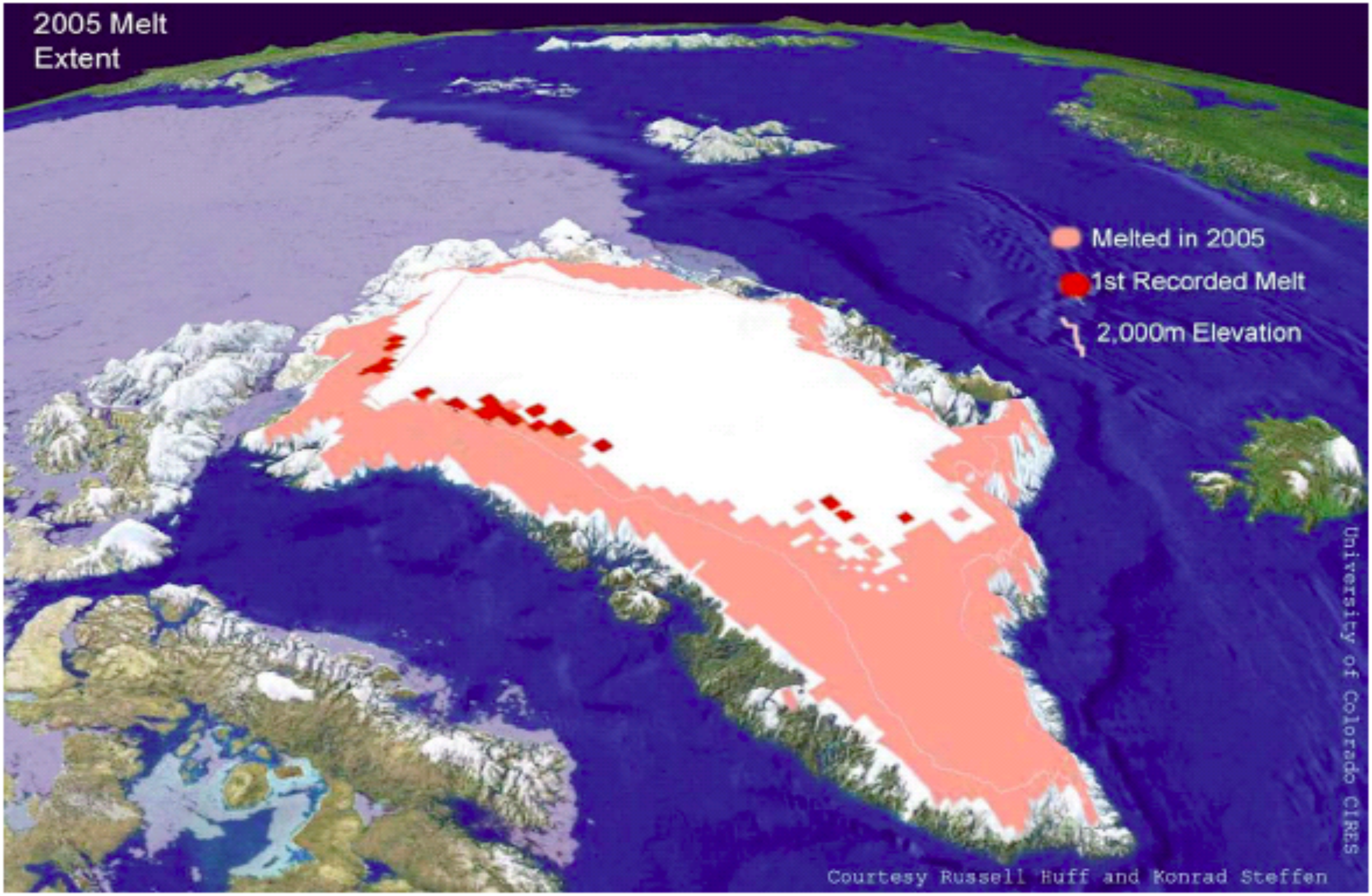
Rising waters threaten ecosystems, freshwater supplies, and human developments along coasts.



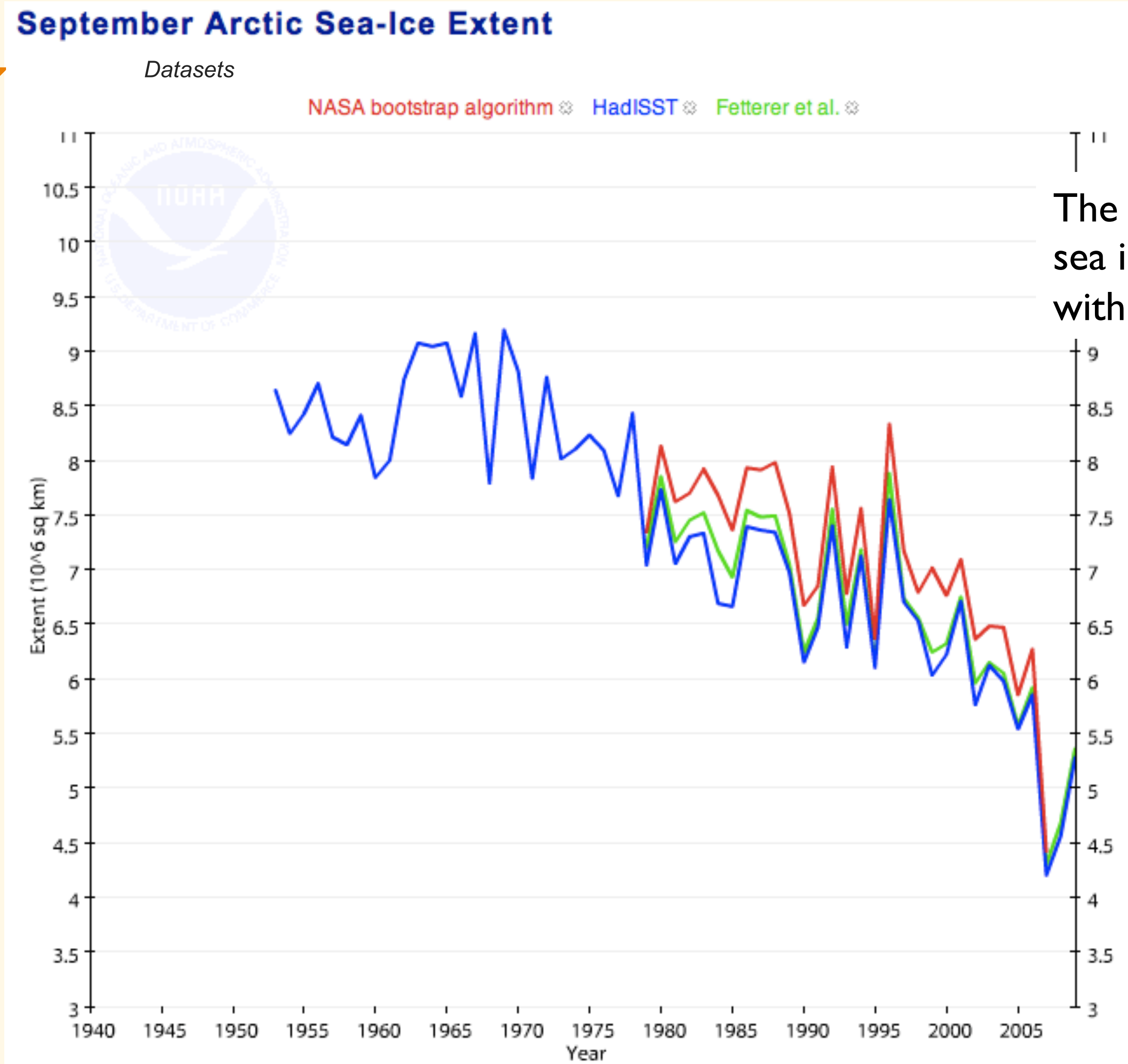
Mean Sea Level Trend – Charleston, South Carolina



Greenland is melting



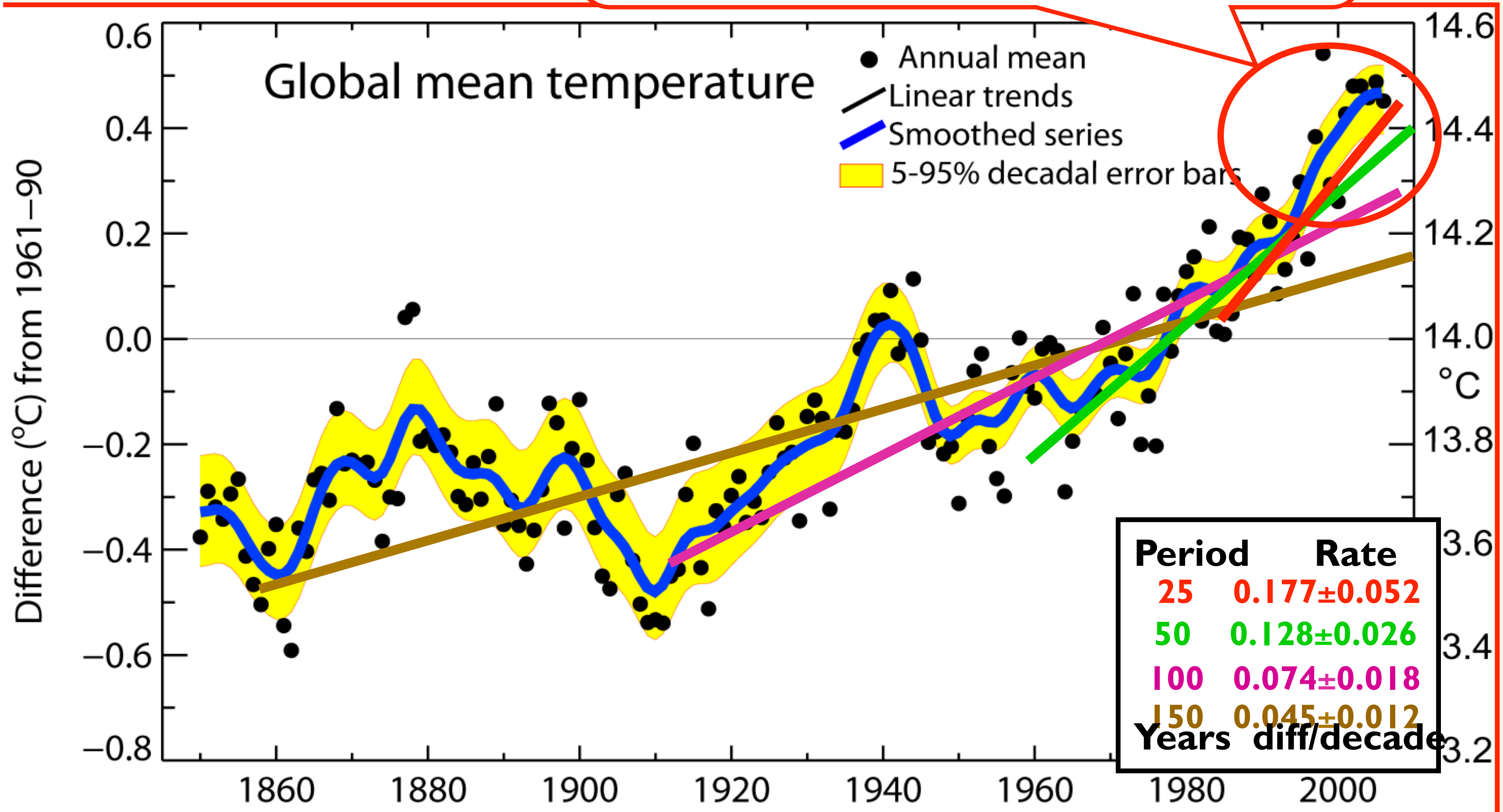
Source: University of Colorado CIRES (courtesy Russell Huff and Konrad Steffen)



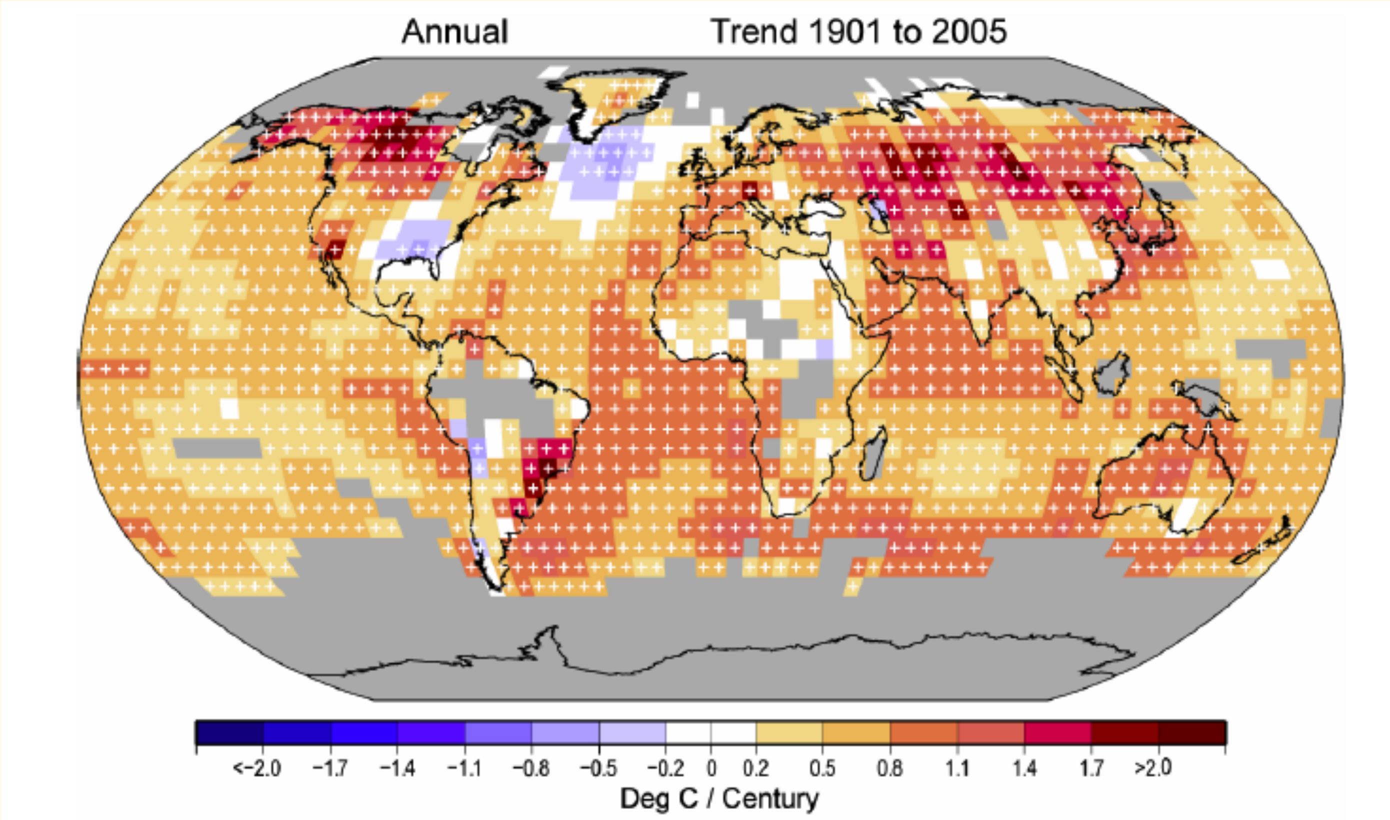
The area of the Arctic sea ice is diminishing with time.

Global mean temperatures are rising faster with time

Warmest 12 years:
1998,2005,2003,2002,2004,2006,
2001,1997,1995,1999,1990,2000



The World Has Warmed



Last ten years: warmest decade since at least the late 1800s

Widespread warming has occurred. Globally averaged, the planet is about 0.75°C warmer than it was in 1880, based upon dozens of high-quality long records using thermometers worldwide, including land and ocean.

Data from NASA

IPCC, WG1, 2007

1	2010
2	2005
3	1998
4	2002
5	2007
6	2003
7	2009
8	2006
9	2012
10	2011
11	2001
12	2004
13	2008
14	1997
15	1995
16	1999
17	2000
18	1990
19	1991
20	1988
21	1996
22	1987
23	1994
24	1981
25	1983

So, global climate is changing…

in the direction of average warming, accompanied by many phenomena consistent with this,

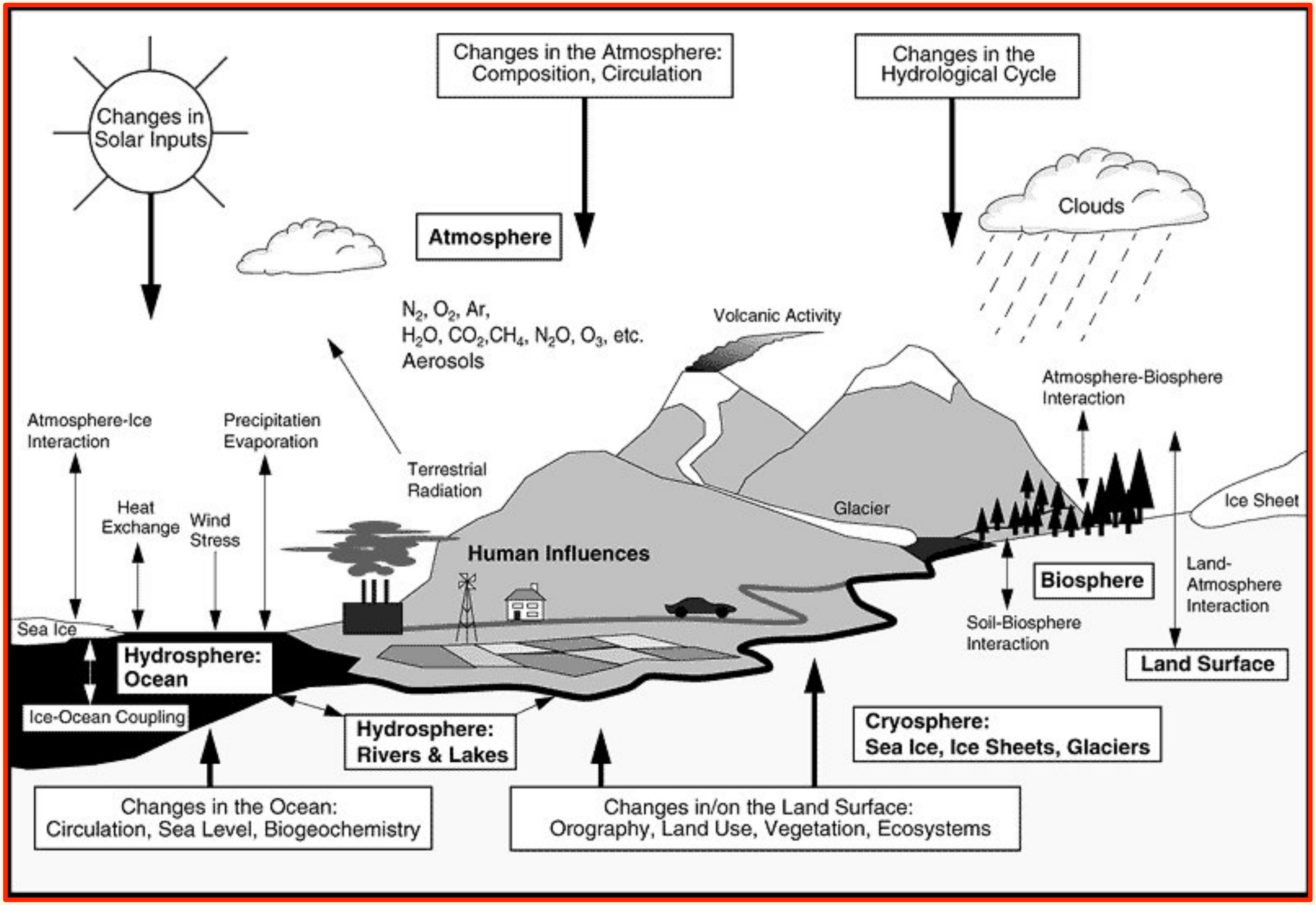
and at a pace that is unusual in the recent historical record.

But we know climate has sometimes changed quite abruptly in the past from <u>natural</u> causes.

Is it really the Industrial Age that is responsible for what is happening now? Or is it nature?

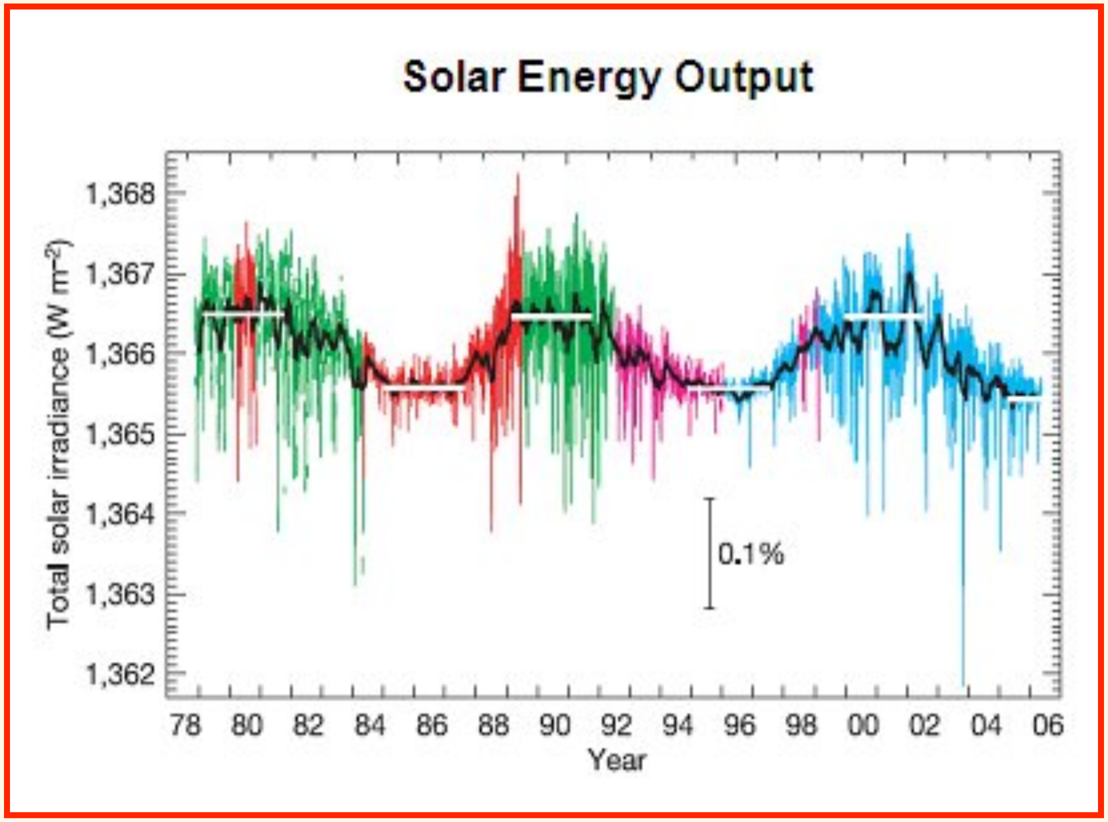
What is the evidence?

Possible changes in the Earth's Climate other than the Industrial Age



Possible factors underlying climate change

1. Variations in solar irradiance have been small- ~0.1%



Normal solar cycle variations in solar radiation

2. Milankovitch Cycles - orbital changes – Too slow

Earth's rotation and revolution combine to make the planet "wobble" in its orbit

This changes the position of the earth and affects seasonal temperatures and albedo

Such changes are believed to be principally responsible for the waxing and waning of glacial periods (100,000 yr. time spans) and normal climate cycles (20,000 – 40,000 year cycles)

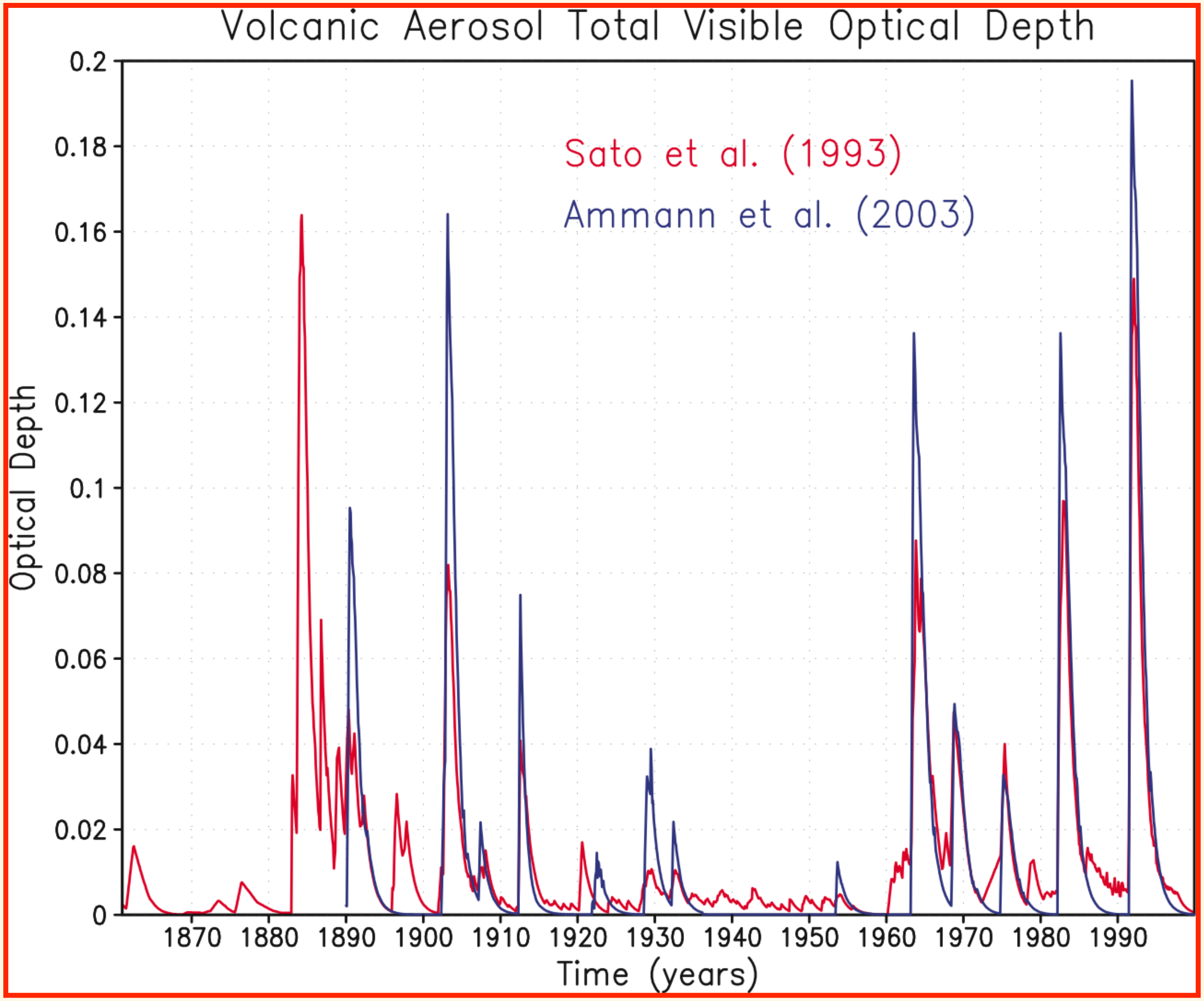
And the climate change induced would appear over many years, not abruptly.

3. Volcanoes and Dust: too short an effect

Volcanic dust blasted into the atmosphere causes temporary cooling.

The amount of cooling depends on the amount of dust put into the air.

The duration of the cooling depends on the size of the dust particles

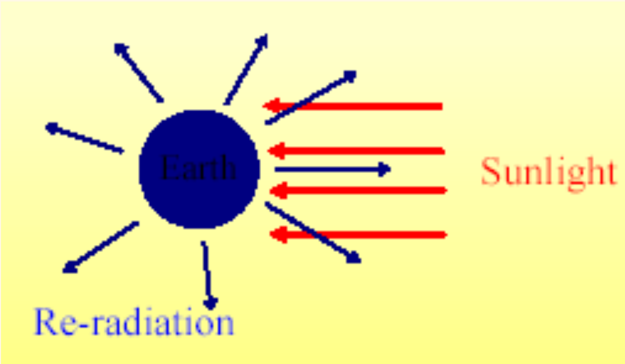


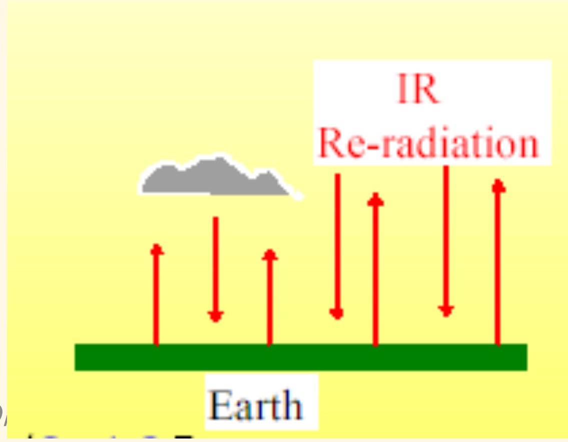
Volcanic activity is episodic and short-lived

One explanation: The Greenhouse Effect

The Earth receives ultraviolet (UV) radiation from the sun, absorbs it, and then radiates the energy out as infrared radiation

If the Earth behaved as a simple blackbody then the Earth's average temperature would be –18° C





However, the Earth's average temperature is 15° C.

The Earth is warmer because our atmosphere traps some of the outgoing IR radiation and this heat re-radiates to the Earth's surface.

This is a natural process known as the greenhouse effect.

However, the Industrial Age may be changing the balance.

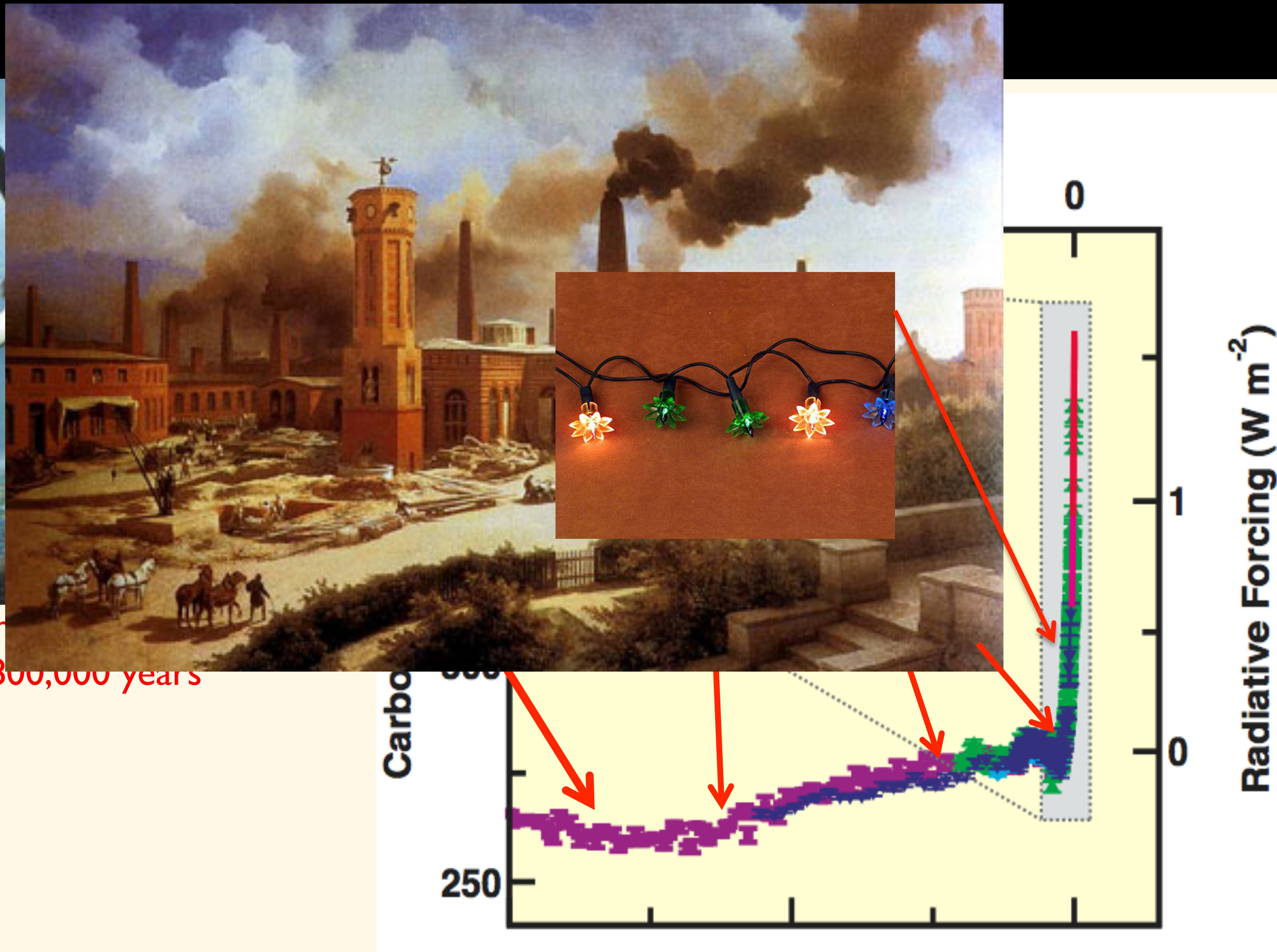
Greenhouse Gases

Greenhouse gases are atmospheric gases that trap infrared radiation emitted from the earth.

Most of the significant greenhouse gases are long-lived and well-mixed:

- Long-lived means they are chemically stable and therefore last many years in the atmosphere
- Well-mixed means they are evenly distributed in the atmosphere.
- This family includes carbon dioxide, methane, oxides of nitrogen, and halocarbons.

Human Drivers of Climate Change:



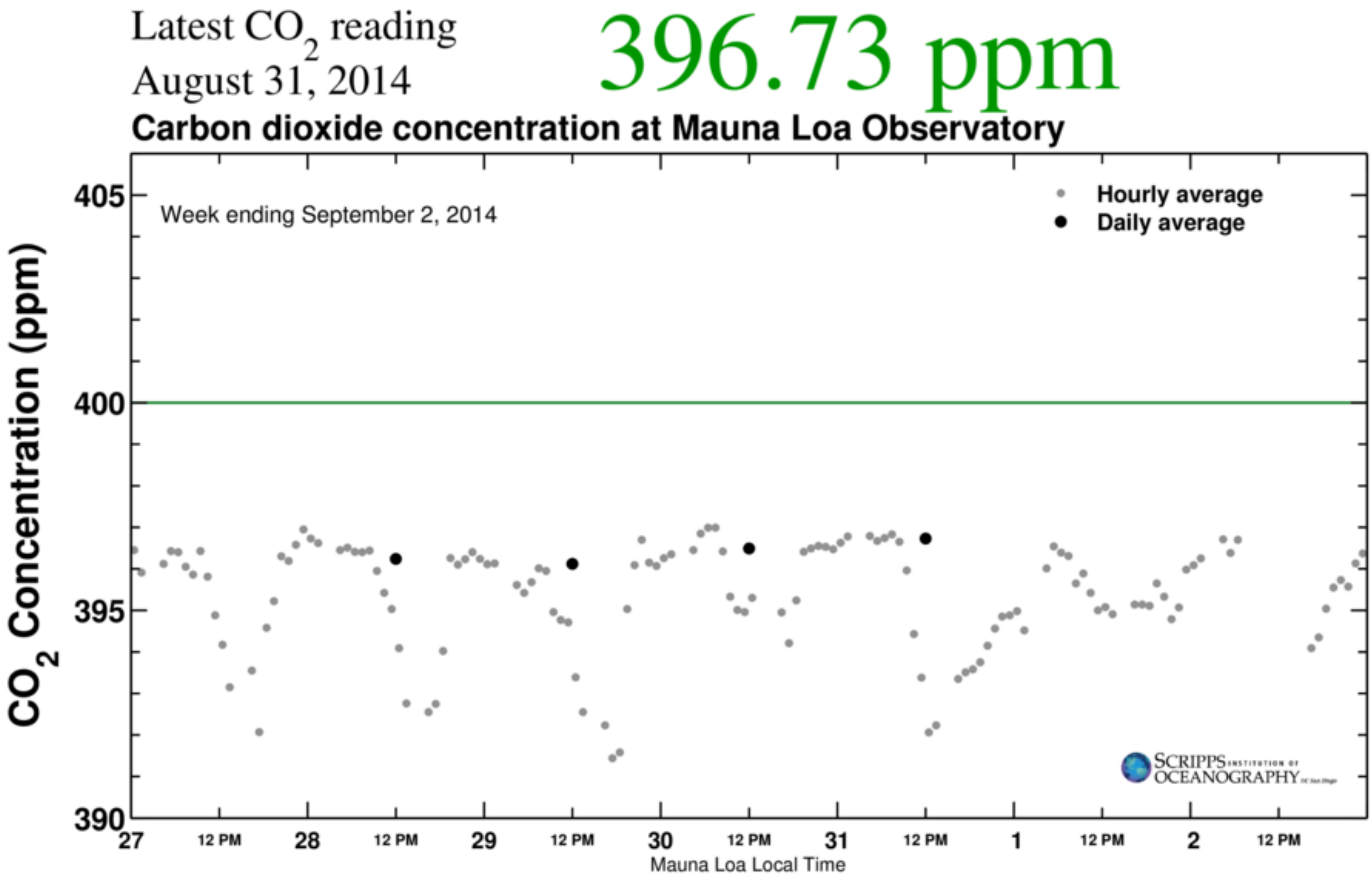
• Higher con
more than 800,000 years

IPCC WG1 (2007) ch 2

Pre-industrial: 270 ppmv Today: almost 390 ppmv

The Keeling curve

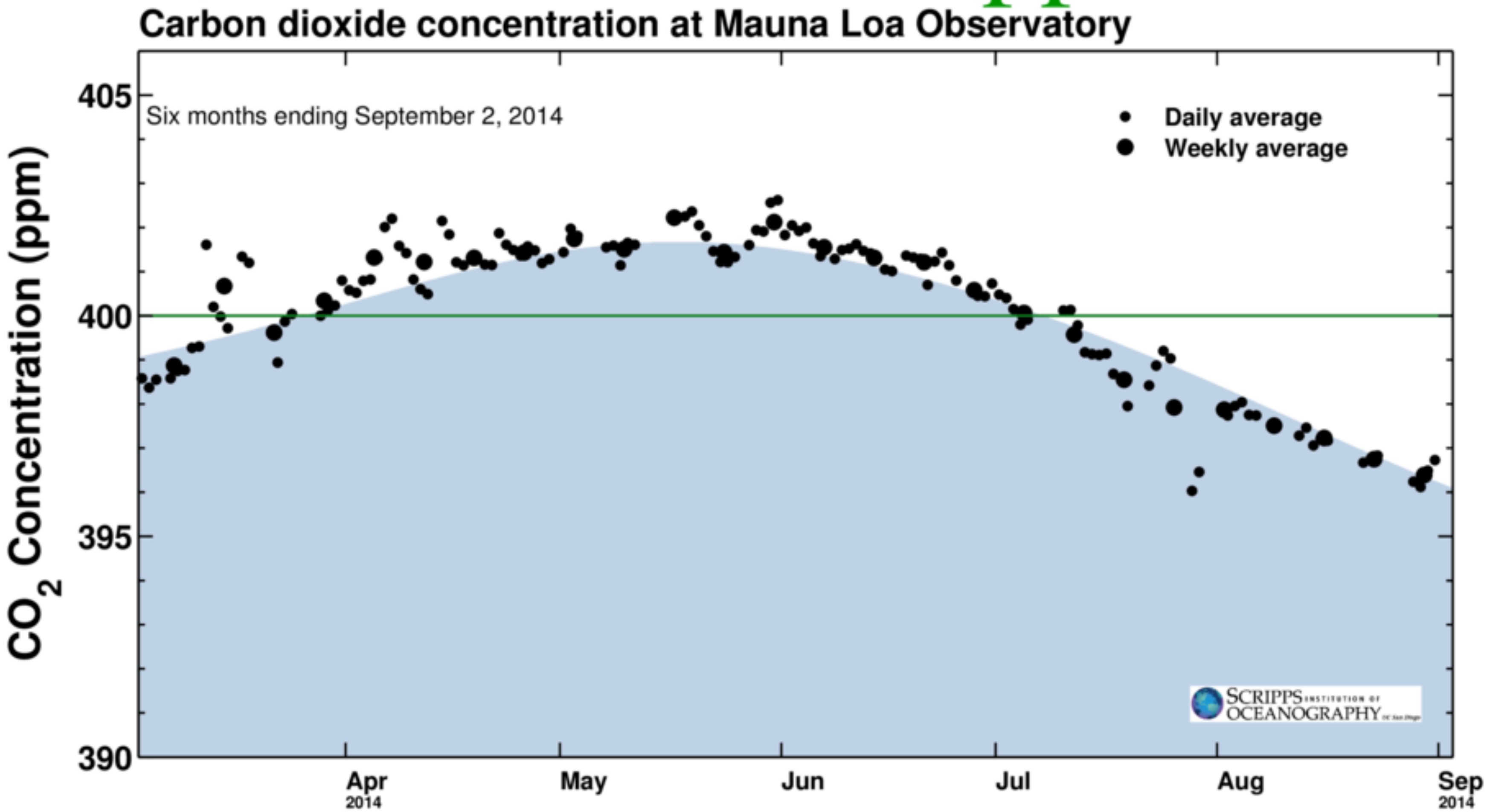
Very important discovery in 20th century science



A week of observations at Mauna Loa Observatory

Latest CO_2 reading
August 31, 2014

396.73 ppm



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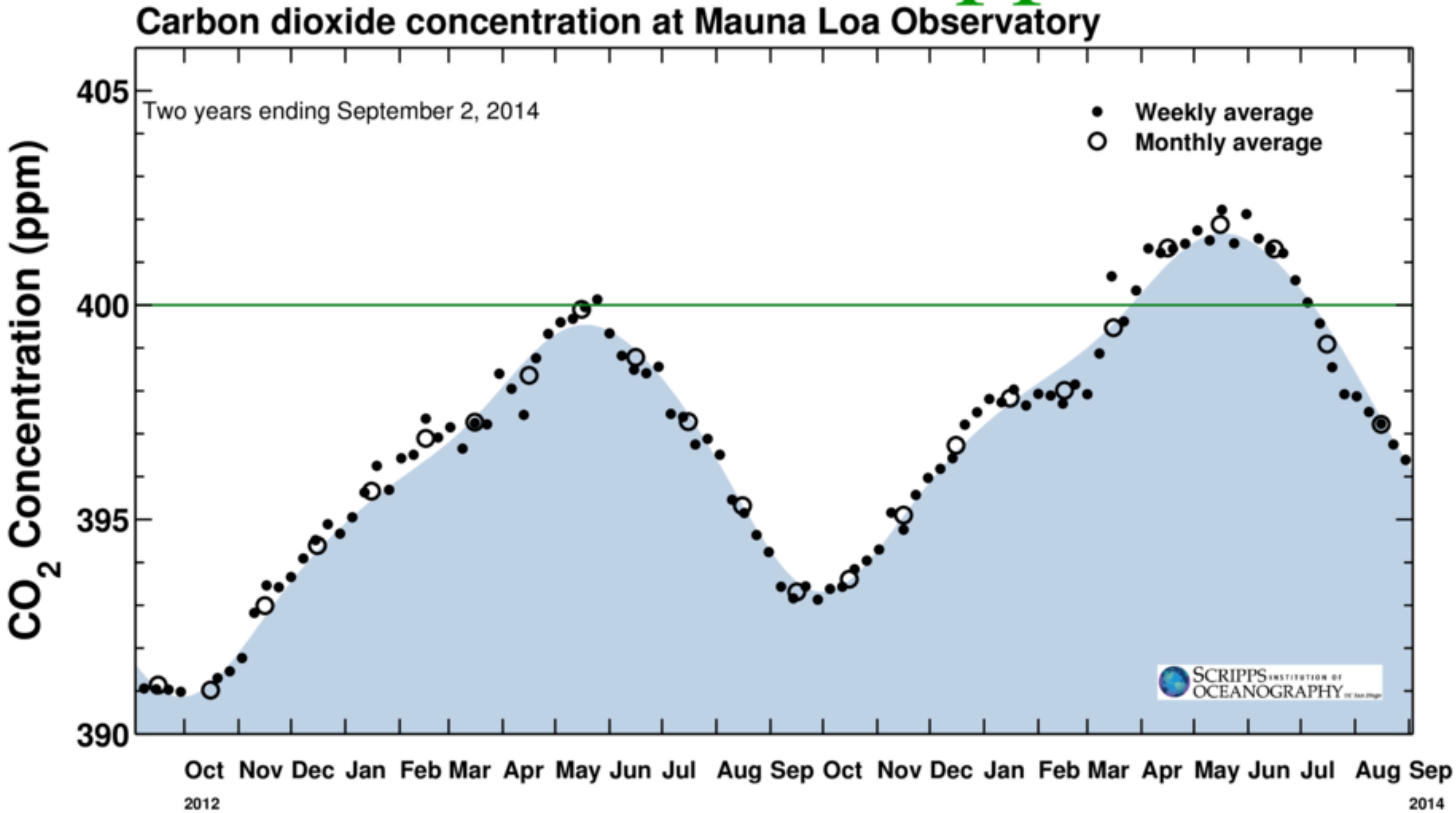
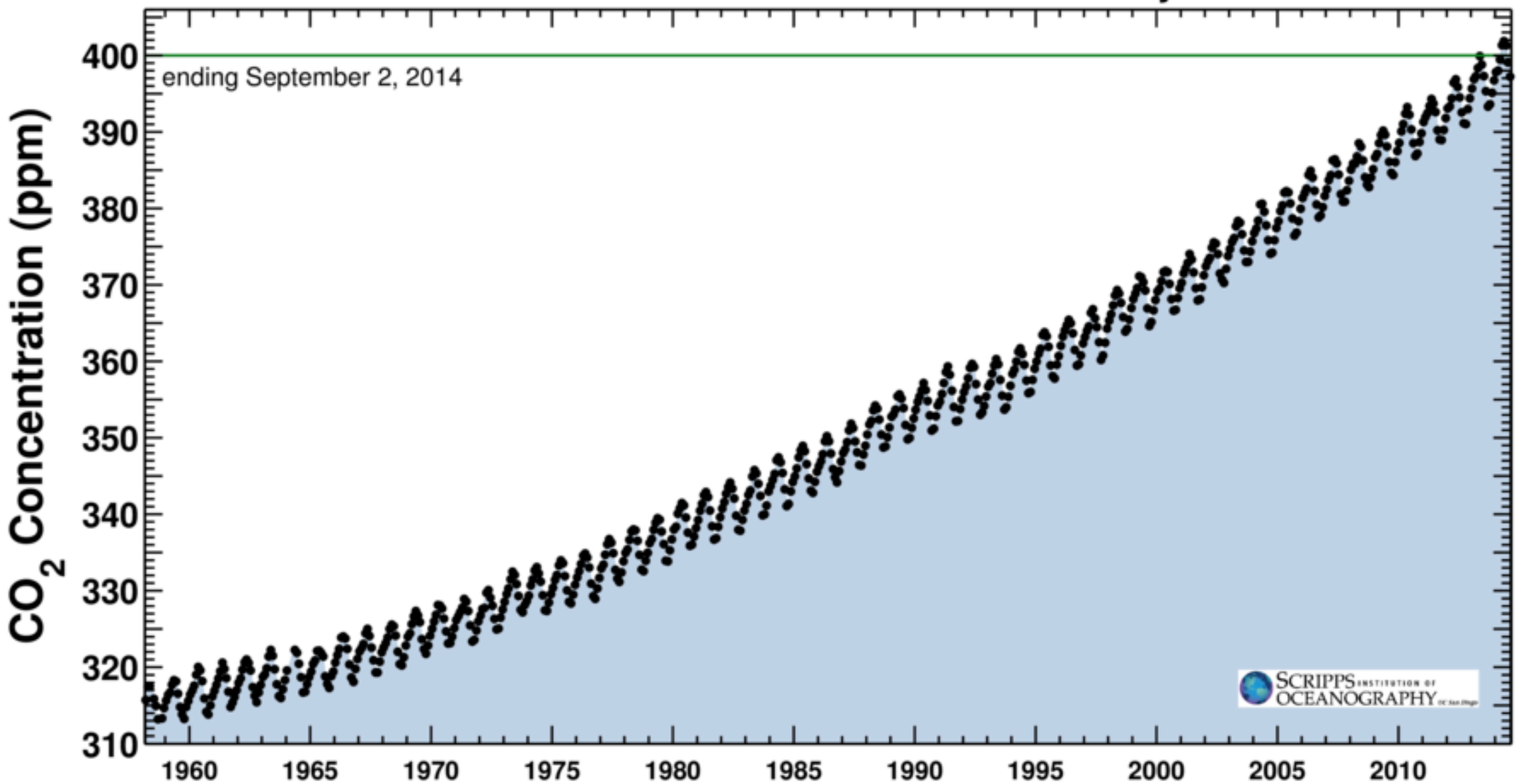
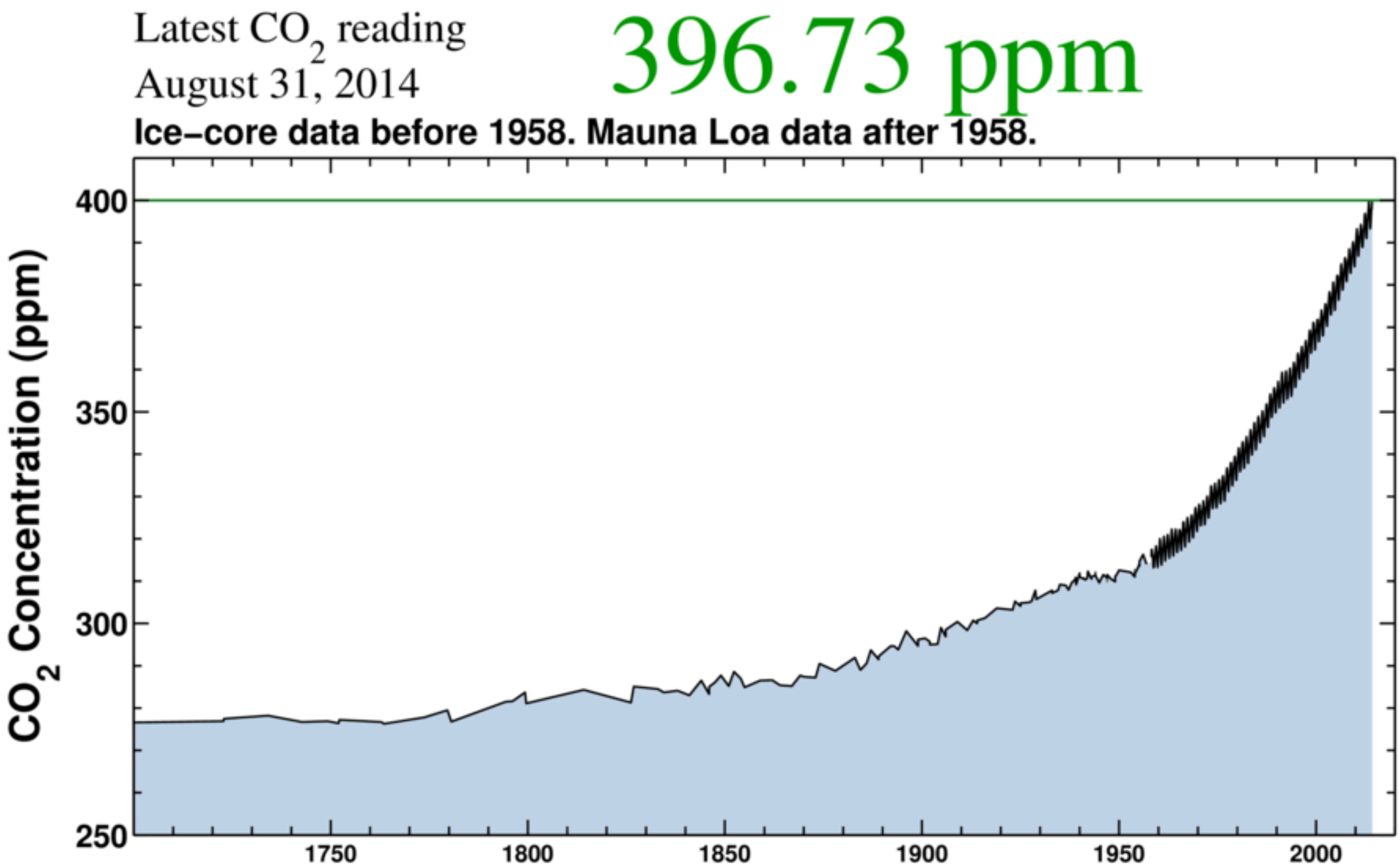


Latest CO_2 reading
August 31, 2014

396.73 ppm

Carbon dioxide concentration at Mauna Loa Observatory

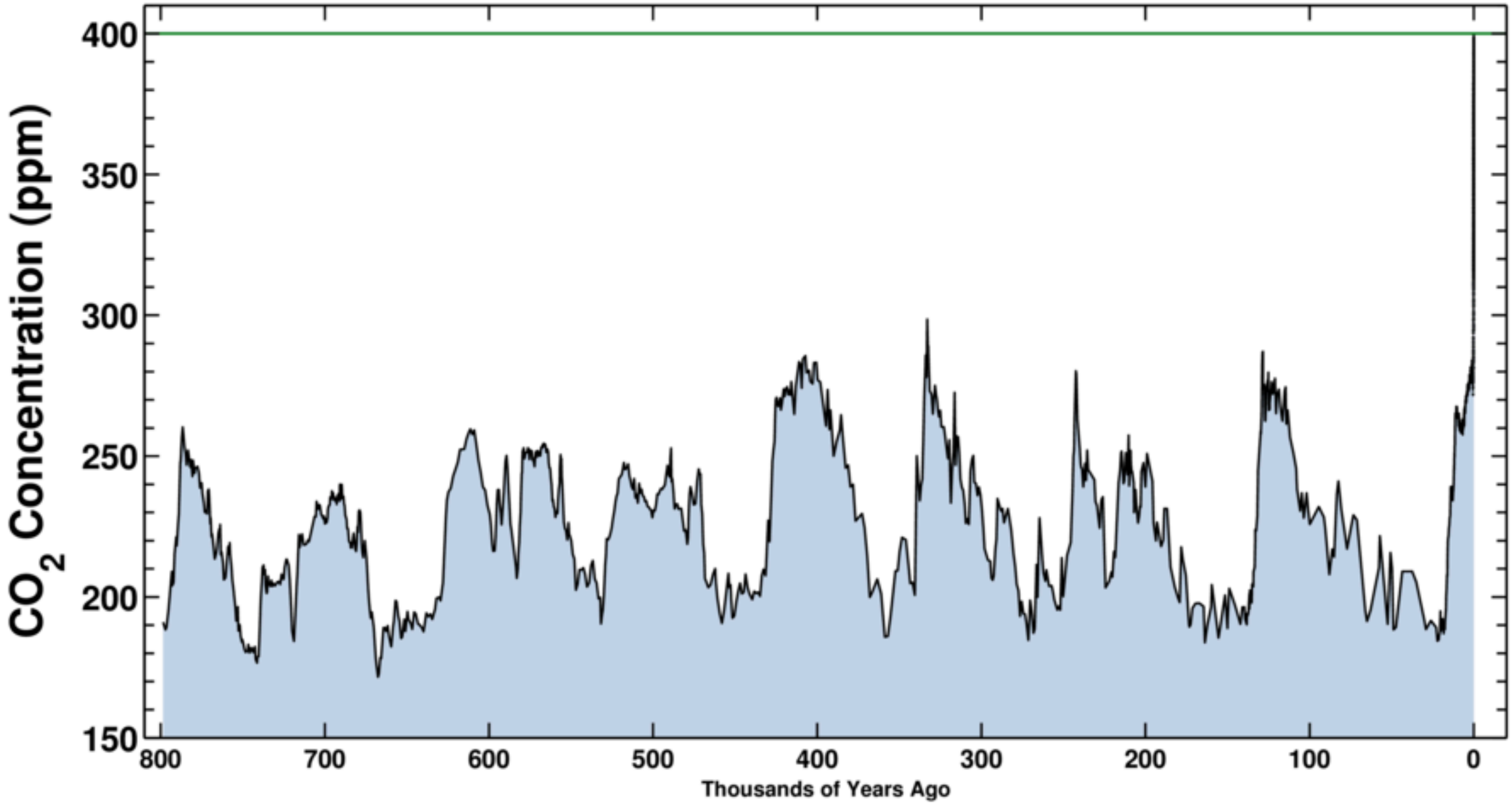



Latest CO_2 reading
August 31, 2014
396.73 ppm
Ice–core data before 1958. Mauna Loa data after 1958.
CO_2 Concentration (ppm)
400
350
300
250
1750
1800
1850
1900
1950
2000

Latest CO_2 reading
August 31, 2014

396.73 ppm

Ice-core data before 1958. Mauna Loa data after 1958.



https://scripps.ucsd.edu/programs/keelingcurve/2014/08/26/as-told-by-the-american-museum-of-natural-history/

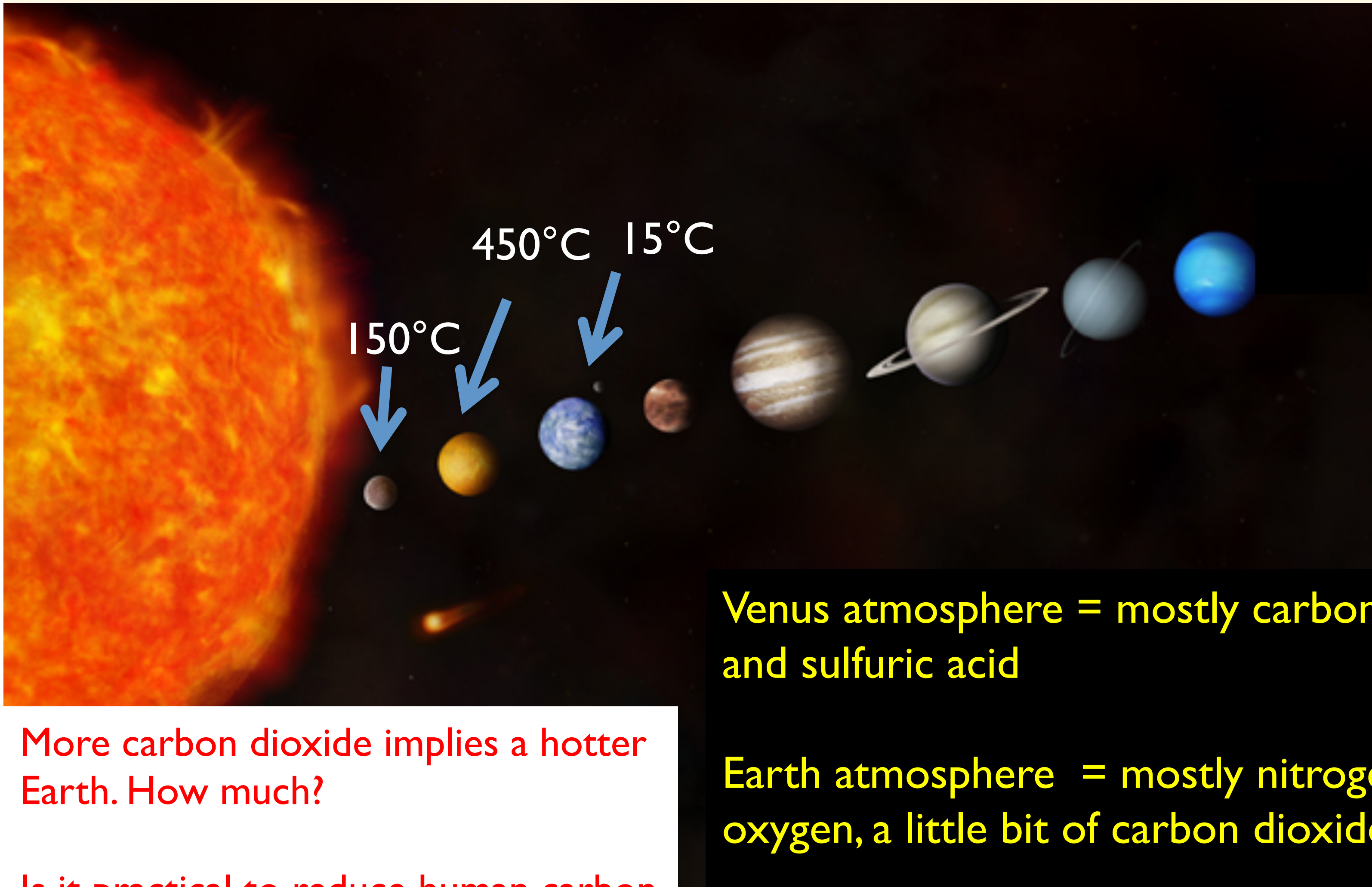
AS TOLD BY THE AMERICAN MUSEUM OF NATURAL HISTORY…

https://scripps.ucsd.edu/programs/keelingcurve/

AUGUST 26, 2014 ROB MONROE

The story of the Keeling Curve is beautifully animated in this new video. The American Museum of Natural History will host a Google+ Hangout Sept. 9, 2014 on the topic of the Keeling Curve.

Do Greenhouse Gases Really Warm a Planet?



Venus atmosphere = mostly carbon dioxide and sulfuric acid

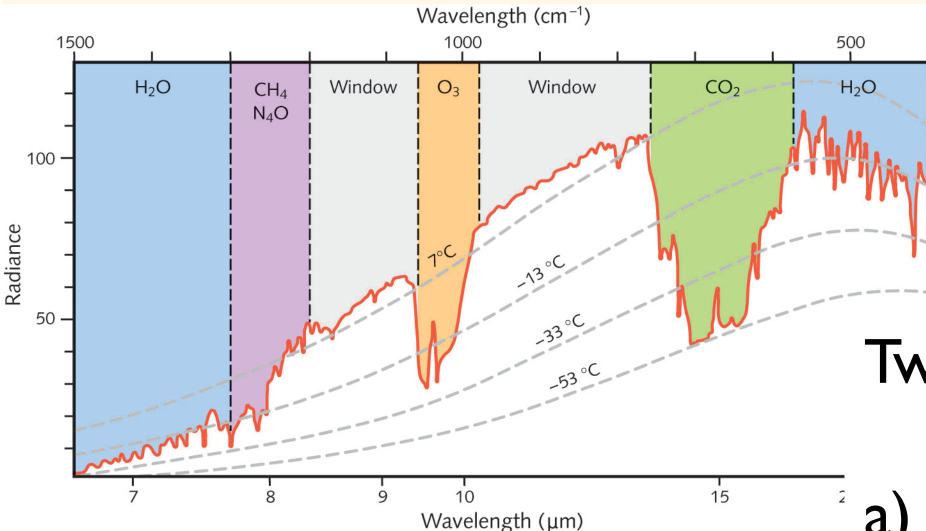
Earth atmosphere = mostly nitrogen and oxygen, a little bit of carbon dioxide

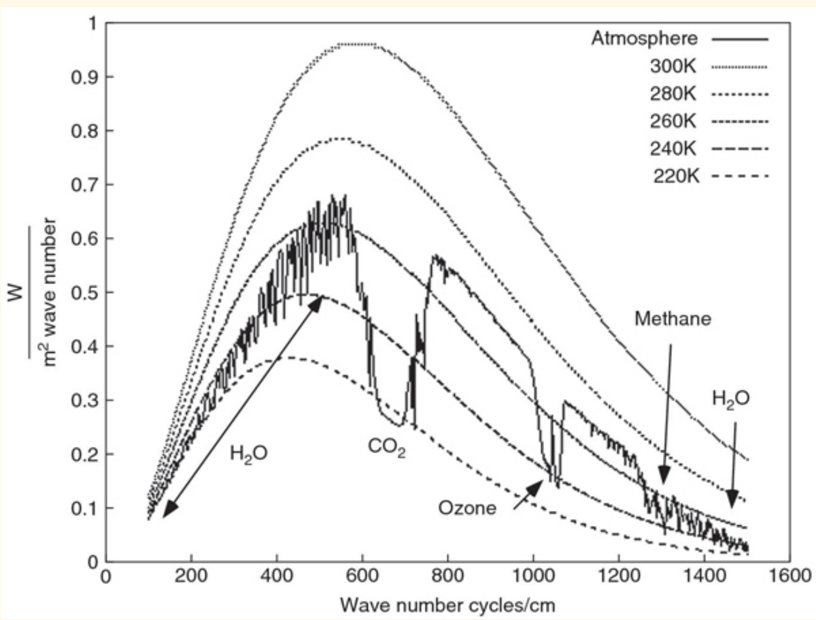
More carbon dioxide implies a hotter Earth. How much?

Is it practical to reduce human carbon dioxide emissions?

Houghton Fig. 2.5

Why CO_2?





Two ways of plotting the IR spectrum

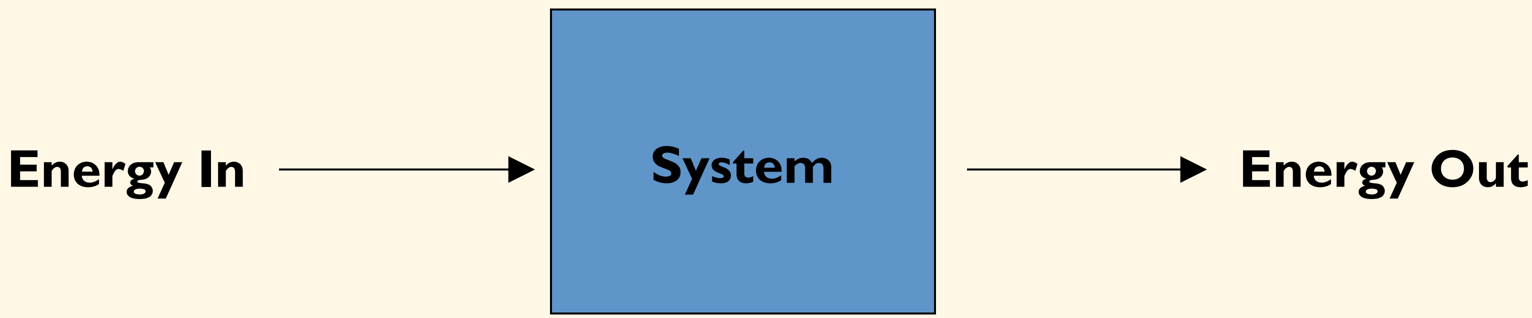
a) As a function of wavelength (m)

b) As a function of wavenumber(cm^{-1})

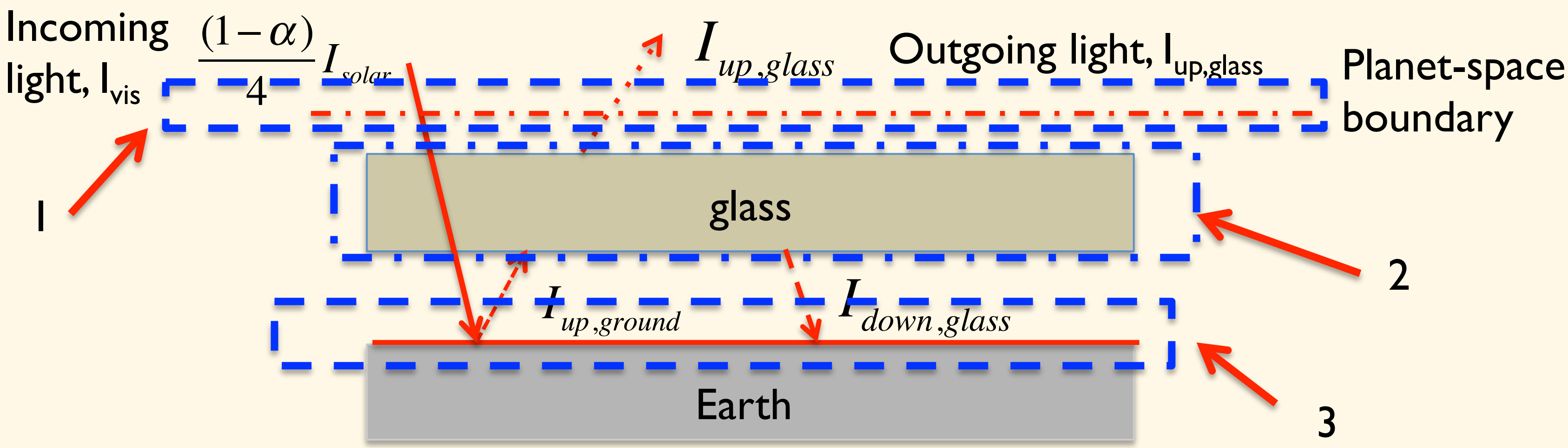
Energy Budget for Steady-State Systems

When the average temperature is constant or in steady-state then the energy into the system must equal the energy leaving the system.

This is a result of the conservation of energy:



We used a simple model to illustrate the greenhouse effect a "toy model"



Energy fluxes in Regions 1, 2, and 3 need all be in separate balance

i.e. The Planet-Space boundary.

the glass pane

The surface of the Earth

$$I_{up,glass} = I_{in,solar}$$

$$I_{up,glass} + I_{down,glass} = I_{up,ground}$$

$$I_{up,ground} = I_{in,solar} + I_{down,glass}$$

Hence, the three energy balance equations are set up.

$$\varepsilon\sigma T_{glass}^4 = \frac{(1-\alpha)}{4} I_{solar}$$

$$\frac{(1-\alpha)}{4} I_{solar} + I_{down,glass} = I_{up,ground}$$

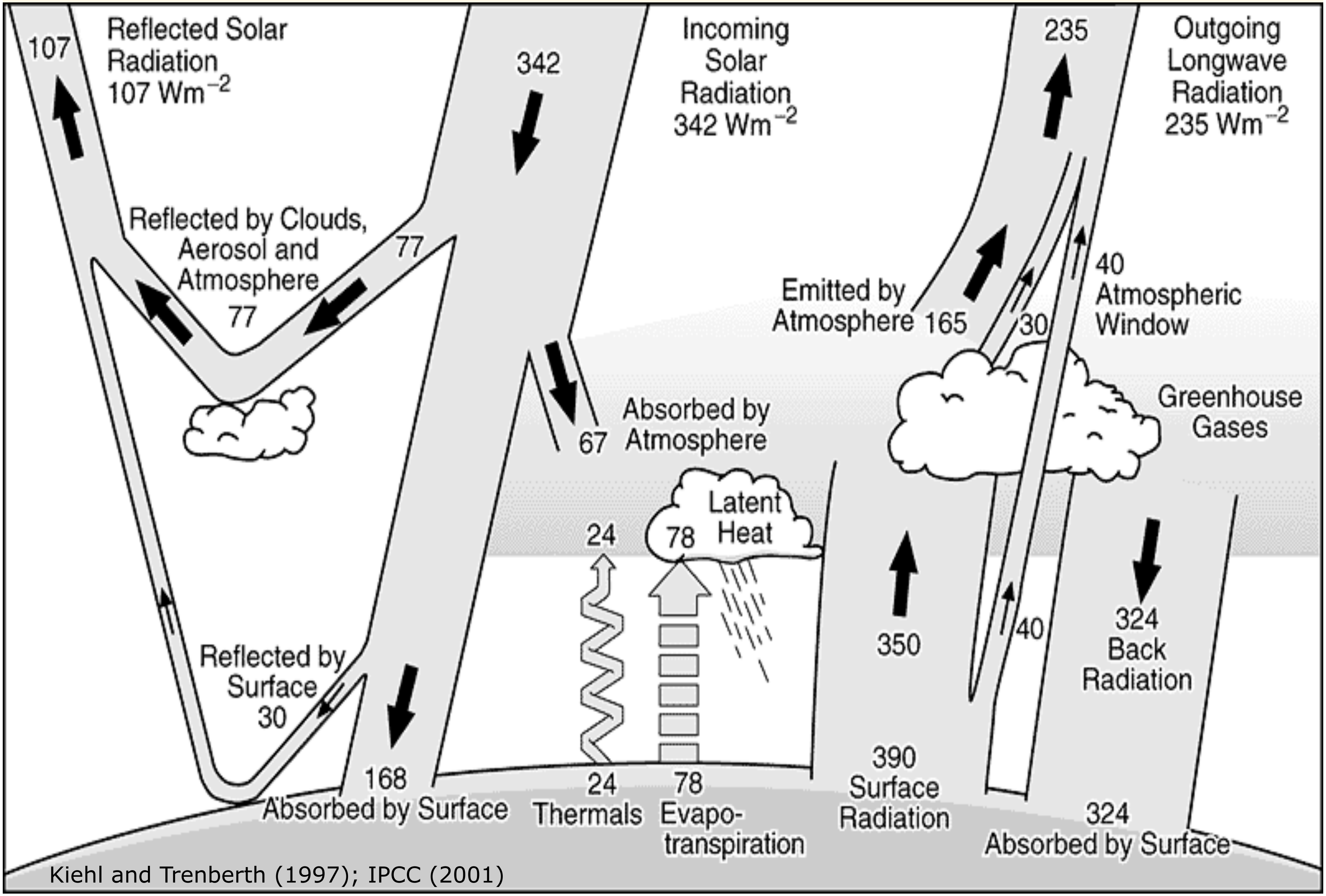
$$\varepsilon\sigma T_{glass}^4 + \varepsilon\sigma T_{glass}^4 = \varepsilon\sigma T_{ground}^4$$

By application of the Stefan-Boltzman radiation law to these relations: $I = A\varepsilon\sigma T^4$

Get: $$T_{ground} = \sqrt[1/4]{2} T_{glass} = 1.189 T_{glass}$$

Thus, the Earth's surface temperature becomes greater than the skin temperature as a result of the greenhouse effect

Global Annual Energy Balance (Watts / meter^2)



Kiehl and Trenberth (1997); IPCC (2001)

To summarize: re Earth's atmosphere

The Earth is about 33^{O}C warmer than expected if we consider only the amount of solar energy received and reflected.

Trace atmospheric gases, H_2O and CO_2, trap infrared radiation that would otherwise be re-emitted into space.

This effect is known as the Greenhouse Effect - the mechanism that keeps greenhouses hotter than we might expect.

The greenhouse gas content has been increasing since the beginning of the Industrial Age

Factors that determine the importance of a greenhouse gas:

- Atmospheric abundance
- The wavelengths of radiation absorbed
- The efficiency of radiation absorption

Greenhouse Gas Concentrations			
Greenhouse gas	**Concentration 1750**	**Concentration 1995**	**Percent Change**
Carbon dioxide, CO_2	280 ppmv	360 ppmv	29%
Methane, CH_4	0.7 ppmv	1.7 ppmv	143%
Nitrous oxide, N_2O	280 ppbv	310 ppbv	11%

Now at 400 ppmv

Summary: the Greenhouse Effect explanation is a successful theory.

Greenhouse effect predicts:

- warmer temperatures at the surface and cooler temperatures aloft.
- warmer temperatures in the polar regions.
- more intense hurricanes (because of higher sea surface temperatures).

Greenhouse effect explains:

- correlation of the rapid rise of global temperature with the onset of the industrial age.
- higher surface temperature over land than sea.
- why the sea level is rising.
- the longer growing seasons (and increased number of forest fires).

The best test of a theory is whether these effects can be modeled.

Difficulties in modeling climate change: scientific

Establishing anthropogenic origins.

Feedbacks, positive (de-stabilizing) and negative (stabilizing).

Oceans – competing effects

- Warming releases CO_2 (Coke)
- Warming may or may not increase plankton growth.

Particulates – smoke, haze, aerosols. Are they net reflectors or absorbers?

Albedo – reflectivity of Earth's surface. Temperature of converted rain forests 3° higher (soil is darker than trees).

Predicting impacts of climate change

Emissions — **Scenarios from population, energy, economics models**

Concentrations
CO_2, methane, sulphates, etc. — **Carbon cycle and chemistry models**

Global climate change
Temperature, rainfall, sea level, etc. — Coupled global climate models

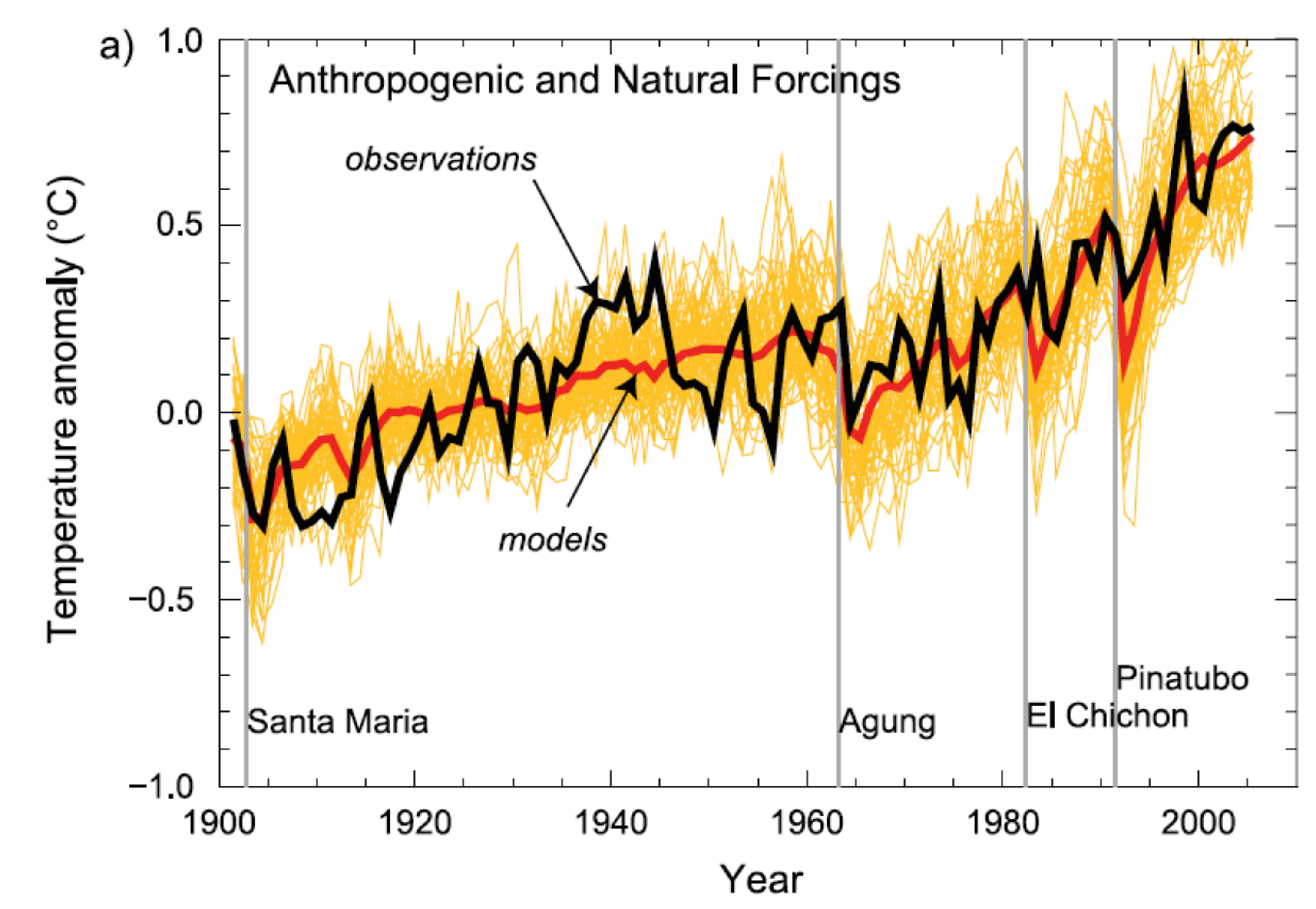
Regional detail
Mountain effects, islands, extreme weather, etc. — Regional climate models

Impacts
Flooding, food supply, etc. — Impacts models

The main stages required to provide climate change scenarios for assessing the impacts of climate change.

Hadley Centre - PRECIS brochure

Anthropogenic with natural forcings fit



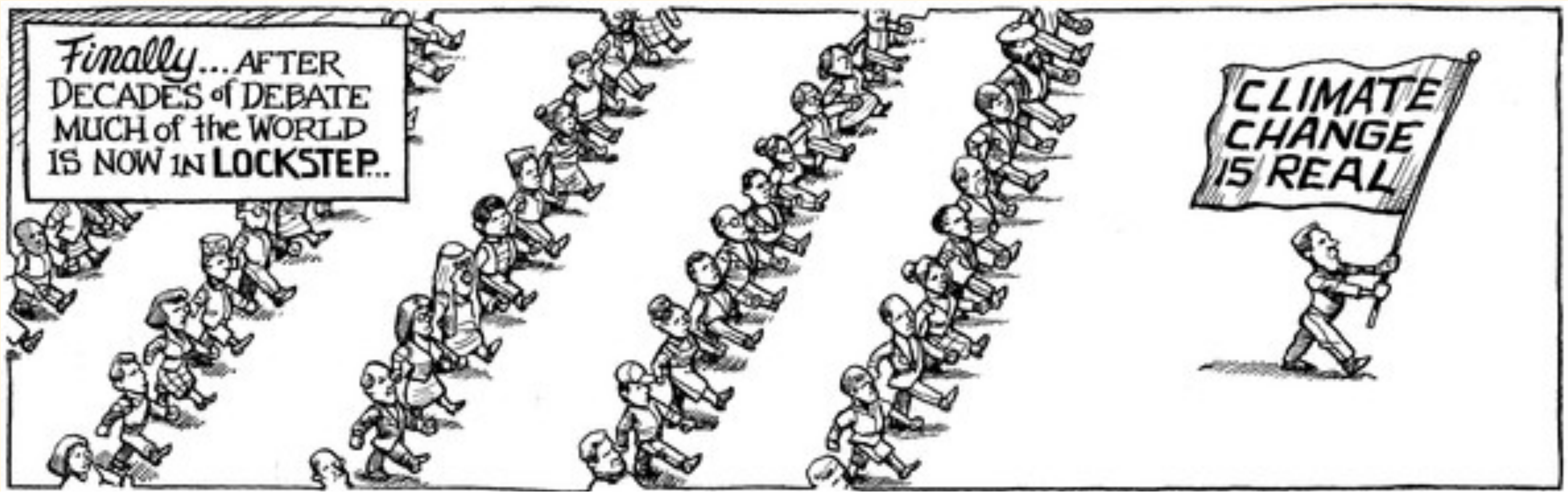
National Academy of Sciences

"**Climate change is real.** There will always be uncertainty in understanding a system as complex as the world's climate.

However there is now strong evidence that significant global warming is occurring. The evidence comes from direct measurements of rising surface air temperatures and subsurface ocean temperatures and from phenomena such as increases in average global sea levels, retreating glaciers, and changes to many physical and biological systems.

It is likely that most of the warming in recent decades can be attributed to human activities. This warming has already led to changes in the Earth's climate."

Where do we go from here?



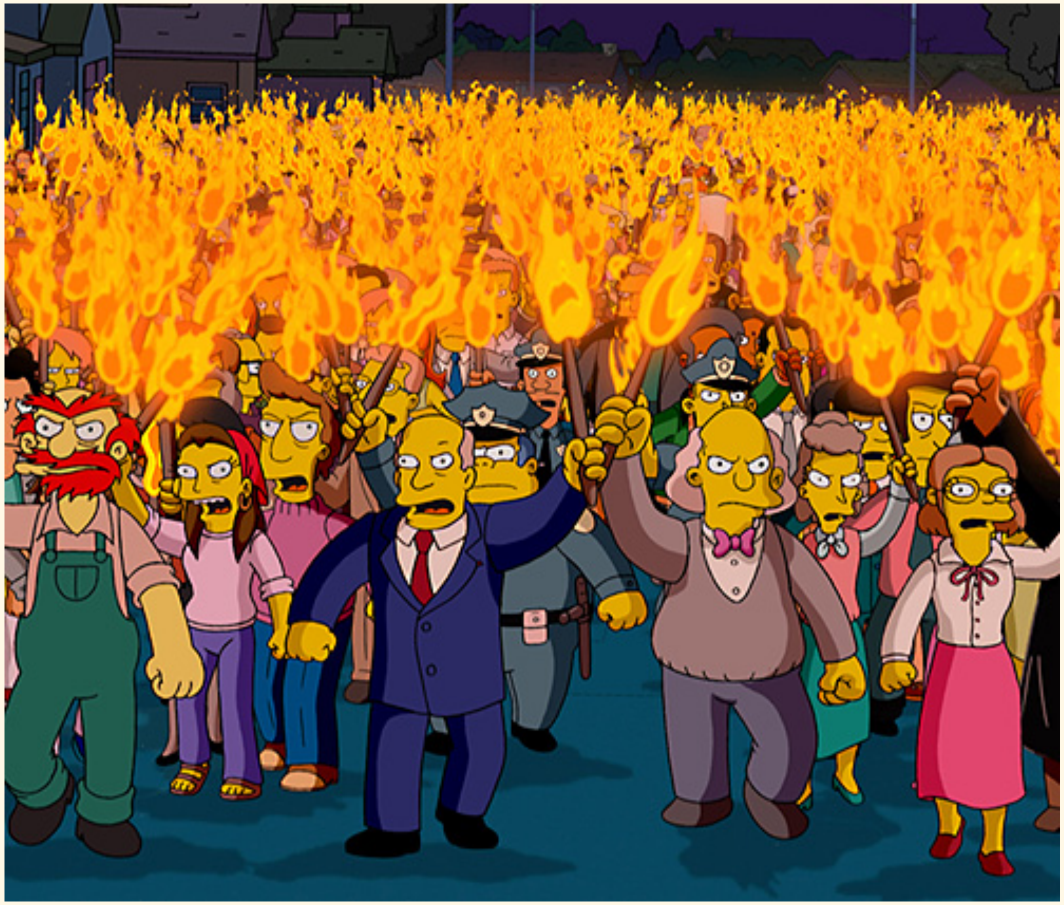
A cacaphony of emotional reactions and special social viewpoints?

Go back to a simpler lifestyle!

Ban planes!

Flooded world tomorrow!

Use climate change to alleviate world poverty!



“Art upsets, science reassures” – Georges Braque

Maybe not in this case.

Population bomb!

Left-wing plot to control our lifestyles!

Third world raid on our money!

Plot for world government!

Assessing a region's ability to handle runoff from heavier precipitation

Adaptation –

Anticipating and adjusting to new conditions

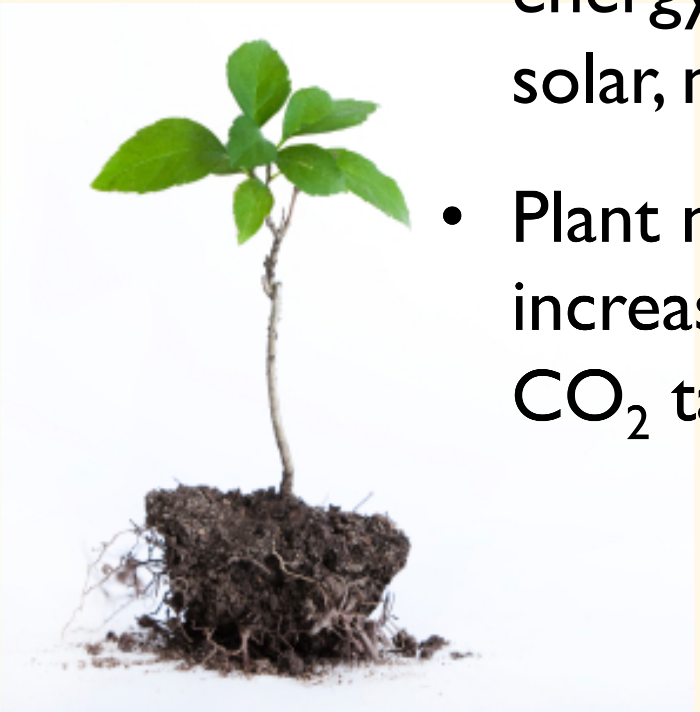
What changes are coming?

What changes do we need to make?

- Protect habitat or structures threatened by sea level rise
- Develop plans to ensure adequate water supplies
- Plant different crops
- Develop new businesses

Mitigation – Reducing CO_2

- Develop new habits to eliminate wasted energy
- Switch to carbon-free energy sources such as solar, nuclear, and wind
- Plant new trees to increase the amount of CO_2 taken up by forests



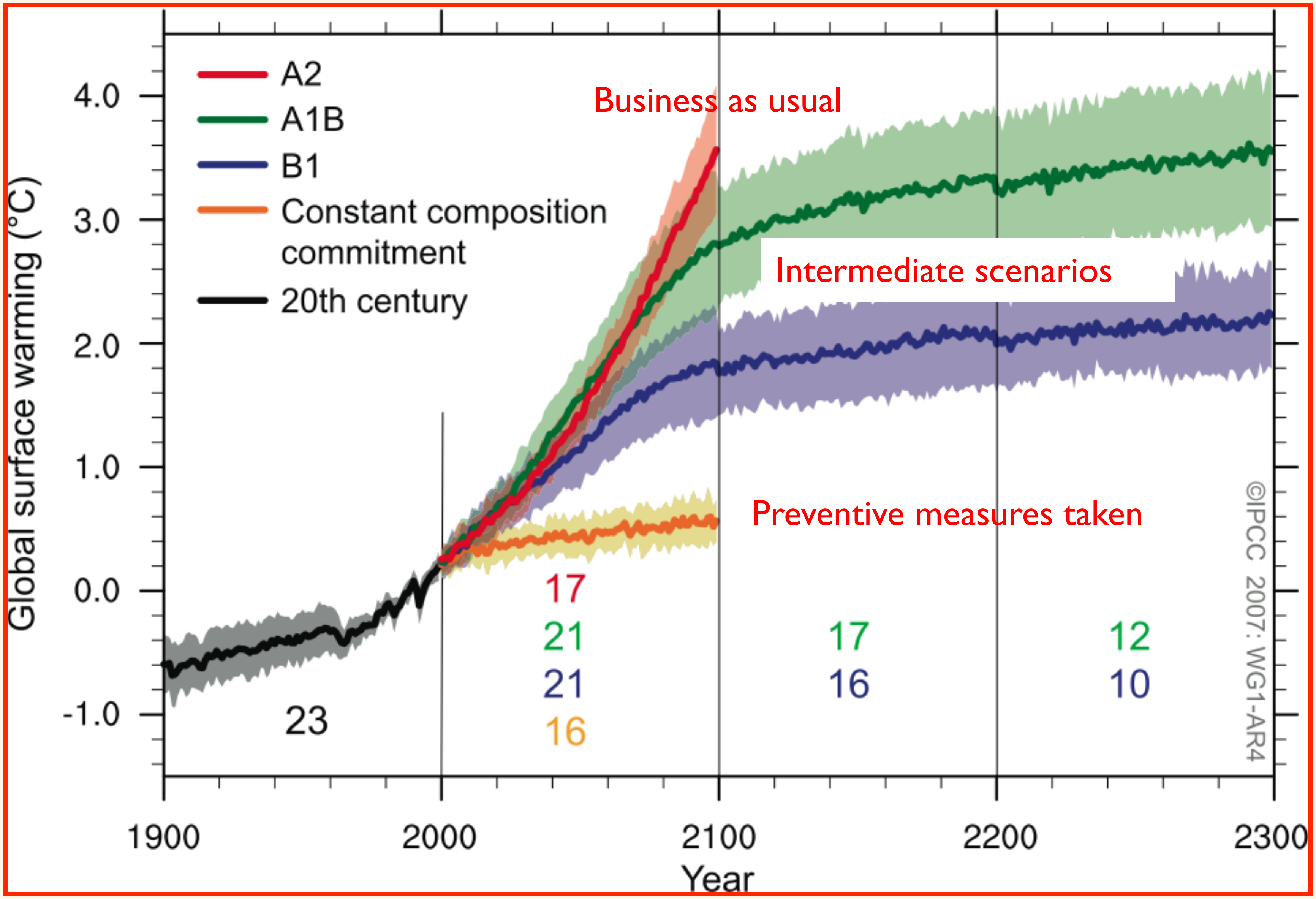
Back One Slide

What happens if we did nothing?

A world of misery,

Especially, for third-world countries

So what lies ahead in our future with "business as usual"?



Global warming of perhaps 2-3 C expected over the next 75 years.

Global Impacts

The BAD: (worse as it warms more)

- Water shortages from snowpack loss…
- Increased floods and droughts…
- Extinction of many species & ecosystems…
- Spread of pests & diseases…
- More heat related illnesses and deaths…
- More intense hurricanes and typhoons

Catastrophic Impacts

- Thermohaline shutdown of Gulf Stream: unknown but likely chaotic impacts
- Ocean acidification: potential collapse of marine foodchains
- Methane release from tundra or ocean clathrates:
  could initiate very rapid warming
- Continental Ice Sheet Collapse: sea level rise of 35-40 feet

Florida with a 1 meter sea level rise or storm surge

How to slow adding CO_2 to the atmosphere? Five solution paths:

-- improve end-user efficiency and conservation

-- increase power generation via clean energy

-- carbon capture and storage: sequestration

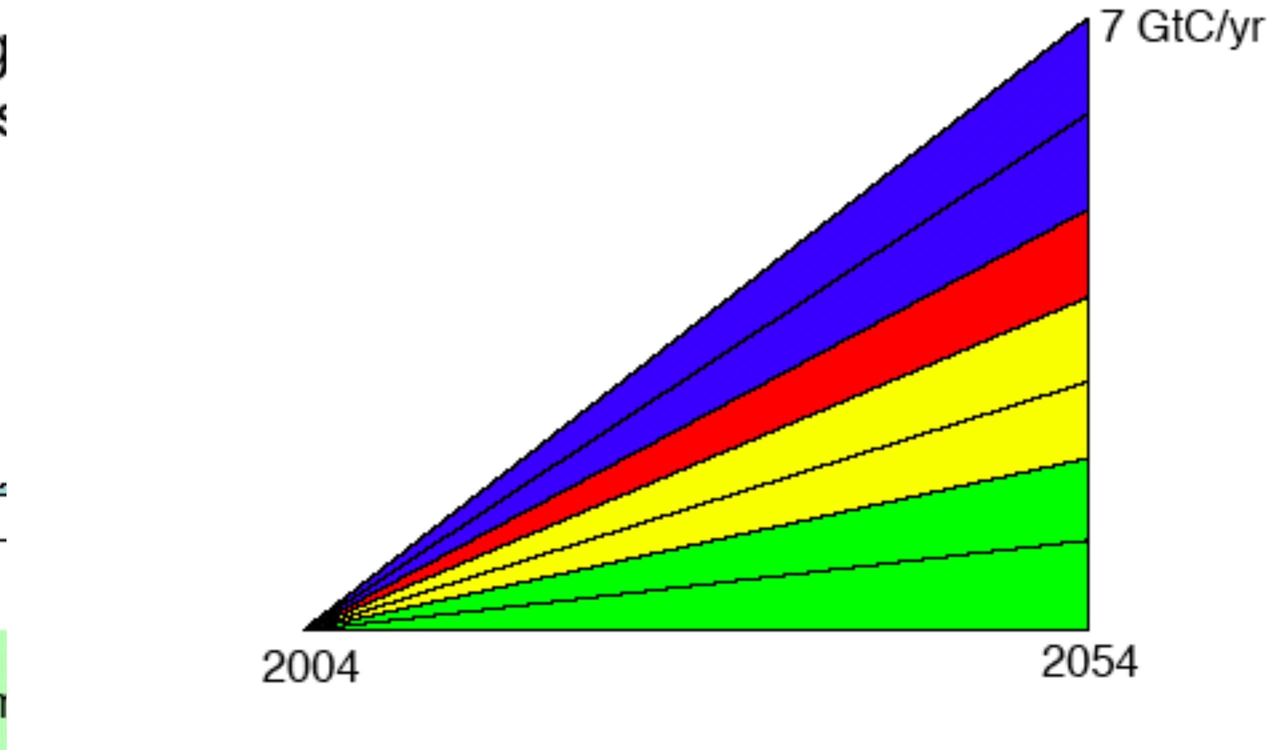
-- improve agriculture and forestry

-- abandon fossil fuel usage

A Range of Future Choices

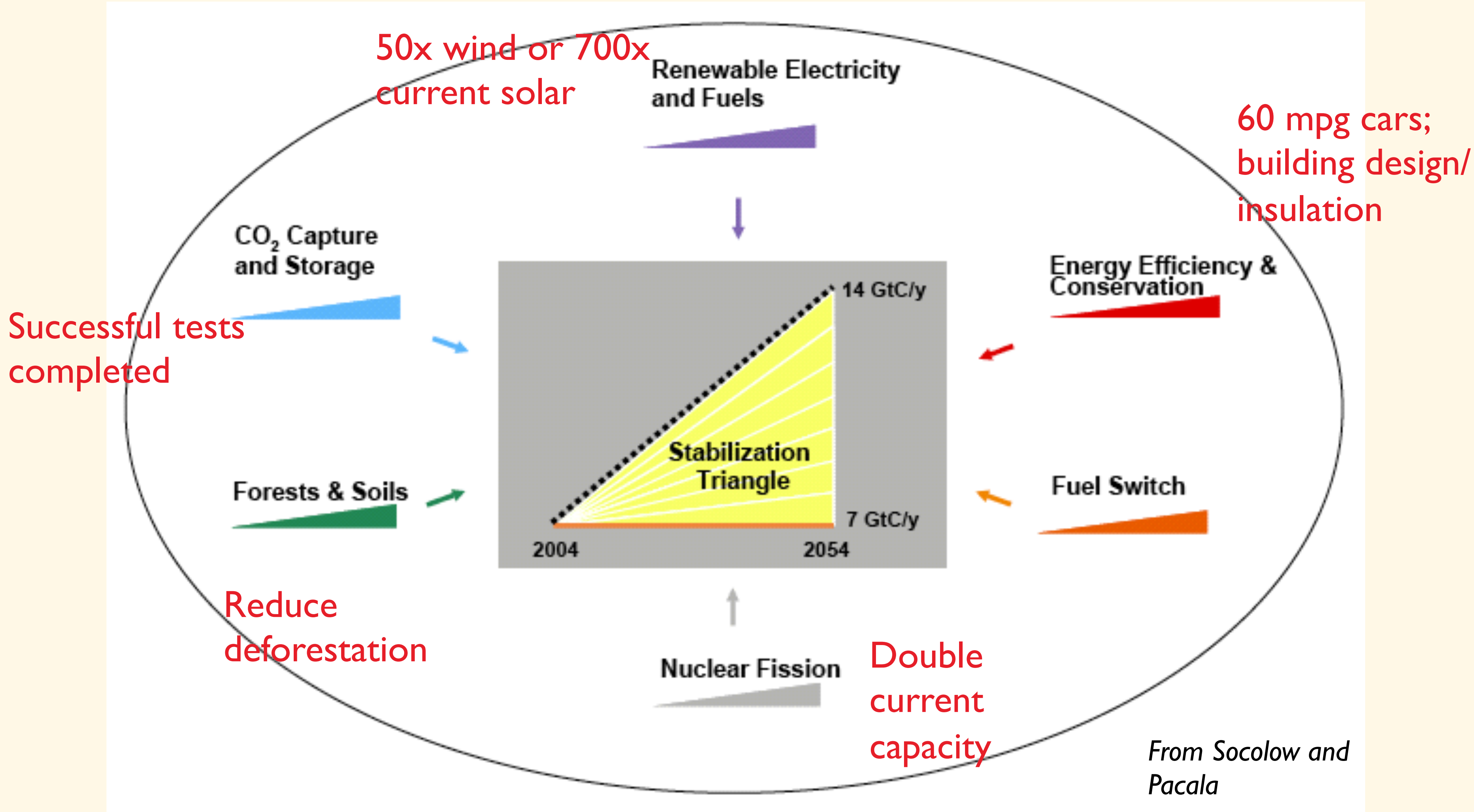
What is a “wedge”?

A “wedg ... n
the atmos ... yr.



Cum

‘Wedges’ illustrating mitigation options: 12 or so needed…



Examples only: No silver bullets but much silver buckshot. Technology development; starting to decarbonize energy supply is key and has other benefits….what to do? R&D

Climate Myths

• Climate has always varied (yes, but a lot of that variability was forced and we know what is forcing current change).

• The upper atmosphere isn't warming - it's only the surface (bad data was confusing for a while….this is not true).

• The sun is causing the current changes (the Sun hasn't changed in recent decades - neither brightness nor cosmic rays nor length of the cycle…).

• Greenhouse gases are natural (sure, but look at how they've changed).

• Water vapor is the dominant GHG (sure, but it responds to changes in climate - it doesn't force them…).

• Good things are happening - longer growing season at mid-latitudes, etc. (good things aren't happening everywhere- ask the polar bears in the Arctic or the citizens of New York City).

Solutions Now (2014) Much Harder to Achieve

Growth in demand for electrification in developing countries, particularly in Asia, led by China & India.

Coal, oil, and gas as primary alternative -- plentiful & cheap.

Chinese plans for bringing on-line a 1 GW-capacity coal-fired power plant per week for decades.

If growth in supply not accompanied by CCS technologies, very difficult to get control of the GW problem.

But energy technology changes slowly & it will take decades to spin up CCS technology to be fully operational & for a very large number of sites to be made ready.

So, Quo Vadis?

We seem to be stuck on the edge of a precipice. It appears to be impossible to avoid doubling CO_2 concentration by 2050. This tips the odds in favor of extreme events.

The EU is ready to move, but, so far, neither the U.S. nor China has been willing to respond in kind.

There can be no global agreement without both those states.

Do they prefer the dance of coordinated unilateral movements while the global negotiation stalls?

We need rapid change, but what is the optimal path?

And will we assist poor, weak states to face the instabilities of a climate fed by such high concentrations of CO_2?

Both China & the US face severe vulnerabilities as well.

"Facts do not cease to exist because they are ignored."

Aldous Huxley

"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."

Roger Revelle

"For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled." Richard Feynman

Susan Solomon is now a MIT Ellen Swallow Richards Professor of Atmospheric Chemistry and Global Change Studies.

She is optimistic that the problems of climate change can be solved.: the signal of temperature increase is going to be booming through in the next few years, and we will more and more be motivated to do something about it.