CHALLENGES TO GLOBAL WARMING SCIENCE

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MCSP Conversation Series

March 29, 2007

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OUTLINE OF TALK

I. A PRELIMINARY QUESTION
II. MEASURING TEMPERATURE
III. SKEPTIC CHEAP SHOTS
IV. SERIOUS SCIENTIFIC CHALLENGES
V. MAKING DECISIONS IN THE FACE OF UNCERTAINTY

I. A PRELIMINARY QUESTION

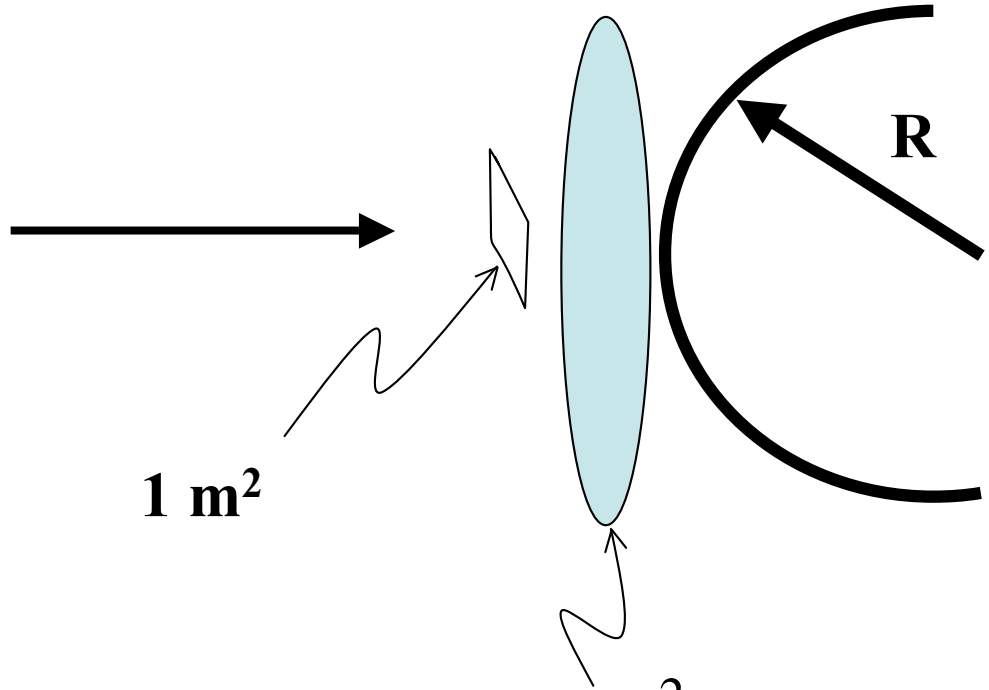
WHY IS EARTH 14 ^{o} (WHY SHOULD THIS QUESTION BE ASKED?)

Constraints From Radiation Physics

As seen from outer space:

Insolation: 1369 W/m²

30 % reflected and averaged over surface leaves 239 W/m² to warm Earth



Capture area $= \pi R^2$

Spread over $4\pi R^2$

Equilibrium :
Radiation in from sun = Radiation back out to space

Stephan-Boltzmann law:

$$\sigma T_E^4 = 239 W / m^2 \Rightarrow$$

$T_E = 255K = -18^o C$ from outer space.

Too cold for life as we know it!

GREENHOUSE GASES TO THE RESCUE!

H_2O vapor:	**+20.6 ^oC (64.4%)**
CO_2:	**+ 7.2 ^oC (22.5%)**
CH_4:	**+ 0.8 ^oC (2.5%)**
Ozone and others:	**+ 3.4 ^oC (10.6%)**

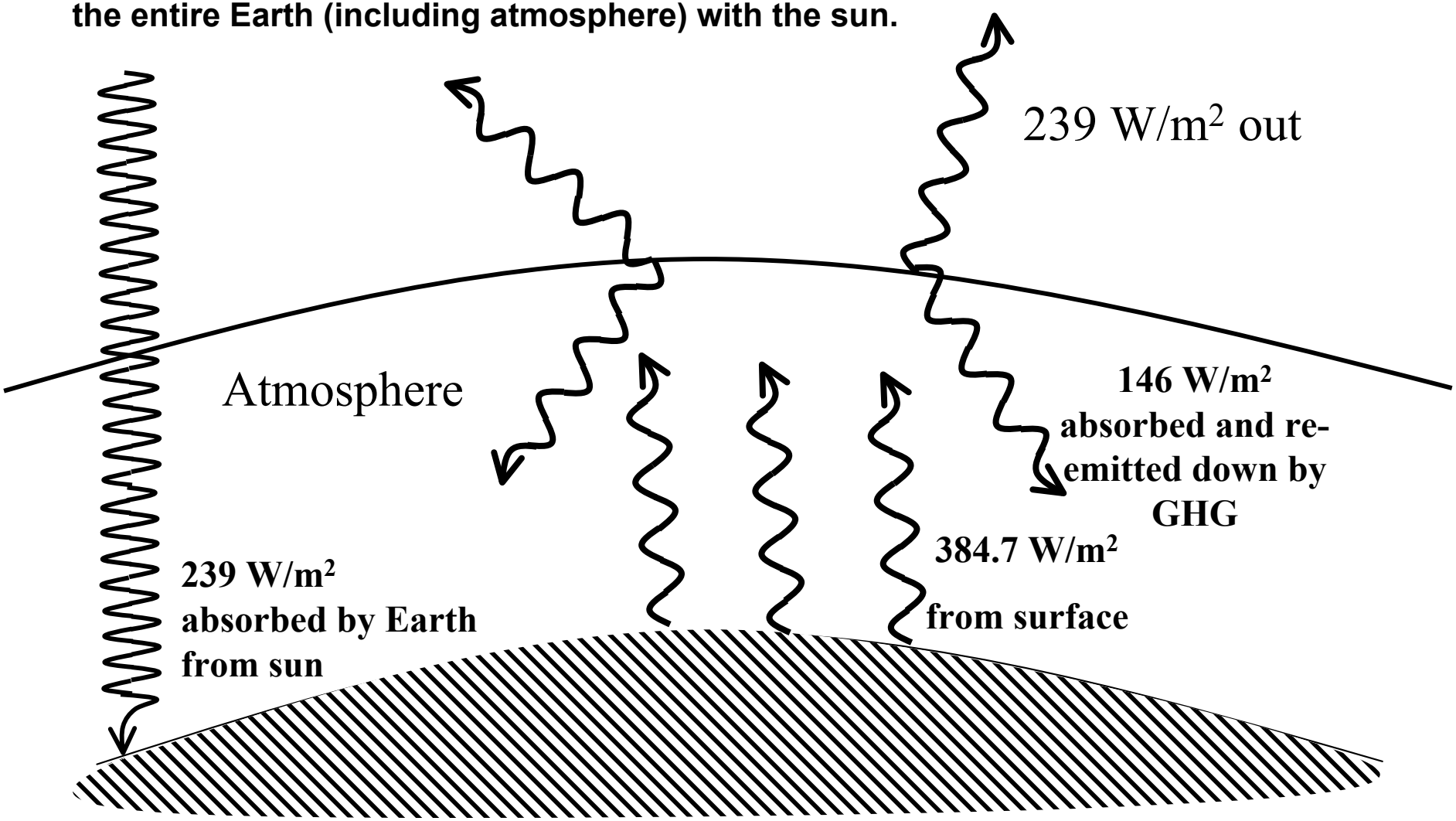
Total warming: +32.0 ^OC, i.e., +14^OC surface temp

SURFACE IS TOASTY, BUT REMEMBER: FROM OUTER SPACE, EARTH IS -18 ^OC.

<u>SOURCE</u>: E. Boeker & R. van Grondelle, *Environmental Physics* (Wiley, 1995), p. 36.

Bare bones explanation of GHG mechanism

Hot, visible short-wavelength radiation from the sun slices through atmosphere; long-wavelength infrared radiation from much cooler Earth is absorbed by GHG; some escapes to space, some is emitted back to Earth. There is overall radiation balance of surface with sun and atmosphere, of the atmosphere with surface, and of the entire Earth (including atmosphere) with the sun.

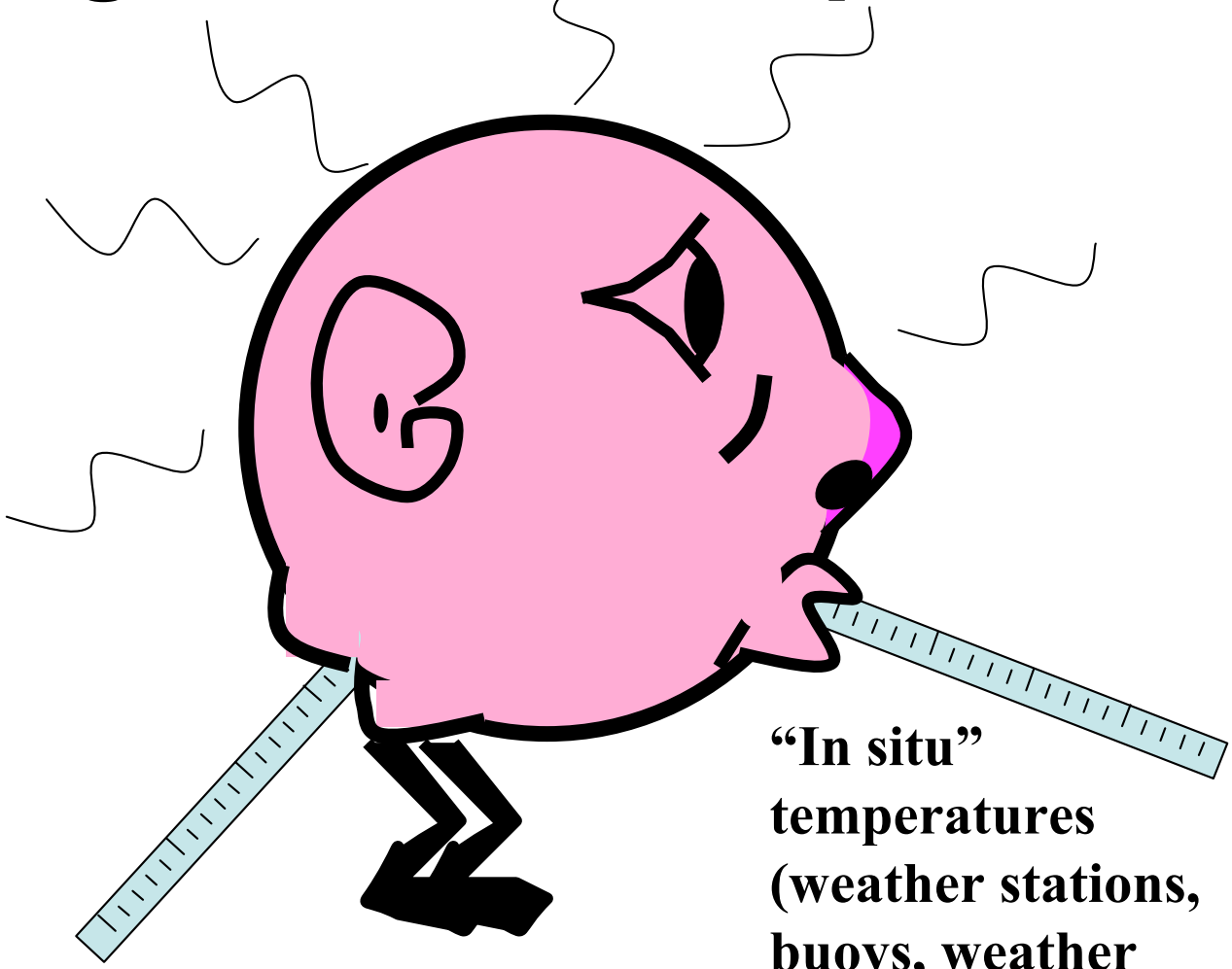


AN IMPORTANT IF OFTEN OVERLOOKED CONCLUSION:

GHG make Earth livable.

II. HOW IS EARTH'S TEMPERATURE MEASURED?

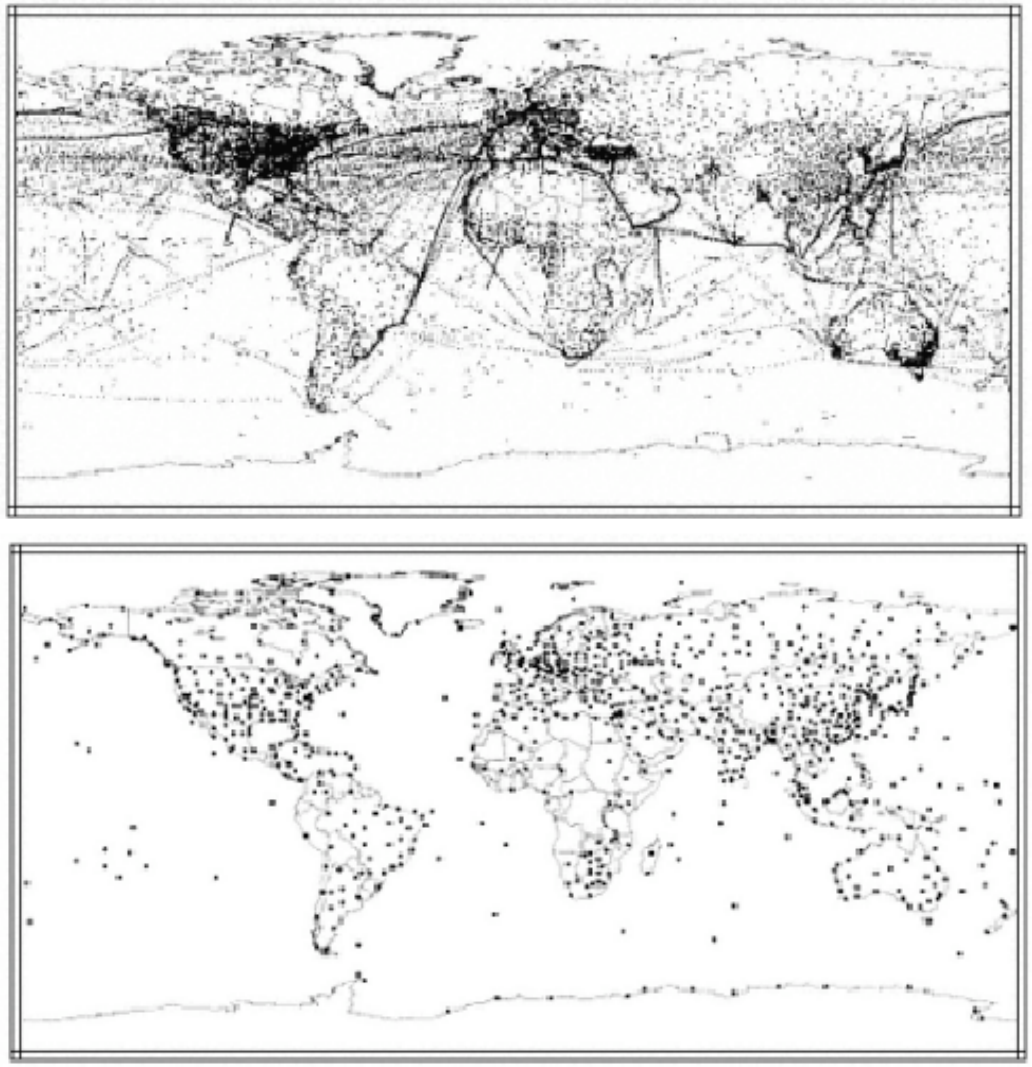
Taking Earth's Temperature



Satellite temps

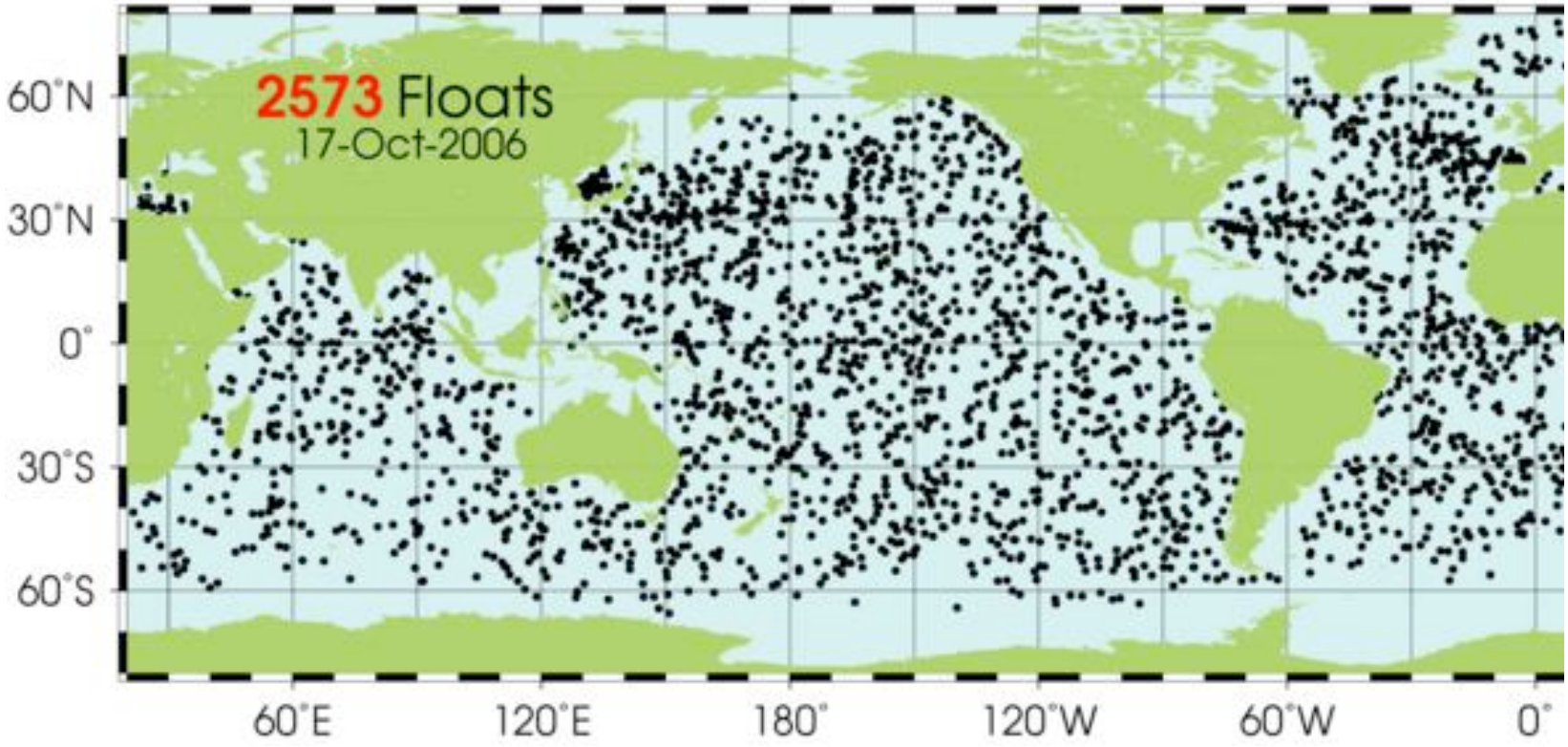
"In situ" temperatures (weather stations, buoys, weather balloons, etc.) needed to calibrate satellite temperatures

Top: WMO surface temperature observations (temperature stations, buoys, & ship-based measurement over a one-week period. Bottom: Weather balloon (radiosonde) stations in the World Meteorological Organization's (WMO) network. SOURCE: Reconciling Observations of Global Temperature Change (Nat'l Acad. Press, 2000)

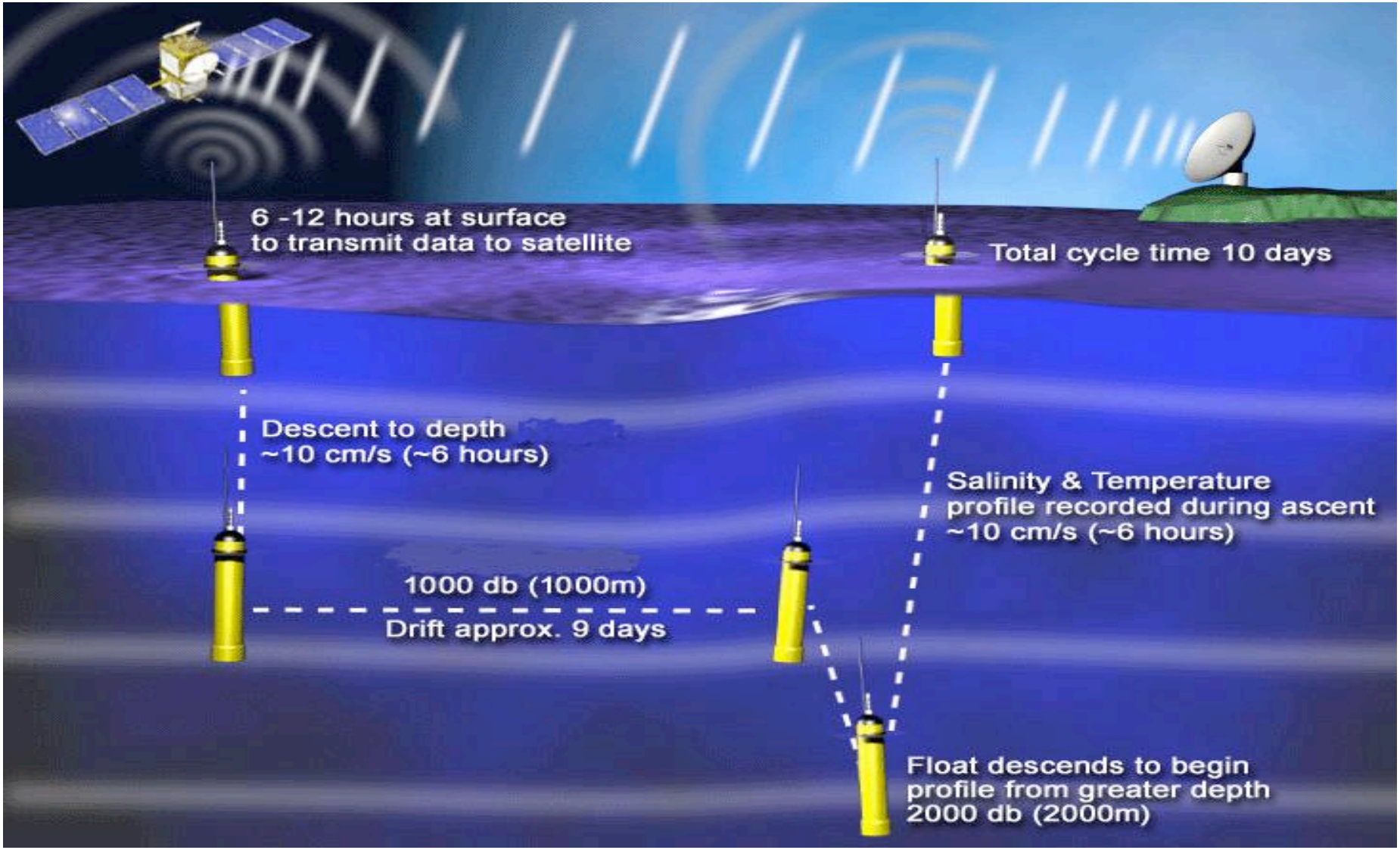


The ARGO project for sea surface temperatures

file://localhost/The Argo network. SOURCE/ http/::www.argo.ucsd.edu

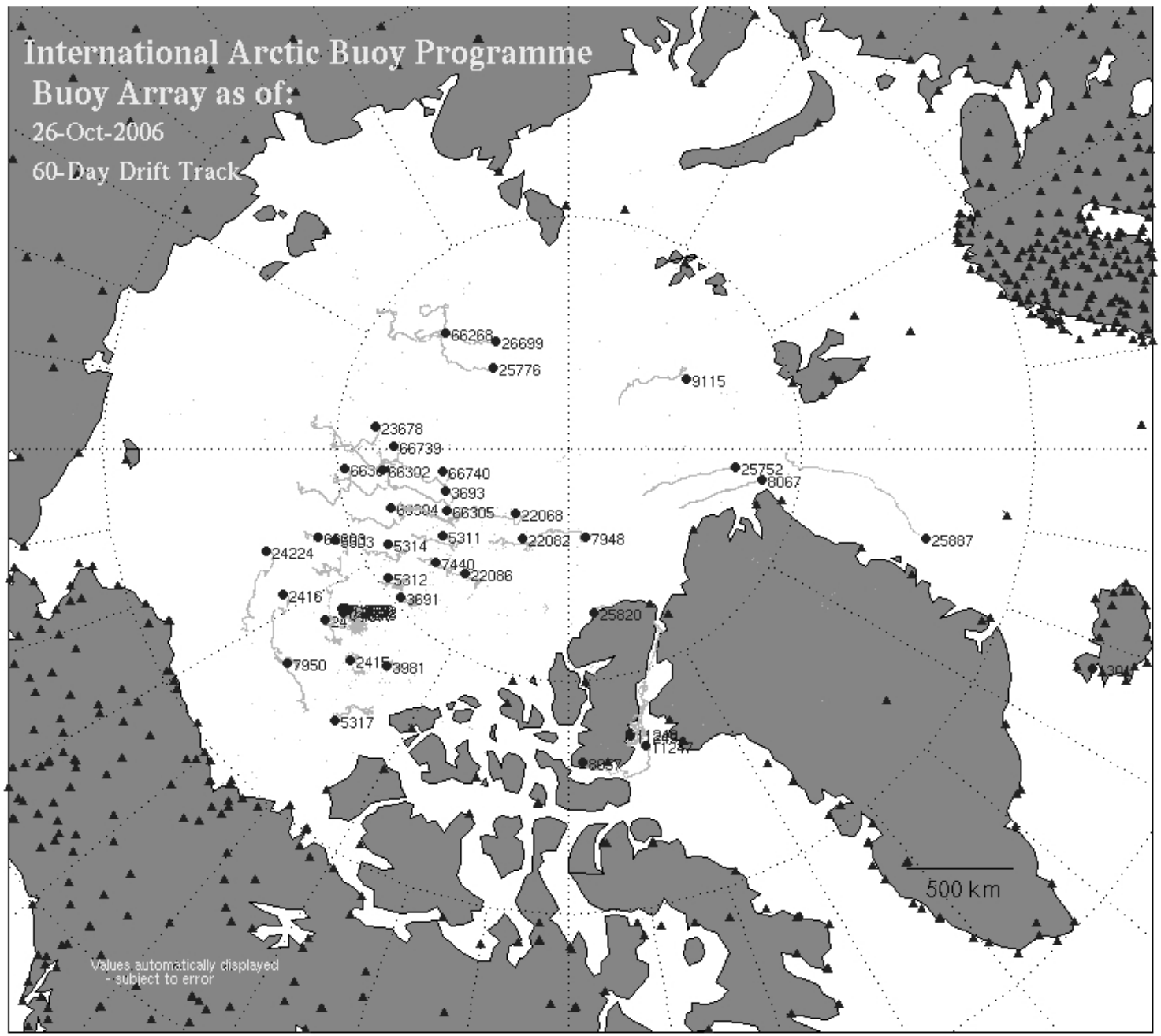


Argo in operation



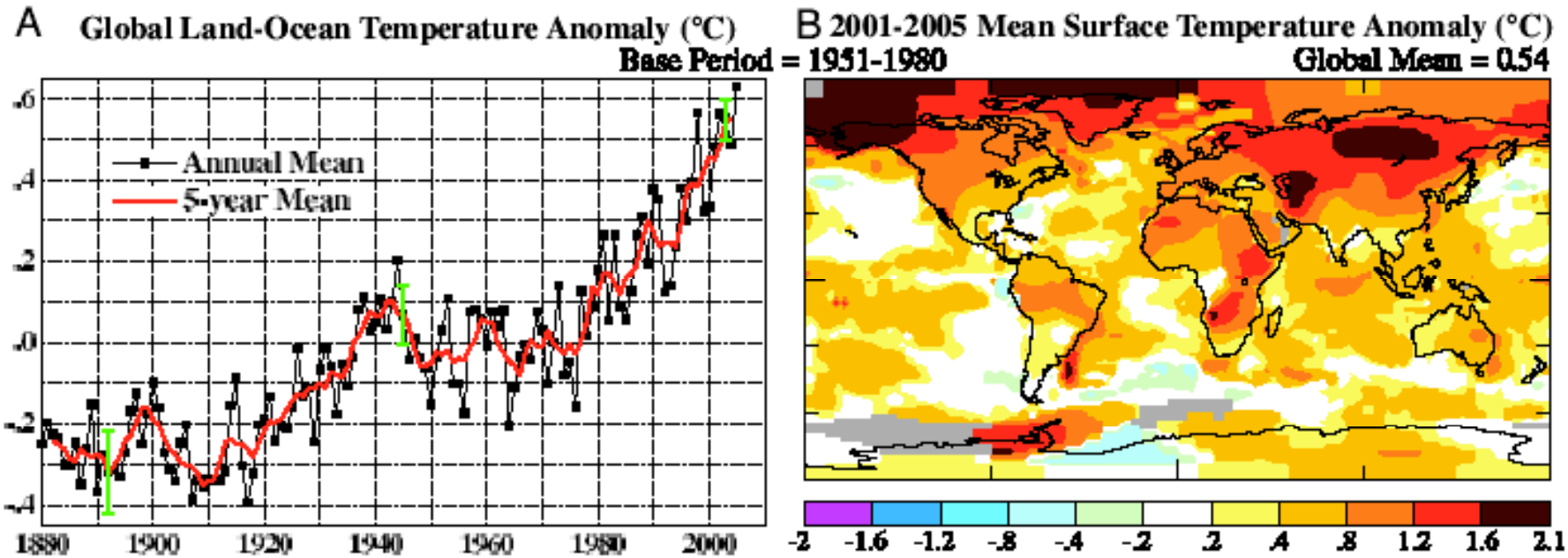
International Arctic Buoy Program (IABP)

Daily Buoy Track Map(60 days up to 26 Oct 2006)



Polar orbiting satellites (some carry the Advanced Very High Resolution Radiometer, MSU, and other instruments)

THE RESULT:



Source: J.M. Hansen et.al., "Global Temperature Change," Proc. Natl. Acad. Sci., 103 (#39), 26 Sept 2006

Rapid temperature change in Siberia is worrisome--methane, a GHG, is released when permafrost melts.

A FEW NATURAL THERMOMETERS

Red line: Summer, 1979; photo, summer 2003

GLACIER MELING IN NORTHERN CLIMES

SOURCE: Sierra Magazine (Sierra Club, Jan-Feb 2006 issue). From top to bottom:

Athabasca Glacier, Jasper National Park, Canada, 1917 and 2005

Grinnell Glacier, Glacier National Park, Montana, USA, 1911 and 2000

Portage Glacier, Alaska, USA, 1914 and 2004

Pasterze Glacier, Austria, 1875 and 2004

All in the temperate zone

So Far, no controversies

- Everyone agrees that Earth would be ice-cold without GHG, particularly H_20_v and CO_2.
- Everyone agrees the surface temperature is rising.

What are the controversies?

In broad terms:

- **The *amount* of warming caused by CO_2 and other "anthropogenic" GHG**
- **The *effect* of the warming on coastal cities, agriculture, water supply, and the environment at large.**

TWO OPPOSING POSITIONS

ON ONE SIDE WE HAVE GLOBAL WARMERS:

GLOBAL WARMING IS REAL, SERIOUS, AND IS CAUSED BY HUMAN ACTIVITIES (BURNING OF FOSSIL FUELS, AGRICULTURE, DEFORESTATION).

ON THE OTHER SIDE WE HAVE "SKEPTICS" OR "CONTRARIANS":

GLOBAL WARMING IS MODERATE AND JUST A NORMAL VARIATION OF CLIMATE. FORGET FOSSIL FUEL BURNING--IT'S MINOR.

How to decide who's right?

A MODEST PROPOSAL:

Track legitimate *scientific* challenges to global warming science and see how the challenges have been or are being resolved.

III. FIRST, A FEW SKEPTIC CHEAP SHOTS

First one:

"There IS a problem with global warming--it stopped in 1998"

By Bob Carter, The Telegraph (UK), June 9, 2006

Sure Bob, and smoking doesn't cause cancer.

Has Carter invented a new principle of statistics? As I see it, he must assume:

~~"If a time series (e.g., temperature) ever decreases, then there's no upward trend."~~

Not a single statistician or natural scientist would agree with this. Random variables can have trend too.

(Note: the spike in 1998 temperature that captivates Carter was caused by an El Nino that elevated temperatures world-wide.)

CHEAP SHOT #2:

**"ANTARCTICA IS COOLING--
GLOBAL WARMING IS FALSE!"**

(A skeptic claim regarding two articles on the subject, one in *Nature* the other in *Science)*

Lead author of the *Nature* article is Peter Doran:

Antarctic climate cooling and terrestrial ecosystem response

Peter T. Doran*, John C. Priscu†, W. Berry Lyons‡, John E. Walsh§, Andrew G. Fountain||, Diane M. McKnight¶, Daryl L. Moorhead#, Ross A. Virginia☆, Diana H. Wall**, Gary D. Clow††, Christian H. Fritsen‡‡, Christopher P. McKay§§ & Andrew N. Parsons**

NATURE | 13 January 2002 | DOI 10.1038/nature710 | www.nature.com

Let's hear from Doran ("Cold Hard Facts," *NYT*, 27 July 2006):

"Our report…found that, from 1966 to 2000, more of the continent had cooled than had warmed. Newspapers and television reports focused on this part of the paper."

Doran continues:

"In a rebuttal in The Providence Journal, the lead author of the *Science* paper and I explained that our studies offered no evidence that the earth was cooling. But the misinterpretation had already become legend, and in the four and a half years since, it has only grown."

He goes on to say:

"[Climate] models, conspicuously *missing* from the warming-skeptic literature, suggest that as the ozone hole heals--thanks to world-wide bans on ozone-destroying chemicals--all of Antarctica is likely to warm with the rest of the planet. *An inconvenient truth?*"

[Emphasis mine]

Doran concludes:

"I would like to remove my name from the list of scientists who dispute global warming. I know my coauthors would *as well*."

A few additional points:

(1) Antarctica is the highest continent in the world--the s. Pole is about 10,000 ft above sea level.

(2) the antarctic mainland is isolated from global climate because of strong circumpolar winds and sea currents.

(3) the antarctic peninsula, not isolated by currents, is experiencing great warming and melting.

Before continuing to serious challenges, an advisory on *responsible* skepticism:

1. **Skepticism is very important in science.**
2. ***A responsible* scientist must be ruthlessly skeptical about a new theory *while at the same time* being open-minded to the same theory.**
3. **Too often, climate skeptics are not open minded.**

IV. SERIOUS CHALLENGES TO GLOBAL WARMING SCIENCE

1. **Ocean absorption of CO_2 (1900-1958)**
2. **H_2O vapor dominance (1930-1960)**
3. **Satellite discrepancies (1985-2006)**
4. **"It's the Sun!" (1900-2006)**
5. **Natural variations in climate (1900-2006)**
6. **H_2O vapor feedback (1997-2007--)**
7. **The continuing modeling challenge**

START AT THE BEGINNING.

1896: The birth of global warming.

The great chemist Arrhenius makes the first calculation:

Doubling of CO_2 over the natural level ~+5 °C.

$\Longrightarrow$

CHALLENGE #1

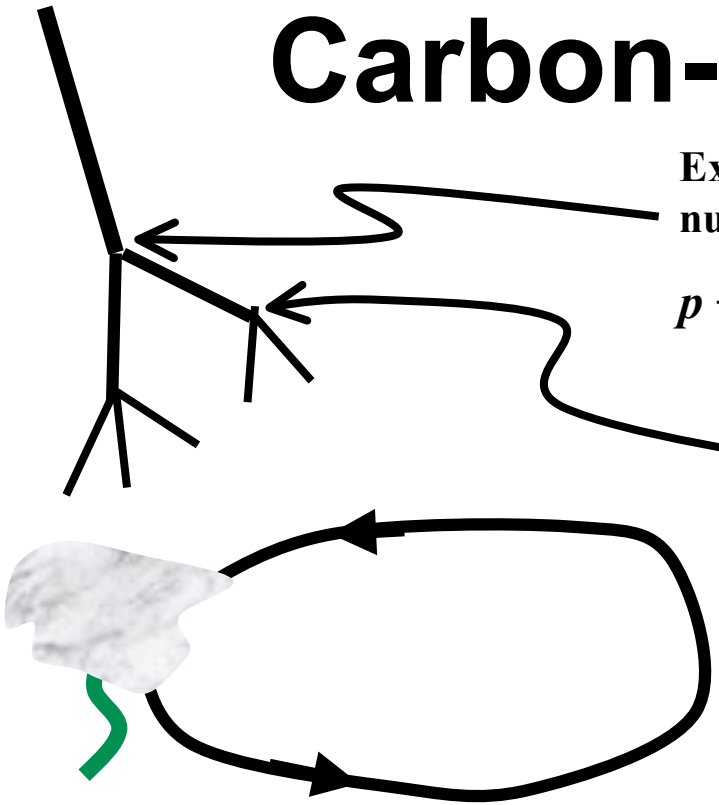
THE FIRST CHALLENGE CAME FROM MANY SIDES:

"CO_2 is absorbed by the ocean--little or none goes into the atmosphere."

(Accepted for decades after Arrhenius.)

A PARTIAL RESOLUTION OF THE CHALLENGE INVOLVES CARBON DATING

Carbon-14 production



Extraterrestrial cosmic ray smashes a nitrogen nucleus, producing neutrons and other fragments:

$$p + N \text{ or } O \longrightarrow n + \text{fragments}$$

$$n + {}^{14}N \longrightarrow {}^{14}C + p$$

A *living* cotton plant exchanges carbon with atmosphere and has a *fixed* proportion of C-14 in it while alive.

When the cotton plant dies (or is pulled up), no more carbon is exchanged; it's stuck with what it had when it died.

The C-14 in the dead plant then decays:

$$^{14}C \longrightarrow {}^{14}N + e^{-} \text{ (5730-year half life)}$$

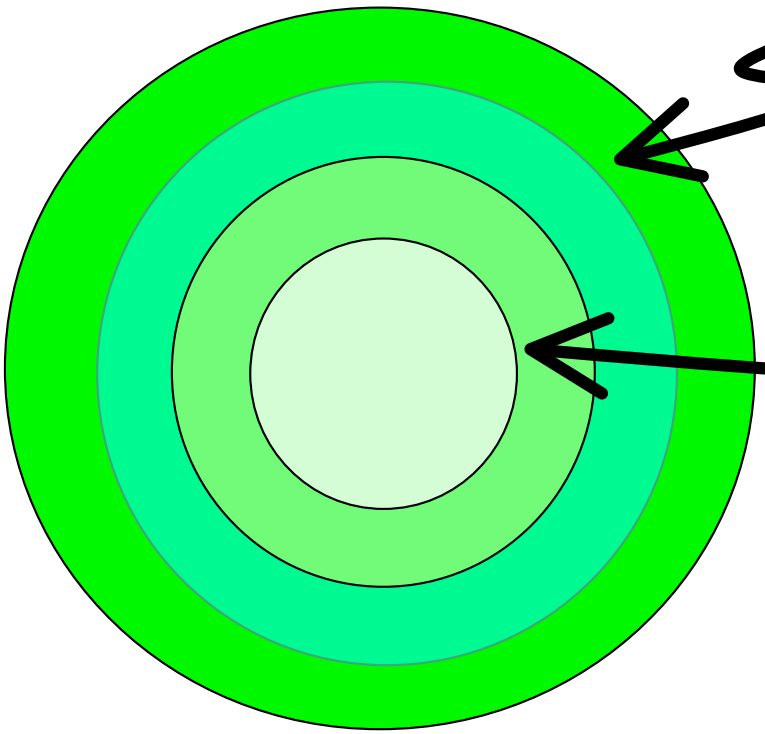
So once a plant dies, the C-14 in it slowly disappears.

OLD, less ^{14}C **NEW, more ^{14}C**

Cotton fabrics of different ages, but otherwise identical

APPLY TO TREE RINGS.

What we expect:

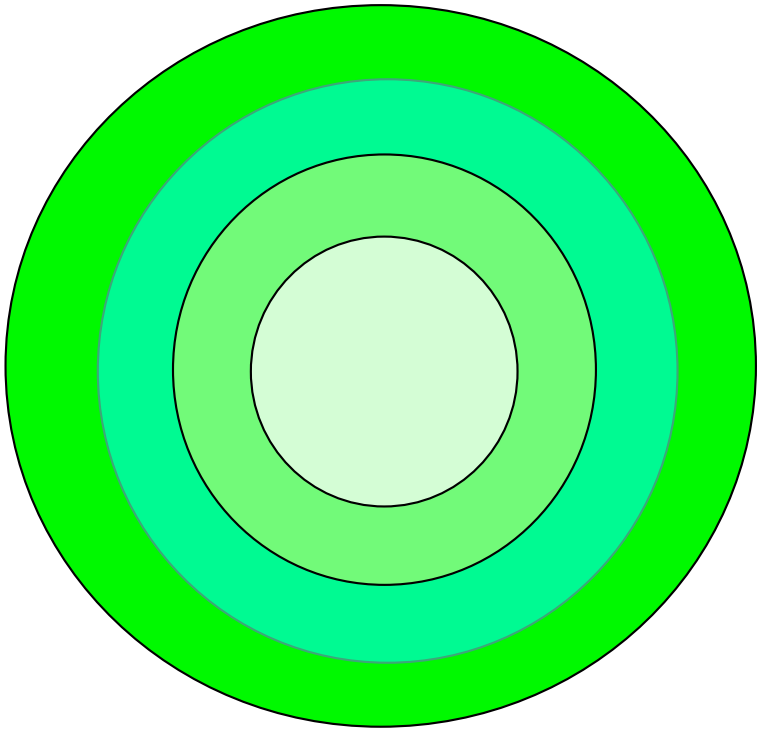


YOUNGER RING, RELATIVELY MORE C-14

OLDER RING, RELATIVELY LITTLE C-14

True **of a tree that has been dead for thousands of years.**

What Hans Suess noticed in 1953:



"Adolescent" tree rings formed only 100-200 years ago have *more* C-14 than "infant" tree rings a few years old!

WHAT'S HAPPENING?

SUESS'S SUSPICION:

"Infant" **tree rings contain less C-14 because in recent years, the tree was "eating"** ***old*** **carbon from fossil fuels (millions of years old) burned by humans.**

"Adolescent" rings 100-200 years old have ***more*** **C-14 because the tree was consuming CO_2 not diluted with old fossil fuel carbon.**

Preliminary conclusion:

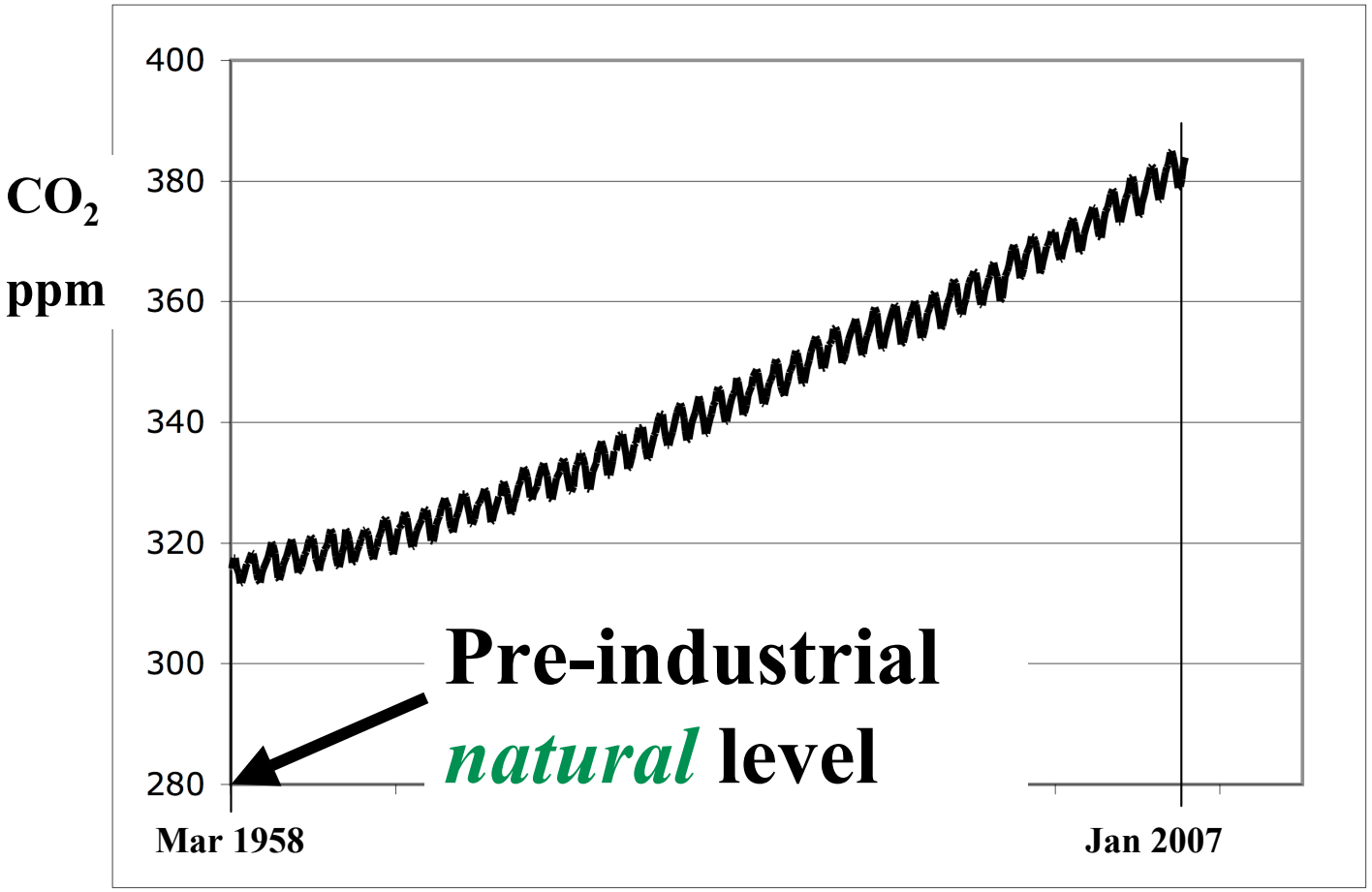
Some “old” carbon from fossil fuel burning must be staying in the air.

It is *not* all in oceans!

A more direct refutation of the challenge:

- Measure the amount of CO_2 in the atmosphere.
- Not easy to do--only about 3 of every 10,000 air molecules is CO_2.

CHARLES KEELING FIGURED OUT HOW TO DO IT IN 1958:



SOURCE: http://www.cmdl.noaa.gov/projects/web/trends/co2_mm_mlo.dat

CONCLUSION

Only about 50% of all CO_2 released in the past century was absorbed by the ocean. The rest remains in the atmosphere.

This Round:

Global warmers: 1*
Skeptics: 0

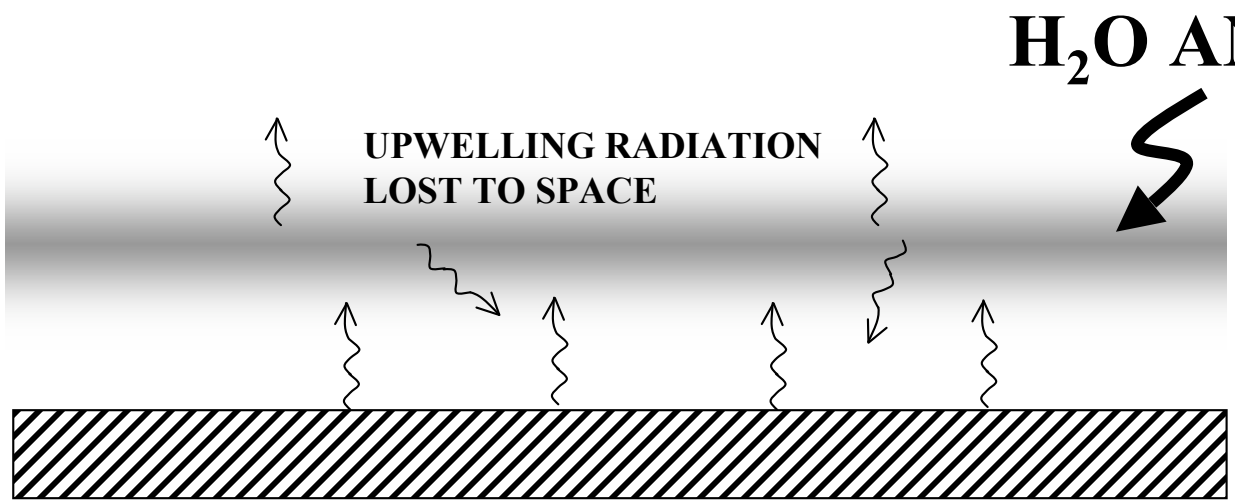
The "1" means that the contention that CO_2 is increasing in the atmosphere is a certainty (probability = 1), I.e., we are 100% certain it is true. The "0" means that there is no chance the opposing view is correct.

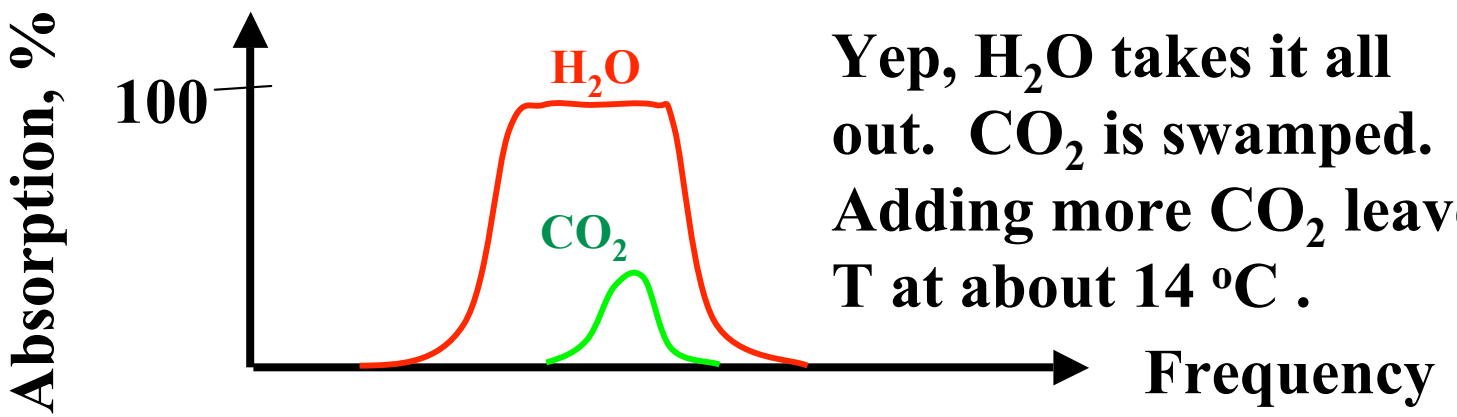
CHALLENGE #2
Saturation effect of H_2O vapor

Claim of the Challengers:

1. **Water vapor absorbs the same infrared frequencies that CO_2 absorbs.**
2. **There's so much H_2O that it absorbs *all* of the infrared that CO_2 might absorb.**
3. **Adding more CO_2 to the atmosphere will not affect Earth's temperature.**
4. **So don't worry--burn fossil fuels!**

True in the *lower* atmosphere:





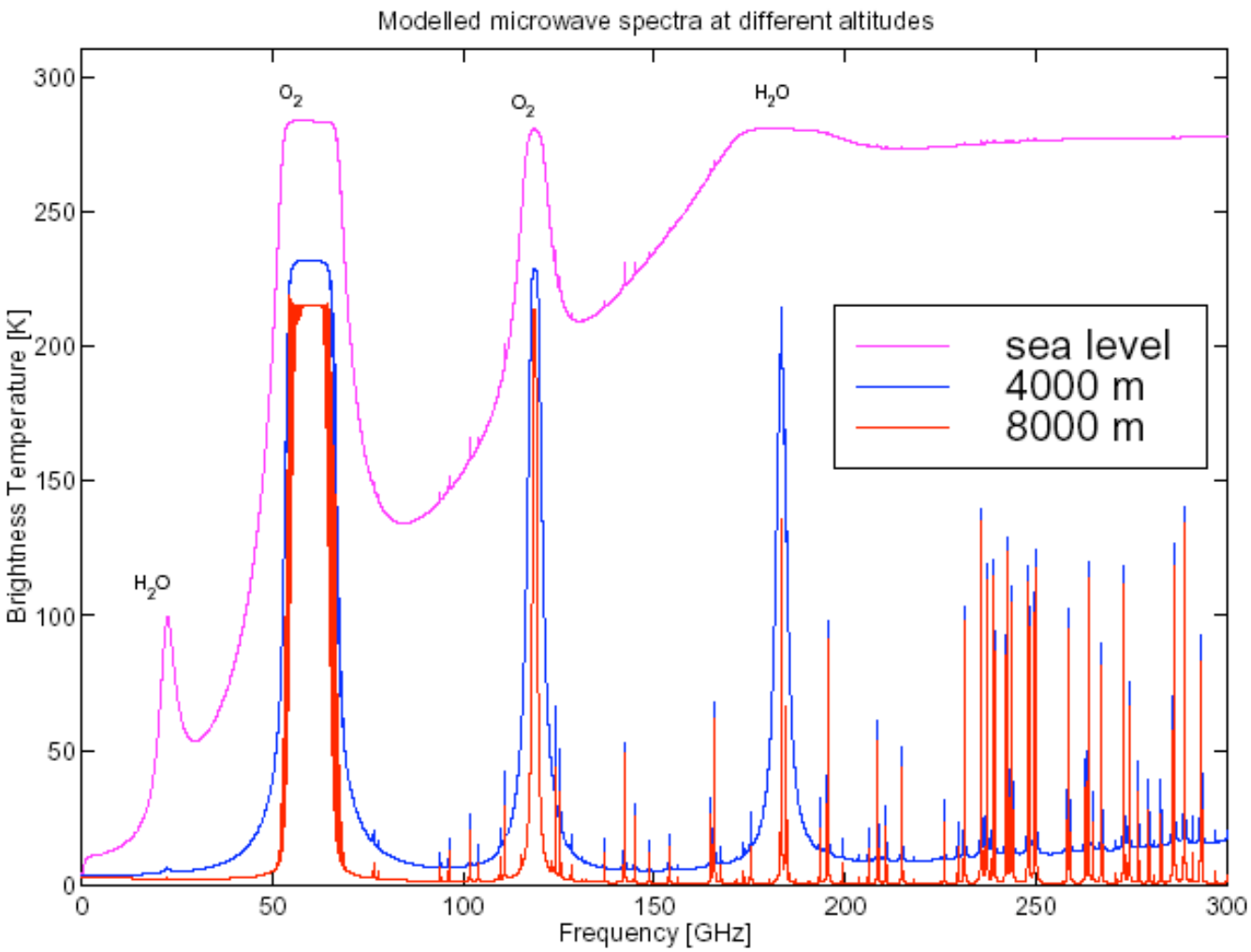
Yep, H_2O takes it all out. CO_2 is swamped. Adding more CO_2 leaves T at about 14 ^oC .

But what about upper atmosphere?

1. Less H_2O (most H_2O_v is below 1-2 km)
2. Proportionately more CO_2
3. Lower pressure and temperature, therefore sharper CO_2 and H_2O_v absorption lines.

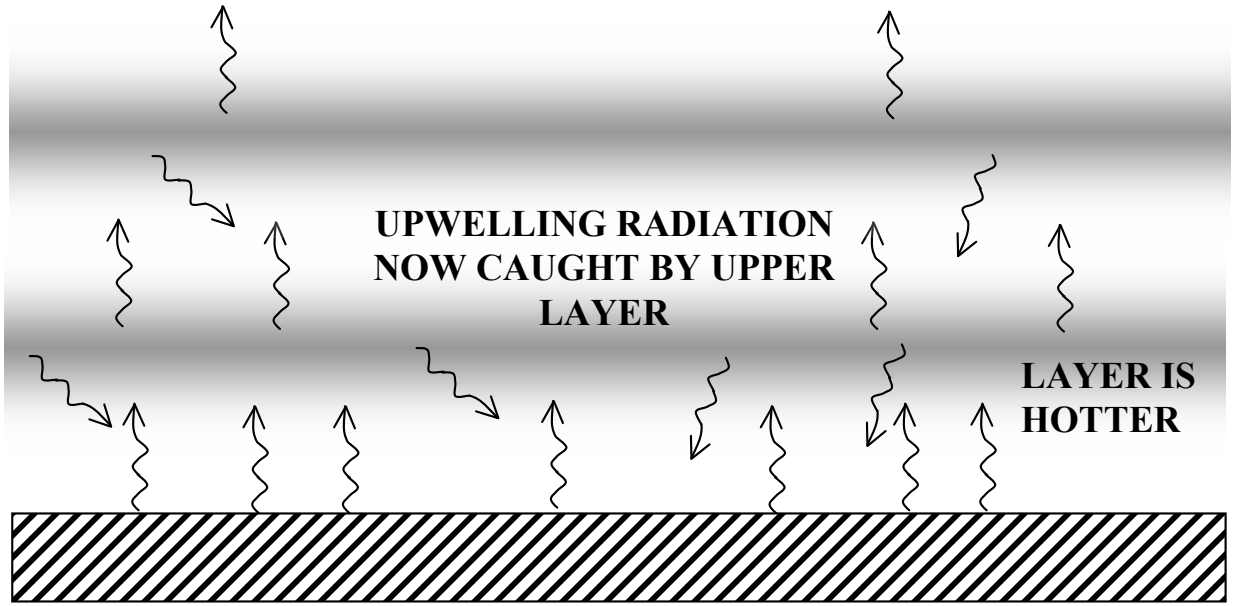
Here's an example of the effect of altitude and temperature (H_2O_v):

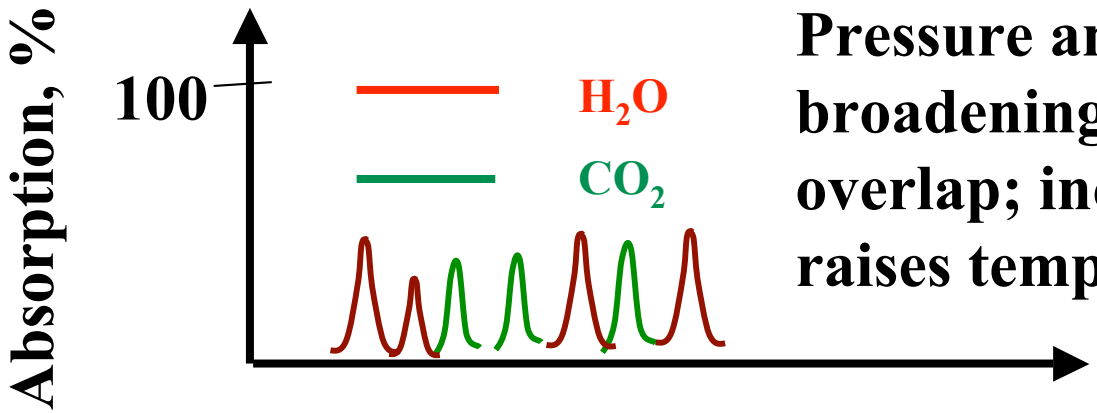
Atmospheric microwave spectra (uplooking)



SOURCE; Measuring the stratospheric water vapor distribution with ground-based and airborne microwave radiometers
Dietrich G. Feist, Vladimir Vasi´c, Stefan M¨ uller, Beat Deuber, Alexander Haefele und Niklaus K¨ampfer
Institute of Applied Physics
University of Bern
December 12, 2004
DARC Seminar, University of Reading

Lower temperature and pressure make a difference.



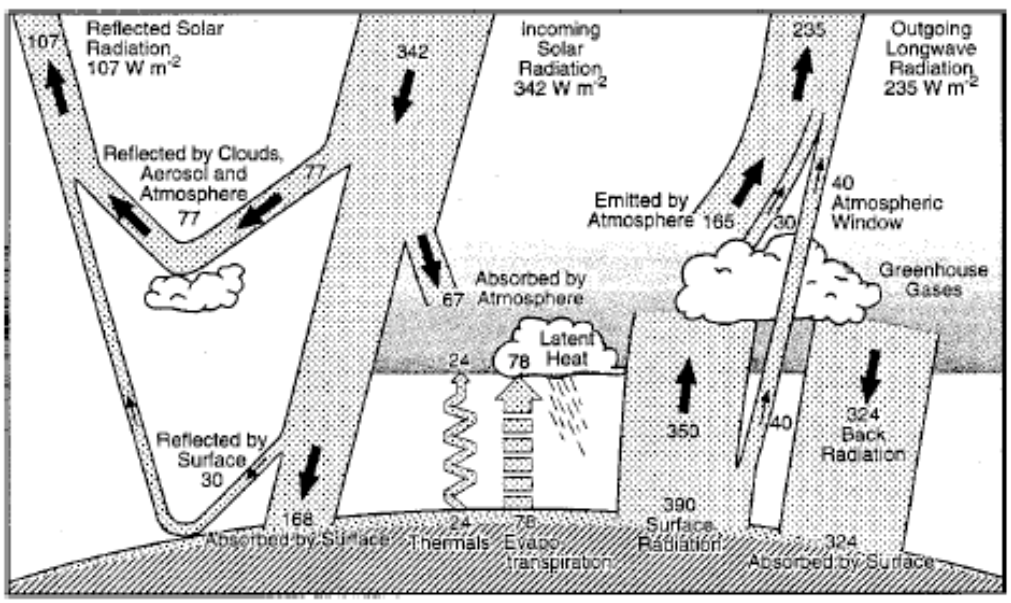


Pressure and Doppler broadening reduced; no overlap; increasing CO_2 raises temperature > 14 °C

Technical note #1

In the previous diagram, we see two units of infrared (ir) radiation given off by the top layer. But this layer is in equilibrium--it emits two units to the level below it, and absorbs four units from that layer. So it gives off four units and receives four, I.e., it is in thermal equilibrium.. This same argument applies to the level below the top one and the combined radiation sent to it from surface and top layer. This is an extremely simplified *radiation transfer* model that neglects latent heats and convection processes. The diagram below shows the more realistic case. The simple radiation model, though incorrect in details, points the direction any more complex model must point, Indeed, the simple model is important for understanding the upwelling radiation satellites receive. See, e.g., the arguments in Challenge #6 below.

The optical depth or thickness of a layer of air is defined in terms of the amount of radiation absorbed by it. One optical thickness absorbs about 2/3 of the radiation incident on it. For global warming, we are interested in the optical thickness for the specific wavelengths absorbed by a particular GHG. In general, if all of the GHG consist of *n* optical thicknesses, the surface temperature T_s is given by $T_s = T_e(n + 1)^{1/4}$, where T_e is the equilibrium temperature of the outermost part of the atmosphere as seen from outer space--about -18 ^oC for Earth. An interesting example of this equation is the planet Venus, whose thick atmosphere consists of about 70 optical thicknesses of CO_2. Its equilibrium temperature with the sun is only about 263 K, because even though it is closer to the sun (only about 2/3 of Earth's distance), its albedo is about 0.65, I.e., it reflects about twice as much sunlight as Earth does. The 70 optical thicknesses of CO_2 result in a surface temperature on Venus of about 762 K--a dramatic illustration of layered CO_2 heating up a planet. A similar calculation for Earth (T_s = 287 K, T_e = 255 K) indicates there is only about 0.6 of an optical thickness of GHG (including water vapor). A more careful but still elementary calculation shows that there are approximately 2 optical thicknesses. See R.M. Goody and J.C.G. Walker, *Atmospheres* (Prentice-Hall, 1972), recounted in D. Hartmann, *Global Physical Climatology (Academic Press,* 1994), pp.61-63.



Source for figure: Kiehl and Trenberth, "Earth's Annual Global Mean Energy Budget," Bull. Am. Met. Soc., Vol. 78, No. 2, February, 1997

Lesson learned:

1. Contrary to skeptics, the atmosphere doesn't stop 2 or 3 km up!
2. More CO_2 at higher altitudes absorbs *more* infrared radiation and Earth's temperature *does* increase.

This round:

GLOBAL WARMERS:	1
SKEPTICS:	0

REFUTATION OF CHALLENGE #2 RAISES CHALLENGE #3:

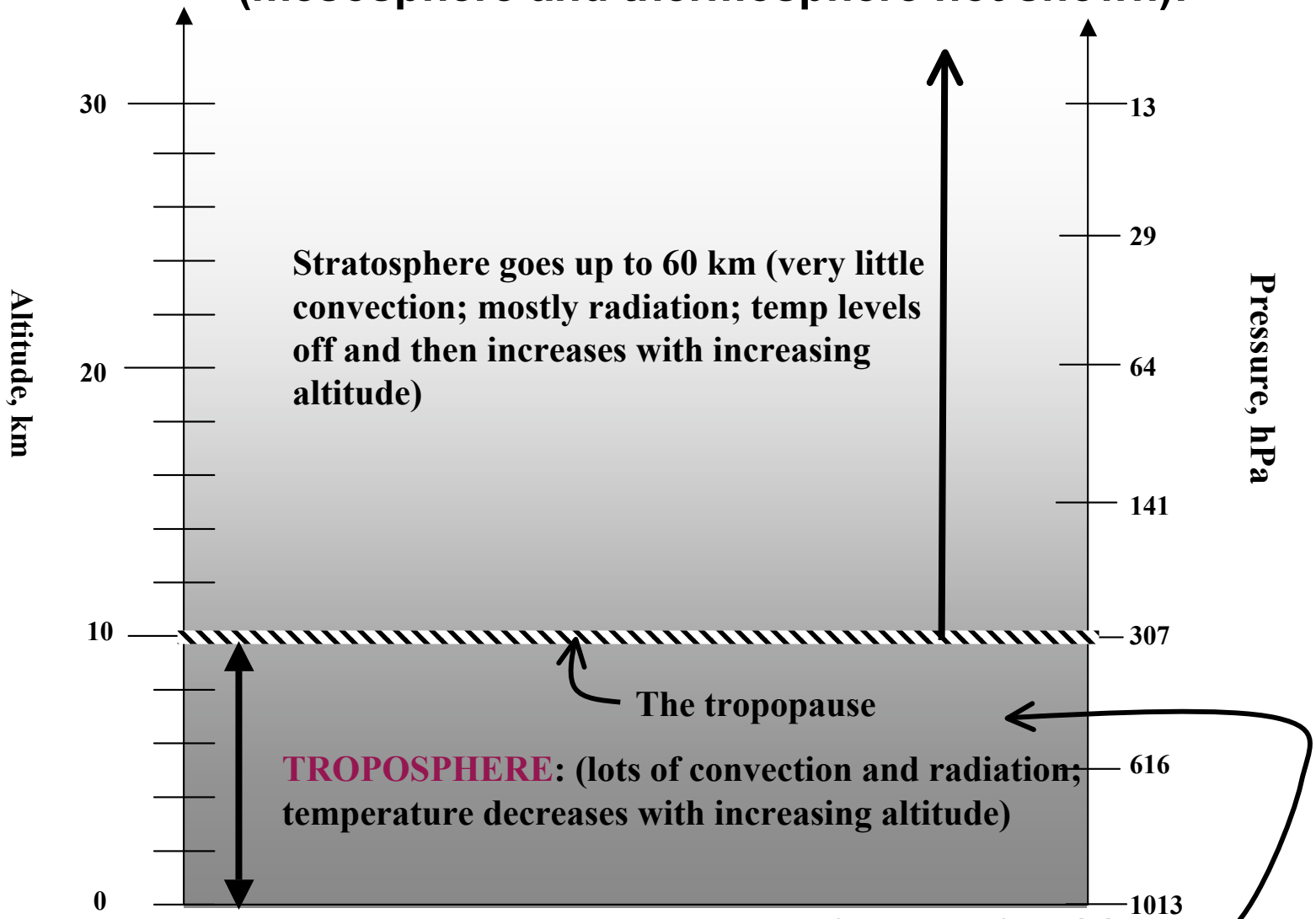
Since GHG absorb infrared radiation,
***air temperature should increase with time*, just as the surface does.**

But satellite data since 1979
***seemed* to say NO!**

Proponents of the challenge (respected scientists):

Roy Spencer and John Christy, who pioneered analysis of satellite data.

First, look at the two lowest layers of the atmosphere (mesosphere and thermosphere not shown):



Troposphere temperature increasing??

Satellites seemed to say NO

Difficulties with satellite measurements

1. Satellites mainly look down through the air; difficult to specify what the temperature at a given altitude is.
2. Satellite orbits drift with time.
3. Instruments must be carefully calibrated due to exposure to sunlight and extreme temperatures, cosmic rays, etc.

1998: most consequences of orbital decay worked out

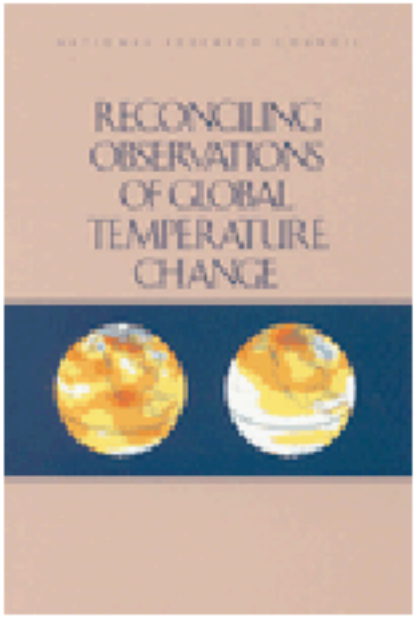
Letters to Nature

Nature **394**, 661-664 (13 August 1998) | doi:10.1038/29267; Received 24 February 1998; Accepted 7 July 1998

Effects of orbital decay on satellite-derived lower-tropospheric temperature trends

Frank J. Wentz[1] and Matthias Schabel[1]1.Remote Sensing Systems, 438 First Street, Suite 200, Santa Rosa, California 95401, USACorrespondence to: Frank J. Wentz[1] Correspondence and requests for materials should be addressed to F.J.W. (e-mail: Email:/\wentz@remss.com).

Two years later, a collaborative study tackles the issue (NRC 2000 study; panel included Christy and Spencer)



Reconciling Observations of Global Temperature Change

Panel on Reconciling Temperature Observations, National Research Council

ISBN: 0-309-59400-6, 104 pages, 6 x 9, (2000)

Conclusion of the 2000 NRC Study:

Disparity **between surface and troposphere temperature trends during the satellite era (1979-1999) is "probably *partially real*." [Emphasis mine]**

Natural influences **(e.g., volcanic activity and El Nino events) and remaining uncertainties inherent in temperature measurements "*preclude more definitive conclusions*." [Emphasis mine]**

(CAREFULLY QUALIFIED!)

FURTHER RESEARCH, JULY 2003:

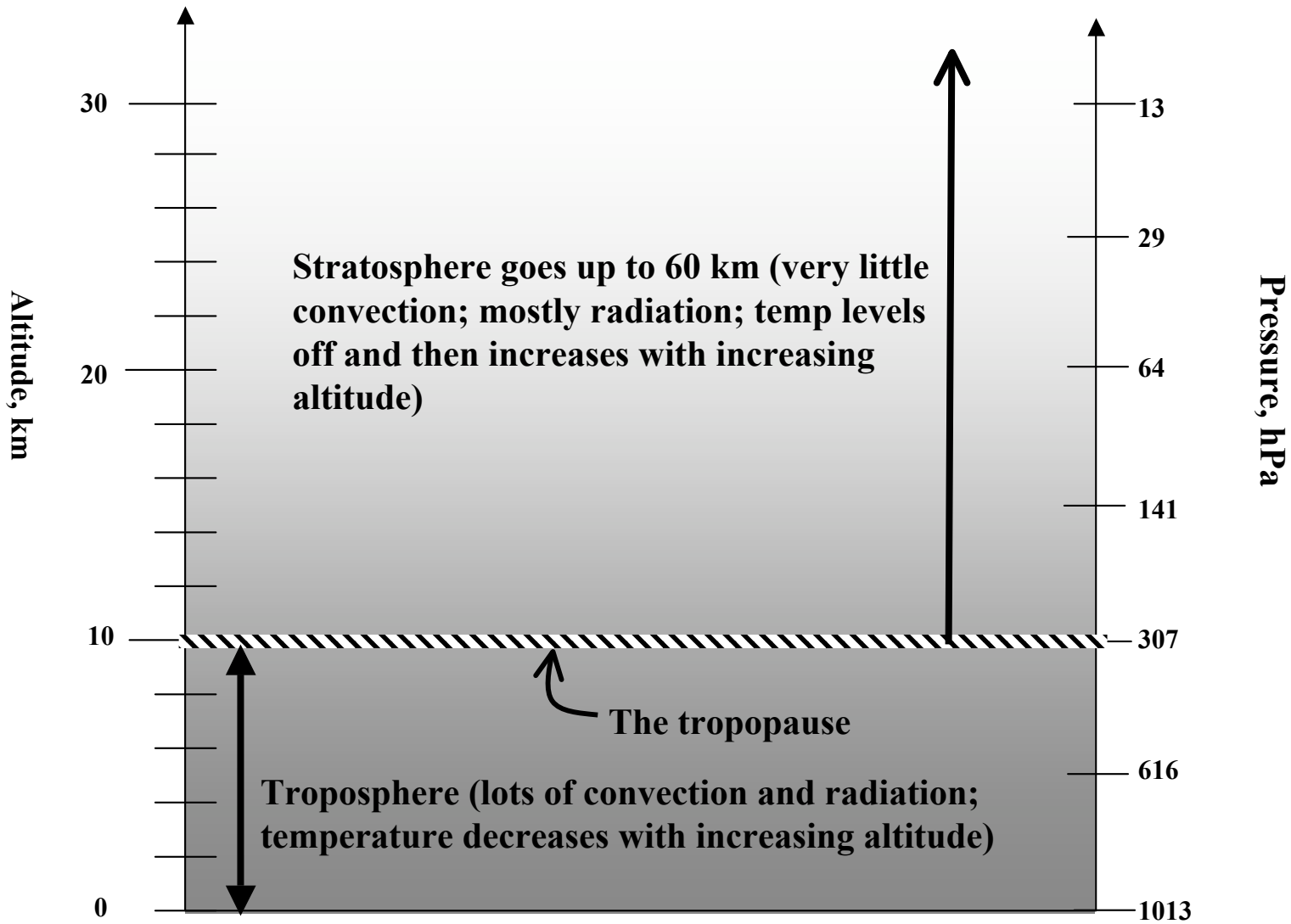
Contributions of Anthropogenic and Natural Forcing to Recent Tropopause Height Changes

B. D. Santer,[1*] M. F. Wehner,[2] T. M. L. Wigley,[3] R. Sausen,[4] G. A. Meehl,[3] K. E. Taylor,[1] C. Ammann,[3] J. Arblaster,[3] W. M. Washington,[3] J. S. Boyle,[1] W. Brüggemann[5]

Observations indicate that the height of the tropopause—the boundary between the stratosphere and troposphere—has increased by several hundred meters since 1979. Comparable increases are evident in climate model experiments. The latter show that human-induced changes in ozone and well-mixed greenhouse gases account for ~80% of the simulated rise in tropopause height over 1979–1999. Their primary contributions are through cooling of the stratosphere (caused by ozone) and warming of the troposphere (caused by well-mixed greenhouse gases). A model-predicted fingerprint of tropopause height changes is statistically detectable in two different observational ("reanalysis") data sets. This positive detection result allows us to attribute overall tropopause height changes to a combination of anthropogenic

www.sciencemag.org SCIENCE VOL 301 25 JULY 2003 ating.

Remember the tropopause:



Tropopause height is rising:

Heating causes expansion. The rise of the tropopause (by several hundred meters) is strong evidence that the troposphere IS indeed heating up as expected by global warming science.

And in Sept. 2005, further clarification:

The Effect of Diurnal Correction on Satellite-Derived Lower Tropospheric Temperature

Carl A. Mears and Frank J. Wentz

Satellite-based measurements of decadal-scale temperature change in the lower troposphere have indicated cooling relative to Earth's surface in the tropics. Such measurements need a diurnal correction to prevent drifts in the satellites' measurement time from causing spurious trends. We have derived a diurnal correction that, in the tropics, is of the opposite sign from that previously applied. When we use this correction in the calculation of lower tropospheric temperature from satellite microwave measurements, we find tropical warming consistent with that found at the surface and in our satellite-derived version of middle/upper tropospheric temperature.

2 SEPTEMBER 2005 VOL 309 SCIENCE www.sciencemag.org

FINALLY IN 2006:

- **PANEL CONVENED BY THE U.S. CLIMATE CHANGE SCIENCE PROGRAM**

- **(Again, panel includes Christy and Spencer)**

Temperature Trends in the Lower Atmosphere

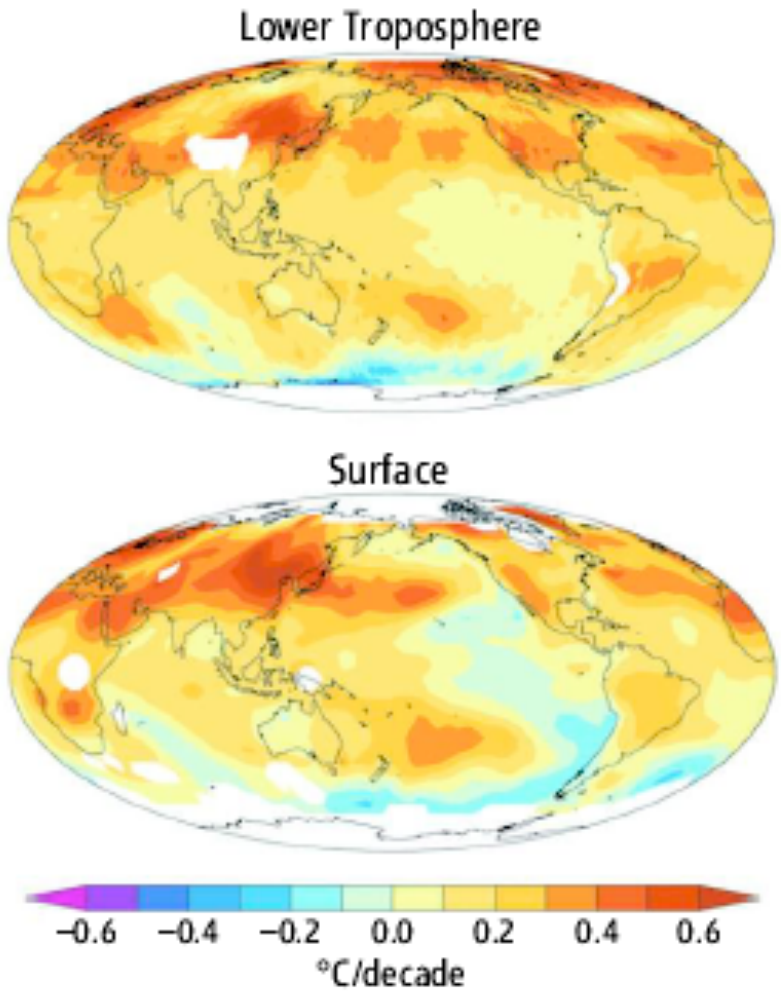
Steps for Understanding and Reconciling Differences

Synthesis and Assessment Product 1.1
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

From the abstract (April 2006):

"[S]urface data showed substantial global-average warming, while early versions of satellite and radiosonde [weather balloons] data showed little or no warming above the surface. This significant discrepancy no longer exists …"

[Emphasis mine]



A decent match. Warming of the lower atmosphere as measured from satellites (yellows and oranges, *top*) now resembles surface warming (*bottom*) measured by thermometers.

From R.A. Kerr, "No Doubt About It, the World Is Warming," Science, vol. 312, 12 May 2006, p. 825.

An unresolved issue…

"…discrepancies in the tropics remain to be resolved…"

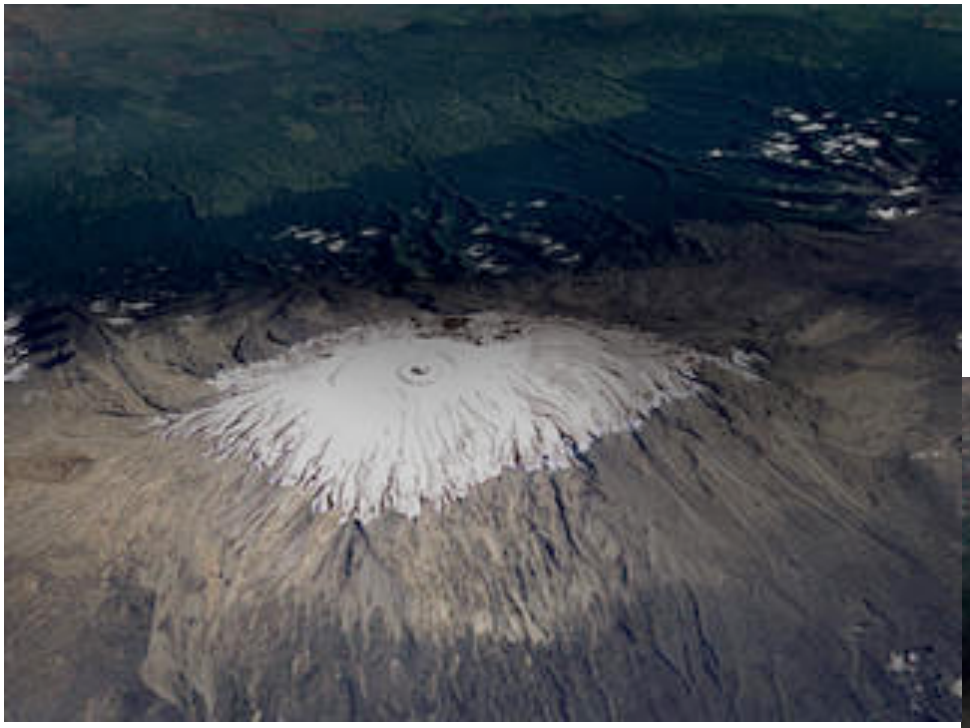
New evidence in the report favors the conclusion that *misinterpretation of data sets* lead to "biased long-term trends."

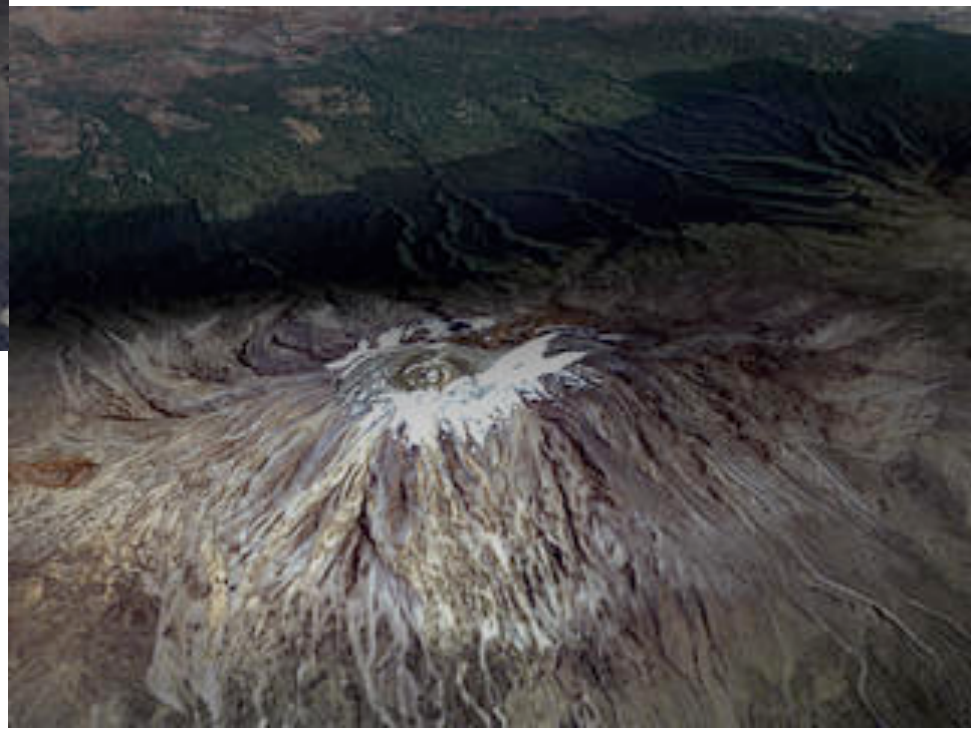
[Emphasis mine]

But there is circumstantial evidence for warming in the TROPICAL troposphere: tropical ice caps and glaciers at higher altitudes are melting.

- Kilimanjaro (Africa)
- Qori Kalis (Peru)
- Huscaran (Peru)
- Dunde (Tibetan Plateau)
- Plus about 8 others in the tropics

Kilimanjaro, 17 Feb 1993 and 21 Feb 2000





SOURCE: NASA/Goddard Space Flight Center Scientific Visualization Studio and USGS (Landsat images)

The Qori Kalis Glacier in the Peruvian Andes

SOURCE: RealClimate, http://www.realclimate.org/index.php/archives/2005/05/tropical-glacier-retreat/, webpage on tropical glacier retreat.

THIS ROUND:

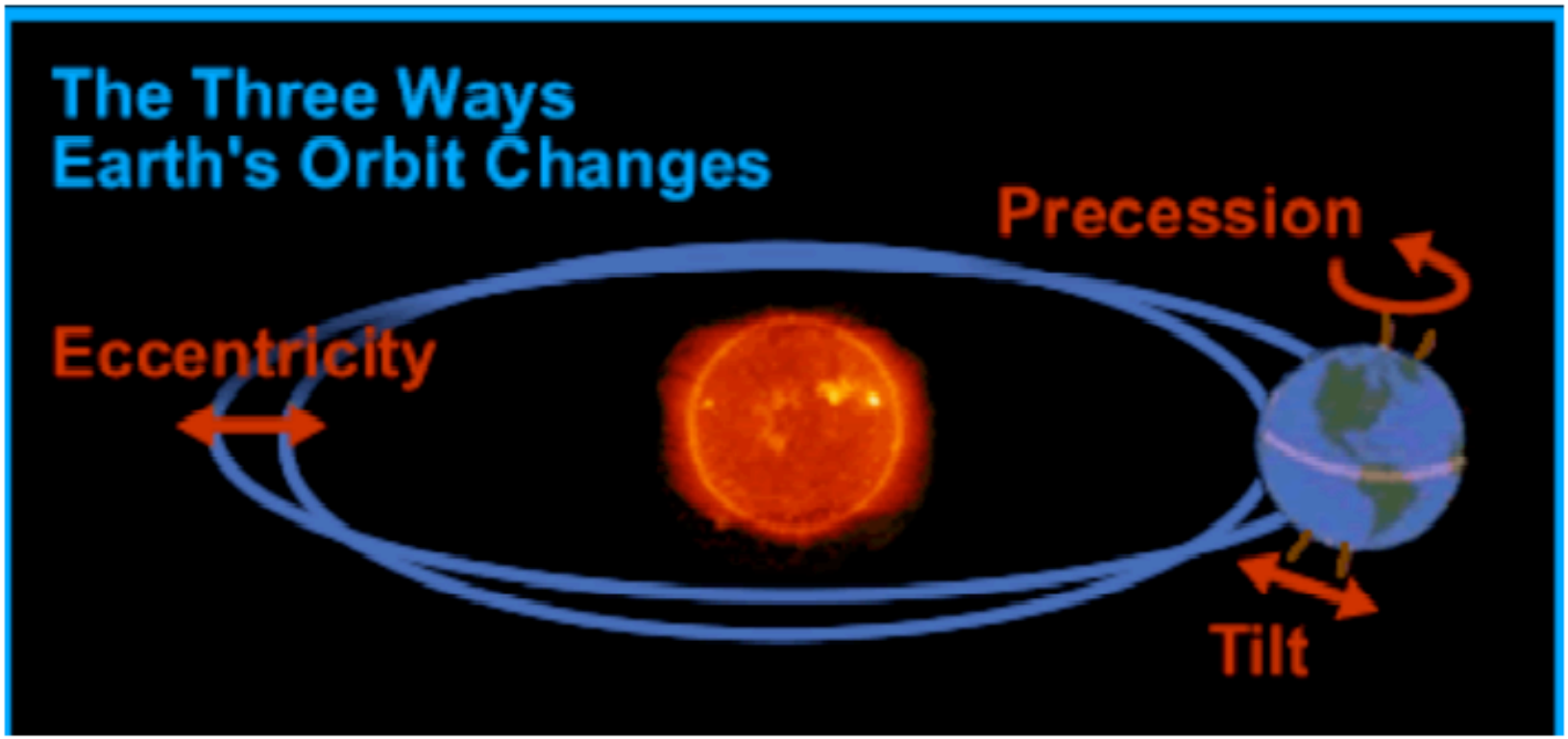
GLOBAL WARMERS	**0.9**
SKEPTICS	**0.1***

***There is a 10% chance that the satellite data needs new adjustments that might leave the tropospheric temperature constant. But it is much more likely (90%) that the troposphere is warming. These percentages, expressed as probability fractions in the score, represent the author's best *subjective/scientific* estimate.**

Challenge 4:

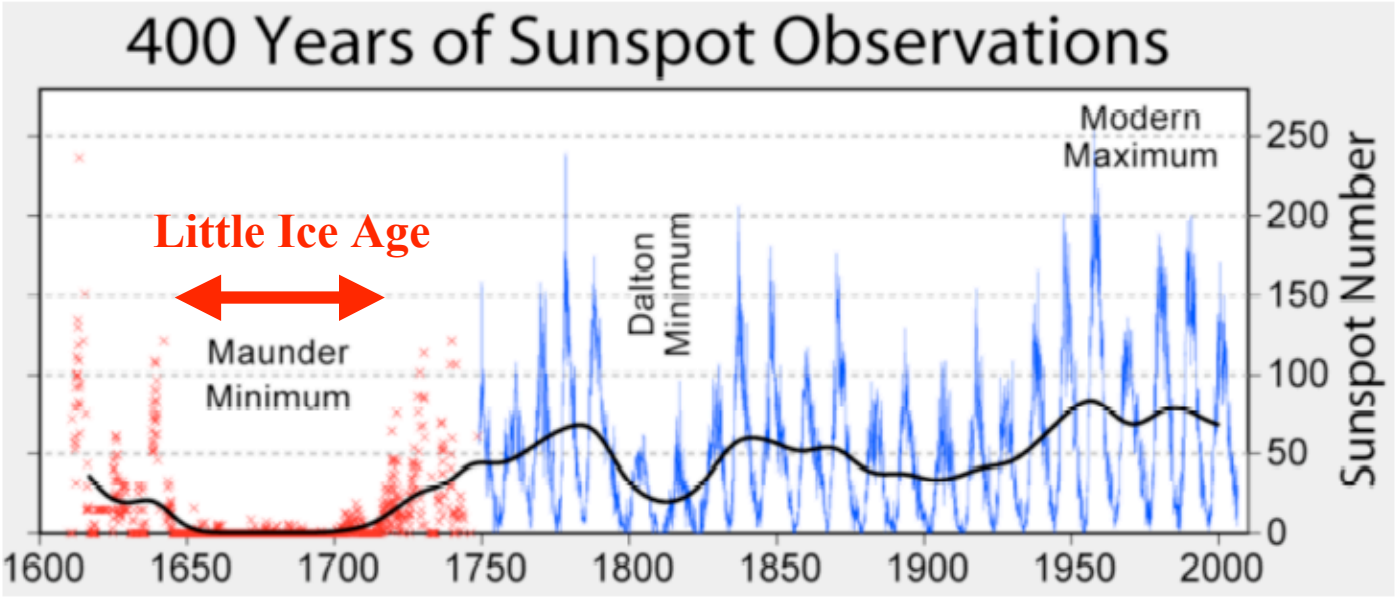
“It’s the sun!”

Everyone agrees the sun influences climate. Over the long term, Milankovitch cycles:



The changes are very slow--over tens of thousands of years.

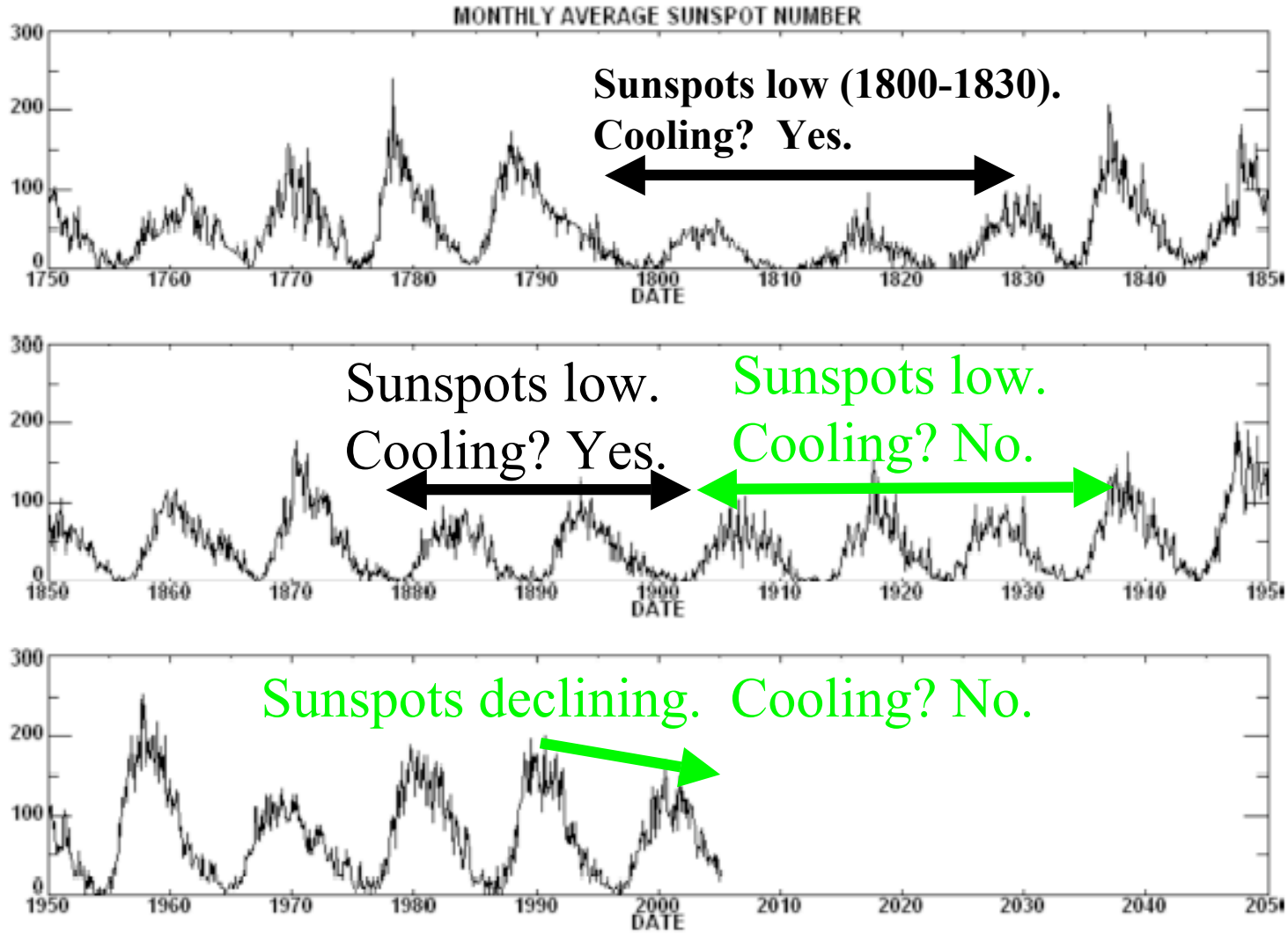
Everyone agrees that sunspots influence climate on a short time scale:



file:///Global%20warming/Solar%20and%20Milankovitch/Solar%20variation%20-%20Wikipedia,%20the%20free%20encyclopedia.webarchive

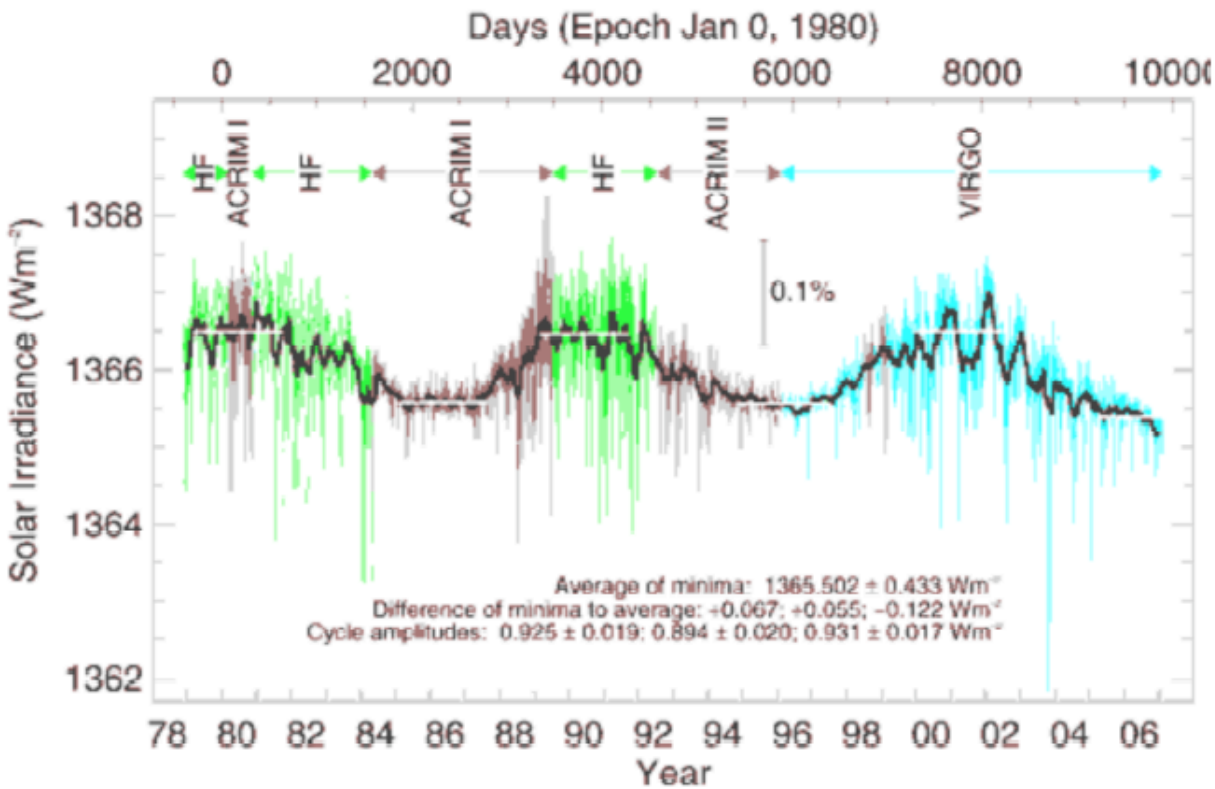
Note the well-known 11-year sunspot cycle

But sunspots can't be the whole story :



Source: NASA (http://science.nasa.gov/ssl/pad/solar/images/zurich.gif)

RECENT SOLAR OUTPUT: (1978-2006)



SOURCE: http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant
Physicalisch-Meteorologisches Observatorium Davos
World Radiation Center

Ups and downs correspond to 11-year sunspot cycle

No trend during a period of rapid warming.

Another recent speculation: it's an increase in solar uv radiation

PERSPECTIVES: PALEOCLIMATE

Toward Solving the UV Puzzle

Jelte Rozema, Bas van Geel, Lars Olof Björn, Judith Lean, Sasha Madronich

www.sciencemag.org SCIENCE VOL 296 31 MAY 2002

Hypothesis: *uv* affects ozone in stratosphere which changes T in stratosphere which can affect troposphere & surface.

Intriguing, but uv correlates with sunspots, and as we've already seen….

Another recent speculation:

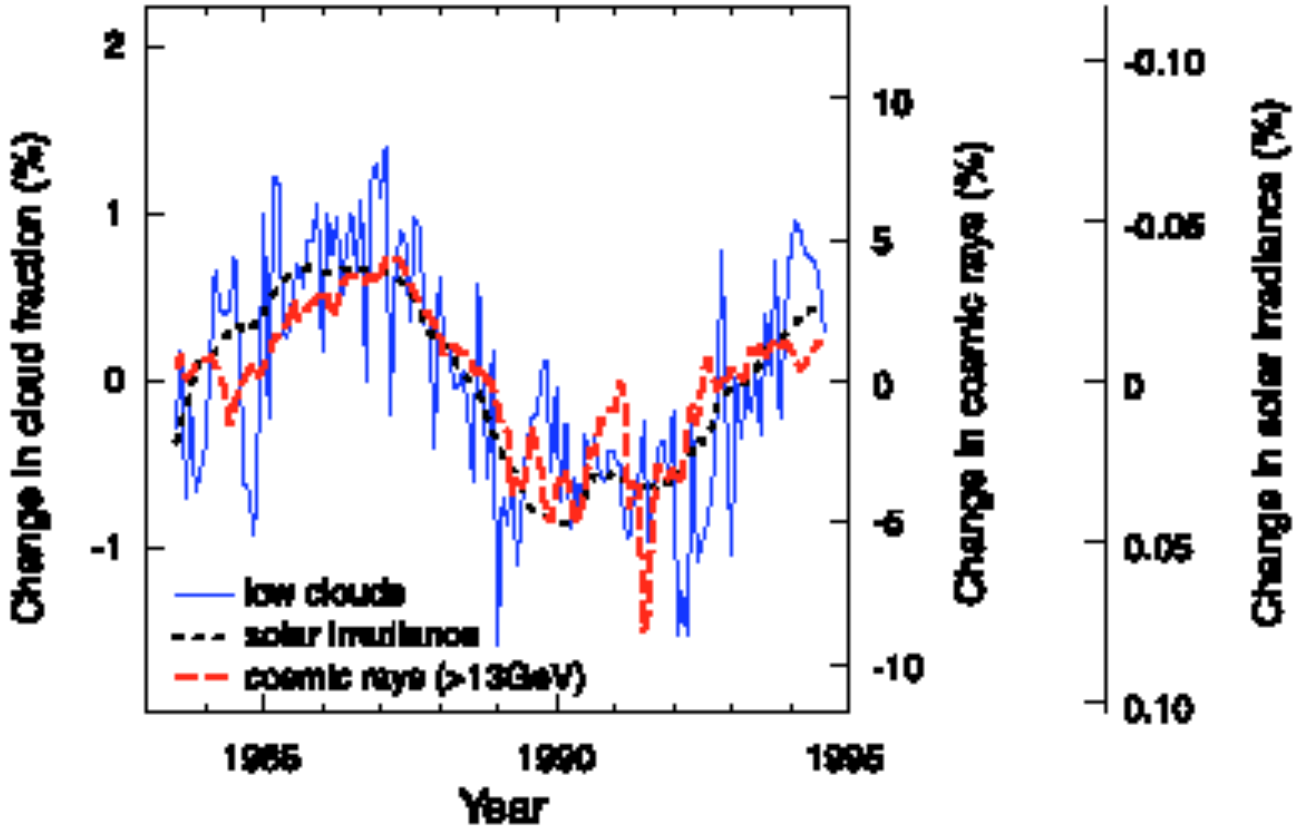
Cosmic rays promote cloudiness.

Sun's magnetic field deflects cosmic rays.

Sun's magnetic field larger during sunspot max

Therefore, sunspot max means fewer cosmic rays & fewer clouds and more solar heating.

Look at cloud-cosmic ray data, 1980-1995:



SOURCE: Cosmic Rays, Clouds, and Climate, K. S. Carslaw, et al., Science, vol. 298 , 1732 (2002); DOI: 10.1126/science.1076964

Again, no up or down trend during a period of rapid warming. (And again, 11-year sunspot cycle appears.)

The problem with cosmic rays is same as the problem with sunspots:

If sunspots don’t tell the whole story, then neither do cosmic rays (which are inversely related to sunspots and clear skies).

This round:

Global warmers:	**0.95**
Skeptics:	**0.05***

***Even Sallie Baliunas, an accomplished Harvard astrophysicist and long-time proponent of the solar connection to recent warming, has relented her case without totally resting it. See her essay "Possible Effects of Solar Variability on the Earth's Ecosystems" in the collection of skeptic essays in *Shattered Consensus: The true state of global warming,* Patrick J. Michaels ed. (Rowman & Littlefield, New York, 2005).**

Challenge #5:

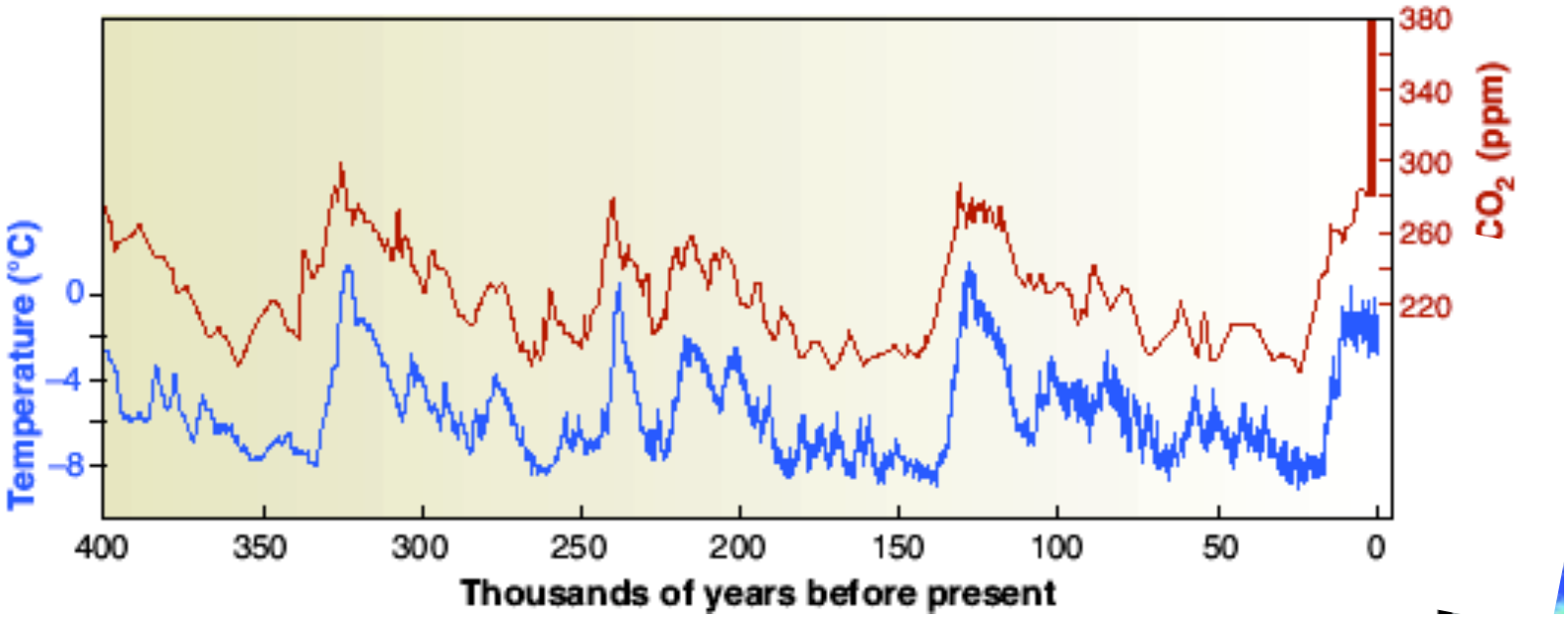
“Climate is naturally variable, and that’s all we’re seeing now.”

Climate is indeed naturally variable. (Red: CO_2; blue: temperature)

CAUTIONS:

(1) Correlation only; causation suggested but not proved.

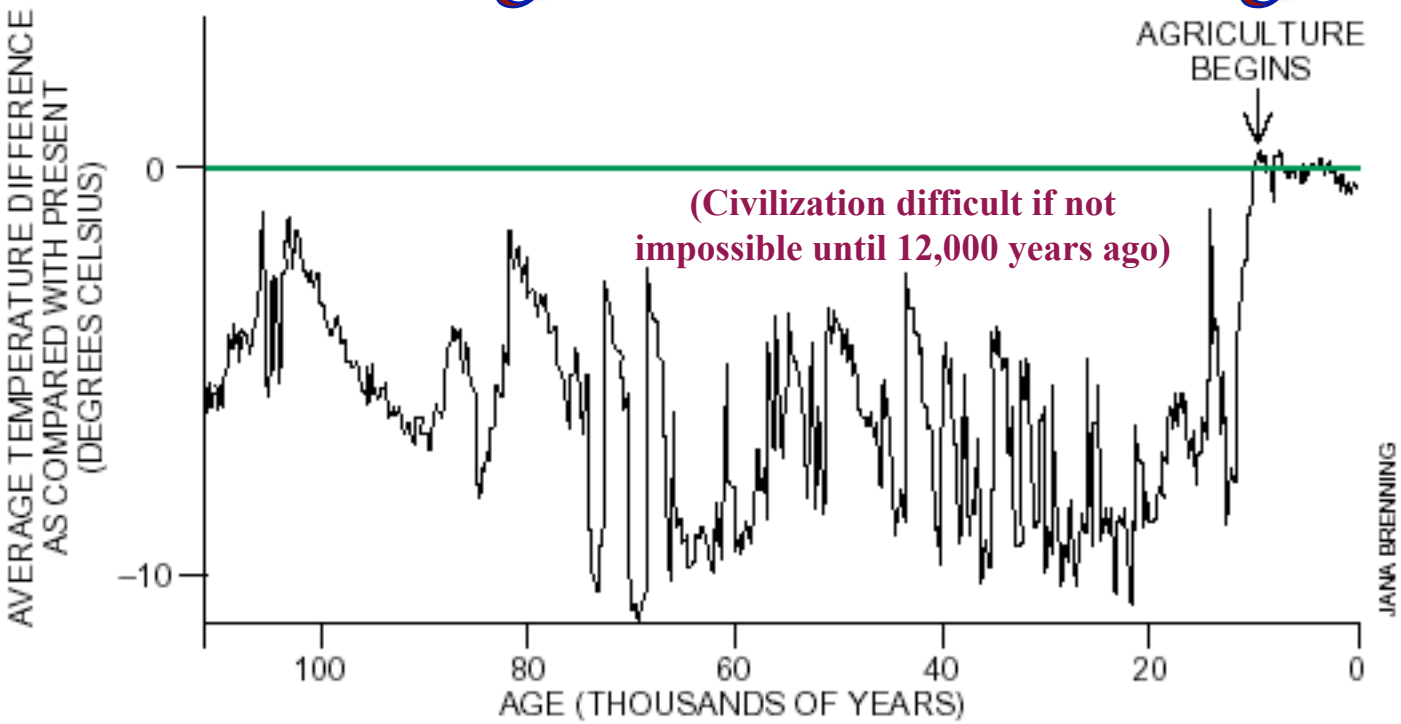
(2) Match with today's temperature is not possible.



SOURCE: A.V. Federov et.al., "The Pliocene Paradox (Mechanisms for a Permanent El Nin˜o)" (*Science*, VOL 312 9 JUNE 2006), pp. 1485-1489. (Data derived from Antarctic ice cores.)

Climate was chaotic! Civilization not possible until about 12,000 years ago!!

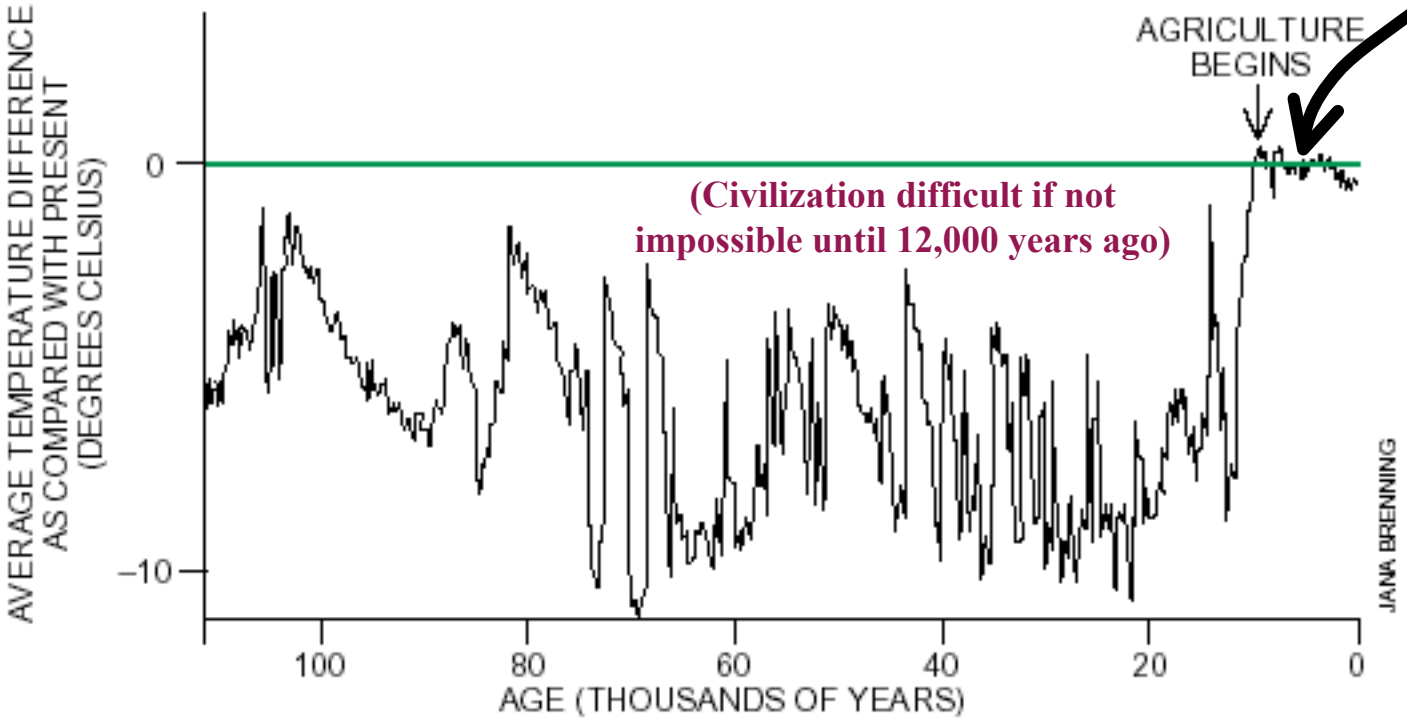
Are we tickling the tale of the dragon?



ICE CORE DATA (from Greenland's ice cap) show the variability of the earth's climate during the past 100,000 years. Temperature variations are measured by the "proxy" of the oxygen 18/oxygen 16 isotope ratio in ice core air bubbles.

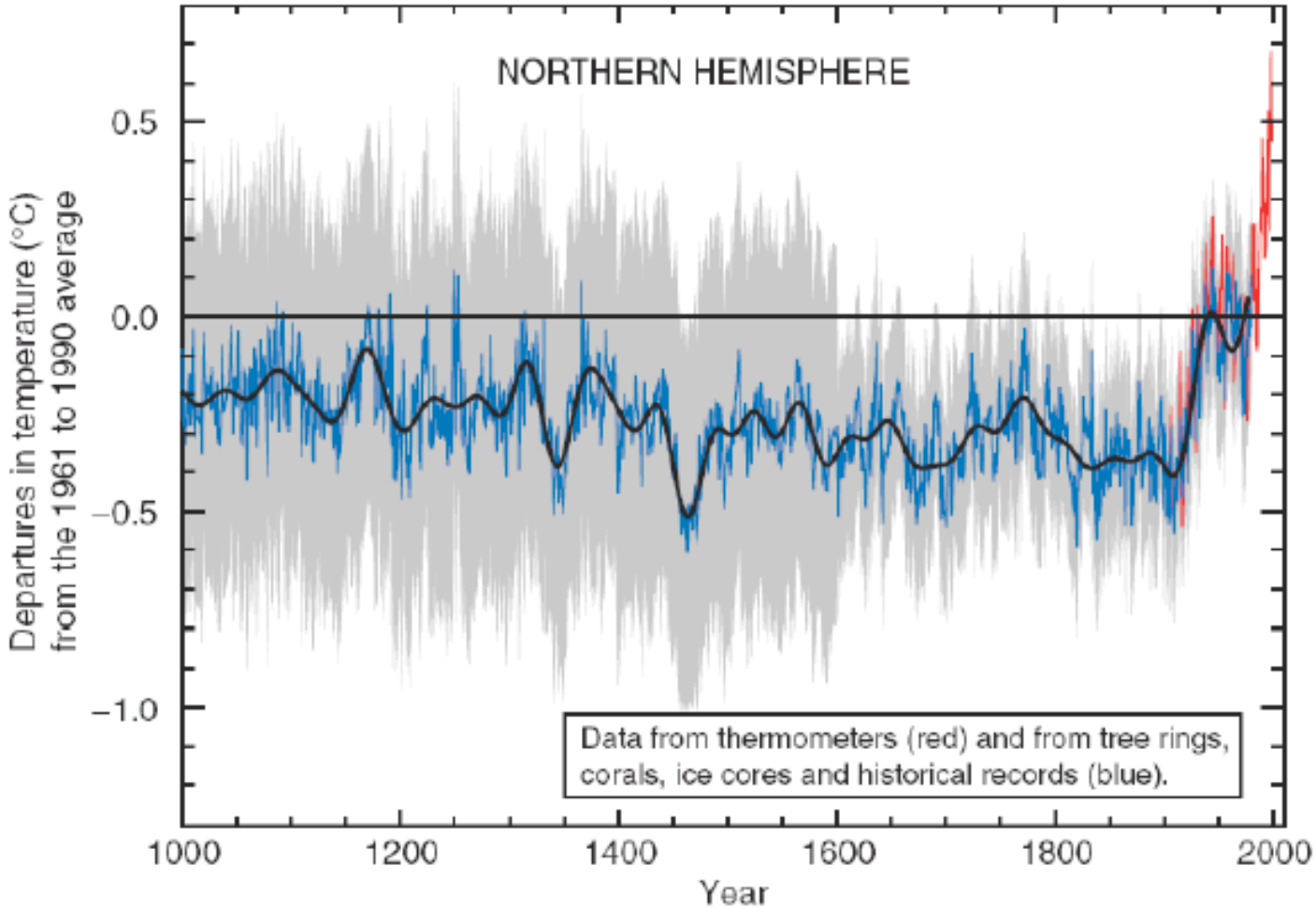
SOURCE: W.S. Broecker, "Chaotic Climate," Scientific American, November, 1995

Take a closer look at last 1,000 post-agriculture years:



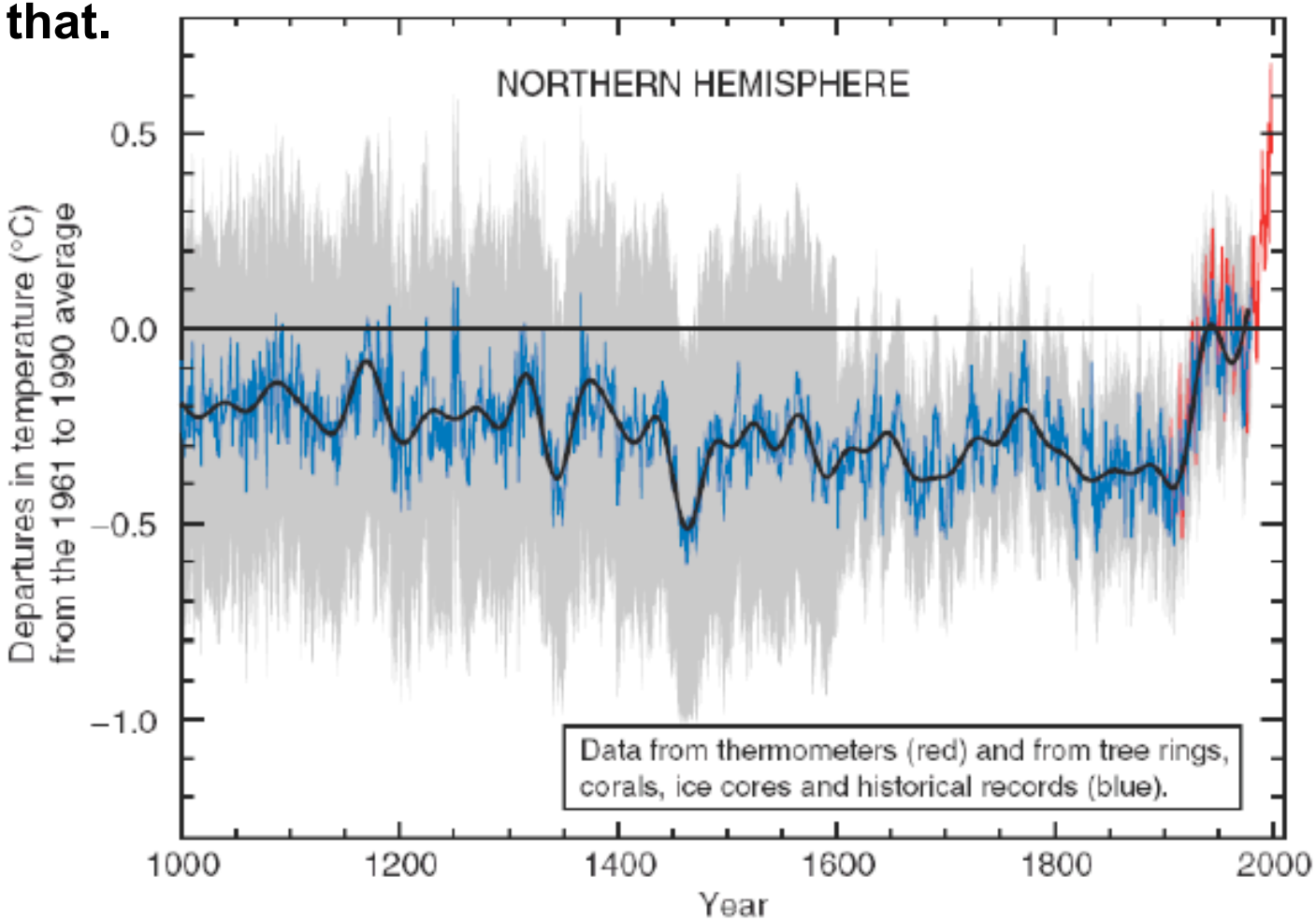
WE HAVE HAD *RELATIVELY* STABLE TEMPS FOR ABOUT 12,000 YEARS, BUT NOW…

The "hockey stick," the first temperature reconstruction of the previous 1000 years (blue). Thermometer record, red (ends at 1998).

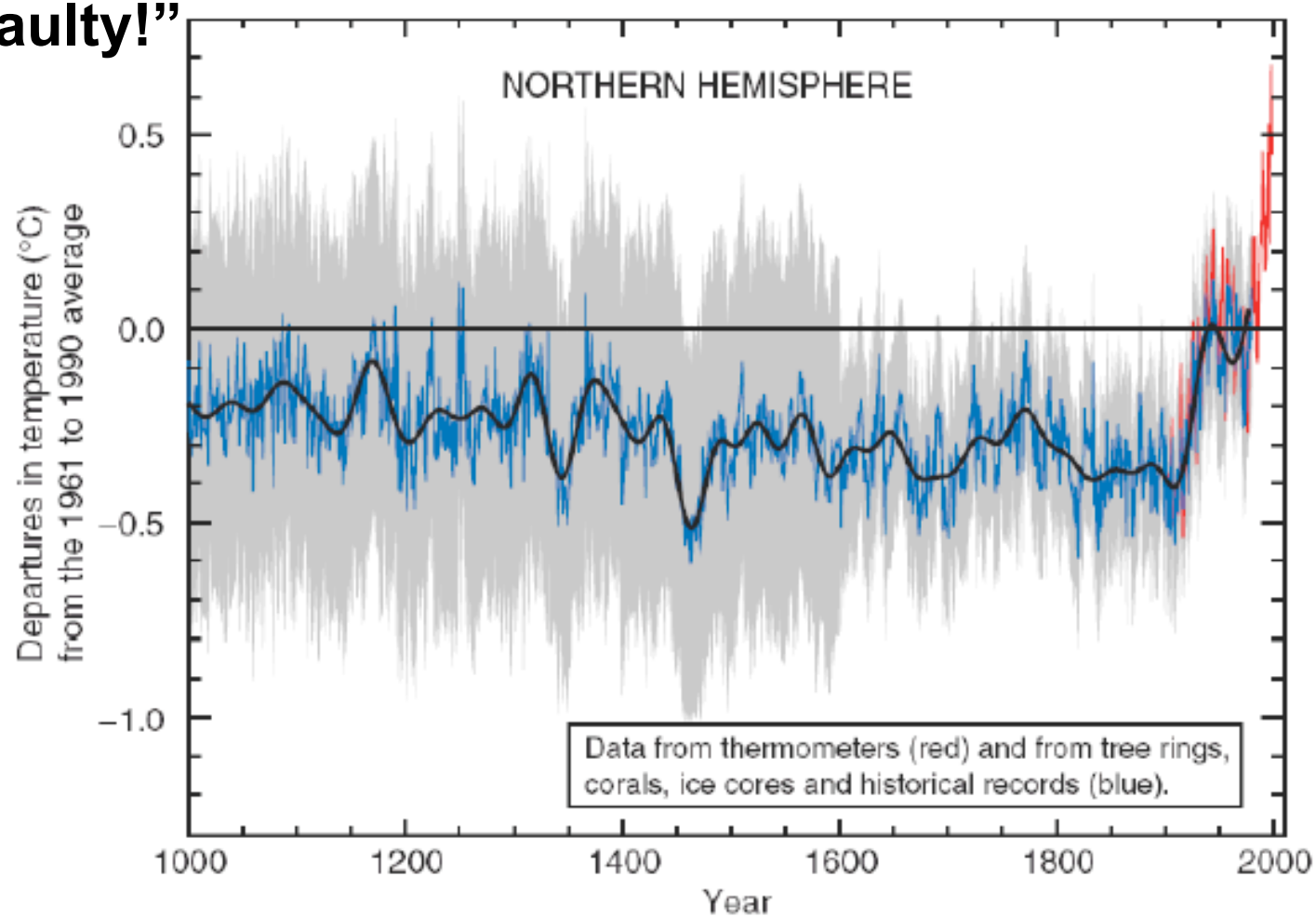


SOURCE: Mann, M.E., R.S. Bradley, and M.K. Hughes. 1999. Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations. Geophysical Research Letters 26(6):759-762.

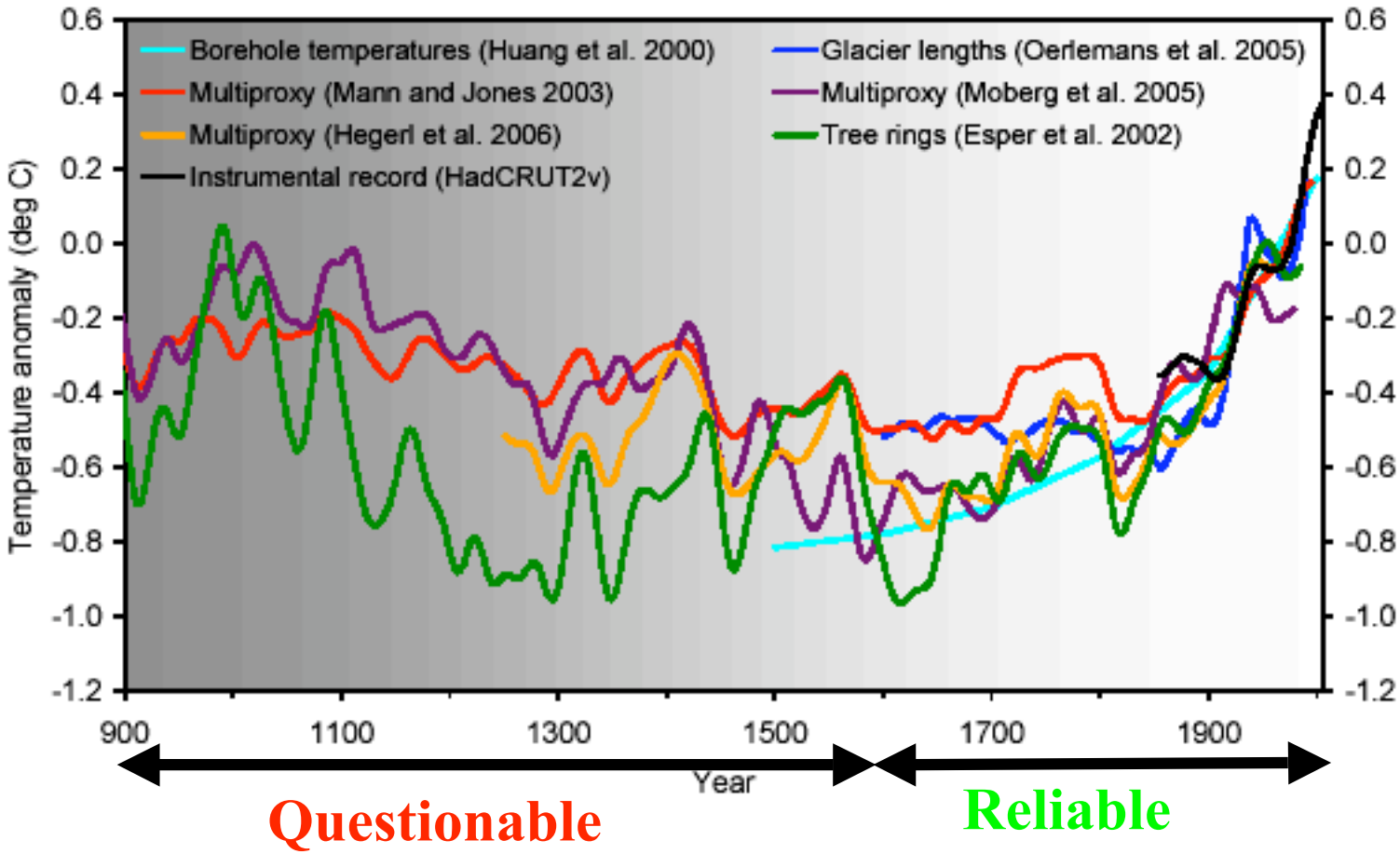
Look at error bars: OK back about 400 years. Iffy prior to that.



Heavily criticized by skeptics: "PCA analysis faulty!"



NRC weighs in (2006):



For now, temperature reconstructions *calibrated to today's* are meaningful for only 400 years before present. (N.B.: *Correlations*, e.g., between CO_2 and temperature, can be meaningful over thousands or even millions of years.)

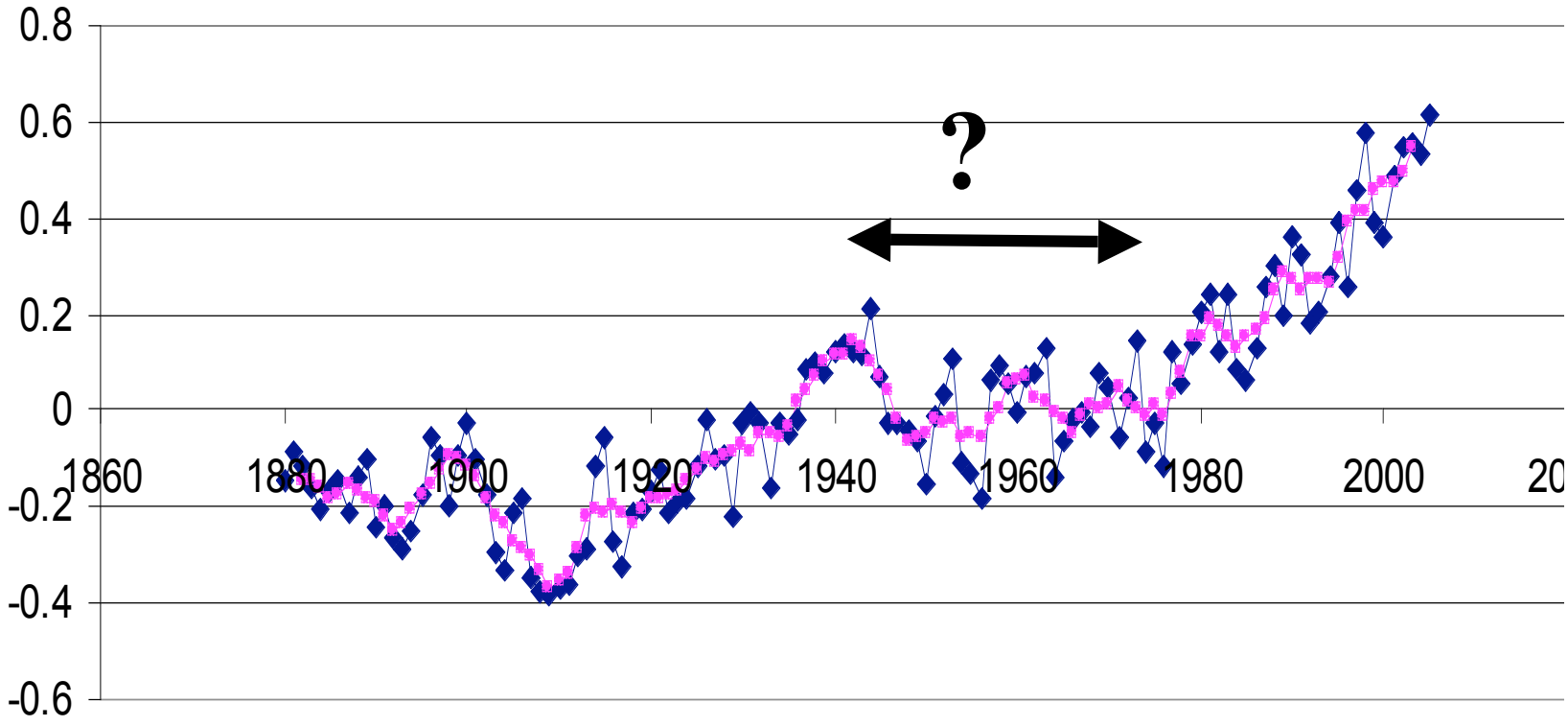
Preliminary conclusion:

Temperature increase in the last 100 years stands out. Partly natural, but more likely to be human-caused.

"Preliminary" because one more thing must be looked at. Go back to NCDC temperature record:

What's with 1940-1979? Looks like a natural leveling off of temperature!

NCDC Annual and 5-year moving average of Land-Sea Temperatures (Anomalies from 20th Century Average)



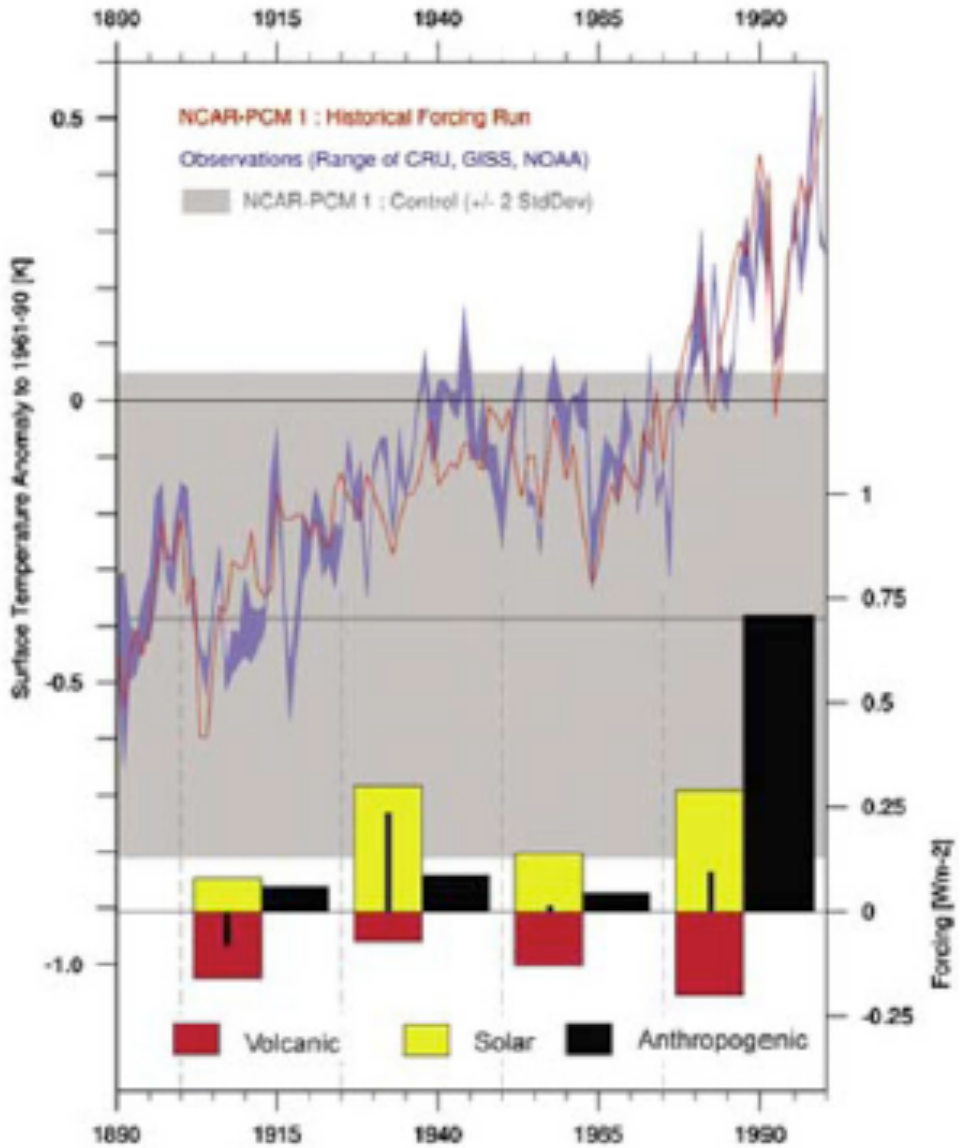
To understand the leveling, we must recognize <u>three</u> major determinants of global temperature:

1. **Anthropogenic (primarily fossil fuel-burning) effects;**
2. **Variations in solar radiation;**
3. **Aerosols & dust produced by volcanic eruptions and human activity.**

Note difference:

1950-1974, solar canceled by volcanic aerosols, and GHG warming reduced by pollution!

1975-1999: solar largely offset by volcanic; but now GHG dominate.



SOURCE: Casper Ammann et.al., "A monthly and latitudinally varying volcannic forcing dataset in simulations of 20th century climate, *Geophysical Research Letters*, 30, No. 12, 1657, doi:10.1029/2003GL016875, 2003

The evidence is in:

We are now in the “anthropogenic” age when climate is dominated by the addition of GHG from burning of fossil fuels.

This round:

Global warmers: 0.95

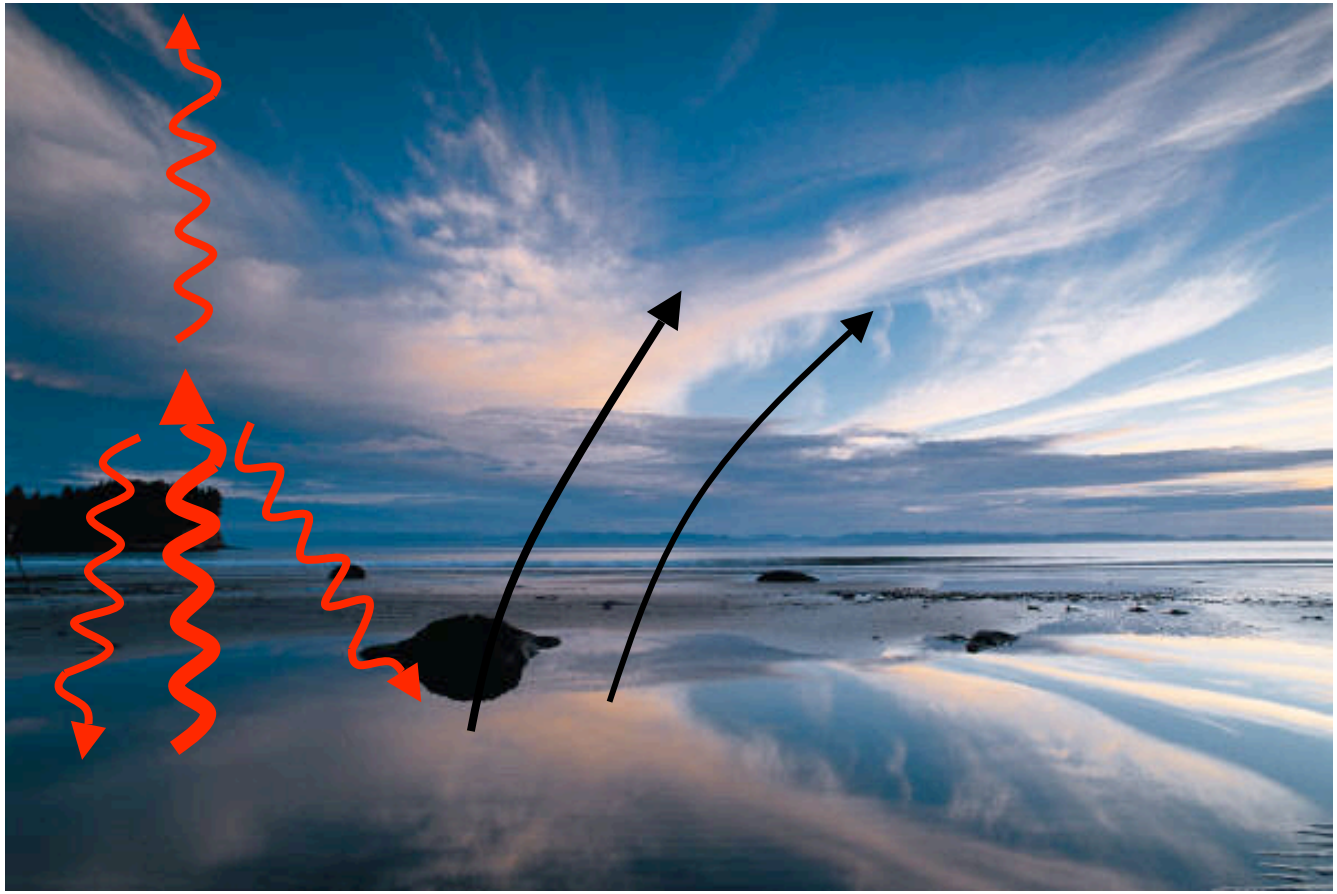
Skeptics: 0.05

CHALLENGE #6

Water vapor feedback: positive or negative?

The positive feedback mechanism

Increased CO_2 warms the oceans → **Increased ocean temperature causes increased evaporation, i.e., increased H_2O_v.** → **Increased H_2O_v adds to temperature rise caused by CO_2**



SOURCE for background picture: iBook clip art (Nature-"Skyscape")

The negative *feedback challenge**

1. **Most H_2O_v is below a few km.**
2. **At low altitudes, existing H_2O_v saturates absorption.**
3. **Global warming reduces evaporation from clouds and increases rainfall.**
4. **Therefore, H_2O_v will not get up to higher altitudes where it can almost double warming from CO_2.**
5. **The upper troposphere will *dry out*, thus *cooling* the planet.**

*R. Lindzen, "Some coolness concerning global warming," Bull. Am. Meteor. Soc., **71**, 288-299 (1990)

A great difficulty:

We are looking for *changes* in water vapor. The changes are very important to global warming but are *small* and very difficult to measure.

Soden et.al.'s clever response to the challenge

Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor

Brian J. Soden,[1]* Richard T. Wetherald,[1] Georgiy L. Stenchikov,[2] Alan Robock[2]

The sensitivity of Earth's climate to an external radiative forcing depends critically on the response of water vapor. We use the global cooling and drying of the atmosphere that was observed after the eruption of Mount Pinatubo to test model predictions of the climate feedback from water vapor. Here, we first highlight the success of the model in reproducing the observed drying after the volcanic eruption. Then, by comparing model simulations with and without water vapor feedback, we demonstrate the importance of the atmospheric drying in amplifying the temperature change and show that, without the strong positive feedback from water vapor, the model is unable to reproduce the observed cooling. These results provide quantitative evidence of the reliability of water vapor feedback in current climate models, which is crucial to their use for global warming projections.

SOURCE: *Science*, vol 296, 26 April 2002, 727-730.

See what volcanic-induced cooling does to H_2O_v

- Volcanic aerosols produce a *global cooling*
- The massive 1991 Pinatubo eruption caused a *decrease* in total "column" H_2O_v
- Challenger's argument implies that cooling should *decrease* H_2O_v.
- Conclusion: the opposite situation, a CO_2-induced warming, should *increase* H_2O_v and cause a *positive* feedback.

Wait a minute--

- “Volcanic eruptions are not perfect reverse proxies for greenhouse gas climate change.”*
- But Soden *et.al.* analysis, while not perfect, is nevertheless meaningful.
- Another argument would help Soden *et.al.’s case*.

*Anthony D. Del Genio, “The Dust Settles on Water Vapor Feedback,” *Science*, vol 296, 26 April 2002.

Technical note #2 on Pinatubo "experiment"

Vapor pressure of H_2O increases rapidly with T. Therefore, we expect H_2O_v concentration to increase as the planet warms. This yields a positive feedback, roughly doubling the change in temperature, (T_{CO2}) caused by only CO_2.

Volcanoes provide a *transient* "experiment" to test H_2O_v feedback. H_2SO_{4g} combined with $H_2O_{v,}$ yield aerosols that scatter light more than they absorb, thus cooling Earth, so this cooling should result in a *decrease* of H_2O_v, the implication being that warming would result in an *increase* of H_2O_v.

Pinatubo (June 1991) cooled Earth, & total column H_2O_v did decrease. But it is important to look at the change in higher-altitude H_2O_v, because this has the biggest effect.

Model simulations were done from Jan 1991 to Dec 1995. Three pairs of simulation experiments were done, each pair consisting of one with no aerosols, one with Pinatubo aerosols. Observations & model simulations yield a decrease in absorbed SW radiation about twice the increase in LW, similar to ERBS-observed changes.

MSU measurements give the maximum magnitude of cooling as 0.5^o C peak 18 months after eruption. Models reproduce this very well.

El Nino and other internal oscillations were not included in the simulations, because an El Nino began before 1991 and was constant during the 5-year period of interest and therefore doesn't affect *anomalies* from 1979-1990 baseline.

Models and NVAP (Nasa H_2O_v Project) satellite observations indicate a 3% decline in global H_2O_v for the 0.5 deg C cooling max. The *rate* of drying (~6%/K) is approximately equal to the rate of decrease of saturation pressure,$P_{sa,t}$, with T in the lower troposphere, and this indicates that the relative

(continued)

Technical note #2 (cont)

humidity stays constant as altitude and temperature change.

Changes in total column H_2O_v are dominated by the response of H_2O_v in the *lower* troposphere But since changes in H_2O_v in the upper troposphere are more important for cooling, Soden *et.al.* look at H_2O_v at 300-500 hPa, using data from NVAP and TIROS-TOVS satellites. Both show drying, but TOVS is > NVAP. Also, H_2O_v recovers faster in NVAP data.

The discrepancy between TOVS and NVAP can be reduced by looking at satellite-observed *radiances*. Soden *et.al.* looked at the TOVS 6.7-micrometer Planck T ($T_{6.7}$), a water absorption line measured with HIRS Channel 12 at 44.78 GHz. $T_{6.7}$ is sensitive to RH in a deep (200-500 hPa) layer. Thus, the authors say, if the H_2O_v mass in the upper troposphere declines (thus conserving RH as the air there cools), a smaller change in $T_{6.7}$ should result. Why? Because cooling reduces radiance overall while a decline in H_2O_v in the upper troposphere reduces the attenuation of radiation from warmer lower levels. If H_2O_v in the upper troposphere didn't decline in step with decreasing T, $T_{6.7}$ would decline by ~ 0.8 K, more than twice the observed.

Simulations were also done for a GCM with *no* H_2O_v feedback and then compared with MSU observations. Of course, T decreases even if no feedback occurs, but it is only 0.19 K compared to the observed 0.30 K. So H_2O_v feedback increases the change in T by ~ 58%, close to what is theoretically expected.

Three years later, Soden and a different group of researchers respond:

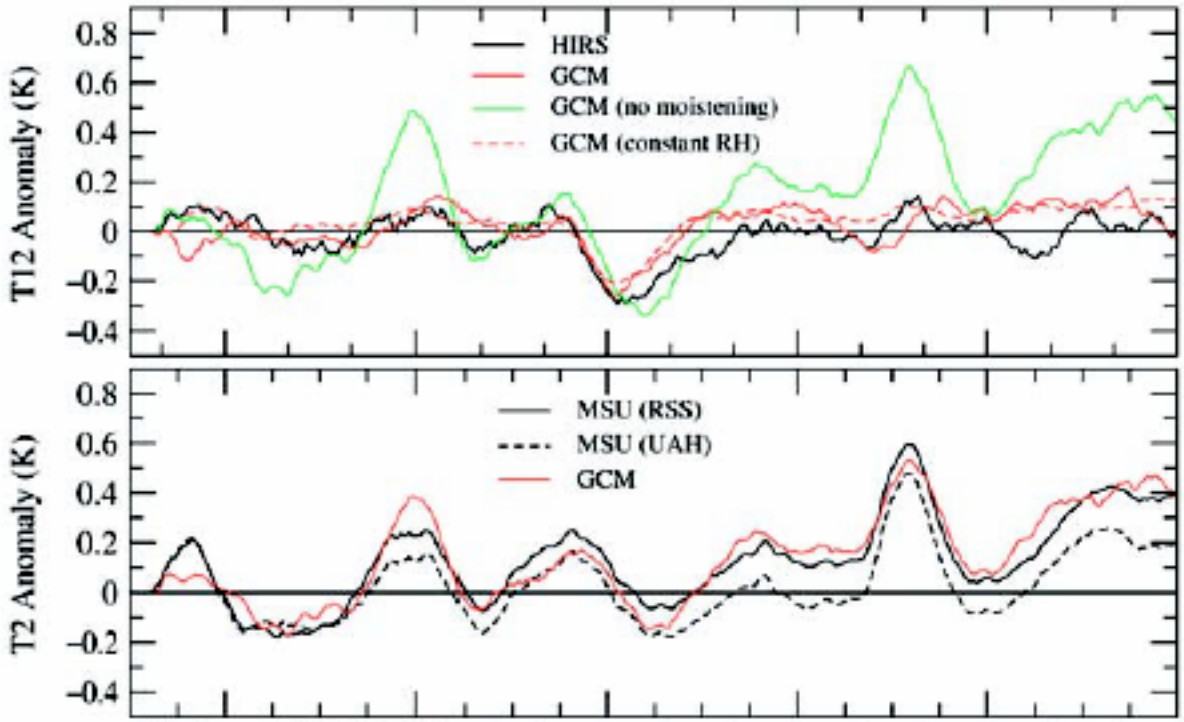
The Radiative Signature of Upper Tropospheric Moistening

Brian J. Soden,[1*] Darren L. Jackson,[2] V. Ramaswamy,[3]
M. D. Schwarzkopf,[3] Xianglei Huang[4]

Climate models predict that the concentration of water vapor in the upper troposphere could double by the end of the century as a result of increases in greenhouse gases. Such moistening plays a key role in amplifying the rate at which the climate warms in response to anthropogenic activities, but has been difficult to detect because of deficiencies in conventional observing systems. We use satellite measurements to highlight a distinct radiative signature of upper tropospheric moistening over the period 1982 to 2004. The observed moistening is accurately captured by climate model simulations and lends further credence to model projections of future global warming.

SOURCE: *Science*, vol 310, 4 November 2005, 841-844

The results:



Top graph (black line): The constancy of H_2O_v radiance indicates an increase of water vapor. Bottom graph (black line): The rise of O_2 radiance indicates an increase in temperature. (See Technical note #3 for a description of the colored lines.)

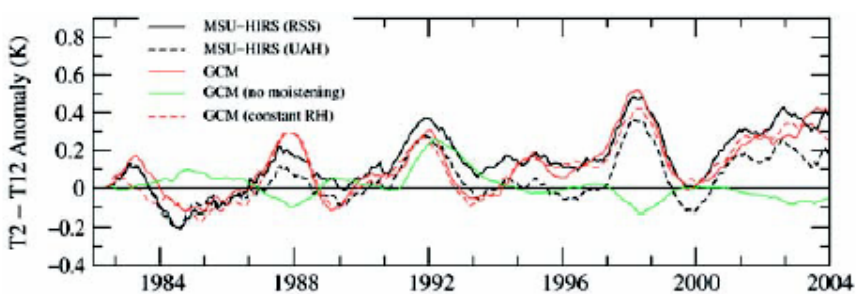
SOURCE: *Science*, vol 310, 4 November 2005, 841-844

Technical note #3

Soden *et.al.*'s procedure to investigate evidence for positive H_2O_v feedback was as follows. First, they looked at infrared radiation measured (1979-present) by Channel 12 of the HIRS satellite instrument. Channel 12 is sensitive to H_2O_v emission at 6.7 micrometers (44.78 GHz) originating from a layer from about 6 km to 12 km altitude (500 hPa to 200 hPa). This yields the temperature T_{12} (= $T_{6.7}$ in Technical Note #2), which is essentially the Planck temperature from the measured radiance. Next, they obtained an independent temperature measurement, T_2, from MSU Channel 2. Channel 2 is sensitive to oxygen (O_2) emission from a layer stretching from about 2 km to 12 km (800 hPa to 200 hPa), so T_2 indicates the temperature at a somewhat lower average altitude then T_{12} does.

If warming causes an increase of H_2O_v in the upper troposphere such that relative humidity stays constant, then the absolute mass density of H_2O_v will increase, and the combination of the increase of radiance from the additional high-altitude H_2O_v and the decrease of radiance from warmer lower levels tend to cancel, leaving T_{12} constant over times long enough for the effects of abrupt events like volcanic eruptions (see Technical note #2) to subside. But the mass density and altitude distribution of O_2 remains relatively constant, with the result that warming causes T_2 to increase. This is shown in the bottom graph of the previous slide which also shows how well a climate model with constant RH tracks the changes.

The importance of increasing H_2O_v in the upper troposphere can be further illustrated by considering the average levels (i.e., altitudes) of emission of radiation that T_{12} and T_2 are based on. As mentioned, T_{12} measures the radiant temperature of H_2O_v from a higher layer of atmosphere than T_2 does. The constancy of T_{12} all by itself is reminiscent of Challenge #3's claim that the temperature of the troposphere is *not* increasing, while the increase of T_2 indicates that the troposphere *is* warming. Given the reality of warming as reflected by T_2, the constancy of T_{12} discussed above can only result if the average level of emission measured by T_{12} increases. If the warming were due to an extraneous factor, e.g., an increase in solar radiation, and H_2O_v did not increase at higher altitudes, then both T_{12} and T_2 would increase. The difference between T_2 and T_{12} is manifestly obvious from the constancy of T_{12} and the rise of T_2, but subtracting T_{12} from T_2 emphasizes the fact that H_2O_v increases in the upper layers, which is necessary for a feedback effect. The difference is shown here.



SOURCE: *Science*, vol 310, 4 November 2005, 841-844

Still missing:

Direct measurements of H_2O_v in upper troposphere over a long period of warming.

(Weather balloons directly measure H_2O_v, but the data suffers from numerous technical difficulties.)

This round:

Global warmers: 0.8

Skeptics: 0.2

CHALLENGE #7

THE MOST DAUNTING CHALLENGE TO CLIMATOLOGISTS:

MODELING CLIMATE.

MODELS ARE ESSENTIAL TO UNDERSTAND THE PAST AND PLAN FOR THE FUTURE.

DIFFICULT TO MAKE PRECISE CLIMATE ESTIMATES--TRUE OF *ANY* MODEL OF A CHAOTIC PROCESS, AND CLIMATE IS CHAOTIC!

Are today's climate models perfect?

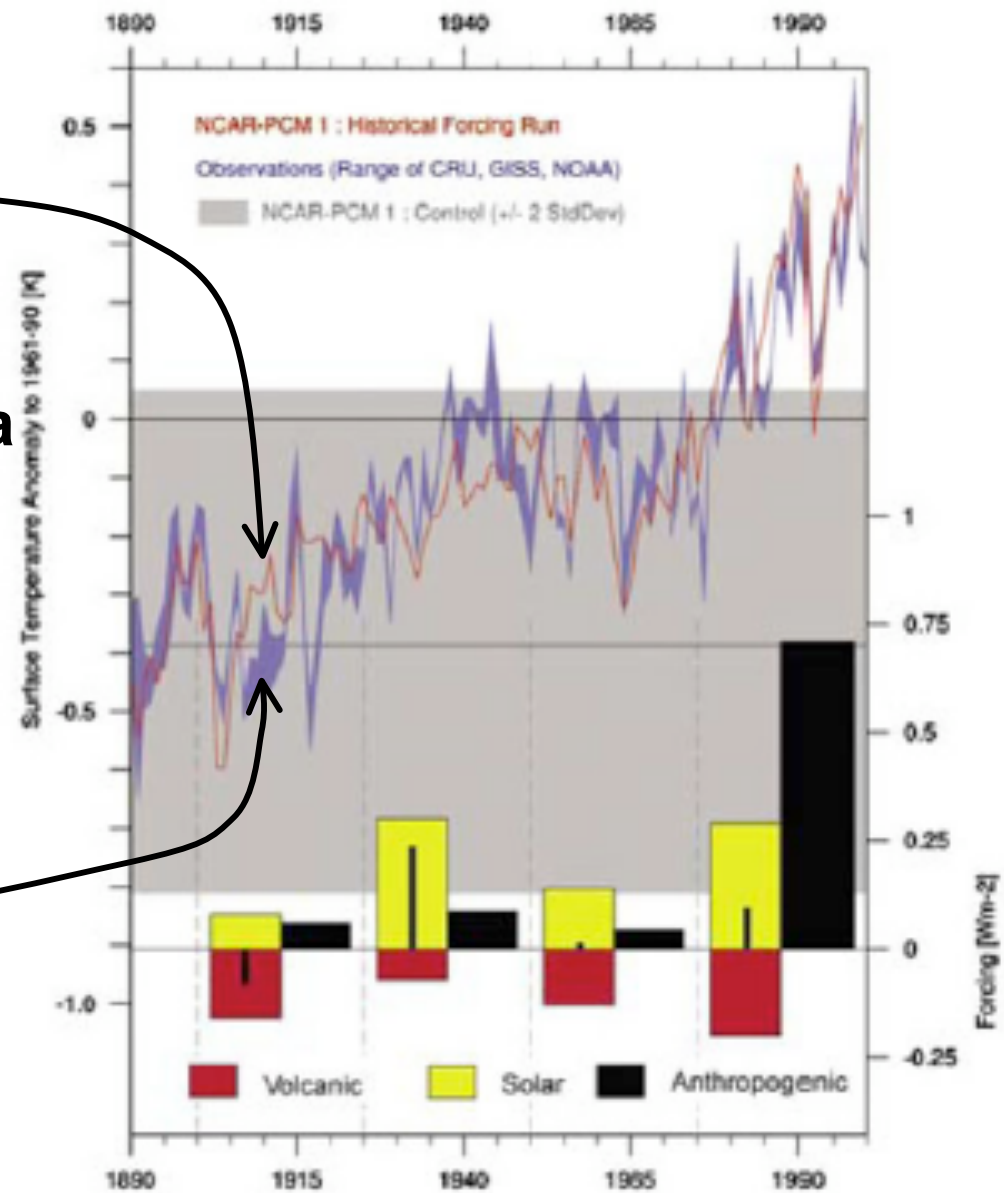
NO.

Are today's climate models useful and necessary?

ABSOLUTELY!!

Models can reproduce temperatures:

Global climate model (red) closely simulates temperature data (blue).



Models can estimate sea level rise:

Conservative **IPCC estimates for year 2095 range from:**

3 **0.18 to 0.38 meters above 1980-1999 average for a *doubling* of GHG above the natural level;**

0.23 to 0.51 meters for a *quadrupling*.

These figures exclude a rise from melting of ice sheets.

Models can estimate sea level rise:*

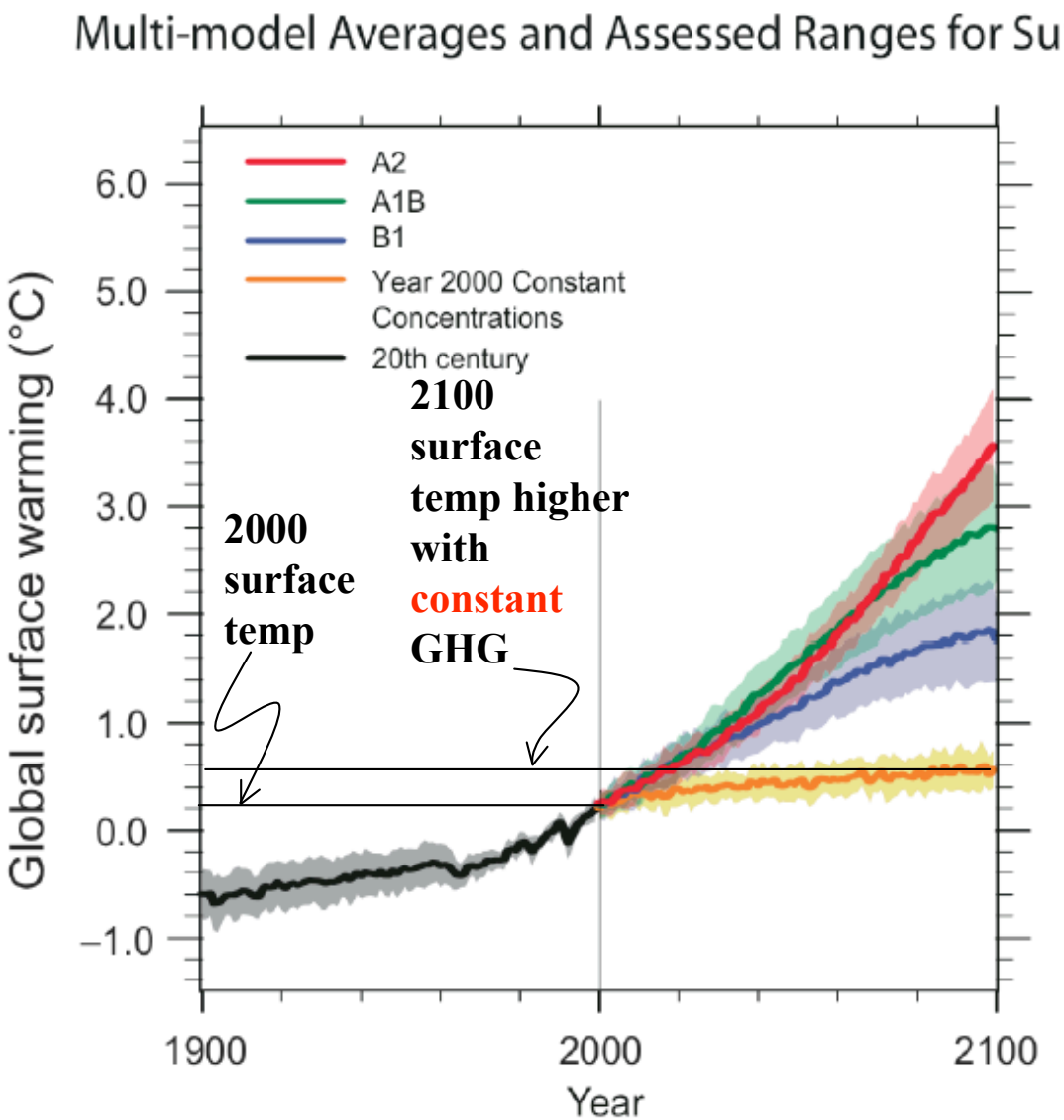
Conservative IPCC estimates for year 2095 range from:

a) 0.18 to 0.38 meters above 1980-1999 average for a *doubling* of GHG above the natural level;

b) 0.23 to 0.51 meters for a *quadrupling*.

** These figures exclude a rise from melting of ice sheets.*

Models can estimate surface temperature:



Error ranges are "likely," i.e., with > 90% probability of occurrence.

By year 2100 (ppm CO_2 equiv.): B1, 600; A1T, 700; B2, 800; A1B, 850; A2, 1250; A1FI, 1550

SOURCE: IPCC Fourth Assessment Report, February, 2007, "Summary for Policymakers."

Virtually certain conclusions from climate models:

- Increase in GHG causes global temperature to rise.
- Additions of GHG above natural (pre-industrial) levels will persist for 100 years or more--our future is mortgaged and there is very little we can do about it once the imbalance occurs.
- It is not prudent to wait 20 or 30 or 50 years until we have better prediction models. We've already caused serious damage.

Toughest outstanding modeling challenges

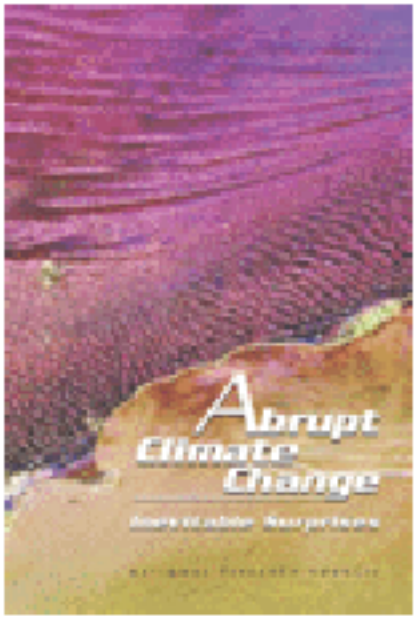
- Cloud cover
- Ocean absorption of heat
- Precipitation and drought
- Abrupt climate change

Toughest outstanding modeling challenges

- Cloud cover
- Ocean absorption of heat
- Precipitation and drought
- Abrupt climate change

Last item deserves a closer look

2002, NRC sponsored a study on the subject.



Abrupt Climate Change: Inevitable Surprises

Committee on Abrupt Climate Change, National Research Council

ISBN: 0-309-51284-0, 244 pages, 6x9, (2002)

This PDF is available from the National Academies Press at:
http://www.nap.edu/catalog/10136.html

From the Executive Summary:

“Recent scientific evidence shows that major and widespread climate changes have occurred with startling speed.

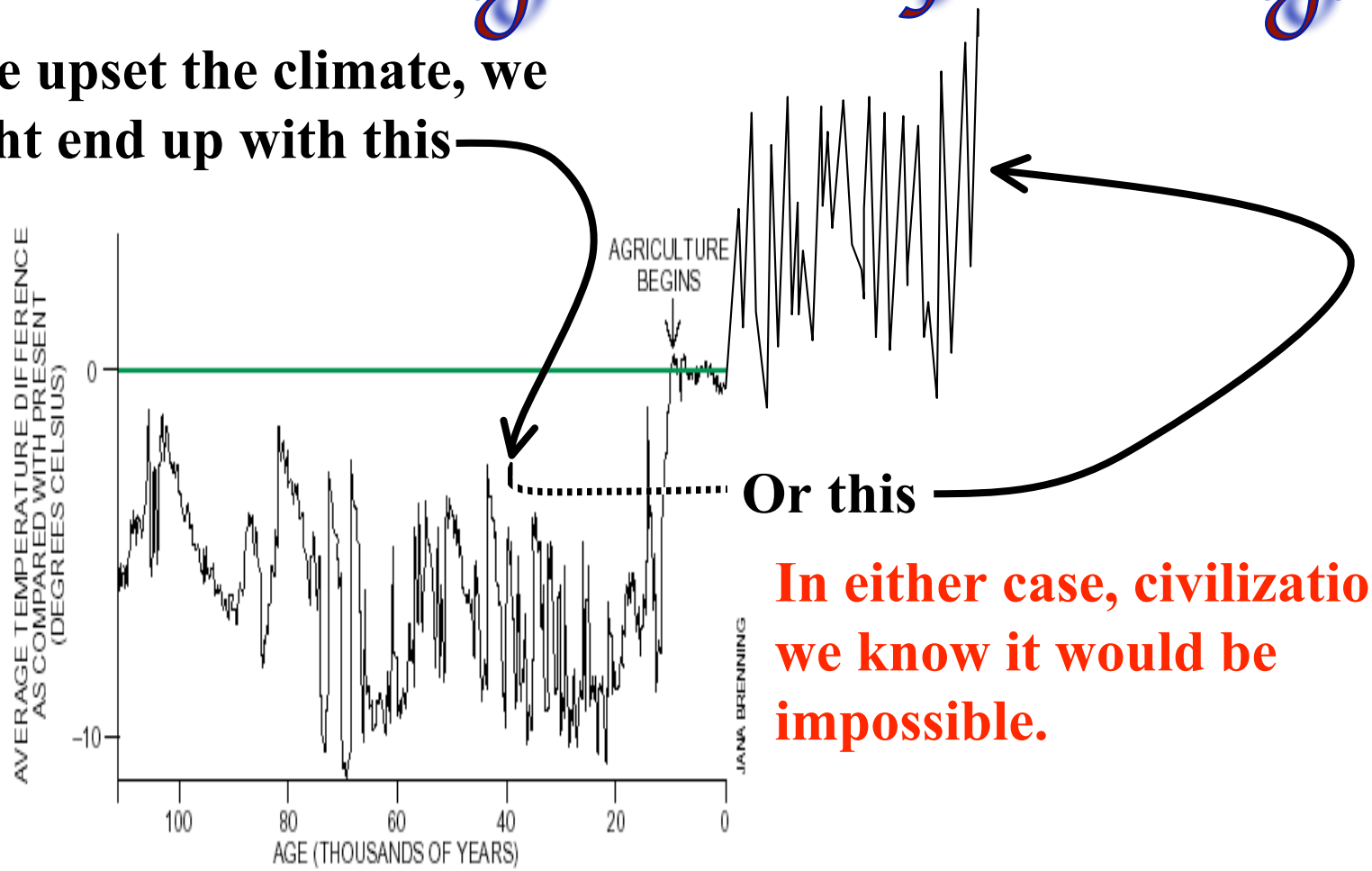
Continuing…

The abrupt changes of the past are not fully explained yet, and climate models [i.e., reconstructions] typically *underestimate* the size, speed, and extent of those changes. Hence, future abrupt changes cannot be predicted with confidence, and climate surprises are to be expected."

A repeat of a warning:

Are we tickling the tale of the dragon?

If we upset the climate, we might end up with this



Or this

In either case, civilization as we know it would be impossible.

This round:

Global warmers: **0.7** **(Models still need a number of important Improvements but have shown usefulness)**

Skeptics: **0.3** **(While models are indeed useful, conclusions regarding consequences of fossil fuel use are too quickly drawn.)**

FINAL SCIENCE "SCORE":

- **Global warmers: 6.3/7 = 0.9**

- **Skeptics: 0.7/7 = 0.1**

***The "scare quotes" on SCORE indicate that this is an unorthodox way to compound probabilities. In the present context, with only two alternatives, it is meaningful.**

CONCLUSION:

Not only is Earth warming, but anthropogenic GHG are *very likely a primary cause of the warming. While skeptics are right to continue to raise alternatives to the "conventional wisdom" on global warming, there is no solid scientific evidence to date for their challenges, but there is much evidence for the impact of fossil fuel use on global climate.**

***The IPCC uses the following terms to indicate the likelihood, "using expert judgment, of an outcome or a result: *Virtually certain* > 99% probability of occurrence, *Extremely likely* > 95%, *Very likely* > 90%, *Likely* > 66%, *More likely than not* > 50%, *Unlikely* < 33%, *Very unlikely* < 10%, *Extremely unlikely* < 5%."**

SOURCE: IPCC Fourth Assessment Report, February, 2007, "Summary for Policymakers," p. 4.

V. MAKING DECISIONS IN THE FACE OF UNCERTAINTY

MAJOR UNCERTAINTIES *BEYOND* OUR CONTROL:

1. VOLCANIC ACTIVITY;
2. SOLAR OUTPUT;
3. INTERNAL CLIMATE DYNAMICS (E.G., ENSO, NAO)

CLIMATE IS PARTLY RANDOM; WE CAN NEVER BE SURE WHAT THE FUTURE HOLDS.

BUT ONE MAJOR ACTIVITY *IS* IN OUR CONTROL:

PRODUCTION OF GHG.

WE CAN USE ENERGY (EVEN FOSSIL FUELS) MORE EFFICIENTLY.

WE CAN REDUCE FOSSIL FUEL USE.

WHY GO TO THE TROUBLE OF REDUCING FOSSIL FUEL USE?

Let's compare the consequences of errors in the skeptic and global warmer positions.

A SKEPTIC ERROR

Suppose skeptics are wrong, global warming *is* caused by fossil fuel use, but we continue to use fossil fuels anyway. What happens?

CONSEQUENCES:

- **Not only do we risk negative effects of global warming (some of which are unknown to us), but we will *certainly* suffer:**
- **More pollution (especially particulate poison and acid rain);**
- **More pressure for warfare to control scarce fossil fuel supplies (especially oil and natural gas);**
- **A less energy-efficient economy that is less able to compete in a world where other countries are cutting fossil fuel use and economizing energy usage.**

ALL consequences are negative.

IT'S NOT WORTH THE GAMBLE!

DON'T TEMPT CHAOTIC CLIMATE!

A GLOBAL WARMER ERROR

Now suppose global warmers are wrong and warming *is not* caused by fossil fuel use but by *nature*. If we *decrease* our use of fossil fuels in the future anyway, what happens?

CONSEQUENCES OF A GLOBAL WARMER ERROR

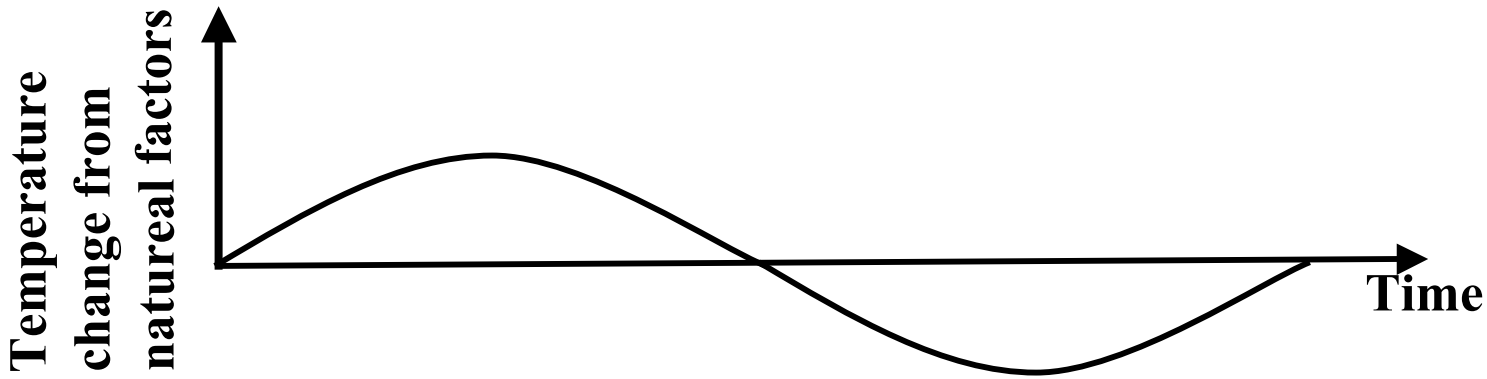
Global warming is caused by *nature*--maybe it'll get worse, maybe it'll cool off a bit.

In any case, we can insure that reduction of fossil fuel use will give us:

1. **LESS *pollution;***
2. **LESS *pressure for warfare to control fossil fuel supplies;***
3. ***A* MORE *energy-efficient economy better able to compete.***

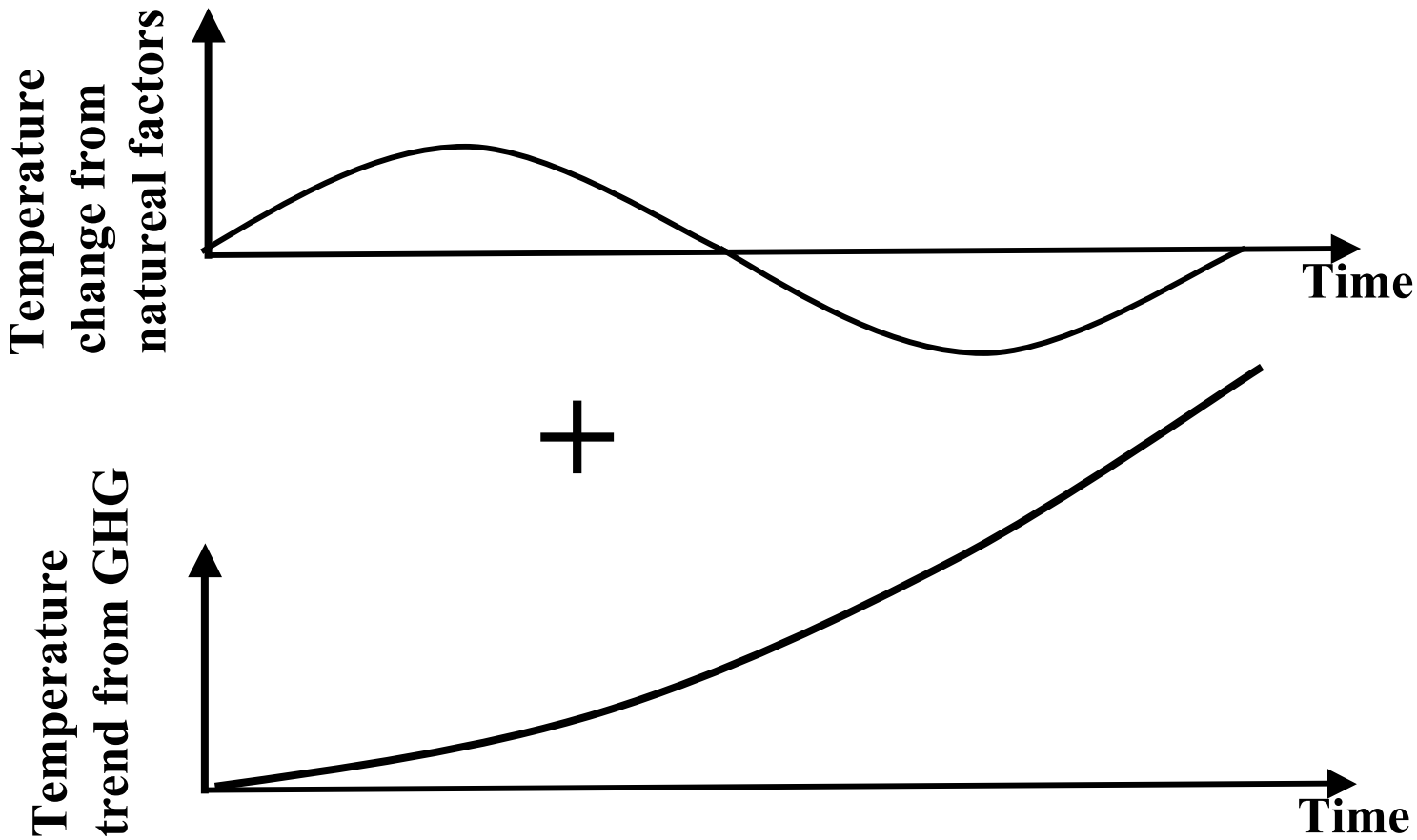
BEFORE ENDING, A WARNING

We know volcanoes, changes in solar radiation, and internal climatic cycles can change temperature:

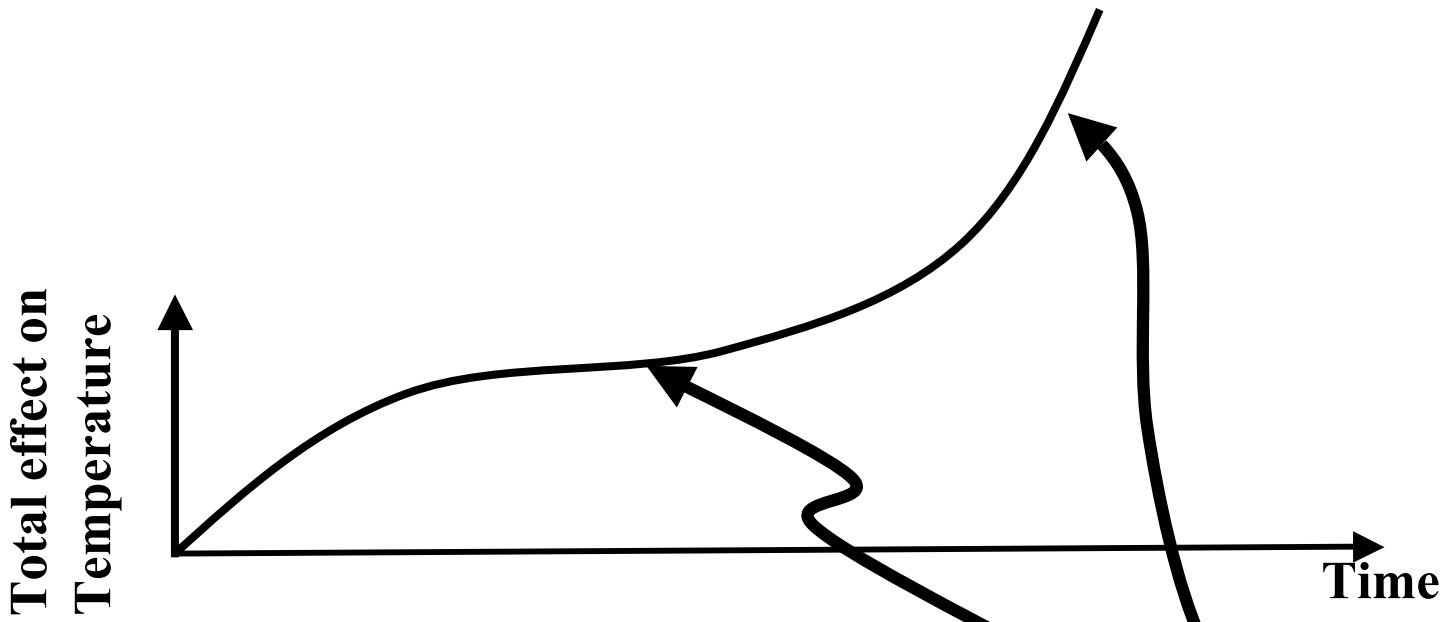


ADD GHG LIKE IN THE PAST:

An increasing upward temperature trend results:



AND YOU GET:

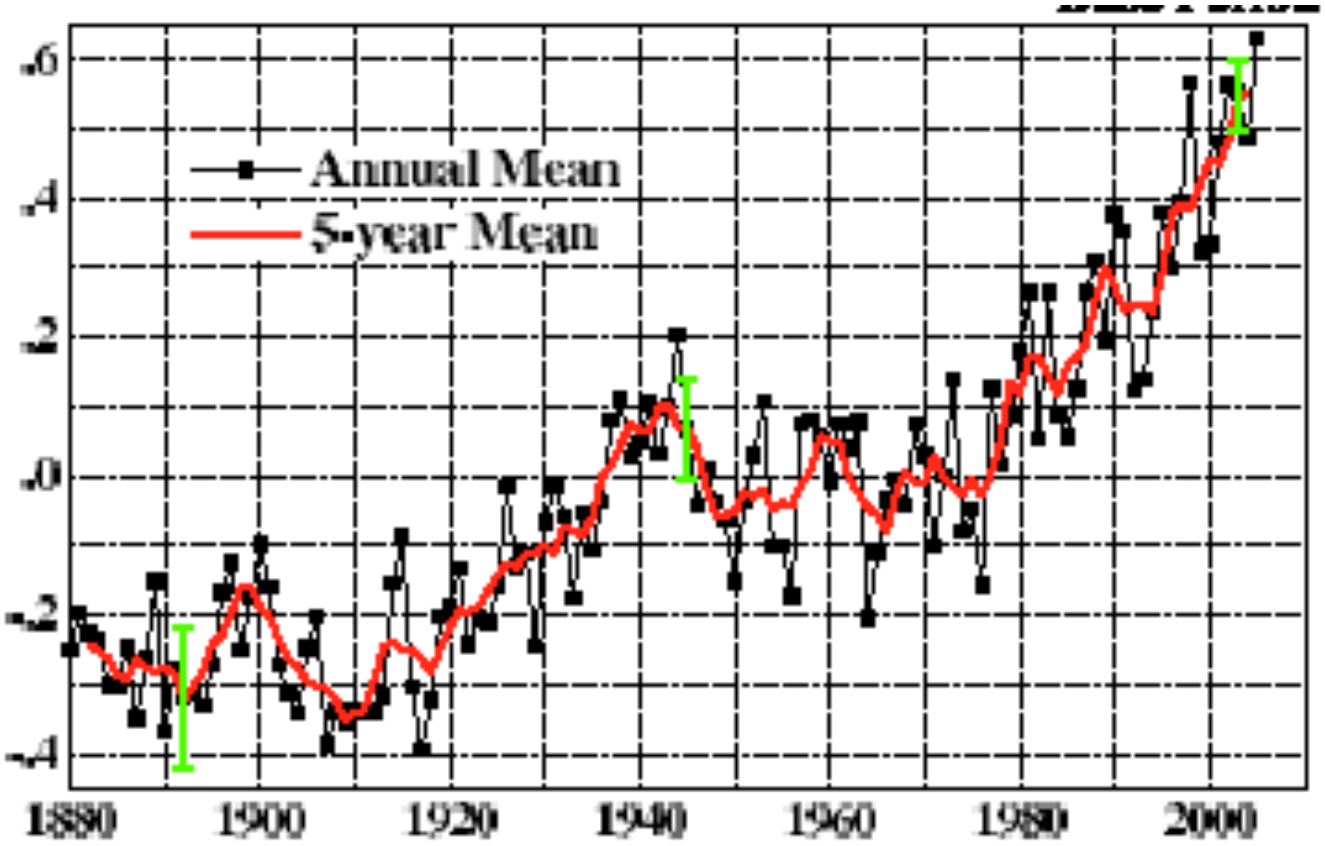


Looks like global warming is gone,

but after a few decades, it's back

WITH A VENGEANCE!

SOUND FAMILIAR? SOMETHING LIKE THIS HAPPENED IN 1940-1979.



Source: J.M. Hansen et.al., "Global Temperature Change," Proc. Natl. Acad. Sci., 103 (#39), 26 Sept 2006

SO IF WARMING LEVELS OFF, DON'T THINK IT'S GONE FOREVER!

NO REGRETS--

Reduce pollution!

Reduce conflict for energy supplies!

Increase economic energy efficiency!

REDUCE FOSSIL FUEL DEPENDENCY!