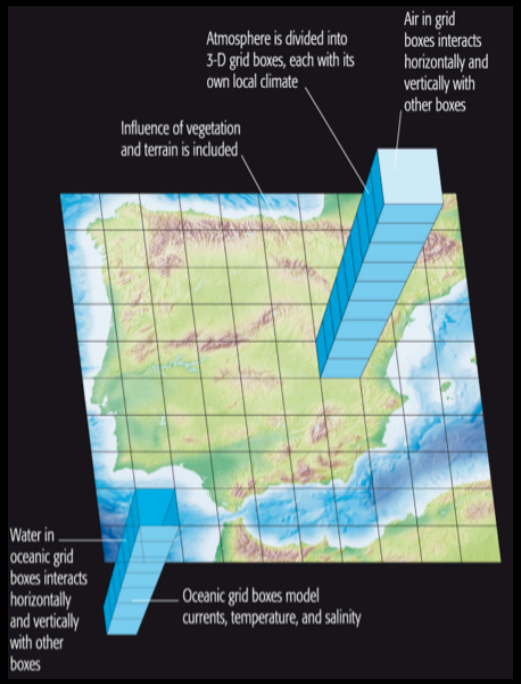
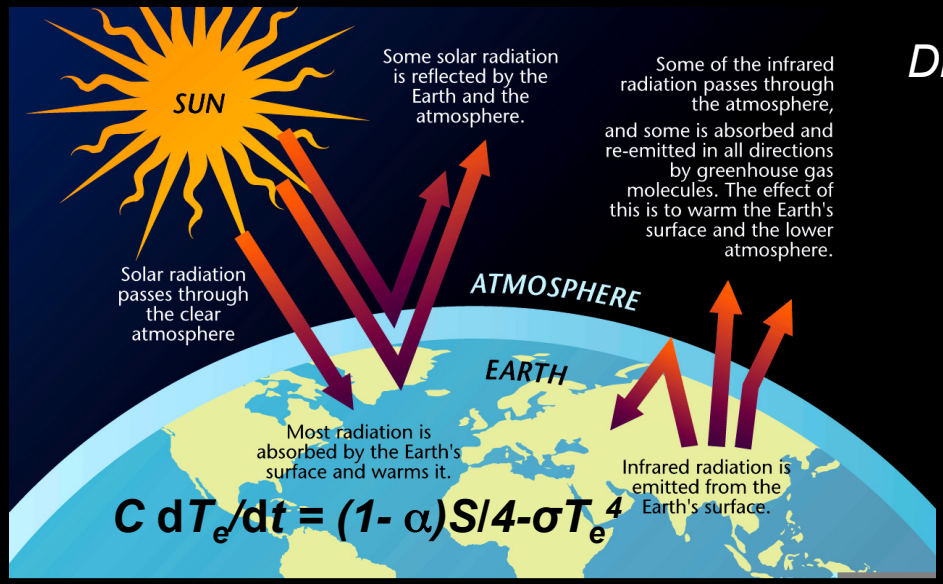
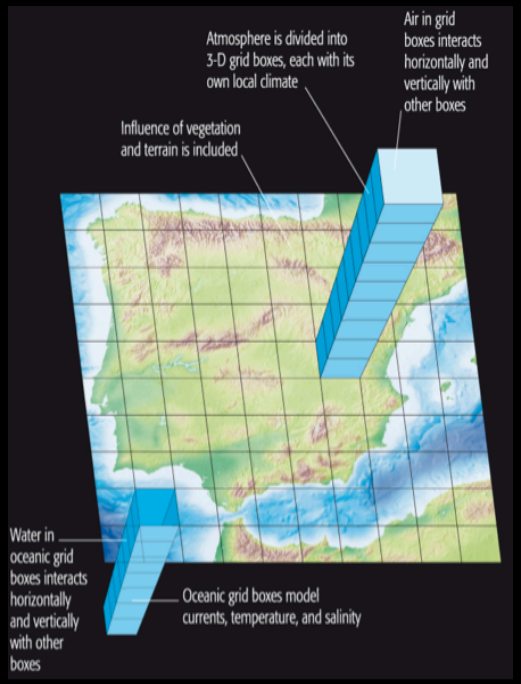


The Physics of Climate Change

Michael E. Mann
Departments of Meteorology and Geosciences & Earth and Environmental Systems Institute
Director, Earth System Science Center
Penn State University



Physics Department
University of Virginia
Charlottesville, VA
Feb 5, 2016



The Physics of Climate Change

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- ***The Zero-Dimensional EBM***
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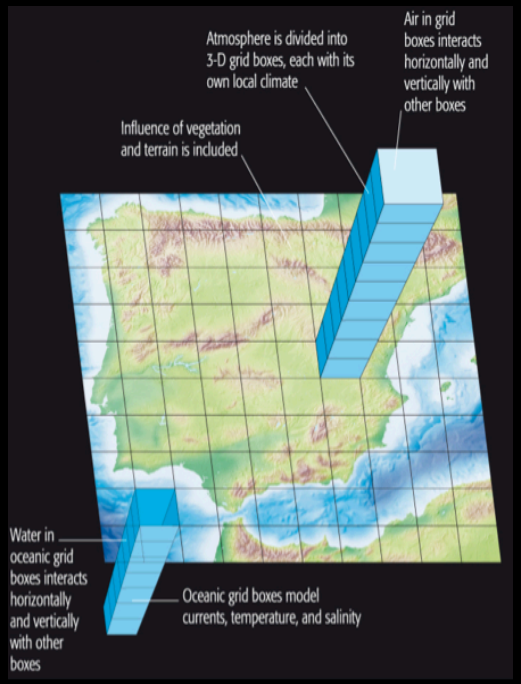

The Physics of Climate Change

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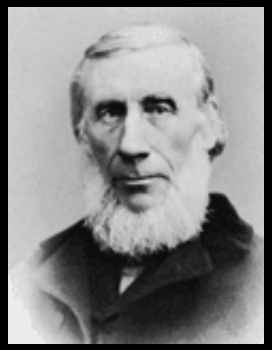
Discovery of the Greenhouse Effect

Joseph Fourier (1827)

Recognized that gases in the atmosphere might trap the heat received from the Sun.

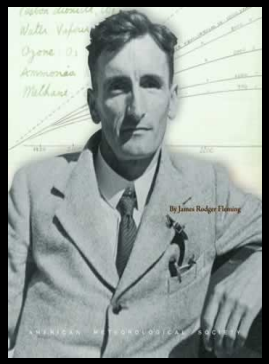


James Tyndall (1859)

Careful laboratory experiments demonstrated that several gases could trap infrared radiation. The most important was simple water vapor. Also effective was carbon dioxide, although in the atmosphere the gas is only a few parts in ten thousand.

Svante Arrhenius (1896)

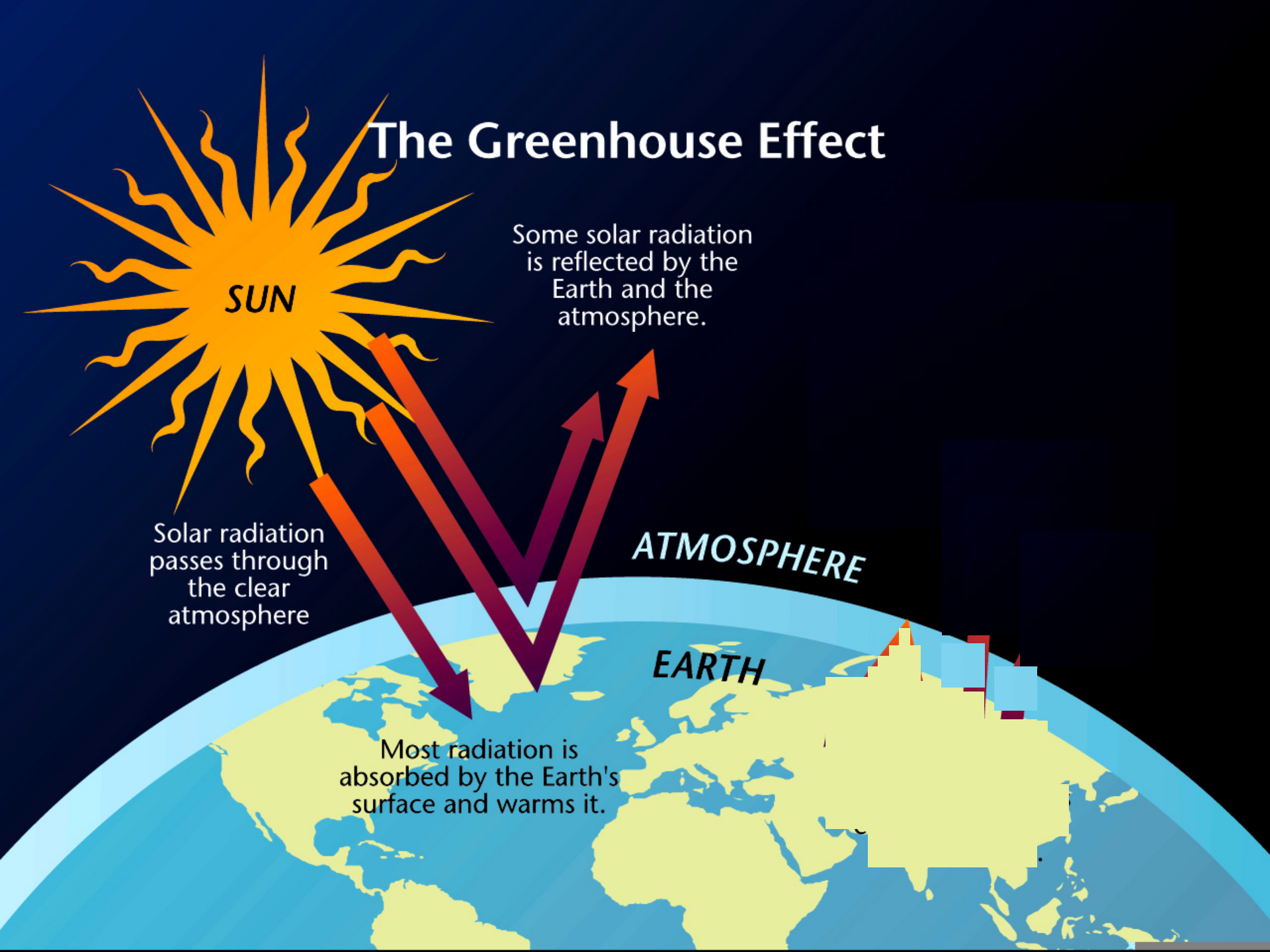
Performed numerical calculations that suggested that doubling the amount of carbon dioxide in the atmosphere could raise global mean surface temperatures by 5-6°C.



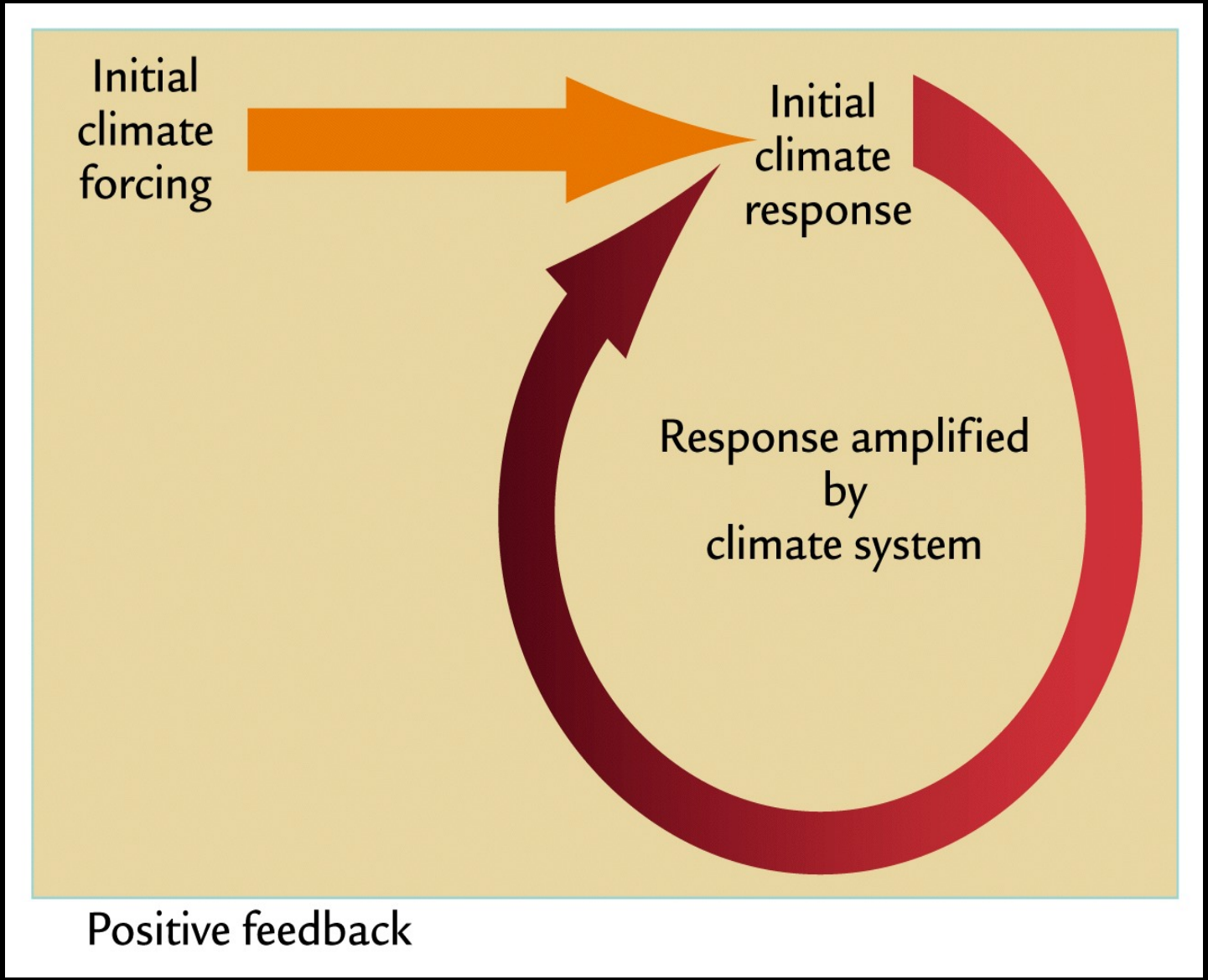
Guy Callendar (1939)

Argued that rising levels of carbon dioxide were responsible for measurable increases in Earth surface temperatures. Estimated that doubling the amount of CO_2 in the atmosphere could raise global mean surface temperatures by 2°C.

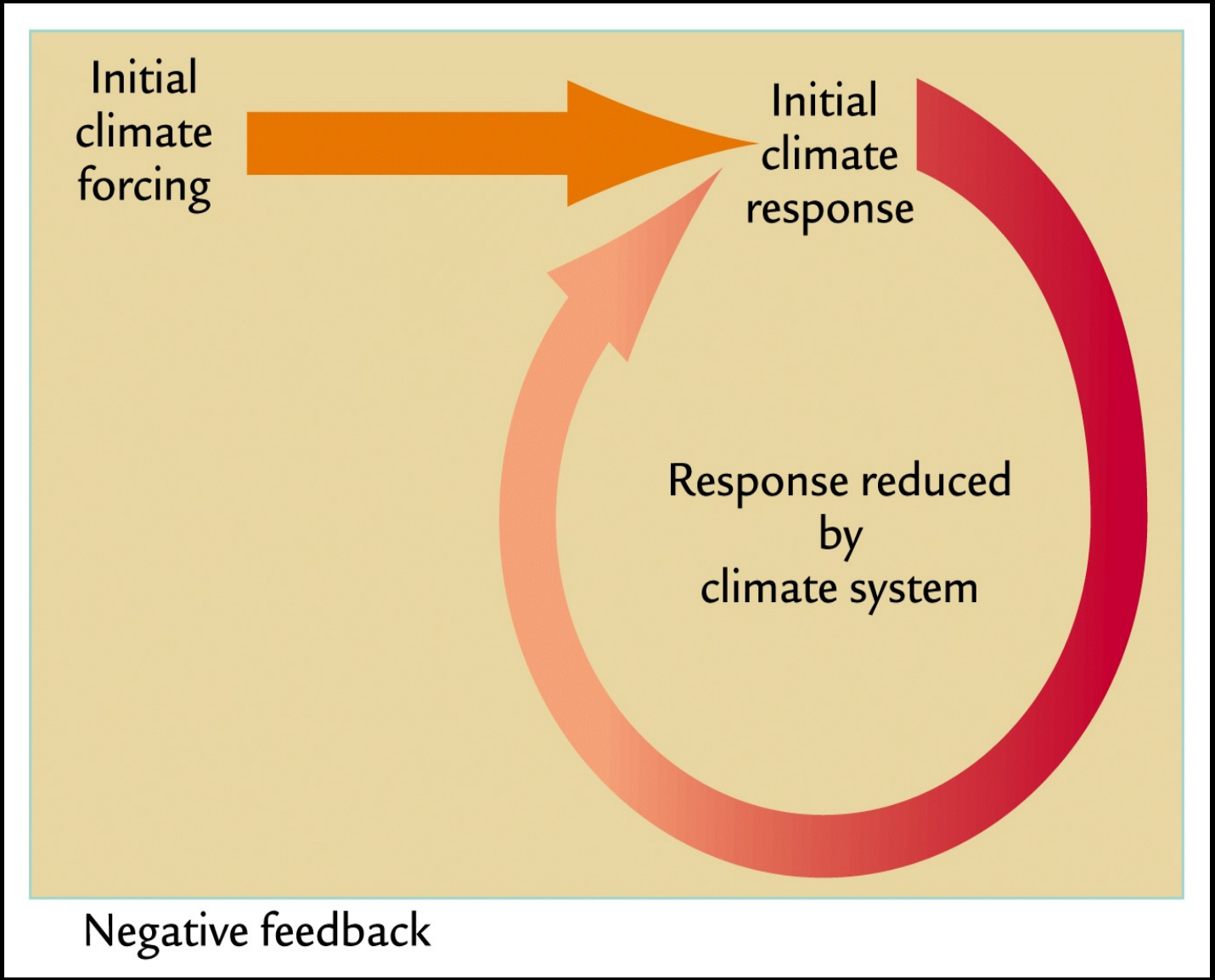
GREENHOUSE EFFECT?

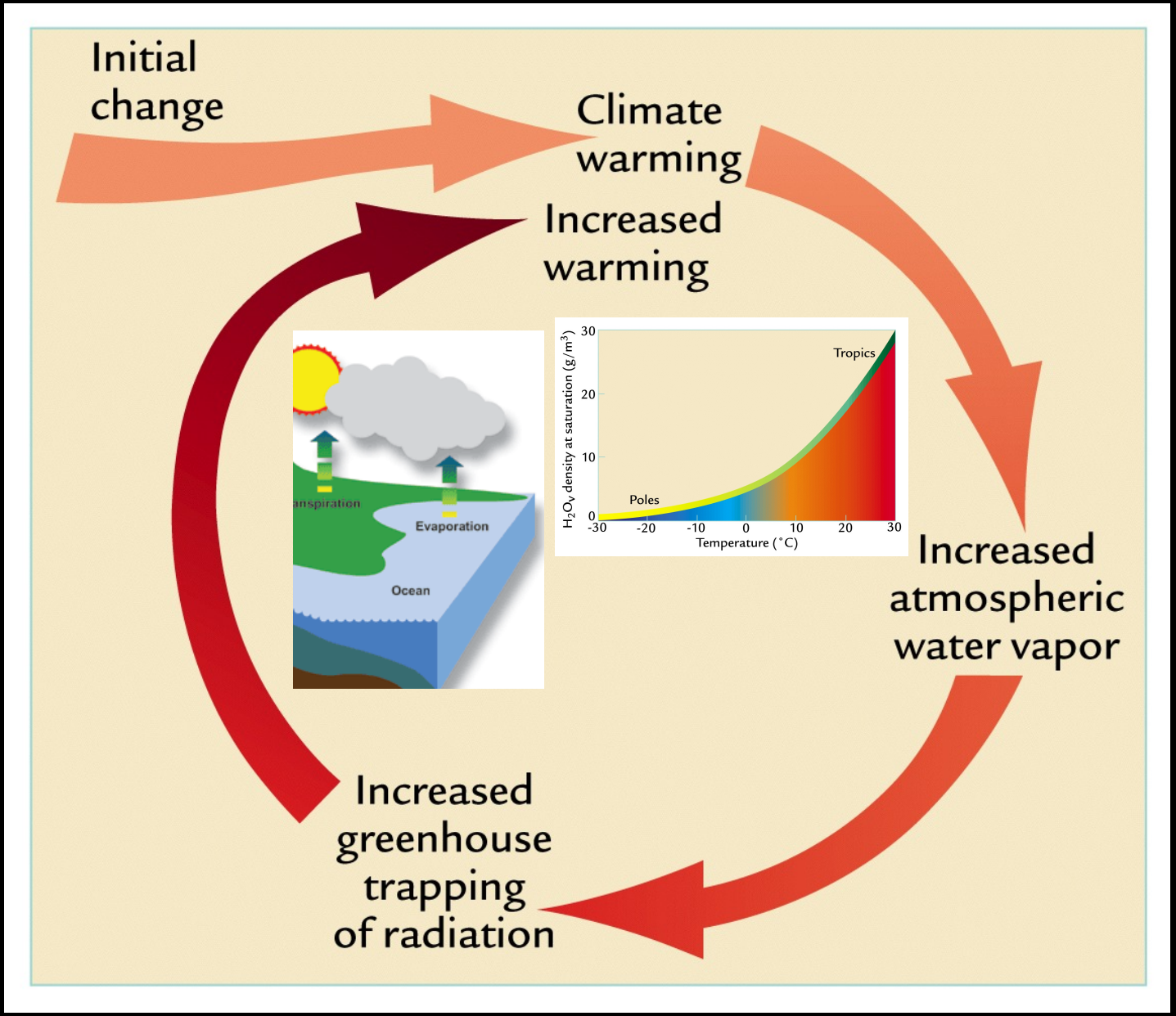

The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Solar radiation passes through the clear atmosphere
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.

Feedbacks

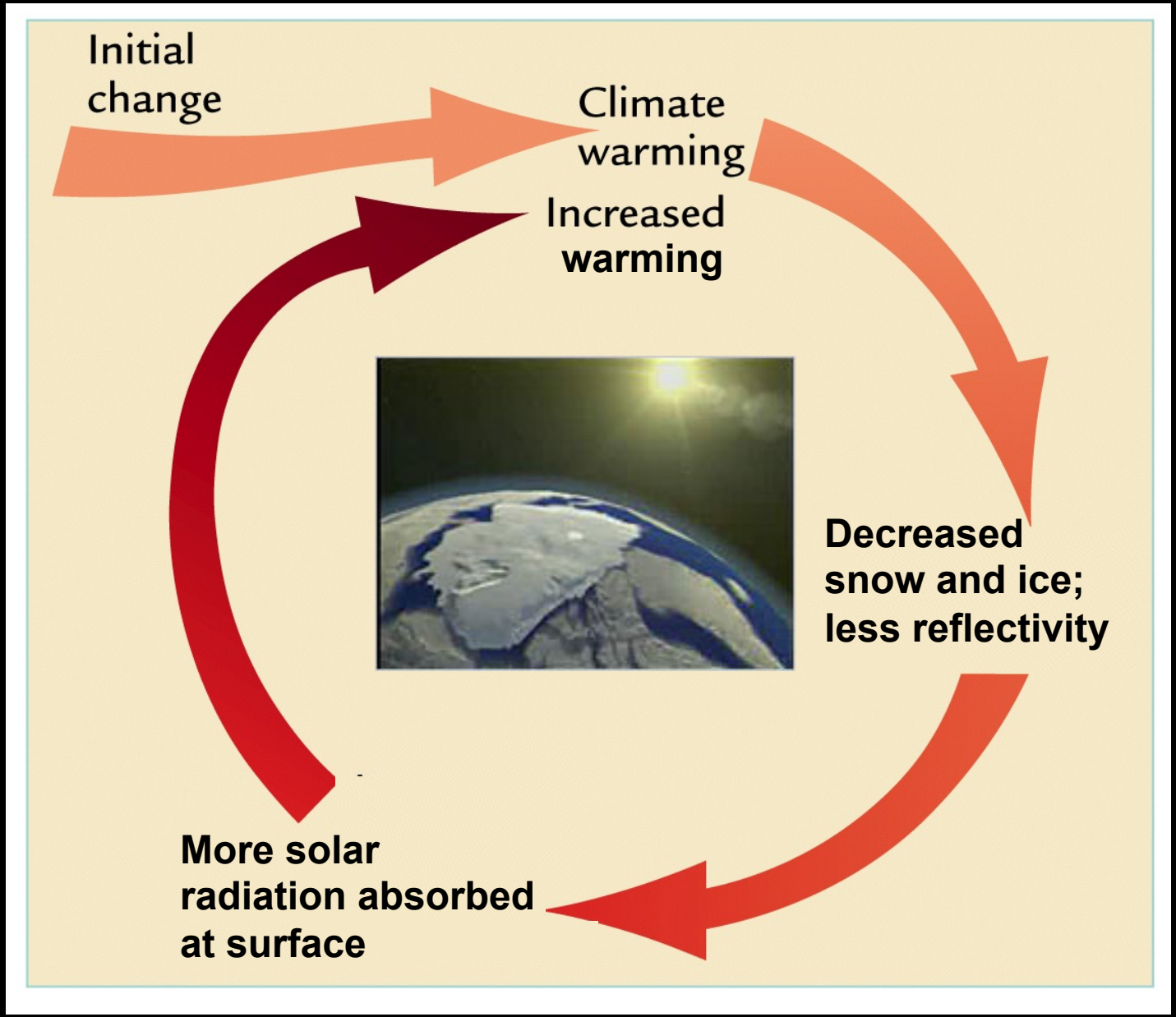

Initial climate forcing
Initial climate response
Response amplified by climate system
Positive feedback

Feedbacks

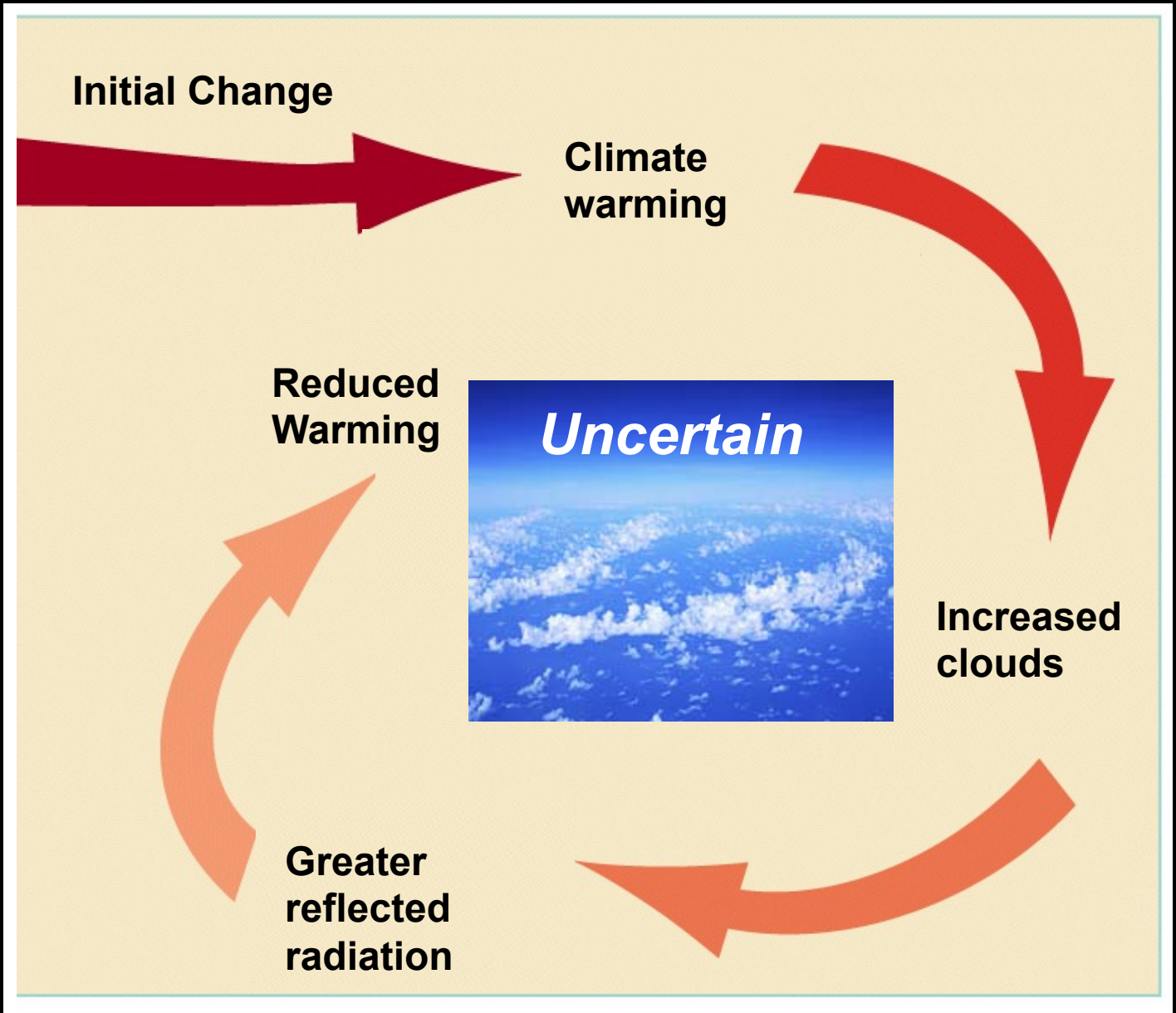

Initial climate forcing
Initial climate response
Response reduced by climate system
Negative feedback



Water Vapor Feedback



Ice-Albedo Feedback



Cloud Radiative Feedbacks

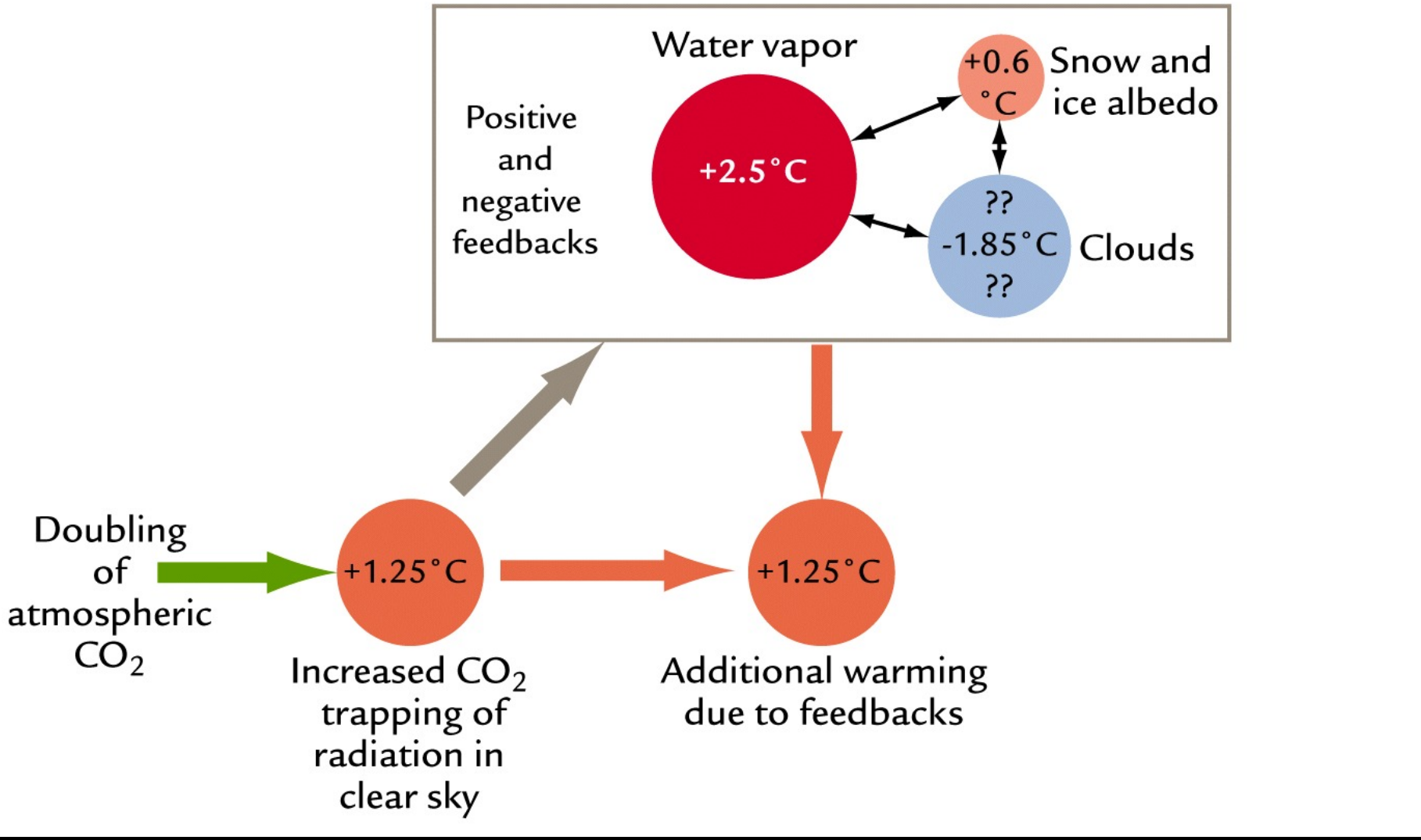
FEEDBACKS INVOLVED IN GLOBAL WARMING

Doubling of atmospheric CO_2 

FEEDBACKS INVOLVED IN GLOBAL WARMING

Doubling of atmospheric CO_2 

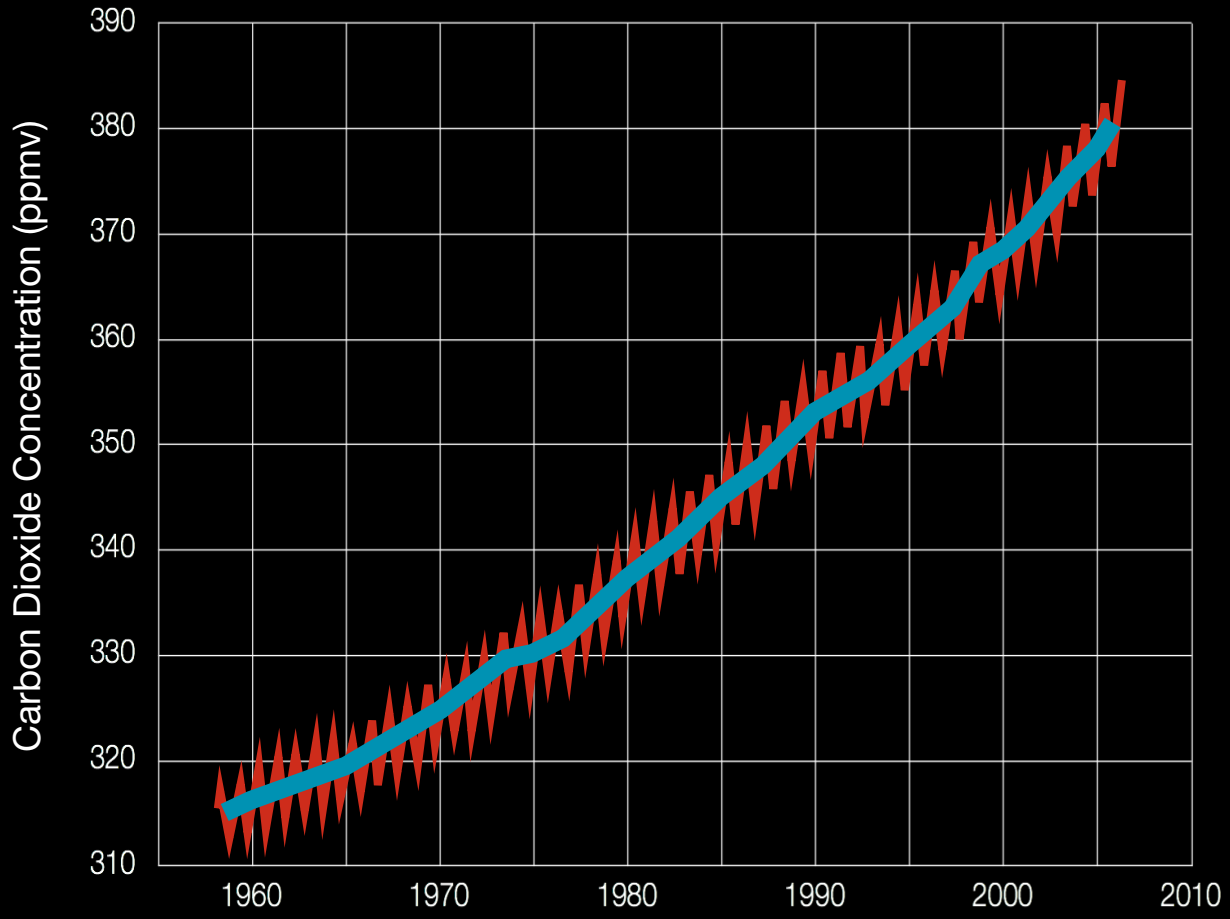
FEEDBACKS INVOLVED IN GLOBAL WARMING



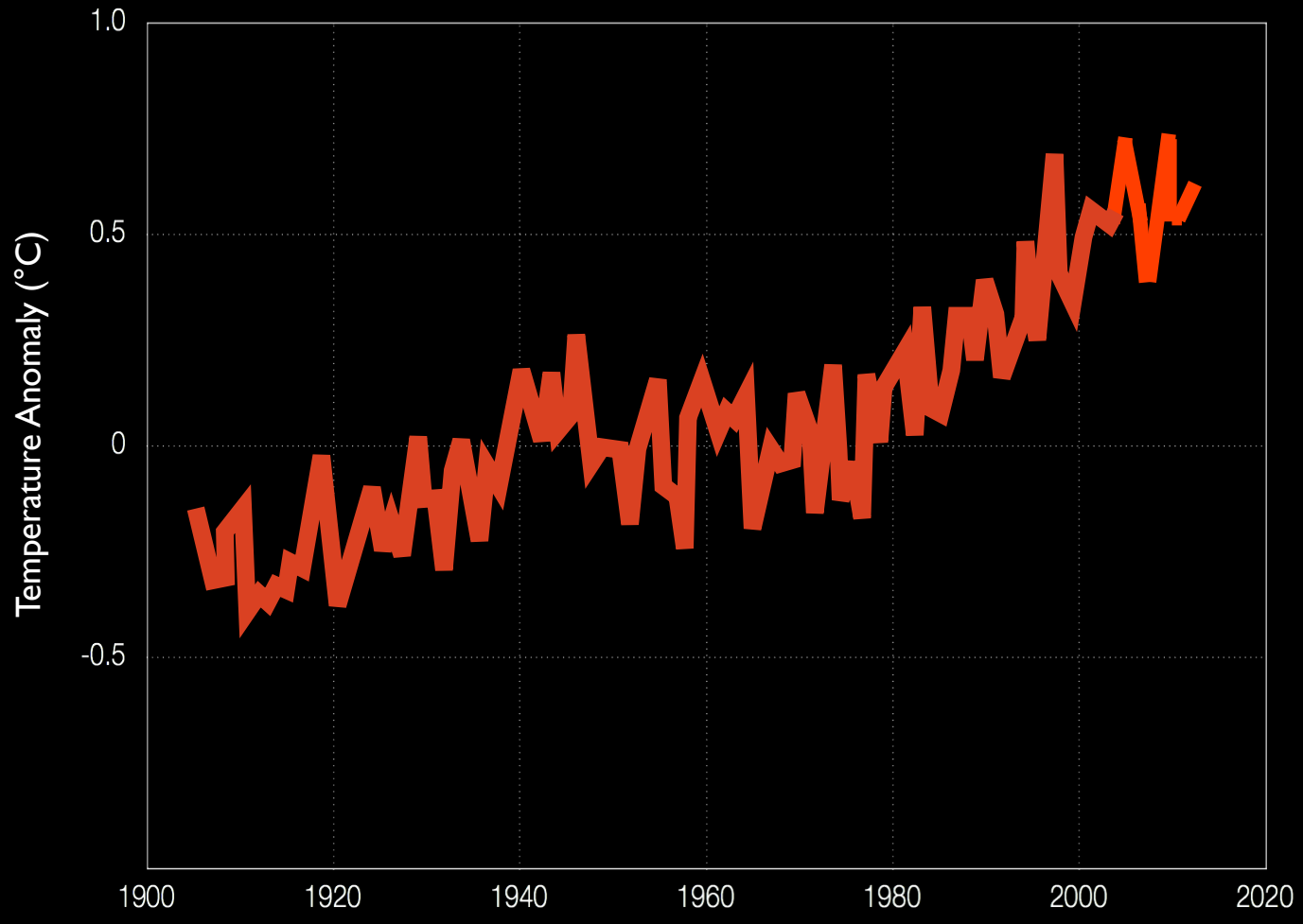
OBSERVATIONS

Atmospheric Carbon Dioxide

Measured at Mauna Loa, Hawaii



Surface Temperature Changes



"All the News That's Fit to Print"

The New York Times

Late Edition

Today, mostly sunny, less windy, seasonably cold, high 27. **Tonight,** cloudy, rising temperatures late, low 26. **Tomorrow,** rain moves in, high 43. Weather map, Page C8.

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, plenty of sunshine, cold, high 35. **Tonight,** clear to partly cloudy, cold, low 23. **Tomorrow,** cloudy much of the time, cold, high 33. Weather map is on Page A24.

VOL. CLXV . . . No. 57,118 NEW YORK, THURSDAY, JANUARY 21, 2016 $2.50

TALIBAN ATTACK PAKISTAN SCHOOL, RENEWING FEARS

AT LEAST 20 ARE KILLED

New Brutality by Group Marginalized After 2014 Massacre

This article is by ***Declan Walsh, Ihsanullah Tipu Mehsud and Ismail Khan.***

CAIRO — Attacks on education have long been a signature atrocity of the Pakistani Taliban, whose militants have set schools on fire, banished girls from classrooms and gunned down students at their desks in a quest to impose an extremist ideology on Pakistani society.

The height of the attacks seemed to come in December 2014 when gunmen swarmed through a school in Peshawar, massacring dozens of schoolchildren in an assault that prompted widespread revulsion and a fierce military crackdown on militants.

But on Wednesday, Pakistanis were drawn back into their national nightmare. At least four Taliban attackers stormed a university campus in another northwestern town, gunning down at least 20 people, most of them students and teachers.

After a year in which the Pakistani Taliban had finally seemed to be pushed to the margin, with

SALWAN GEORGES FOR THE NEW YORK TIMES

Lockers near the swimming pool typify the decay at the Charles L. Spain school in Detroit.

Crises in Two Cities Test Michigan's Governor

Dire Conditions in Public Schools Threaten Detroit's Recovery

As Water Problems Grew, Officials Belittled Complaints From Flint

2015 Far Eclipsed 2014 As World's Hottest Year, Climate Scientists Say

A System 'Warming Up, Relentlessly' — Greenhouse Gases Are Blamed

By JUSTIN GILLIS

Scientists reported Wednesday that 2015 was the hottest year in the historical record by far, breaking a mark set only the year before — a burst of heat that has continued into the new year and is roiling weather patterns all over the world.

In the contiguous United States, the year was the second-warmest on record, punctuated by a December that was both the hottest and the wettest since record-keeping began. One result has been a wave of unusual winter floods coursing down the Mississippi River watershed.

Scientists started predicting a global temperature record months ago, in part because an El Niño weather pattern, one of the largest in a century, is releasing an immense amount of heat from the Pacific Ocean into the atmosphere. But the bulk of the record-setting heat, they say, is a consequence of the long-term planetary warming caused by human emissions of greenhouse gases.

"The whole system is warming up, relentlessly," said Gerald A. Meehl, a scientist at the National Center for Atmospheric Research in Boulder, Colo.

problem seized on that slow period to argue that "global warming stopped in 1998," with these claims and similar statements reappearing recently on the Republican presidential campaign trail.

Statistical analysis suggested all along that the claims were false, and that the slowdown was, at most, a minor blip in an inexorable trend, perhaps caused by a temporary increase in the absorption of heat by the Pacific Ocean.

"Is there any evidence for a pause in the long-term global warming rate?" said Gavin A. Schmidt, head of NASA's climate-science unit, the Goddard Institute for Space Studies, in Manhattan. "The answer is no. That was true before last year, but it's much more obvious now."

Michael E. Mann, a climate scientist at Pennsylvania State University, calculated that if the global climate were not warming, the odds of setting two back-to-

Continued on Page A8

Global Surface Air Temperatures

Compared with the average from 1901 to 2000

°F +1

2020

el States last year. Records were set across large areas of every inhabited continent. And the ocean surface was unusually warm virtually everywhere except near Antarctica, the scientists said, providing the energy that fueled

one of the agencies that track global temperatures.

Of the large land areas where many people live, only the eastern portion of the United States recorded below-average temperatures in 2014, in sharp con-

lease of greenhouse gases, though that is not proven.

Several scientists said the most remarkable thing about the 2014 record was that it had occurred in a year that did not feature a strong El Niño, a large-

now being surpassed every four or five years, and 2014 was the first time that happened without a significant El Niño. Gavin A. Schmidt, head of NASA's Goddard Institute for Space Studies

Continued on Page A6

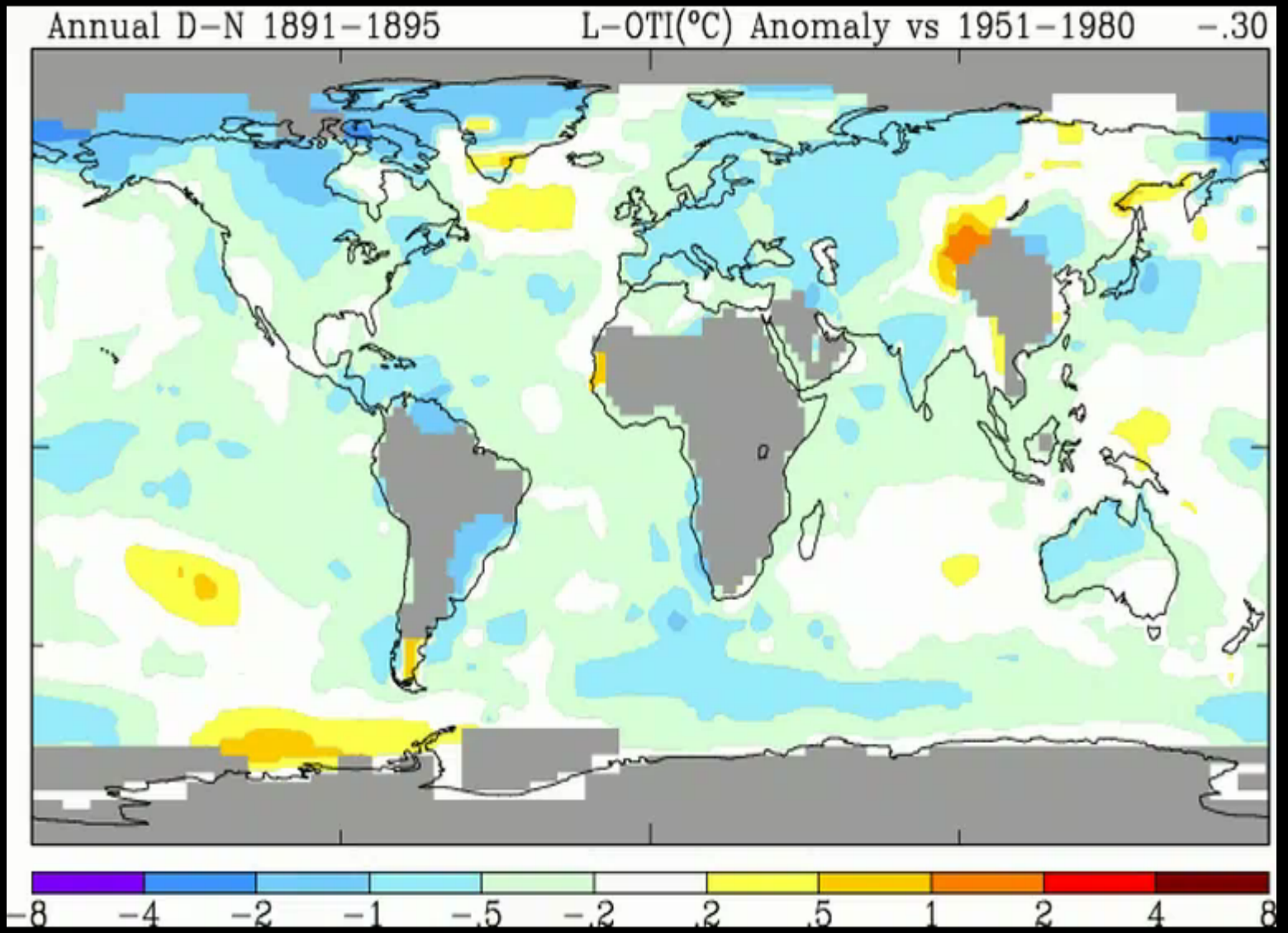
Gay rights advocates hailed the court's move on Friday as one of the final steps in a decades-long journey toward equal treatment, and they expressed confidence they would prevail.

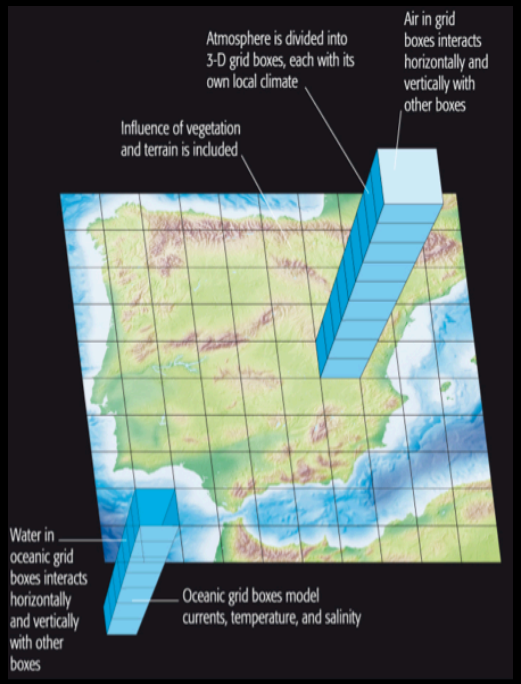
"We are finally within sight of

JABIN BOTSFORD/THE NEW YORK TIMES

A flag backing same-sex marriage, at the Supreme Court.

Surface Temperature Changes





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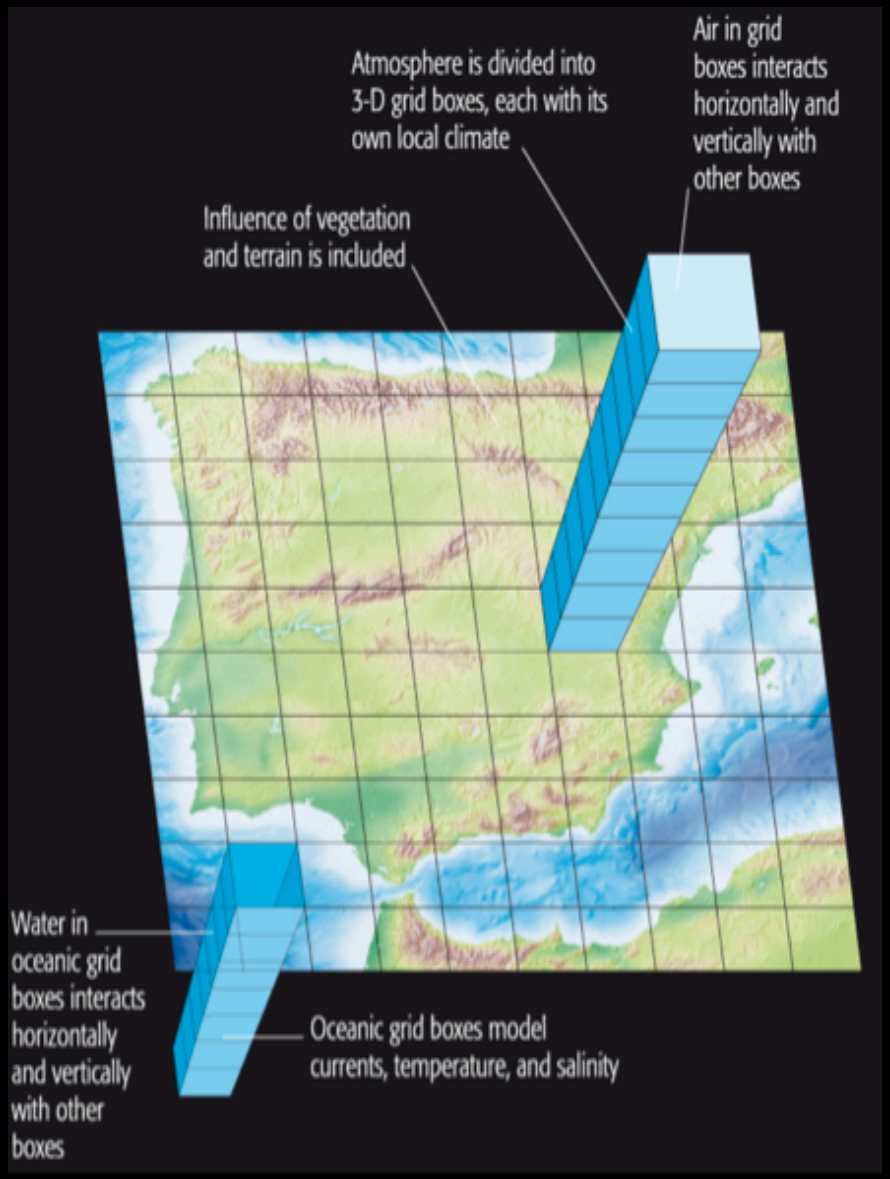
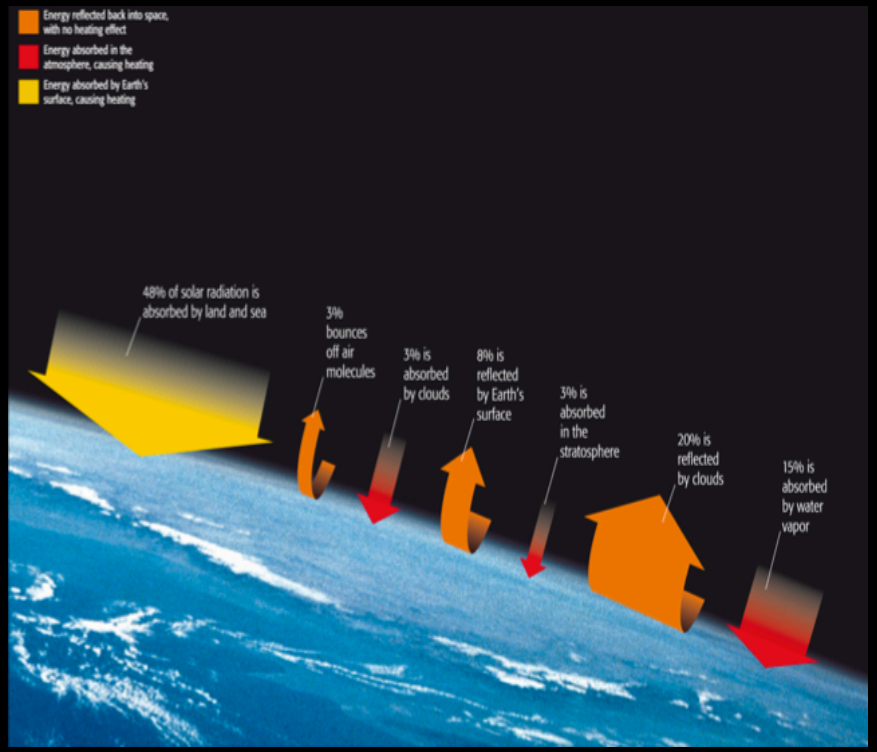
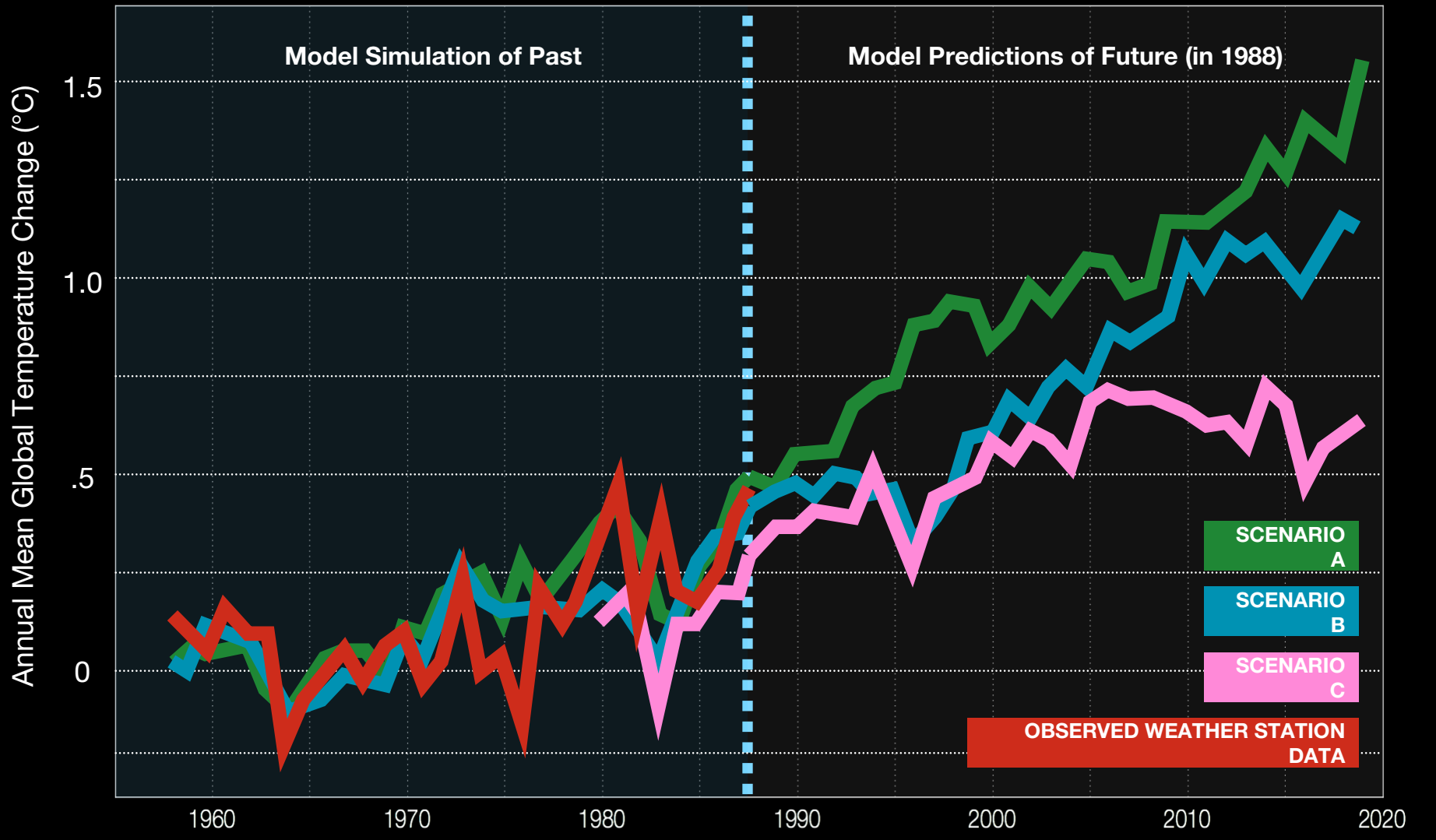
Climate Models






RESTAURANT

Hansen's 1988 Predictions



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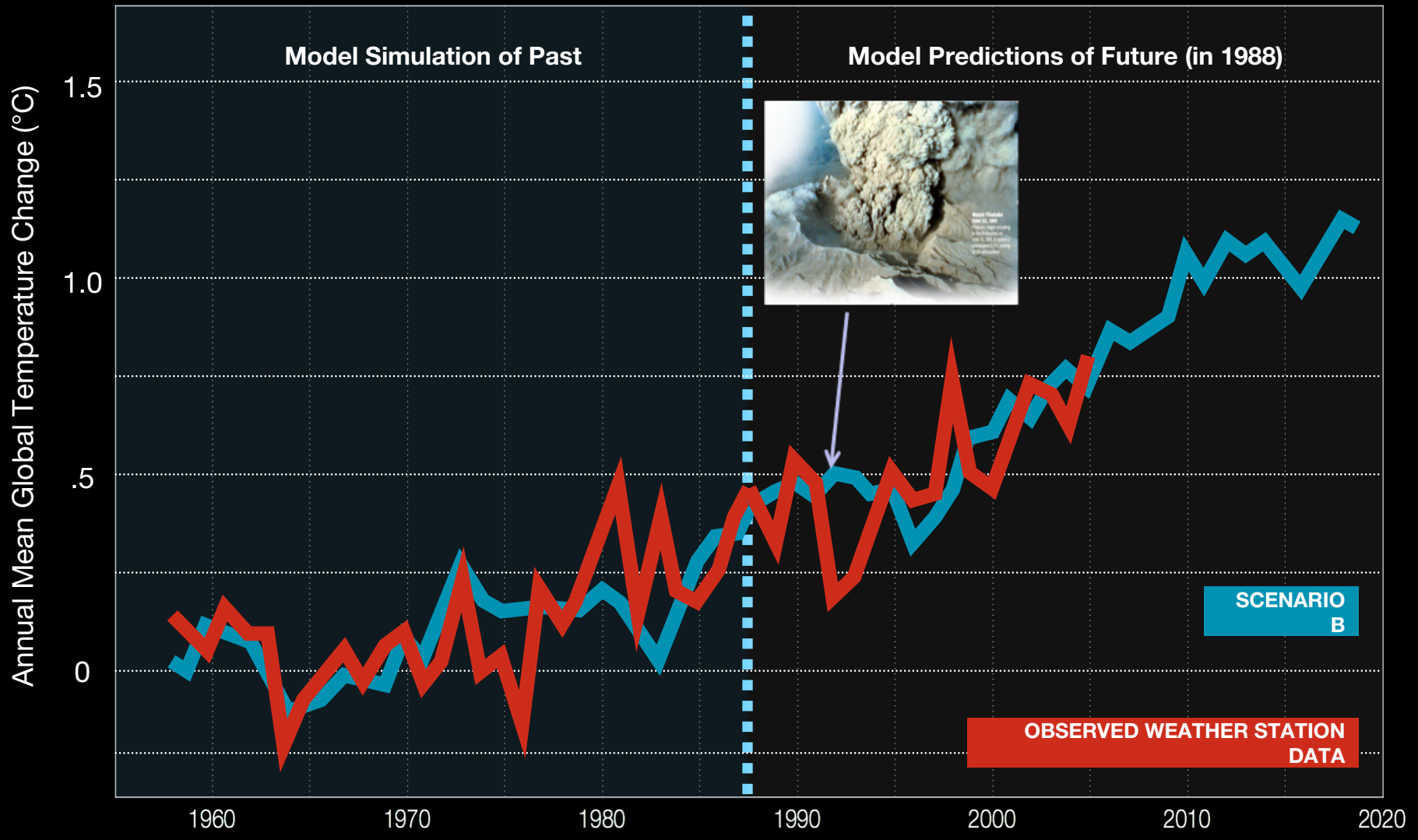
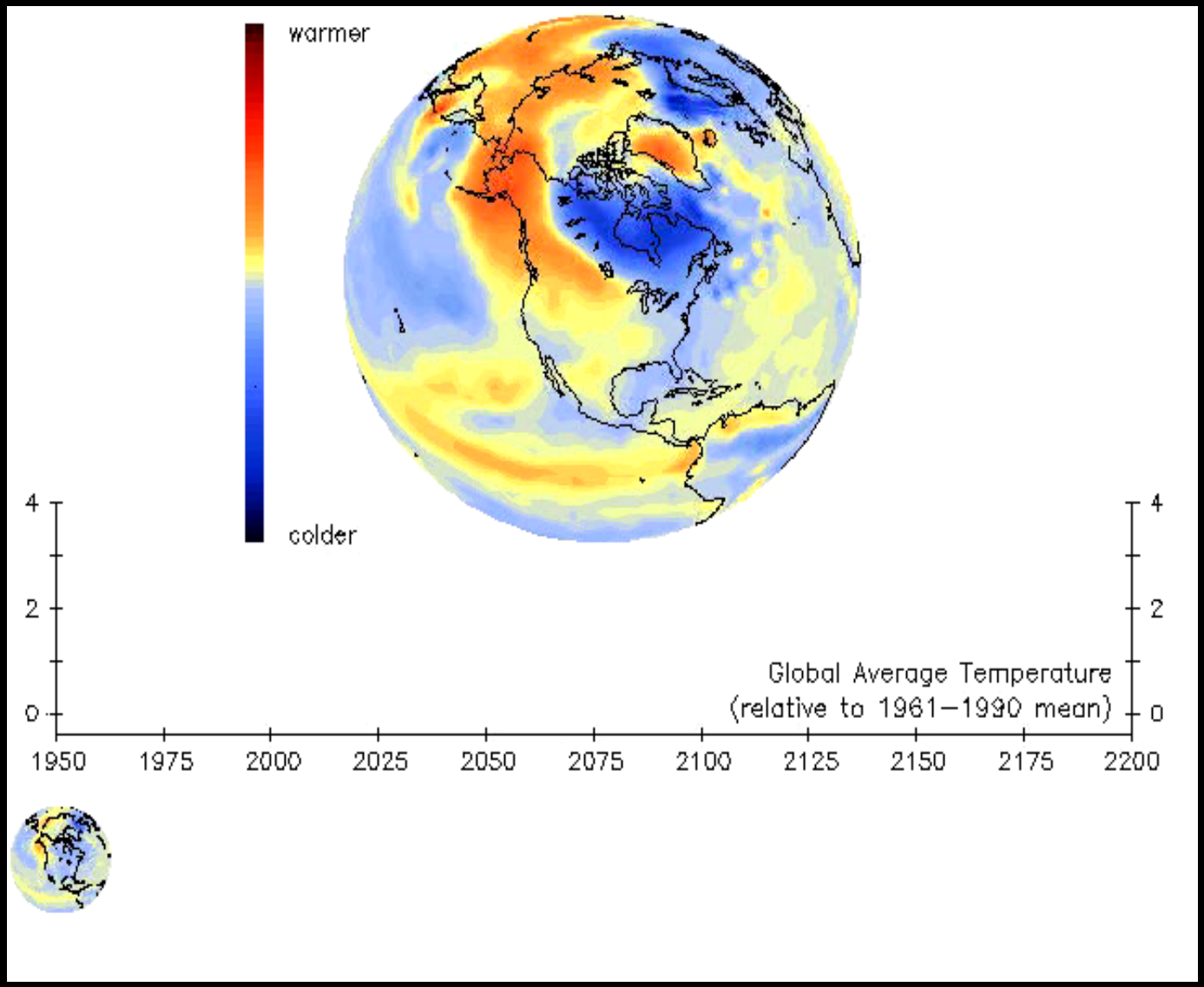
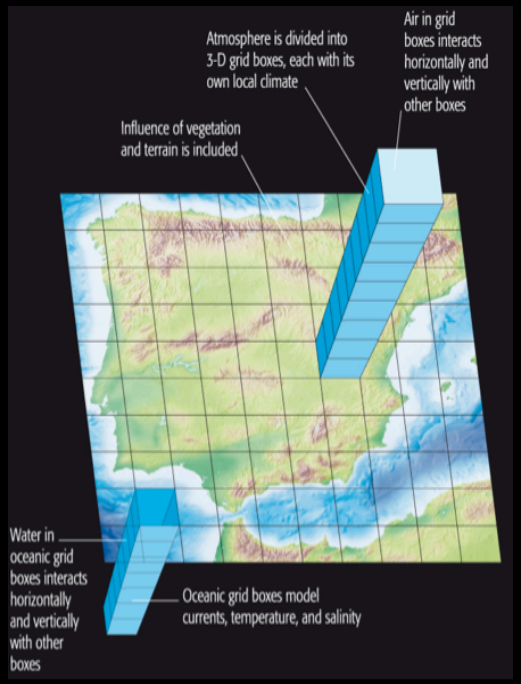


Projected Future Warming





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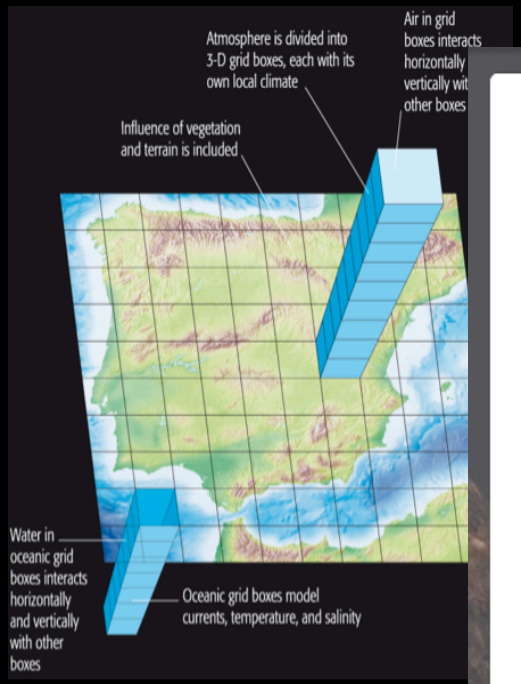

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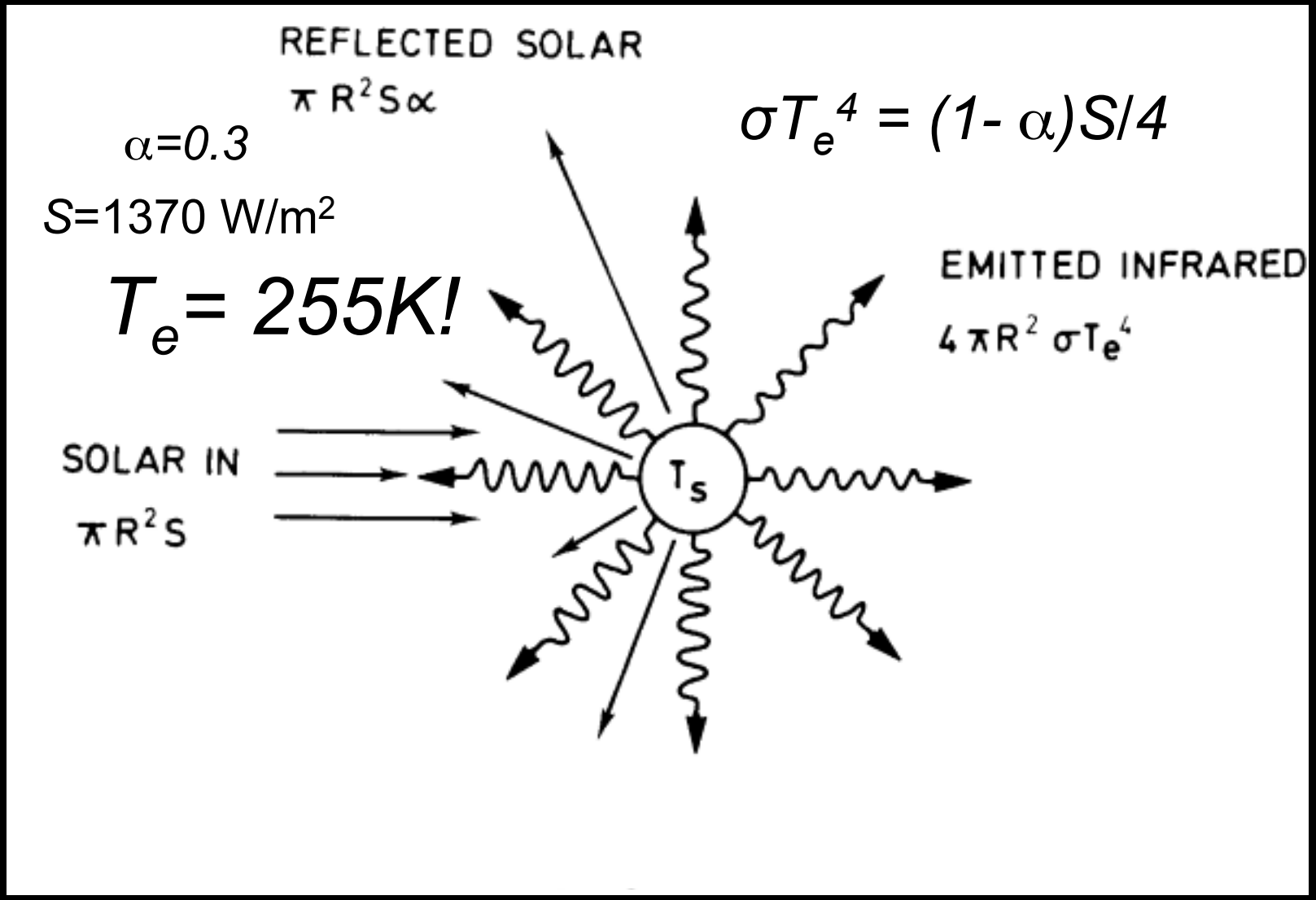
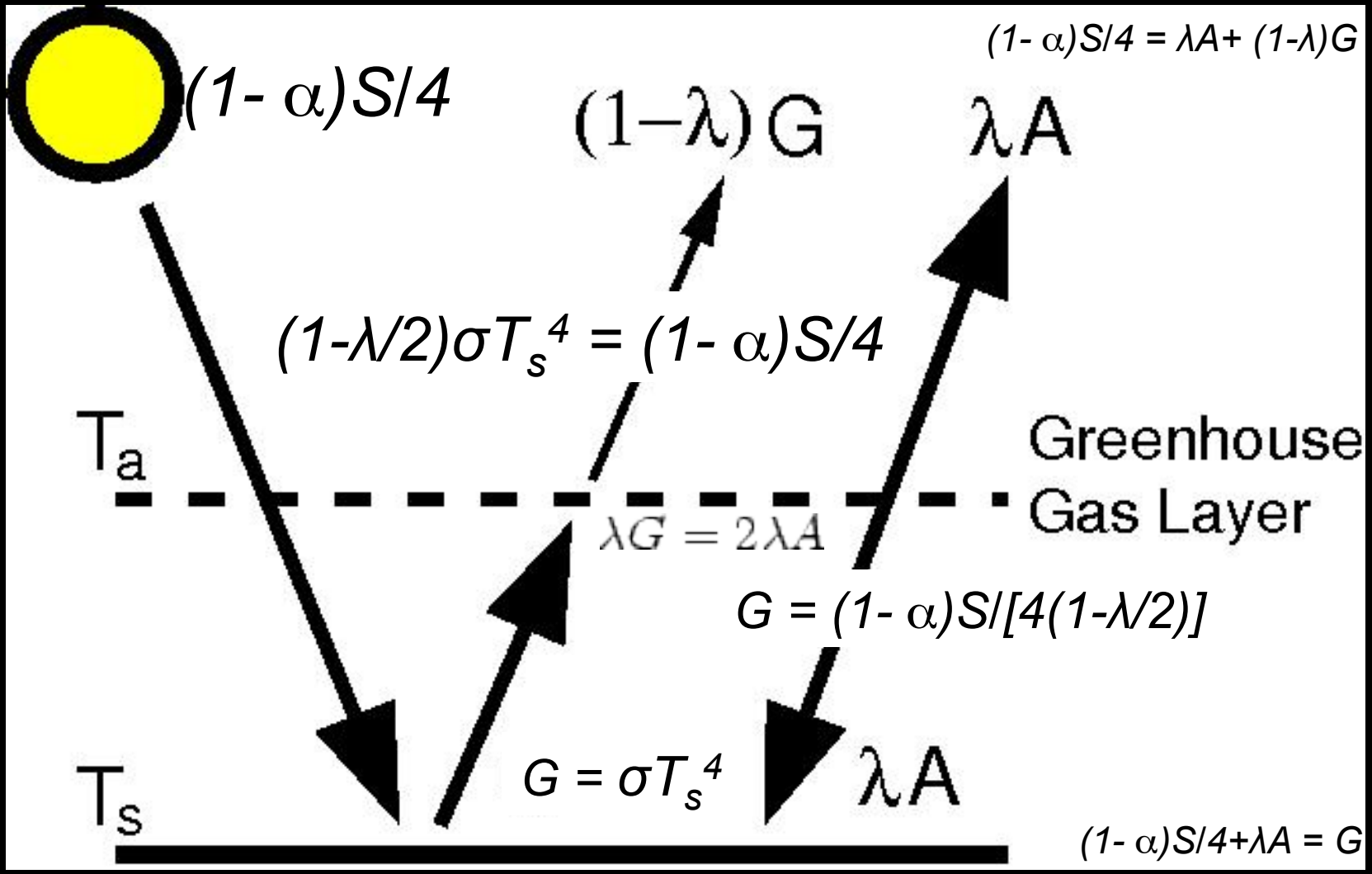
ZERO-DIMENSIONAL EBM



***A Climate Modeling Primer*, A. Henderson-Sellers and K. McGuffie, Wiley (1987).**

ZERO-DIMENSIONAL EBM



http://www.realclimate.org/index.php/archives/2007/04/learning-from-a-simple-model/

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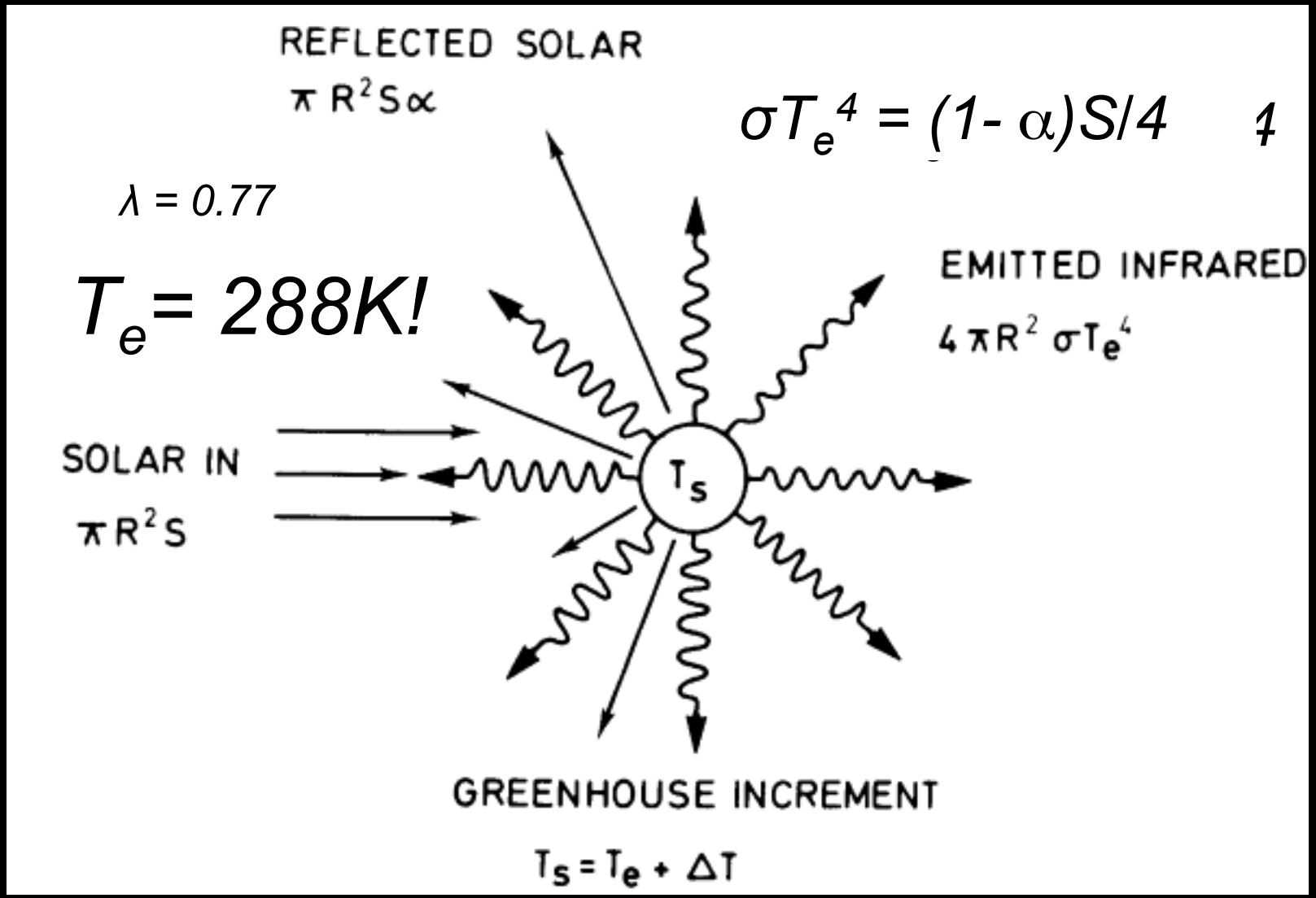

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ZERO-DIMENSIONAL EBM

(Equilibrium) $(1-\lambda/2)\sigma T_s^4 = (1-\alpha)S/4$

What about *non-equilibrium*?

$$C dT_s/dt = (1-\alpha)S/4 - (1-\lambda/2)\sigma T_s^4$$

Account for stochastic weather forcing,

$$C dT_s/dt = (1-\alpha)S/4 - (1-\lambda/2)\sigma T_s^4 + w(t)$$

linearize the quartic term, $\sigma T_s^4 = a+bT$

$$C dT/dt = F - BT + w(t)$$

$$F \equiv (1-\alpha)S/4 - a(1-\lambda/2)$$

$$B \equiv (1-\lambda/2)b$$

ZERO-DIMENSIONAL EBM

Take:

C=2.08 x 10^8 J $K^{-1}m^{-2}$ (effective heat capacity associated with 70 m depth mixed-layer ocean covering 70% of Earth surface.

In equilibrium, we have: $\Delta F = B\Delta T$

$$\Delta T/\Delta F = 1/B$$

$$\Delta F_{2xCO2}=3.74\ Wm^{-2}$$

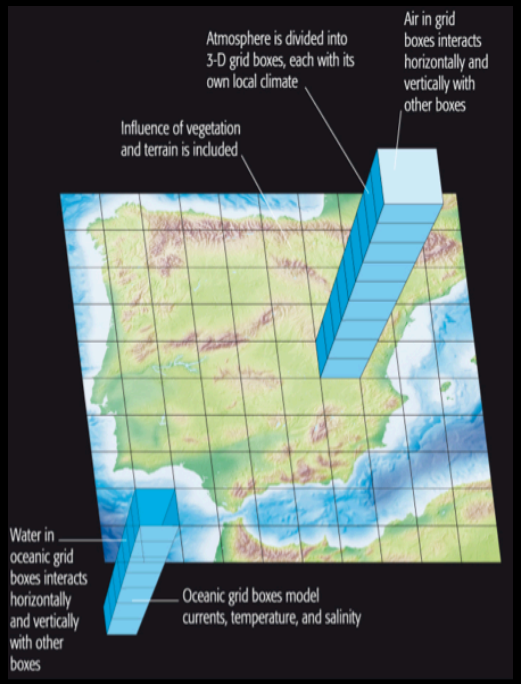
Equilibrium climate sensitivity (ECS) ΔT_{2xCO2}

For B=1.25 $Wm^{-2}K^{-1}$, $\Delta T_{2xCO2}=3.0^oC$

$$CdT/dt = F - BT + w(t)$$

$$F \equiv (1-\alpha)S/4 - a(1-\lambda/2)$$

$$B \equiv (1-\lambda/2)b$$



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CLIMATE CHANGE

False Hope

The rate of global temperature rise may have hit a plateau, but a climate still looms in the near future

By Michael E. Mann

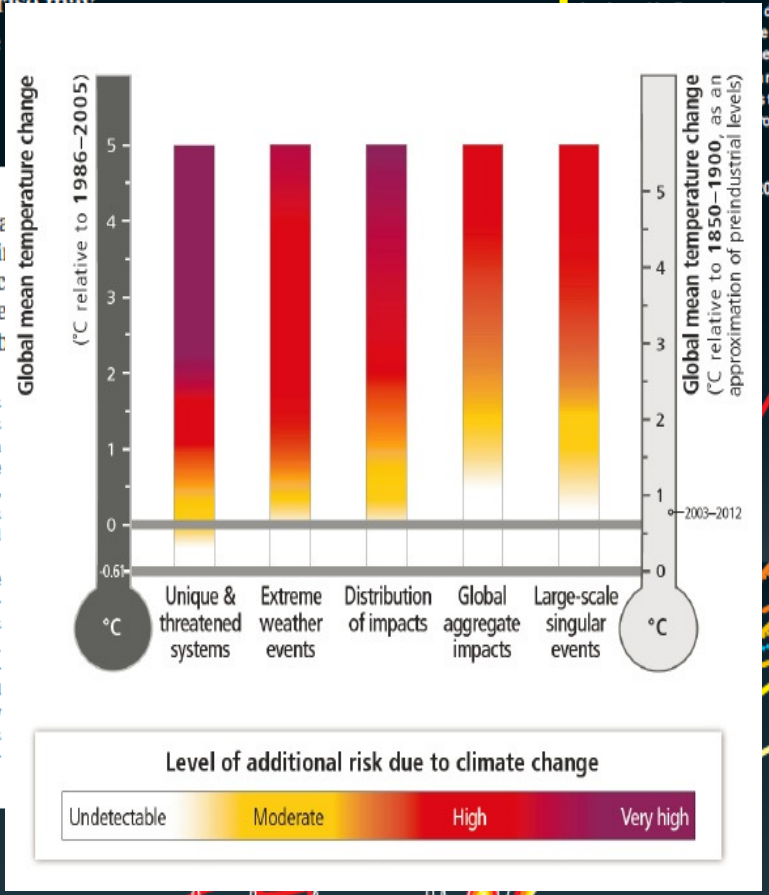
"Temperatures have been flat for 15 yea
Wall Street Journal says. "Global warmi
Arctic sea ice has already started to rec
ing claims about climate abound in the
at best. Global warming continues unab

The misunderstanding stems from data showing that during the past decade there was a slowing in the rate at which the earth's average surface temperature had been increasing. The event is commonly referred to as "the pause," but that is a misnomer: temperatures still rose, just not as fast as during the prior decade. The important question is, What does the short-term slowdown portend for how the world may warm in the future?

The Intergovernmental Panel on Climate Change (IPCC) is charged with answering such questions. In response to the data, the IPCC in its September 2013 report lowered one aspect of its prediction for future warming. Its forecasts, released every five to seven years, drive climate policy worldwide, so even the small change raised debate over how fast the planet is warming and how much time we have to stop it. The IPCC has not yet weighed in on the impacts of the warming or how to mit-

Danger Zone in 22 Years

If the Northern Hemisphere's surface temperatures rise more than two degrees Celsius above preindustrial levels (*baseline*), human civilization will suffer dangerous harm, scientists say. When will that occur if the world keeps burning fossil fuels at current rates? The answer comes from entering estimates for equilibrium climate sensitivity (ECS)—how sensitive the atmosphere is to the heating effect of greenhouse gases (*five solid curves*)—into a so-called energy balance model of climate. The estimate that best agrees with recorded data reflecting the sensitivity of the earth's climate (*white*) indicates
degrees C threshold in 2036, only
e reported recent slowdown in
etimes inappropriately called
more persistent pattern, then
the past 15 years or so, and
oss the danger line.



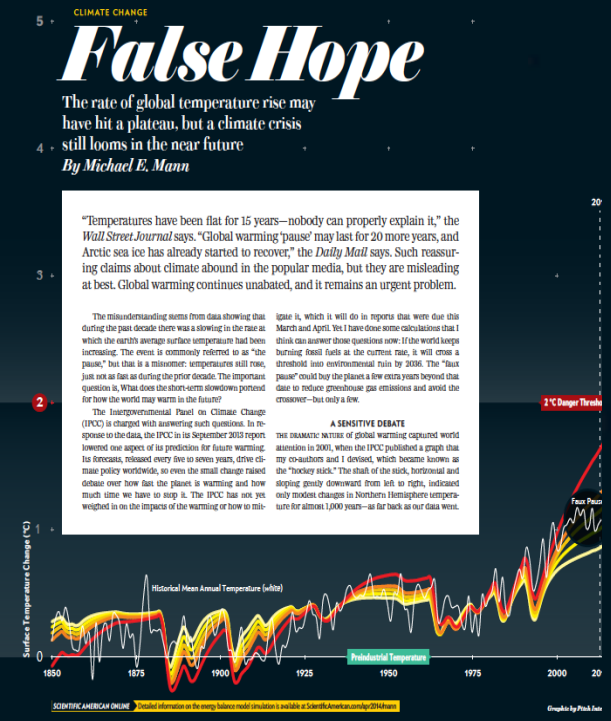
Where to Hold the Line

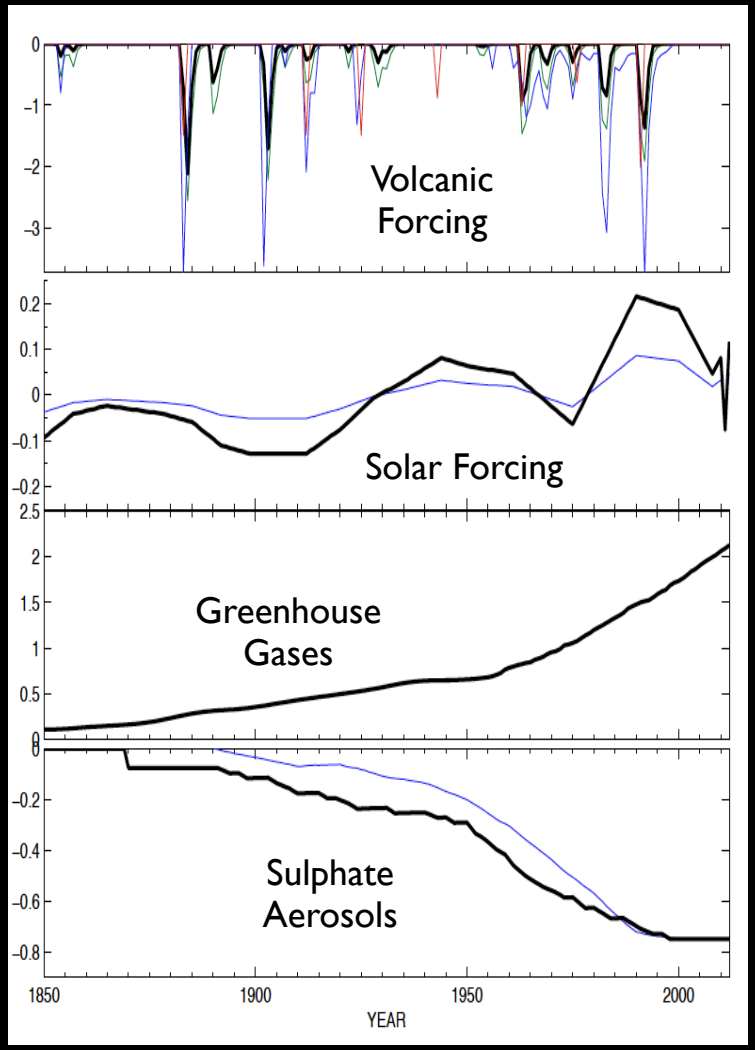
Scientists and policy makers commonly say that the world has to keep atmospheric CO_2 levels below 450 ppm to avoid two degrees C of warming (the level briefly hit 400 ppm in 2013). Yet if the atmosphere's climate sensitivity is three degrees C (*orange*), warming can be limited to that amount only if we keep emitting polluting aerosols (particles in the atmosphere that partly block the sun's heat) at current rates (*dashed orange*). Ironically, the reduction in coal burning needed to lower CO_2 emissions also lessens aerosols, sending temperatures across the danger line (*dotted orange*). The same is true if the sensitivity is 2.5 degrees C (*gold*). These data therefore indicate that to reliably avoid two degrees C of warming, CO_2 levels should be held to 405 ppm (*blue*)—barely above the 393 to 400 ppm levels observed in the past year.

SOURCE: MICHAEL E. MANN

SCIENTIFIC AMERICAN ONLINE Detailed information on the energy balance model simulation is available at ScientificAmerican.com/apr2014/mann

Graphic by Pitch Interactive

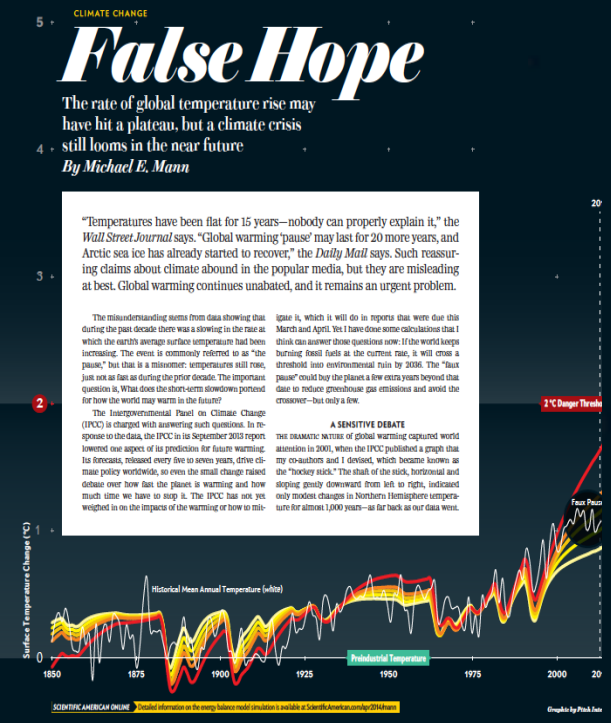




$$CdT/dt = F - BT$$

$$F \equiv (1-\alpha)S/4 - a(1-\lambda/2)$$

$$B \equiv (1-\lambda/2)b$$



CLIMATE CHANGE

False Hope

The rate of global temperature rise may have hit a plateau, but a climate crisis still looms in the near future

By Michael E. Mann

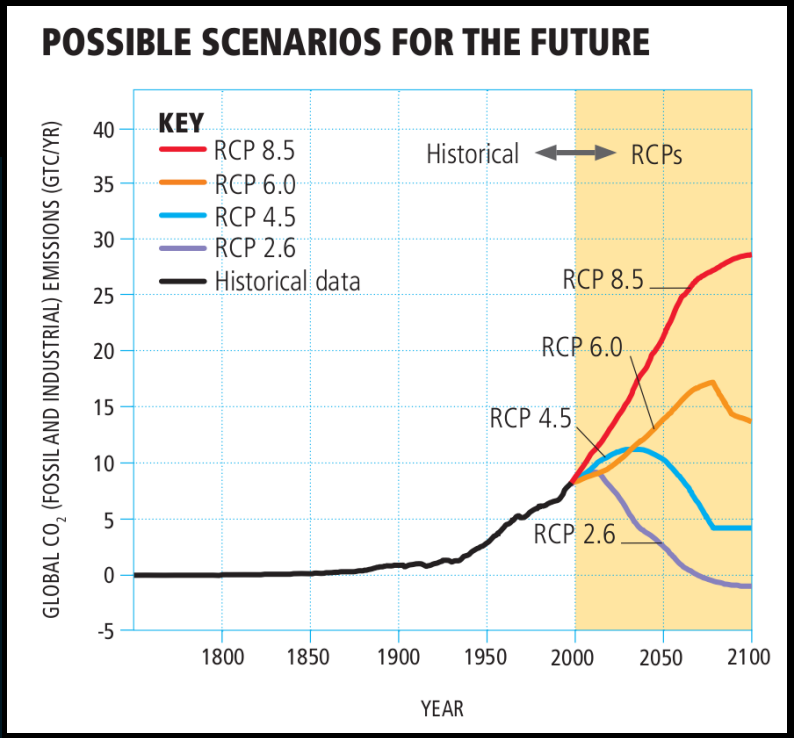
"Temperatures have been flat for 15 years—nobody can properly explain it," the *Wall Street Journal* says. "Global warming 'pause' may last for 20 more years, and Arctic sea ice has already started to recover," the *Daily Mail* says. Such reassuring claims about climate abound in the popular media, but they are misleading at best. Global warming continues unabated, and it remains an urgent problem.

The misunderstanding stems from data showing that during the past decade there was a slowing in the rate at which the earth's average surface temperature had been increasing. The event is commonly referred to as "the pause," but that is a misnomer: temperatures still rose, just not as fast as during the prior decade. The important question is, What does the short-term slowdown portend for how the world may warm in the future?

The Intergovernmental Panel on Climate Change (IPCC) is charged with answering such questions. In response to the data, the IPCC in its September 2013 report lowered one aspect of its prediction for future warming. Its forecasts, released every five to seven years, drive climate policy worldwide, so even the small change raised debate over how fast the planet is warming and how much time we have to stop it. The IPCC has not yet weighed in on the impacts of the warming or how to mitigate it, which it will do in reports that were due this March and April. Yet I have done some calculations that I think can answer those questions now. If the world keeps burning fossil fuels at the current rate, it will cross a threshold into environmental ruin by 2036. The "faux pause" could buy the planet a few extra years beyond that date to reduce greenhouse gas emissions and avoid the crossover—but only a few.

A SENSITIVE DEBATE

THE DRAMATIC NATURE of global warming captured world attention in 2001, when the IPCC published a graph that my co-authors and I devised, which became known as the "hockey stick." The shaft of the stick, horizontal and sloping gently downward from left to right, indicated only modest changes in Northern Hemisphere temperature for almost 1,000 years—as far back as our data went.



$$CdT/dt = F - BT$$

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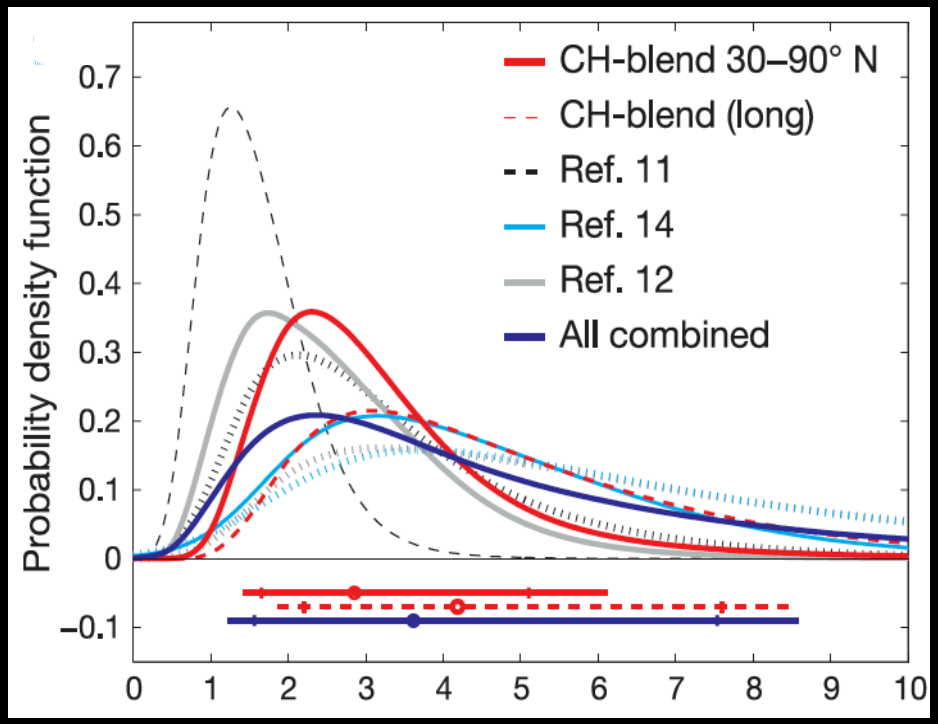
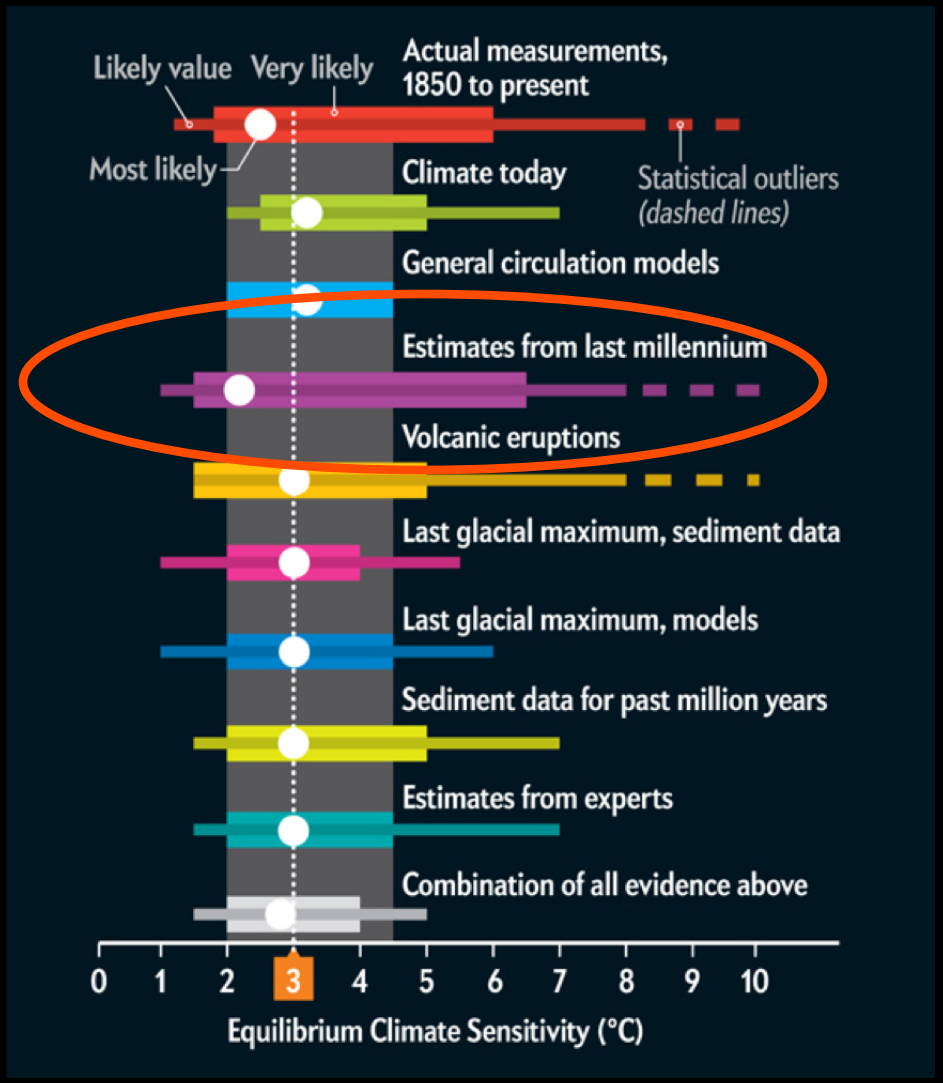
$$B \equiv (1-\lambda/2)b$$

Refining ECS estimates with paleodata



Hegerl G.C. *et al*, Climate sensitivity constrained by temperature reconstructions over the past seven centuries. *Nature* 440, 1029–1032 (2006).



Climate Sensitivity underestimated?

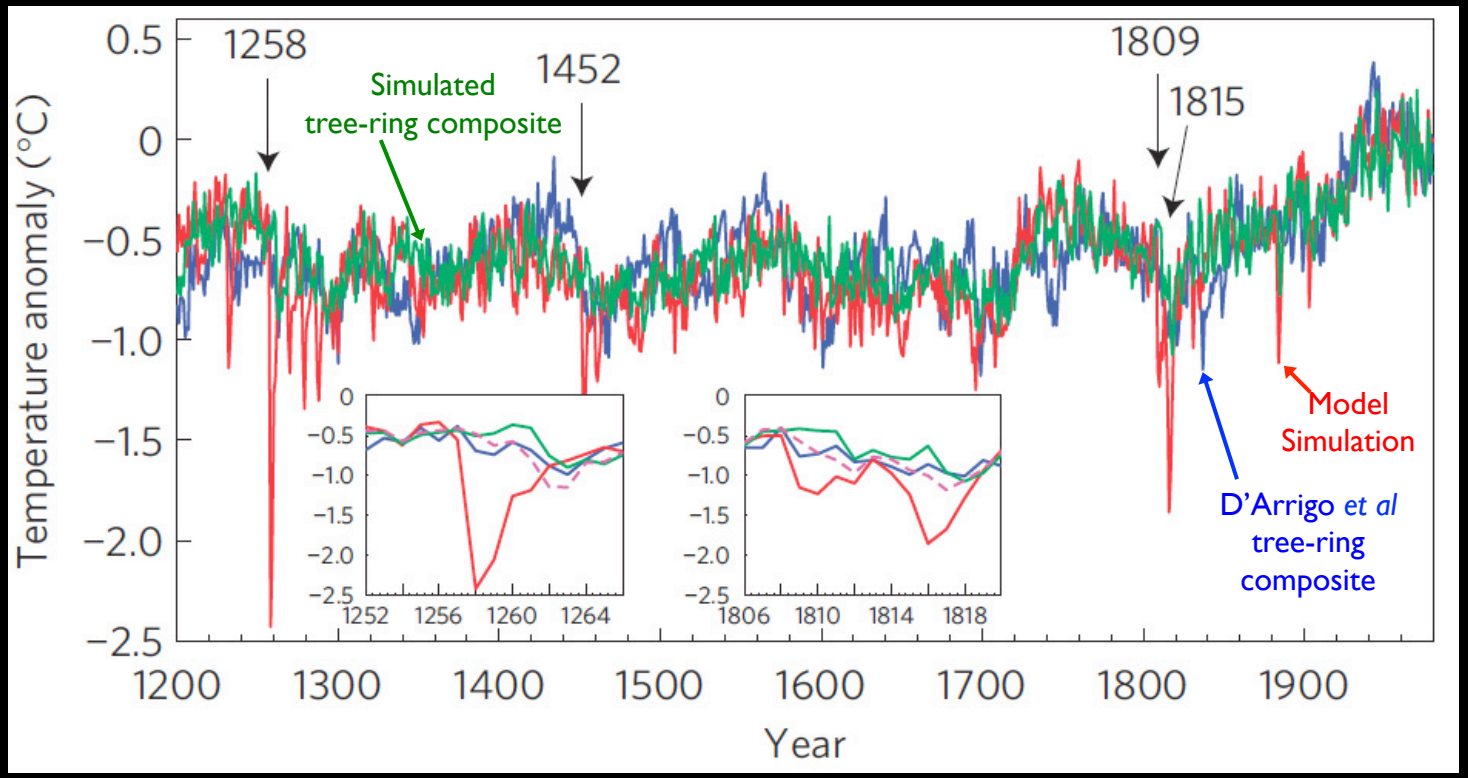
Refining ECS estimates with paleodata

LETTERS
PUBLISHED ONLINE: 5 FEBRUARY 2012 | DOI: 10.1038/NGEO1394
nature geoscience

Underestimation of volcanic cooling in tree-ring-based reconstructions of hemispheric temperatures

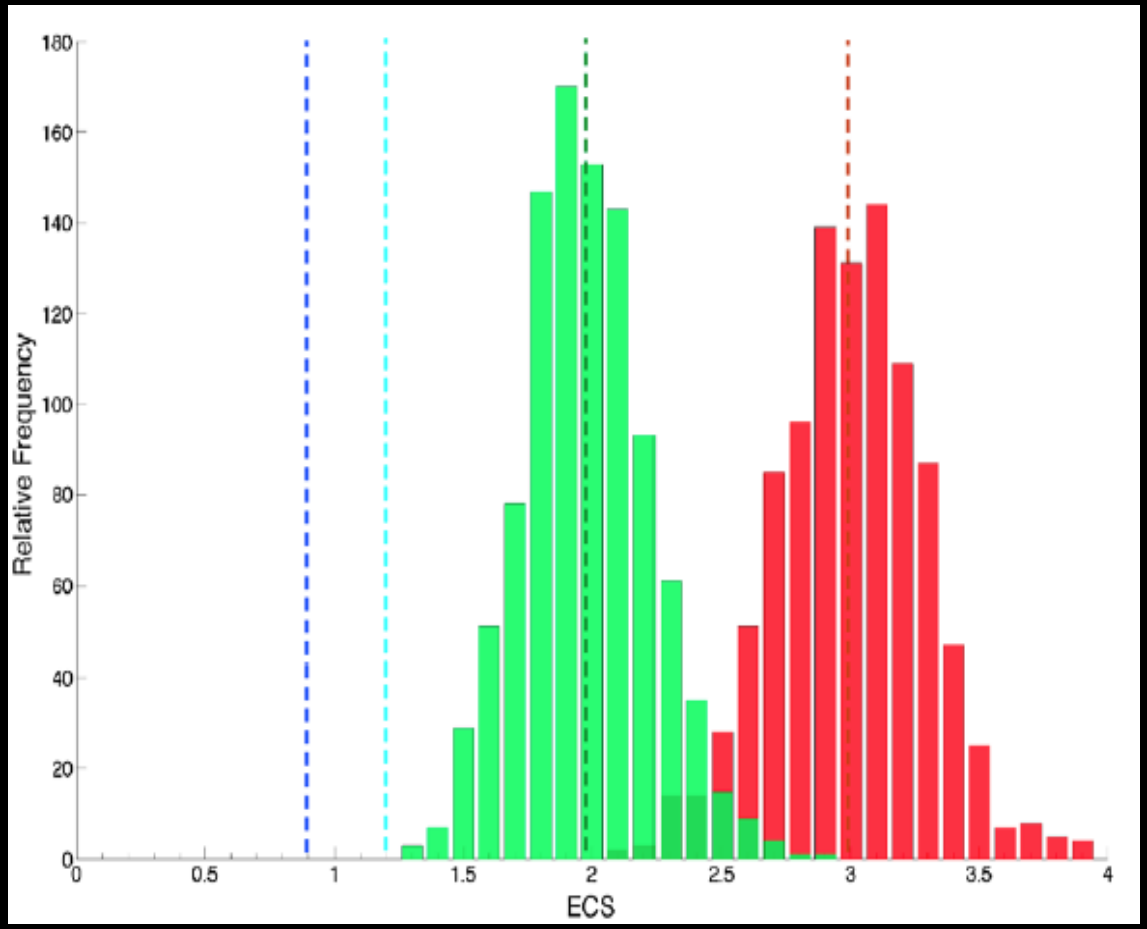
Michael E. Mann[1]*, Jose D. Fuentes[1] and Scott Rutherford[2]

Climate Sensitivity underestimated?



D'Arrigo et al tree-ring based NH reconstruction (blue) along with the climate model (NCAR CSM 1.4) simulated NH mean temperatures (red) and the "simulated tree-ring" NH temperature series based on driving the biological growth model with the climate model simulated temperatures (green). The two insets focus on the response to the AD 1258 and AD 1809+1815 volcanic eruption sequences.

Refining ECS estimates with paleodata



PDF of ECS using decadally smoothed data between) AD 1300–1849 (red = simulated actual temperature series; green = synthetic tree ring temperature series). Shown by dashed vertical lines are mean of the ESC distribution for simulated temperature series (red), mean of ECS distribution for synthetic tree ring temperature series (green), ECS estimate using MFR12 simulated tree ring temperature series where chronological error accumulation due to inferred missing rings is taken into account (cyan), and sensitivity estimate for D06 tree ring temperature reconstruction (blue). True value of ESC is 3.0 in both cases.

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 7617–7627, doi:10.1002/jgrd.50609, 2013

Discrepancies between the modeled and proxy-reconstructed response to volcanic forcing over the past millennium: Implications and possible mechanisms

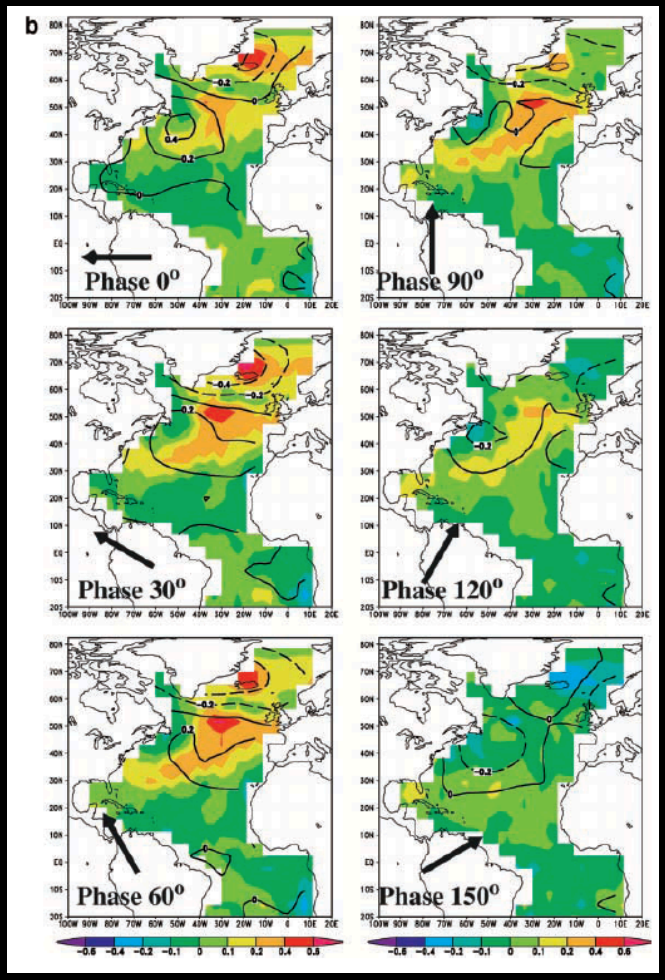
Michael E. Mann,[1] Scott Rutherford,[2] Andrew Schurer,[3] Simon F.B. Tett,[3] and Jose D. Fuentes[4]

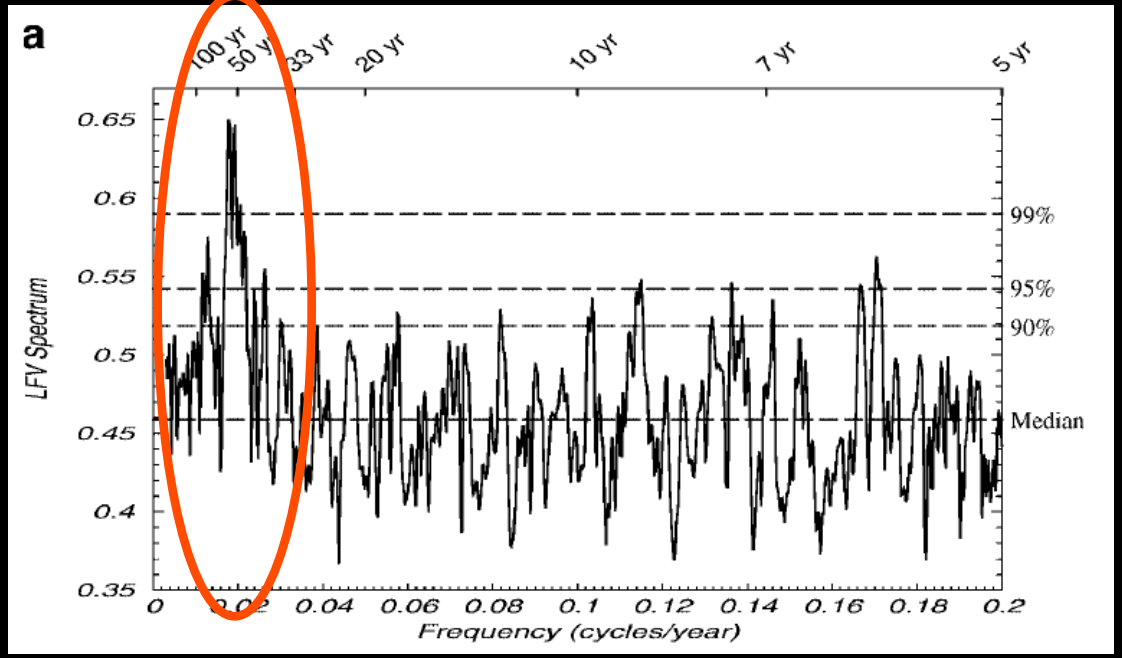
Climate Signal Detection

Climate Dynamics (2000) 16:661–676

T. L. Delworth · M. E. Mann

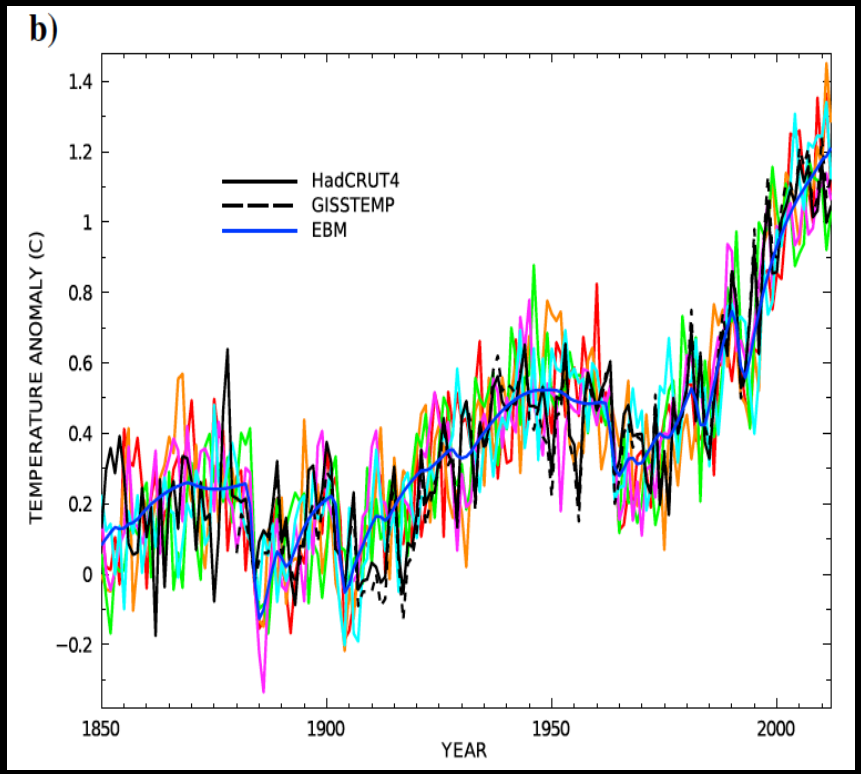
Observed and simulated multidecadal variability in the Northern Hemisphere





The "AMO"

Climate Signal Detection



AGU PUBLICATIONS

Geophysical Research Letters

FRONTIER ARTICLE
10.1002/2014GL059233

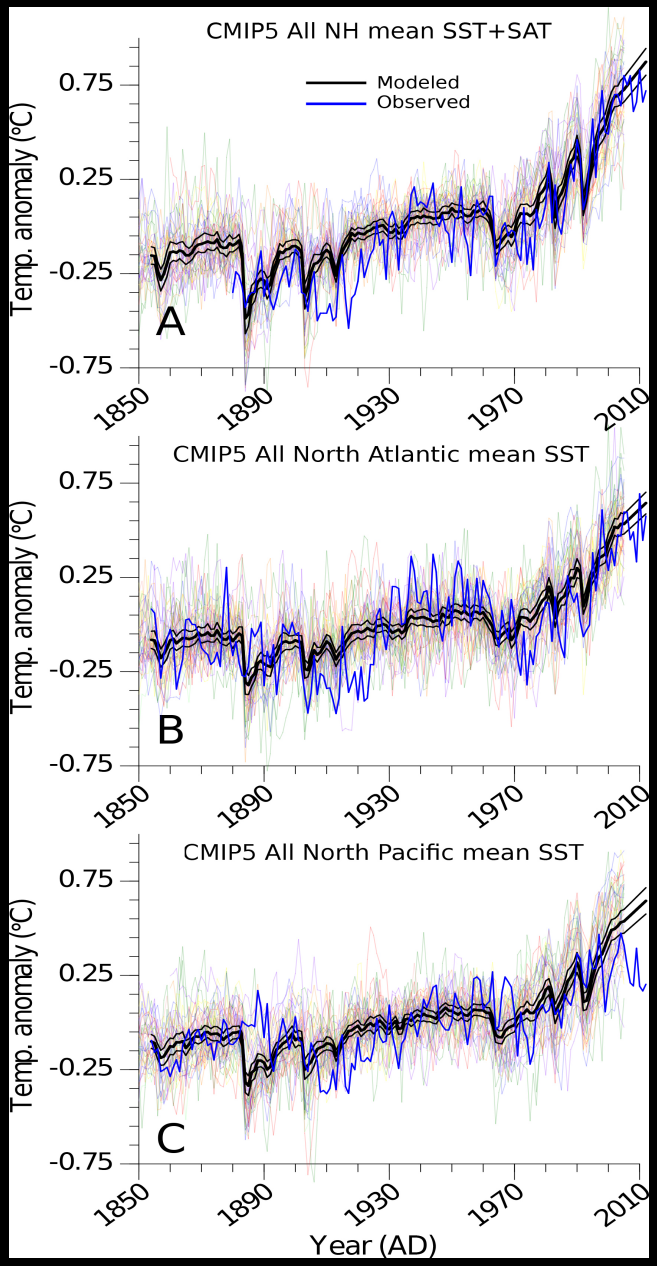
Key Points:
- Certain common procedures fail to isolate internal variability in climate
- AMO appears to have been in a cool phase in recent decades
- 'Stadium wave' patterns are likely an artifact of flawed assessment procedures

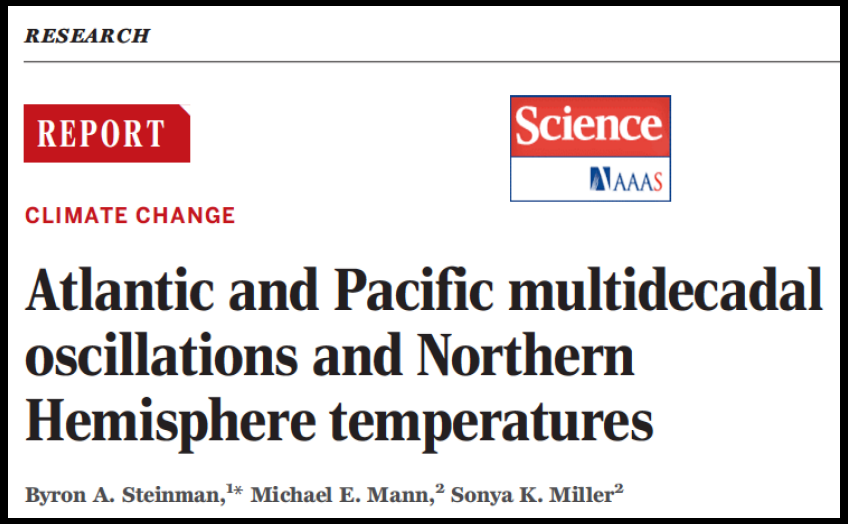
On forced temperature changes, internal variability, and the AMO

Michael E. Mann[1], Byron A. Steinman[1], and Sonya K. Miller[1]

[1]Department of Meteorology and Earth and Environmental Systems Institute, Pennsylvania State University, University Park, Pennsylvania, USA

Climate Signal Detection





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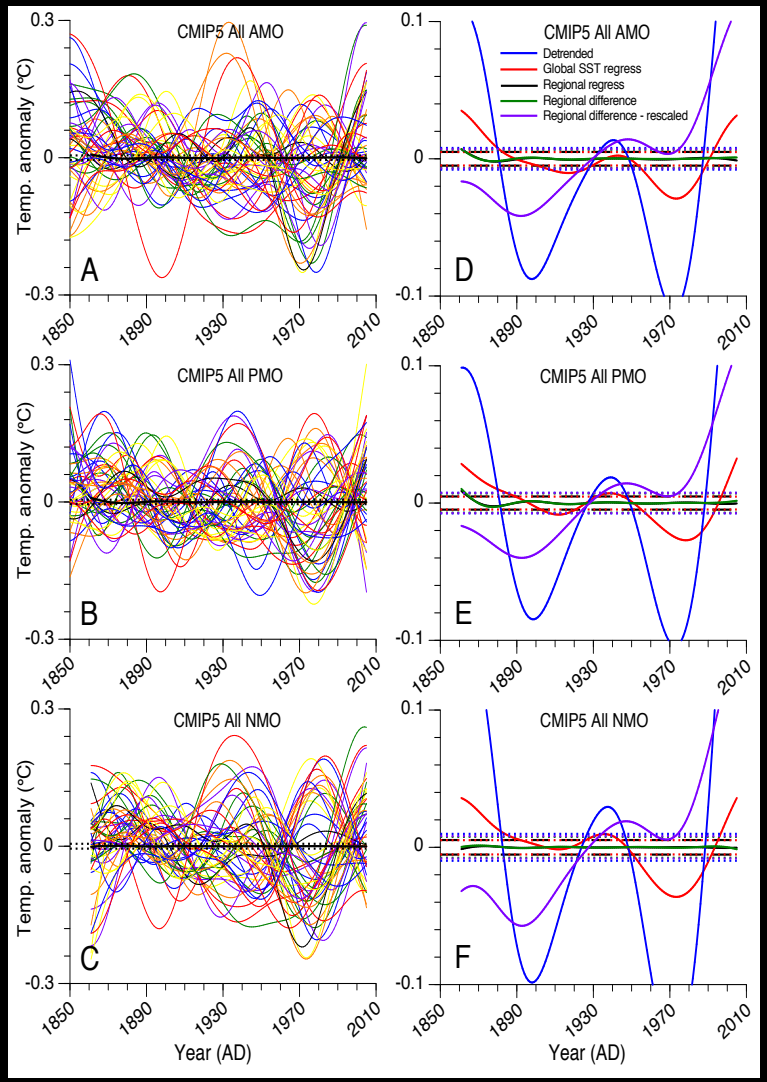
CLIMATE CHANGE

Atlantic and Pacific multidecadal oscillations and Northern Hemisphere temperatures

Byron A. Steinman,[1]* Michael E. Mann,[2] Sonya K. Miller[2]

CMIP5-All ensemble mean of Northern Hemisphere SST+SAT, North Atlantic SST, and North Pacific SST (black curves) shown with individual model means (colored curves). Thin black line depicts the 95% confidence limits of the model mean determined via bootstrap resampling. Blue line depicts observed temperatures

Climate Signal Detection



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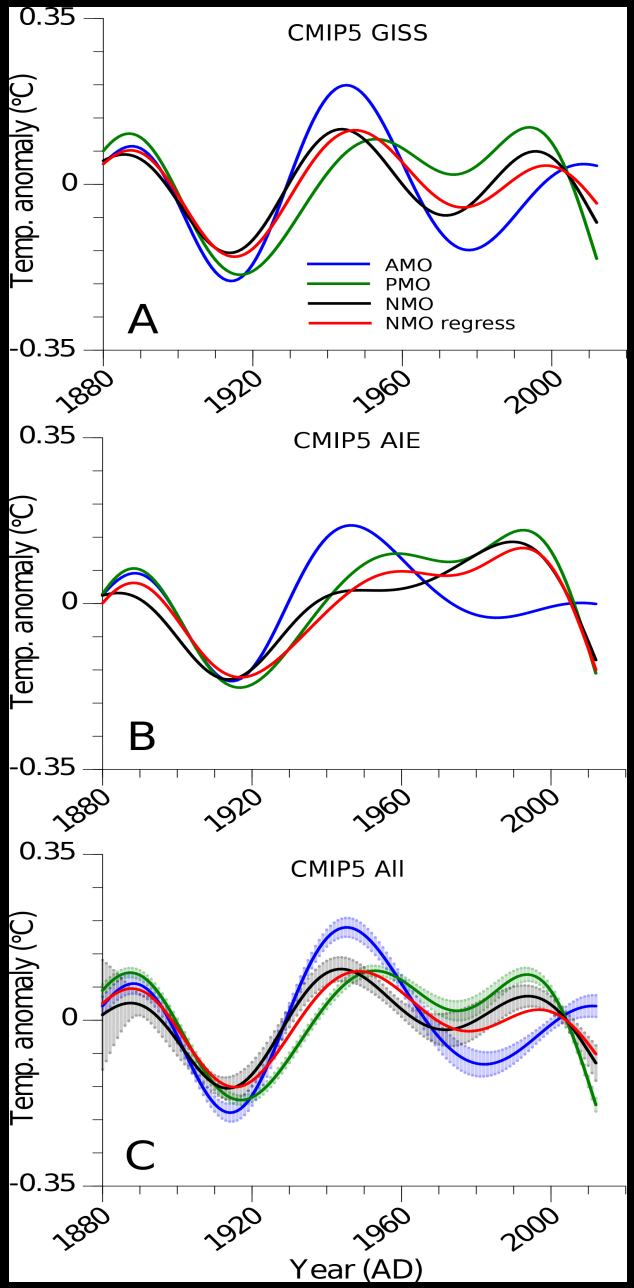
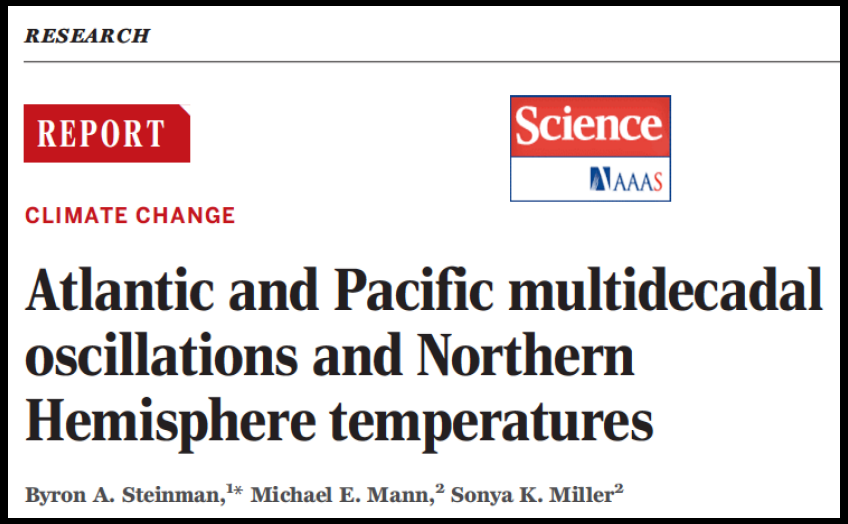
Byron A. Steinman,[1]* Michael E. Mann,[2] Sonya K. Miller[2]

(A-C) CMIP5-all mean (black lines) and 24 individual realizations (colored lines) of AMO, PMO and NMO determined using target region regression. Predicted 1 sigma limits for mean series are shown by two horizontal dashed lines. (D-F) Mean (solid lines) and 1 sigma limits determined using detrending (blue) global SST regression (red) target region regression (black), target region differencing (green), and rescaled target region differencing (purple).

Climate Signal Detection





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Atlantic and Pacific multidecadal oscillations and Northern Hemisphere temperatures

Byron A. Steinman,[1]* Michael E. Mann,[2] Sonya K. Miller[2]

Semi-empirical estimate of AMO (blue), PMO (green), and NMO (black) based on target region regression using (A) CMIP5-GISS, (B) CMIP5-AIE, and (C) CMIP-All historical climate model realizations. Bivariate regression-based approximation of NMO (red) strongly correlates (R2=0.86/0.88/0.91 for CMIP5-All/CMIP5-GISS, CMIP5-AIE, respectively) with semi-empirical NMO estimate (black). 95% confidence limits of the AMO, PMO, and NMO CMIP5-All means (determined using bootstrap resampling) are shown as colored shading.

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OPEN The Likelihood of Recent Record

, Byron A. Steinman[3], Martin Tingley[4] & Sonya K. Miller[1]

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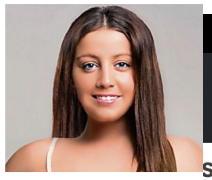
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Humans ARE to blame for record temperatures: Global warming caused by greenhouse gas emissions has led to 13 of the world's hottest years, study claims

- Scientists said it is 'extremely likely' humans caused soaring temperatures
- 13 of the 15 warmest years on record have occurred since the millennium
- Researchers say the odds of this happening naturally are one in 170,000
- It comes just days after data revealed 2015 was the hottest year on record

study

New calculations shows there is just a 0.01% chance that recent run of global heat records could have happened due to natural climate variations

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Recent record temperature years 'extremely unlikely' without global warming, scientists say

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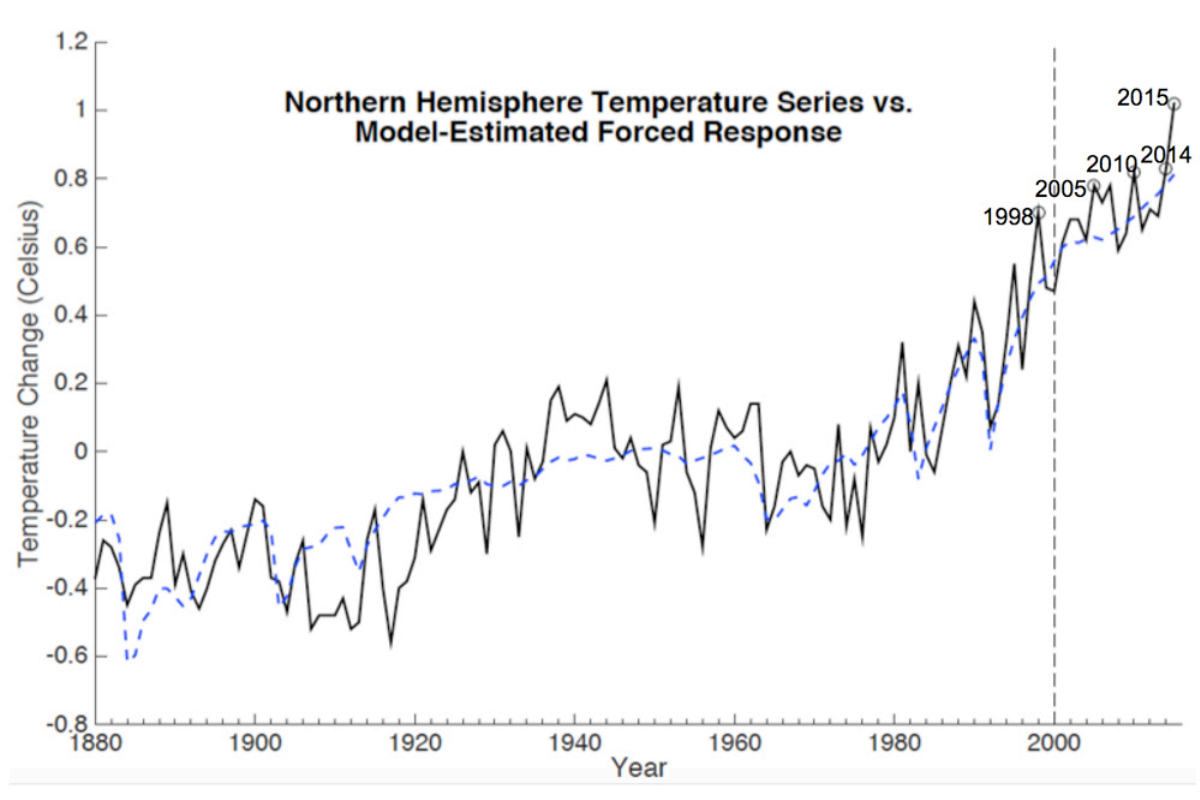
The Likelihood of Recent Record Warmth

Michael E. Mann[1], Stefan Rahmstorf[2], Byron A. Steinman[3], Martin Tingley[4] & Sonya K. Miller[1]

Received: 24 July 2015
Accepted: 16 December 2015
Published: 25 January 2016

2014 was nominally the warmest year on record for both the globe and northern hemisphere based on historical records spanning the past one and a half centuries[1,2]. It was the latest in a recent run of record temperatures spanning the past decade and a half. Press accounts reported odds as low as one-in-650 million that the observed run of global temperature records would be expected to occur in the absence of human-caused global warming. Press reports notwithstanding, the question of how likely observed temperature records may have have been both with and without human influence is interesting in its own right. Here we attempt to address that question using a semi-empirical approach that combines the latest (CMIP5[3]) climate model simulations with observations of global and hemispheric mean temperature. We find that individual record years and the observed runs of record-setting temperatures were extremely unlikely to have occurred in the absence of human-caused climate change, though not nearly as unlikely as press reports have suggested. These same record temperatures were, by contrast, quite *likely* to have occurred in the *presence* of anthropogenic climate forcing.



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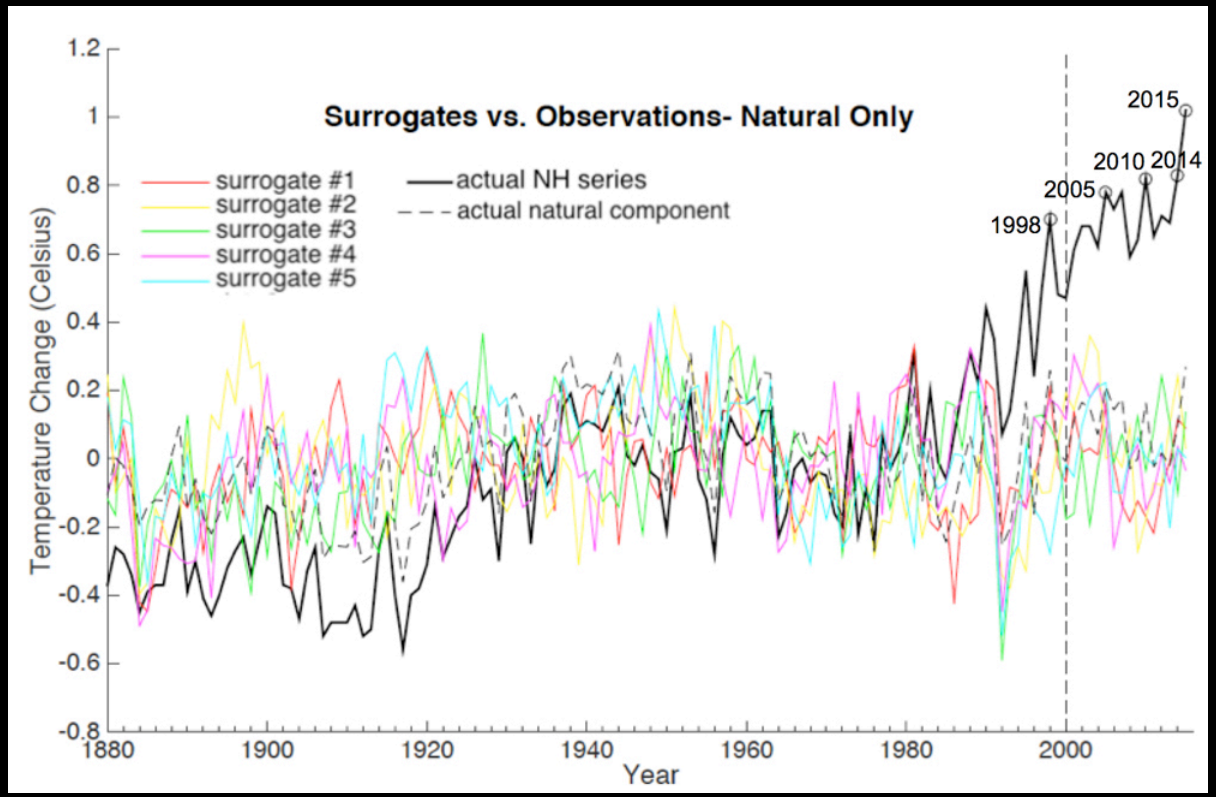

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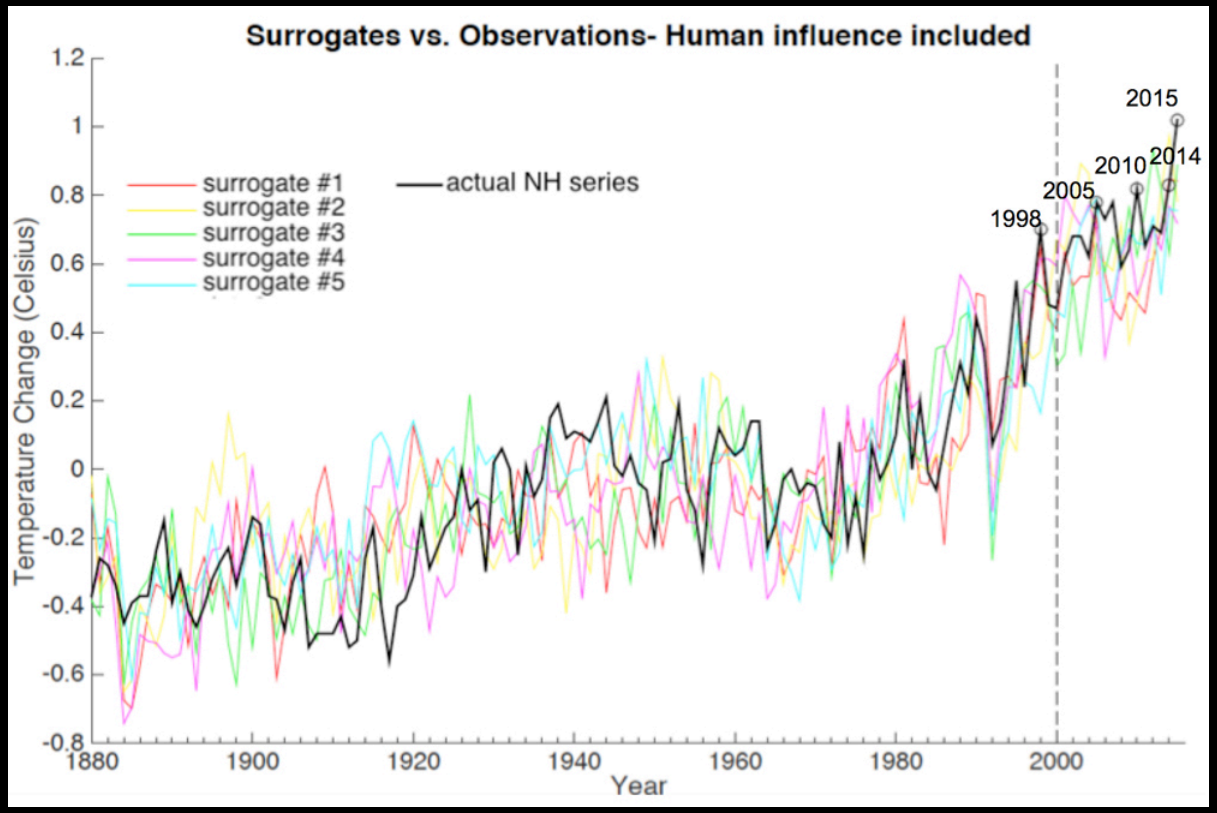

Conclusions

- The 0d EBM is useful for exploring a broad range of climate change issues.
- Uncertainty in ECS unlikely to buy significant time in avoiding 2C warming under business-as-usual carbon emissions.
- Very low-end sensitivity (~2.0C) in some paleoclimate studies likely an artifact of biases in estimated volcanic cooling.
- Recent temperature records *very unlikely* to have happened in absence of human-caused climate change.