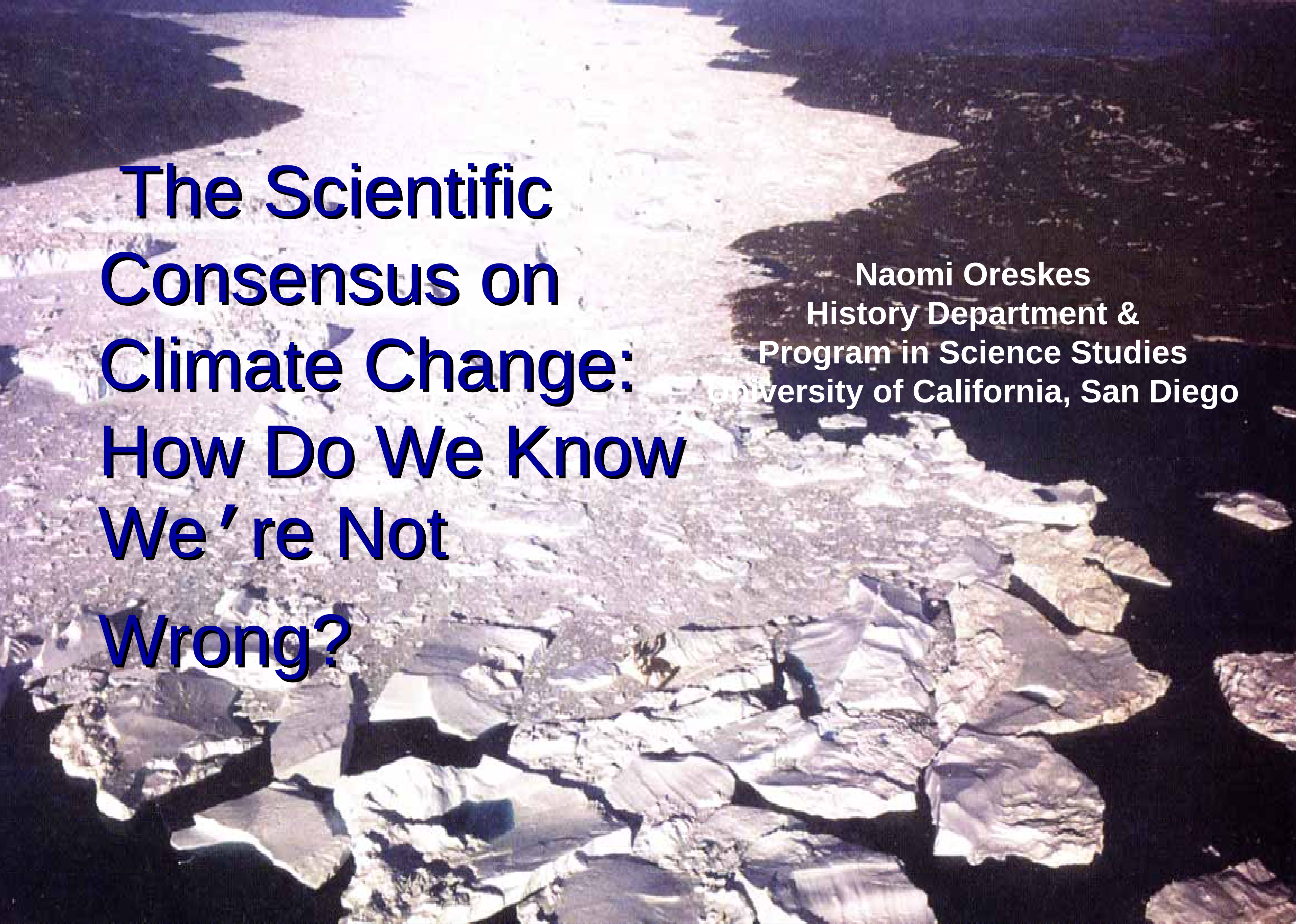


The Scientific Consensus on Climate Change: How Do We Know We’re Not Wrong?

Naomi Oreskes
History Department &
Program in Science Studies
University of California, San Diego

June 2, 2005, SAN FRANCISCO

"I say the debate is over.
We know the science.
We see the threat, and we know the time for action is now.”

--Arnold Schwarzenegger
San Francisco, June 2, 2005

There is a scientific consensus over the reality of anthropogenic global warming

"…most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations."

IPCC 3rd Assessment (2001)

IPCC:
Intergovernmental Panel on Climate Change

- Established in 1988 by United Nations Environment Programme and World Meteorological Organization
- *Response* to scientific predictions of 1970s: global warming due to greenhouse gas emissions likely to become problem.
- Today: scientific experts from > 130 countries.
  - Most recent report > 800 authors, >1000 peer reviewers
- Historically unprecedented: scale, scope, ambition.
  - Not to do research, but to synthesize and assess it.

February 2007: Fourth Assessment Report

"…most of the observed warming over the last 50 years is very likely to have been due to the increase in greenhouse gas concentrations."

IPCC 4th Assessment (2007)

Scientific position has not really changed since 2001.

Hardly changed since 1979…

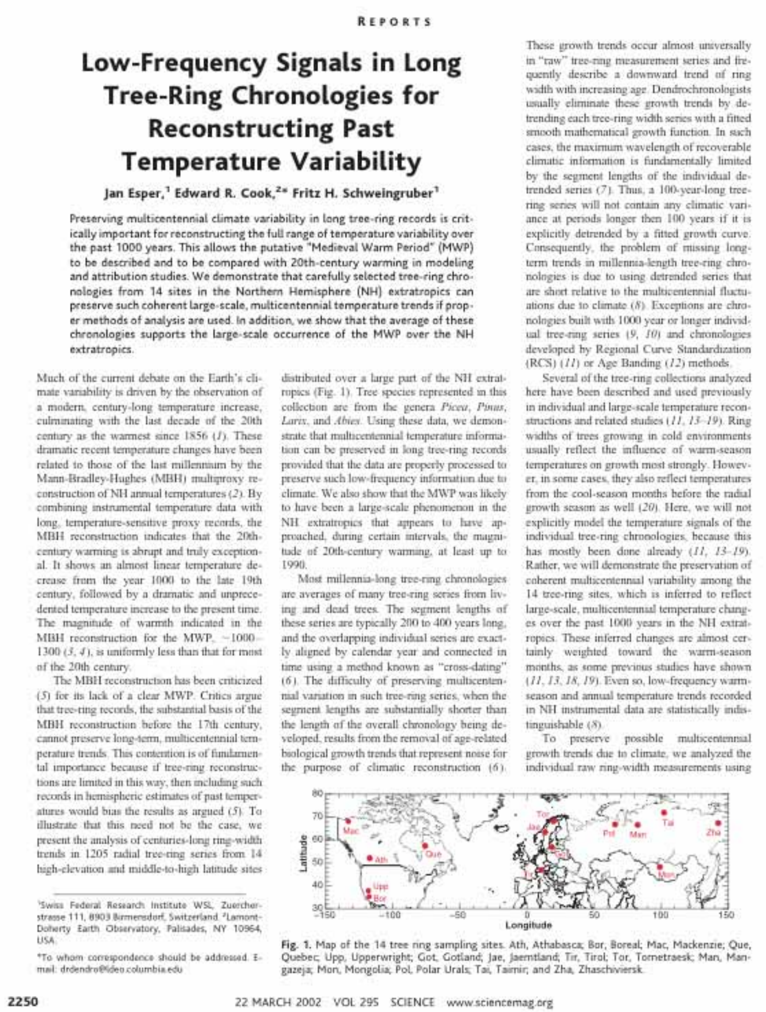
"If carbon dioxide continues to increase, [we] find no reason to doubt that climate changes will result, and no reason to believe that these changes will be negligible."

U.S. National Academy of Sciences
"Carbon Dioxide and Climate: A Scientific Assessment," (Charney report), 1979

"A plethora of studies from diverse sources indicates a consensus that climate changes will result from man's combustion of fossil fuels and changes in land use."

National Academy of Sciences Archives, An Evaluation of the Evidence for CO_2-Induced Climate Change, Assembly of Mathematical and Physical Sciences, Climate Research Board, Study Group on Carbon Dioxide, 1979, Film Label: CO_2 and Climate Change: Ad Hoc: General

What's new since 1979?



REPORTS

Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability

Jan Esper,[1] Edward R. Cook,[2*] Fritz H. Schweingruber[1]

Preserving multicentennial climate variability in long tree-ring records is critically important for reconstructing the full range of temperature variability over the past 1000 years. This allows the putative "Medieval Warm Period" (MWP) to be described and to be compared with 20th-century warming in modeling and attribution studies. We demonstrate that carefully selected tree-ring chronologies from 14 sites in the Northern Hemisphere (NH) extratropics can preserve such coherent large-scale, multicentennial temperature trends if proper methods of analysis are used. In addition, we show that the average of these chronologies supports the large-scale occurrence of the MWP over the NH extratropics.

Much of the current debate on the Earth's climate variability is driven by the observation of a modern, century-long temperature increase, culminating with the last decade of the 20th century as the warmest since 1856 (*1*). These dramatic recent temperature changes have been related to those of the last millennium by the Mann-Bradley-Hughes (MBH) multiproxy reconstruction of NH annual temperatures (*2*). By combining instrumental temperature data with long, temperature-sensitive proxy records, the MBH reconstruction indicates that the 20th-century warming is abrupt and truly exceptional. It shows an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time. The magnitude of warmth indicated in the MBH reconstruction for the MWP, ~1000–1300 (*3, 4*), is uniformly less than that for most of the 20th century.

The MBH reconstruction has been criticized (*5*) for its lack of a clear MWP. Critics argue that tree-ring records, the substantial basis of the MBH reconstruction before the 17th century, cannot preserve long-term, multicentennial temperature trends. This contention is of fundamental importance because if tree-ring reconstructions are limited in this way, then including such records in hemispheric estimates of past temperatures would bias the results as argued (*5*). To illustrate that this need not be the case, we present the analysis of centuries-long ring-width trends in 1205 radial tree-ring series from 14 high-elevation and middle-to-high latitude sites distributed over a large part of the NH extratropics (Fig. 1). Tree species represented in this collection are from the genera *Picea*, *Pinus*, *Larix*, and *Abies*. Using these data, we demonstrate that multicentennial temperature information can be preserved in long tree-ring records provided that the data are properly processed to preserve such low-frequency information due to climate. We also show that the MWP was likely to have been a large-scale phenomenon in the NH extratropics that appears to have approached, during certain intervals, the magnitude of 20th-century warming, at least up to 1990.

Most millennia-long tree-ring chronologies are averages of many tree-ring series from living and dead trees. The segment lengths of these series are typically 200 to 400 years long, and the overlapping individual series are exactly aligned by calendar year and connected in time using a method known as "cross-dating" (*6*). The difficulty of preserving multicentennial variation in such tree-ring series, when the segment lengths are substantially shorter than the length of the overall chronology being developed, results from the removal of age-related biological growth trends that represent noise for the purpose of climatic reconstruction (*6*). These growth trends occur almost universally in "raw" tree-ring measurement series and frequently describe a downward trend of ring width with increasing age. Dendrochronologists usually eliminate these growth trends by detrending each tree-ring width series with a fitted smooth mathematical growth function. In such cases, the maximum wavelength of recoverable climatic information is fundamentally limited by the segment lengths of the individual detrended series (*7*). Thus, a 100-year-long tree-ring series will not contain any climatic variance at periods longer then 100 years if it is explicitly detrended by a fitted growth curve. Consequently, the problem of missing long-term trends in millennia-length tree-ring chronologies is due to using detrended series that are short relative to the multicentennial fluctuations due to climate (*8*). Exceptions are chronologies built with 1000 year or longer individual tree-ring series (*9, 10*) and chronologies developed by Regional Curve Standardization (RCS) (*11*) or Age Banding (*12*) methods.

Several of the tree-ring collections analyzed here have been described and used previously in individual and large-scale temperature reconstructions and related studies (*11, 13–19*). Ring widths of trees growing in cold environments usually reflect the influence of warm-season temperatures on growth most strongly. However, in some cases, they also reflect temperatures from the cool-season months before the radial growth season as well (*20*). Here, we will not explicitly model the temperature signals of the individual tree-ring chronologies, because this has mostly been done already (*11, 13–19*). Rather, we will demonstrate the preservation of coherent multicentennial variability among the 14 tree-ring sites, which is inferred to reflect large-scale, multicentennial temperature changes over the past 1000 years in the NH extratropics. These inferred changes are almost certainly weighted toward the warm-season months, as some previous studies have shown (*11, 13, 18, 19*). Even so, low-frequency warm-season and annual temperature trends recorded in NH instrumental data are statistically indistinguishable (*8*).

To preserve possible multicentennial growth trends due to climate, we analyzed the individual raw ring-width measurements using

Fig. 1. Map of the 14 tree ring sampling sites. Ath, Athabasca; Bor, Boreal; Mac, Mackenzie; Que, Quebec; Upp, Upperwright; Got, Gotland; Jae, Jaemtland; Tir, Tirol; Tor, Tornetraesk; Man, Mangazeja; Mon, Mongolia; Pol, Polar Urals; Tai, Taimir; and Zha, Zhaschiviersk.

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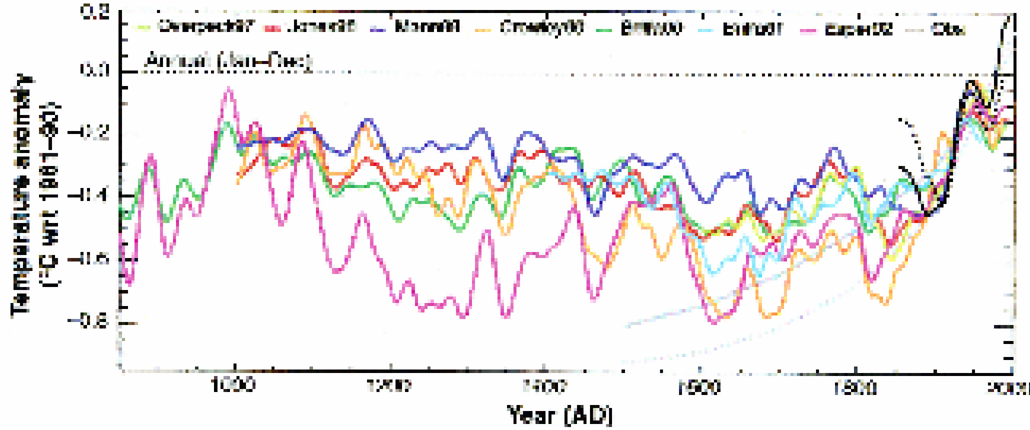

Records of past climate. Solid colored lines indicate seven reconstructions of Northern Hemisphere climate: yellow, (4); red, (5); purple, (3); orange, (6); green, (7); blue, (8); and pink (1). All records were re-calibrated with linear regression against 1881–1960 mean annual temperature observations averaged over land areas north of 20°N, and the results smoothed with a 50-year filter. The black dotted line shows the estimate that would be made if the predictor was observed warm-season temperatures from the same region, highlighting the difference between warm season and annual temperature changes during the observed record. Black solid line: smoothed observations, truncated in 1993 when the record of Esper et al. ends. Gray lines: annual temperature changes estimated from Northern Hemisphere borehole temperature profiles [dotted line, unweighted average of many sites (9); solid line, records gridded before averaging].

Climate change no longer a prediction, now an observed fact.

Since the mid 1980s, there has been a steady stream of claims challenging climate science…

These claims include…

- No ‘proof’ (science is uncertain)
- No ‘consensus’ (scientists are divided).
- If warming is happening, it’s not anthropogenic (natural variability).
- If it is anthropogenic, it isn’t necessarily bad. Warnings are “alarmist,” “catastrophist.” Changes may be beneficial. (NASA administrator Griffin)
- We can readily adapt to any changes that occur.
- Controlling GHG emissions would destroy the US economy

Not just “lunatic fringe” or talk radio…

- Leading screenwriter and novelist of our day (Crichton)
- Leaders of U.S. Congress (Senator Inhofe, Congressman Barton)
- Major U.S media outlets (Wall Street Journal, Forbes, Fortune, Financial Times)
- Influential think-tanks (American Enterprise Institute, Competitive Enterprise Institute, Heritage Foundation)
- President and Vice President of the United States

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EXCLUSIVE: Cheney on Global Warming

Vice President's Views At Odds With Majority Of Climate Scientists

Vice President Dick Cheney talked about global warming in an exclusive interview today with ABC's Jonathan Karl. (J. Scott Applewhite/AP Photo)

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abc NEWS

Sydney, Australia, Feb. 23, 2007 — In an exclusive interview today, ABC's Jonathan Karl asked Vice President Dick Cheney about the topic of global warming, a subject Mr. Cheney has rarely addressed in the past. The vice president agreed that the earth is warming but, like President Bush, maintained there is debate over whether humans or natural cycles are the cause— a position that puts the administration at odds with the vast majority of climate scientists.

The Intergovernmental Panel on Climate Change — made up of thousands of scientists from around the world — reported earlier this month they are more certain than ever that humans are heating earth's atmosphere through the burning of fossil fuels. In Australia, for example, the IPCC said that rising ocean temperatures brought on by global warming could make Australia's Great Barrier Reef "functionally extinct" by 2050.

Here is a portion of the transcript from Jonathan Karl's conversation with Mr. Cheney:

JONATHAN KARL: I want to ask you about another issue that's been a subject of controversy here in Australia,

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Last February…

- "I think there's an emerging consensus that we do have global warming. …Where there does not appear to be a consensus…is the extent to which that's part of a normal cycle versus the extent to which it's caused by man, greenhouse gases, etc."

Misleading in two ways

I. Consensus is not “emerging” (1992)

Called on world leaders to translate the written document into "concrete action to protect the planet."

IPCC Second Assessment Report (1995)

Summary for Policymakers: The Science of Climate Change - IPCC Working Group I

Contents

Considerable progress has been made in the understanding of climate change[1] science since 1990 and new data and analyses have become available.

1. Greenhouse gas concentrations have continued to increase

Increases in greenhouse gas concentrations since preindustrial times (i.e., since about 1750) have led to a positive radiative forcing[2] of climate, tending to warm the surface and to produce other changes of climate.

- The atmospheric concentrations of greenhouse gases, inter alia, carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) have grown significantly: by about 30%, 145%, and 15%, respectively (values for 1992). These trends can be attributed largely to human activities, mostly fossilfuel use, landuse change and agriculture.
- The growth rates of CO2, CH4 and N2O concentrations were low during the early 1990s. While this apparently natural variation is not yet fully explained, recent data indicate that the growth rates are currently comparable to those averaged over the 1980s.
- The direct radiative forcing of the longlived greenhouse gases (2.45 Wm2) is due primarily to increases in the concentrations of CO2 (1.56 Wm2), CH4 (0.47 Wm2) and N2O (0.14 Wm2) (values for 1992).
- Many greenhouse gases remain in the atmosphere for a long time (for CO2 and N2O, many decades to centuries), hence they affect radiative forcing on long timescales.
- The direct radiative forcing due to the CFCs and HCFCs combined is 0.25 Wm2. However, their net radiative forcing is reduced by about 0.1 Wm2 because they have caused stratospheric ozone depletion which gives rise to a negative radiative forcing.
- Growth in the concentration of CFCs, but not HCFCs, has slowed to about zero. The concentrations of both CFCs and HCFCs, and their consequent ozone depletion, are expected to decrease substantially by 2050 through implementation of the Montreal Protocol and its Adjustments and Amendments.
- At present, some longlived greenhouse gases (particularly HFCs (a CFC substitute), PFCs and SF6) contribute little to radiative forcing but their projected growth could contribute several per cent to radiative forcing during the 21st century.
- If carbon dioxide emissions were maintained at near current (1994) levels, they would lead to a nearly constant rate of increase in atmospheric concentrations for at least two centuries, reaching about 500 ppmv (approaching twice the pre-industrial concentration of 280 ppmv) by the end of the 21st century.
- A range of carbon cycle models indicates that stabilization of atmospheric CO2 concentrations at 450, 650 or 1000 ppmv could be achieved only if global anthropogenic CO2 emissions drop to 1990 levels by, respectively, approximately 40, 140 or 240 years from now, and drop substantially below 1990 levels subsequently.
- Any eventual stabilized concentration is governed more by the accumulated anthropogenic CO2 emissions from now until the time of stabilization than by the way those emissions change over the period. This means that, for a given stabilized concentration value, higher emissions in early decades require lower emissions later on. Among the range of stabilization cases studied, for stabilization at 450, 650 or 1000 ppmv, accumulated anthropogenic emissions over the period 1991 to 2100 are 630 GtC[3], 1030 GtC and 1410 GtC, respectively (approximately 15% in each case). For comparison the corresponding accumulated emissions for IPCC IS92 emission scenarios range from 770 to 2190 GtC.
- Stabilization of CH4 and N2O concentrations at today's levels would involve reductions in anthropogenic emissions of 8% and more than 50% respectively.
- There is evidence that tropospheric ozone concentrations in the Northern Hemisphere have increased since preindustrial times because of human activity and that this has resulted in a positive radiative forcing. This forcing is not yet well characterized, but it is estimated to be about 0.4 Wm2 (15% of that from the longlived greenhouse gases). However, the

“The balance of evidence… suggests a discernible human influence on global climate….”

ESSAY

BEYOND THE IVORY TOWER

This year's essay series highlights the benefits that scientists, science, and technology have brought to society throughout history.

The Scientific Consensus on Climate Change

Naomi Oreskes

Policy-makers and the media, particularly in the United States, frequently assert that climate science is highly uncertain. Some have used this as an argument against adopting strong measures to reduce greenhouse gas emissions. For example, while discussing a major U.S. Environmental Protection Agency report on the risks of climate change, then–EPA administrator Christine Whitman argued, "As [the report] went through review, there was less consensus on the science and conclusions on climate change" (*1*). Some corporations whose revenues might be adversely affected by controls on carbon dioxide emissions have also alleged major uncertainties in the science (*2*). Such statements suggest that there might be substantive disagreement in the scientific community about the reality of anthropogenic climate change. This is not the case.

The scientific consensus is clearly expressed in the reports of the Intergovernmental Panel on Climate Change (IPCC). Created in 1988 by the World Meteorological Organization and the United Nations Environmental Programme, IPCC's purpose is to evaluate the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature (*3*). In its most recent assessment, IPCC states unequivocally that the consensus of scientific opinion is that Earth's climate is being affected by human activities: "Human activities … are modifying the concentration of atmospheric constituents … that absorb or scatter radiant energy. … [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" [p. 21 in (*4*)].

IPCC is not alone in its conclusions. In recent years, all major scientific bodies in the United States whose members' expertise bears directly on the matter have issued similar statements. For example, the National Academy of Sciences report, *Climate Change Science: An Analysis of Some Key Questions*, begins: "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise" [p. 1 in (*5*)]. The report explicitly asks whether the IPCC assessment is a fair summary of professional scientific thinking, and answers yes: "The IPCC's conclusion that most of the observed warming of the last 50 years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue" [p. 3 in (*5*)].

Without substantial disagreement, scientists find human activities are heating the Earth's surface.

Others agree. The American Meteorological Society (*6*), the American Geophysical Union (*7*), and the American Association for the Advancement of Science (AAAS) all have issued statements in recent years concluding that the evidence for human modification of climate is compelling (*8*).

The drafting of such reports and statements involves many opportunities for comment, criticism, and revision, and it is not likely that they would diverge greatly from the opinions of the societies' members. Nevertheless, they might downplay legitimate dissenting opinions. That hypothesis was tested by analyzing 928 abstracts, published in refereed scientific journals between 1993 and 2003, and listed in the ISI database with the keywords "climate change" (*9*).

The 928 papers were divided into six categories: explicit endorsement of the consensus position, evaluation of impacts, mitigation proposals, methods, paleoclimate analysis, and rejection of the consensus position. Of all the papers, 75% fell into the first three categories, either explicitly or implicitly accepting the consensus view; 25% dealt with methods or paleoclimate, taking no position on current anthropogenic climate change. Remarkably, none of the papers disagreed with the consensus position.

Admittedly, authors evaluating impacts, developing methods, or studying paleoclimatic change might believe that current climate change is natural. However, none of these papers argued that point.

This analysis shows that scientists publishing in the peer-reviewed literature agree with IPCC, the National Academy of Sciences, and the public statements of their professional societies. Politicians, economists, journalists, and others may have the impression of confusion, disagreement, or discord among climate scientists, but that impression is incorrect.

The scientific consensus might, of course, be wrong. If the history of science teaches anything, it is humility, and no one can be faulted for failing to act on what is not known. But our grandchildren will surely blame us if they find that we understood the reality of anthropogenic climate change and failed to do anything about it.

Many details about climate interactions are not well understood, and there are ample grounds for continued research to provide a better basis for understanding climate dynamics. The question of what to do about climate change is also still open. But there is a scientific consensus on the reality of anthropogenic climate change. Climate scientists have repeatedly tried to make this clear. It is time for the rest of us to listen.

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3. See www.ipcc.ch/about/about.htm.
4. J. J. McCarthy *et al.*, Eds., *Climate Change 2001: Impacts, Adaptation, and Vulnerability* (Cambridge Univ. Press, Cambridge, 2001).
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6. American Meteorological Society, *Bull. Am. Meteorol. Soc.* **84**, 508 (2003).
7. American Geophysical Union, *Eos* **84** (51), 574 (2003).
8. See www.ourplanet.com/aaas/pages/atmos02.html.
9. The first year for which the database consistently published abstracts was 1993. Some abstracts were deleted from our analysis because, although the authors had put "climate change" in their key words, the paper was not about climate change.
10. This essay is excerpted from the 2004 George Sarton Memorial Lecture, "Consensus in science: How do we know we're not wrong," presented at the AAAS meeting on 13 February 2004. I am grateful to AAAS and the History of Science Society for their support of this lectureship; to my research assistants S. Luis and G. Law; and to D. C. Agnew, K. Belitz, J. R. Fleming, M. T. Greene, H. Leifert, and R. C. J. Somerville for helpful discussions.

10.1126/science.1103618

Published by AAAS

- Broad consensus of major scientific organizations: IPCC, NAS, AMS, AGU, AAAS
- Supported by data base analysis of the published scientific literature: No disagreement about fact of GW and its mostly human causes
- Consensus established by 1993.

II. The consensus includes the question of cause

"…most of the observed warming over the last 50 years is very likely to have been due to the increase in greenhouse gas concentrations."

IPCC 4th Assessment (2007)

IPCC explicitly rejects the claim that observed changes are natural variation

"The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is *extremely unlikely* that global climate change of the past fifty years can be explained without external forcing…."

Naysaying has clearly had an effect, because despite the overwhelming scientific evidence, many Americans are still doubtful or confused

Pew Research Center for The People and the Press, July 2006

"Little consensus on global warming"…

- 70% do believe there is "solid evidence of global warming" but…
- Only 41% believe warming is caused by human activities.

ABC News Poll, March 2006

--64% perceive “a lot of disagreement among scientists” on the question

--Only 1/3 think scientists agree that global warming has begun

--Only 1/3 think rise in world temperatures is “mainly caused by things people do”

Abcnews.go.com/technology/GlobalWarming/Story?id-1750492

Doubts matter

- Views on scientific consensus predict levels of concern, and willingness to act.
- Those who think scientists mainly agree are

  much more likely to say the federal government should do something about it.

Abcnews.go.com/technology/GlobalWarming/Story?id-1750492

Americans are much less concerned about global warming than others…

When asked how "personally concerned"

Only 19% Americans said "a great deal"

- 46% in France
- 51% in Spain
- 66% in Japan
- Even Chinese were more concerned: 20%

Pew Research Center for The People and the Press, July 2006

But we should be *more* concerned, because we are the number 1 producer of GHG (and have been for a long time)

There is a scientific consensus, but…

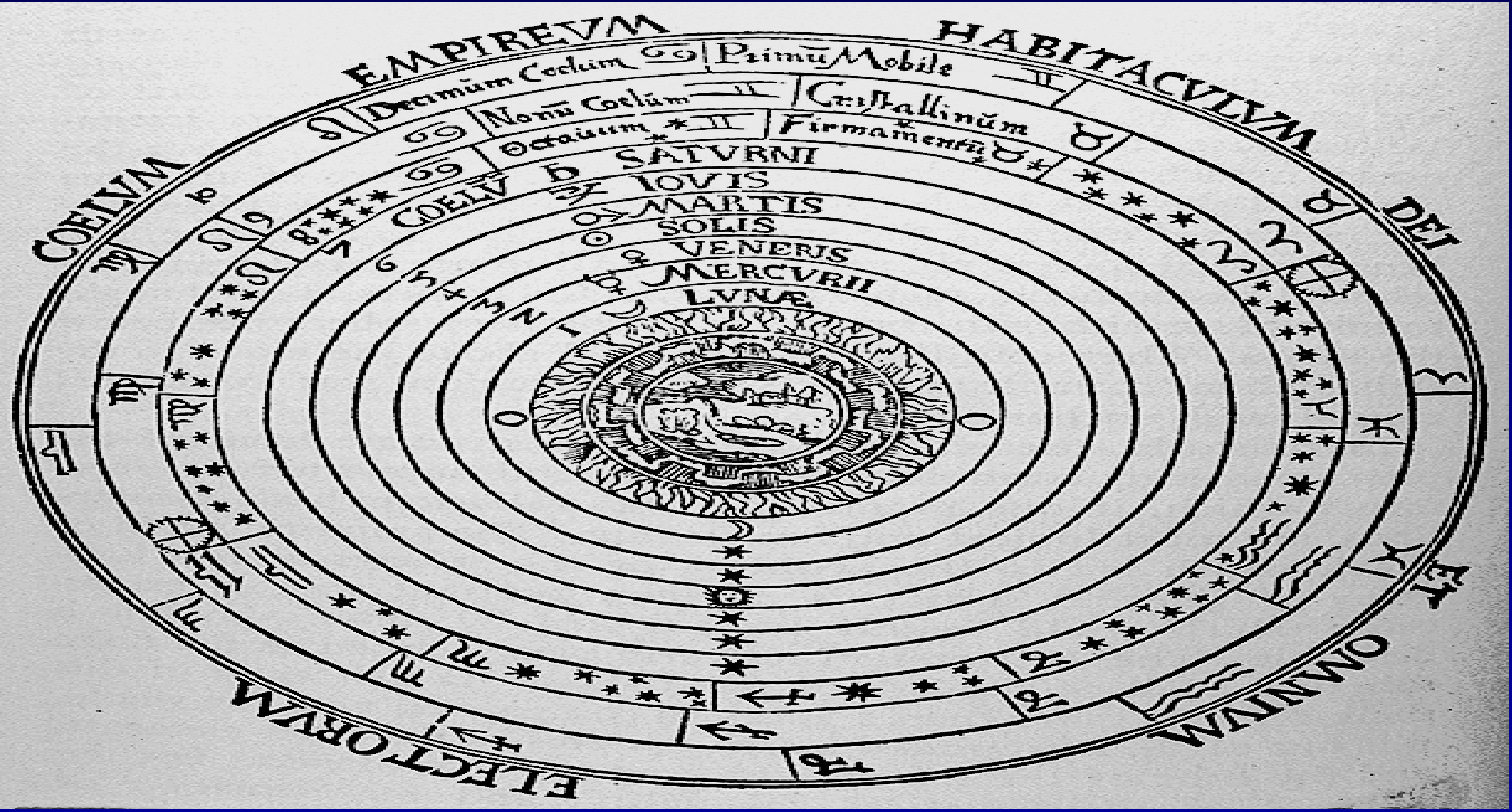
How do we know that the consensus is correct?

How do we know we’re not wrong?

Given what we know about history of science, isn't it quite possible that the climate consensus is wrong?

Yes, it is possible.

Science is fallible.



Numerous examples from history of science of consensus, overturned

- Geocentric Universe
- Fixity of species
- Absolute nature of time and space, pervaded by luminiferous aether
- Deterministic character of atomic interactions
- Fixity of continents

Fair to ask, how do we know our current science won't be similarly overturned?

How can we justify using science to inform policy, if the science might be wrong?

Historians and philosophers have extensively analyzed the processes that contribute to the reliability of scientific knowledge

We *can* use this to evaluate any current science.

Ideal world:

Did scientists follow the scientific method?

If they did, all is well.
If they didn't, there's a problem.

Real world:
There is no scientific method
(singular).

However, there are scientific *methods.*

Accepted scientific standards for evaluating claims.

Many have been around for a long time.

Five main candidates for scientific methods and standards

1. Methodological standards: Science is reliable by virtue of using correct method

- Induction: generalization from observations.
- Deduction: hypothetico-deductive method.
- Falsification: science must be *dis*provable.
- (Cf. appeals to authority or articles of faith.)

2. Evidential standards: Science is reliable by virtue of how it evaluates evidence

Tests of reliability

--Replication, witnessing, and peer review

Tests of consistency

--Consilience of Evidence

3. Performance standards: How well does knowledge hold up in action?

- Does it stand up to predictive tests?
- Has it held up over time?
- Can we use it to do things in world?

4. Inference to the best explanation

5. Community standards (Kuhn)

Scientists sometimes defend their work (and attack their colleagues) by reference to their preferred standard.

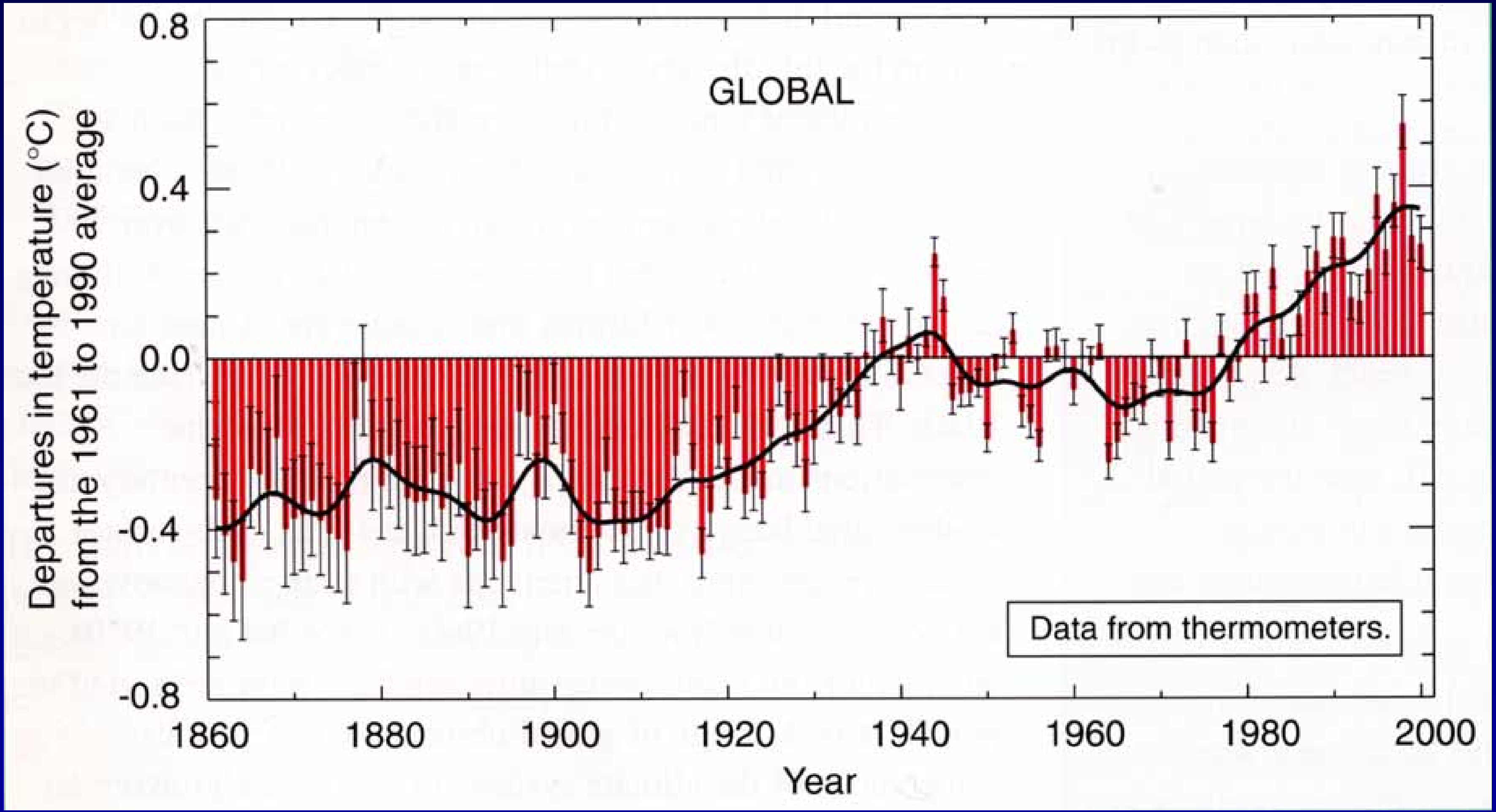
We can ask:

How does a particular scientific claim stand up to *all* these standards?

1. Methodological standards

- Is there inductive evidence backing the scientific claims?
- Has climate science passed any deductive tests?
- Is it falsifiable?

1.1. Induction: Generalization from evidence



150 years of temperature record, from weather stations around the globe,

for reasons entirely independent of concern about global warming.

Independent corroboration...

Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability

Jan Esper,[1] Edward R. Cook,[2*] Fritz H. Schweingruber[1]

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Much of the current debate on the Earth's climate variability is driven by the observation of a modern, century-long temperature increase, culminating with the last decade of the 20th century as the warmest since 1856 (*1*). These dramatic recent temperature changes have been related to those of the last millennium by the Mann-Bradley-Hughes (MBH) multiproxy reconstruction of NH annual temperatures (*2*). By combining instrumental temperature data with long, temperature-sensitive proxy records, the MBH reconstruction indicates that the 20th-century warming is abrupt and truly exceptional. It shows an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time. The magnitude of warmth indicated in the MBH reconstruction for the MWP, ~1000–1300 (*3, 4*), is uniformly less than that for most of the 20th century.

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Most millennia-long tree-ring chronologies are averages of many tree-ring series from living and dead trees. The segment lengths of these series are typically 200 to 400 years long, and the overlapping individual series are exactly aligned by calendar year and connected in time using a method known as "cross-dating" (*6*). The difficulty of preserving multicentennial variation in such tree-ring series, when the segment lengths are substantially shorter than the length of the overall chronology being developed, results from the removal of age-related biological growth trends that represent noise for the purpose of climatic reconstruction (*6*). These growth trends occur almost universally in "raw" tree-ring measurement series and frequently describe a downward trend of ring width with increasing age. Dendrochronologists usually eliminate these growth trends by detrending each tree-ring width series with a fitted smooth mathematical growth function. In such cases, the maximum wavelength of recoverable climatic information is fundamentally limited by the segment lengths of the individual detrended series (*7*). Thus, a 100-year-long tree-ring series will not contain any climatic variance at periods longer then 100 years if it is explicitly detrended by a fitted growth curve. Consequently, the problem of missing long-term trends in millennia-length tree-ring chronologies is due to using detrended series that are short relative to the multicentennial fluctuations due to climate (*8*). Exceptions are chronologies built with 1000 year or longer individual tree-ring series (*9, 10*) and chronologies developed by Regional Curve Standardization (RCS) (*11*) or Age Banding (*12*) methods.

Several of the tree-ring collections analyzed here have been described and used previously in individual and large-scale temperature reconstructions and related studies (*11, 13–19*). Ring widths of trees growing in cold environments usually reflect the influence of warm-season temperatures on growth most strongly. However, in some cases, they also reflect temperatures from the cool-season months before the radial growth season as well (*20*). Here, we will not explicitly model the temperature signals of the individual tree-ring chronologies, because this has mostly been done already (*11, 13–19*). Rather, we will demonstrate the preservation of coherent multicentennial variability among the 14 tree-ring sites, which is inferred to reflect large-scale, multicentennial temperature changes over the past 1000 years in the NH extratropics. These inferred changes are almost certainly weighted toward the warm-season months, as some previous studies have shown (*11, 13, 18, 19*). Even so, low-frequency warm-season and annual temperature trends recorded in NH instrumental data are statistically indistinguishable (*8*).

To preserve possible multicentennial growth trends due to climate, we analyzed the individual raw ring-width measurements using

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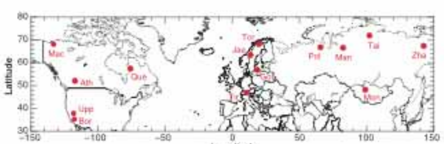
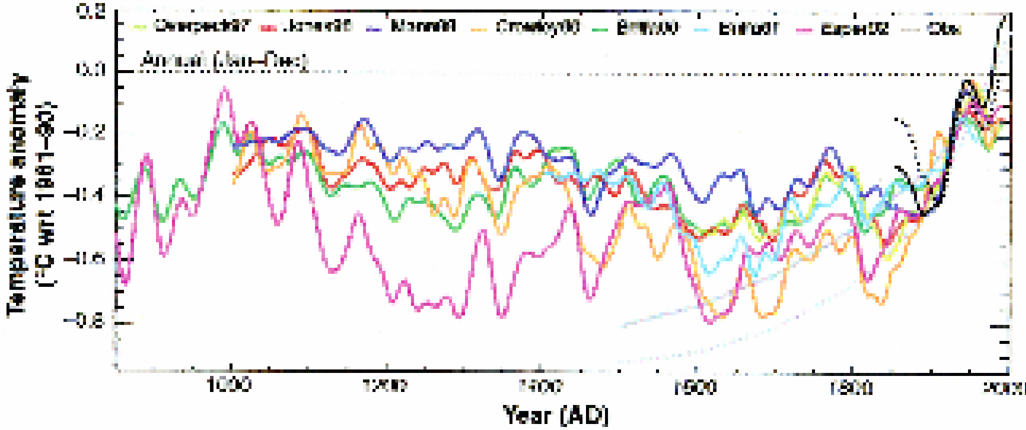
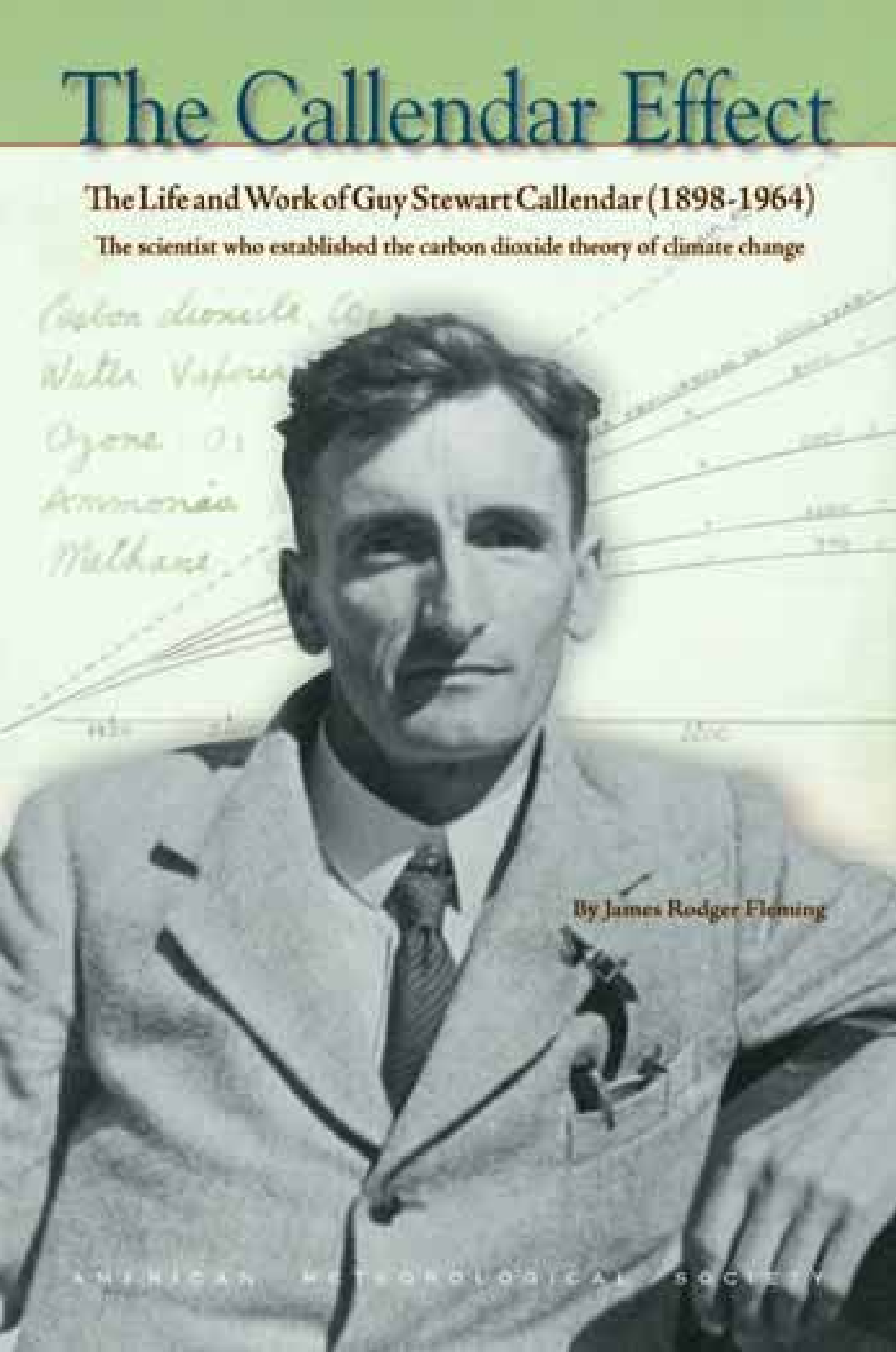


Fig. 1. Map of the 14 tree ring sampling sites. Ath, Athabasca; Bor, Boreal; Mac, Mackenzie; Que, Quebec; Upp, Upperwright; Got, Gotland; Jae, Jaemtland; Tir, Tirol; Tor, Tornetraesk; Man, Mangazeja; Mon, Mongolia; Pol, Polar Urals; Tai, Taimir; and Zha, Zhaschiviersk.



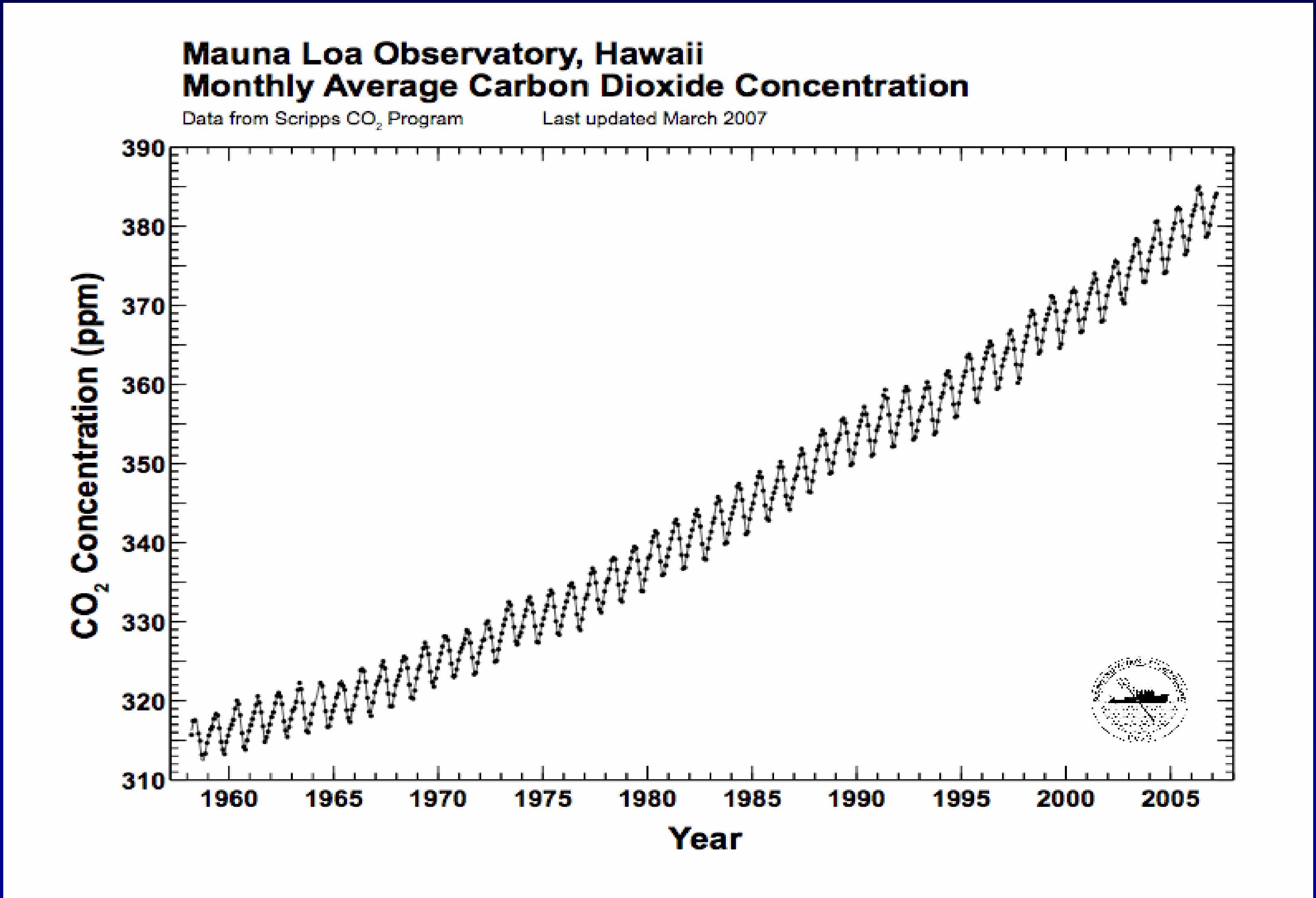
Records of past climate. Solid colored lines indicate seven reconstructions of Northern Hemisphere climate: yellow, (4); red, (5); purple, (3); orange, (6); green, (7); blue, (8); and pink (1). All records were re-calibrated with linear regression against 1881–1960 mean annual temperature observations averaged over land areas north of 20°N, and the results smoothed with a 50-year filter. The black dotted line shows the estimate that would be made if the predictor was observed warm-season temperatures from the same region, highlighting the difference between warm season and annual temperature changes during the observed record. Black solid line: smoothed observations, truncated in 1993 when the record of Esper et al. ends. Gray lines: annual temperature changes estimated from Northern Hemisphere borehole temperature profiles [dotted line, unweighted average of many sites (9); solid line, records gridded before averaging].

1.2 Deduction: If carbon dioxide rises, then we expect increases in temperature



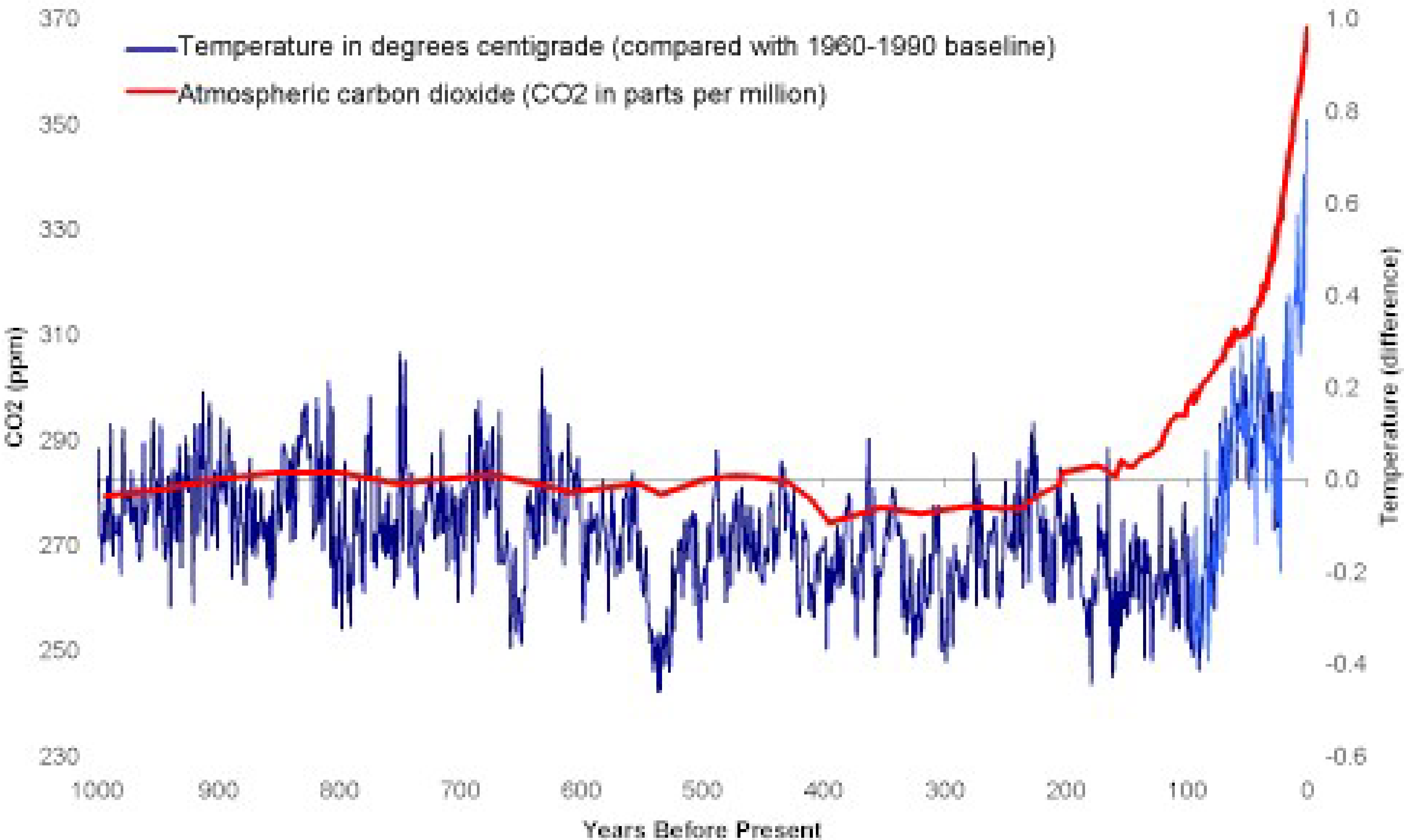
1930:
Guy Stewart Callendar

1958: Has carbon dioxide risen? Yes.



Has temperature rising along with it?

http://www.climateaudit.org/wp-content/1000yearsco2small.jpg



Climate science passes the deductive test

Not just a "correlation"

<u>It's a confirmation of a prediction</u>

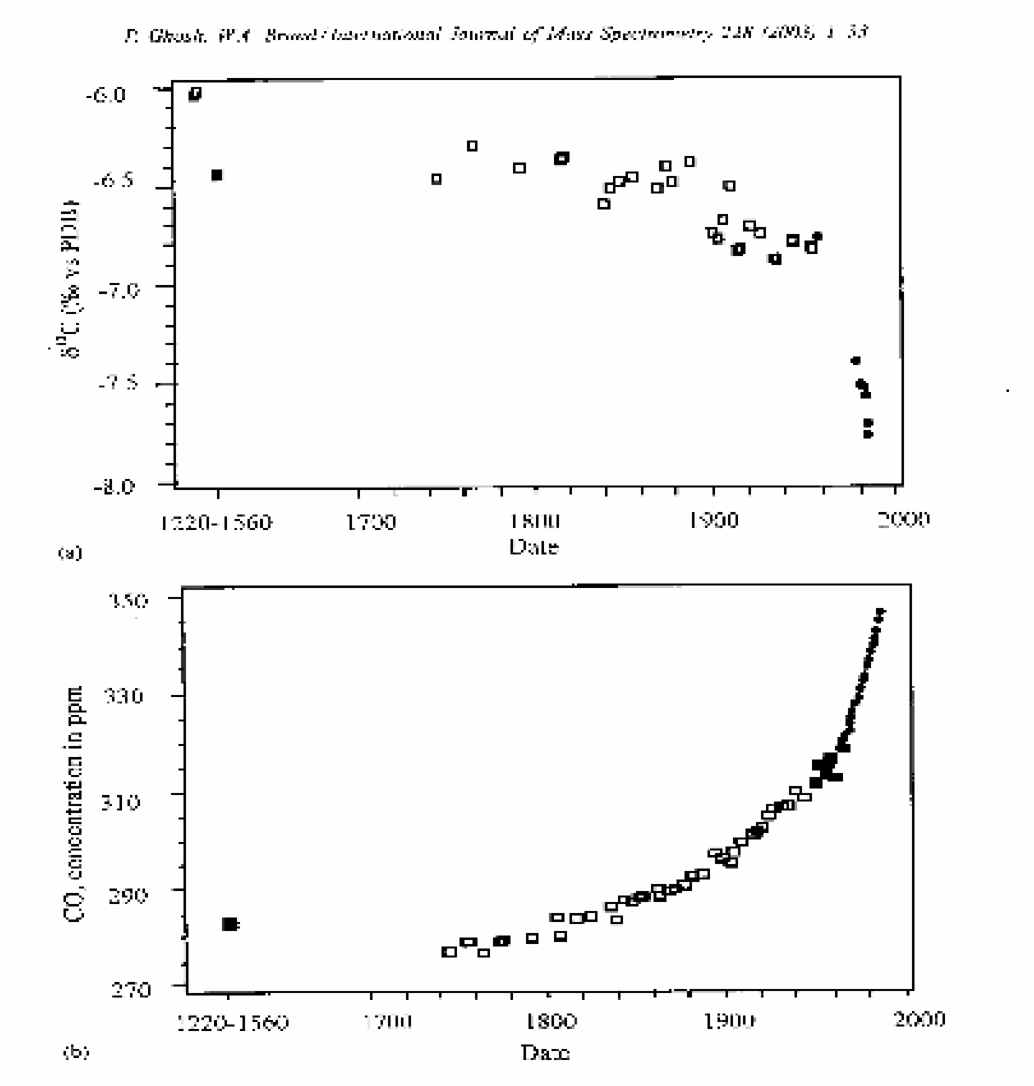
("The scientific method")

1.3 Falsification: Is there some way the consensus could be proved wrong?

How do we know that the CO_2 comes from human activities?

Maybe it comes from volcanoes....

Clear evidence that this CO_2 has been produced by burning fossil fuels (Ghosh and Brand, 2003)



- Clear correlation of falling ^{13}C values with rising CO_2
- Absolute values indicate organic carbon source (not volcanoes...)

Calculations of fossil fuel use since 1850s…

tional base pair on the DNA oligomer caused the RD complex to "disappear," presumably because the repressor could slide back and forth along the extended DNA and thus prevent the determination of a defined static (on the NMR time scale) RD complex structure.

The *lac* repressor and its complexes with DNA have long served as a central paradigm in the quest for an overarching molecular basis for protein-DNA recognition and for the mechanisms of transcription regulation. The study by Kalodimos *et al.* (*2*) provides a thoroughly satisfying structural conclusion to this saga.

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3. Wild-type *lac* repressor exists as a tetramer, but the "head-groups" of only two subunits at a time bind to an operator or nonspecific DNA site, and only these DNA binding domains of the repressor have an important role in the DNA-protein interaction. Hence, the dimer of DNA binding domains studied here provides a valid representation of the interactions of the repressor molecule with dsDNA for both the RO and the RD complexes.
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18. This so-called one-dimensional diffusion is not—indeed cannot be—faster than three-dimensional diffusion in free solution. Instead, one-dimensional diffusion speeds target location by reducing the volume of the solution that must be searched, rather than by increasing the rate of the searching process itself.
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20. Supported by NIH grants GM-15792 and GM-29158. P.H.v.H. is an American Cancer Society Research Professor of Chemistry.

OCEAN SCIENCE

The Fate of Industrial Carbon Dioxide

Taro Takahashi

The atmospheric CO_2 concentration has increased from about 280 parts per million (ppm) in 1800—the beginning of the industrial age—to 380 ppm today (*1*). During this time, the observed annual rate of increase has been about 50% of that expected from the estimated industrial CO_2 emission rate into the atmosphere. This means that an amount of CO_2 equivalent to about one-half of the industrial CO_2 emitted each year has been missing, and thus Earth's atmosphere is receiving only one-half the full impact of the anthropogenic CO_2 emissions. What process has been taking up the "missing carbon"? An answer to this question is fundamental not only for our understanding of the natural carbon cycle, but also for formulating a sound global CO_2 emission strategy. As reported on page 367 of this issue, Sabine *et al.* (*2*) used an extensive data set obtained for CO_2 concentration and other chemical properties during recent global oceanographic programs, together with a computational method developed by Gruber *et al.* (*3*), and provided a solid estimate for the total amount of CO_2 taken up by the global oceans from 1800 to 1994. Their results show that the oceans store a major proportion of the anthropogenic CO_2 and provide a better understanding of the carbon cycle. In an accompanying report on page 362, Feely *et al.* (*4*) show how the acidification of ocean waters that resulted from the dissolution of anthropogenic CO_2 has changed an important carbon pathway in the oceans—the production, dissolution, and accumulation of biogenic $CaCO_3$.

Enhanced online at www.sciencemag.org/cgi/content/full/305/5682/352

Ocean waters are stratified according to their density. In subsurface regimes, waters flow from polar regions toward lower latitudes along constant-density horizons, with little mixing between different densities. A parcel of water that is found at depths today was located at some past time near the sea surface, where it acquired CO_2 and oxygen from the overlying atmosphere (see the figure). During its course of subsurface travel, CO_2 was added from the oxidation of biogenic debris and dissolved organic compounds as well as from the dissolution of skeletal $CaCO_3$ falling through the water column. To compute the amount of CO_2 addition attributable to the atmospheric CO_2 increase, the background and biogenic additions must be subtracted from the measured value. Sabine *et al.* used several assumptions for estimating the biogenic contributions. The $P:N:C:O_2$ stoichiometry for decomposing organic matter is assumed to be constant. The amount of oxygen used for the oxidation is estimated to be the difference between the observed concentration and the original oxygen concentration, which in turn is obtained by assuming saturation with the atmosphere at the temperature of water. The amount of $CaCO_3$ dissolution is estimated from the difference between the observed alkalinity value and the original at-surface (or preformed) value that is estimated as a function of salinity, phosphate, and oxygen concentration (*3*). The background CO_2 concentration in seawater is estimated assuming that the water contained the preformed alkalinity and was in equilibrium with the preindustrial air for waters at depths below about 2000 m, or with atmospheric CO_2 at the time of the last contact with air for depths above about 2000 m. The age of the water sample is estimated from chlorofluorocarbon or tritium data. The overall uncertainty of the global inventory of anthropogenic CO_2 has been estimated to be about ±20% (*3*).

In table 1 of the Sabine *et al.* report (*2*), the 1800–1994 inventory for anthropogenic CO_2 thus estimated for the global ocean and other carbon pools is summarized. Two well-known quantities in the global carbon cycle are the emissions from fossil fuel combustion plus cement production of 244 ± 20 Pg C (petagrams of carbon, 1 Pg = 10^{15} g) and the amount of excess carbon in the atmosphere of 165 ± 4 Pg C as of 1994. The 1800–1994 ocean inventory of 118 ± 19 Pg C reported by Sabine *et al.* yields the following important information. First, the land biosphere carbon pool has decreased by 39 ± 28 Pg C (244 – 165 – 118 = –39) since 1800. This means that the ocean is the major repository of anthropogenic CO_2 and stores nearly 48% of hitherto emitted CO_2 into the atmosphere. Second, if the change in carbon emission from land use of 100 to 180 Pg C (*5*) is accepted, the terrestrial biosphere should have accordingly in-

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- Rise in CO_2 is temporally coincident with massive increases in fossil fuel burning since industrial revolution.
- If this were not so, it would falsify the theory.

2. Evidential standards

2.1 Has the evidence been subject to replication, witnessing, and peer review?

Temperature data has now been extensively replicated using independent methods, such as tree rings and coral reefs. Northern hemisphere data compared with southern.

Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability

Jan Esper,[1] Edward R. Cook,[2*] Fritz H. Schweingruber[1]

Preserving multicentennial climate variability in long tree-ring records is critically important for reconstructing the full range of temperature variability over the past 1000 years. This allows the putative "Medieval Warm Period" (MWP) to be described and to be compared with 20th-century warming in modeling and attribution studies. We demonstrate that carefully selected tree-ring chronologies from 14 sites in the Northern Hemisphere (NH) extratropics can preserve such coherent large-scale, multicentennial temperature trends if proper methods of analysis are used. In addition, we show that the average of these chronologies supports the large-scale occurrence of the MWP over the NH extratropics.

Much of the current debate on the Earth's climate variability is driven by the observation of a modern, century-long temperature increase, culminating with the last decade of the 20th century as the warmest since 1856 (*1*). These dramatic recent temperature changes have been related to those of the last millennium by the Mann-Bradley-Hughes (MBH) multiproxy reconstruction of NH annual temperatures (*2*). By combining instrumental temperature data with long, temperature-sensitive proxy records, the MBH reconstruction indicates that the 20th-century warming is abrupt and truly exceptional. It shows an almost linear temperature decrease from the year 1000 to the late 19th century, followed by a dramatic and unprecedented temperature increase to the present time. The magnitude of warmth indicated in the MBH reconstruction for the MWP, ~1000–1300 (*3, 4*), is uniformly less than that for most of the 20th century.

The MBH reconstruction has been criticized (*5*) for its lack of a clear MWP. Critics argue that tree-ring records, the substantial basis of the MBH reconstruction before the 17th century, cannot preserve long-term, multicentennial temperature trends. This contention is of fundamental importance because if tree-ring reconstructions are limited in this way, then including such records in hemispheric estimates of past temperatures would bias the results as argued (*5*). To illustrate that this need not be the case, we present the analysis of centuries-long ring-width trends in 1205 radial tree-ring series from 14 high-elevation and middle-to-high latitude sites distributed over a large part of the NH extratropics (Fig. 1). Tree species represented in this collection are from the genera *Picea*, *Pinus*, *Larix*, and *Abies*. Using these data, we demonstrate that multicentennial temperature information can be preserved in long tree-ring records provided that the data are properly processed to preserve such low-frequency information due to climate. We also show that the MWP was likely to have been a large-scale phenomenon in the NH extratropics that appears to have approached, during certain intervals, the magnitude of 20th-century warming, at least up to 1990.

Most millennia-long tree-ring chronologies are averages of many tree-ring series from living and dead trees. The segment lengths of these series are typically 200 to 400 years long, and the overlapping individual series are exactly aligned by calendar year and connected in time using a method known as "cross-dating" (*6*). The difficulty of preserving multicentennial variation in such tree-ring series, when the segment lengths are substantially shorter than the length of the overall chronology being developed, results from the removal of age-related biological growth trends that represent noise for the purpose of climatic reconstruction (*6*). These growth trends occur almost universally in "raw" tree-ring measurement series and frequently describe a downward trend of ring width with increasing age. Dendrochronologists usually eliminate these growth trends by detrending each tree-ring width series with a fitted smooth mathematical growth function. In such cases, the maximum wavelength of recoverable climatic information is fundamentally limited by the segment lengths of the individual detrended series (*7*). Thus, a 100-year-long tree-ring series will not contain any climatic variance at periods longer than 100 years if it is explicitly detrended by a fitted growth curve. Consequently, the problem of missing long-term trends in millennia-length tree-ring chronologies is due to using detrended series that are short relative to the multicentennial fluctuations due to climate (*8*). Exceptions are chronologies built with 1000 year or longer individual tree-ring series (*9, 10*) and chronologies developed by Regional Curve Standardization (RCS) (*11*) or Age Banding (*12*) methods.

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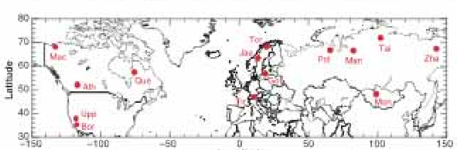

Fig. 1. Map of the 14 tree ring sampling sites. Ath, Athabasca; Bor, Boreal; Mac, Mackenzie; Que, Quebec; Upp, Upperwright; Got, Gotland; Jae, Jaerntland; Tir, Tirol; Tor, Tornetraesk; Man, Mangazeja; Mon, Mongolia; Pol, Polar Urals; Tai, Taimir; and Zha, Zhaschiviersk.

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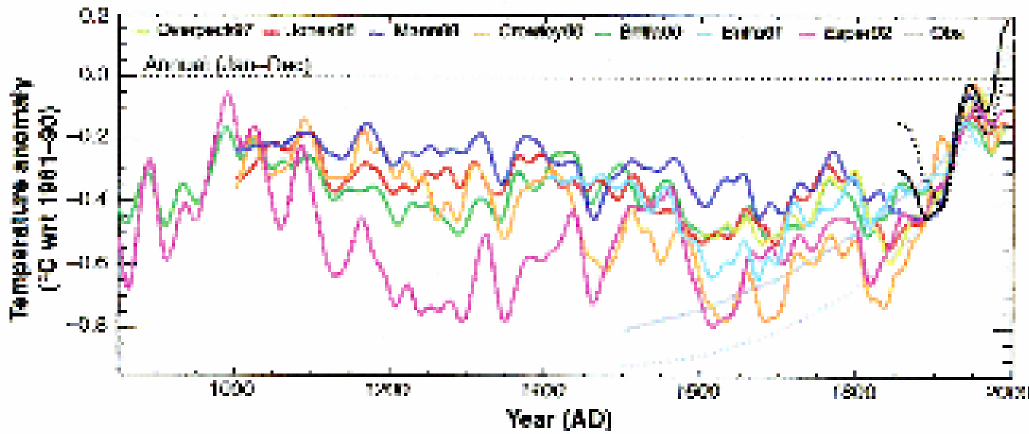
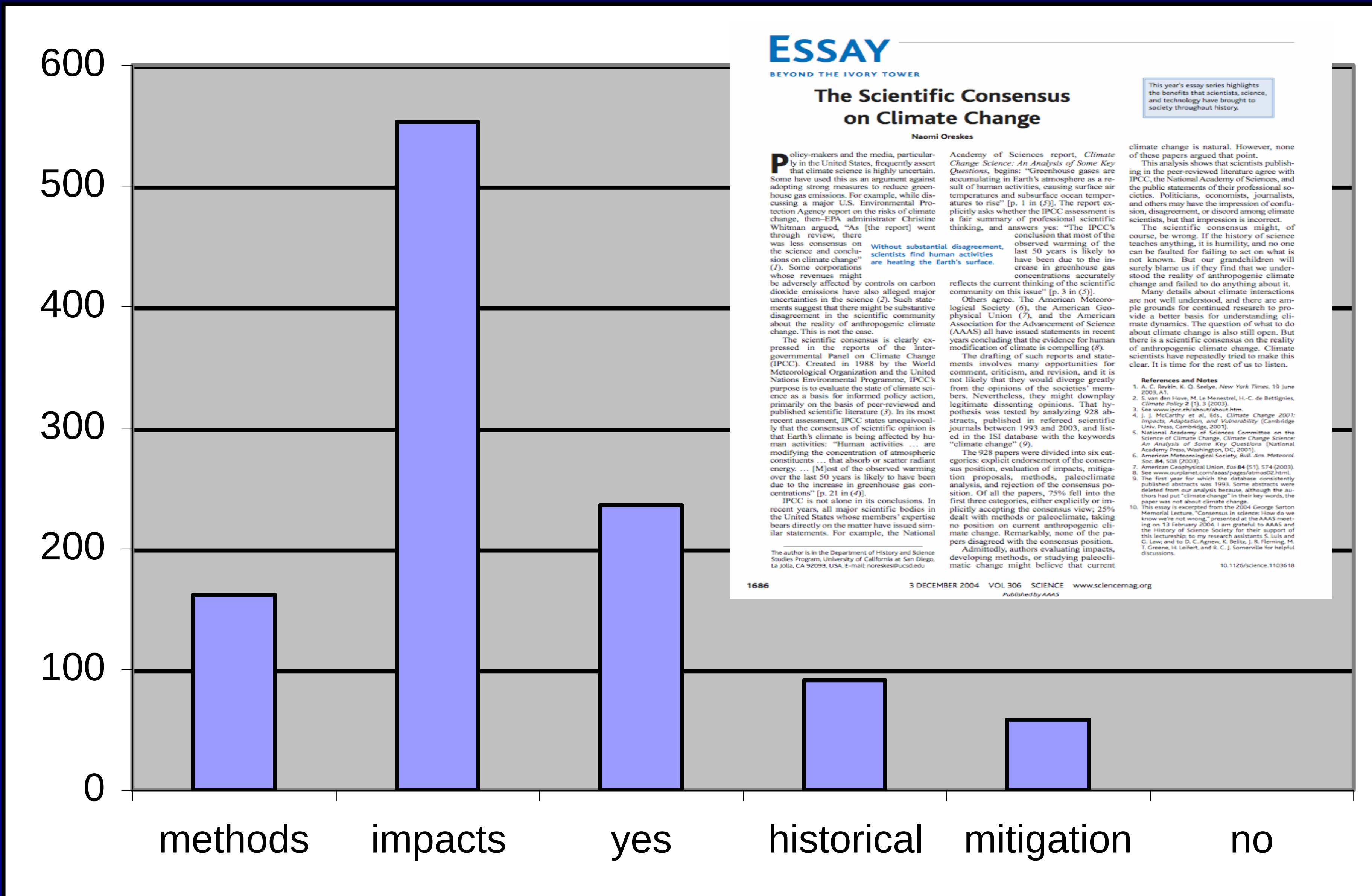


Records of past climate. Solid colored lines indicate seven reconstructions of Northern Hemisphere climate: yellow, (4); red, (5); purple, (3); orange, (6); green, (7); blue, (8); and pink (1). All records were re-calibrated with linear regression against 1881–1960 mean annual temperature observations averaged over land areas north of 20°N, and the results smoothed with a 50-year filter. The black dotted line shows the estimate that would be made if the predictor was observed warm-season temperatures from the same region, highlighting the difference between warm season and annual temperature changes during the observed record. Black solid line: smoothed observations, truncated in 1993 when the record of Esper et al. ends. Gray lines: annual temperature changes estimated from Northern Hemisphere borehole temperature profiles [dotted line, unweighted average of many sites (9); solid line, records gridded before averaging].

- Esper et al, 2002, Science

Peer review? The *contrarian* claims are the ones that fail peer review.



ESSAY

BEYOND THE IVORY TOWER

This year's essay series highlights the benefits that scientists, science, and technology have brought to society throughout history.

The Scientific Consensus on Climate Change

Naomi Oreskes

Policy-makers and the media, particularly in the United States, frequently assert that climate science is highly uncertain. Some have used this as an argument against adopting strong measures to reduce greenhouse gas emissions. For example, while discussing a major U.S. Environmental Protection Agency report on the risks of climate change, then–EPA administrator Christine Whitman argued, "As [the report] went through review, there was less consensus on the science and conclusions on climate change" (*1*). Some corporations whose revenues might be adversely affected by controls on carbon dioxide emissions have also alleged major uncertainties in the science (*2*). Such statements suggest that there might be substantive disagreement in the scientific community about the reality of anthropogenic climate change. This is not the case.

The scientific consensus is clearly expressed in the reports of the Intergovernmental Panel on Climate Change (IPCC). Created in 1988 by the World Meteorological Organization and the United Nations Environmental Programme, IPCC's purpose is to evaluate the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature (*3*). In its most recent assessment, IPCC states unequivocally that the consensus of scientific opinion is that Earth's climate is being affected by human activities: "Human activities … are modifying the concentration of atmospheric constituents … that absorb or scatter radiant energy. … [M]ost of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" [p. 21 in (*4*)].

IPCC is not alone in its conclusions. In recent years, all major scientific bodies in the United States whose members' expertise bears directly on the matter have issued similar statements. For example, the National Academy of Sciences report, *Climate Change Science: An Analysis of Some Key Questions*, begins: "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise" [p. 1 in (*5*)]. The report explicitly asks whether the IPCC assessment is a fair summary of professional scientific thinking, and answers yes: "The IPCC's conclusion that most of the observed warming of the last 50 years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue" [p. 3 in (*5*)].

Without substantial disagreement, scientists find human activities are heating the Earth's surface.

Others agree. The American Meteorological Society (*6*), the American Geophysical Union (*7*), and the American Association for the Advancement of Science (AAAS) all have issued statements in recent years concluding that the evidence for human modification of climate is compelling (*8*).

The drafting of such reports and statements involves many opportunities for comment, criticism, and revision, and it is not likely that they would diverge greatly from the opinions of the societies' members. Nevertheless, they might downplay legitimate dissenting opinions. That hypothesis was tested by analyzing 928 abstracts, published in refereed scientific journals between 1993 and 2003, and listed in the ISI database with the keywords "climate change" (*9*).

The 928 papers were divided into six categories: explicit endorsement of the consensus position, evaluation of impacts, mitigation proposals, methods, paleoclimate analysis, and rejection of the consensus position. Of all the papers, 75% fell into the first three categories, either explicitly or implicitly accepting the consensus view; 25% dealt with methods or paleoclimate, taking no position on current anthropogenic climate change. Remarkably, none of the papers disagreed with the consensus position.

Admittedly, authors evaluating impacts, developing methods, or studying paleoclimatic change might believe that current climate change is natural. However, none of these papers argued that point.

This analysis shows that scientists publishing in the peer-reviewed literature agree with IPCC, the National Academy of Sciences, and the public statements of their professional societies. Politicians, economists, journalists, and others may have the impression of confusion, disagreement, or discord among climate scientists, but that impression is incorrect.

The scientific consensus might, of course, be wrong. If the history of science teaches anything, it is humility, and no one can be faulted for failing to act on what is not known. But our grandchildren will surely blame us if they find that we understood the reality of anthropogenic climate change and failed to do anything about it.

Many details about climate interactions are not well understood, and there are ample grounds for continued research to provide a better basis for understanding climate dynamics. The question of what to do about climate change is also still open. But there is a scientific consensus on the reality of anthropogenic climate change. Climate scientists have repeatedly tried to make this clear. It is time for the rest of us to listen.

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9. The first year for which the database consistently published abstracts was 1993. Some abstracts were deleted from our analysis because, although the authors had put "climate change" in their key words, the paper was not about climate change.

10. This essay is excerpted from the 2004 George Sarton Memorial Lecture, "Consensus in science: How do we know we're not wrong," presented at the AAAS meeting on 13 February 2004. I am grateful to AAAS and the History of Science Society for their support of this lectureship; to my research assistants S. Luis and G. Law; and to D. C. Agnew, K. Belitz, J. R. Fleming, M. T. Greene, H. Leifert, and R. C. J. Somerville for helpful discussions.

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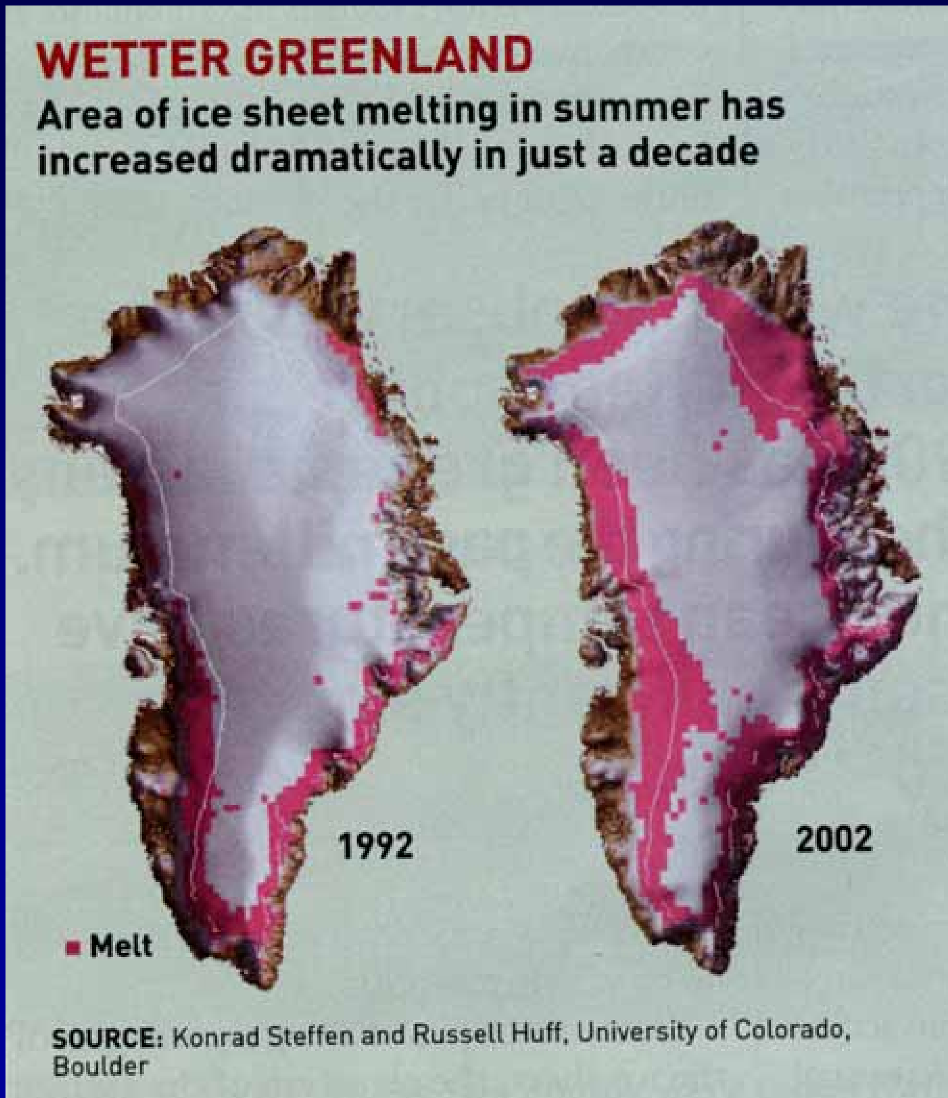
2.2 Consilience of evidence



Sciencexpress Report

Extracting a Climate Signal from 169 Glacier Records

J. Oerlemans

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A temperature history for different parts of the world has been constructed from 169 glacier length records. Using a first-order theory of glacier dynamics, changes in glacier length were related to changes in temperature. The derived temperature histories are fully independent of proxy and instrumental data used in earlier reconstructions. Moderate global warming started in the middle of the 19th century. The reconstructed warming in the first half of the 20th century is 0.5 K. This warming was remarkably coherent over the globe. The warming signals from glaciers at low and high elevations appear to be very similar.

The world-wide retreat of many glaciers during the last few decades is frequently mentioned as a clear and unambiguous sign of global warming (*1*, *2*). Recent glacio-meteorological field experiments and modelling studies have led to a much improved understanding of the link between climate processes and glacier mass balance (*3*, *4*). Yet, the climatic information contained in records of glacier geometry, particularly glacier length, has only partly been exploited. This is perhaps due to the nature of the data. Because data points on glacier length are irregularly spaced in time (Fig. 1), the data are more difficult to handle than some other proxies. Therefore, in most temperature reconstructions of the late Holocene climate glacier records are not included and most information comes from tree rings (*5*, *6*).
Compared to biogenic climate indicators like tree-rings, glacier systems react in a relatively simple way to climate change. The transfer function does not change in time and geometric effects can be dealt with. An interesting aspect of glaciers is that many are found at high elevations. This implies that a climate signal reflected in glacier fluctuations can be studied as a function of height. The recent discussion on the possible discrepancy between surface temperature observations and satellite measurements (*7*) and the problems involved in analysing radiosonde temperature data (*8*) demonstrate the importance of climate proxies from high-elevation sites.

Although glacier retreat is mentioned in almost all assessments on climate change, the number of systematic studies of longer records is remarkably small. Some glaciers have been studied in great detail (*9*, *10*), but the methods used cannot be applied to a large sample because the required input data is not available. Direct mass-balance observations have been analysed to estimate the contribution of glaciers to sea-level change (*11*). Unfortunately, such observations started only in the second half of the 20th century and do not provide information about the transition from the Little Ice Age to the current climatic state.

Here an objective climatic interpretation of glacier length records from all over the world is presented. A linear inverse model provides the basis for an individual treatment of all length records. Differences in the climate sensitivity and response time of glaciers are taken into account.

Records of glacier length were compiled from various sources, building on a dataset from an earlier study (*12*). It was possible to extend the set of 48 records to a set of 169 records from glaciers found at widely differing latitudes and elevations. The core of the dataset comes from the files of the World Glacier Monitoring Service (WGMS, Zürich) (*13*). Records were then included from glaciers in Patagonia (*14*), southern Greenland (*15*), Iceland (*16*) and Jan Mayen (*17*). Additional information was taken from the Satellite Image Atlas of Glaciers of the World (*18*) and from reports of the Swiss Academy of Sciences (*19*). The character of the records differs widely (Fig. 1). Some start in 1600 and have typically 10 data points until 1900, and more afterwards. Other records start around 1900, but have annual resolution throughout. The longest record is that of the Untere Grindelwaldgletscher, which starts in 1534 (*20*).

Data points in the earlier parts of glacier records are sparse, but normally quite reliable. The information on maximum stands from sketches, etches, paintings and photographs can be checked with moraine systems that are still in place today. However, records based on information from moraines dated by lichenometry or fossil wood without any additional evidence have not been used in the present study.

The records are not spread equally over the globe. There is a strong bias towards the European Alps, where a wealth of documents exists and glacier monitoring has been introduced relatively early. Fluctuations of some glaciers in Iceland and Scandinavia before 1800 have also been documented well

Oerlemans, 2002, Utrecht.Analysis of 169 glacial records

3. Performance

Climate models attacked as "unreliable."
Many model-based predictions have come true.

- Melting of polar ice sheets & continental glaciers
- Polar amplification
- Rising sea level
- Earlier spring onset
- More warming at night than in day
- More precipitation in some regions
- Intensification of extreme weather events (Katrina, record-breaking season of 2005)

2005: Most intense hurricane season in history

- Most tropical and subtropical storms (28)
- Record number (15) became hurricanes
- Record number (4) became category 5
  - Most “retired” names
- Katrina: Costliest ($100 billion damages)
- Wilma: Lowest pressure ever recorded in an Atlantic hurricane
- Hurricane season continued long past “official end”
  - Official end is Nov. 30, storms continued into January

Climate models predicted intensification of hurricanes, caused in increase in sea surface temperature, well before 2005

Two papers in summer 2005 (before Katrina) documented increasing hurricane intensity

Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment

P. J. Webster,[1] G. J. Holland,[2] J. A. Curry,[1] H.-R. Chang[1]

We examined the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over the past 35 years, in an environment of increasing sea surface temperature. A large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurred in the North Pacific, Indian, and Southwest Pacific Oceans, and the smallest percentage increase occurred in the North Atlantic Ocean. These increases have taken place while the number of cyclones and cyclone days has decreased in all basins except the North Atlantic during the past decade.

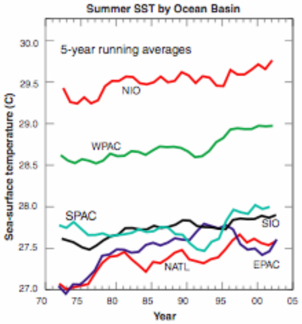

Fig. 1. Running 5-year mean of SST during the respective hurricane seasons for the principal ocean basins in which hurricanes occur: the North Atlantic Ocean (NATL: 90° to 20°E, 5° to 25°N, June-October), the Western Pacific Ocean (WPAC: 120° to 180°E, 5° to 20°N, May-December), the East Pacific Ocean (EPAC: 90° to 120°W, 5° to 20°N, June-October), the Southwest Pacific Ocean (SPAC: 155° to 180°E, 5° to 20°S, December-April), the North Indian Ocean (NIO: 55° to 90°E, 5° to 20°N, April-May and September-November), and the South Indian Ocean (SIO: 50° to 115°E, 5° to 20°S, November-April).

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LETTERS

Increasing destructiveness of tropical cyclones over the past 30 years

Kerry Emanuel[1]

Theory[1] and modelling[2] predict that hurricane intensity should increase with increasing global mean temperatures, but work on the detection of trends in hurricane activity has focused mostly on their frequency[3,4] and shows no trend. Here I define an index of the potential destructiveness of hurricanes based on the total dissipation of power, integrated over the lifetime of the cyclone, and show that this index has increased markedly since the mid-1970s. This trend is due to both longer storm lifetimes and greater storm intensities. I find that the record of net hurricane power dissipation is highly correlated with tropical sea surface temperature, reflecting well-documented climate signals, including multidecadal oscillations in the North Atlantic and North Pacific, and global warming. My results suggest that future warming may lead to an upward trend in tropical cyclone destructive potential, and—taking into account an increasing coastal population—a substantial increase in hurricane-related losses in the twenty-first century.

$$\mathrm{PD} = 2\pi \int_0^{\tau} \int_0^{r_0} C_D \rho |\mathbf{V}|^3 r\,dr\,dt \quad (1)$$

$$\mathrm{PDI} = \int_0^{\tau} V_{max}^3\,dt \quad (2)$$

Webster et al. (2005) Science 309

Emanuel (2005) Science 436

Can we *prove* that the hurricane season of 2005 was caused by global warming?

No.

In principle, other causes could have produced the same effect

But if we make a prediction and it comes true, then it is strong evidence, especially…

- … if there are no other *plausible* causes.
- …if there is no *evidence* of any alternative cause.
- …if there is independent evidence that the proposed cause (global warming) exists.

4. Inference to the best explanation

The goal of science is not merely to develop a possible explanation, you have to develop the *best* explanation….

That explanation must be based on a cause that you know is actually occuring in the world (“vera causa”)

Isaac Newton, *Principia Mathematica* (1687)

"In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true not withstanding any contrary hypothesis that may be imagined…….This rule we must follow, [and] may not be evaded by [speculative] hypotheses."

"Evasion by speculative hypothesis" is precisely what contrarians have done

- Proposed speculative hypotheses (about natural variation) without providing evidence of their actual role.
- Speculative reassurances about human capacity for adaptation.
- Alarmist claims about collapse of US economy, largely without evidence

5. Community standards

- Despite Newton's endorsement, many philosophers uncomfortable with idea of inference to best explanation.
- What constitutes best?
- Who decides?
- Using what criteria?

Answer:
Community of scientific experts

Thomas Kuhn
“Structure of Scientific Revolutions”

Paradigm is not just a particular theory about natural world.
Also a set of standards.

Include things like peer review, and rejection of speculative hypothesis

Recently some have asserted “science is not about consensus”

Opposite is true:

Science is *precisely* about consensus, because consensus is the result of the application of community standards.

Answer to issue of scientists "believing in cooling" in 1970s: There was no consensus

SCIENCE

The Cooling World

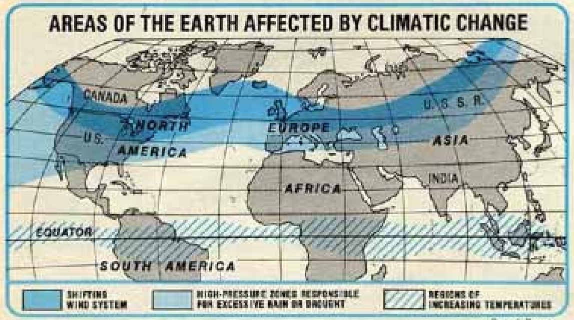
There are ominous signs that the earth's weather patterns have begun to change dramatically and that these changes may portend a drastic decline in food production—with serious political implications for just about every nation on earth. The drop in food output could begin quite soon, perhaps only ten years from now. The regions destined to feel its impact are the great wheat-producing lands of Canada and the U.S.S.R. in the north, along with a number of marginally self-sufficient tropical areas—parts of India, Pakistan, Bangladesh, Indochina and Indonesia—where the growing season is dependent upon the rains brought by the monsoon.

The evidence in support of these predictions has now begun to accumulate so massively that meteorologists are hard-reduce agricultural productivity for the rest of the century. If the climatic change is as profound as some of the pessimists fear, the resulting famines could be catastrophic. "A major climatic change would force economic and social adjustments on a worldwide scale," warns a recent report by the National Academy of Sciences, "because the global patterns of food production and population that have evolved are implicitly dependent on the climate of the present century."

A survey completed last year by Dr. Murray Mitchell of the National Oceanic and Atmospheric Administration reveals a drop of half a degree in average ground temperatures in the Northern Hemisphere between 1945 and 1968. According to George Kukla of Columbia University, satellite photos indicated a sudden, large increase in Northern Hemisphere snow cover in the winter of 1971-72. And ic change is at least as fragmentary as our data," concedes the National Academy of Sciences report. "Not only are the basic scientific questions largely unanswered, but in many cases we do not yet know enough to pose the key questions."

Extremes: Meteorologists think that they can forecast the short-term results of the return to the norm of the last century. They begin by noting the slight drop in over-all temperature that produces large numbers of pressure centers in the upper atmosphere. These break up the smooth flow of westerly winds over temperate areas. The stagnant air produced in this way causes an increase in extremes of local weather such as droughts, floods, extended dry spells, long freezes, delayed monsoons and even local temperature increases—all of which have a direct impact on food supplies.

"The world's food-producing system," warns Dr. James D. McQuigg of NOAA's Center for Climatic and Environmental Assessment, "is much more sensitive to



pressed to keep up with it. In England, farmers have seen their growing season decline by about two weeks since 1950, with a resultant over-all loss in grain production estimated at up to 100,000 tons annually. During the same time, the average temperature around the equator has risen by a fraction of a degree—a fraction that in some areas can mean drought and desolation. Last April, in the most devastating outbreak of tornadoes ever recorded, 148 twisters killed more than 300 people and caused half a billion dollars' worth of damage in thirteen U.S. states.

Trend: To scientists, these seemingly disparate incidents represent the advance signs of fundamental changes in the world's weather. The central fact is that after three quarters of a century of extraordinarily mild conditions, the earth's climate seems to be cooling down. Meteorologists disagree about the cause and extent of the cooling trend, as well as over its specific impact on local weather conditions. But they are almost unanimous in the view that the trend will a study released last month by two NOAA scientists notes that the amount of sunshine reaching the ground in the continental U.S. diminished by 1.3 per cent between 1964 and 1972.

To the layman, the relatively small changes in temperature and sunshine can be highly misleading. Reid Bryson of the University of Wisconsin points out that the earth's average temperature during the great Ice Ages was only about 7 degrees lower than during its warmest eras—and that the present decline has taken the planet about a sixth of the way toward the Ice Age average. Others regard the cooling as a reversion to the "little ice age" conditions that brought bitter winters to much of Europe and northern America between 1600 and 1900—years when the Thames used to freeze so solidly that Londoners roasted oxen on the ice and when iceboats sailed the Hudson River almost as far south as New York City.

Just what causes the onset of major and minor ice ages remains a mystery. "Our knowledge of the mechanisms of climat- the weather variable than it was even five years ago." Furthermore, the growth of world population and creation of new national boundaries make it impossible for starving peoples to migrate from their devastated fields, as they did during past famines.

Climatologists are pessimistic that political leaders will take any positive action to compensate for the climatic change, or even to allay its effects. They concede that some of the more spectacular solutions proposed, such as melting the arctic ice cap by covering it with black soot or diverting arctic rivers, might create problems far greater than those they solve. But the scientists see few signs that government leaders anywhere are even prepared to take the simple measures of stockpiling food or of introducing the variables of climatic uncertainty into economic projections of future food supplies. The longer the planners delay, the more difficult will they find it to cope with climatic change once the results become grim reality.

—PETER GWYNNE with bureau reports

Two major groups of scientists studying climate issues

- Ice ages (CLIMAP), time scale of 10^3-10^4 yr, vs. early work on anthropogenic climate change, 10^1-10^2 yr.
- Hindsight: scientists in Newsweek over-interpreted a short-term signal.
- No general agreement.

The claim that there was just 30 years ago there a consensus that the world was cooling is simply wrong, factually.

Take home:

Climate science satisfies a diversity of evaluative criteria.

Methodological: Both inductive, deductive, and falsifiable.

Evidentiary : Strong consilience of evidence through instrumental and proxy records.

Performance: Predicted effects now observed.

Inference to best explanation. All available evidence points towards role of human effects.

Community standards

And there is no other “contrary hypothesis” for which there is any substantial evidence that can explain the observed effects.

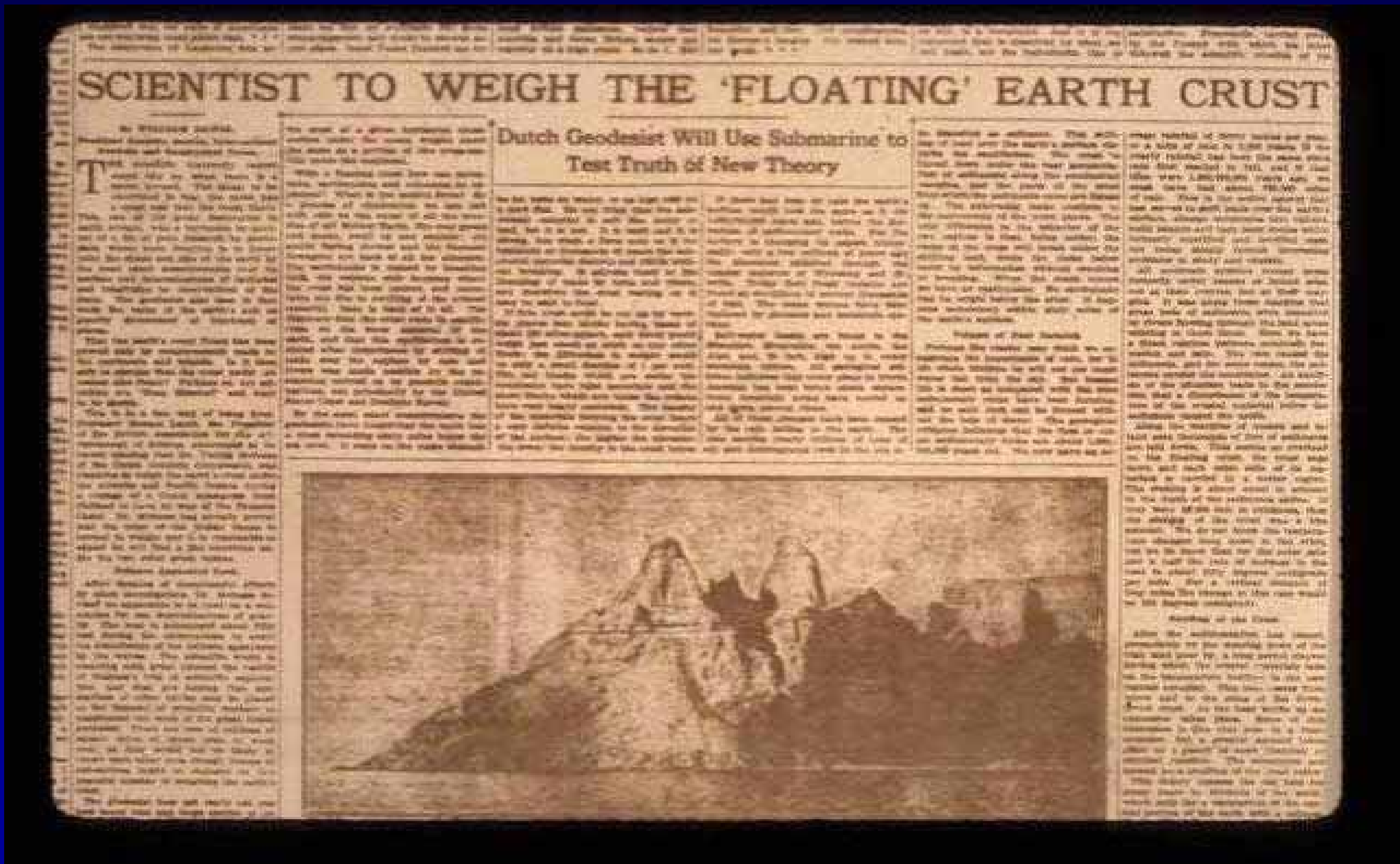
Serious evaluation of any science for policy needs to look at science from diverse angles

Isn’t there a simpler test?

“Consilience of evidence” (William Whewell)

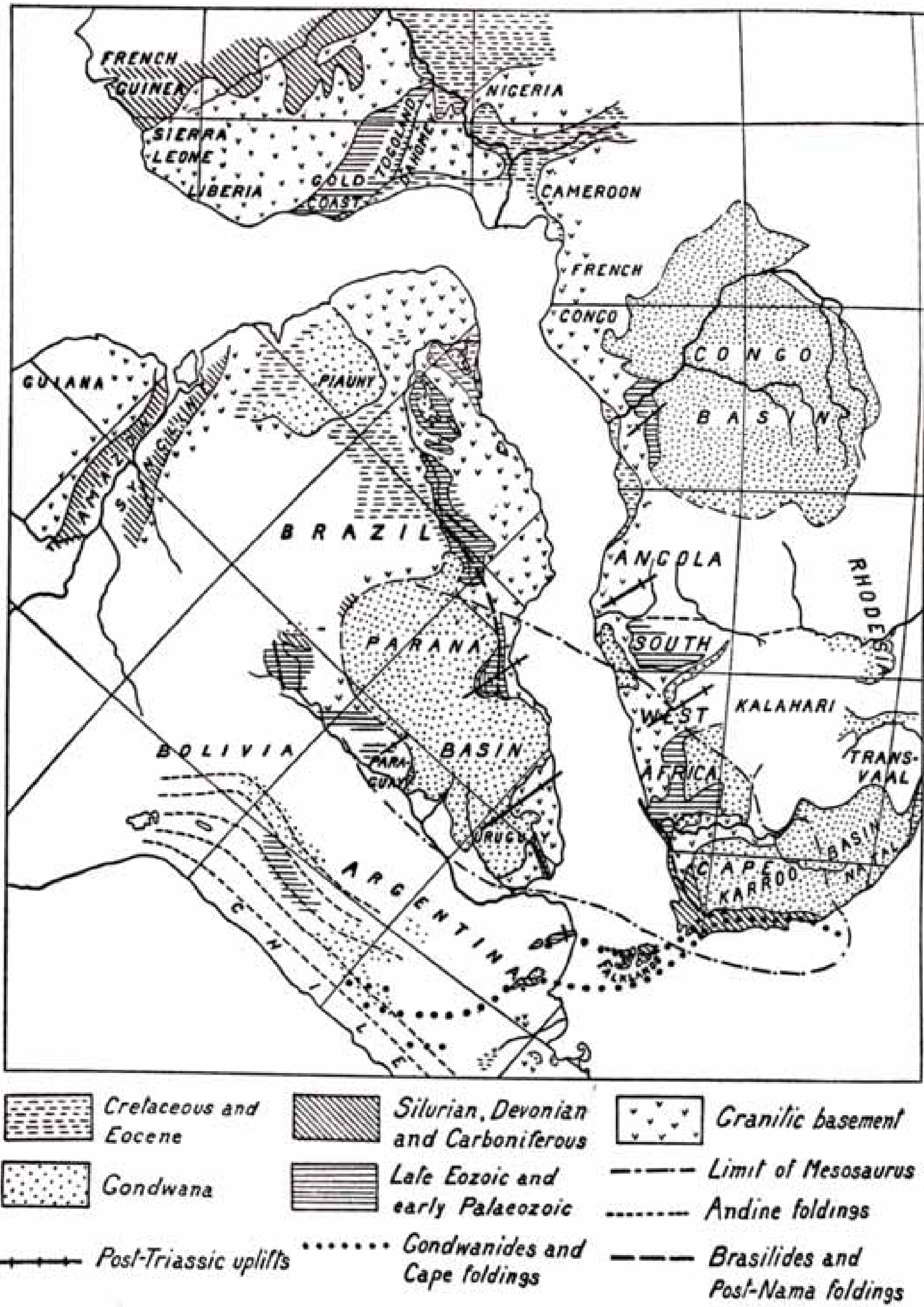
Multiple, independent lines of evidence converging on a single coherent account.

The Rejection of Continental Drift



SCIENTIST TO WEIGH THE 'FLOATING' EARTH CRUST

Dutch Geodesist Will Use Submarine to Test Truth of New Theory



A consilience of evidence

Drawn from well-established scientific traditions:

stratigraphy,

paleontology,

structural geology,

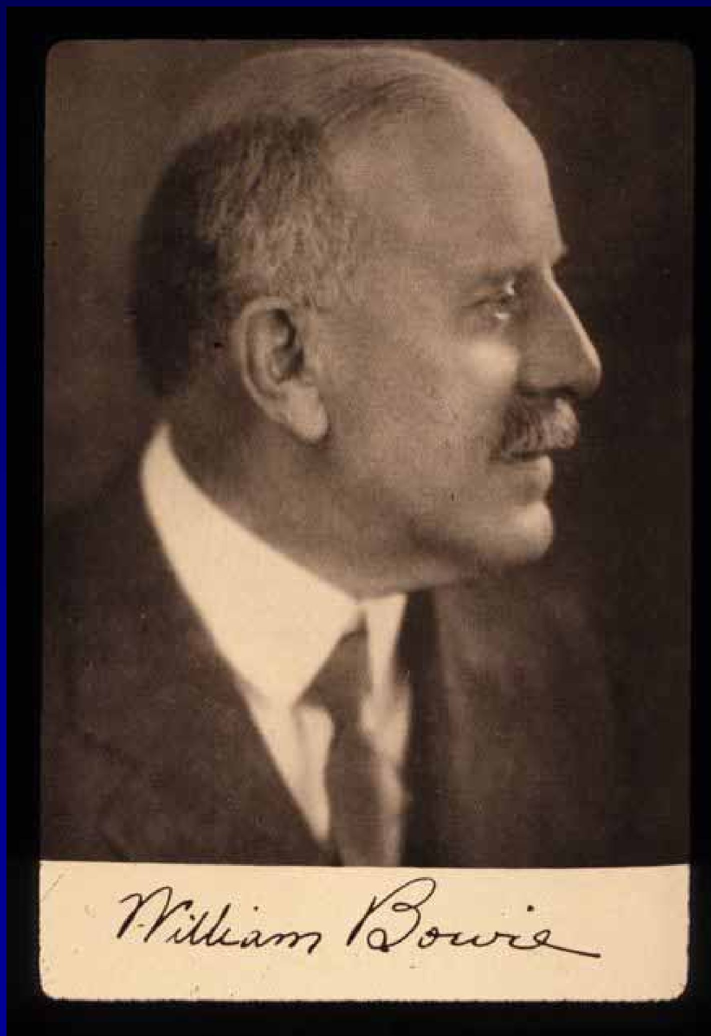
paleo-climatology.

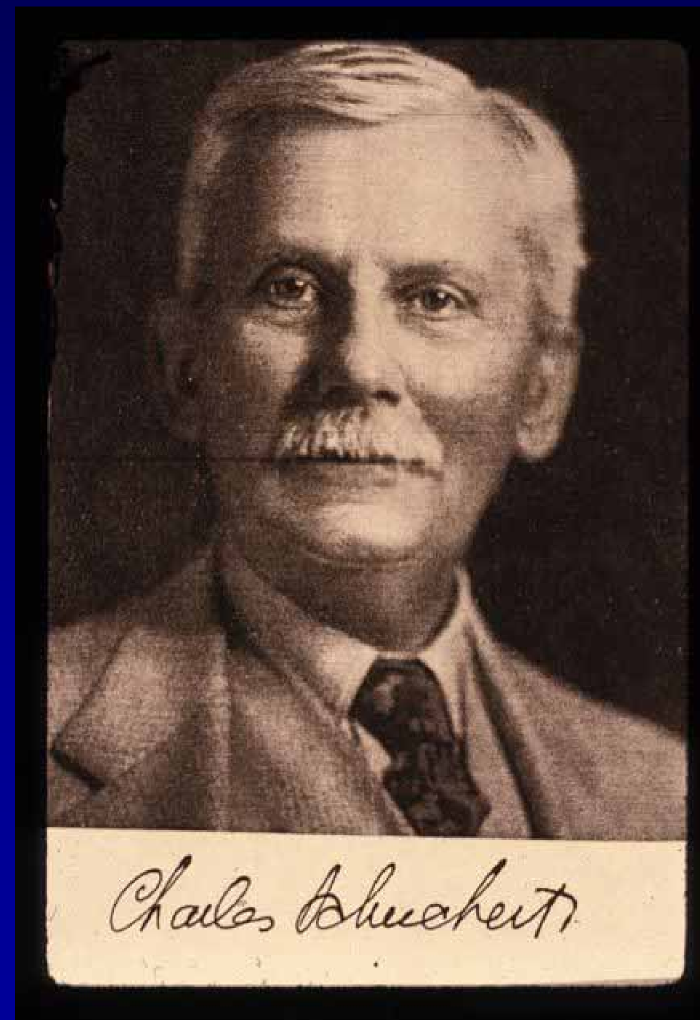
Collected by respected scientists over decades.

All added up

Du Toit (1927)

Why did rejecters reject it?





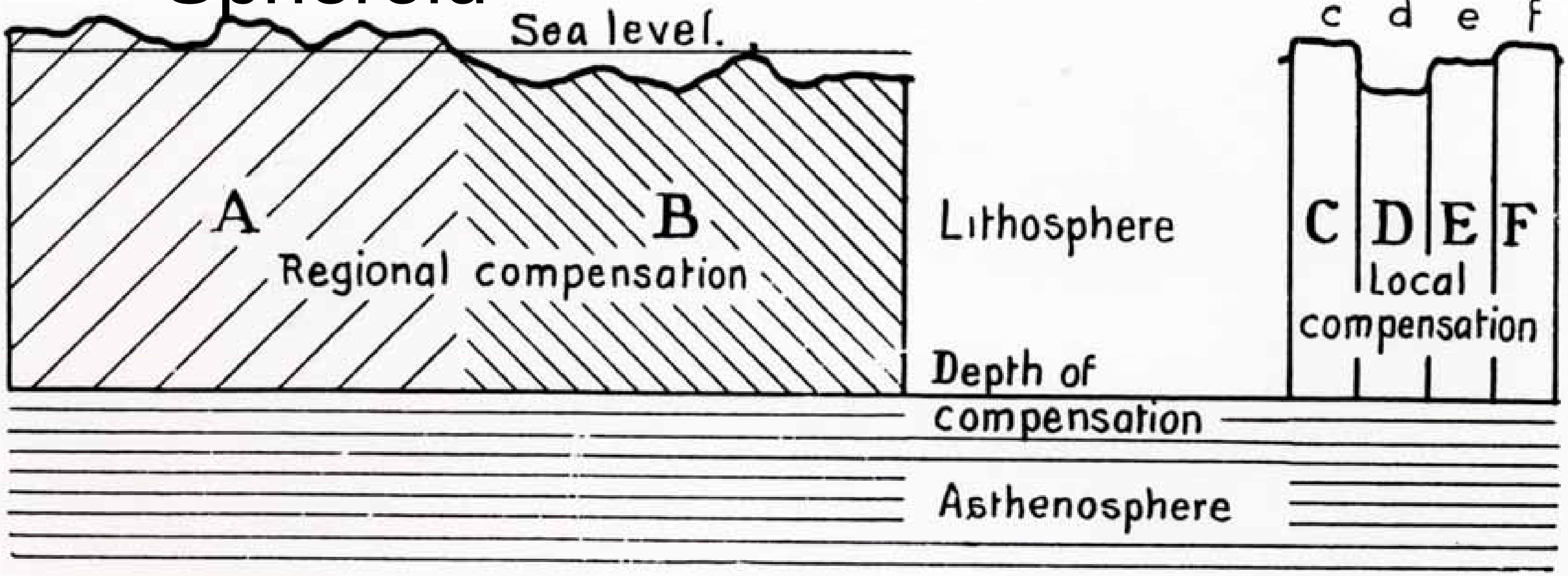
Bowie’s rejection was based on geodetic evidence, collected by his mentor, John Hayford, at US Coast and Geodetic Survey

Bowie’s objection

Continental drift was incompatible with the model of the Earth’s crust accepted by American geophysicists.

The Hayford Spheroid

FIG. 1.



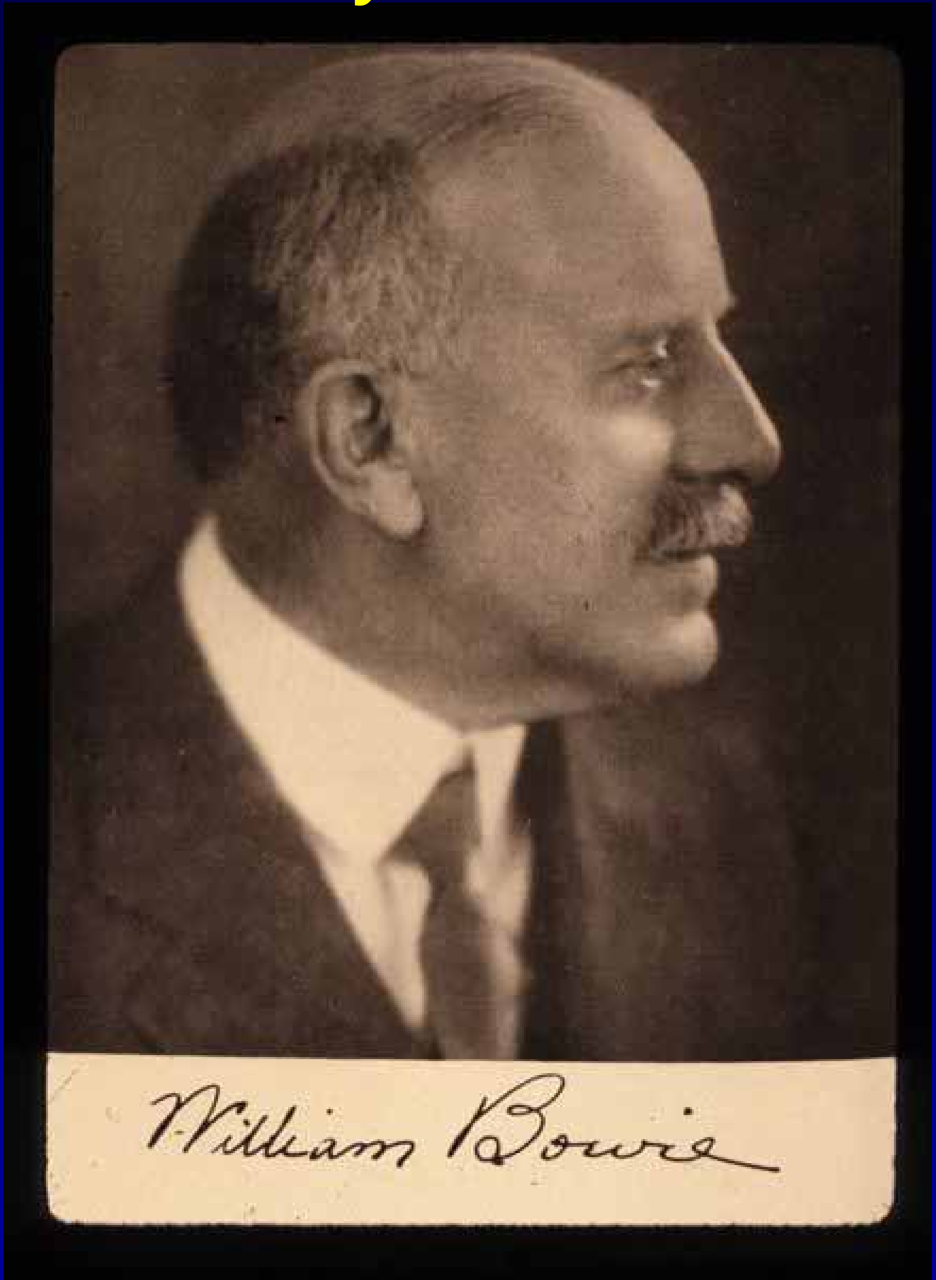
- Early 1900s, American geodesist John Hayford, Chief of Geodesy at the U.S.C.G.S., developed a model to interpret surface gravity measurements.
- Produced a new value for the figure of the Earth

In 1924, Hayford spheroid adopted as international standard by IUGG.

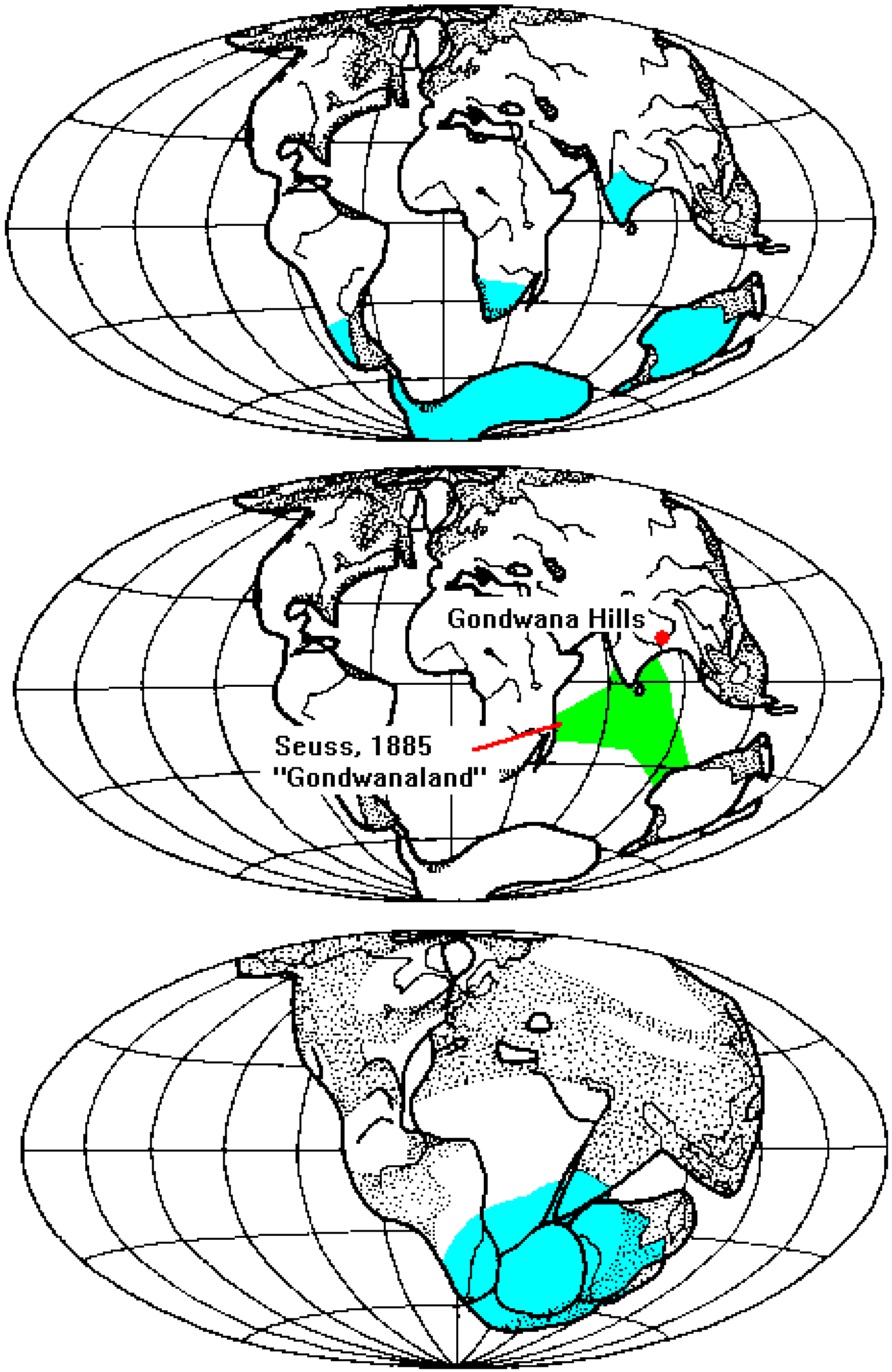
SCIENTIST TO WEIGH THE 'FLOATING' EARTH CRUST

Dutch Geodesist Will Use Submarine to Test Truth of New Theory

The Hayford model was incompatible with drift.



- Bowie, became one of America′s most active and vocal opponents of drift.
- Persuaded many others.
- Major factor in American rejection of theory.



In drawing this conclusion, he ignored all the other data (from stratigraphy, paleontology, paleo-climatology, etc...)

He violated principle of consilience of evidence:

How does *all* the evidence stack up?

Made his choice wholly on the basis of *geodetic* evidence (from his own speciality)…

…and ignored the large body of data from various geological specialties that independently argued in favor of continental drift.

A common pattern:

Prejudice…
Intellectual
chauvinism…

Epistemological affinities

We all gravitate towards certain kinds of evidence and arguments, and they tend to be the ones with which we are most familiar (either intellectually or sociologically)

Charles Richter (1958):
"We are all best impressed by evidence of the type with which we are most familiar."

Bill Menard (1986):
Some...scientists believe in God and some in Country, but all believe that their own ...data are without equal, and they adjust other data to fit them."

No one had to make a huge policy decision in the 1920s that hinged on whether or not continental drift was true

We do have to make decisions about global warming

Doing nothing is a decision.

Why the scale and scope IPCC are so important

It’s all about consilience of evidence.

It’s about looking at the big picture.

In early 1980s, officials in the Reagan administration argued that the situation was not urgent, we had time to wait and see.

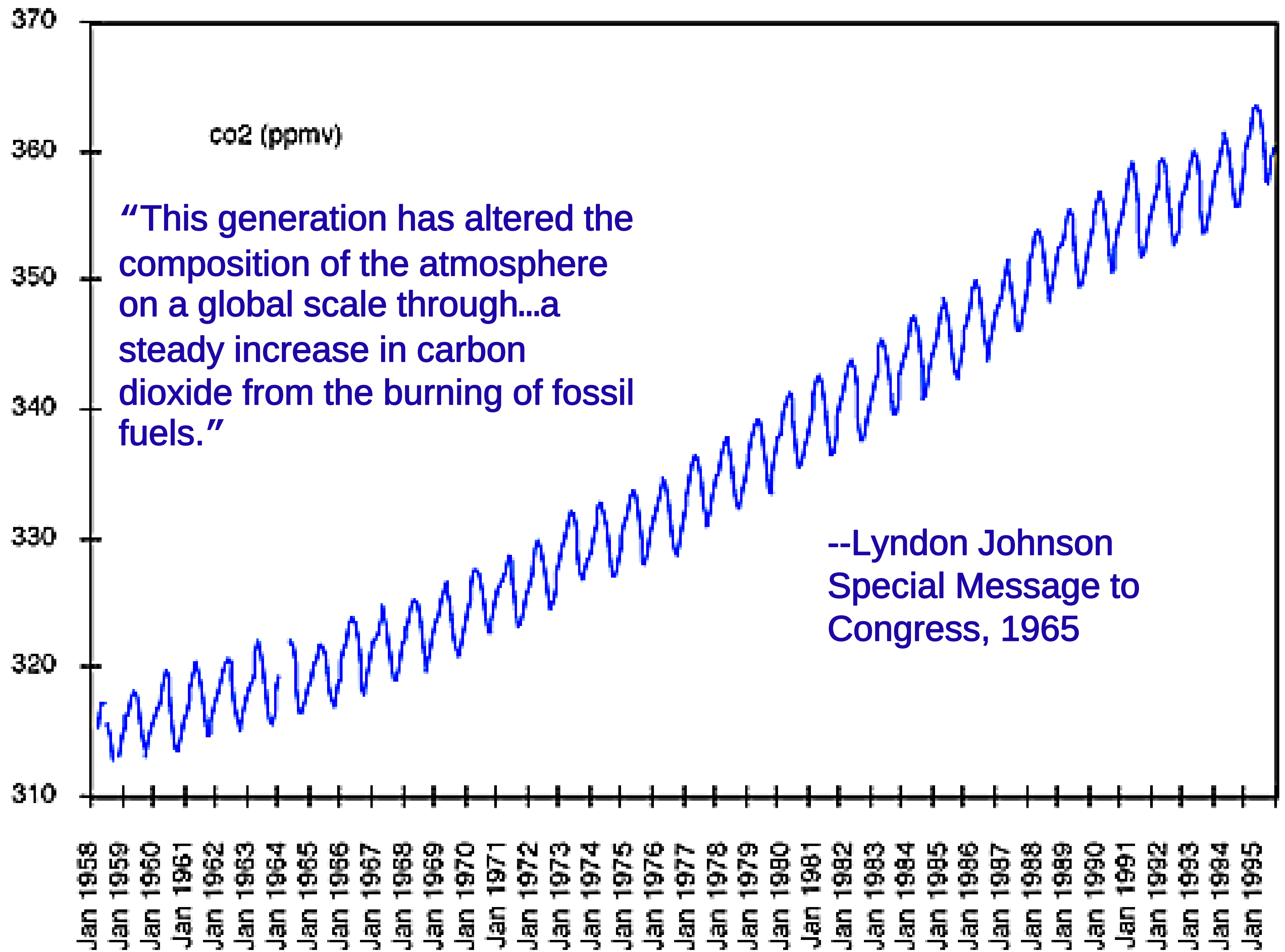
We have waited and we have seen.

Earth scientists been studying the role of carbon dioxide in climate change for longer than it took them to come to consensus on continental drift.

Thousands of scientists have assessed and reviewed the evidence, and assessed and reviewed it again, and again, and again.

In four reports, over nearly 20 years, leading experts around globe have affirmed the reality of anthropogenic warming--now no longer as a prediction, but as an observational reality.

Conclusion they have come to is one that we actually already knew in 1965…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co2 (ppmv)
“This generation has altered the composition of the atmosphere on a global scale through…a steady increase in carbon dioxide from the burning of fossil fuels.”
--Lyndon Johnson Special Message to Congress, 1965
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The effect of that alteration is now clear.

Muir Glacier, Ak: August, 1941 (photo by William Field) August, 2004 (photo by Bruce Molnia)

The End.