EPA-NCEE Seminar

Scientific Uncertainty and the Risks of Climate Change

Jay Gulledge, PhD

Senior Scientist and

Program Manager for Science & Impacts

Pew Center on Global Climate Change

PEW CENTER ON Global CLIMATE CHANGE

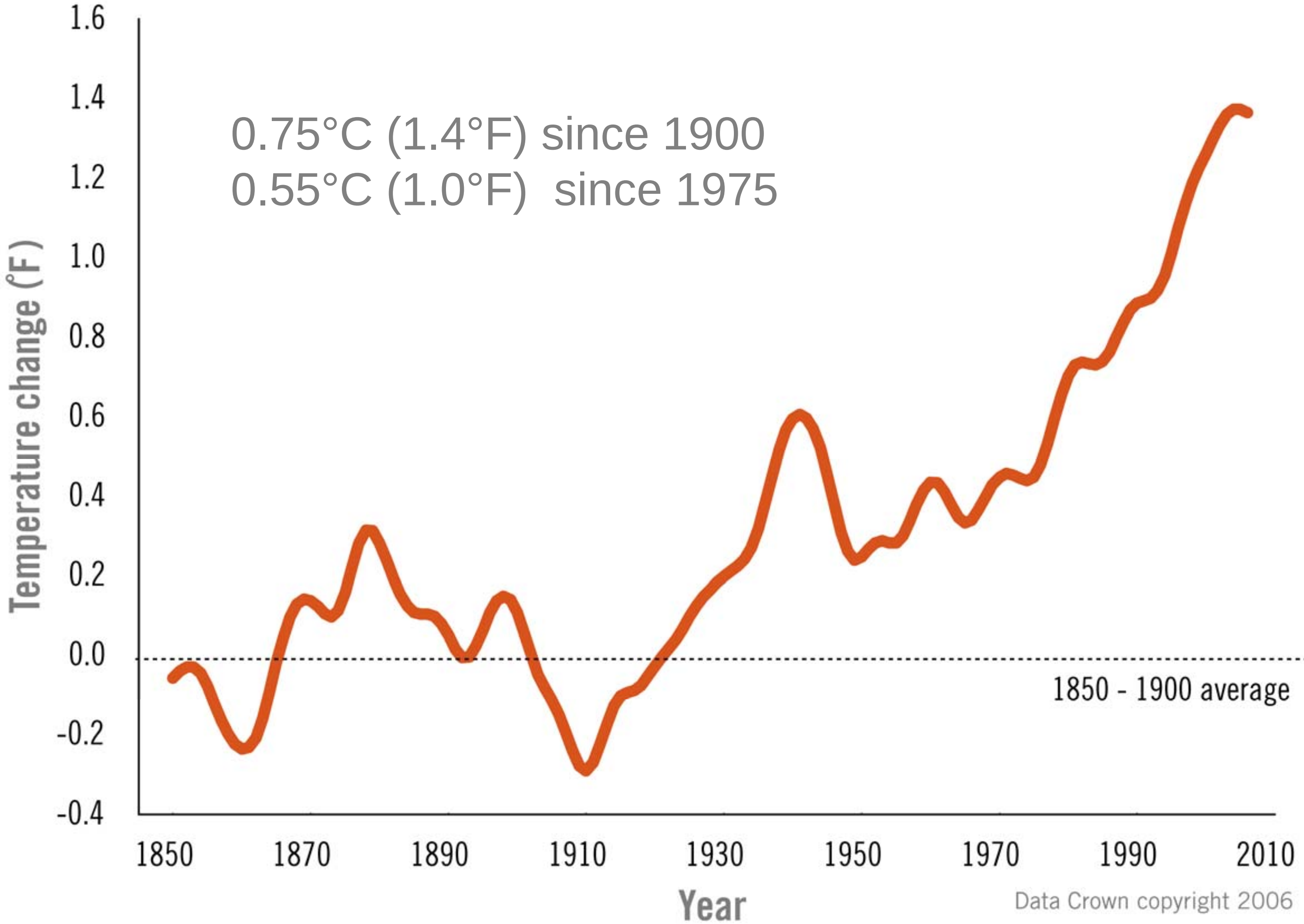
Disclaimer (added by EPA)

This presentation by Dr. Jay Gulledge on May 7, 2009 has neither been reviewed nor approved by the U.S. Environmental Protection Agency. The views expressed by the presenter are entirely his own. The contents do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Outline

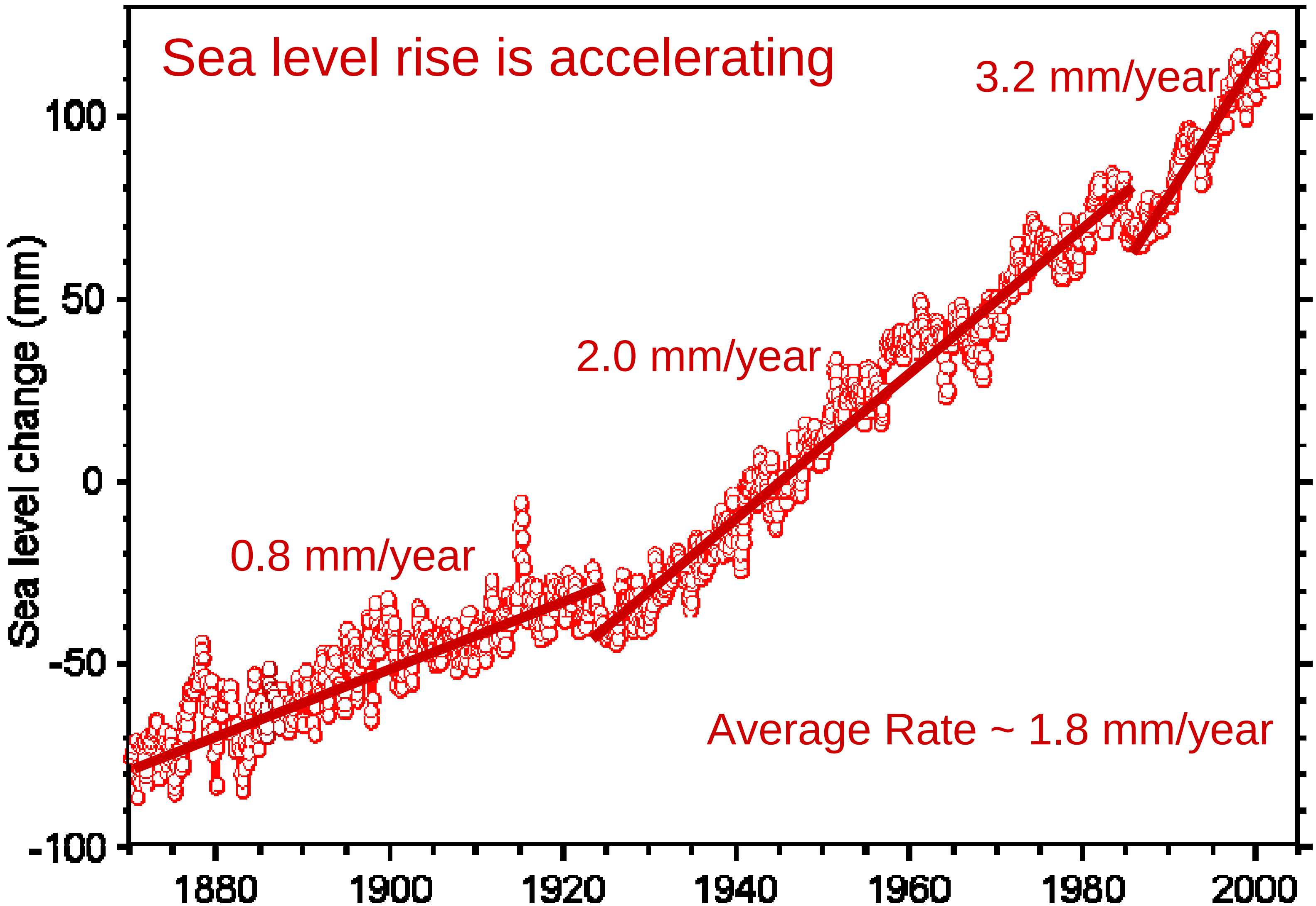
- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

Global Surface Warming



Brohan (2006) JGR

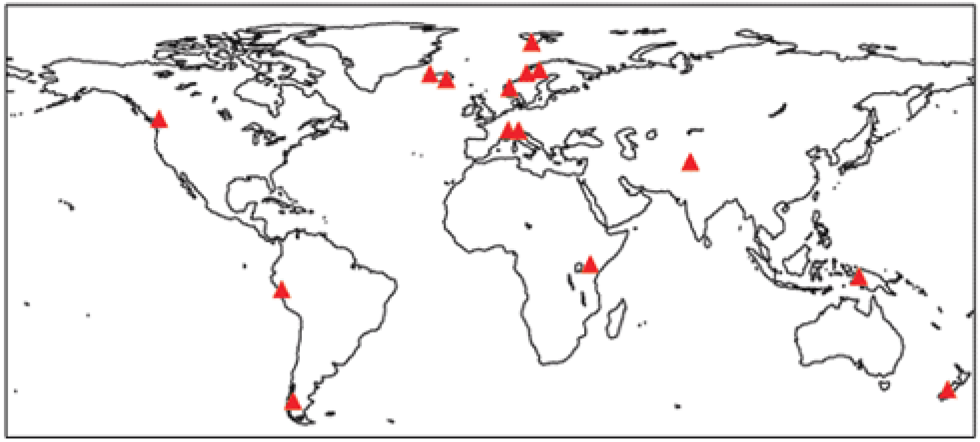
Observed Climate Change: Sea Level Rise

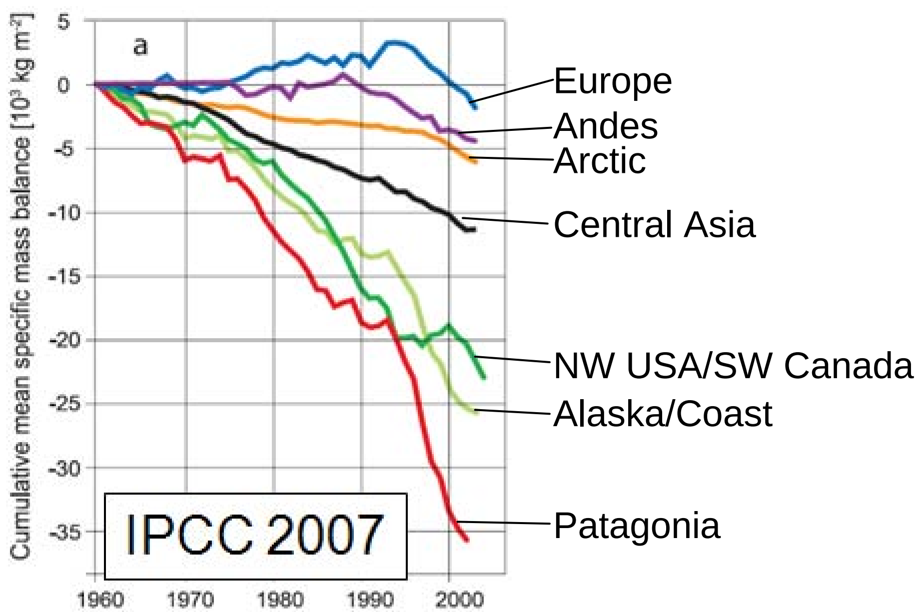


Slide: Courtesy R.S. Nerem

Church and White 2006, GRL 33:L01602

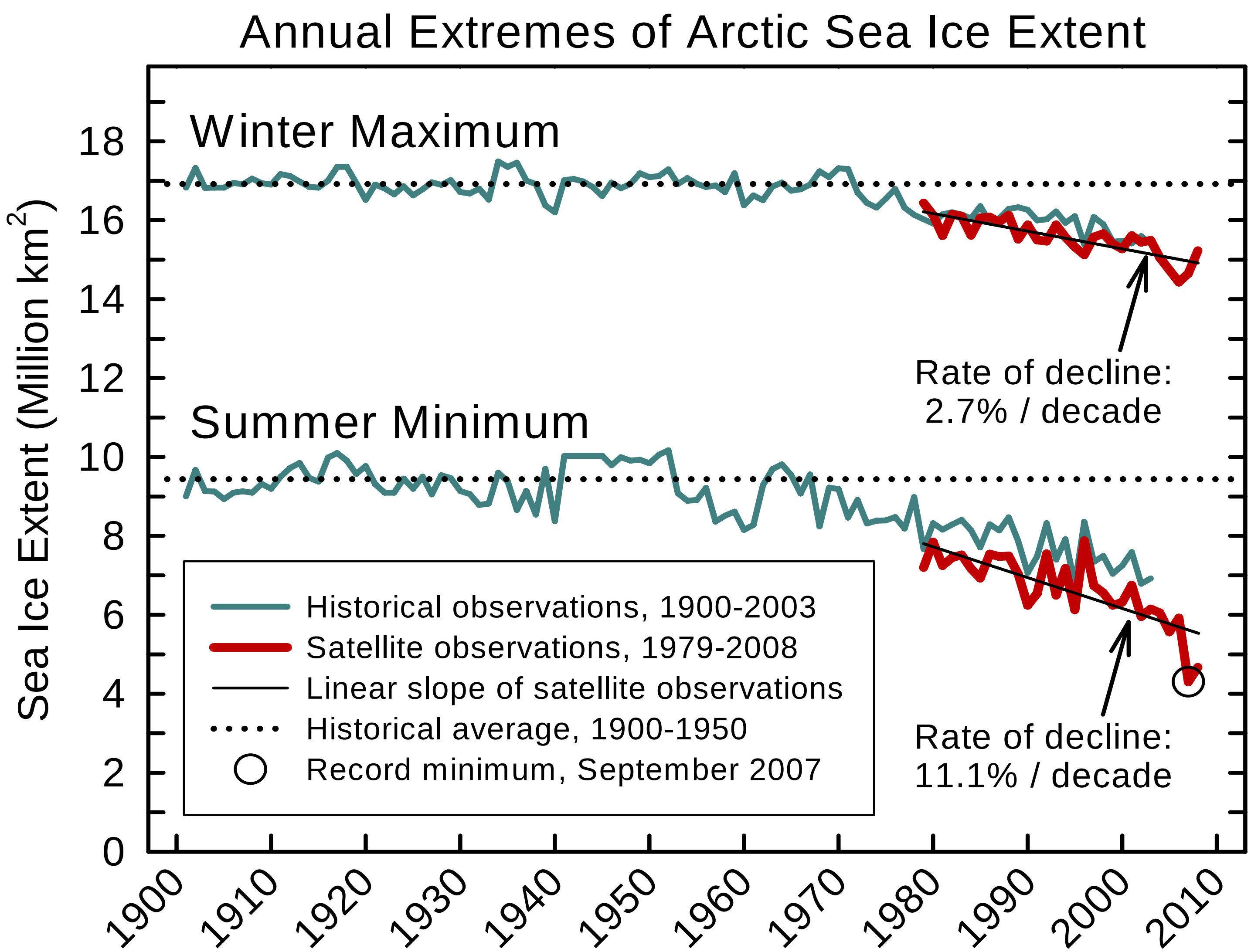
Global Mountain Glacier Retreat



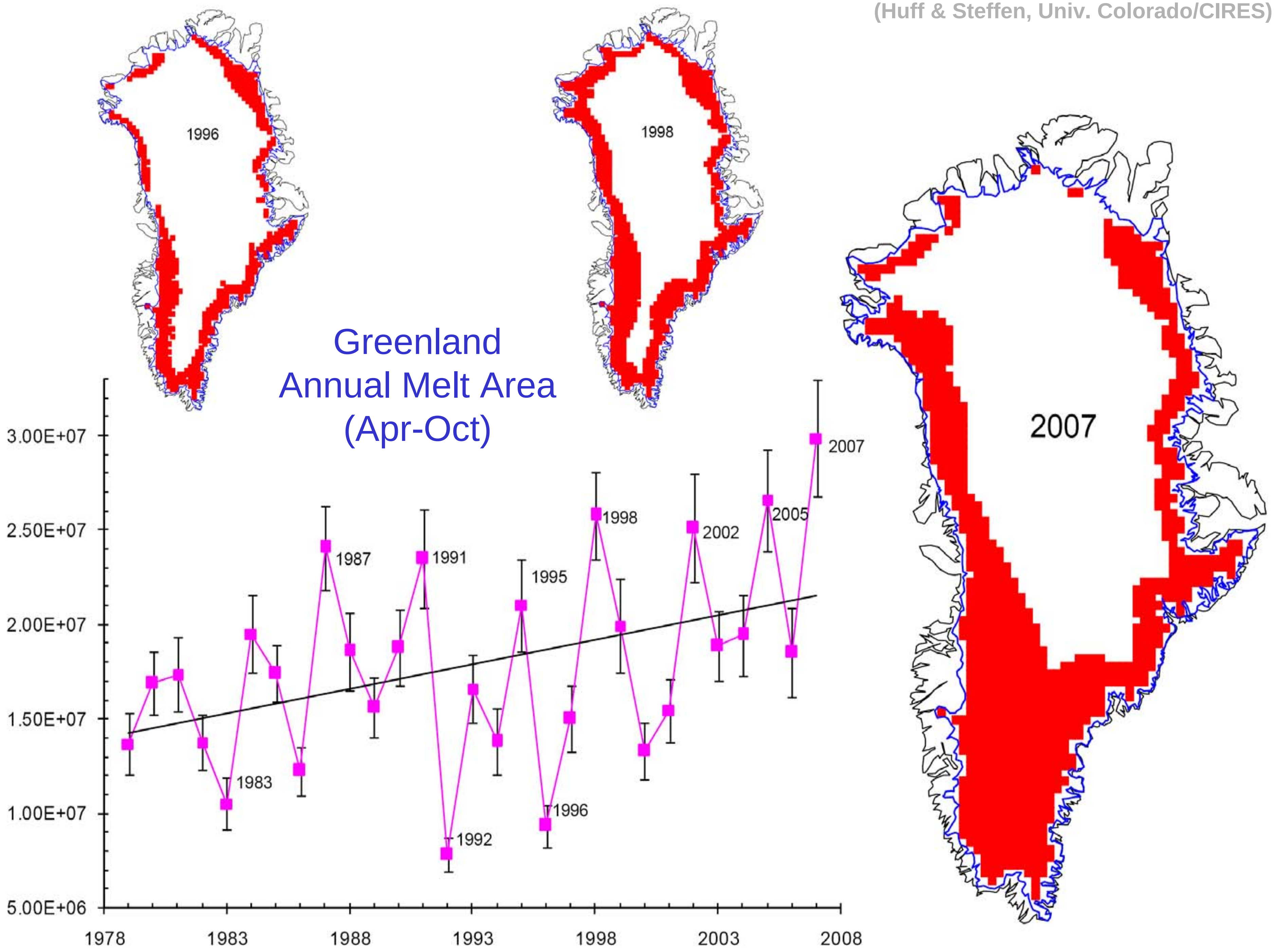


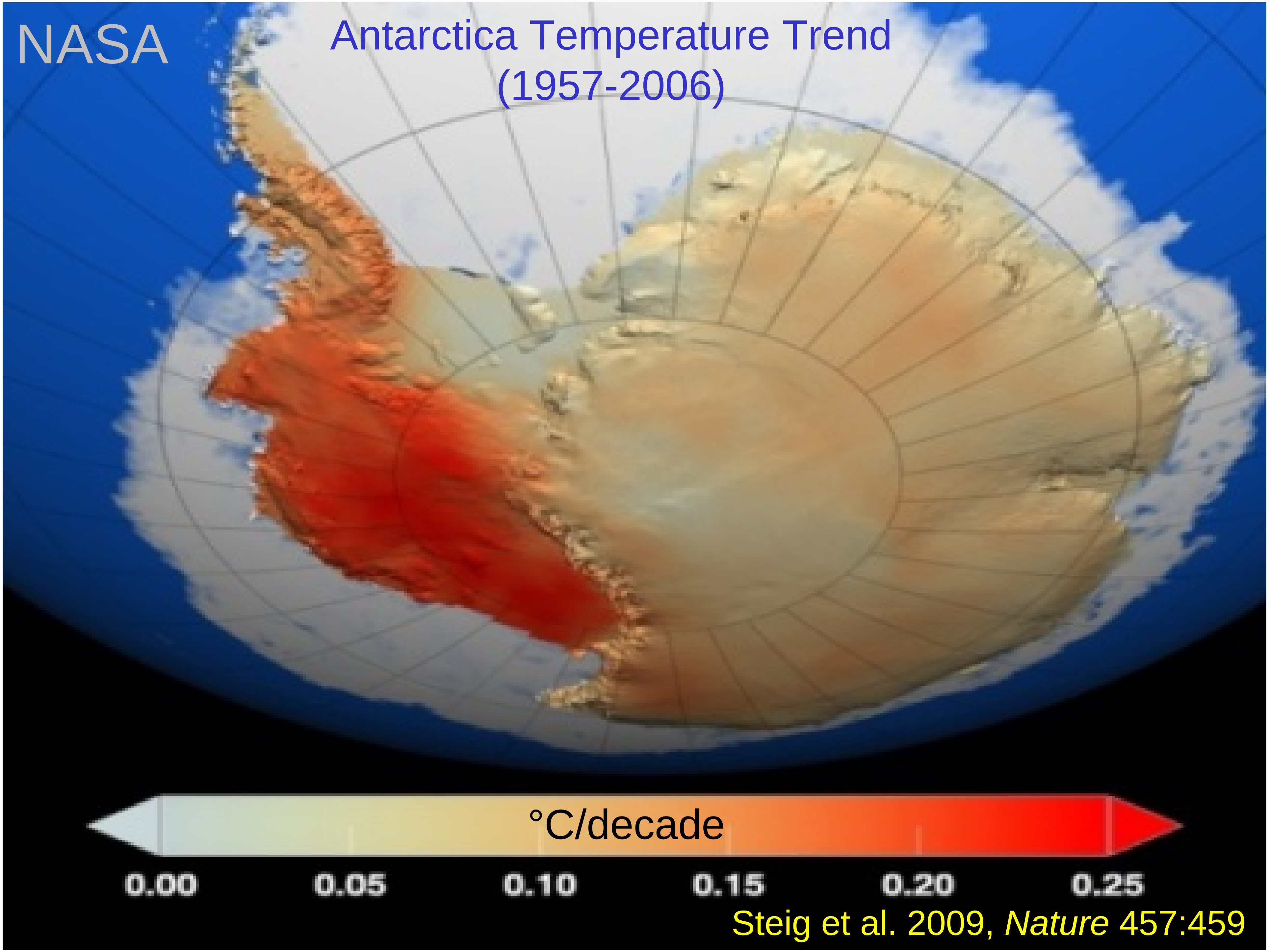
PEW CENTER ON Global CLIMATE CHANGE

Polar Ice Loss



(Huff & Steffen, Univ. Colorado/CIRES)




NASA
Antarctica Temperature Trend
(1957-2006)
°C/decade
0.00
0.05
0.10
0.15
0.20
0.25
Steig et al. 2009, *Nature* 457:459

Polar Ice Loss

Satellite Measurements of Ice Sheet Mass Balance

Study	Sur per	WAIS MB Gt year^{-1}	AIS MB Gt year^{-1}	GIS MB Gt year^{-1}
Wingham *et al.* (*7*)*	1992-	−59 ± 50	−60 ± 76	
Krabill *et al.* (*8*)*	1993-			−47
Rignot and Thomas (*9*)†	1995-	−48 ± 14	−26 ± 37	
Davis and Li (*17*)*	1992-		42 ± 23	
Davis *et al.* (*10*)*	1992-			
Velicogna and Wahr (*11*)‡	2002-			−75 ± 21
Zwally *et al.* (*18*)*	1992-	−47 ± 4	−31 ± 12	11 ± 3
	19			−83 ± 28
Rignot and Kanagaratnam (*12*)†	20			−127 ± 28
	20			−205 ± 38
Velicogna and Wahr (*20*)‡	2002-	−136 ± 19	−139 ± 73	
Ramillien *et al.* (*19*)‡	2002-	−107 ± 23	−40	−129 ± 15
Wingham *et al.* (*14*)*	1992-		27 ± 29	
Velicogna and Wahr (*13*)‡	2002-			−227 ± 33
Chen *et al.* (*15*)‡	2002-			−219 ± 21
Luthcke *et al.* (*16*)‡	2003-			−101 ± 16
Range		−136 to −47	−139 to 42	−227 to 11
Median Estimate	**+33**	**−91.5**	**−48.5**	**−108**

Shepherd & Wingham, *Science* 2007

IPCC Consensus Statement

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level

IPCC 2007

Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

Physical Laws: Internal Variability

Internal variability

- Natural cycles
  - El Niño/Southern Oscillation
  - Pacific Decadal Oscillation
  - Arctic/Antarctic Oscillations
  - Atlantic Multidecadal Oscillation
- Move energy from one place to another
- No net change of heat in climate system

PEW CENTER ON Global CLIMATE CHANGE

Physical Laws: External Forcing

- Net energy (heat) change in the climate system as a whole
  - Natural forcings
    - Solar irradiance
    - Volcanic emissions
  - Manmade forcings
    - Greenhouse gases
    - Anthropogenic aerosols
  - Feedbacks—internal response that amplifies or dampens effect of external forcing

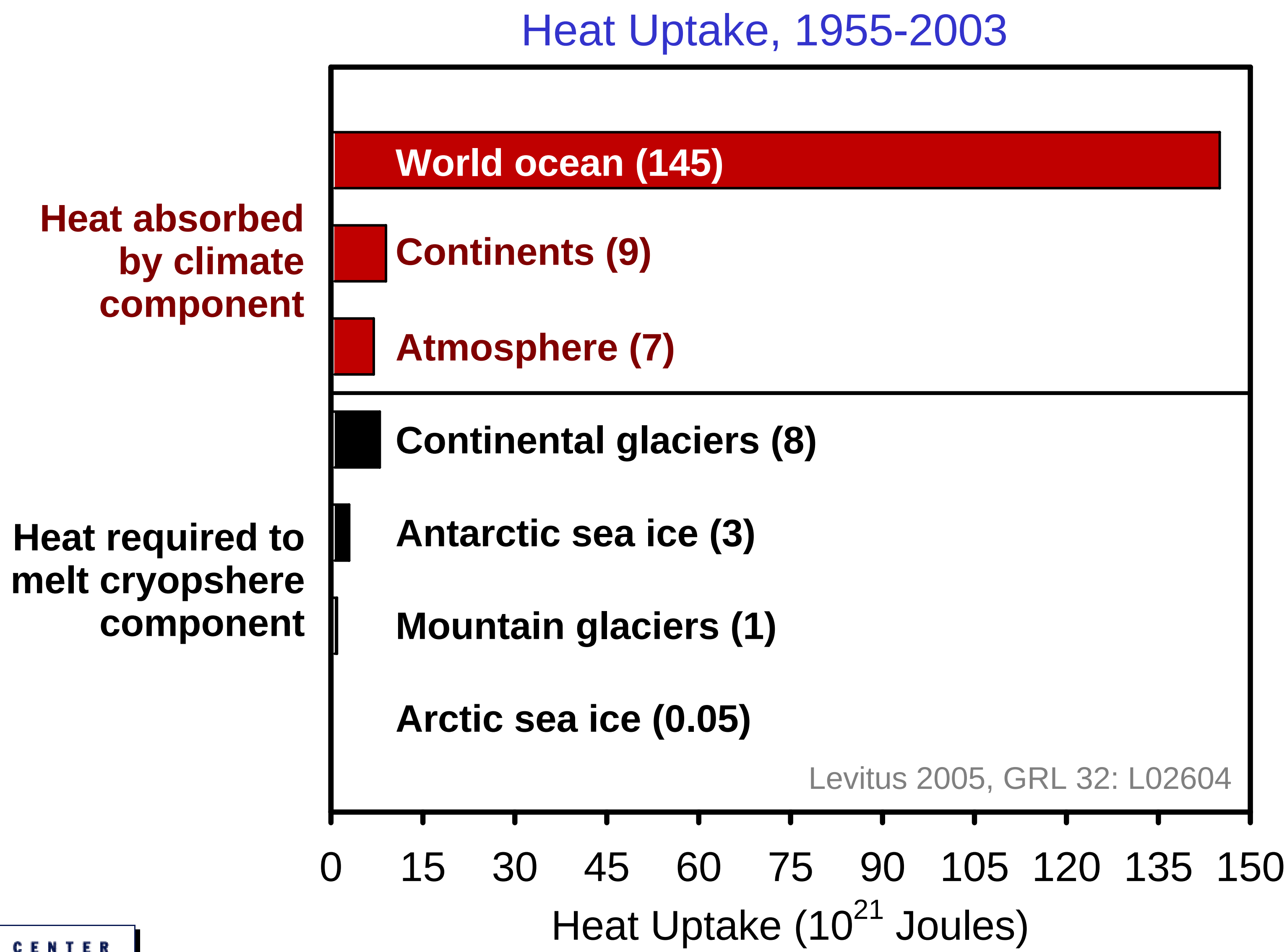
Internal Variability or External Forcing?

How to distinguish between internal variability and external forcing?

Is the climate system as a whole gaining heat?

- **Yes:** External forcing is required
- **No:** No significant external forcing

Physical Laws: Energy Budget



External Forcing is responsible

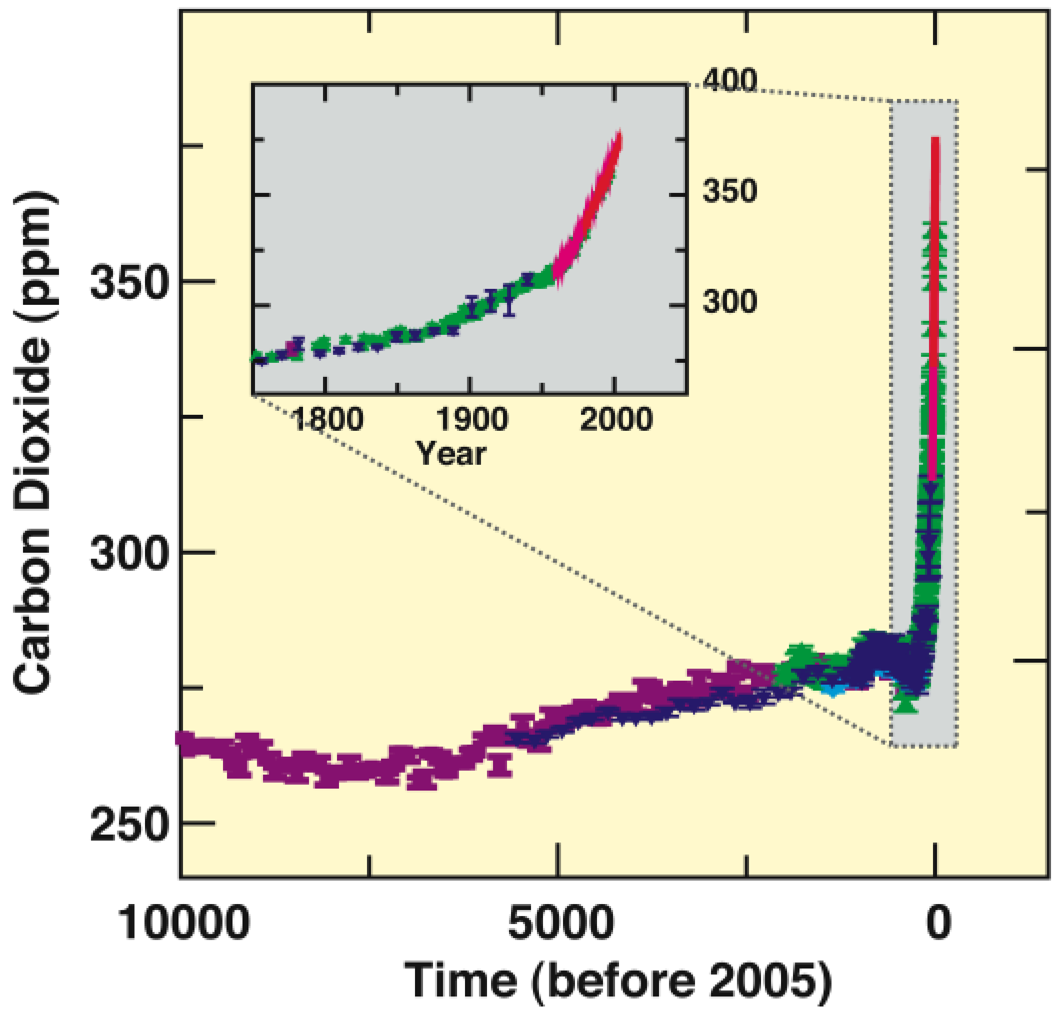
Detection of external forcing

- All climate components are gaining energy
- Vast majority of new heat is in the ocean; other components cannot compensate (not internal variability)
  - ***External forcing detected*** (based on physical laws, not models)
- Claims that "natural cycles" are to blame must explain net gain of heat in system.

Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

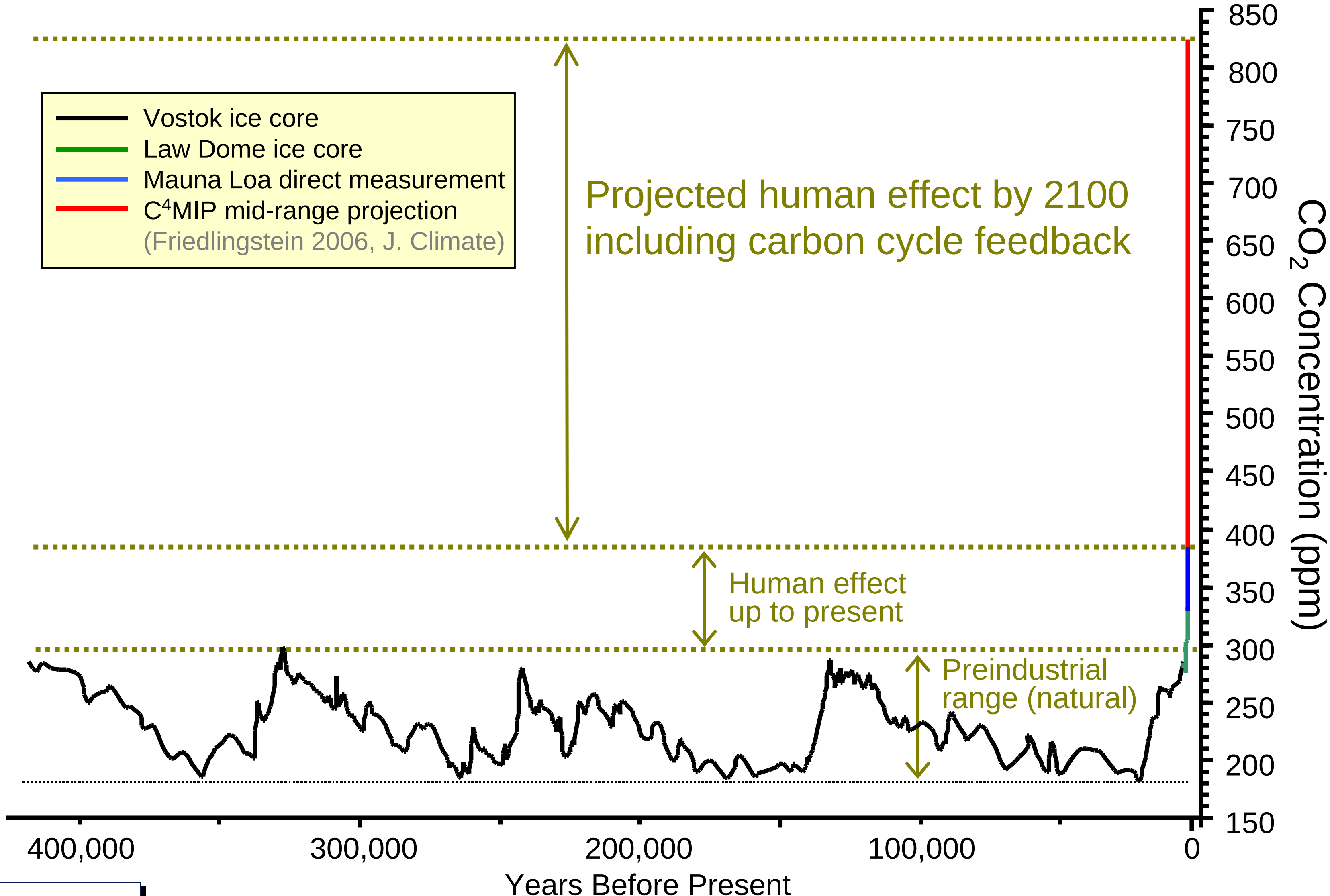
History of Atmospheric CO_2



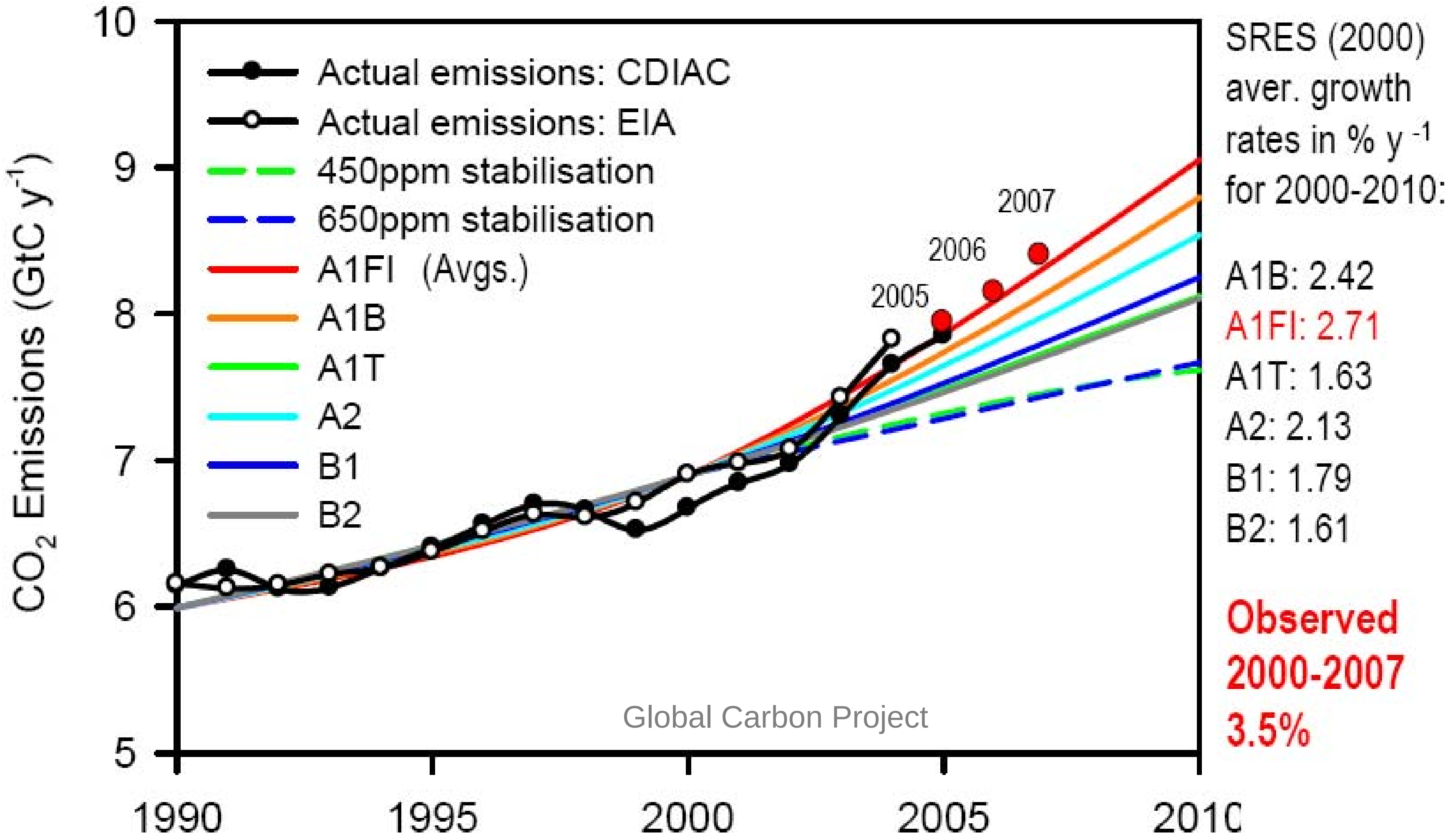
IPCC 2007

PEW CENTER ON Global CLIMATE CHANGE

Human Contribution to Atmospheric CO_2



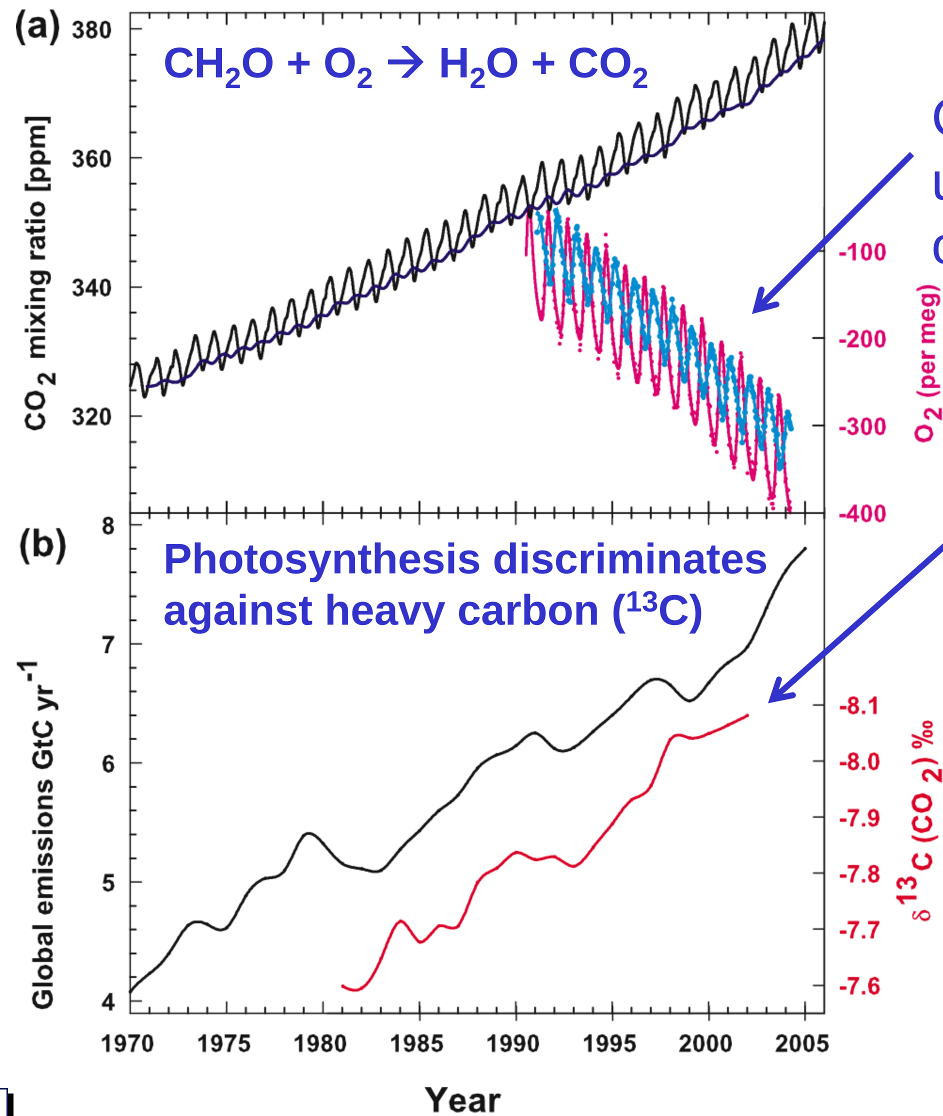
Manmade CO_2 Emissions are Growing Faster than Expected



PEW CENTER ON Global CLIMATE CHANGE

Slide: courtesy Pep

Evidence of Manmade CO_2



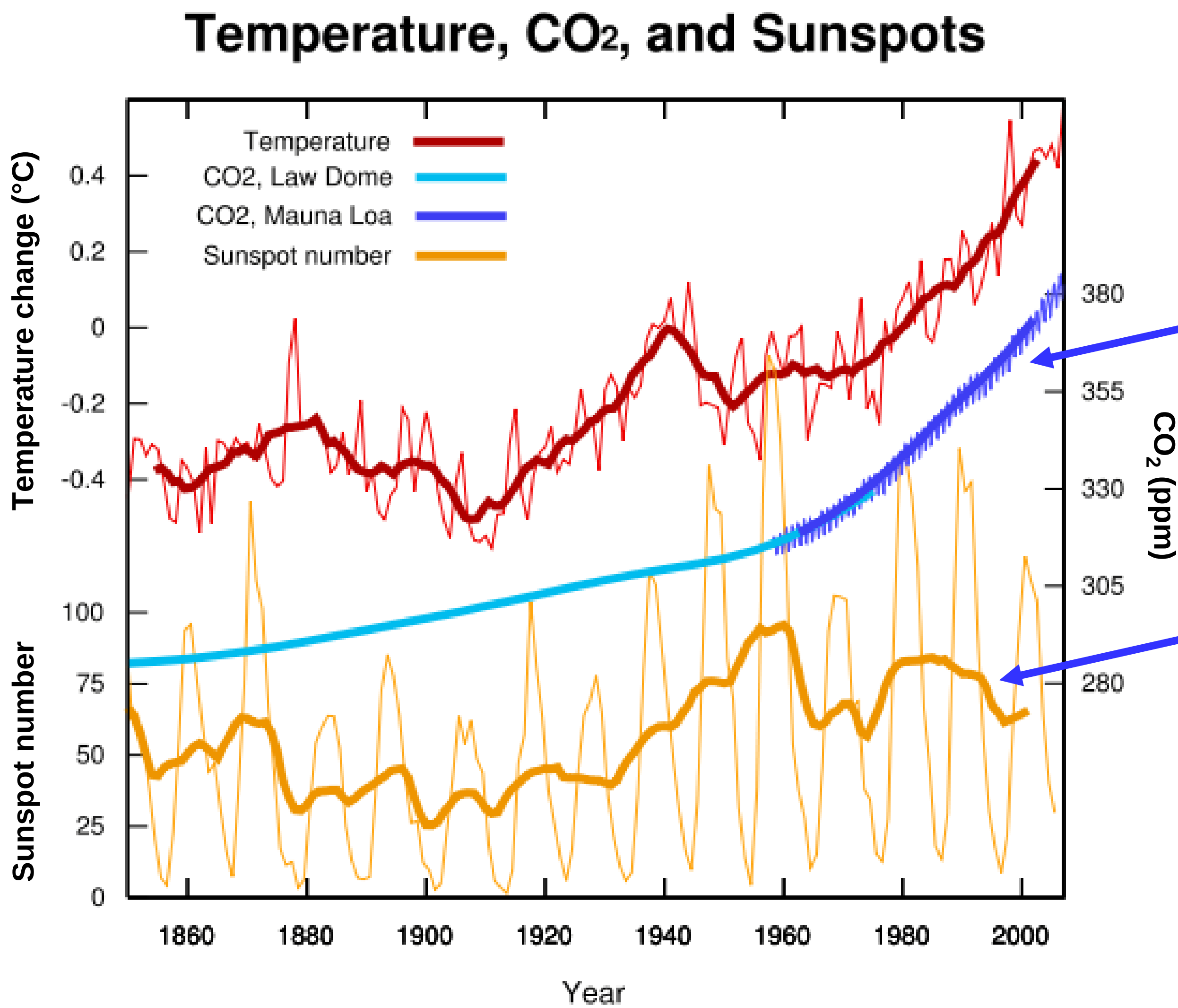
CO_2 production uses atmospheric oxygen

Carbon source is organic

Carbon source is ancient (^{14}C depleted; data not shown)

PEW CENTER ON Global CLIMATE CHANGE

Causes of Global Warming



- The increase of CO_2 can explain recent warming
- Sun's activity cannot explain recent warming

Stanford Solar Center

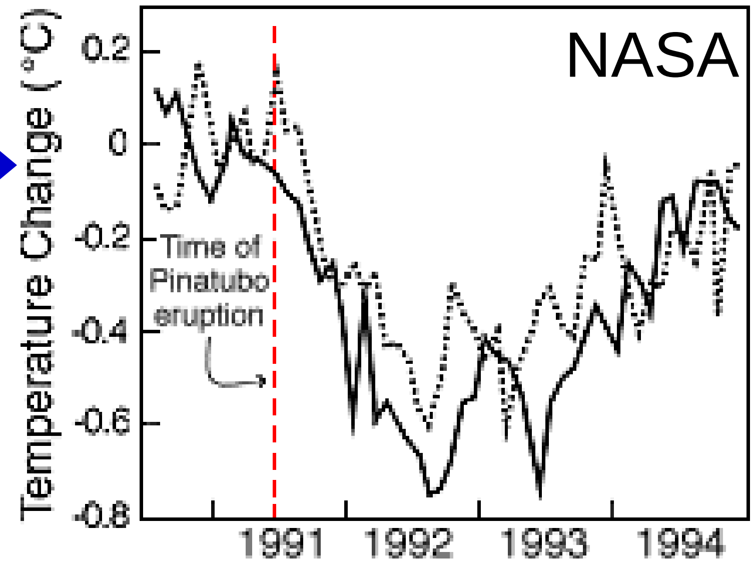
Causes of Global Warming

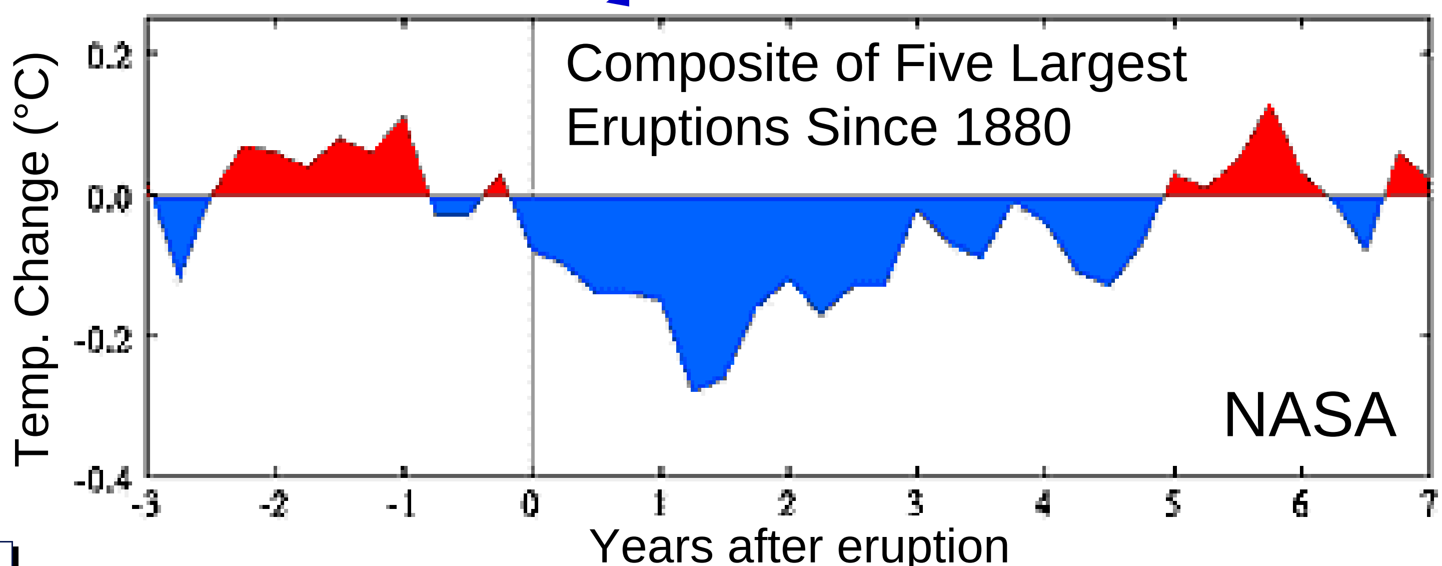
"There is considerable evidence for solar influence on the Earth's pre-industrial climate and the Sun may well have been a factor in post-industrial climate change in the first half of the last century. Here we show that over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures."

Lockwood & Frölich, 2007
Proc. R. Soc. A 463:2447

Natural Variability: Volcanic Eruptions

- We know volcanoes cool the Earth temporarily from both theory and observations
- The five largest eruptions since 1880 all had similar effect

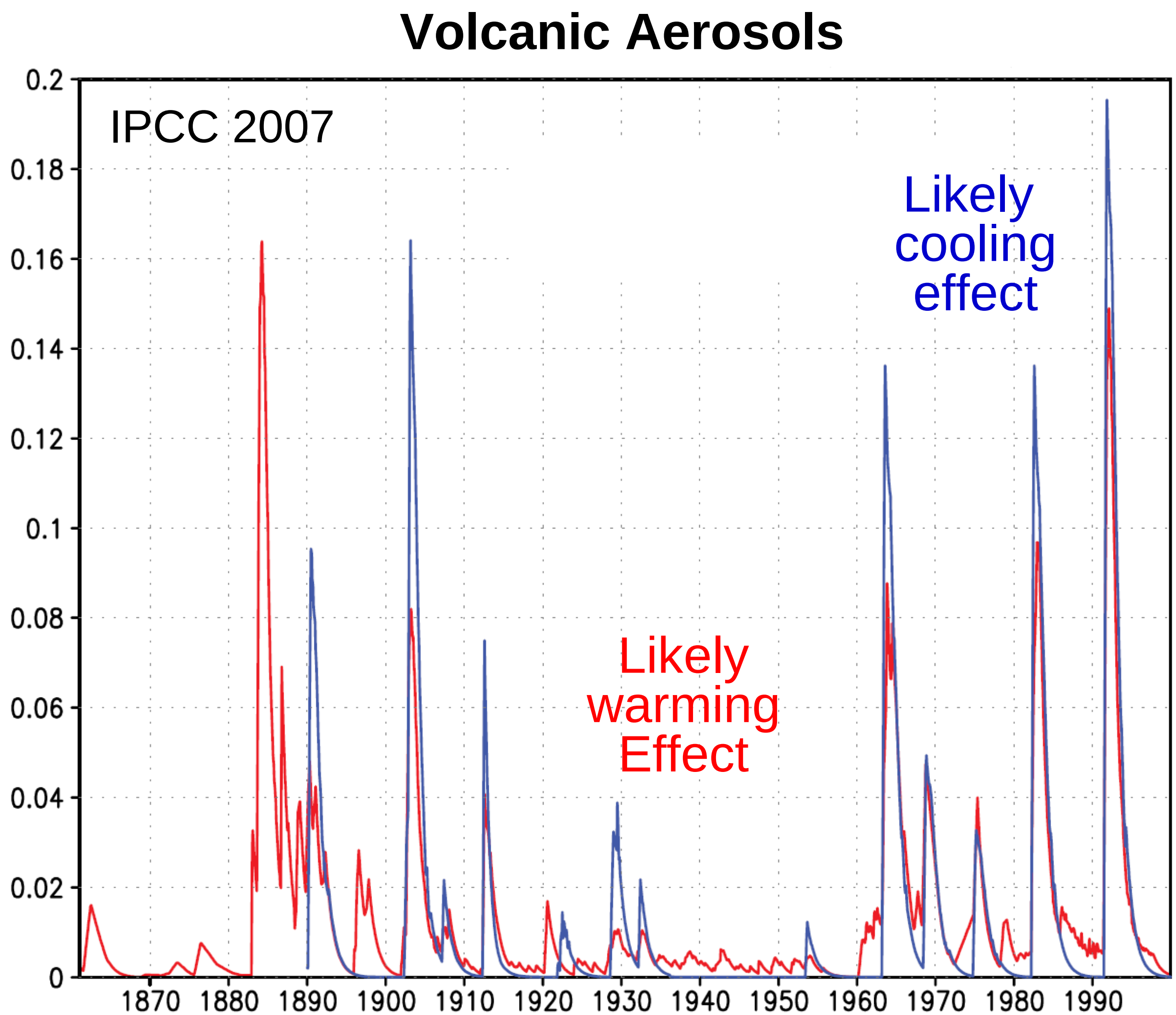




PEW CENTER ON Global CLIMATE CHANGE

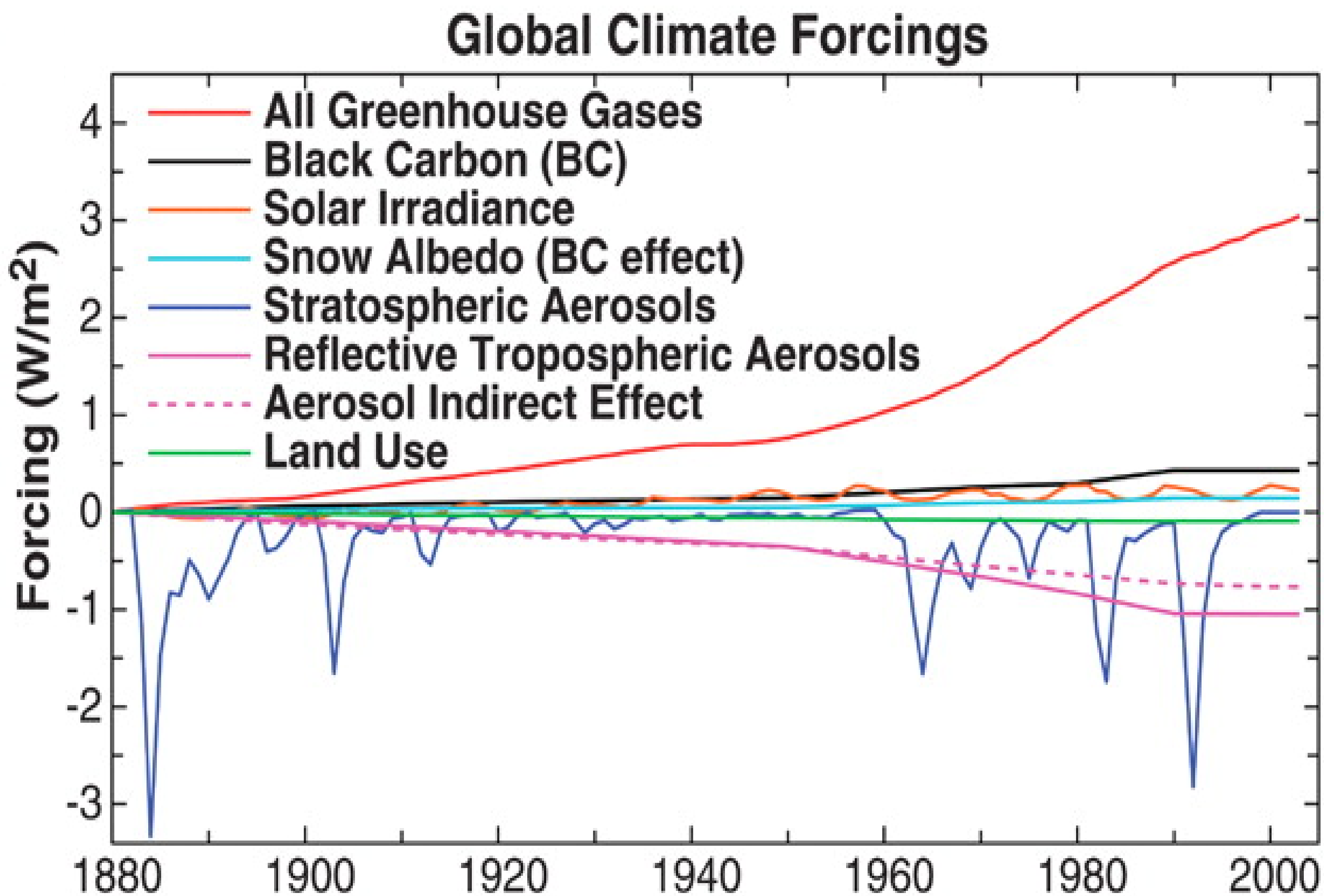
Natural Variability: Volcanic Eruptions

- Volcanic activity has a net cooling effect
- Some of the early warming may have been from low volcanic activity
- Higher volcanic activity during the second half of the 20th century
- Most of the warming was after 1975

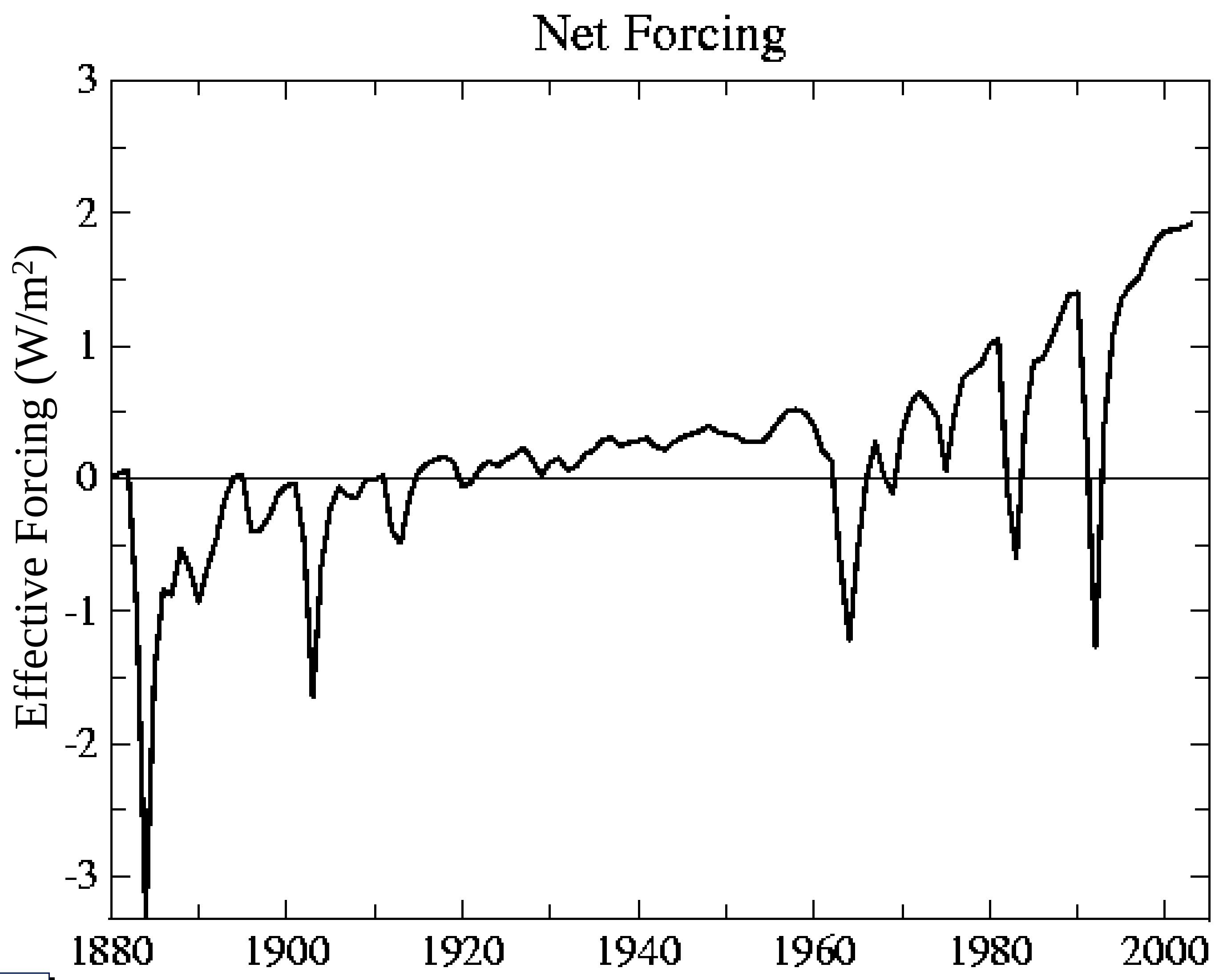


PEW CENTER ON Global CLIMATE CHANGE

Attribution: Possible External Forcings

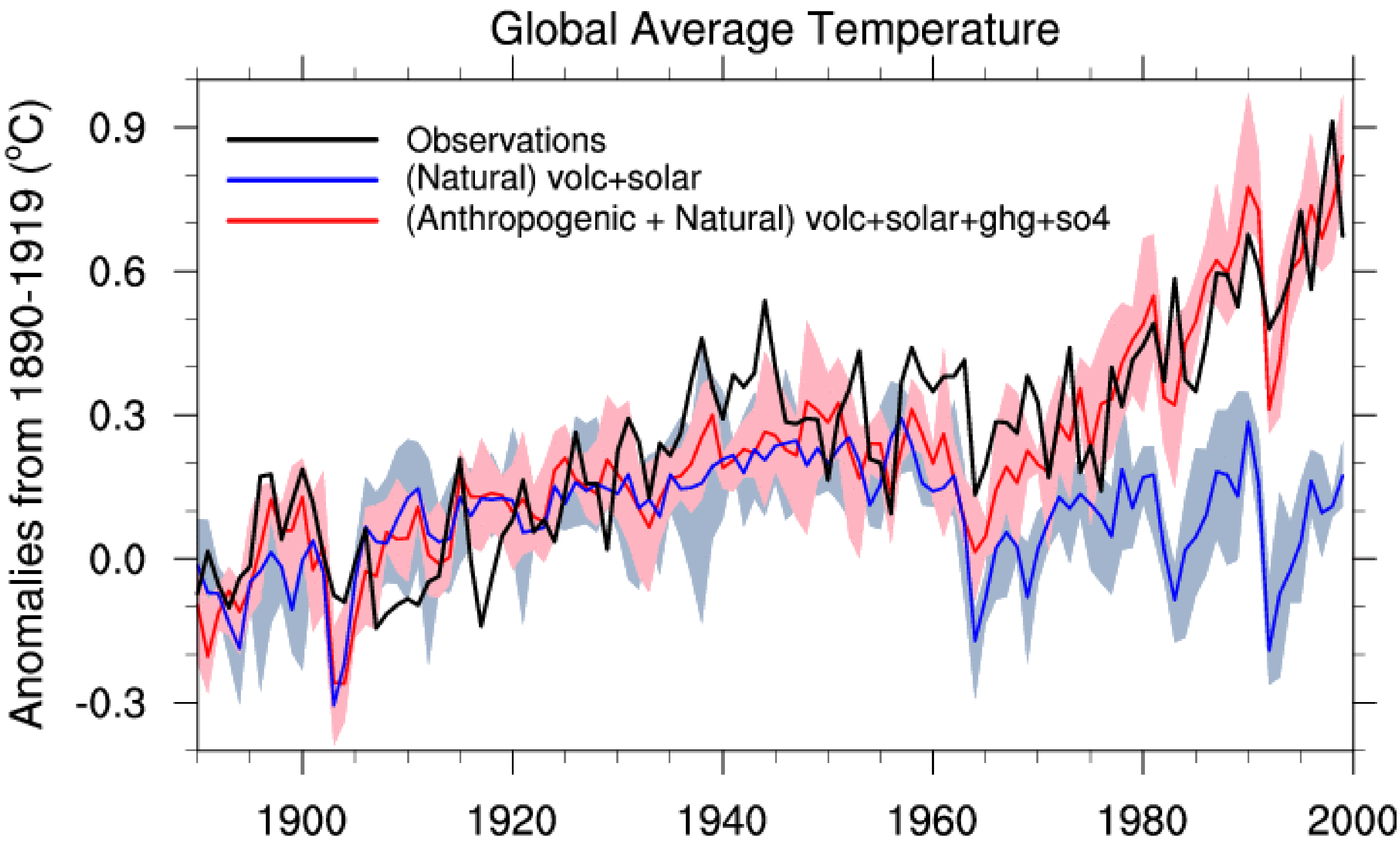


Attribution: Net External Forcing



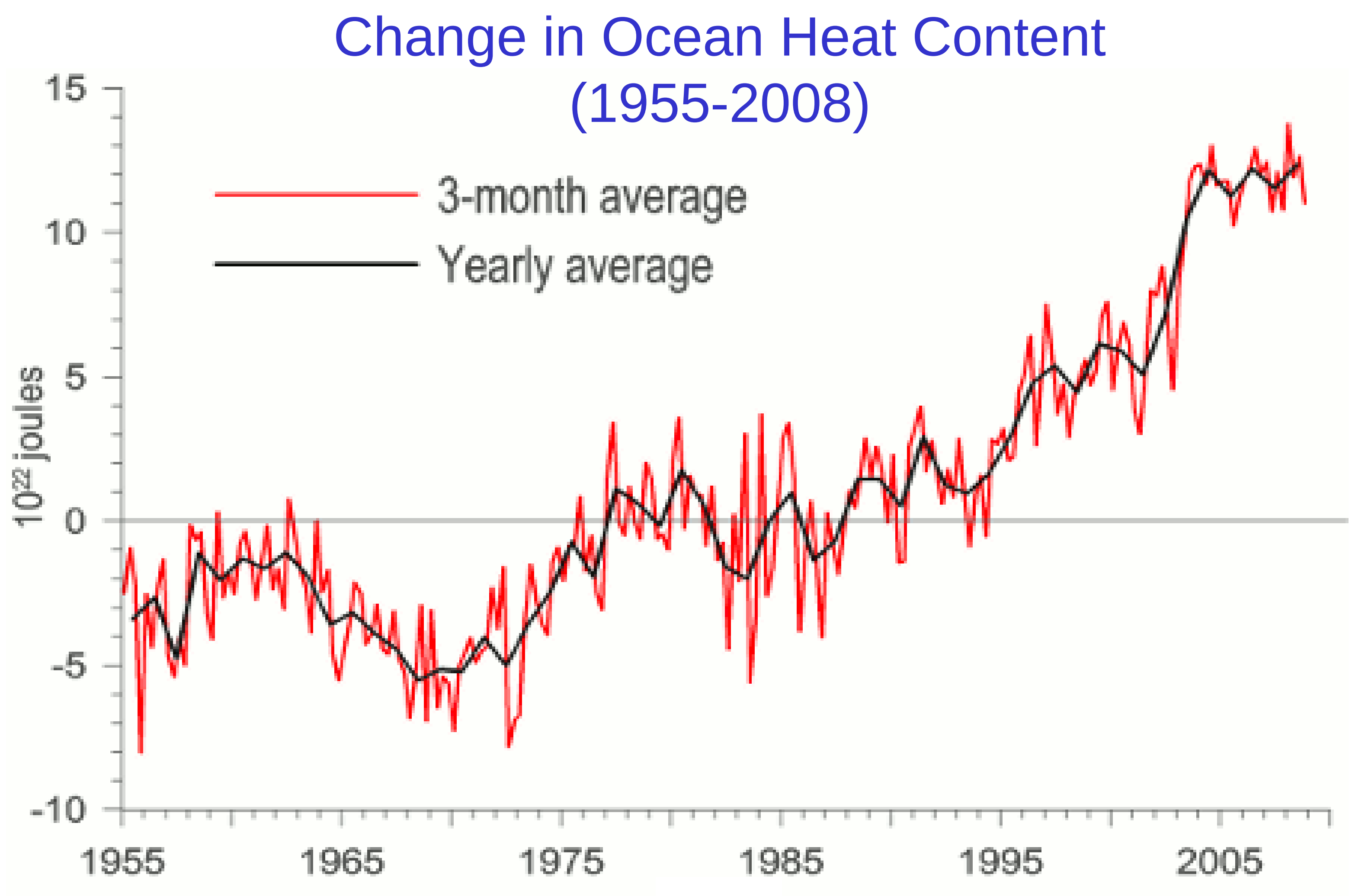
PEW CENTER ON Global CLIMATE CHANGE

Causes of Global Warming



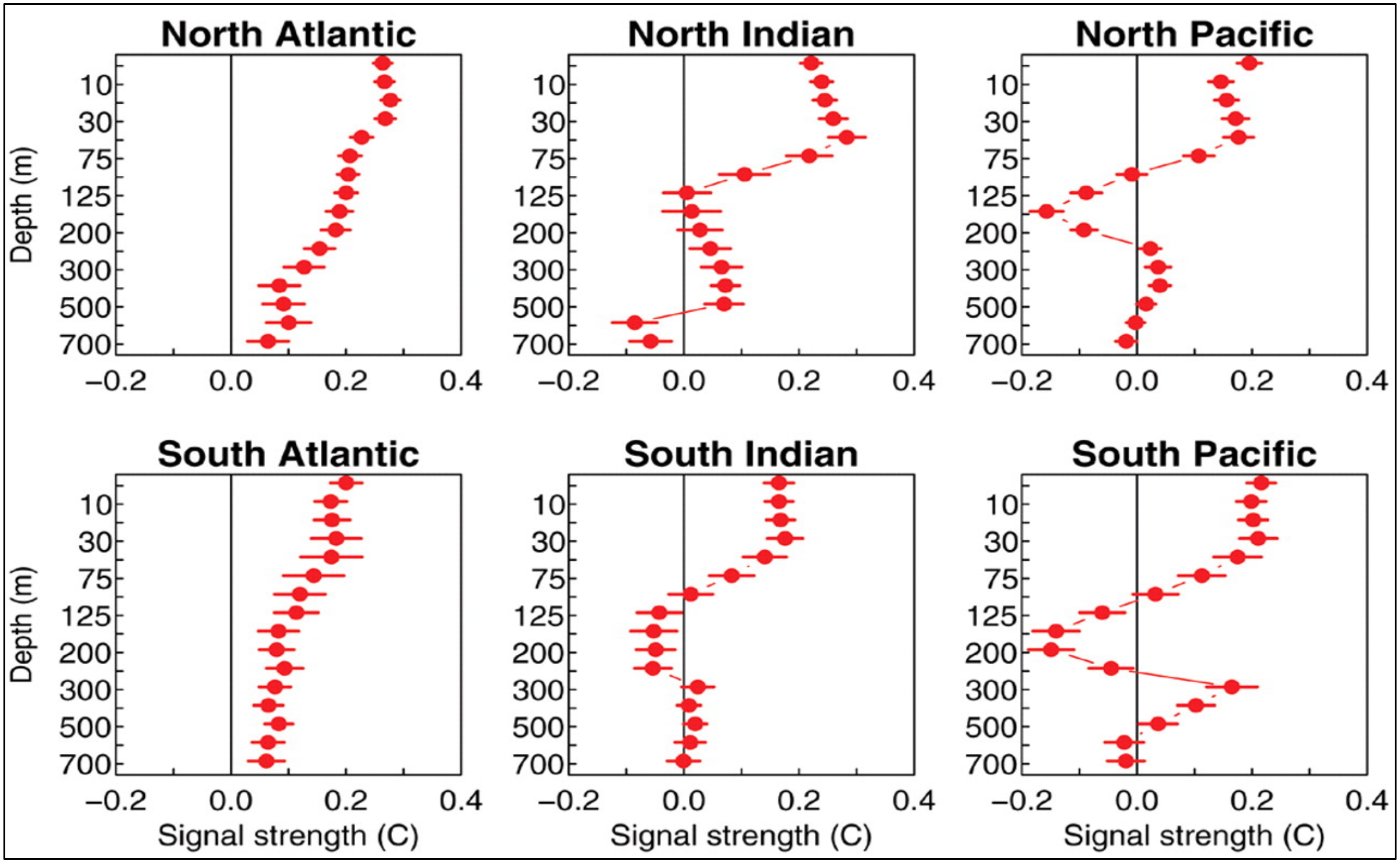
Meehl 2004, J. Climate 17:3721

Global Ocean Warming Trend



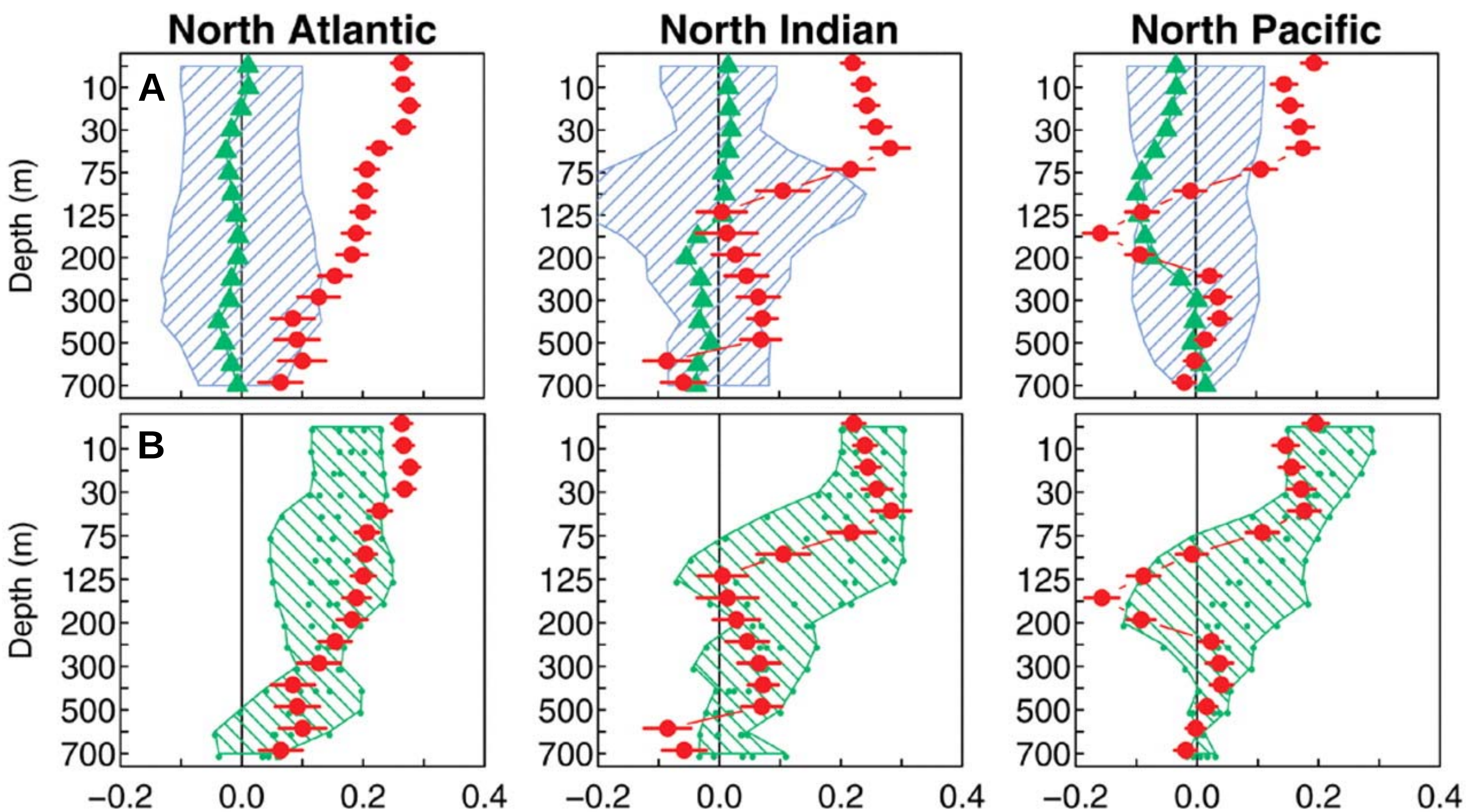
Levitus 2009, *GRL* 36:doi:10.1029/2008GL037155

Global Ocean Warming Trend



PEW CENTER ON Global CLIMATE CHANGE

Human Fingerprint in the Ocean



IPCC Consensus Statement

Most of the observed increase in global average temperatures since the mid-20th century is very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.

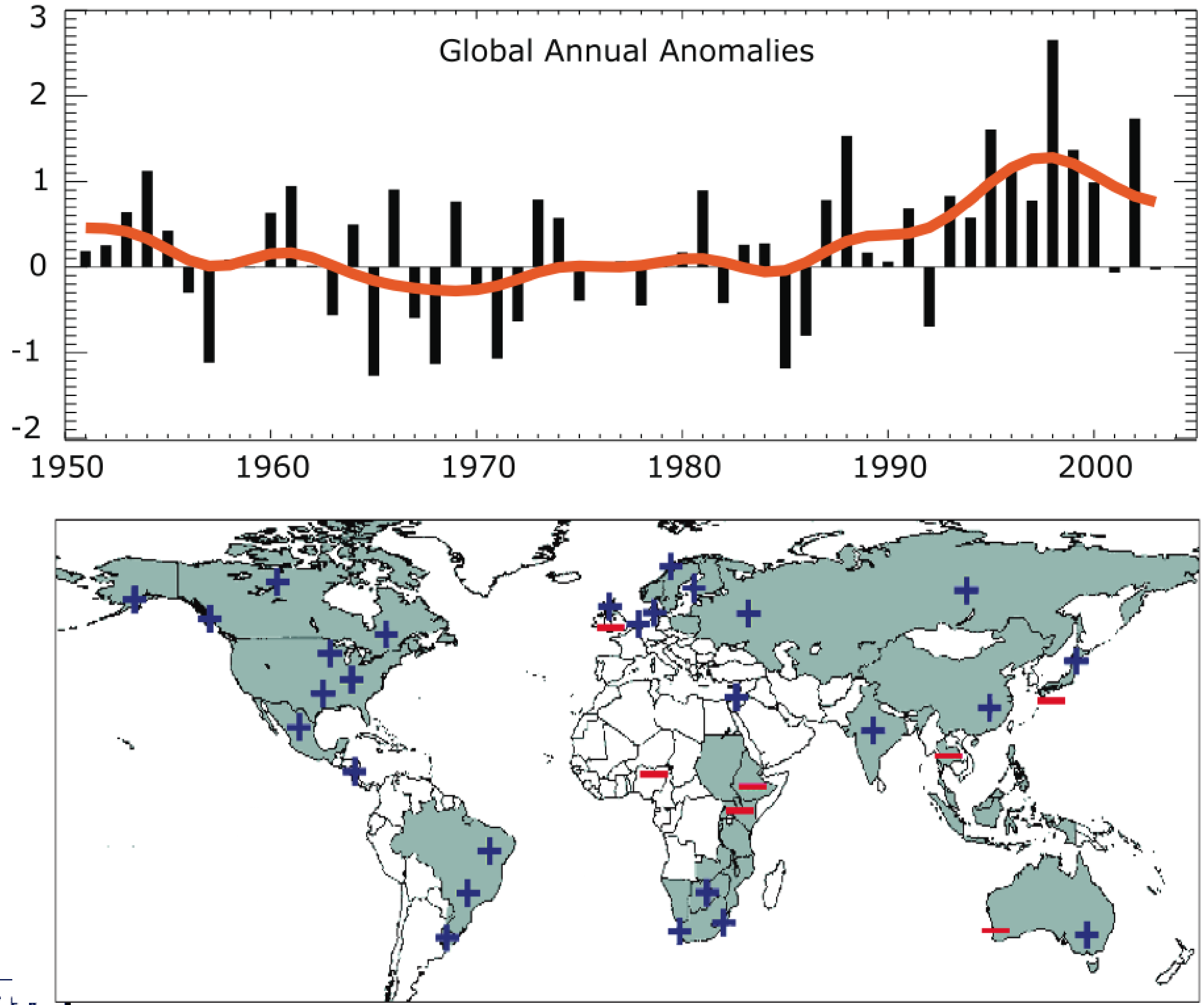
IPCC 2007

*Very Likely: >90% chance

Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

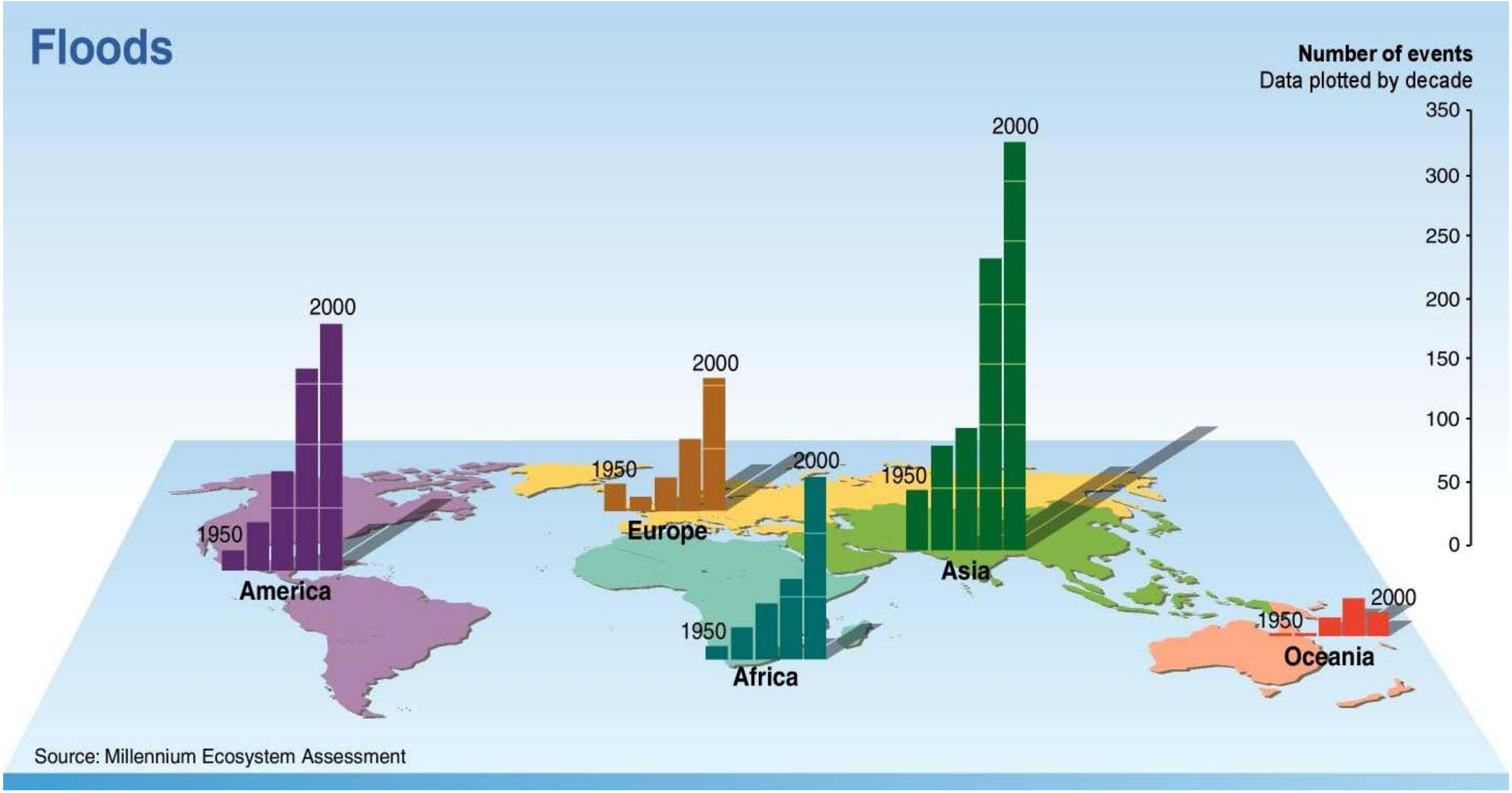
Observed Impacts: Extreme Precipitation



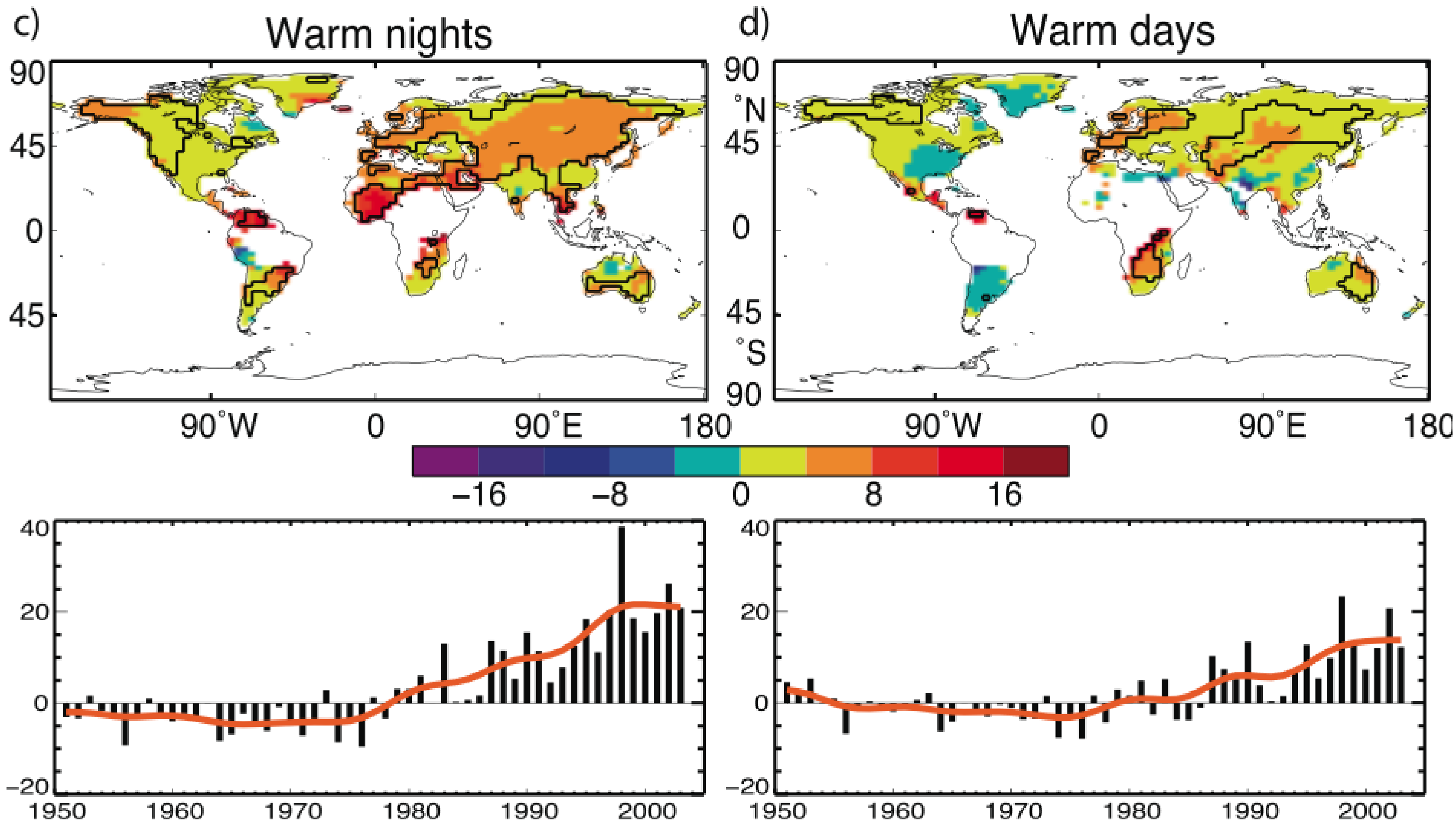
PEW CENTER ON Global CLIMATE CHANGE

IPCC 2007-WGI, Fig. 3.39

Observed Climate Change: Flooding Frequency



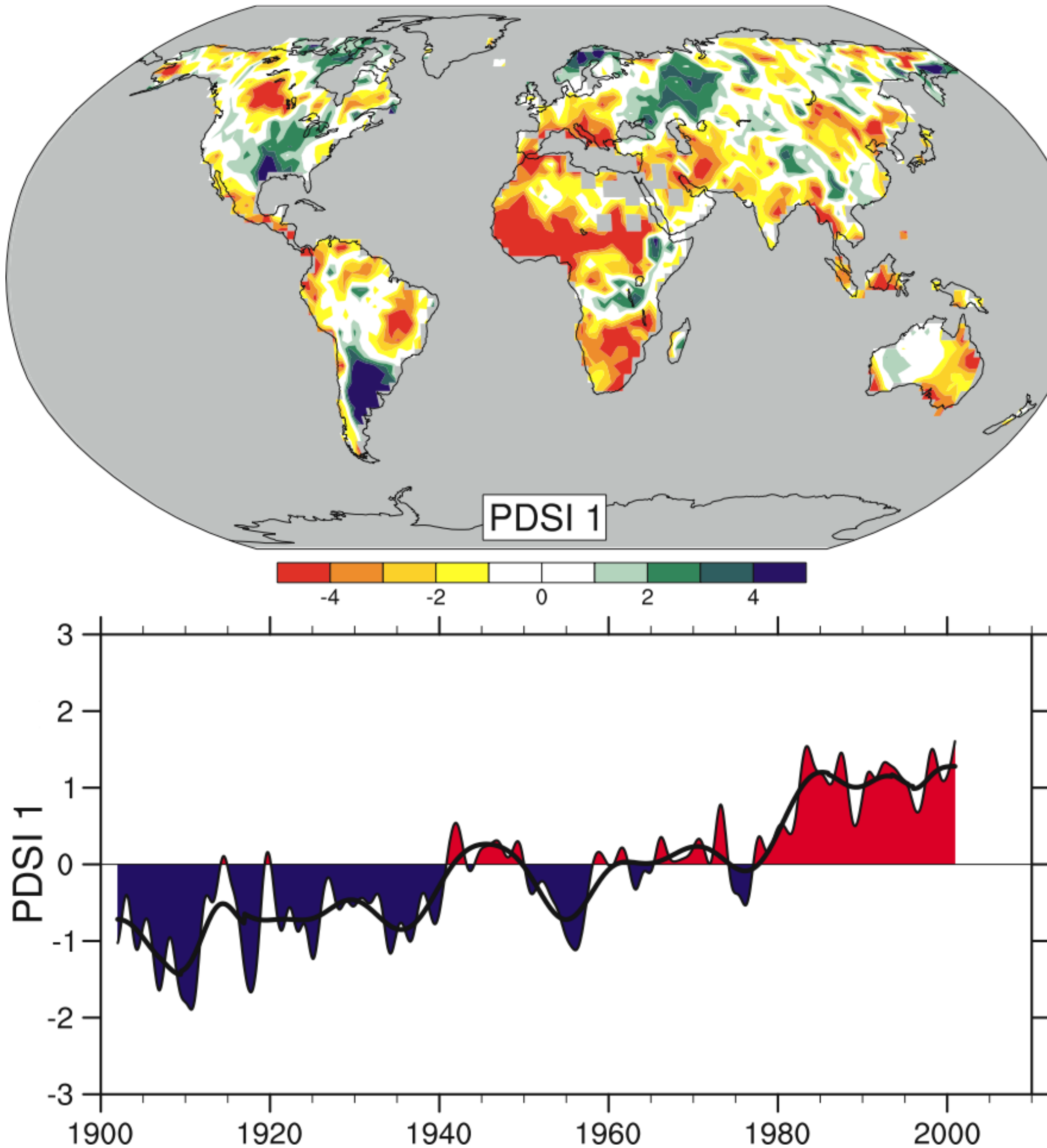
Observed Impacts: Temperature Extremes



PEW CENTER ON Global CLIMATE CHANGE

IPCC 2007-WGI, FAQ 3.3, Fig. 1

Observed Impacts: Global Drought

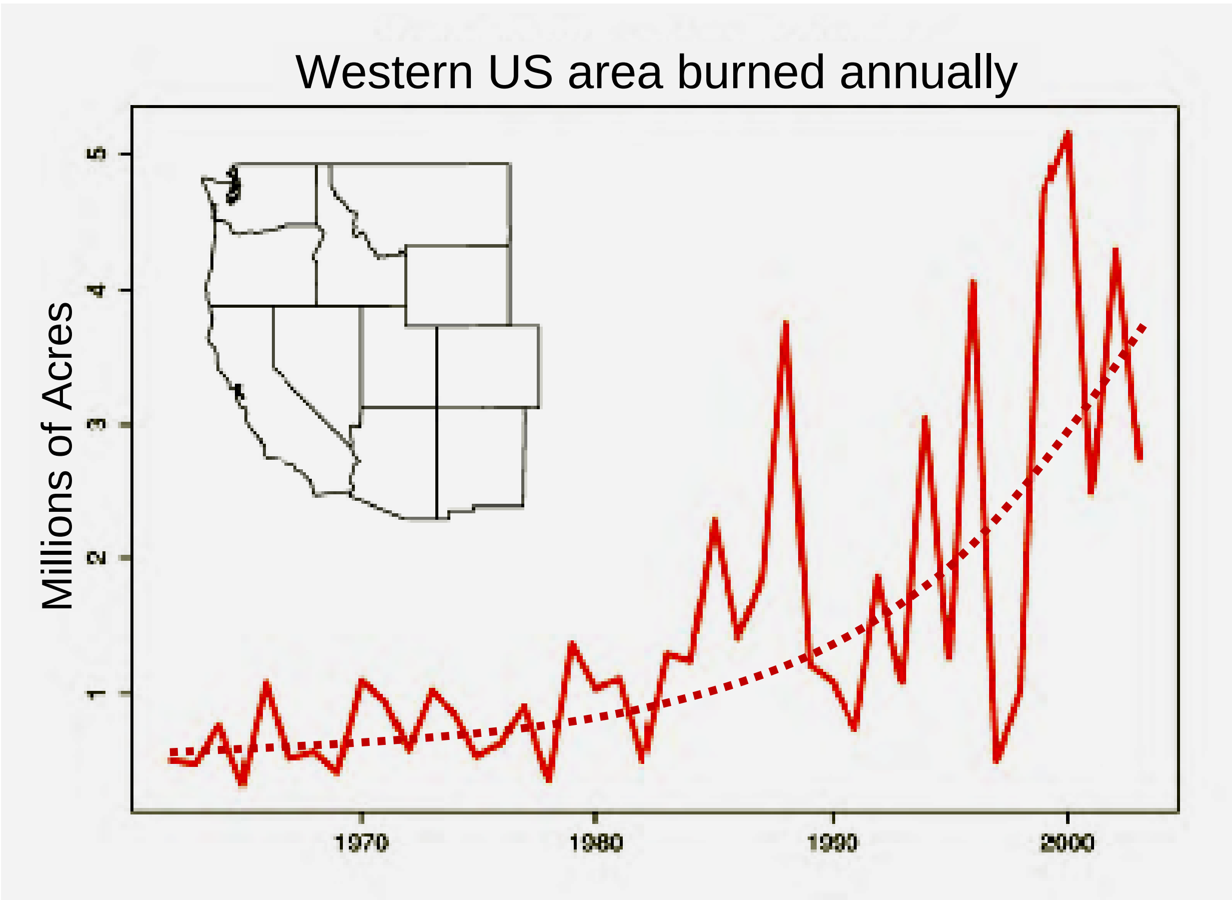


PEW CENTER ON Global CLIMATE CHANGE

IPCC 2007-WGI; FAQ 3.2, Fig. 1

Observed Climate Change: Wildfire Fire Frequency

Area burned in the Western US has increased 6-fold in the last 30 years.

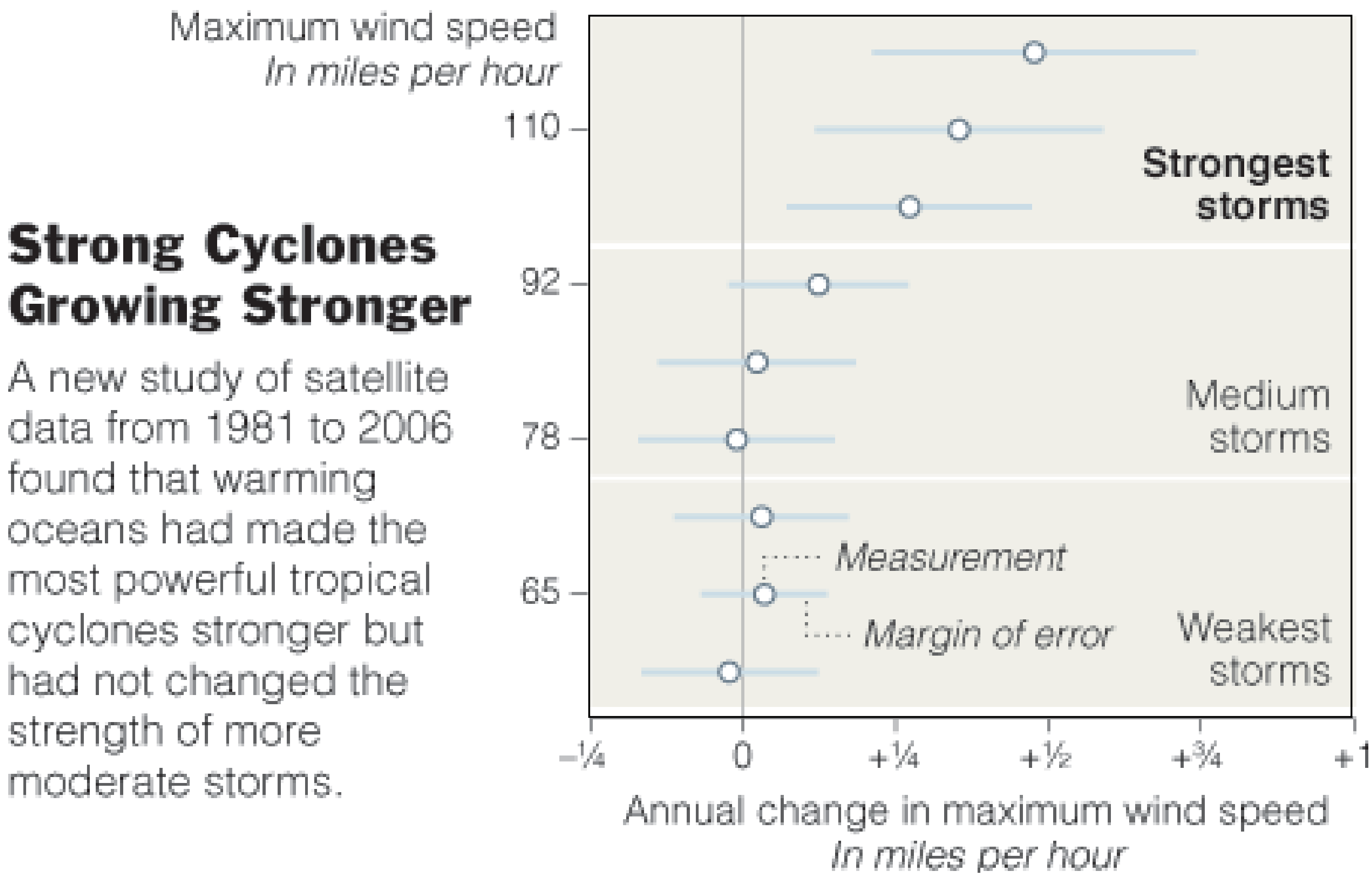


- Longer growing season
- Earlier snowmelt
- Hotter summers

PEW CENTER ON Global CLIMATE CHANGE

Slide: courtesy J. Holdren

Observed Climate Change: Hurricane Intensity

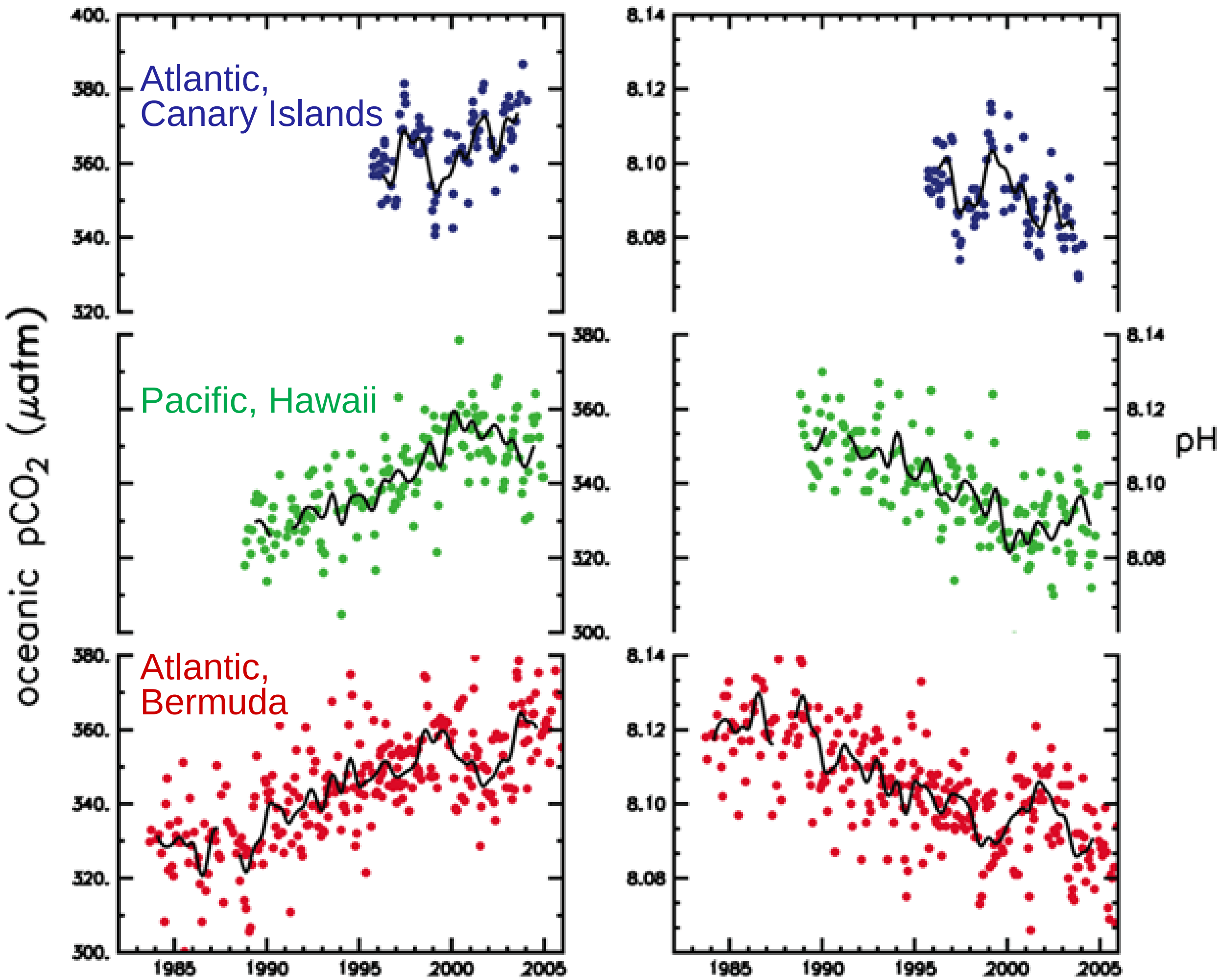


Source: Elsner et al. (2008) The increasing intensity of the strongest tropical cyclones. *Nature* 455:92-95.

PEW CENTER ON Global CLIMATE CHANGE

Observed Impacts: Ocean CO_2 & Acidity

- When CO_2 dissolves in water, it makes carbonic acid
- Ocean pH has dropped 0.1 unit since ~1950
- 0.2 unit drop damages shell-forming marine organisms
- Coral reefs provide ~70% of protein for low-latitude developing countries and huge part of global biodiversity
- Planktonic algae are the base of the food chain in the open ocean



IPCC 2007-WGI, Fig. 5.9

IPCC Consensus Statement

A global assessment of data since 1970 has shown it is likely* that anthropogenic warming has had a discernible influence on many physical and biological systems.

IPCC 2007

*Very Likely: >66% chance

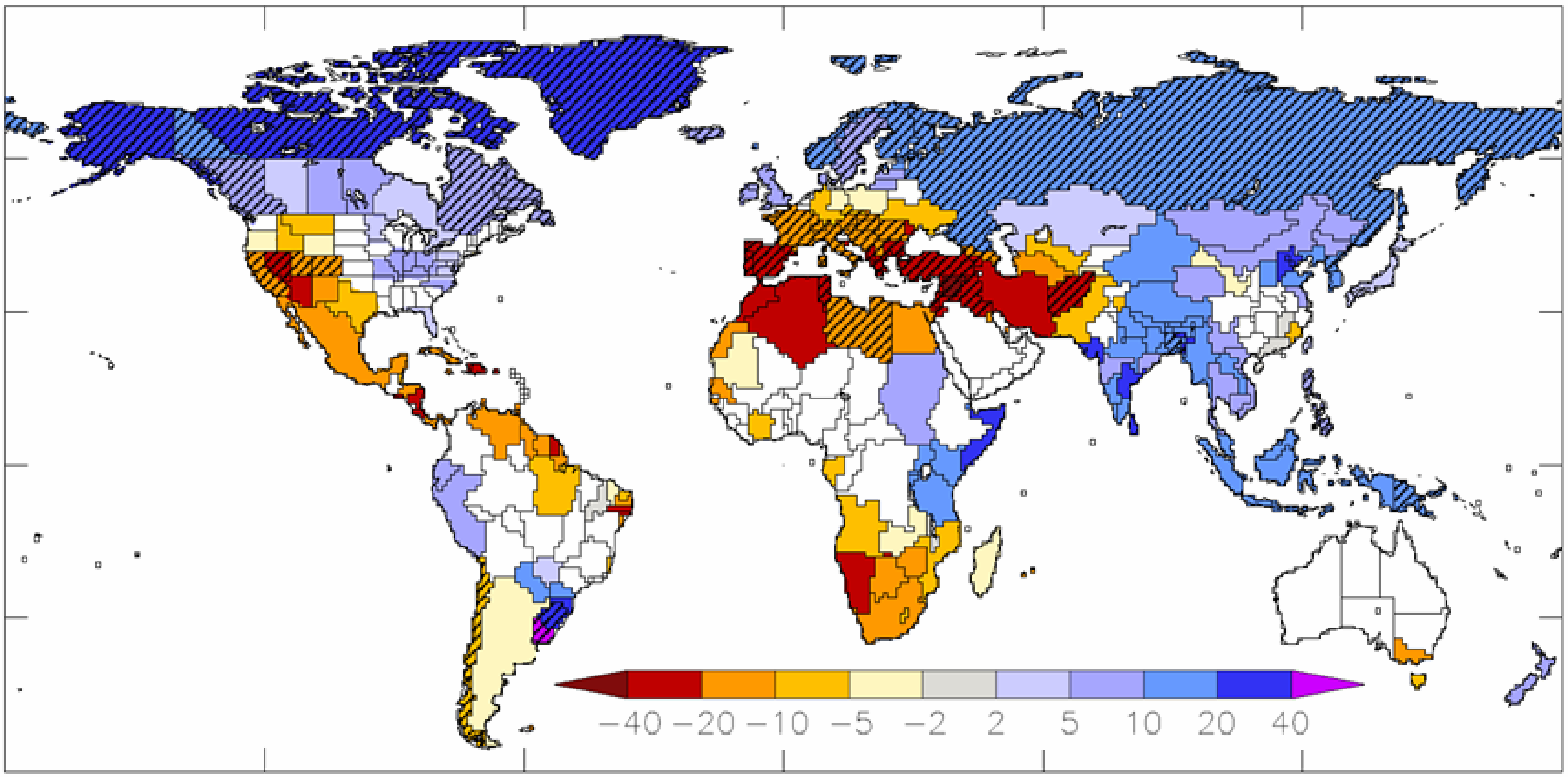
Pew Center on Global Climate Change

Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

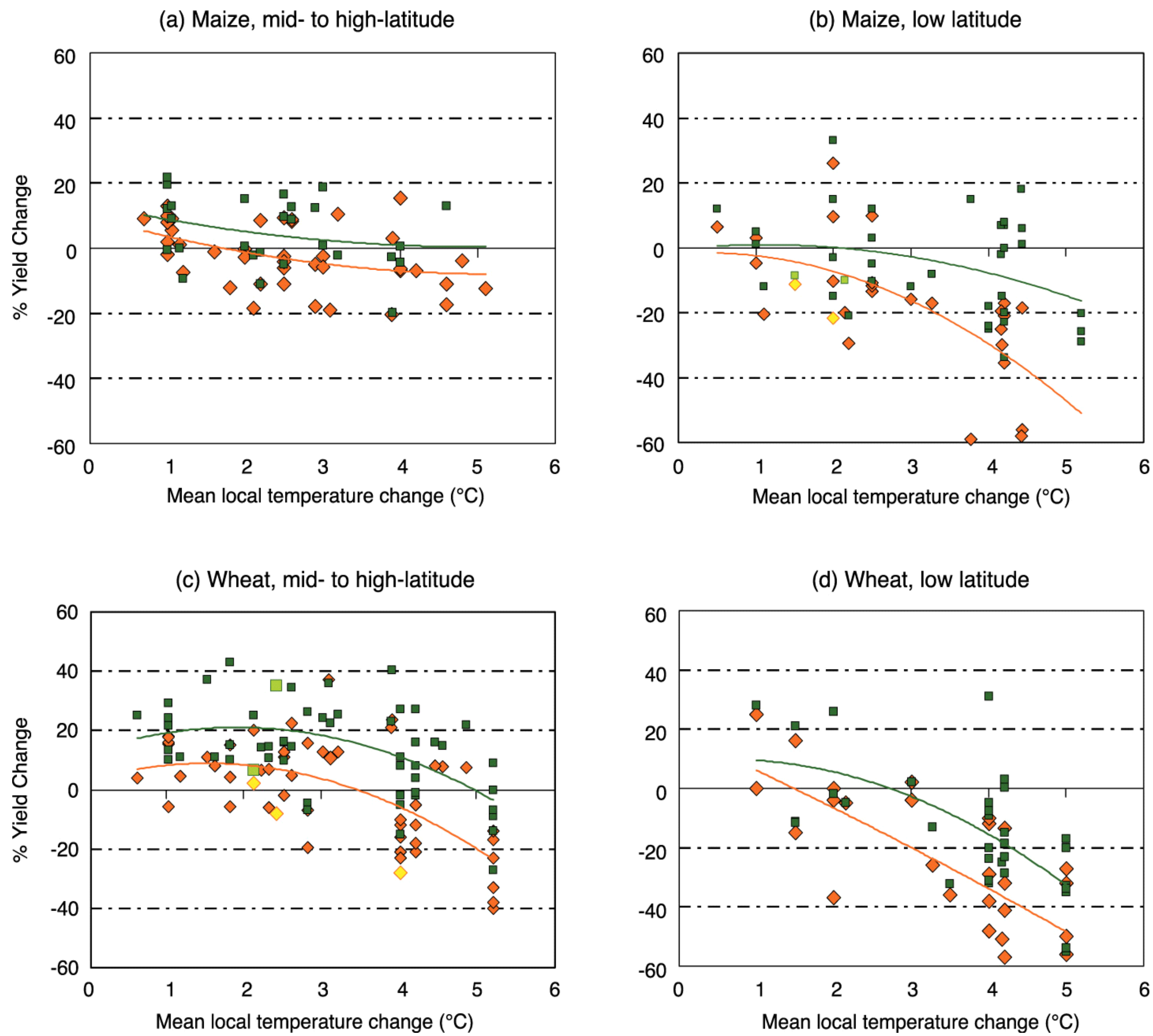
Projected Impacts: Water Availability

Projected Surface Water in 2050 Relative to 1900-1970



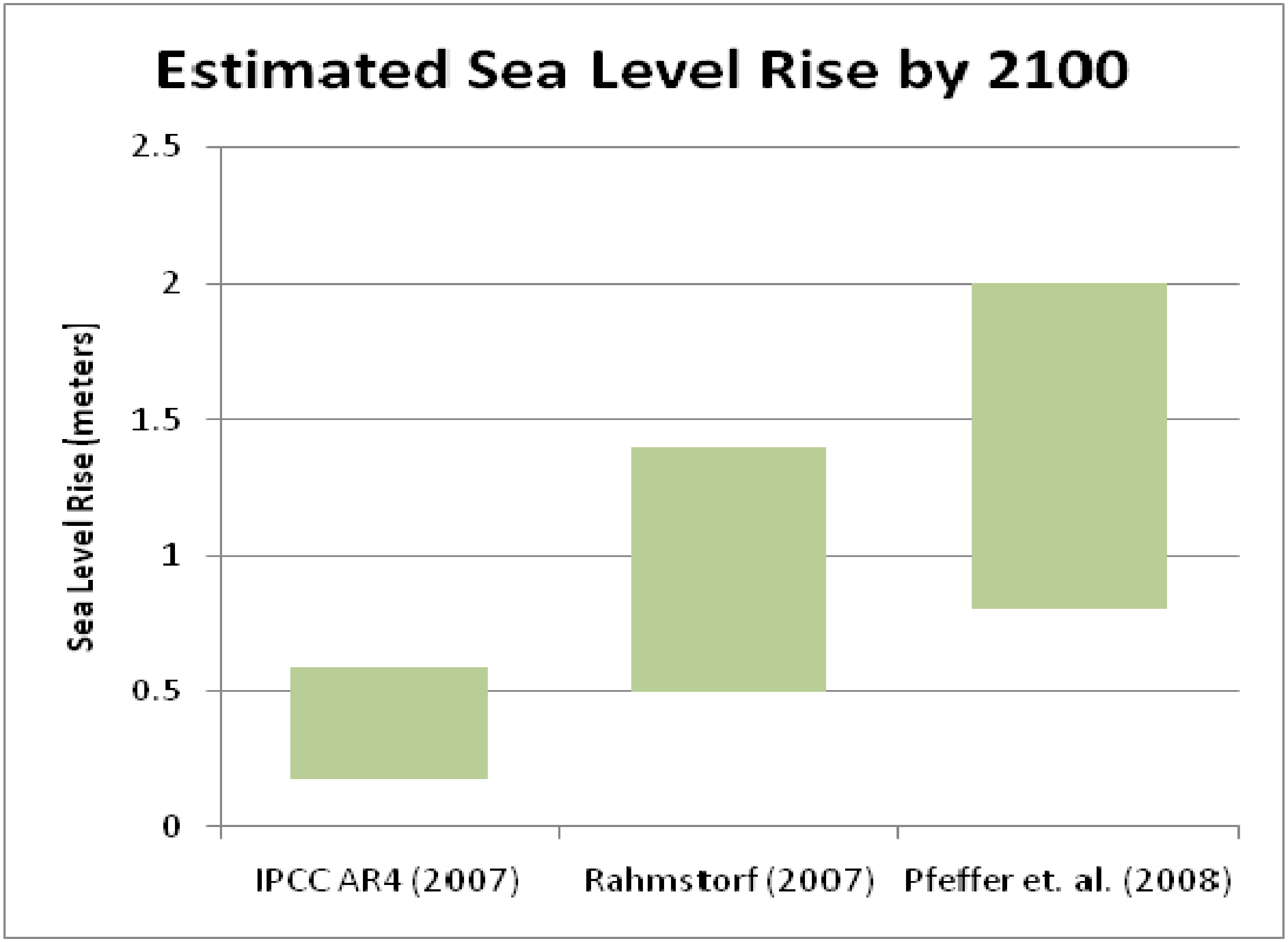
Milly et al. *Nature* 2005, updated

Projected Impacts: Crop Sensitivity



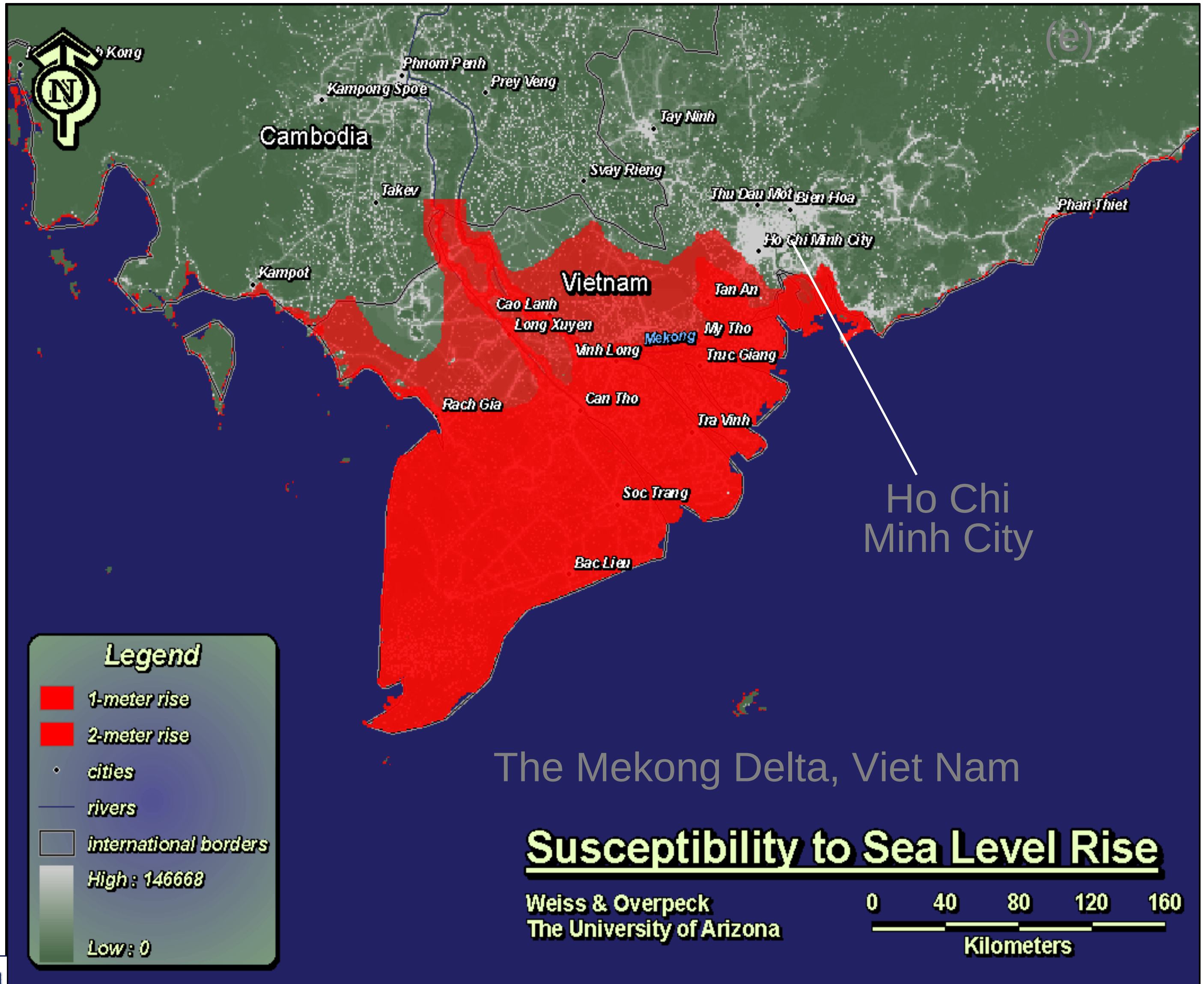
IPCC 2007-WGII, Fig. TS7

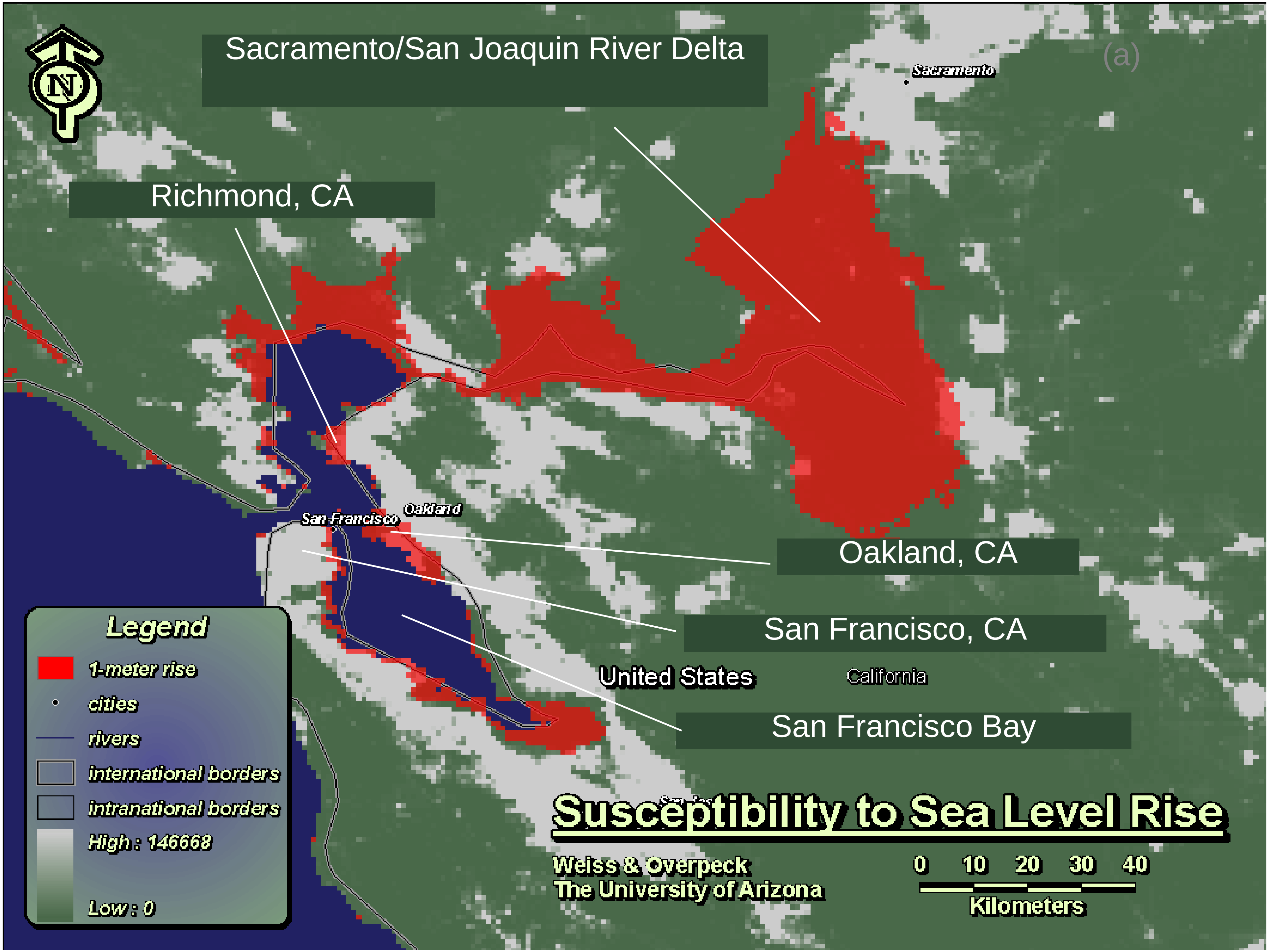
Projected Impacts: Sea Level Ris



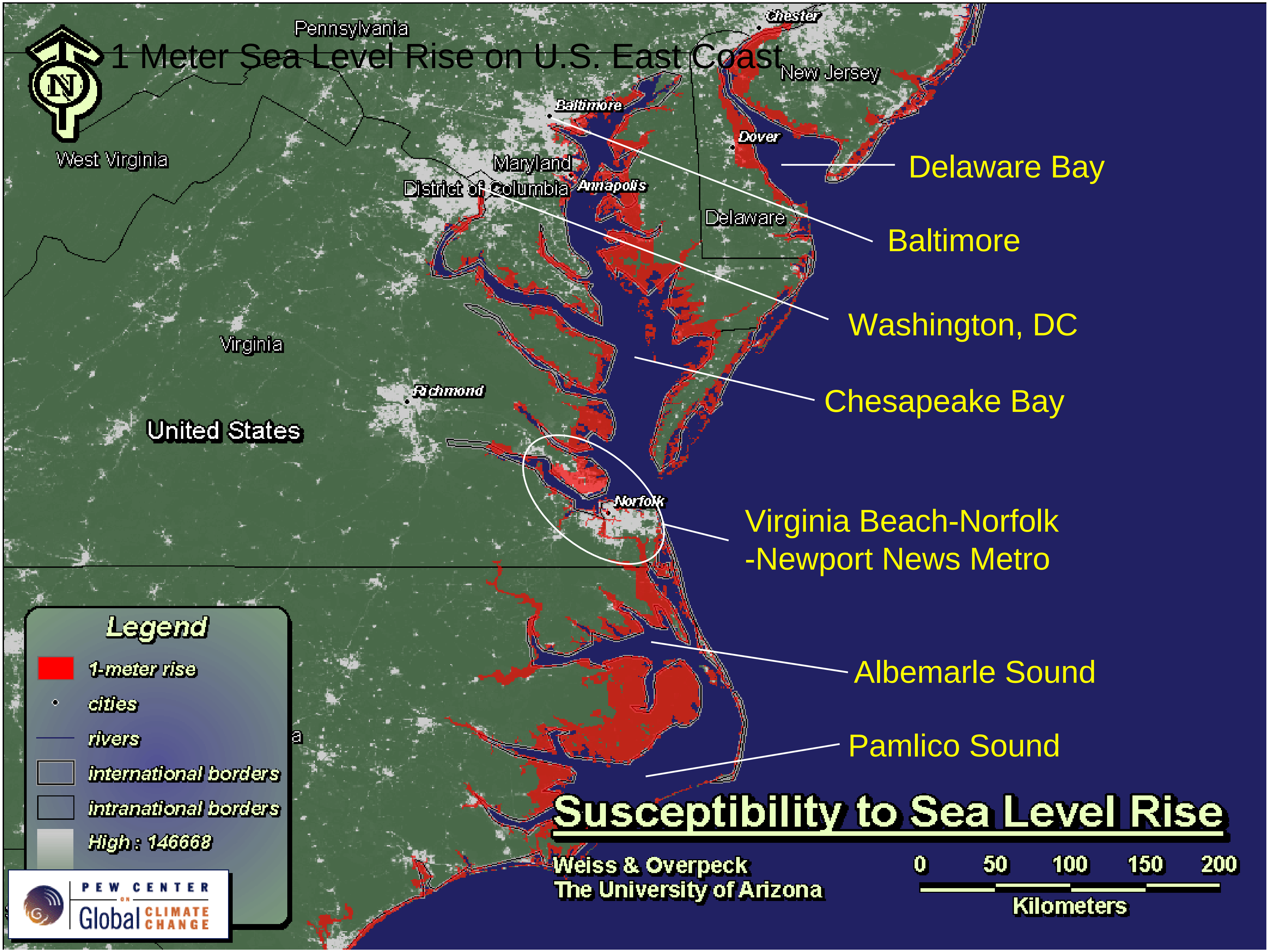
PEW CENTER ON Global CLIMATE CHANGE

Sea Level Rise in Viet Nam





Sacramento/San Joaquin River Delta
(a)
Sacramento
Richmond, CA
Oakland
San Francisco
Oakland, CA
San Francisco, CA
United States
California
San Francisco Bay
Legend
1-meter rise
cities
rivers
international borders
intranational borders
High : 146668
Low : 0
Susceptibility to Sea Level Rise
Weiss & Overpeck
The University of Arizona
0 10 20 30 40
Kilometers



1 Meter Sea Level Rise on U.S. East Coast
Pennsylvania
Chester
New Jersey
Baltimore
Dover
West Virginia
Maryland
District of Columbia
Annapolis
Delaware
Delaware Bay
Baltimore
Washington, DC
Virginia
Chesapeake Bay
Richmond
United States
Norfolk
Virginia Beach-Norfolk
-Newport News Metro
Albemarle Sound
Pamlico Sound
Legend
1-meter rise
cities
rivers
international borders
intranational borders
High : 146668
PEW CENTER ON Global CLIMATE CHANGE
Susceptibility to Sea Level Rise
Weiss & Overpeck
The University of Arizona
0 50 100 150 200
Kilometers

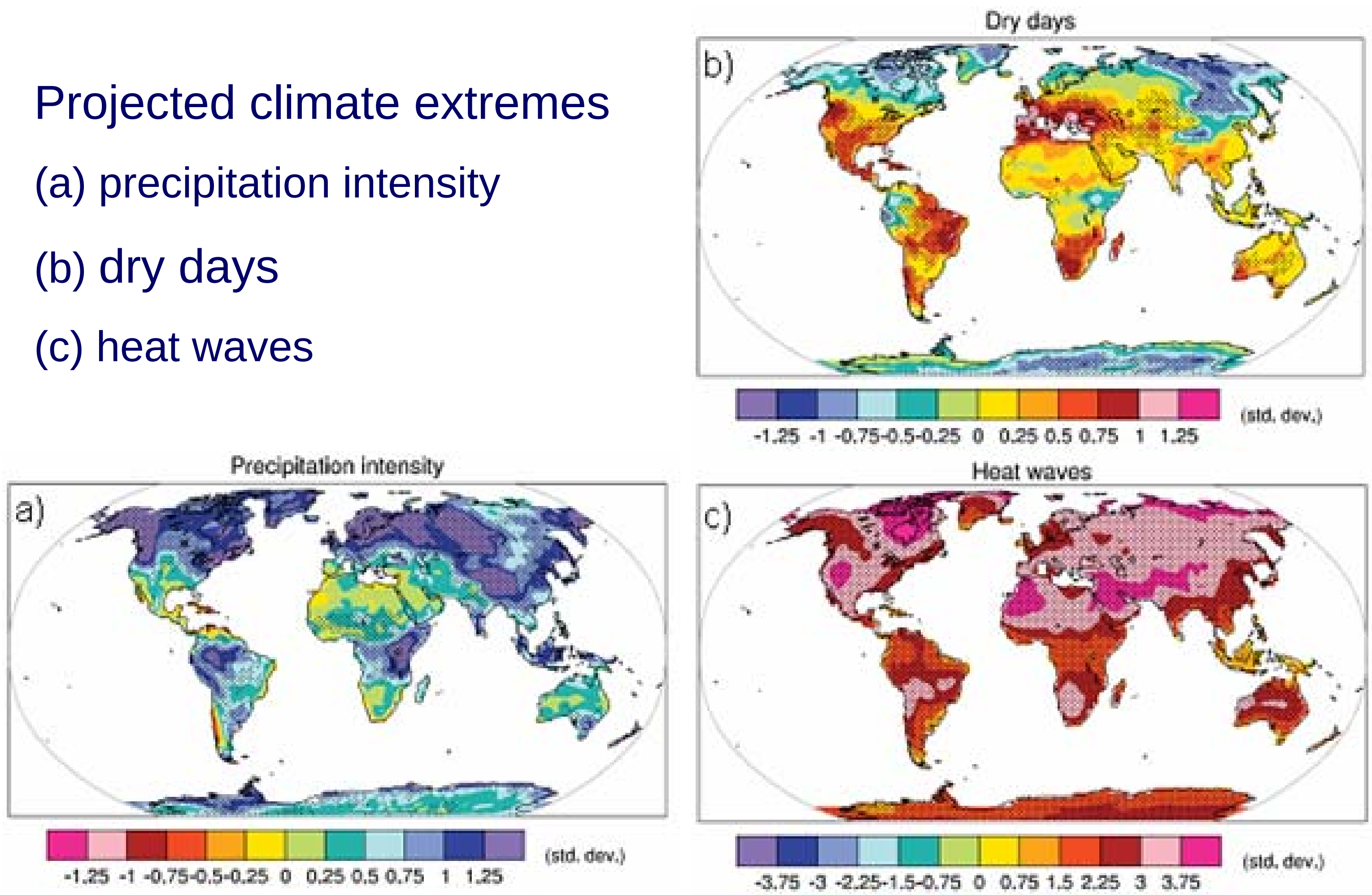
Projected Impacts: Climate Extremes

Projected climate extremes

(a) precipitation intensity

(b) dry days

(c) heat waves

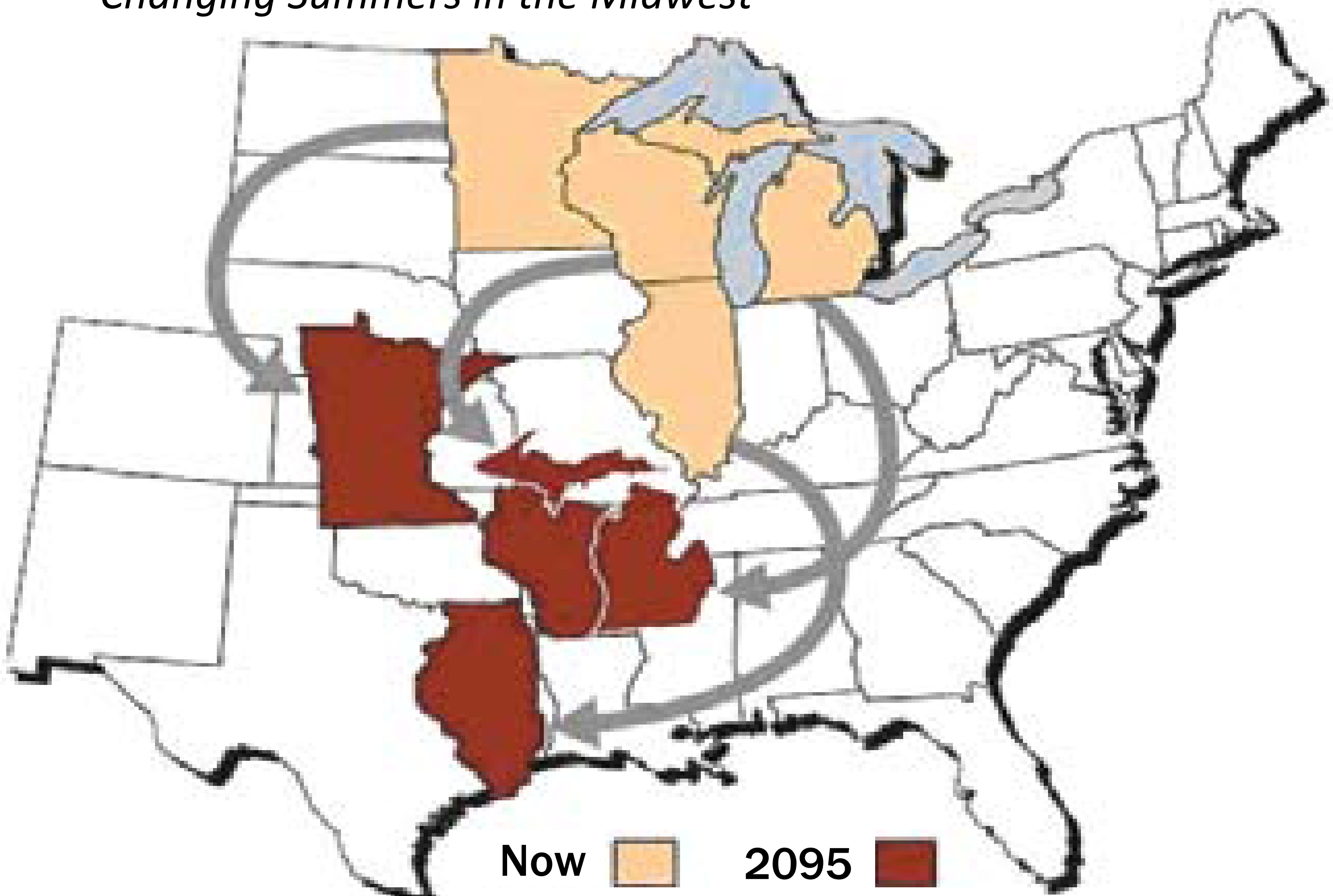


AR4-WG1-Ch10 (2007)

Projected Impacts: Climate Extremes

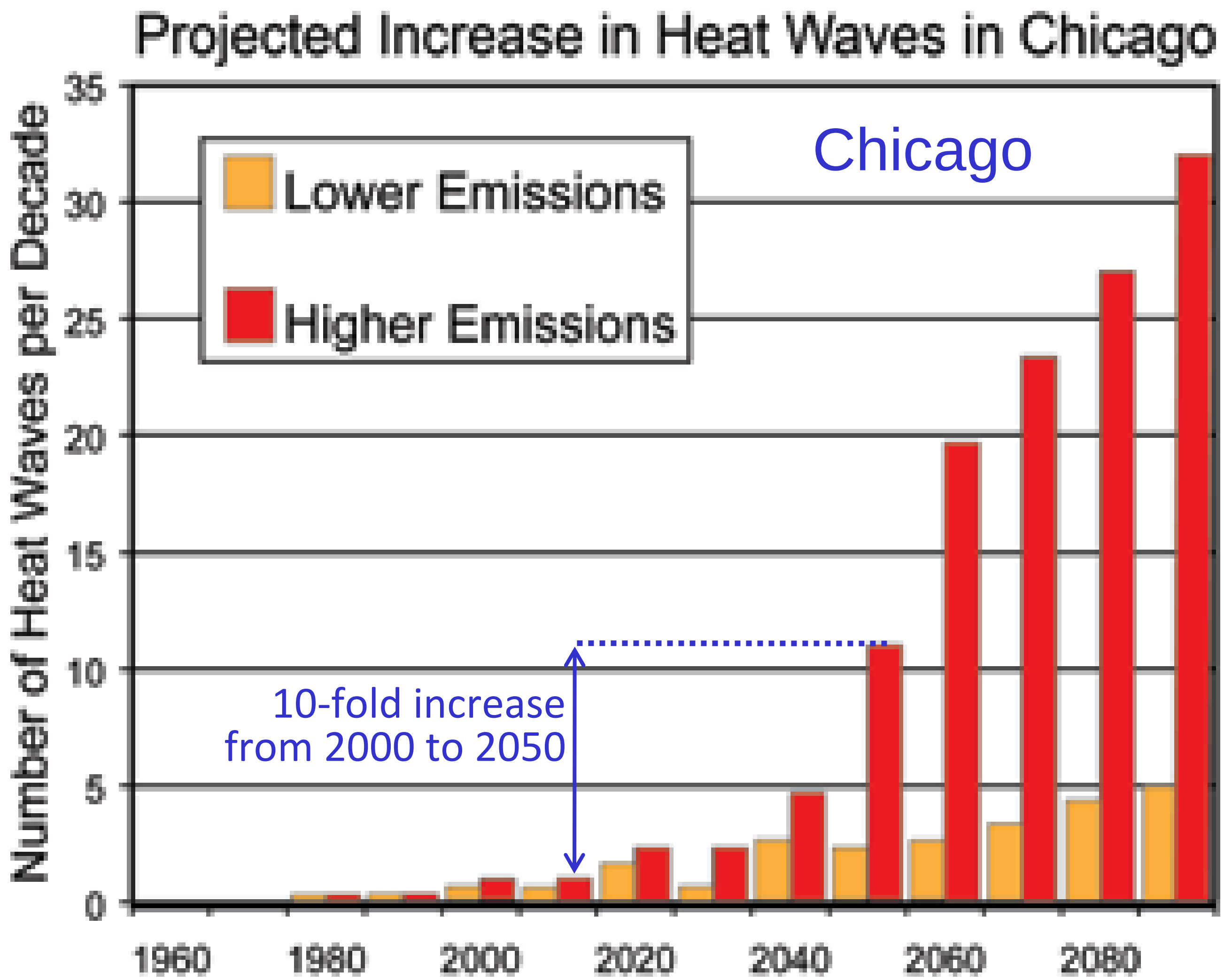
Climate on the Move:

Changing Summers in the Midwest



U.S. Climate Change Science Program Draft Unified Synthesis Product Report, NOAA 2008.

Increased heat wave frequency

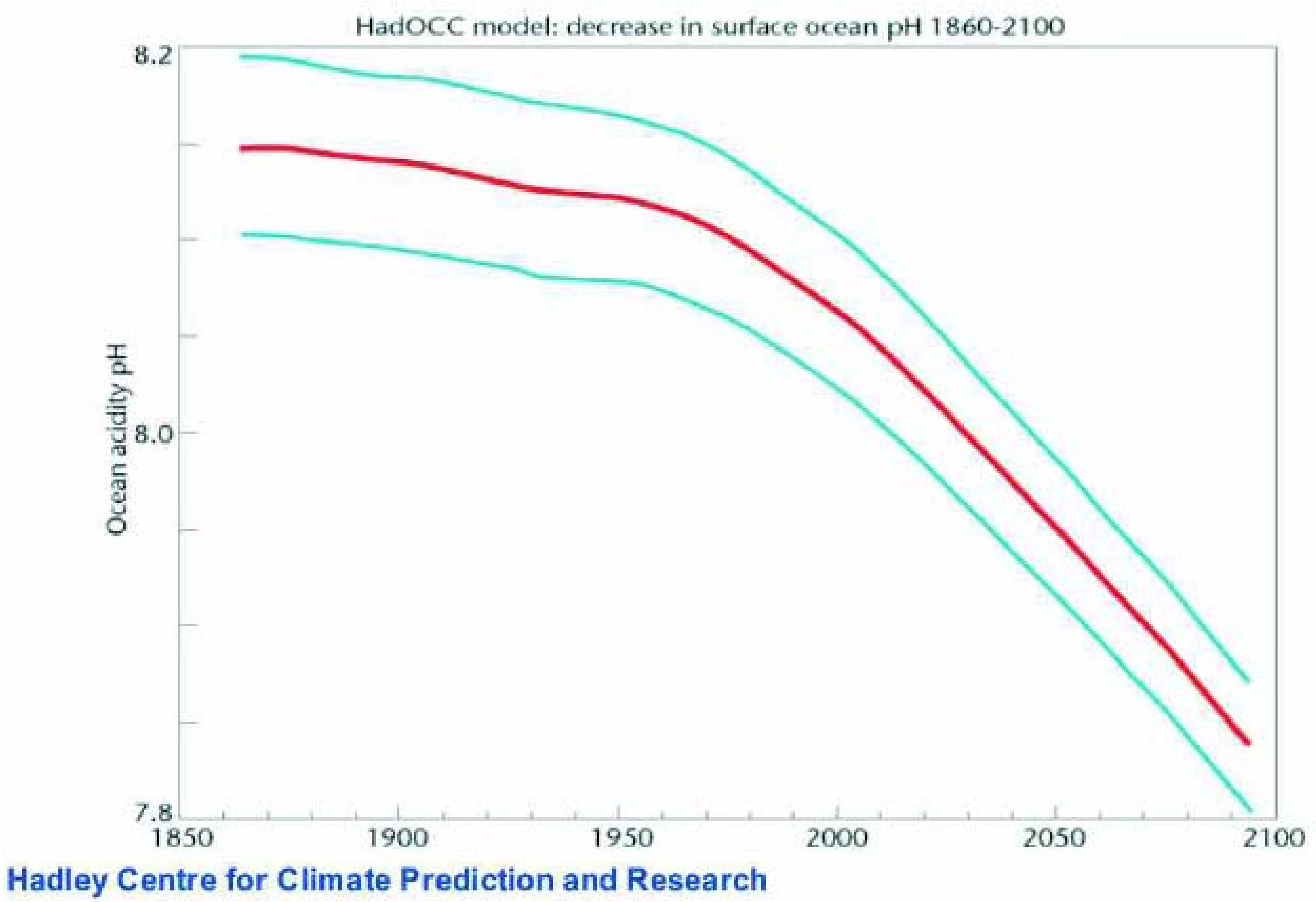


Source: U.S. *CCSP Draft Unified Synthesis Product,* 14 July, 2008.

PEW CENTER ON Global CLIMATE CHANGE

Slide: courtesy R. Bierbaum

Observed Impacts: Oceans acidifying

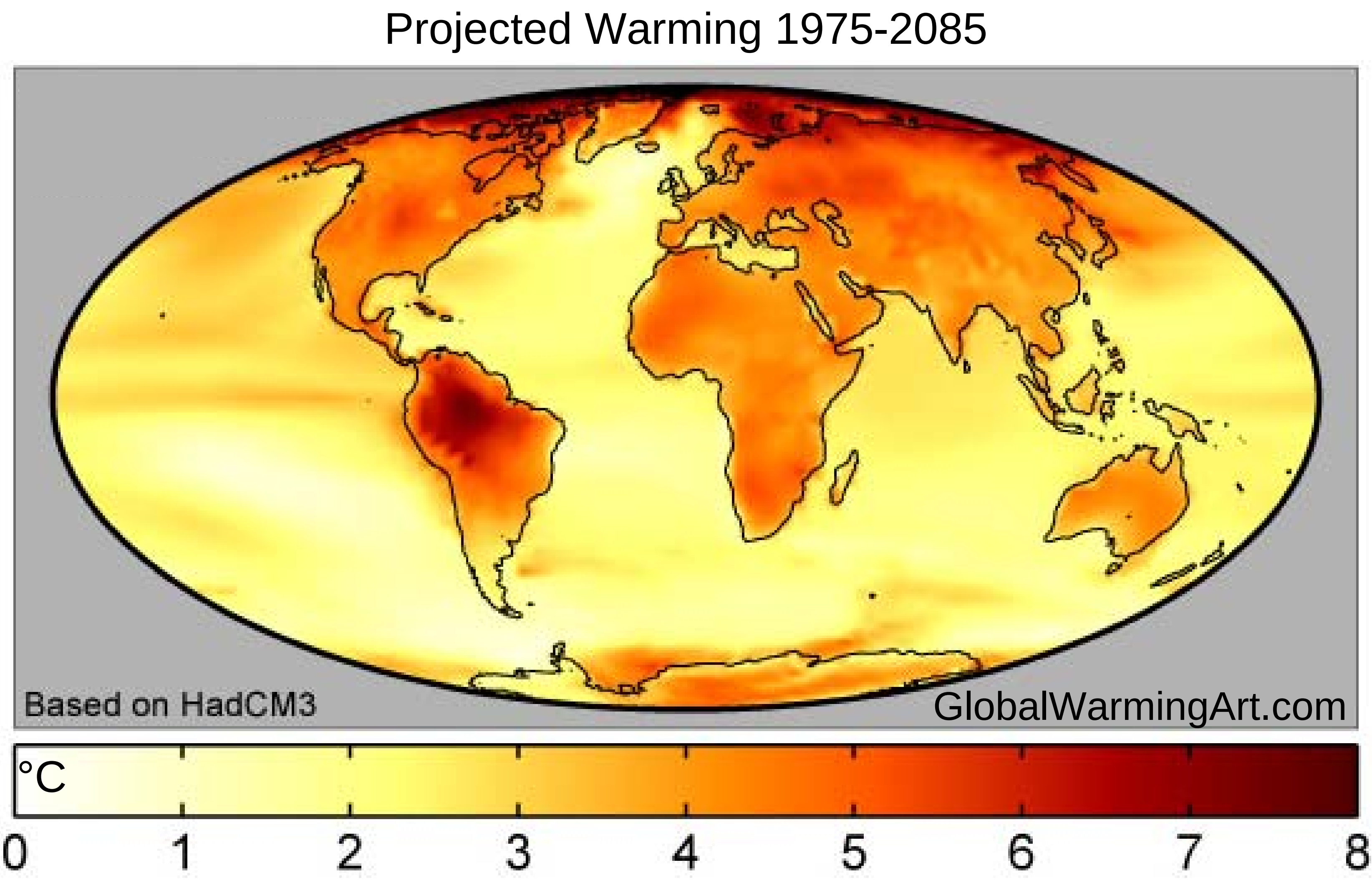


Slide: courtesy J. Holdren

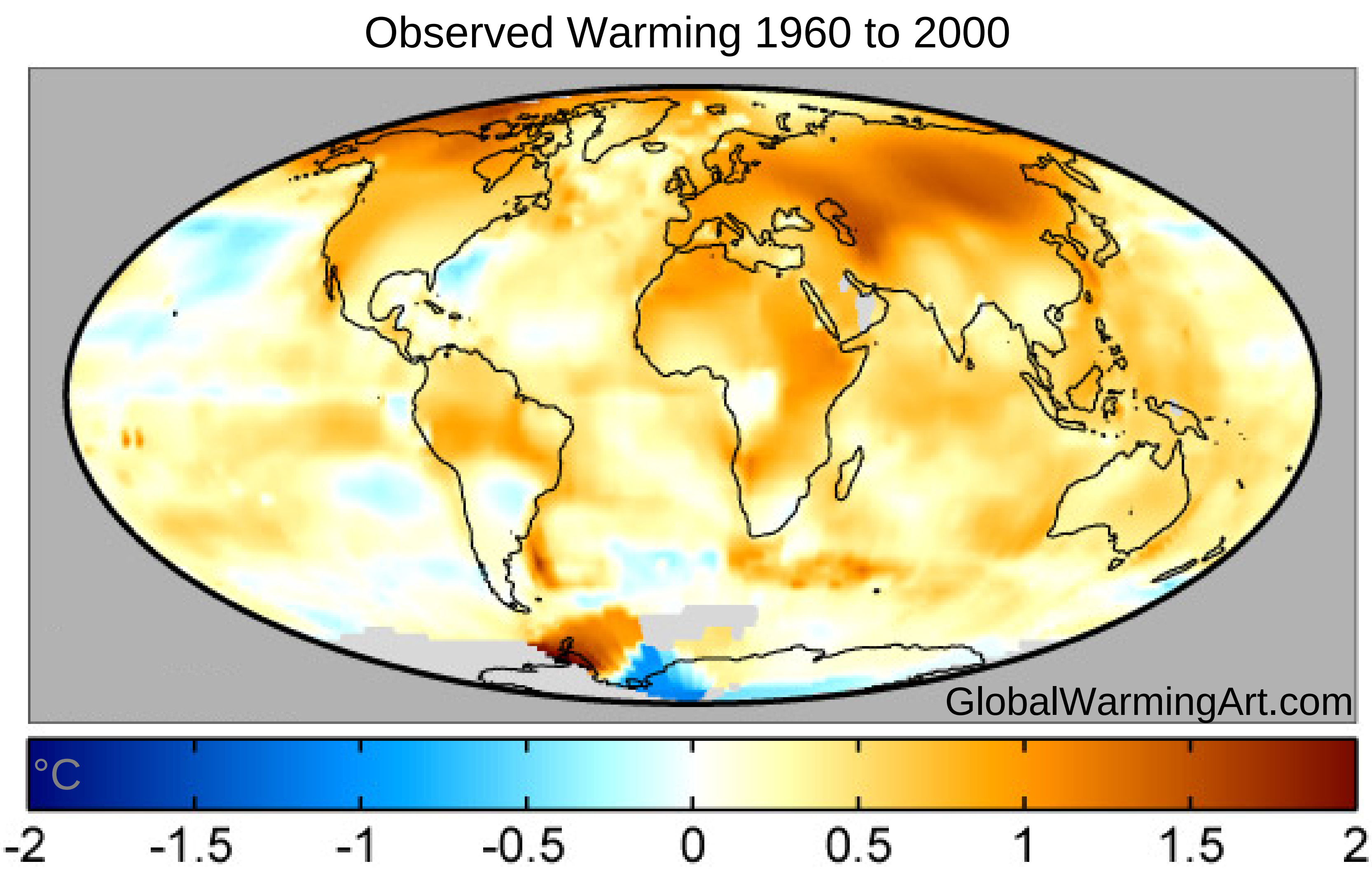
Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

What can Models Tell Us?



What can Models Tell Us?



PEW CENTER ON Global CLIMATE CHANGE

What can Models Tell Us?

Many predicted changes have been observed

- Land surface warming more than sea surface
- Northern Hemisphere warming more than SH
- Polar ice sheets are losing ice
- Mountain glacier retreat is accelerating
- Arctic sea ice decreasing - area & volume
- Sea level rise is accelerating
- Precipitation is increasing in wet regions and decreasing in dry regions
- Northern ecosystems changing as predicted

Large-scale patterns are developing as predicted

What can Models ***Not*** Tell Us?

Many risk-intensive issues are unresolved

- Timing and magnitude of future change
- Regional details of future change
- Timing/effect of positive feedbacks
- Thresholds/tipping points/irreversibility

Where and when will climate change abruptly or irreversibly or catastrophically?

Structural Uncertainties in Models

Amplifying (positive) feedbacks are omitted

- Net ecosystem C loss (increases CO_2 efflux)
- Ocean CO_2 outgassing (lower solubility)
- Permafrost thaw emitting methane
- Some evidence that these feedbacks could be happening already

Nonlinearities

- Nonlinear responses to warming
- Discontinuities—thresholds that shift climate components to new states

Models may systematically underestimate warming per unit of man-made greenhouse gas emitted

Projections Underestimate Change

1) Large polar ice sheets losing ice 100 years sooner than expected (IPCC 2007; Shepherd & Wingham 2007, *Science*)

2) Small glaciers & ice caps losing ice faster than projected (Meier et al. 2007, *Science*)

3) Boreal forests are responding to global warming sooner than expected (Soja et al. 2007, *Global & Planetary Change*)

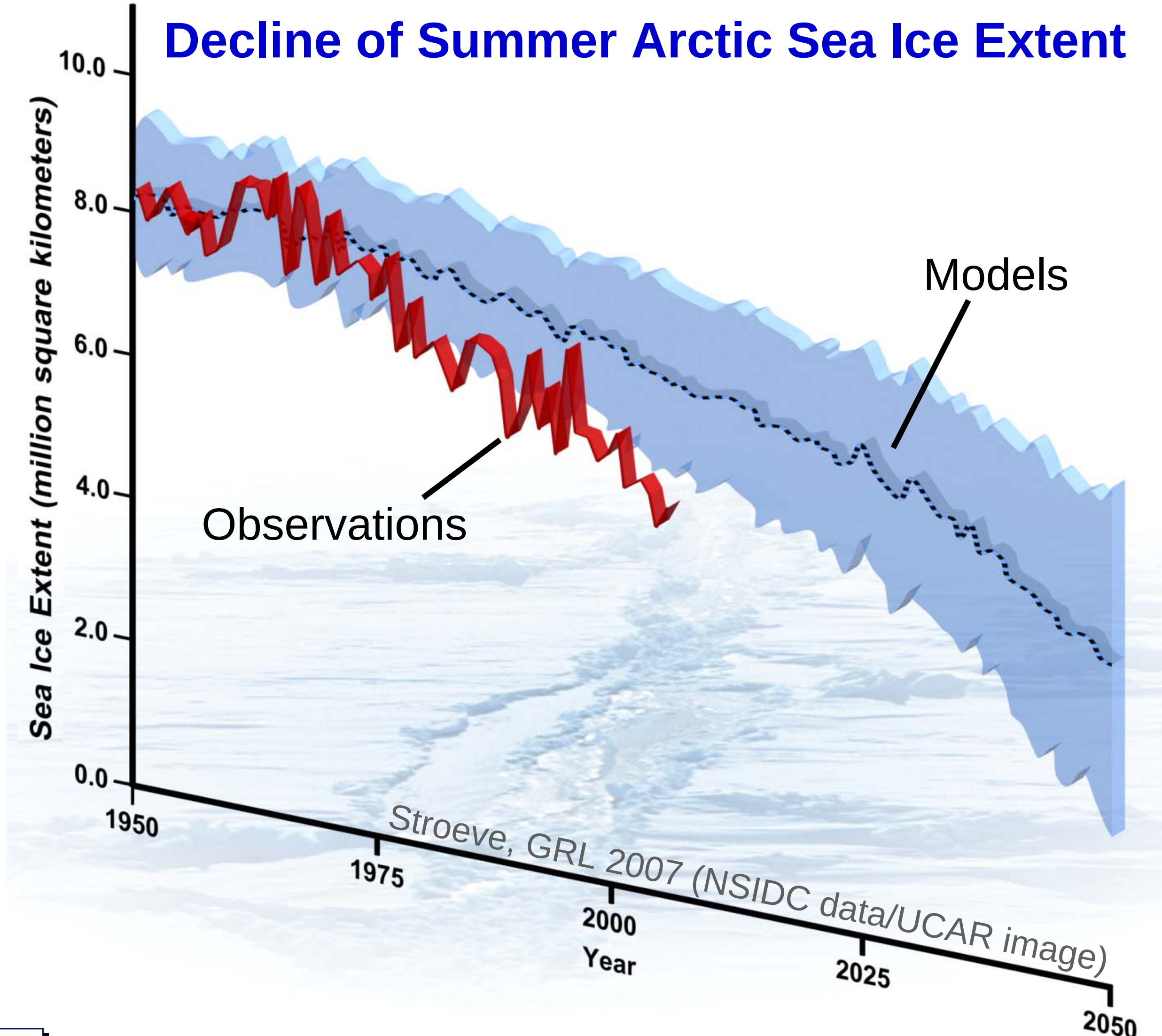
4) Observed sea level rise nearly 2X faster than projected (Rahmstorf et al. 2007, *Science*)

5) Global precipitation changing 2X faster than projected (Wentz et al. 2007, *Science*; Zhang et al. 2007, *Nature*)

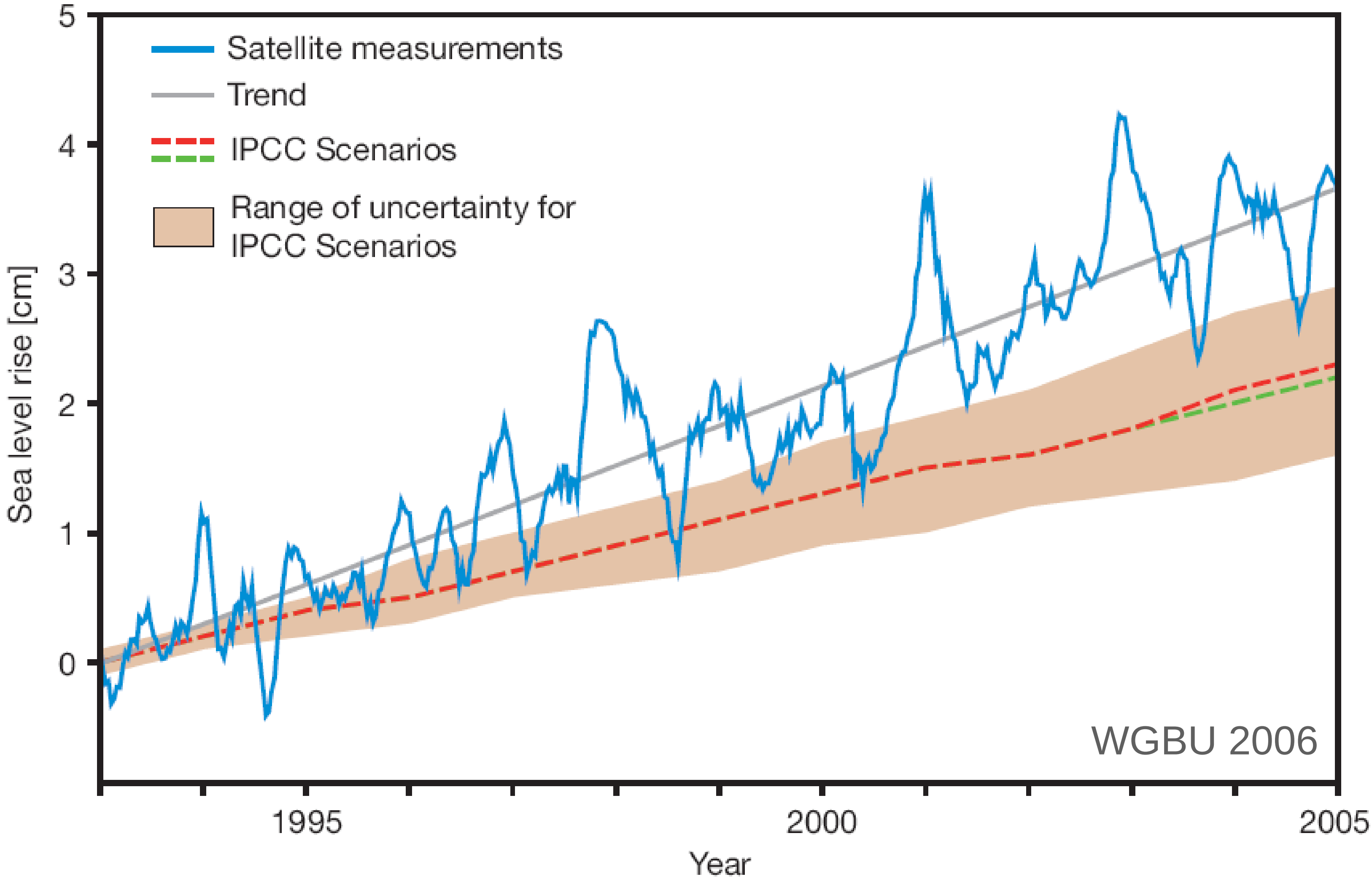
6) Observed Arctic sea ice loss 3X faster than projected (Stroeve et al. 2007, *Geophysical Research Letters*)

Models may underestimate response per unit warming

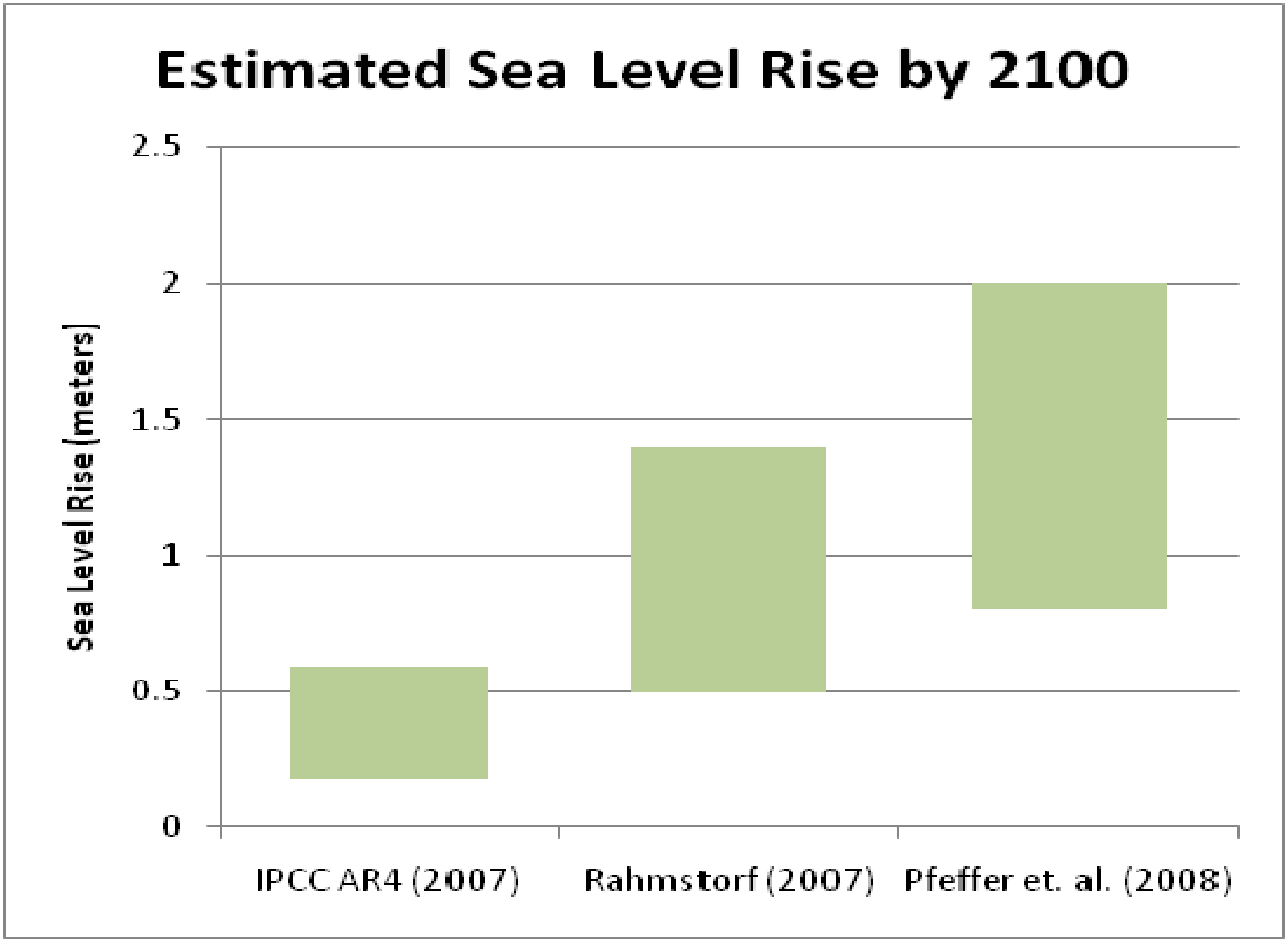
Projections Underestimate Change



Projections Underestimate Change



Range of Uncertainty Informs Risk



Asymmetry of Uncertainty

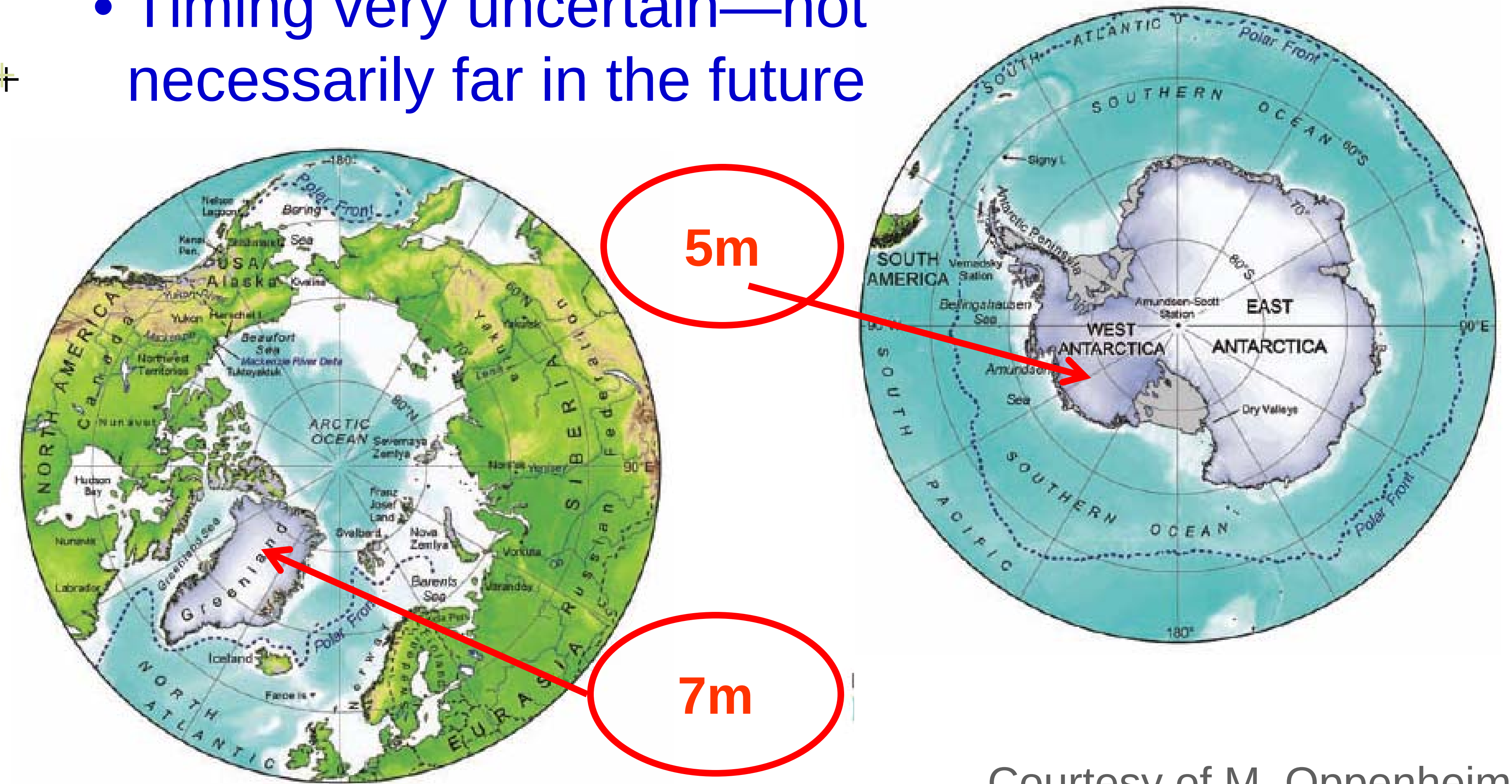
"A [sea level] rise by over one meter by 2100 for strong warming scenarios cannot be ruled out… On the other hand, very low sea level rise values as reported in the IPCC… now appear rather implausible in the light of the observational data."

Rahmstorf, 2007 *Science*

Uncertainty about sea level rise is at the upper end, not the lower end.

Ice Sheets and Sea Level Rise

- Potential for catastrophic sea level rise
- Destabilization threshold 1-4 ^{0}C
- Timing very uncertain—not necessarily far in the future



Courtesy of M. Oppenheimer

Previous Rapid Sea Level Rise

nature geoscience | ADVANCE ONLINE PUBLICATION LETTERS

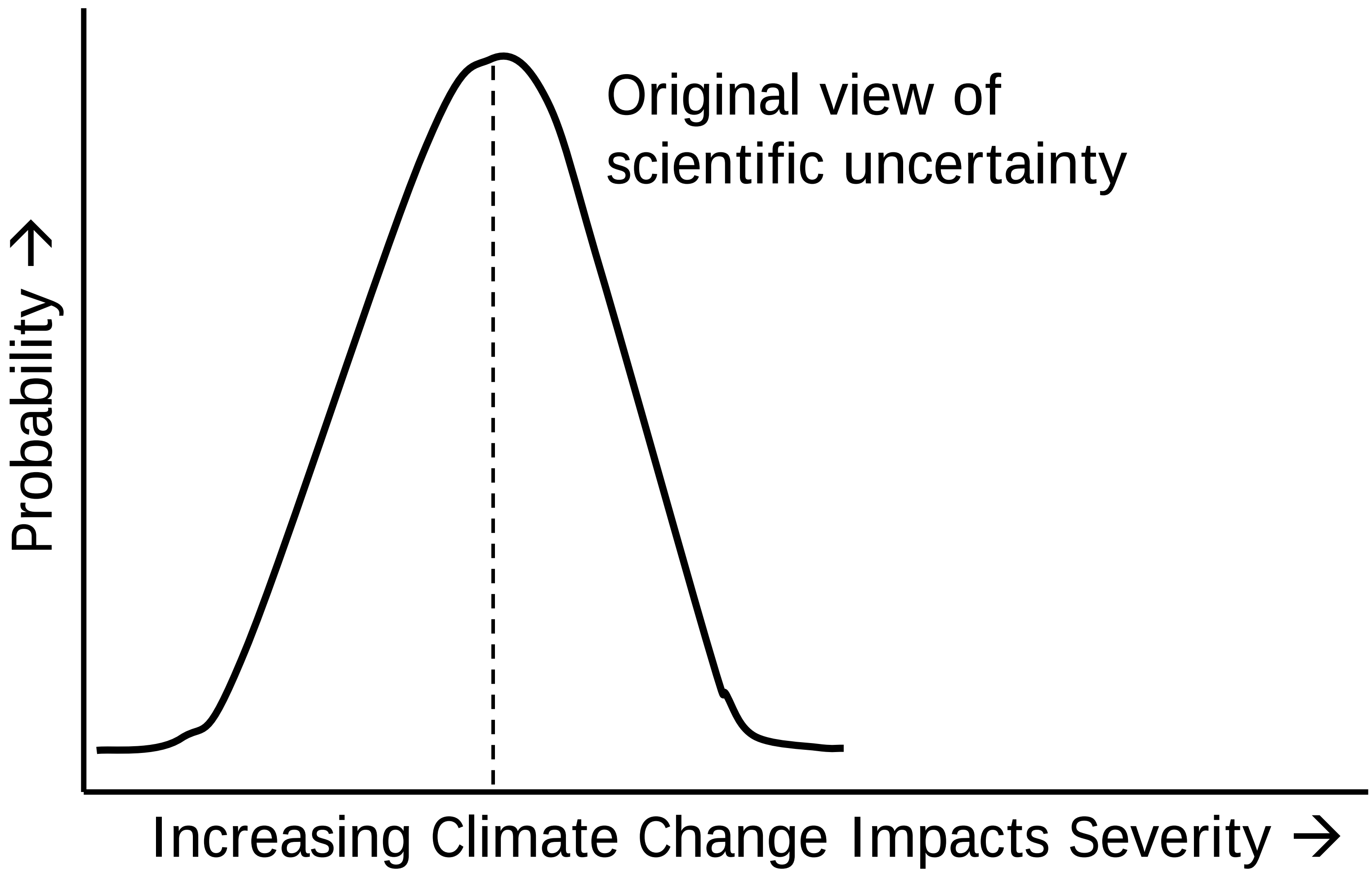
High rates of sea-level rise during the last interglacial period

E. J. ROHLING[1]*, K. GRANT[1], CH. HEMLEBEN[2]*, M. SIDDALL[3], B. A. A. HOOGAKKER[4], M. BOLSHAW[1] AND M. KUCERA[2]

Published online: 16 December 2007; doi:10.1038/ngeo.2007.28

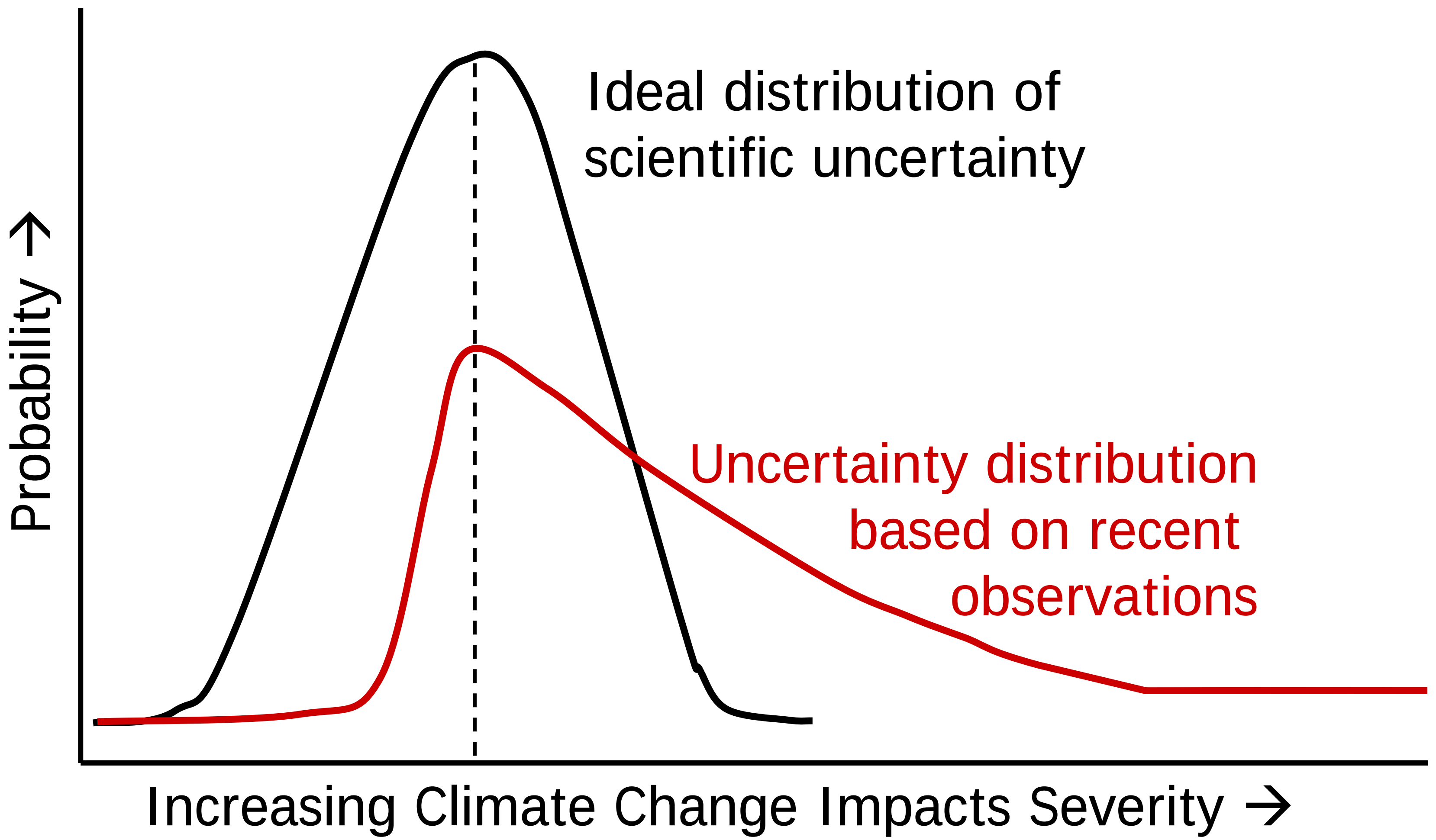
"We find average rates of sea-level rise of 1.5 m [5 ft.] per century. As global mean temperatures … were comparable to projections for future climate change under the influence of anthropogenic greenhouse-gas emissions these observed rates of sea-level change inform the ongoing debate about high versus low rates of sea-level rise in the coming century."

Asymmetry of Uncertainty



PEW CENTER ON Global CLIMATE CHANGE

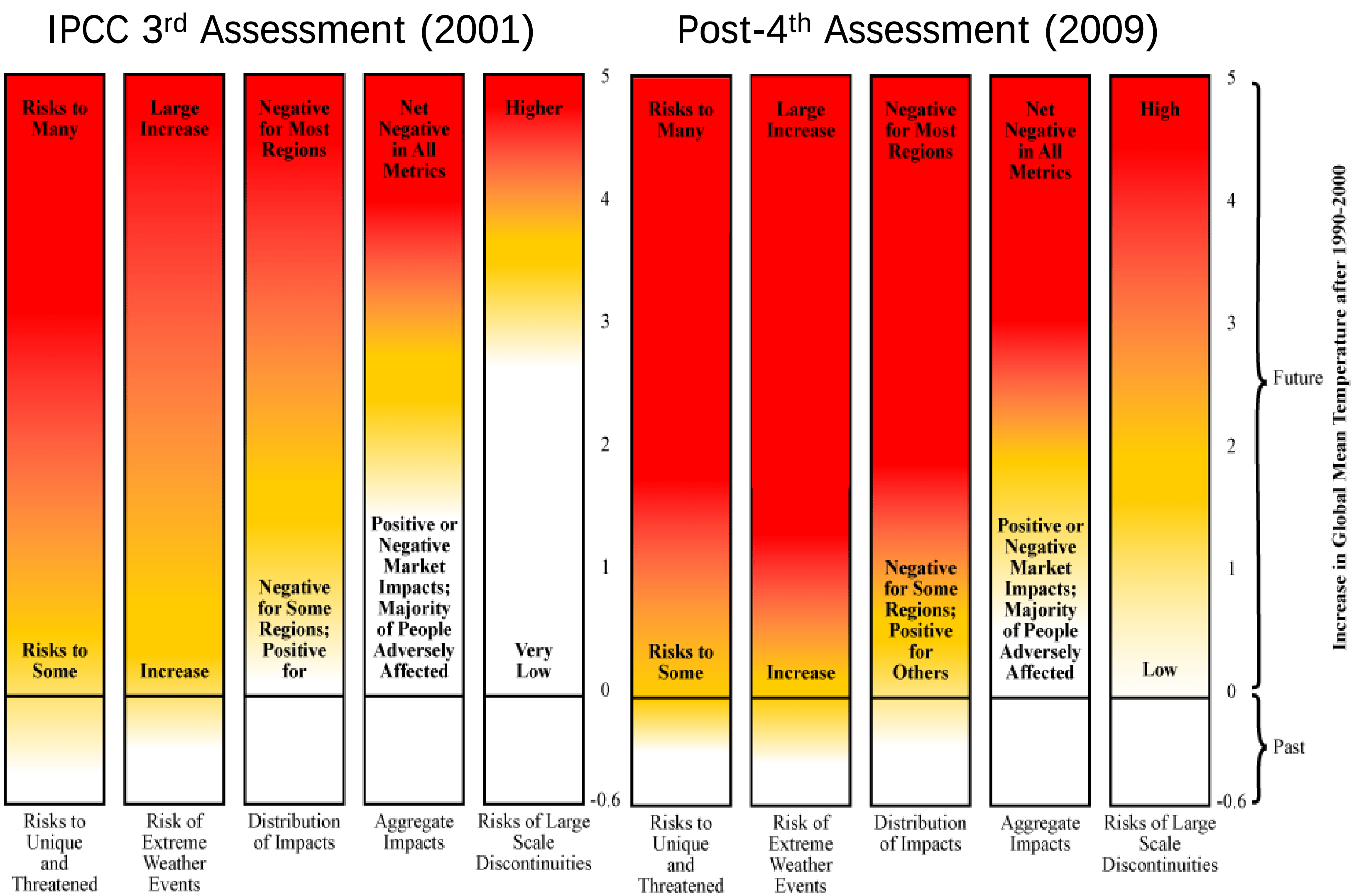
Asymmetry of Uncertainty



Asymmetry of uncertainty = Elevated Risk

Asymmetry of Uncertainty

Revised IPCC Reasons for Concern



Smith et al., *PNAS* 2004

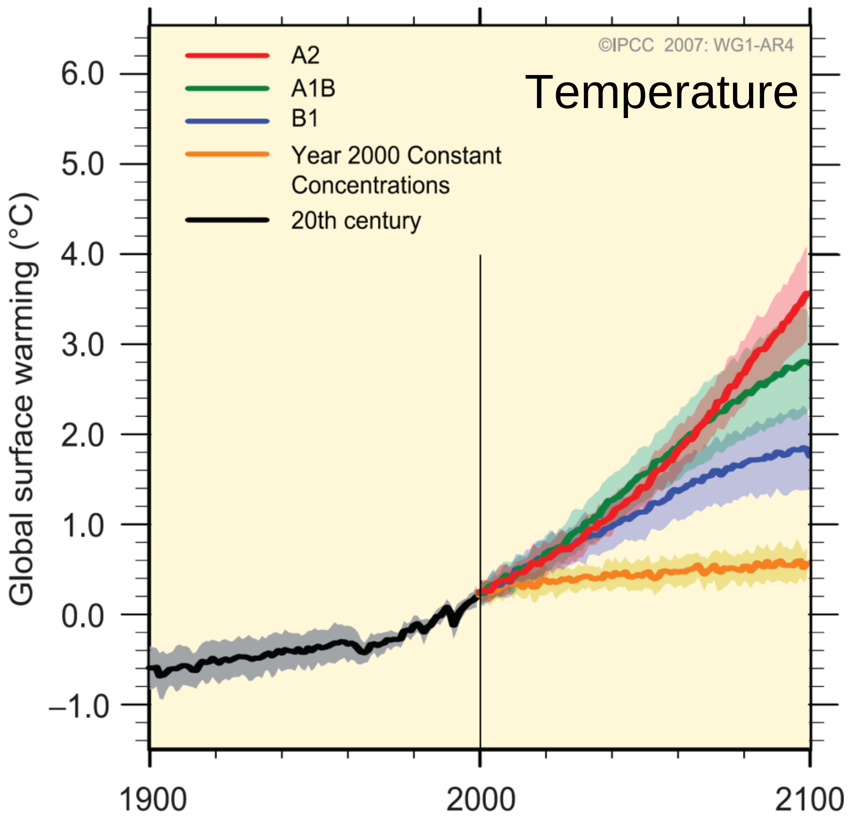
Risks of Climate Change

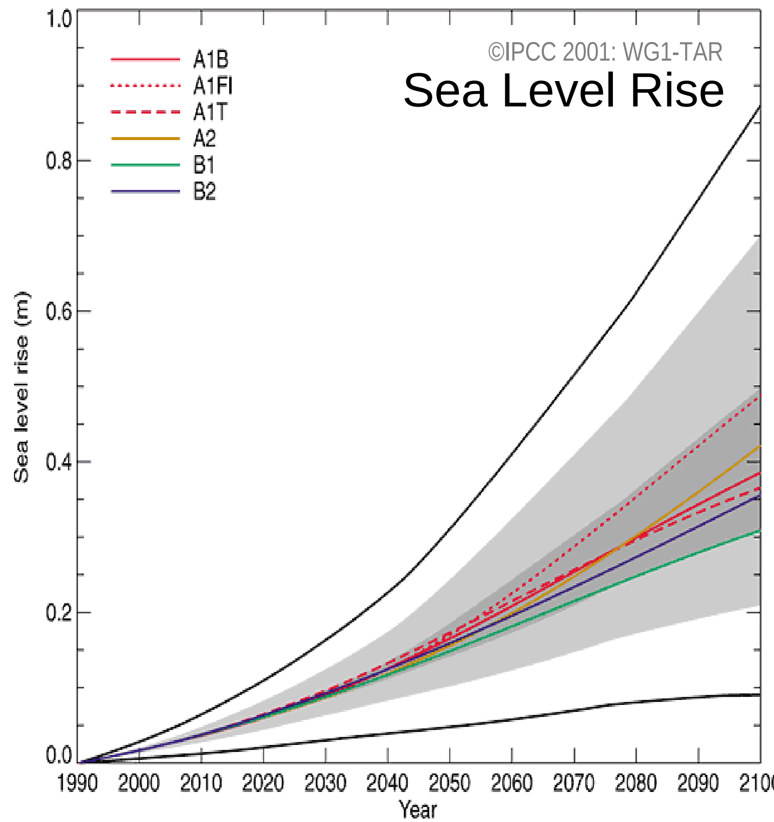
Accurate risk perception is critical to effective decision making.

- Low probability does not equal low risk.
- Risk is high where high-impact outcomes are plausible, even if probability is low.
- The likelihood of severe or catastrophic outcomes is probably significantly higher than the public and decision makers realize.

Perception of Risk

Myth—*Smooth/gradual climate change*



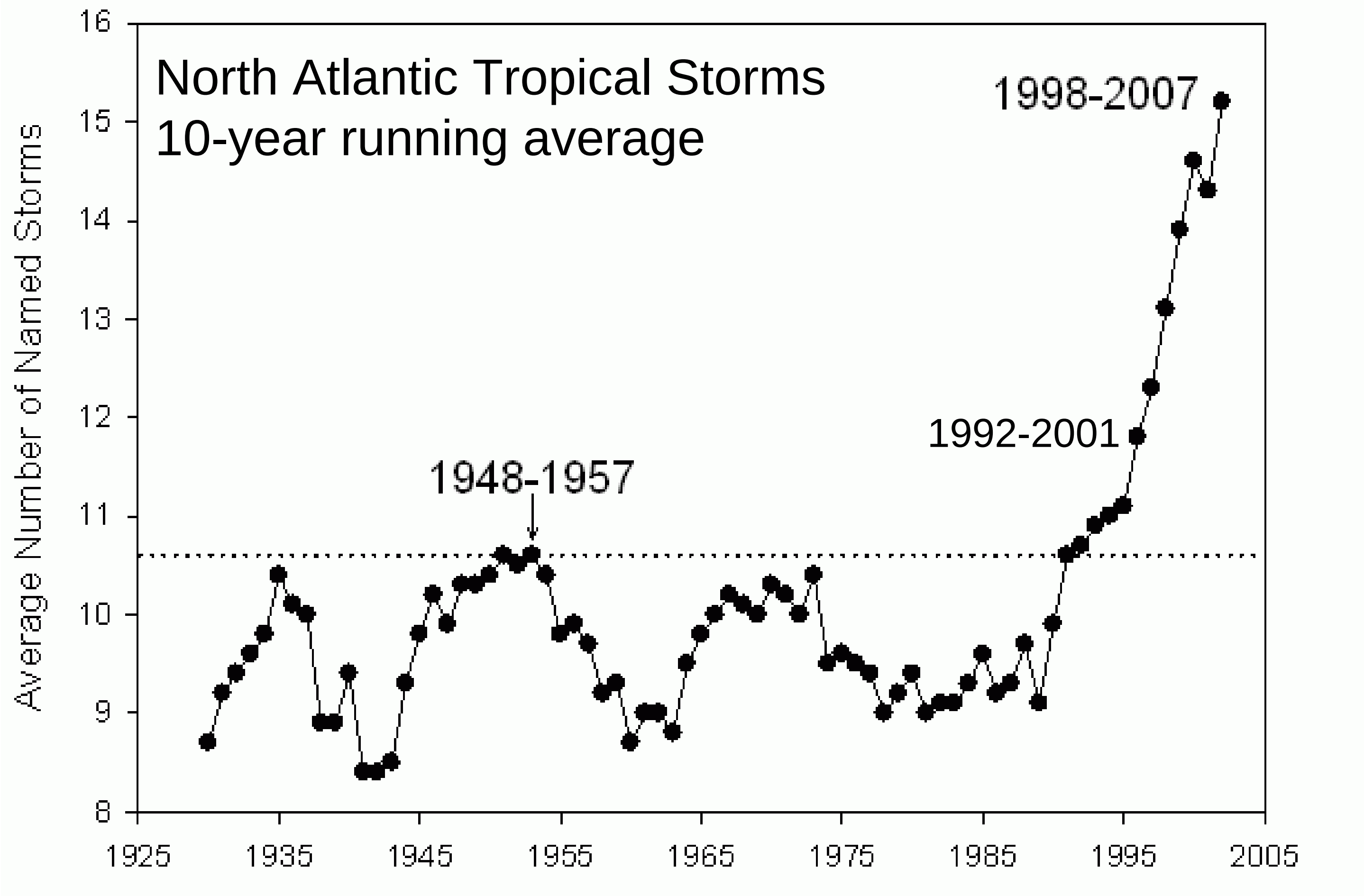


- Model projections average over large space and long time.
- Gives false impression of smooth/gradual future change.

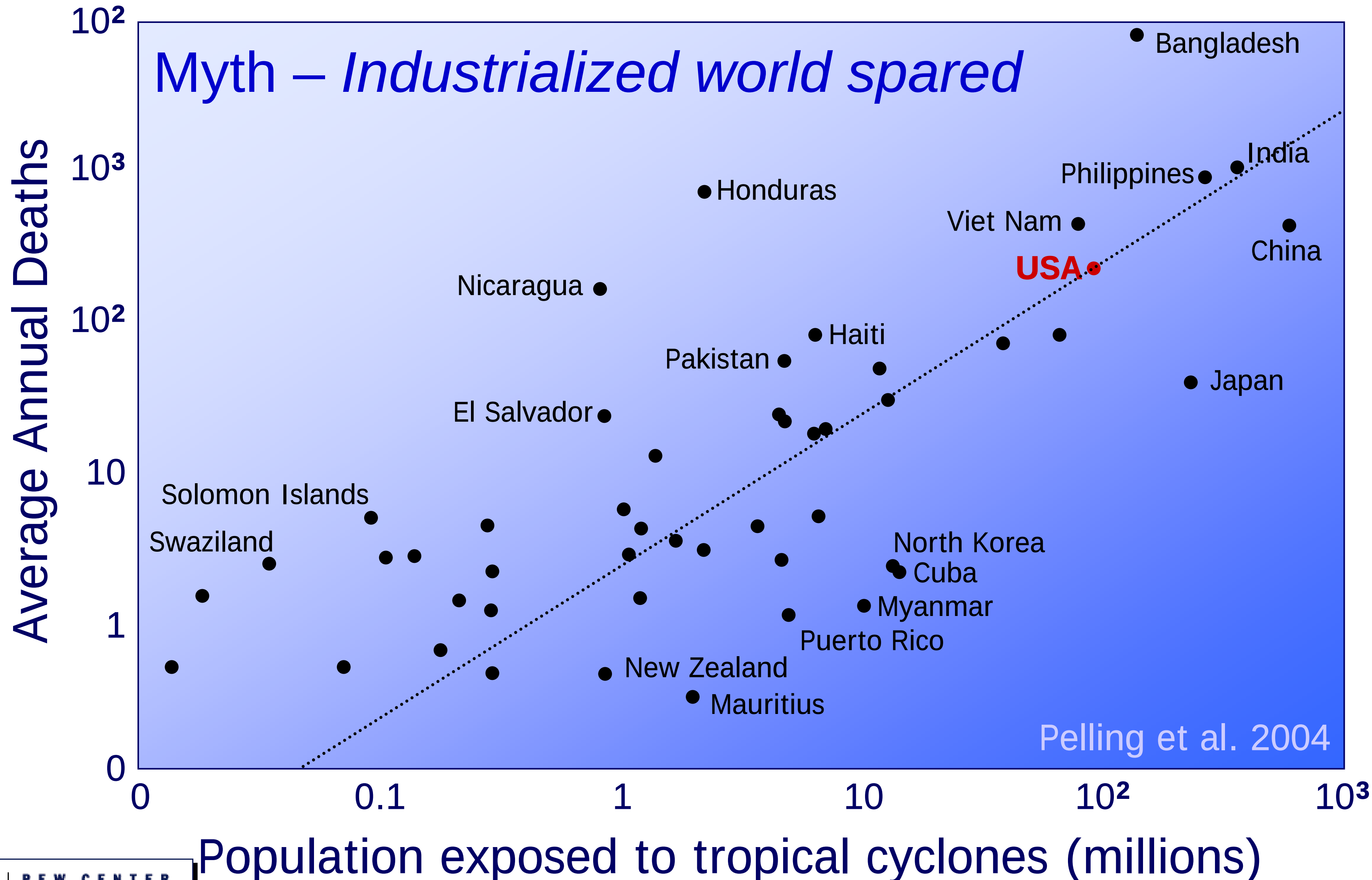
PEW CENTER ON Global CLIMATE CHANGE

Perception of Risk

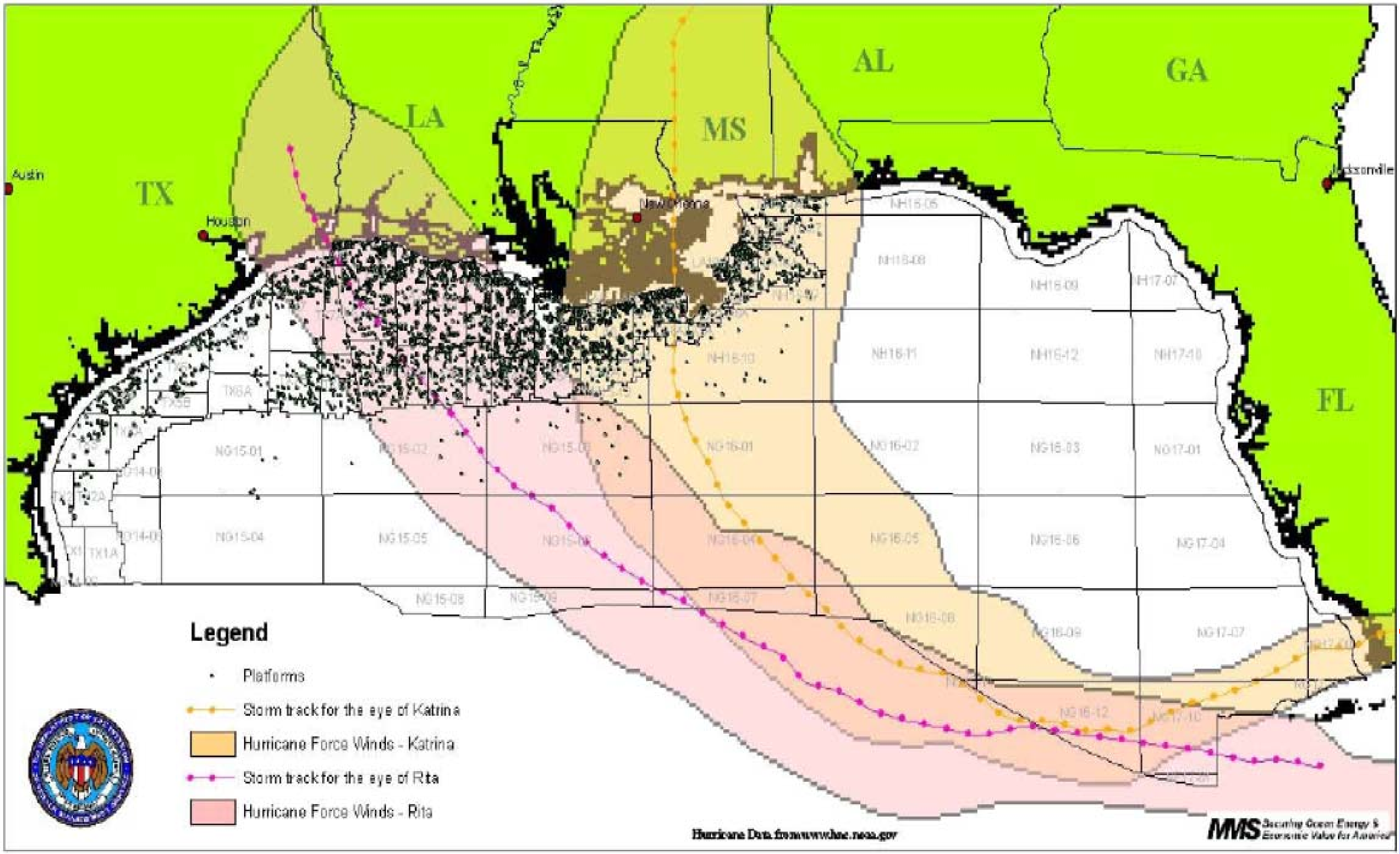
Myth—*Smooth/gradual climate change*



Perception of Risk



Perception of Risk



operations were otherwise suspended.

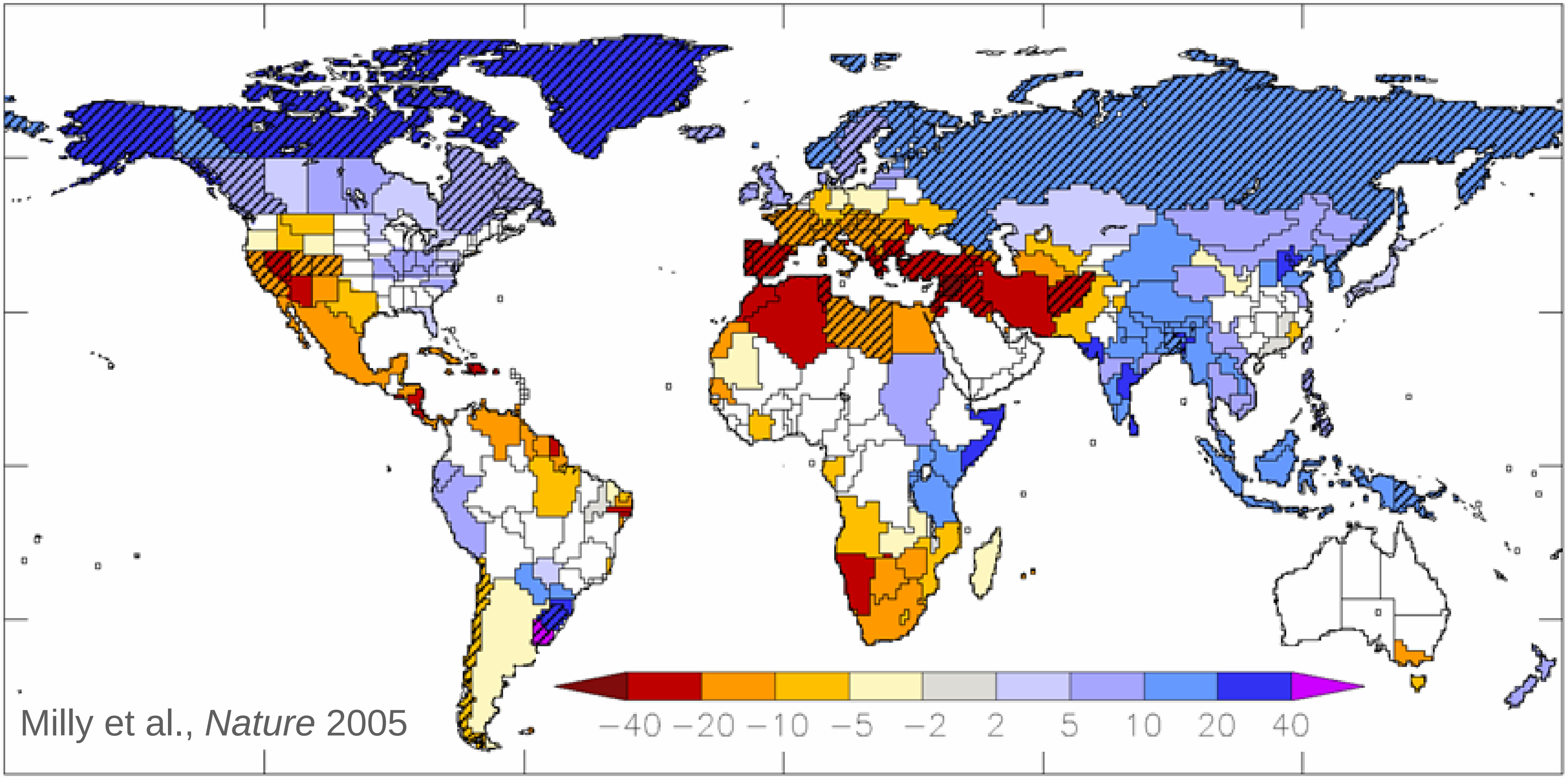
Slide: courtesy R. Bierbaum

PEW CENTER ON Global CLIMATE CHANGE

Perception of Risk

Myth – *Industrialized world spared*

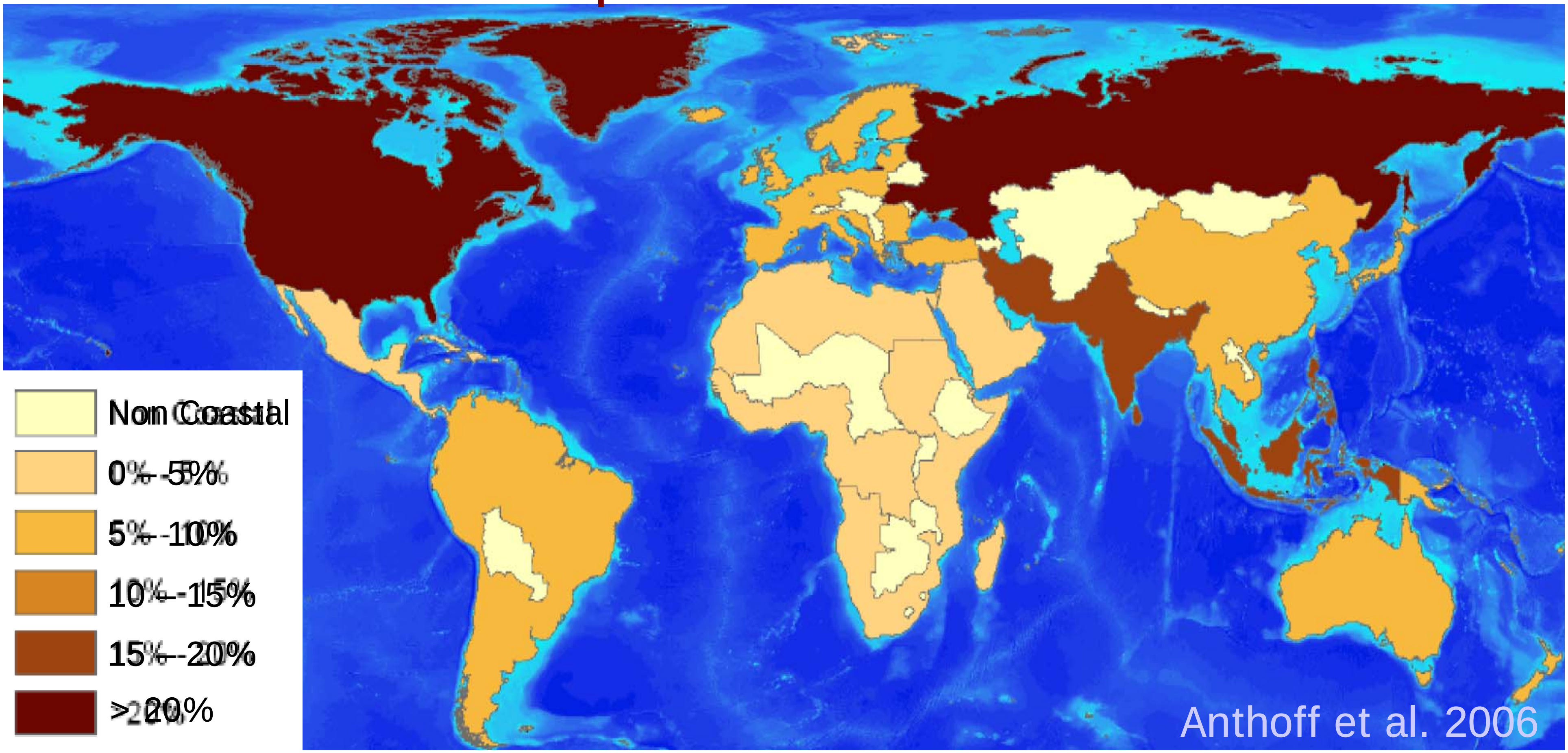
Projected Surface Water in 2050 Relative to 1900-1970



Perception of Risk

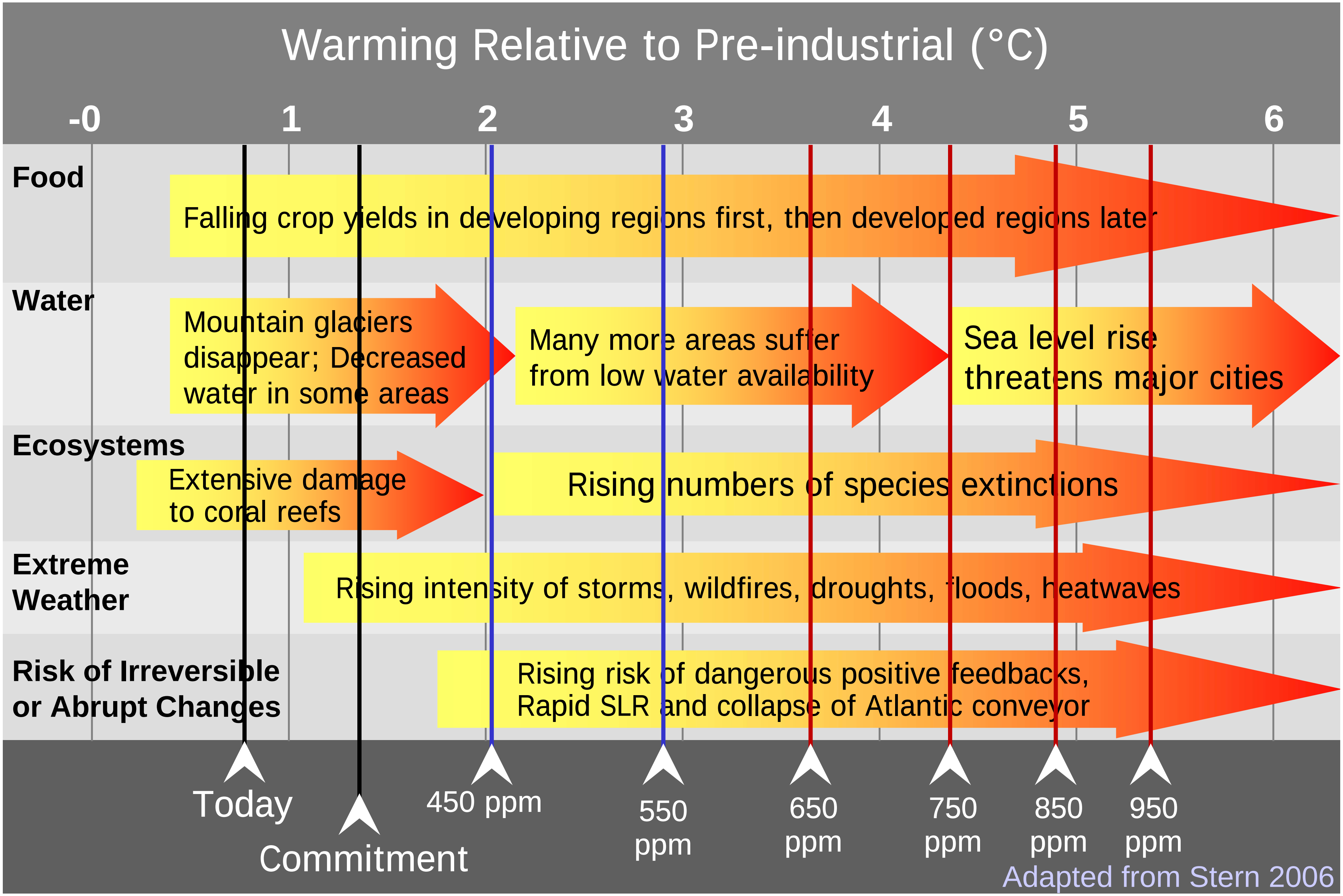
Myth – *Industrialized world will be spared*

Coastal Exposure to Sea Level Rise

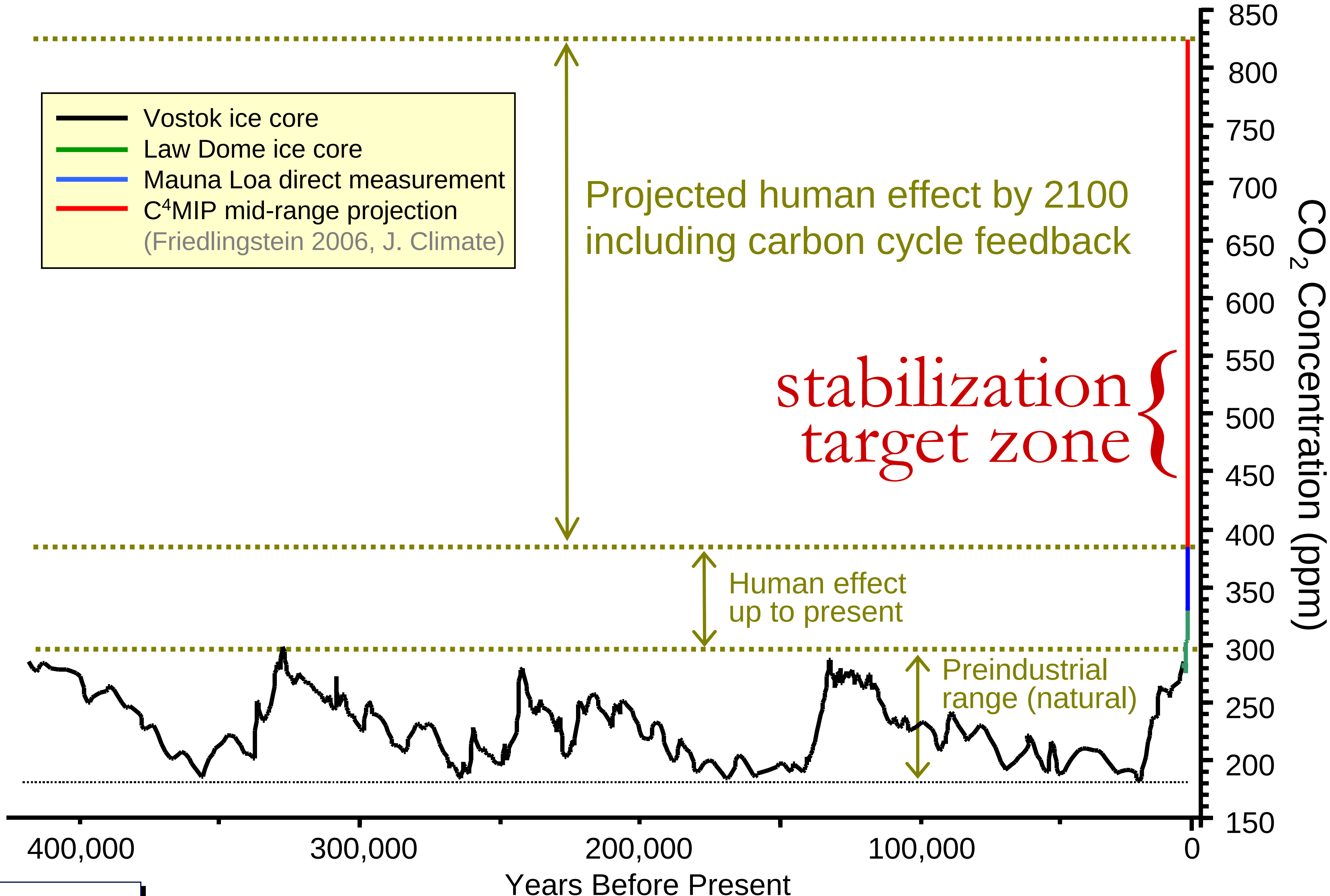


PEW CENTER ON Global CLIMATE CHANGE

Avoiding the Greatest Risks



Risk of Overshooting



PEW CENTER ON Global CLIMATE CHANGE

Risk of Surprises: Impacts NOT Projected

1) Abrupt, extreme sea level rise
2) Death by a Thousand Cuts
   Familiar extreme events increase nonlinearly everywhere
3) The George Foreman Effect
   A particular type of extreme event strikes repeatedly on primary population centers or food-producing regions
4) Breadbasket Bandits
   Atmospheric reorganization shifts rain belts away from grain-exporting regions
5) Geo-engineering: Self-inflicted Abrupt Change
   Attempts to engineer the climate stimulate rapid warming or atmospheric reorganization

Risk of Irreversibility

- Manmade CO_2 emissions have accelerated beyond the highest projections.
  (Canadell 2008)
- Half of the carbon we emit to the atmosphere is permanent on social time scales.
  (IPCC 2007)
- Warming from manmade CO_2 causes additional CO_2 to accumulate in the atmosphere.
  (IPCC 2007)
- Warming resulting from CO_2 emissions persists for more than 1000 years.
  (Matthews & Caldeira 2008; Solomon et al. 2009)

Risks from Climate Change

Risks from climate change are high

- Catastrophic change can happen but is uncertain.
- U.S. has naturally high exposure to climate impacts.
- Abrupt regional changes are likely but unpredictable.
- Models are correct about patterns yet underestimate magnitude of observed change.
- Thresholds/tipping points are real but unpredictable.
- Uncertainty about timing and magnitude of change.
- Uncertainty about regional details of change.
- Uncertainty is skewed toward more severe impacts.

Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

Pew Center Workshop

Assessing The Economic Benefits of Avoided Climate Change

March 16-17, 2009

- 75 experts discussed the science, risks, and economics of climate change
- Keynote addresses by Dina Kruger (EPA Climate Change Director) & Gary Yohe (IPCC Lead Author)
- 17 video presentations by experts on climate change impacts and economics
- OMB recommendations on the use of CBA

http://www.pewclimate.org/benefitsworkshop-March09

Climate Change Economics

Problems with quantifying economic impacts

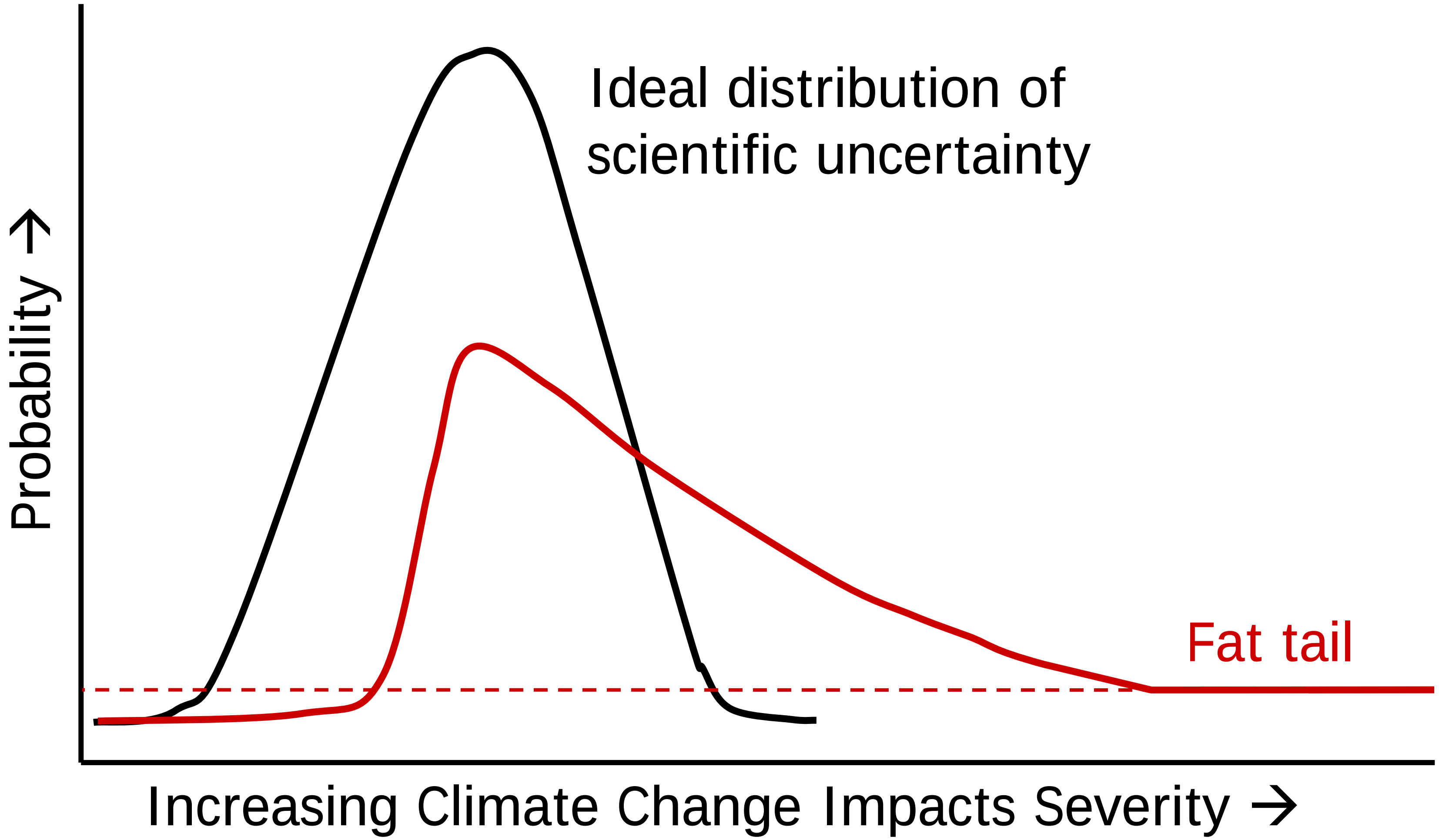
- Time scale (intergenerational)
- Scientific uncertainties
  - Timing, distribution, severity of impacts
  - Potential for abrupt, catastrophic changes
- Economic uncertainties
  - Future return on investments
  - Social risk perception and aversion
  - Value of nonmarket goods & services
  - Pricing of unknown, non-zero probability of catastrophe
- Unresolved ethical questions
  - Proper rate of intergenerational discounting
  - Proper role of public investment vs. private investment (Should risk be handled differently?)

Omitted Impacts

Incomplete impacts inventory		Uncertainty in Valuation of Impacts →		
		Market	**Non-Market**	**Socially Contingent**
Uncertainty in Predicting Climate Change ↓	**Projection** (e.g., mean sea level Rise; mean temperature change)	**I** • Coastal protection • Loss of dryland • Energy for heating and cooling	**IV** • Heat stress • Wetland loss	**VII** • Regional costs • Investment
	Bounded Risks (e.g. droughts, floods, storms)	**II** • Agriculture • Water Variability	**V** • Ecosystem change • Biodiversity • Loss of life • Secondary social effects	**VIII** • Comparative advantage • Market structures
	System change & surprises (e.g. major events)	**III** • Above, plus • Significant loss of land and resources • Non-marginal effects	**VI** • Higher order • Social effects • Regional collapse	**IX** • Regional collapse

Yohe & Tirpak, *IA Journal,* 2008

Fat-Tailed Risks



Fat Tails = Elevated Risk

PEW CENTER ON Global CLIMATE CHANGE

Climate Change Economics

Economically correct response to uncertainty

- What we know
  - The planet is warming
  - Climate is changing at accelerating rates
  - Manmade GHGs are the principal cause
  - Human-induced climate change contributed to the 2003 European heat-wave that killed tens of thousands

"Even though substantial uncertainties persist … this knowledge is sufficient to establish the need to respond in the near-term…

"Indeed, looking at uncertainty through a risk-management lens makes the case for near-term action…"

"It then follows from simple economics that this near-term action should begin immediately if we are to minimize the expected cost of meeting any long-term objective." (Economist Gary Yohe, 2009)

PEW CENTER ON Global CLIMATE CHANGE

Outline

- The warming globe
- External forcing, not internal variability
- External forcing mostly from human activities
- Impacts are here and caused by human-induced warming
- Projected impacts are significant
- Uncertainty and risk
- Economically correct response to uncertainty about risk
- Under-pricing risk is risky

Under-pricing Risk

"In 2005, I raised concerns that the protracted period of underpricing of risk, if history was any guide, would have dire consequences. This crisis, however, has turned out to be much broader than anything I could have imagined."

"…those of us who have looked to the self-interest of lending institutions to protect shareholder's equity (myself especially) are in a state of shocked disbelief. Such counterparty surveillance is a central pillar of our financial markets' state of balance. If it fails, as occurred this year, market stability is undermined."

"It was the failure to properly price such risky assets that precipitated the crisis."

Former Fed Chairman, Alan Greenspan
prepared testimony to the House Committee
on Government Oversight and Reform
October 23, 2008

Under-pricing Risk

"What is the essence of the economic problem posed by climate change? The economic uniqueness of the climate-change problem is not just that today's decisions have difficult-to-reverse impacts that will be felt very far out into the future… Much more unsettling for an application of (present discounted) expected utility analysis are the unknowns: deep structural uncertainty in the science coupled with an economic inability to evaluate meaningfully the catastrophic losses from disastrous temperature changes."

"Even just acknowledging more openly the incredible magnitude of the deep structural uncertainties that are involved in climate-change analysis—and explaining better to policy makers that the artificial crispness conveyed by conventional IAM-based CBAs here is especially and unusually misleading compared with more-ordinary non-climate-change CBA situations—might go a long way towards elevating the level of public discourse concerning what to do about global warming."

Economist Martin Weitzman, On Modeling and Interpreting the Economics of Catastrophic Climate Change

Pew Center Workshop – Key Insights

R. Howarth: “For a broad class of models”

•“The discount rate is set equal to the risk-free rate (~1.0%) plus a risk premium (Howarth, 2009; Howarth and Borsuk, 2009)”

•“The risk premium is negative for precautionary actions that reduce perceived risks to future social welfare”

– Implies willingness to pay more than the expected value for investments if they provide a safety net for consumption under uncertainty:

“Insurance pays off exactly when wealth and consumption would otherwise be low—you get a check when your house burns down. For this reason, you are happy to hold insurance, even though you expect to lose money—even though the price of insurance is greater than its expected payoff discounted at the risk-free rate” (**Cochrane 2005**)

•Public goods in particular are viewed as precautionary investments that warrant risk-free discounting.

Pew Center Workshop – Key Insights

R. Howarth: Standard Ramsey discounting model is unable to simulate observed behavior under uncertainty.

- The discounting argument between Stern and Nordhaus is intractable in the Ramsey framework.
  - **Stern:** to be fair to future generations, pure time preference = 0
  - **Nordhaus:** To maximize fairness across generations, discount rate should be set to the market rate of return (~6-7%)
- Both arguments are subjective.
- Empirical observations of investment behavior support neither assertion, per se, although Stern is numerically closer.

Pew Center Workshop – Key Insights

R. Howarth: "For a broad class of models"

"Insurance pays off exactly when wealth and consumption would otherwise be low—you get a check when your house burns down. For this reason, you are happy to hold insurance, even though you expect to lose money—even though the price of insurance is greater than its expected payoff discounted at the risk-free rate."

Cochrane 2005

Climate Change Economics

Risk-reduction framework

- Climate stabilization is viewed as insurance against catastrophe and distributional inequality (the poor impacted most)
- Climate stabilization goals are based on science-driven risk assessment that informs values-based policy decisions
- Economic analysis finds the most cost-effective and distributionally fair policies to achieve established goals

For More Information

PEW CENTER ON Global CLIMATE CHANGE

www.PewClimate.org