Meeting the Climate-Change Challenge

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SES Distinguished Scientist Seminar

Marine Biological Laboratory

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In this talk I will argue that…

- Climate change is coming at us faster, with larger impacts and bigger risks, than even most climate scientists expected as recently as a few years ago.
- The stated goal of the UNFCCC – avoiding dangerous anthropogenic interference in the climate – is in fact unattainable, because today we are already experiencing dangerous anthropogenic interference. The real question now is whether we can still avoid catastrophic anthro-pogenic interference in climate.
- There is no guarantee that catastrophe can be avoided even we start taking serious evasive action immediately; but if we wait even one more decade before starting, the chance of avoiding catastrophe will get very much smaller.

And I will talk about what, specifically, we need to do.

What climate change means

Climate consists of averages & extremes of

- hot & cold
- wet & dry
- snowpack & snowmelt
- winds & storm tracks
- ocean currents & upwellings

and the <u>patterns</u> of these in space and time.

Small changes in global-average surface T entail large & consequential changes in climatic patterns. Difference between an ice age & an interglacial is ~5°C.

The stakes in climate change

Climate governs, so climate change alters,

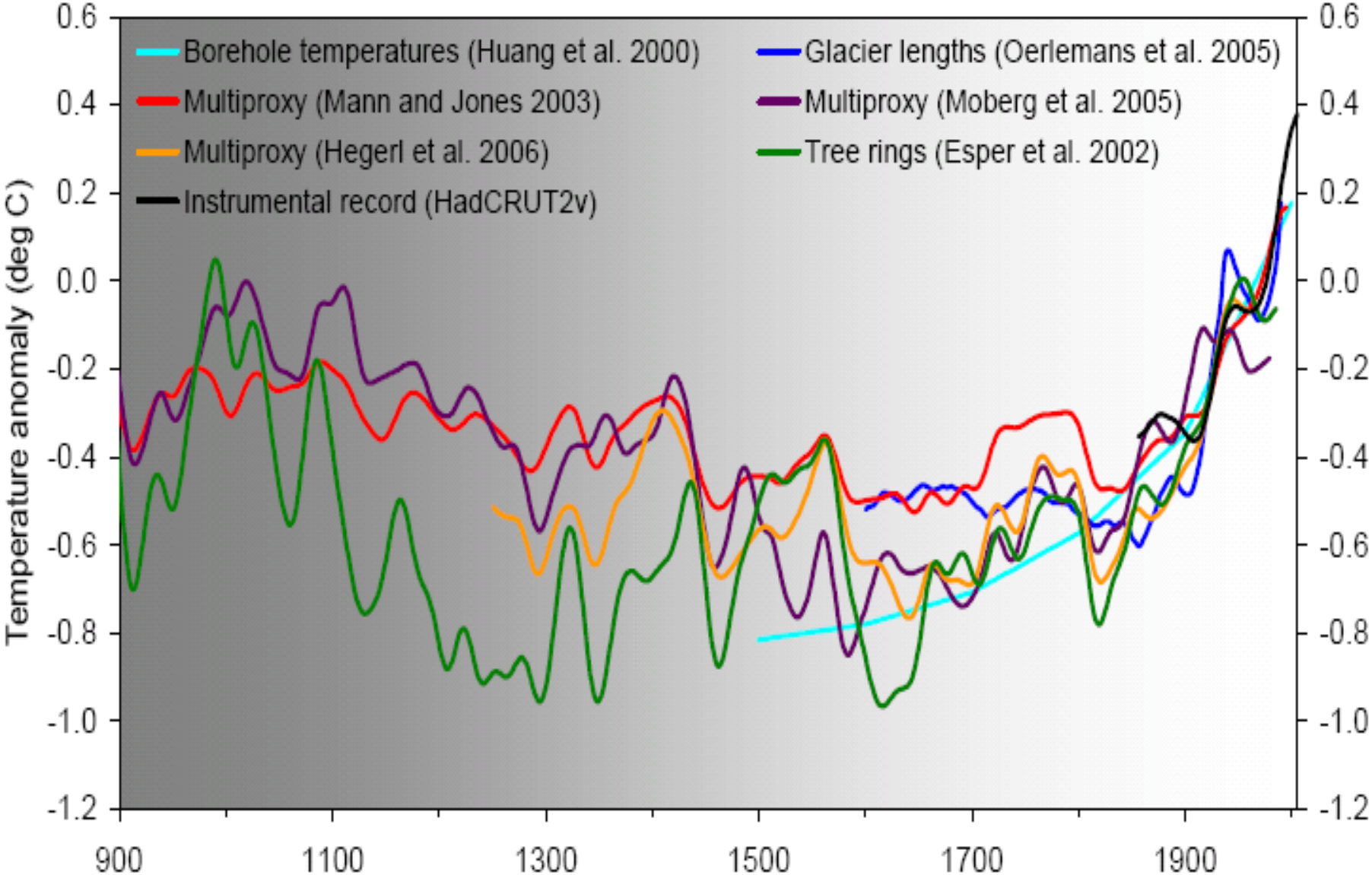
- productivity of farms, forests, & fisheries
- prevalence of oppressive heat &humidity
- geography of disease
- damages from storms, floods, droughts, wildfires
- property losses from sea-level rise
- expenditures on engineered environments
- distribution & abundance of species

What is the evidence that climate is now changing in unusual & threatening ways?

- We know -- from thermometer records in the atmosphere and the oceans, and from ice cores, bore holes, tree rings, corals, pollens, sediments, and more -- that Earth's climate is now changing at a pace far outside the range of expected natural variation, and in the opposite direction from what the known, natural, cyclic influences on climate would otherwise be causing at this time.
- We should be cooling, but we are warming up: by ~0.8 C in T_{avg} in the last 125 years, more over the continents, several times that over the continents at high latitudes.
- On a worldwide average, the 12 warmest years of the last 125 have all occurred since 1990, 20 of the 21 warmest since 1980. The last 50 years appear to have been the warmest half century in 6000 years.

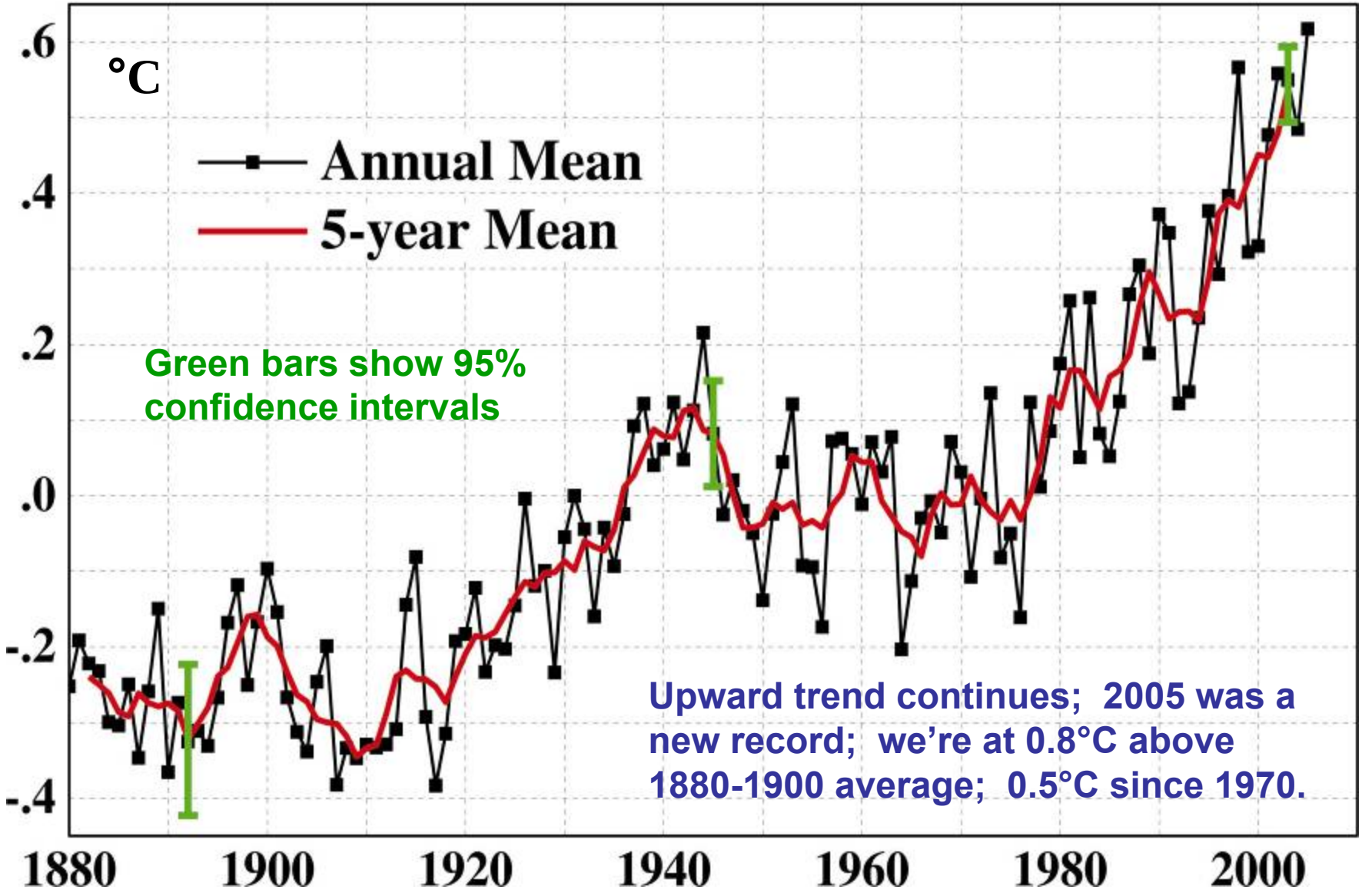
Is current climate change unusual?

1000 years of "proxy" surface temperatures, 100+ from thermometers



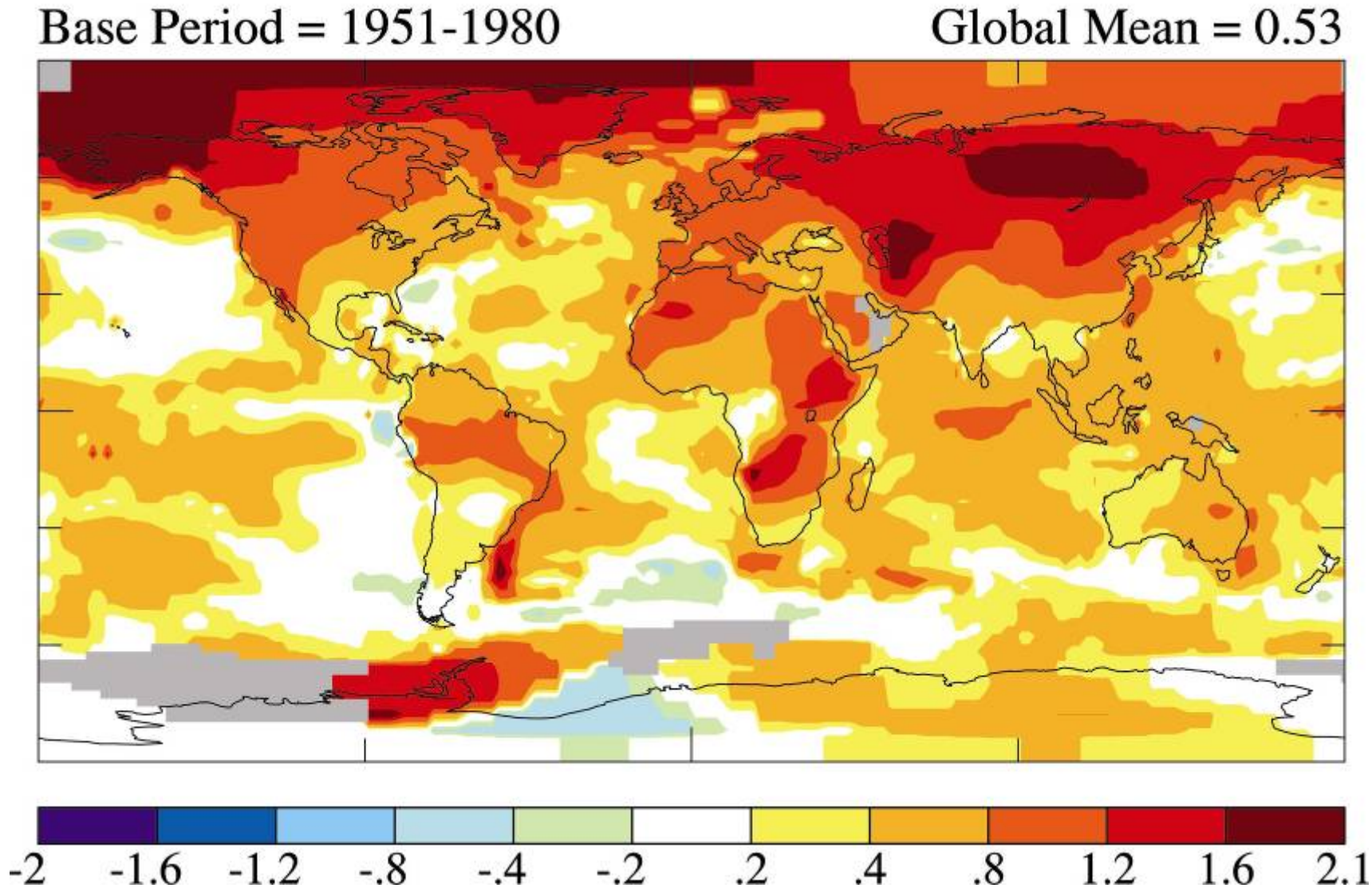
National Research Council, 2006

Thermometers: global T has risen 0.8°C in 125 yrs



J. Hansen et al., *PNAS 103*: 14288-293 (26 Sept 2006)

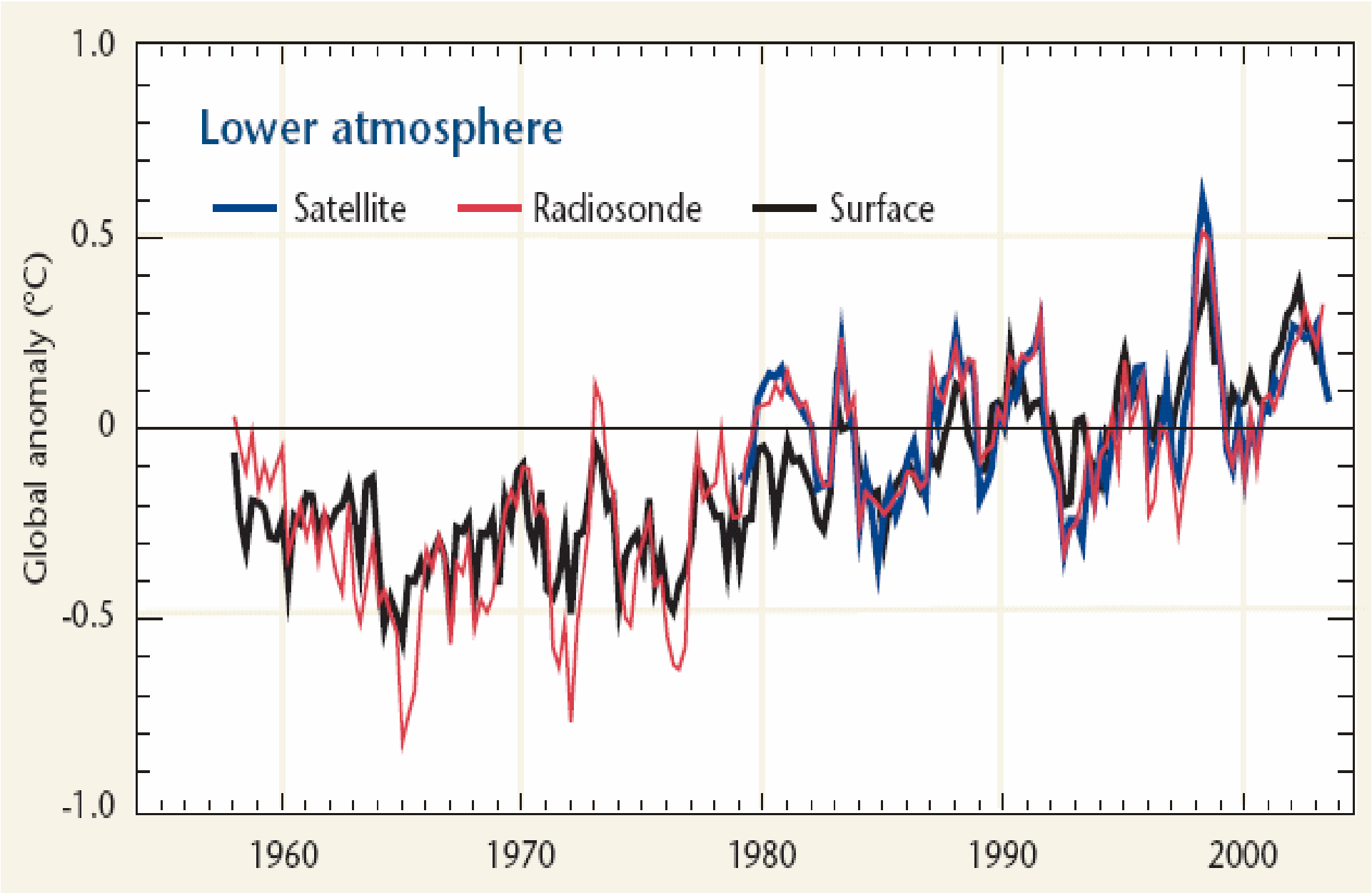
2001-2005 mean ΔT_{avg} above 1951-80 base, °C



Temperature increases are nonuniform: higher mid-continent, highest of all in far North. (These are observations, not modeling results.)

J. Hansen et al., *PNAS 103*: 14288-293 (26 Sept 2006)

Surface, balloon, & satellite temperatures agree



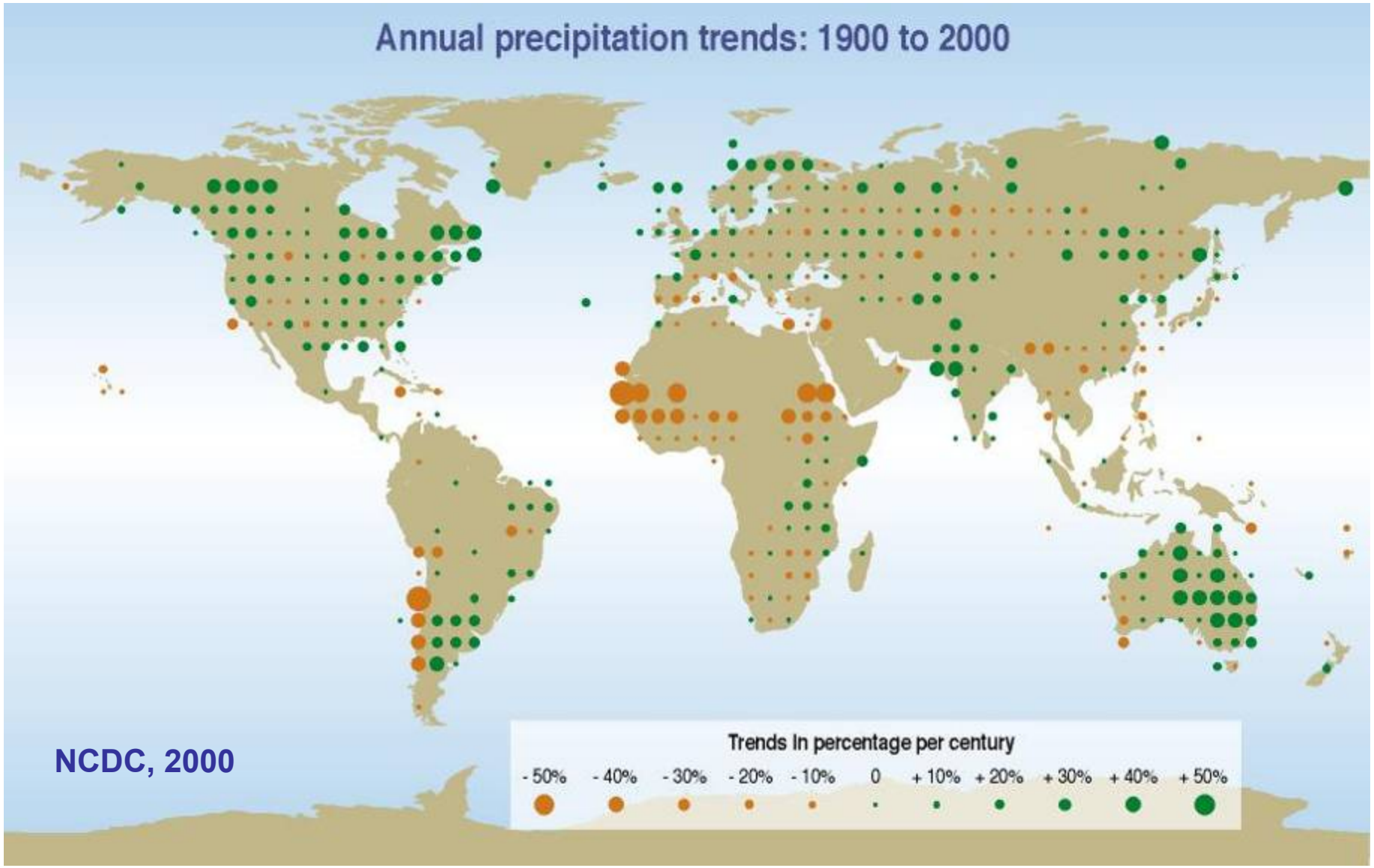
Hadley Centre, 2003

Further evidence of changing climate

As expected in a warming world, observations over recent decades also show…

- Evaporation & rainfall are increasing;
- Coastal glaciers are retreating;
- Mountain glaciers are disappearing;
- Permafrost is thawing;
- Sea ice is shrinking;
- Greenland is melting;
- Sea level is rising;
- Species are moving.

Evaporation & precipitation are increasing



Effect is not uniform; most places getting wetter, some getting drier.

Coastal glaciers are retreating

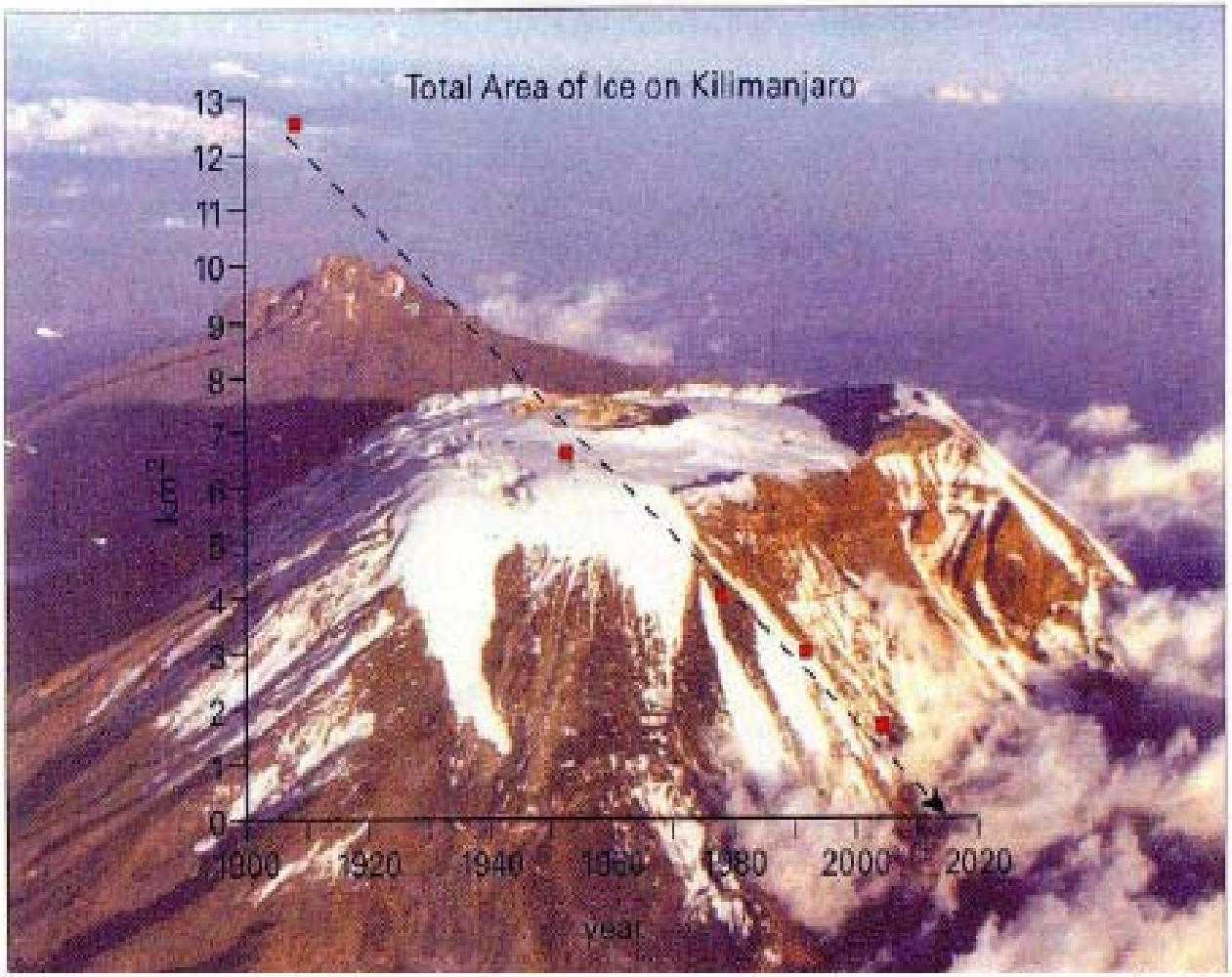
Muir Glacier, Alaska, 1941-2004

August 1941

August 2004

NSIDC/WDC for Glaciology, Boulder, compiler. 2002, updated 2006. *Online glacier photograph database.* Boulder, CO: National Snow and Ice Data Center.

Mountain glaciers are disappearing

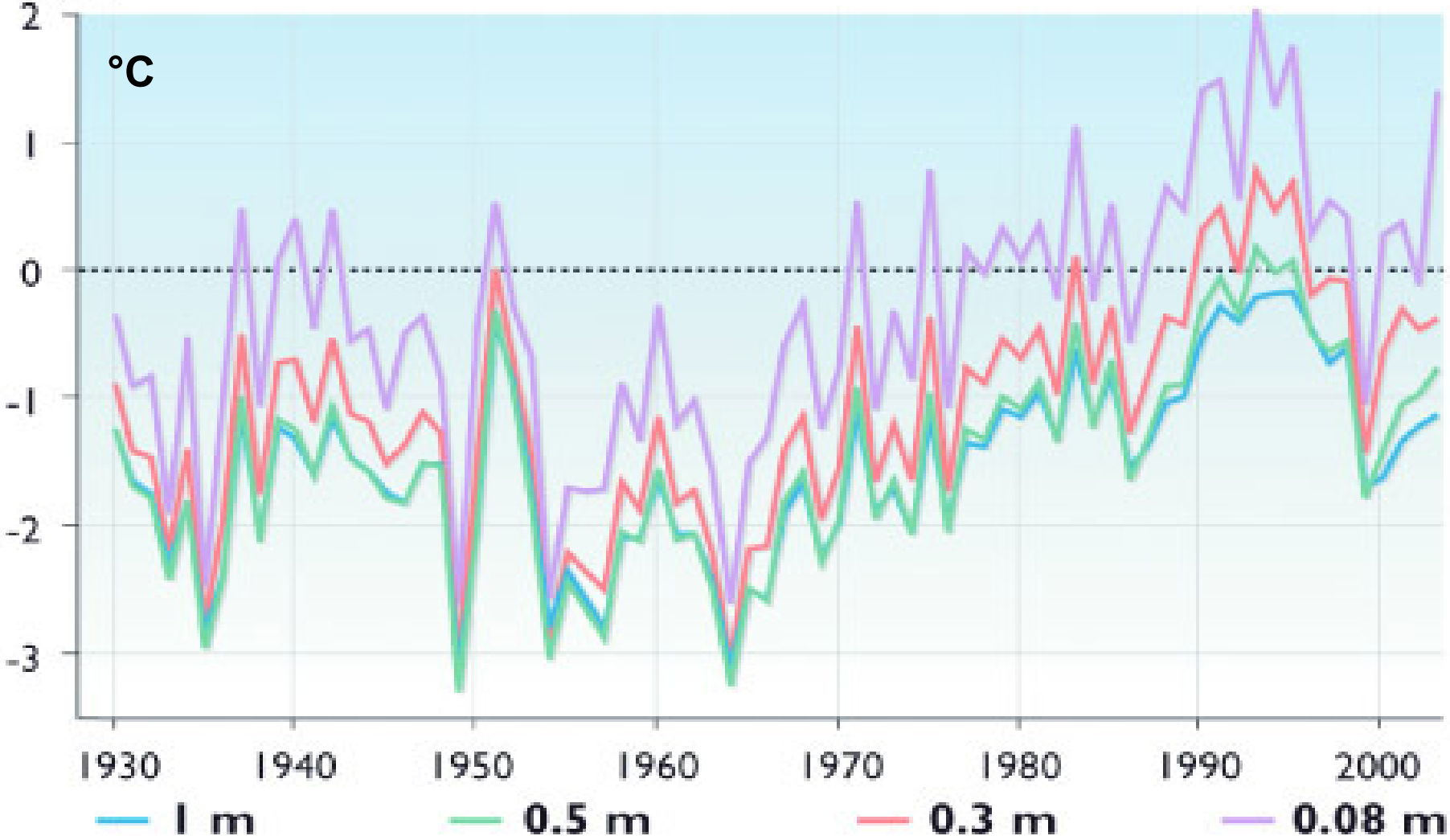


The extent of ice cover on Mt. Kilimanjaro decreased by 81% between 1912 and 2000. Disappearing paleoclimate archives such as this are a priority target of the Global Paleoclimate Observing System currently being proposed by the Past Global Changes (PAGES) scientists.

Courtesy Lonnie Thompson

Permafrost is thawing

Average annual ground temperature, Fairbanks, AK



Permafrost melts when T ≥ 0°C

ACIA 2004

NASA photograph

Sea ice is shrinking

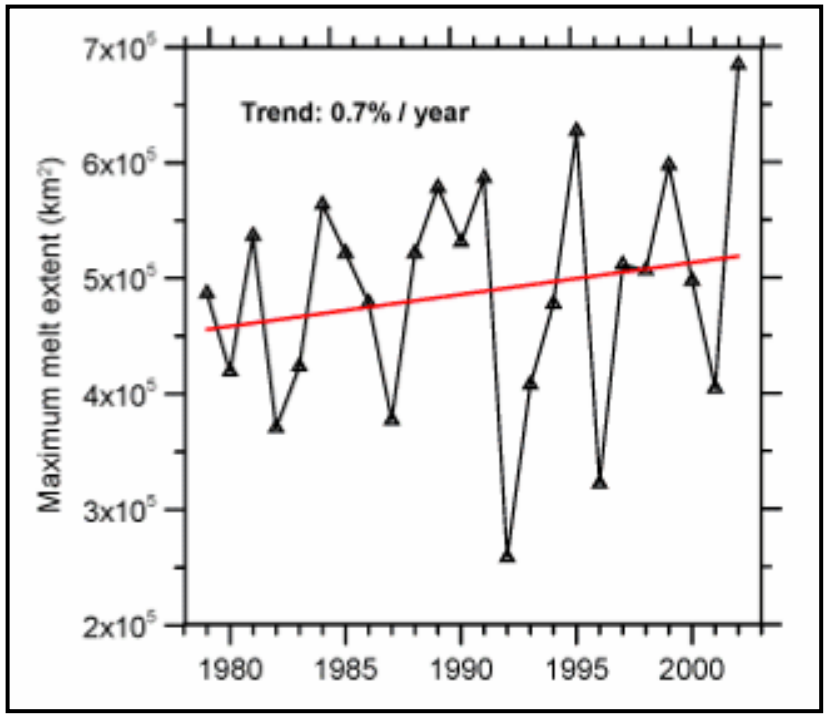
Extent of Arctic summer ice in 1979 (top satellite image) and in 2003 (lower satellite image).

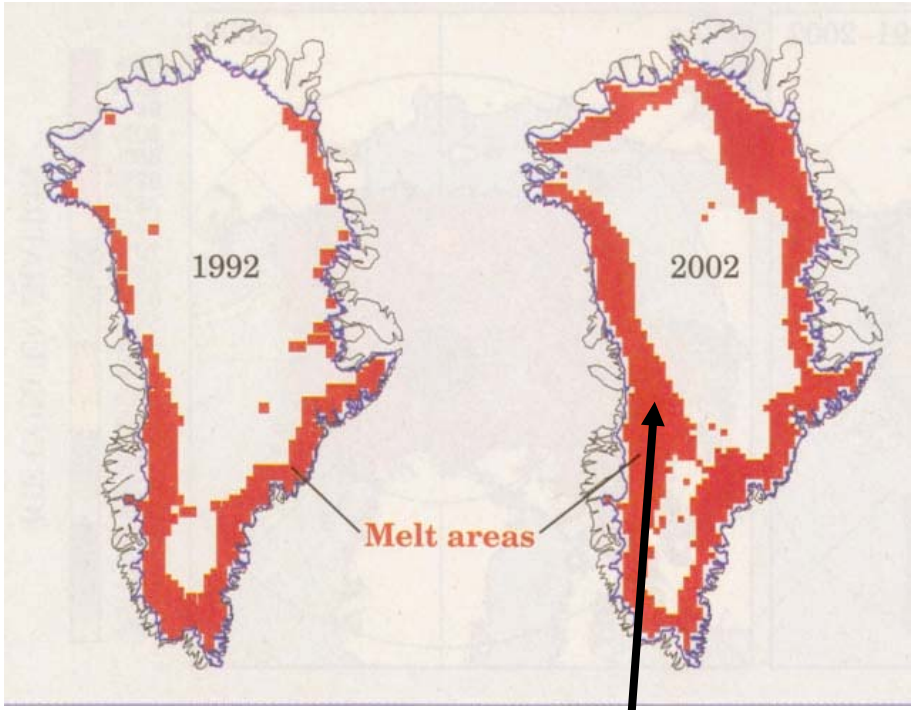
North Polar ice cap is sea ice -- it's floating and so does not change sea level when it melts.

But the reduced reflectivity when the ice is replaced by water amplifies the warming effect of greenhouse gases.

Greenland is melting

Summer surface melting on Greenland, 1979-2002



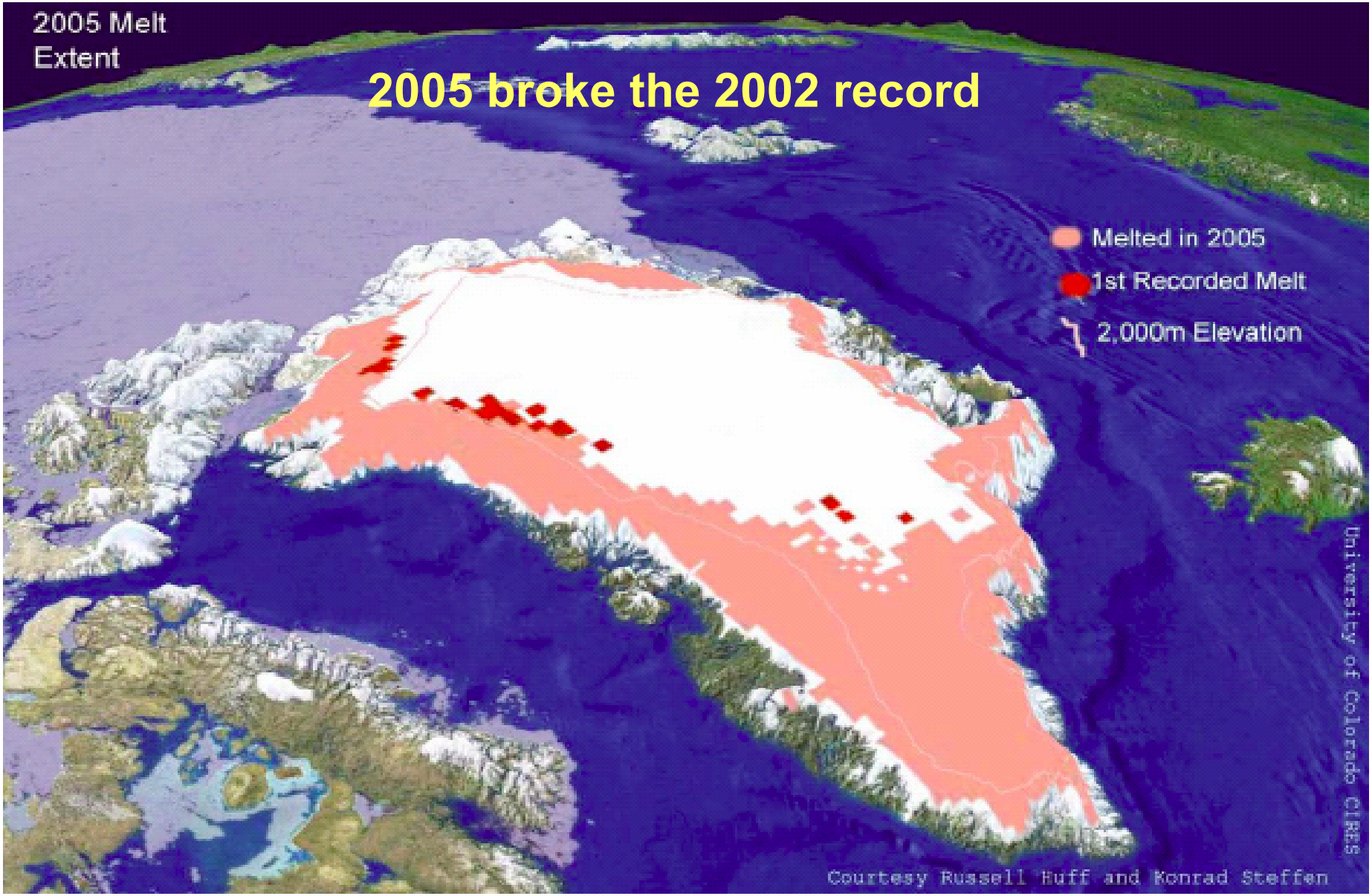


- 2002 all-time record melt area
- Melting up to elevation of 2000 m
- 16% increase from 1979 to 2002

70 meters thinning in 5 years

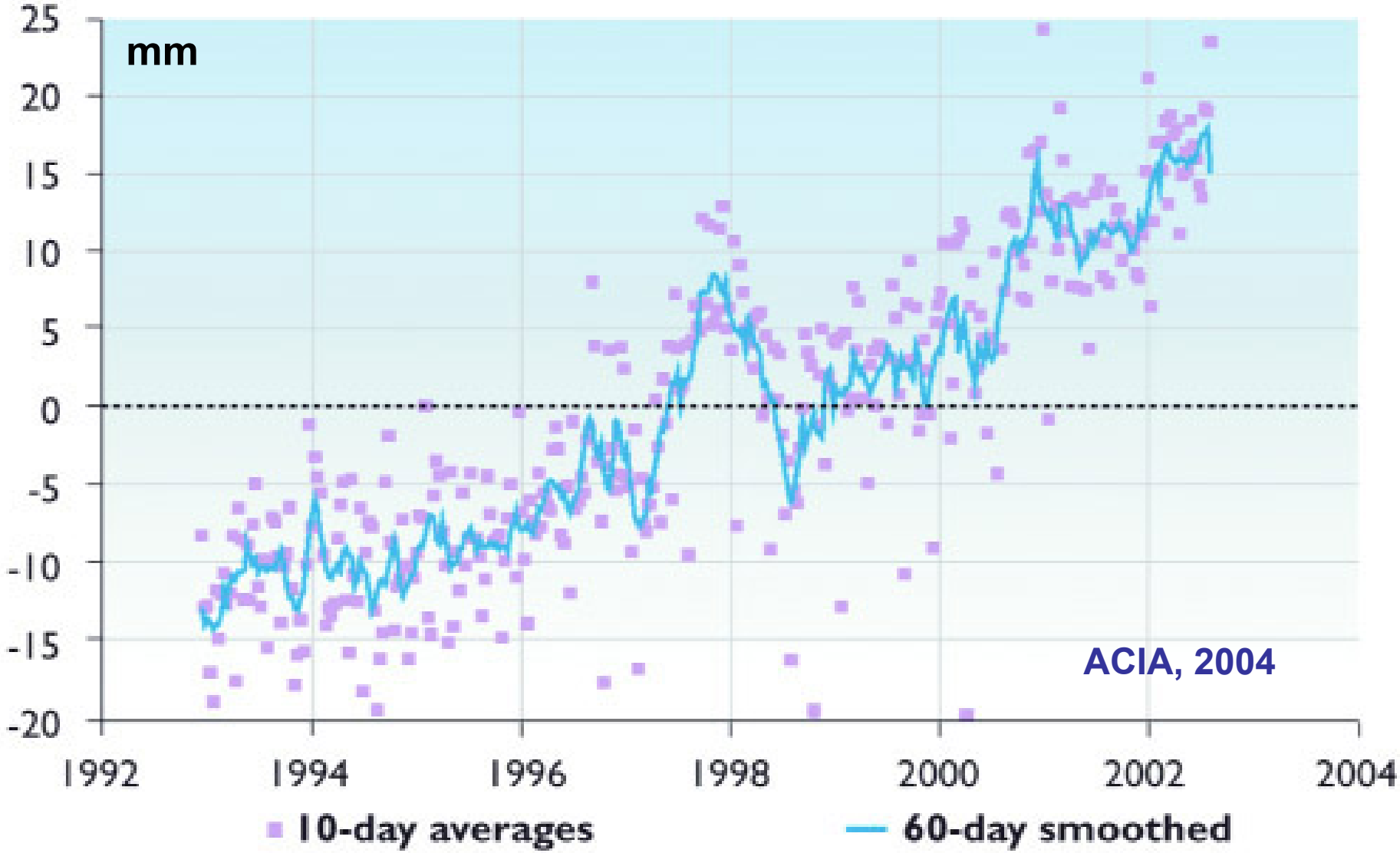
ACIA, 2004

Greenland melting (continued)



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

Sea-level is rising



1993-2003 ≈ 35 mm = 3.5 mm/yr; compare 1910-1990 = 1.5±0.5 mm/yr.

Species are moving

articles

A globally coherent fingerprint of climate change impacts across natural systems

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Causal attribution of recent biological trends to climate change is complicated because non-climatic influences dominate local, short-term biological changes. Any underlying signal from climate change is likely to be revealed by analyses that seek systematic trends across diverse species and geographic regions; however, debates within the Intergovernmental Panel on Climate Change (IPCC) reveal several definitions of a 'systematic trend'. Here, we explore these differences, apply diverse analyses to more than 1,700 species, and show that recent biological trends match climate change predictions. Global meta-analyses documented significant range shifts averaging 6.1 km per decade towards the poles (or metres per decade upward), and significant mean advancement of spring events by 2.3 days per decade. We define a diagnostic fingerprint of temporal and spatial 'sign-switching' responses uniquely predicted by twentieth century climate trends. Among appropriate long-term/large-scale/multi-species data sets, this diagnostic fingerprint was found for 279 species. This suite of analyses generates 'very high confidence' (as laid down by the IPCC) that climate change is already affecting living systems.

NATURE | VOL 421 | 2 JANUARY 2003

So, global climate is changing…

- in the direction of average warming,
- accompanied by many phenomena consistent with this,
- and at pace that is unusual in the recent historical record.

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

Is it really humans who are responsible for what is happening now? Or is it nature? What is the evidence?

How much is human-caused?

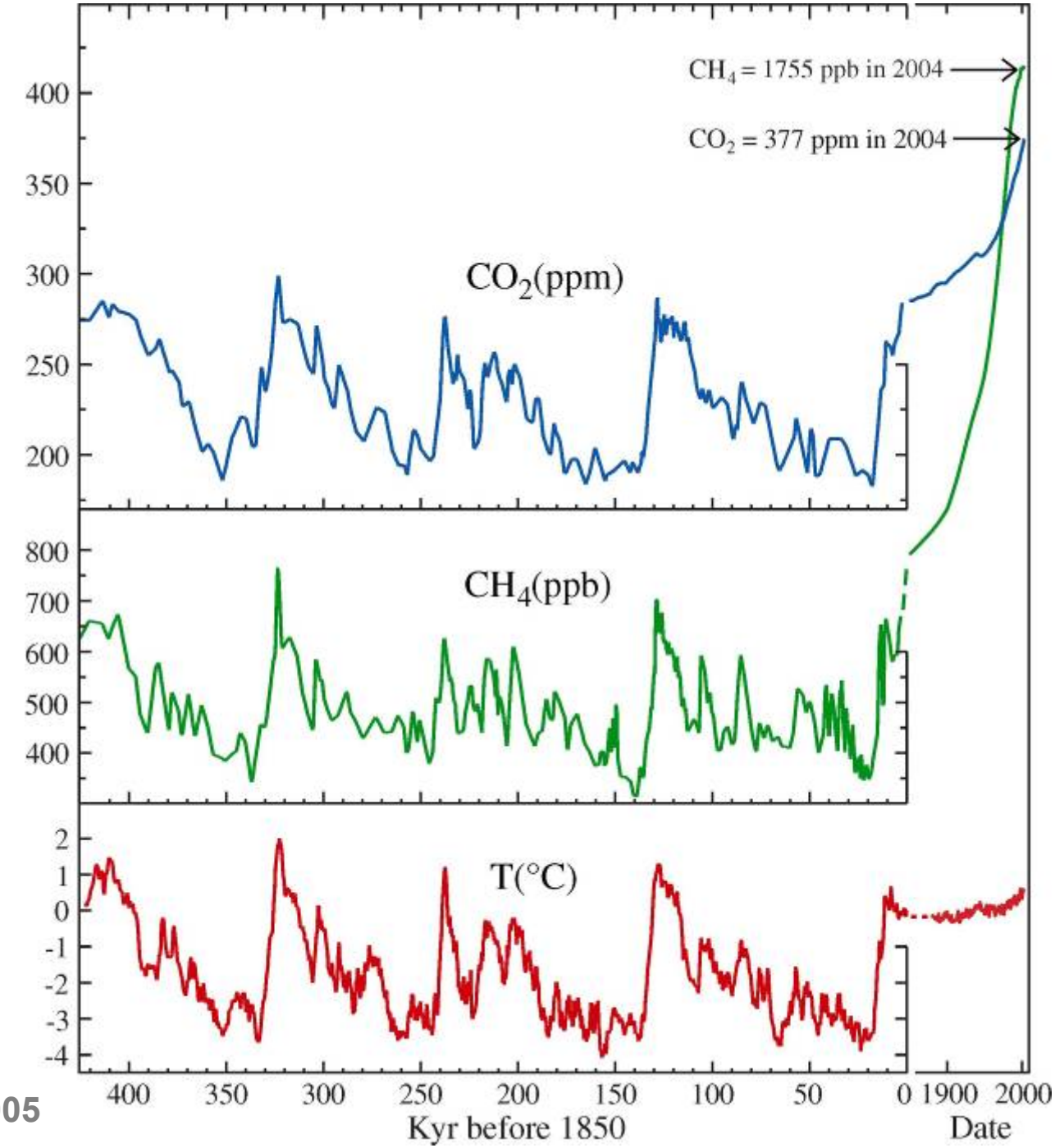
- NATURAL INFLUENCES ON GLOBAL CLIMATE
  - variations in the energy output of the Sun
  - variations in the Earth's orbit and tilt
  - continental drift
  - changes in atmospheric composition from volcanoes, biological activity, weathering of rocks
  - "internal" dynamics of ice-ocean-land-atmosphere system
- HUMAN INFLUENCES ON GLOBAL CLIMATE
  - rising concentration of "greenhouse gases" (GHG) from deforestation, agricultural practices, fossil-fuel burning
  - rising concentration of particulate matter from agricultural burning, cultivation, fossil-fuel burning,
  - alteration of Earth's surface reflectivity by deforestation, desertification
  - increased high cloudiness from aircraft contrails

400,000 years of greenhouse-gas & temperature history based on bubbles trapped in Antarctic ice

Time scale expanded for last 150 years (right side of diagram)

CO_2 & CH_4 are far above range of natural variation in current geologic era.

Last time CO_2 >300 ppm was 25 Myr BP in Eocene.



Hansen,Clim.Change 68, 2005

The strengths of the natural and human influences can be measured or estimated, and then compared.

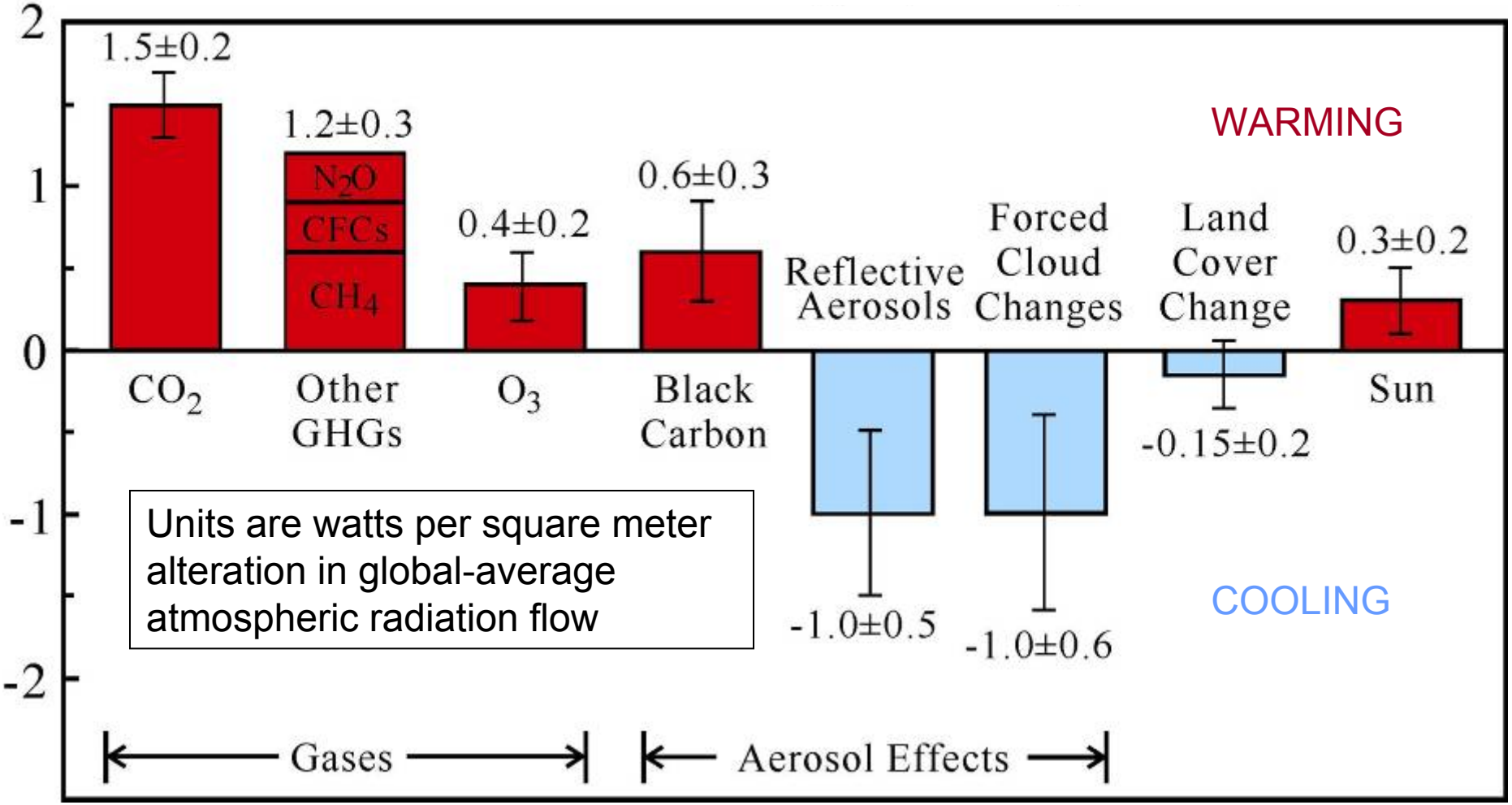
- The measure used in the climate-science community for quantifying and comparing natural & human influences is the change they cause in the flow of radiant energy in the atmosphere. This measure is called radiative forcing or just forcing.

  Its units are watts per square meter (W/m^2), averaged over the globe and over the year, defined as positive when the effect is in the direction of warming Earth's surface.

- The best estimates of the forcings from all the influences on global climate in the 250 years since the beginning of the Industrial Revolution indicate that the biggest effect has been from the rising concentrations of greenhouse gases in this period.

Effective climate forcings 1750-2000

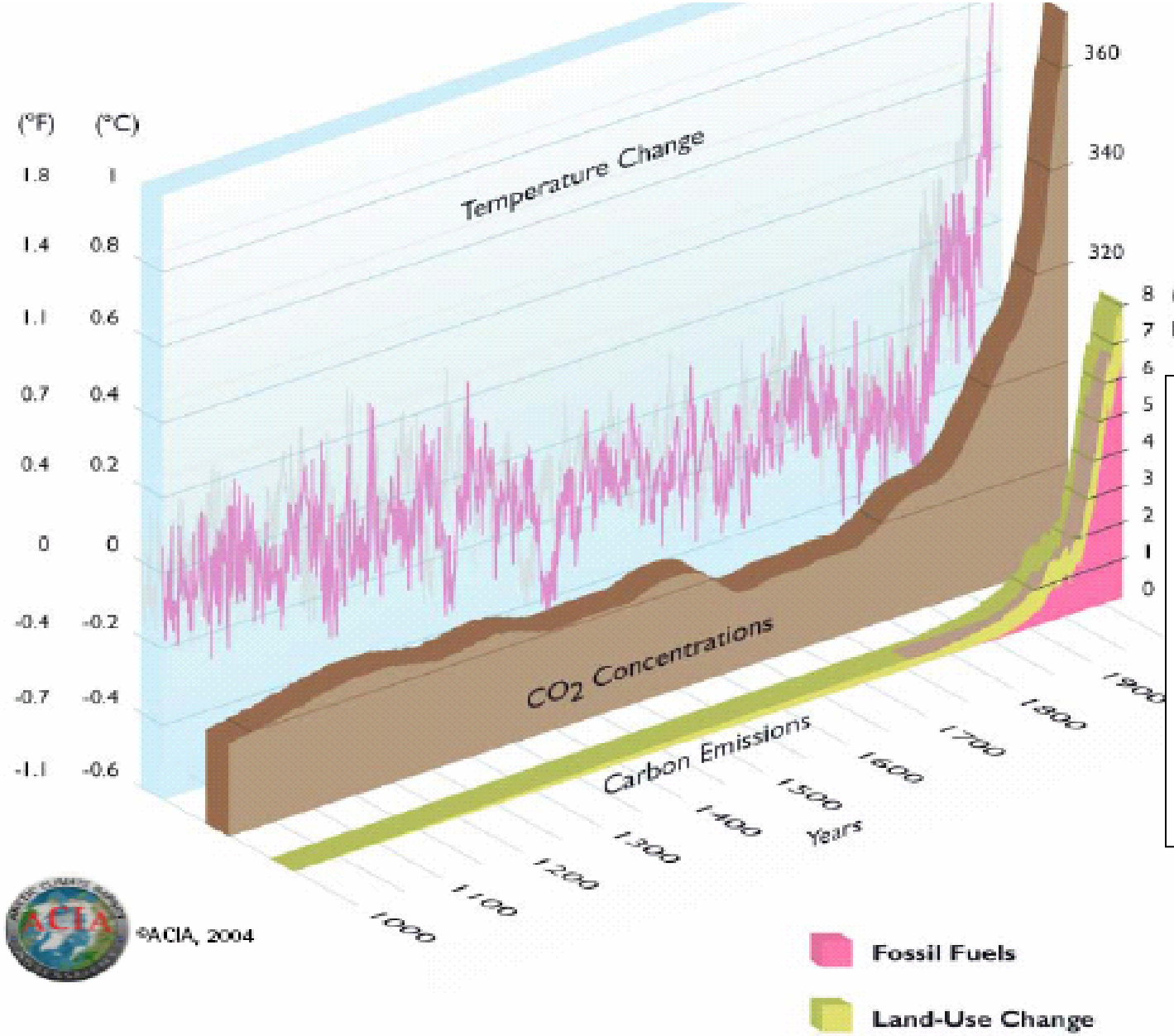
Correlating various lines of evidence has reduced uncertainties



Climate forcing agents in the industrial era. "Effective" forcing accounts for "efficacy" of the forcing mechanism.

Source: Hansen et al., JGR, **110**, D18104, 2005.

The main cause of the CO_2 build-up in the last 250 years has been emissions from fossil fuels & deforestation



©ACIA, 2004

Fossil-fuel contribution is confirmed by reduced C-14 content.

Fossil fuels provide 80% of civilization's energy today.

The "Fingerprint" of GHG on Global Climate

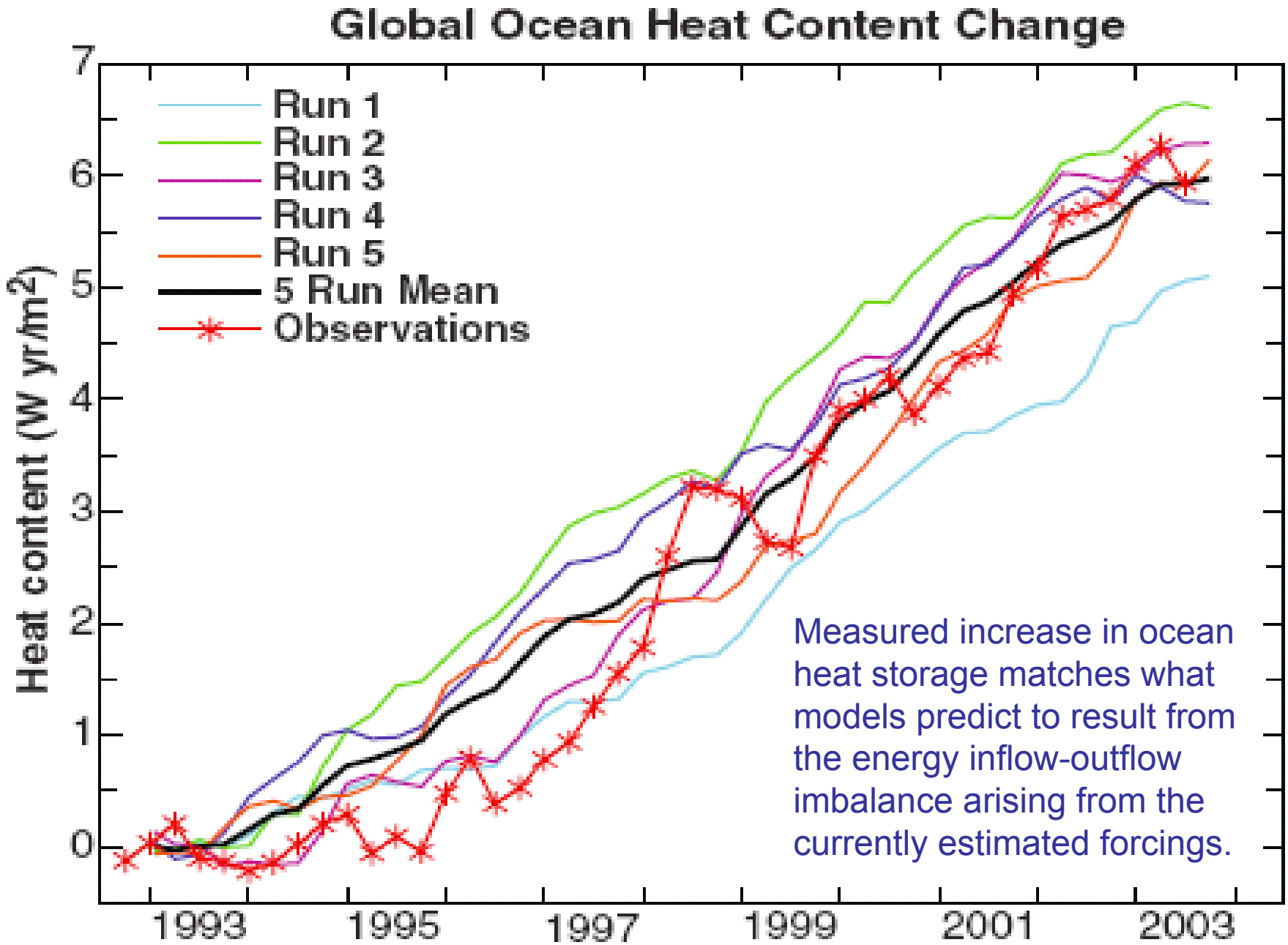
Observations

- warming of near-surface ocean exactly accounts for energy imbalance caused by GHG & particles
- decreased day-night temperature differences
- larger T increases in winter than summer

Match with theory & models

- Magnitudes *and* geographic & temporal patterns of changes match what theory & models say *should* result from the observed changes in GHG, taking into account effects of observed changes in anthropogenic & volcanic particulates + best estimates of changes in solar output.

This pattern match is a "fingerprint" unique to GHG. If something else were driving current climatic change, fingerprint would be different.

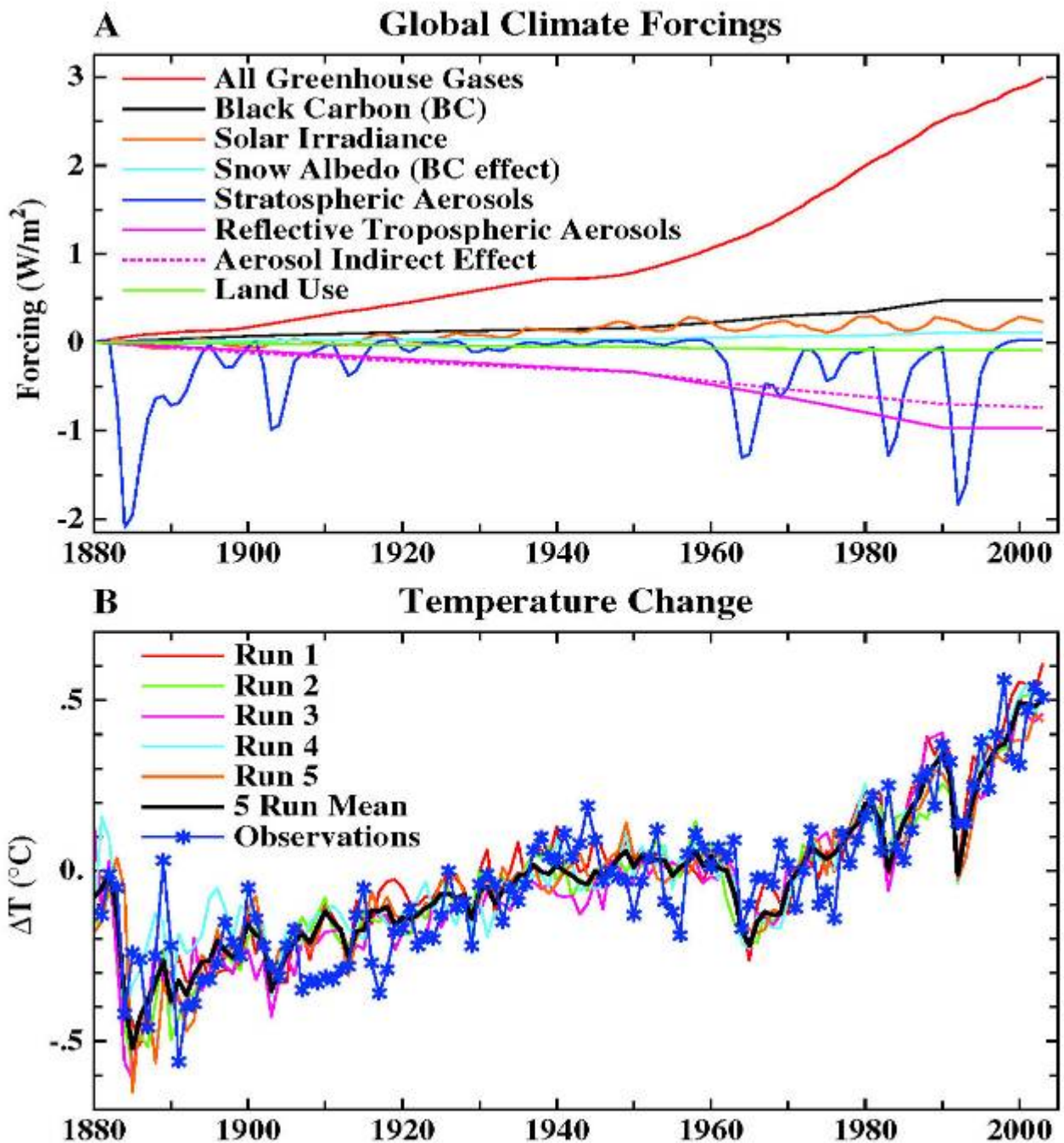


Measured increase in ocean heat storage matches what models predict to result from the energy inflow-outflow imbalance arising from the currently estimated forcings.

Hansen et al., SCIENCE 308:1425-31 (2005)

(A) Forcings used to drive climate simulations.

(B) Simulated and observed surface temperature change.



Source: Hansen et al., Earth's energy imbalance: Confirmation and implications. *Science 308*, 1431, 2005.

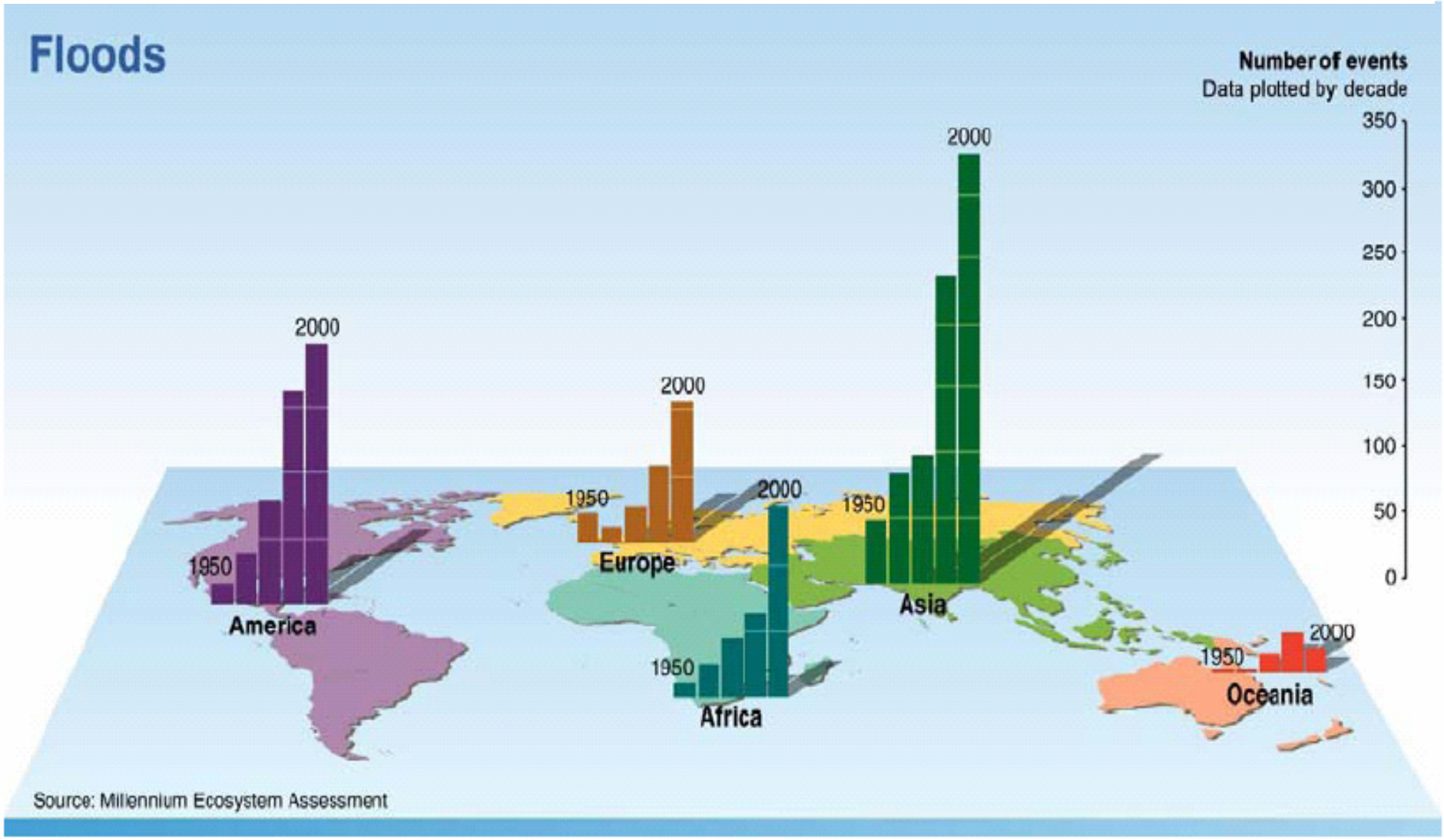
The smoking gun

- Essentially all of the observed climate-change phenomena are consistent with the predictions of climate science for GHG-induced warming.
- No alternative "culprit" identified so far – no potential cause of climate change other than greenhouse gases – yields this "fingerprint" match.
- A credible skeptic would need to explain <u>both</u> what the alternative cause of the observed changes is <u>and</u> how it could be that GHGs are NOT having the effects that all current scientific understanding says they should have. (No skeptic has done <u>either</u> thing.)

Serious impacts are <u>already</u> occurring

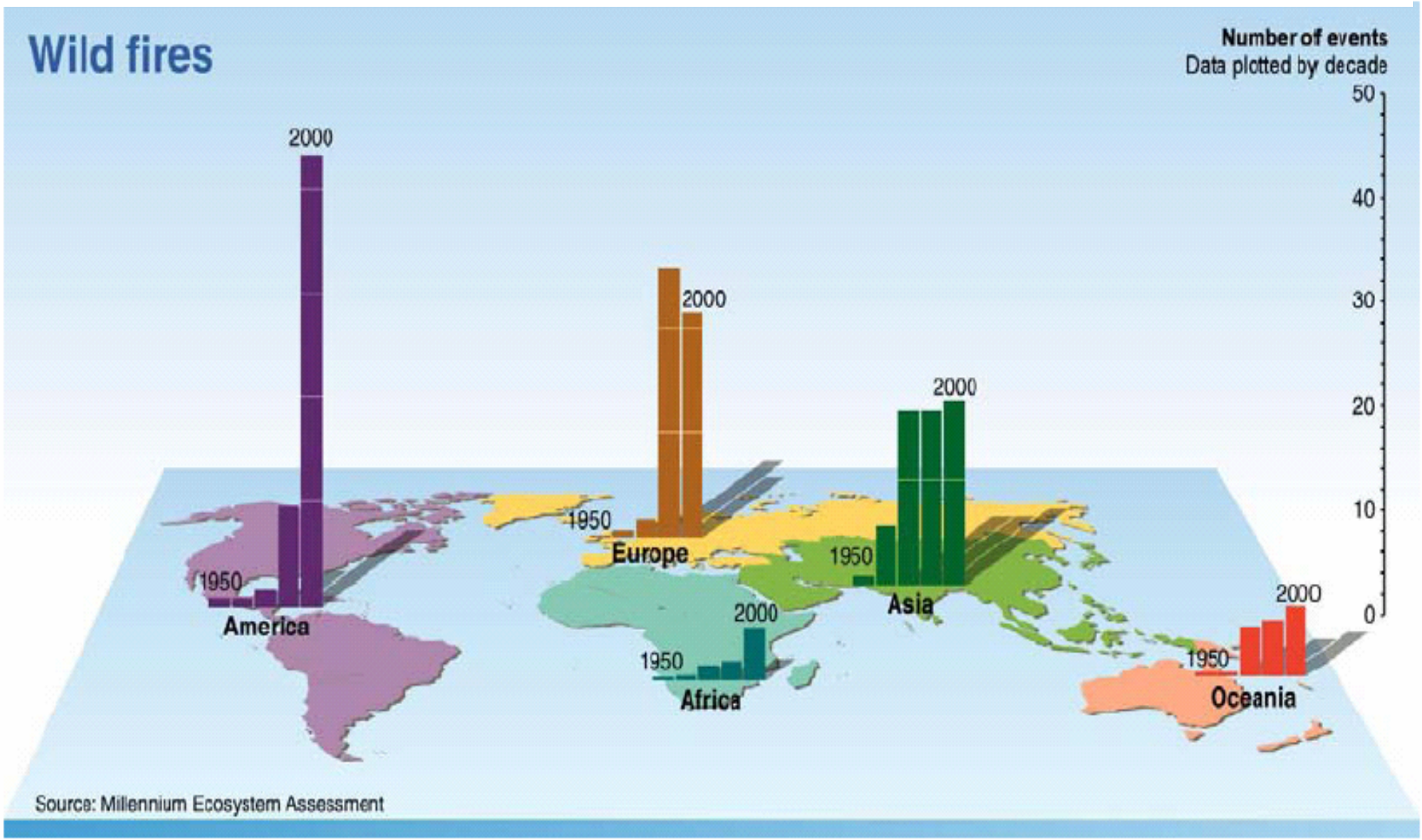
- Frequency of major floods, droughts, heat waves, & wildfires is up all over the world…as predicted by theory & models.
- Evidence is persuasive that increasing frequency of powerful tropical storms is also being driven by global climate change.
- Heat stress from ocean warming is impacting coral reefs worldwide, exacerbated by increasing acidity from CO_2 uptake.
- Moist tropical forests are drying out & burning.
- World Health Organization estimates direct health impacts of climate change already amount to ≥150,000 premature deaths/yr in 2000.

Floods by continent & decade from 1950



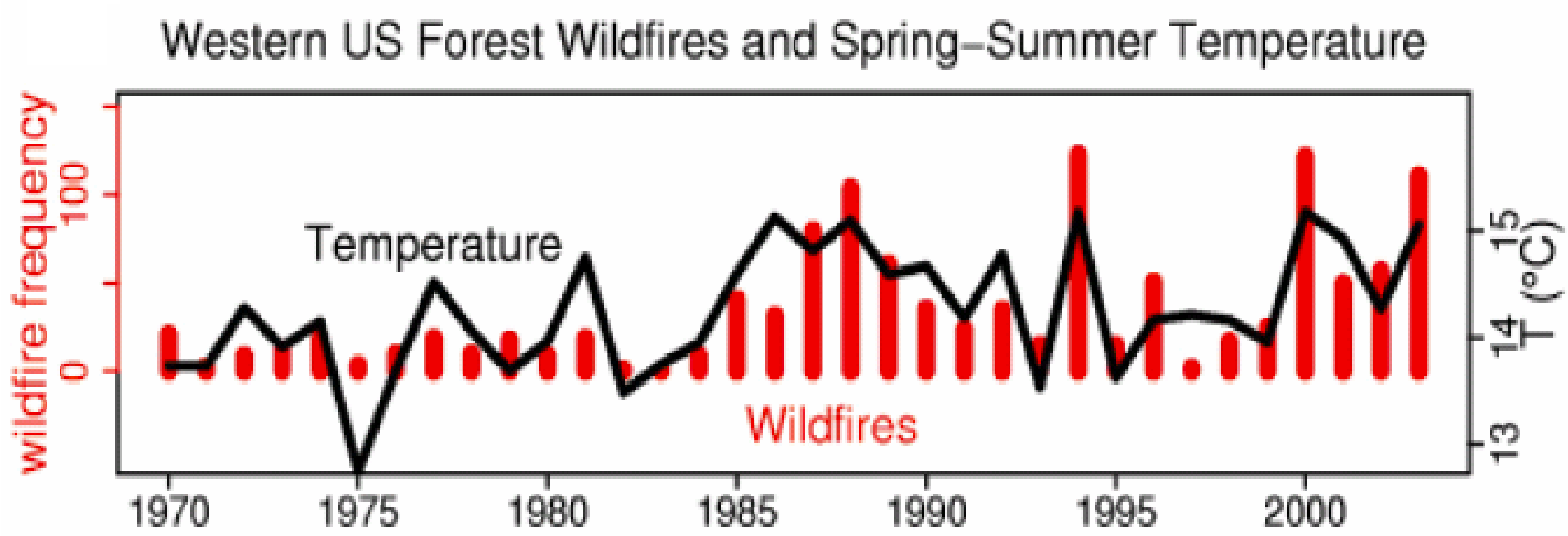
There's a consistent 50-year upward trend in every region except Oceania, where the 1990s were a bit below the 1980s.

Wildfires by continent & decade from 1950



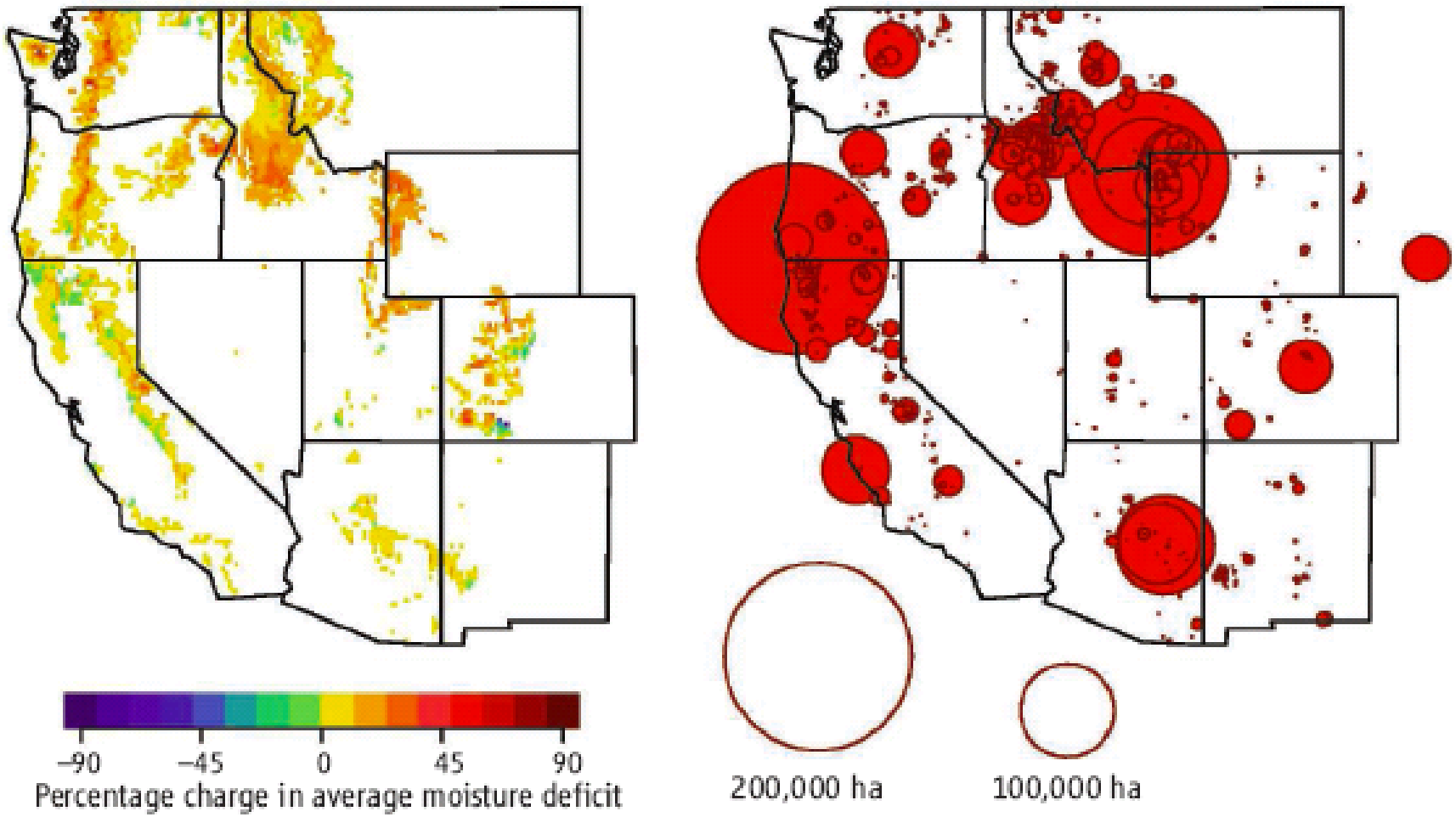
The trend has been upward everywhere.

Correlation of wildfire increases with temperature is clear



Westerling et al., SCIENCE, 18 August 2006

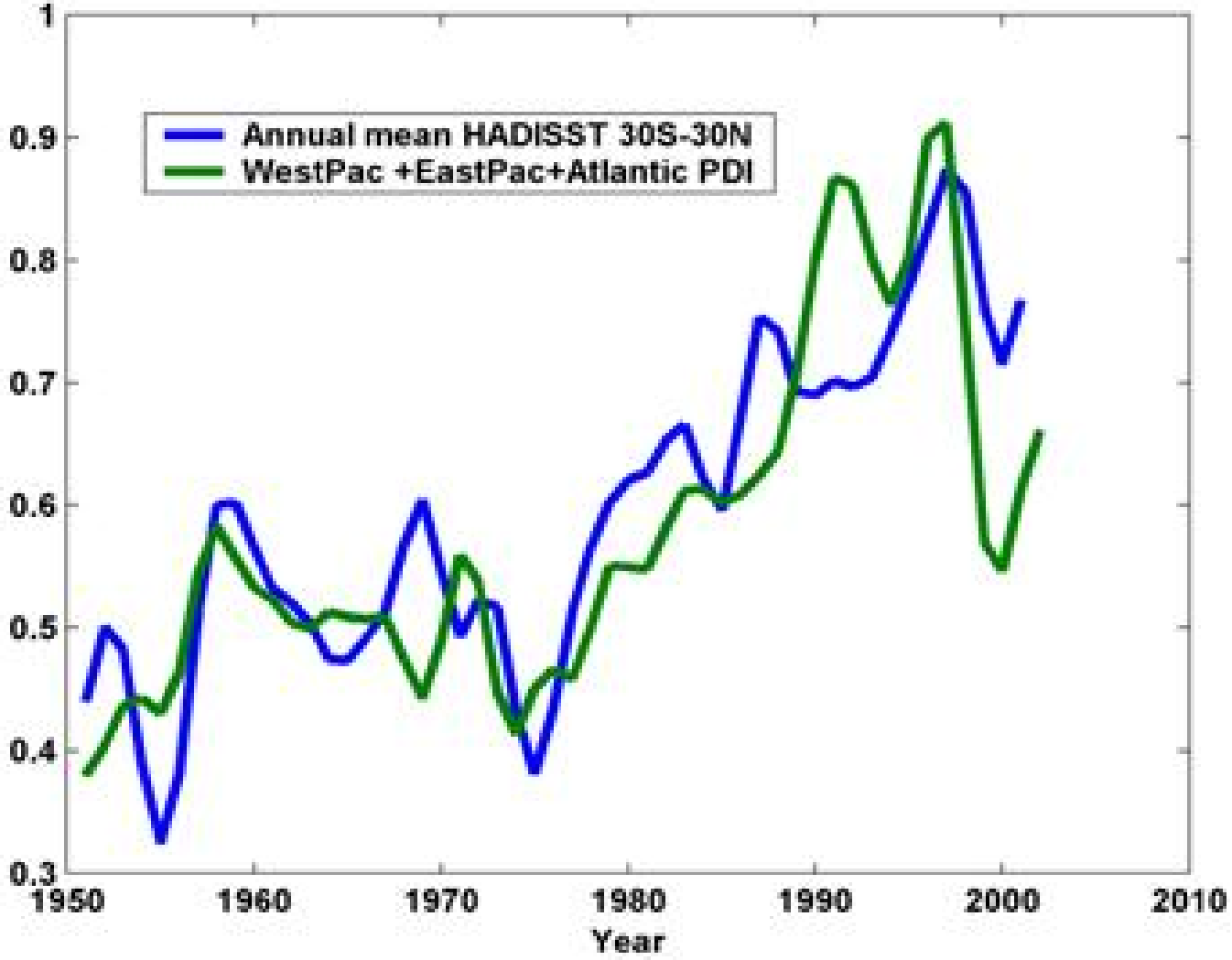
This works in part through soil moisture



Less moisture—more fires. Between 1970 and 2003, spring and summer moisture availability declined in many forests in the western United States (left). During the same time span, most wildfires exceeding 1000 ha in burned area occurred in these regions of reduced moisture availability (right). [Data from (*4*)]

Running, *Science*, 18 August 2006

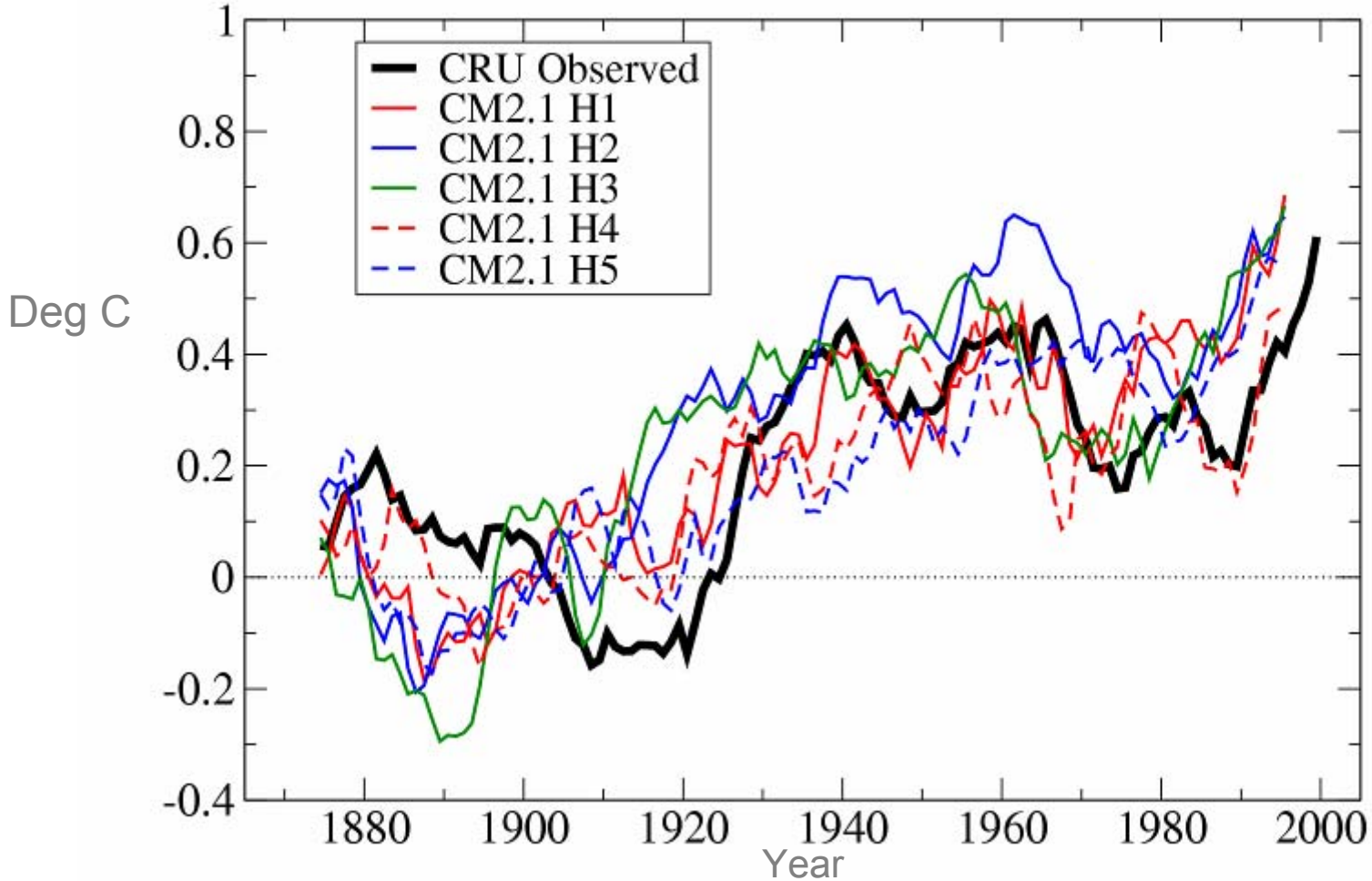
Tropical Cyclone Power Dissipation Index (PDI) has increased substantially over past 50 years along with tropical sea surface temperatures



Source: Kerry Emanuel, MIT, http://wind.mit.edu/~emanuel/anthro2.htm. SST anomaly (deg C) with arbitrary vertical offset. PDI scaled by constant.

Long-term warming of the "Main Development Region" is consistent with climate model historical simulations that include greenhouse gas forcing…

GFDL CM2.1 Historical Forcing Runs Using 5 "Random" Initial Conditions



Source: Knutson et al. (2005) J. of Climate, accepted for publication.

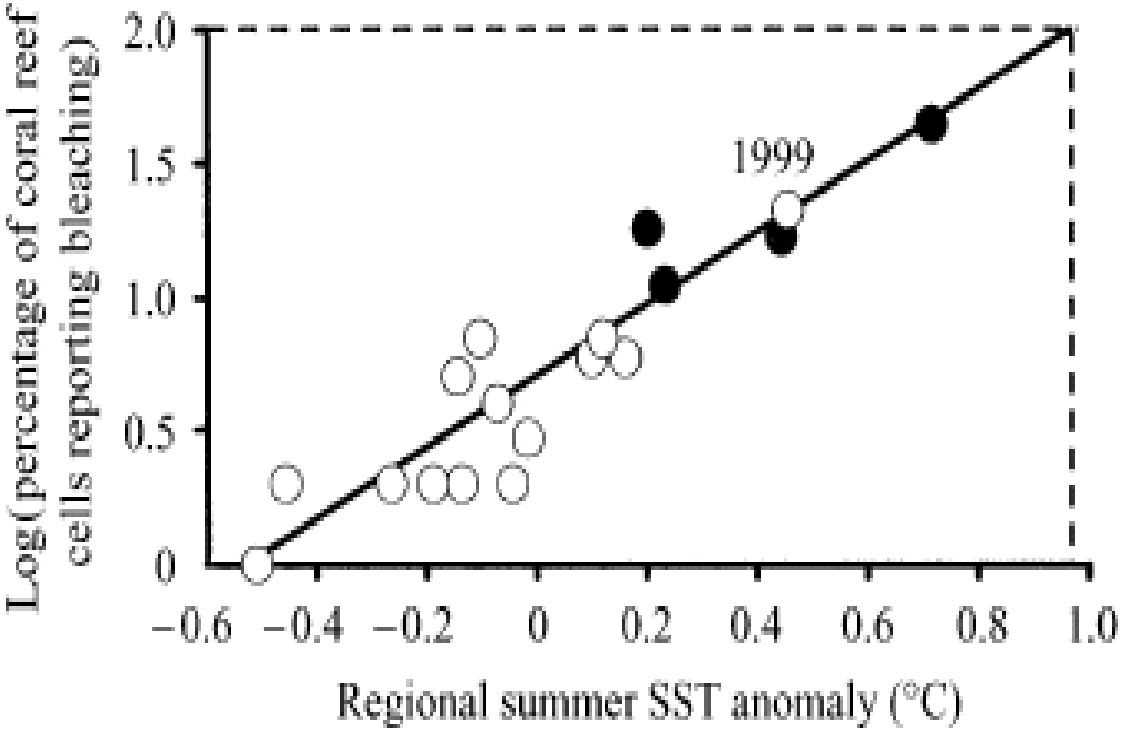


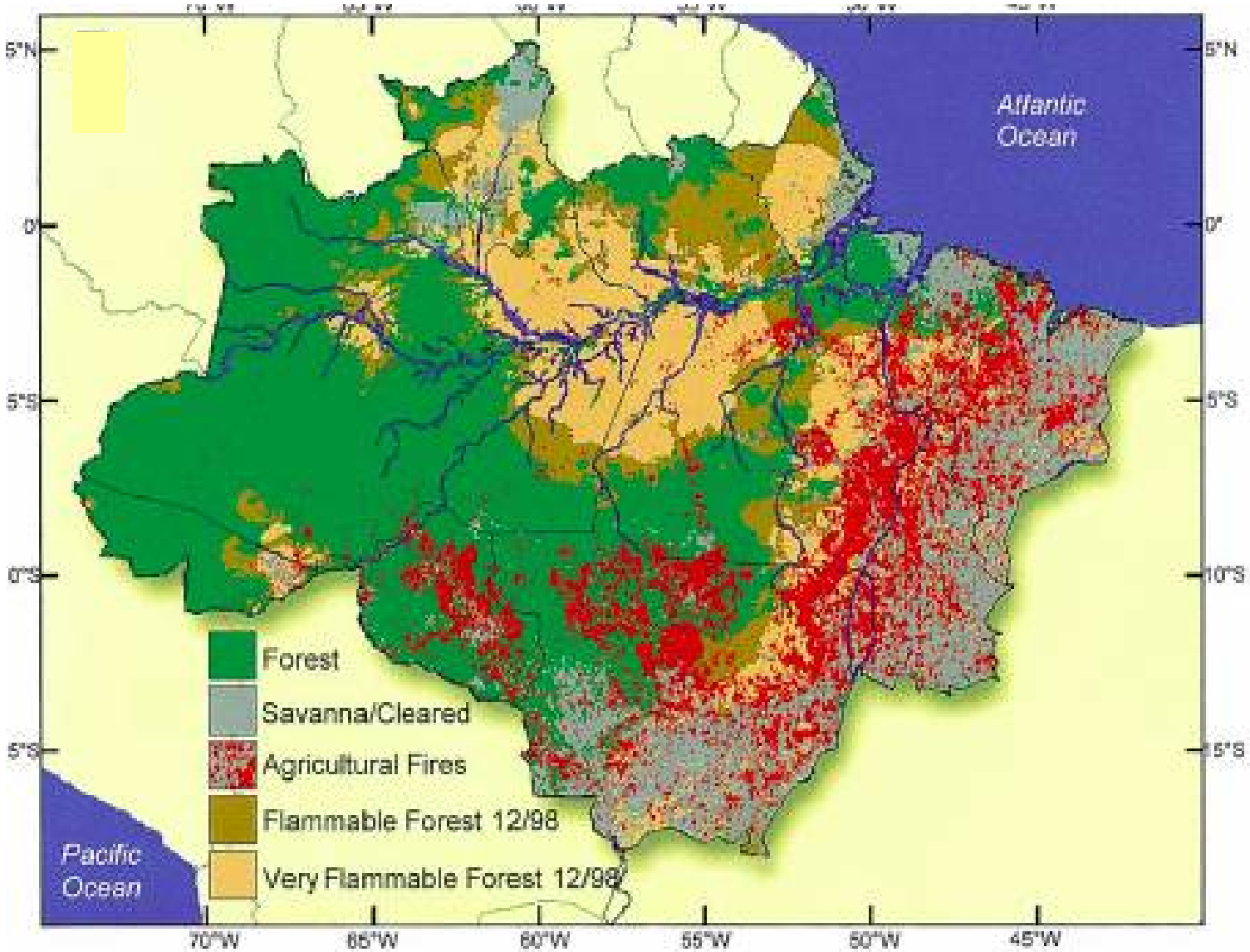
FIG. 2. The relationship between regional SST anomalies and the percentage of 1° cells from which at least one coral bleaching occurrence was recorded during August–October in the Caribbean between 1983 and 2000. Each data point represents one year. Solid circles represent years described in the literature as mass bleaching events, open circles represent other years. The solid line represents the regression line (log[cells] = 1.34[SST] + 0.71; $r^2 = 0.86$, $n = 18$, $P < 0.001$). The dashed line shows the SST at which maximum bleaching extent should occur based on extrapolation of the regression line.

Bleaching of coral reefs has been increasing with sea surface temperature (SST) all over the world.

These results are from the Caribbean.

McWilliams et al., ECOLOGY, 86, 2055, 2005

The Amazon is drying & burning under the influence of deforestation & climate-change-induced drought



Nepstad et al., Forest Ecology & Management 154, 2001

WHO estimates climate change already causing ≥150,000 premature deaths/yr in 2000

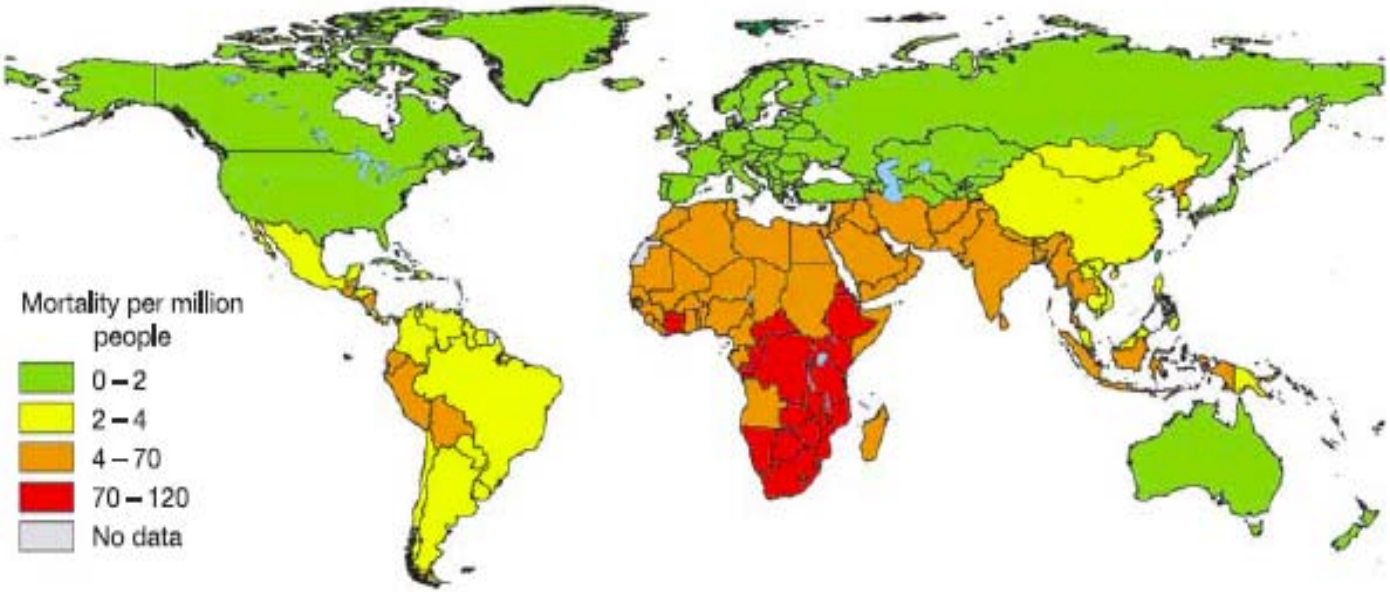
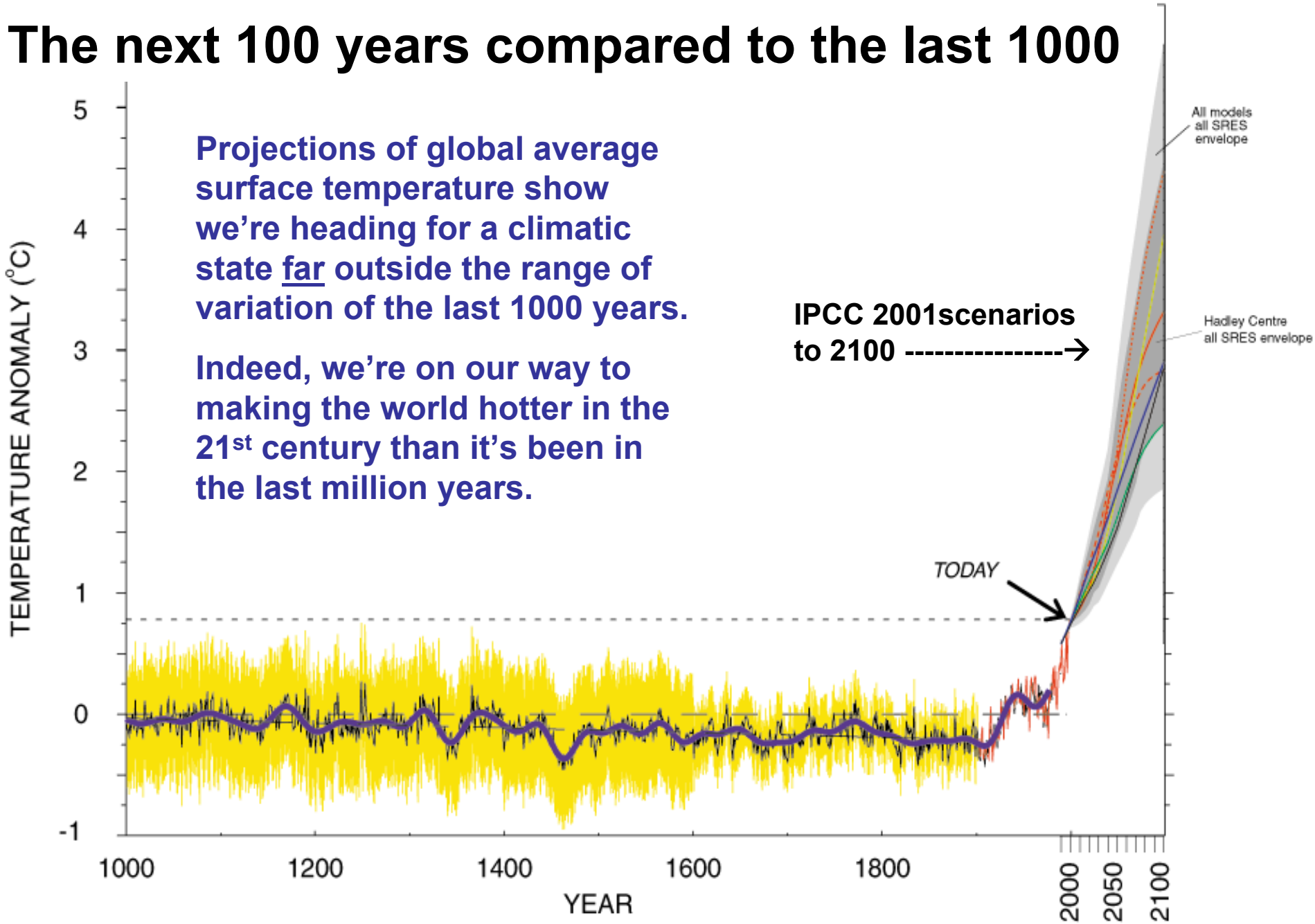


Figure 2 | WHO estimated mortality (per million people) attributable to climate change by the year 2000. The IPCC 'business as usual' greenhouse gas emissions scenario, 'IS92a' and the HadCM2 GCM of the UK Hadley Centre were used to estimate climate changes relative to 'baseline' 1961–1990 levels of greenhouse gases and associated climate conditions. Existing quantitative studies of climate–health relationships were used to estimate relative changes in a range of climate-sensitive health outcomes including: cardiovascular diseases, diarrhoea, malaria, inland and coastal flooding, and malnutrition, for the years 2000 to 2030. This is only a partial list of potential health outcomes, and there are significant uncertainties in all of the underlying models. These estimates should therefore be considered as a conservative, approximate, estimate of the health burden of climate change. Even so, the total mortality due to anthropogenic climate change by 2000 is estimated to be at least 150,000 people per year. Details on the methodology are contained in ref. 57.

Where are we headed?

The next 100 years compared to the last 1000

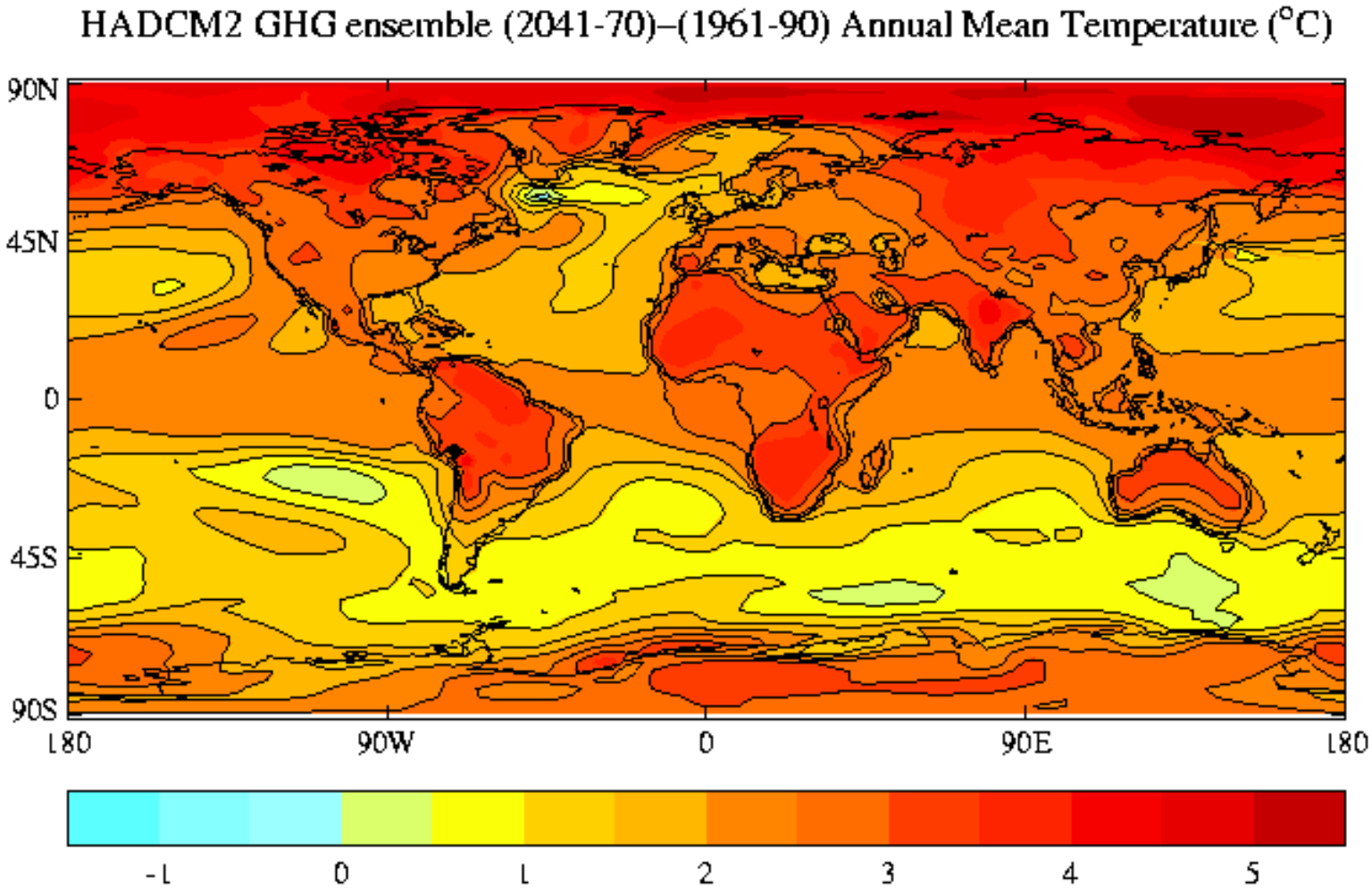


Projections of global average surface temperature show we're heading for a climatic state <u>far</u> outside the range of variation of the last 1000 years.

Indeed, we're on our way to making the world hotter in the 21st century than it's been in the last million years.

IPCC 2001scenarios to 2100 ----------→

Mid-21st century warming under BAU



Note that continental warming far exceeds the global average.

Impacts of BAU climate change

Consequences expected with <u>high likelihood</u> include…

- reduced agricultural productivity in many regions at $\Delta T_{avg} \approx 2\text{-}3°C$; nearly everywhere at $\Delta T_{avg} > 3°C$;
- increasing devastation from droughts, heat waves, wildfires, powerful storms, and floods;
- accelerating loss of biodiversity from its two greatest reservoirs: tropical forests and coral reefs
- expanded geographic ranges of malaria, cholera, dengue fever, and other diseases whose vectors or pathogens are temperature- or moisture-dependent;
- significant property losses from slowly rising sea level (~1.5 feet per century) as a result of thermal expansion of sea water.

Crop yields in tropics start dropping at ΔT ≥ 1-1.5°C

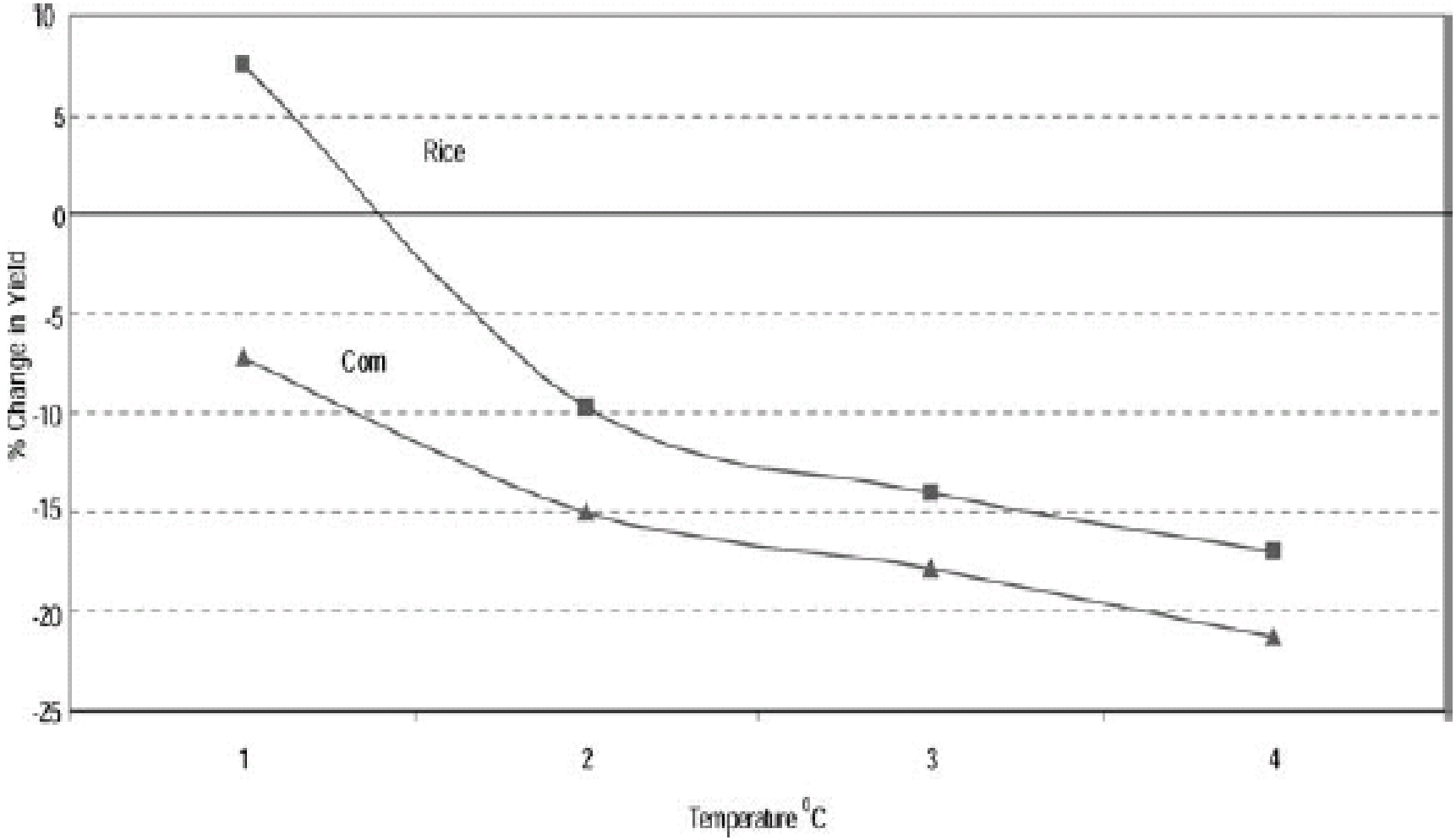


Figure 1. Corn and Rice yields versus temperature increase in the tropics averaged across 13 crop modeling studies. All studies assumed a positive change in precipitation. CO_2 direct effects were included in all studies.

Easterling and Apps, 2005

Temperate-zone crop yields start dropping at $\Delta T \geq 1\text{-}2°C$

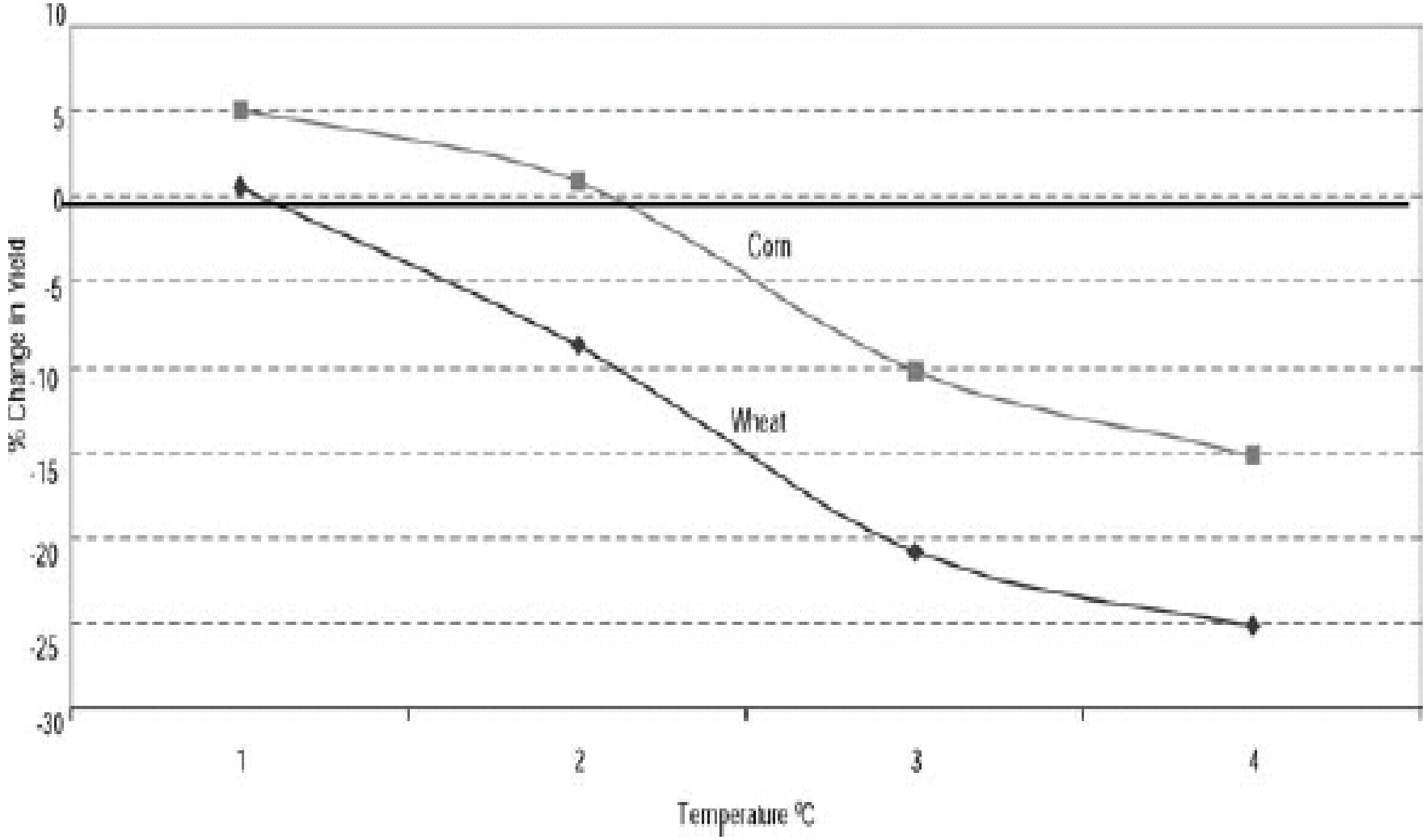
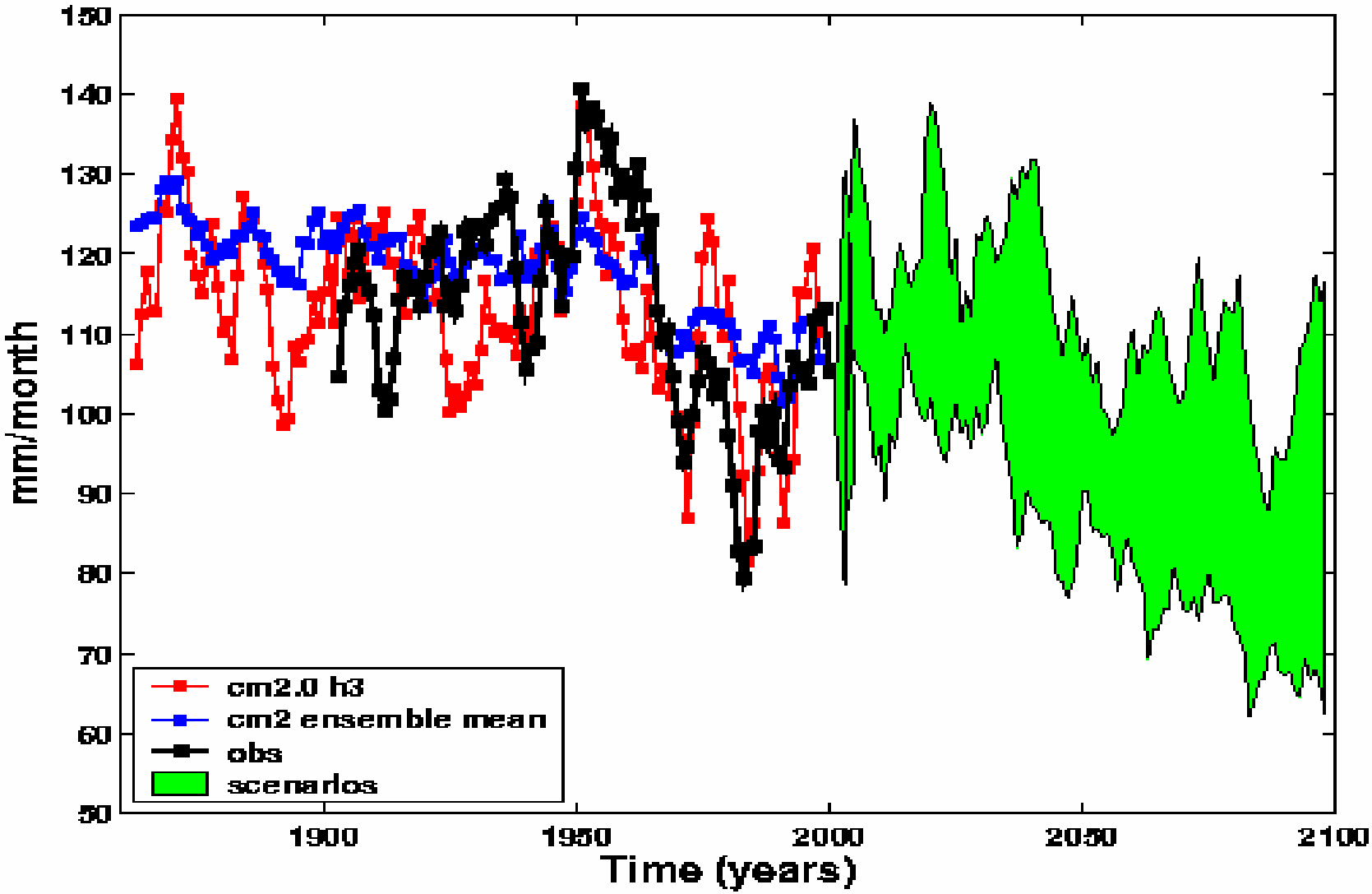


Figure 2. Corn and Wheat yields versus temperature increase in the temperate zone averaged across 30 crop modeling studies. All studies assumed a positive change in precipitation. CO_2 direct effects were included in all studies.

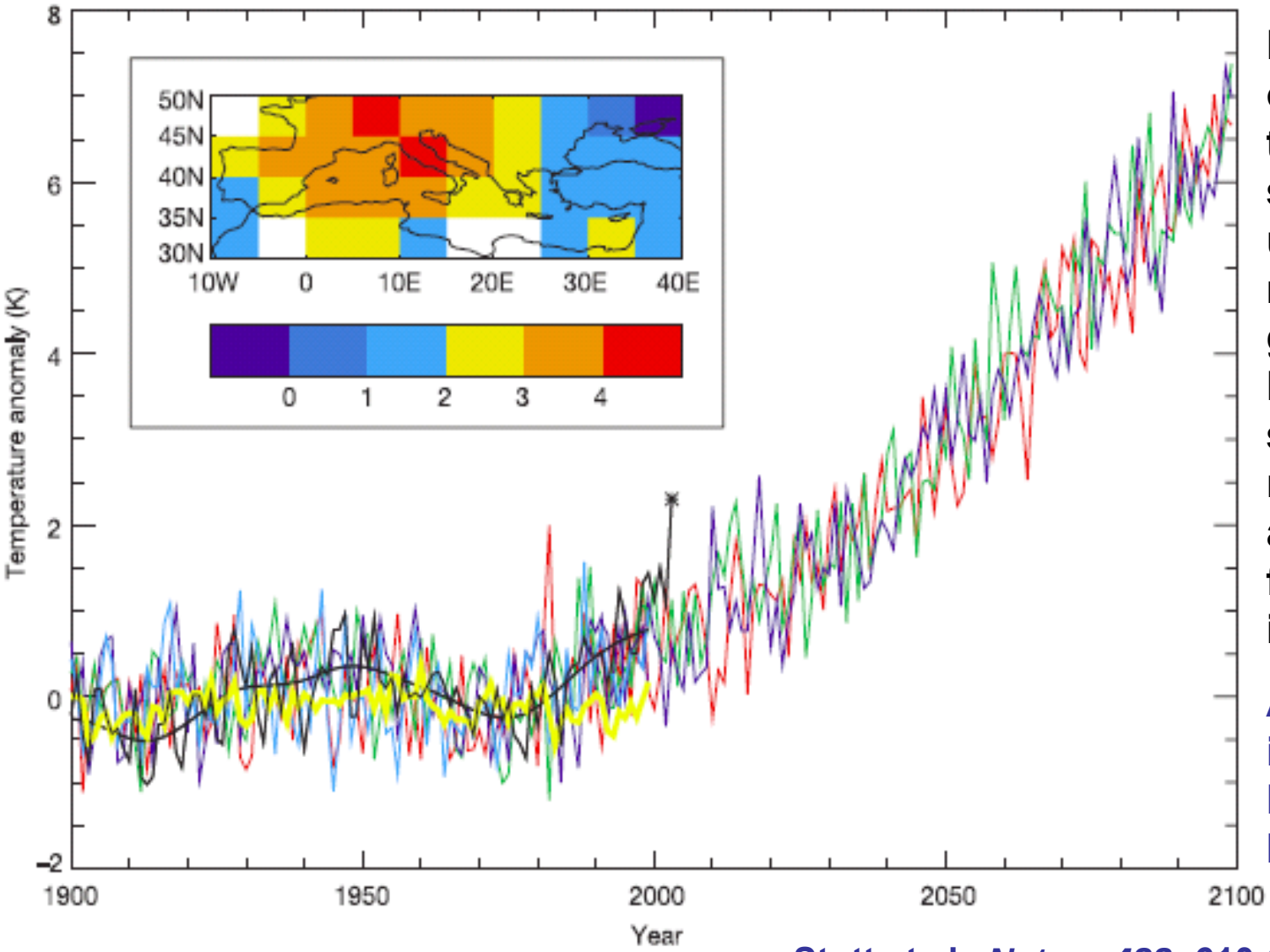
Easterling and Apps, 2005

Drought in the Sahel gets worse in a warming world



Isaac Held, NOAA GFDL, 3-06

Extreme heat waves in Europe are already 2X more frequent due to global warming, with much more to come

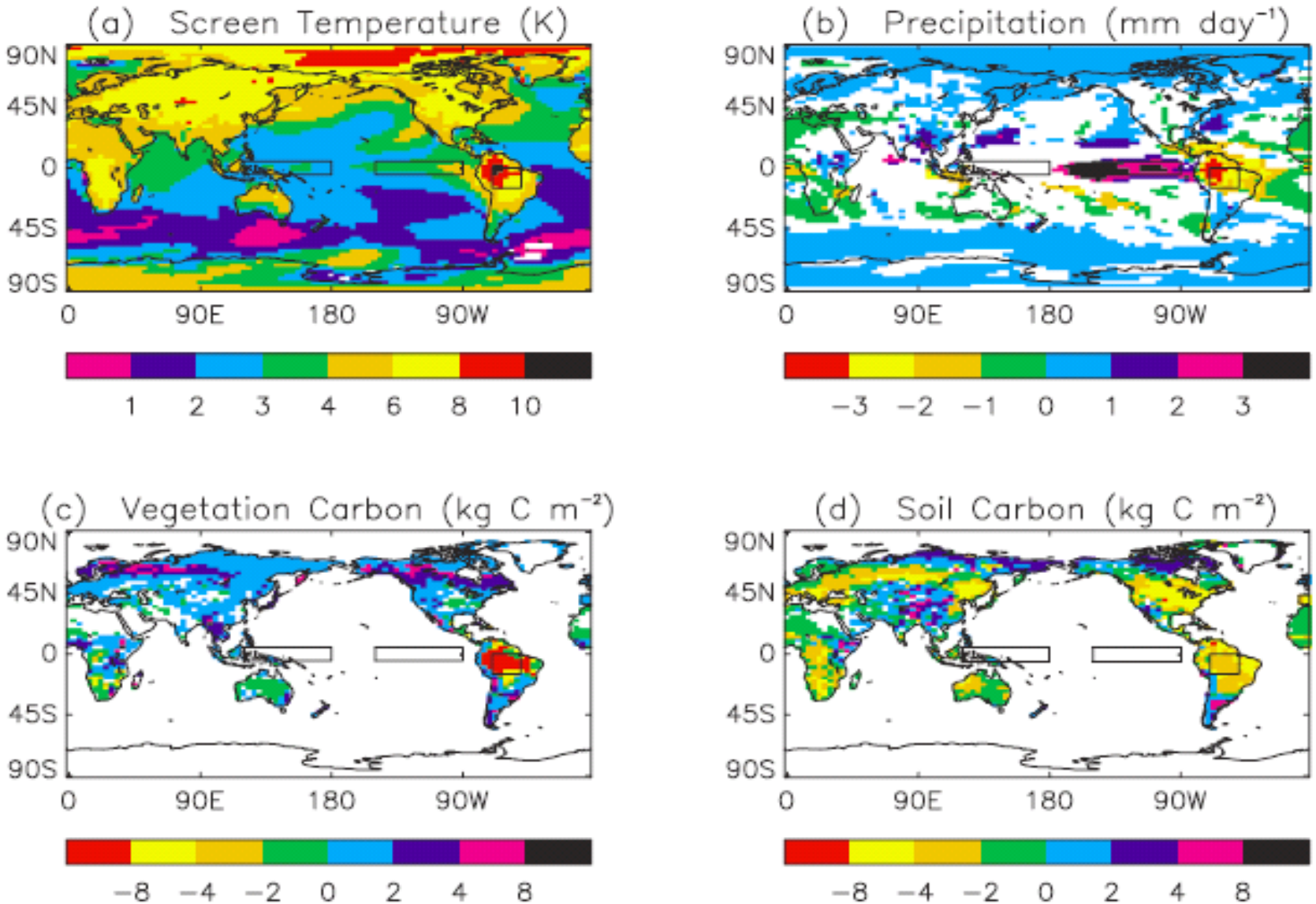


Black lines are observed temps, smoothed & unsmoothed; red, blue, & green lines are Hadley Centre simulations w natural & anthropogenic forcing; yellow is natural only.

Asterisk and inset show 2003 heat wave that killed 35,000.

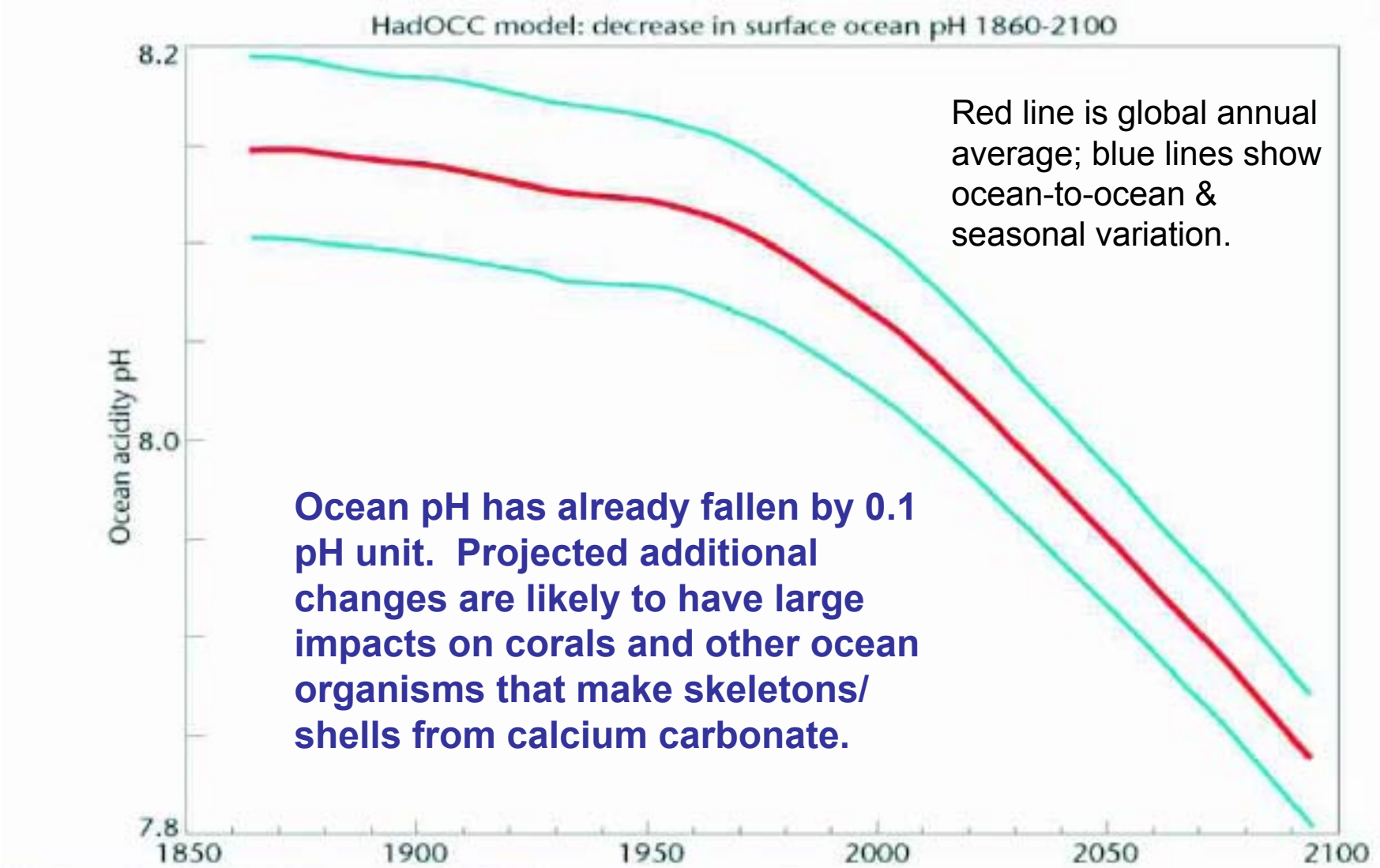
Stott et al., *Nature 432*: 610-613 (2004)

Projected differences 1990s to 2090s by UK model show large warming, drying, carbon loss in Amazon



Cox et al., *Theor. Appl. Climatol. 78*: 137-156 (2004)

Acidification of the ocean from CO_2 uptake: history and "business as usual" projection

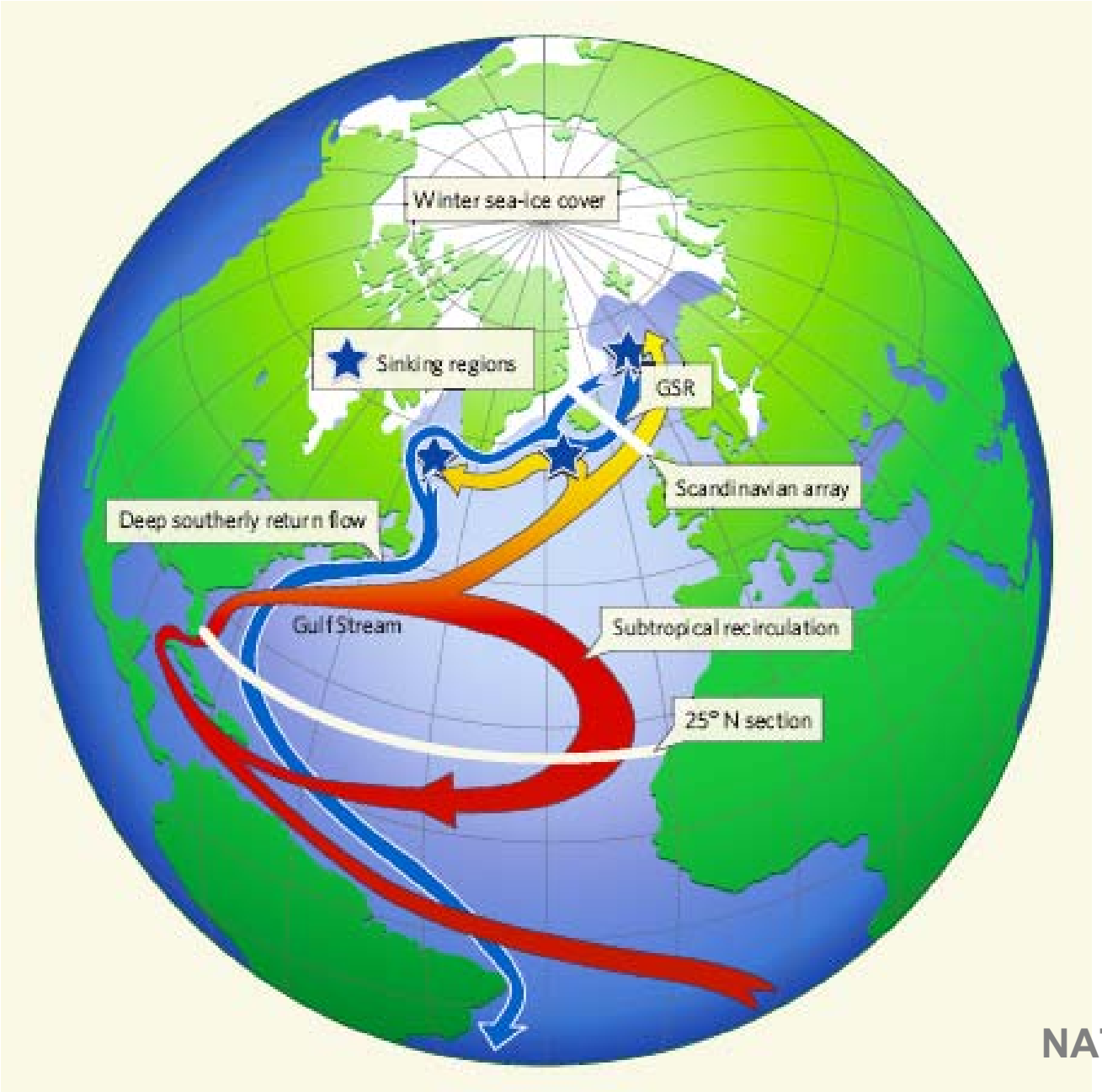


Hadley Centre for Climate Prediction and Research

Additional possible outcomes

- Other possible outcomes for which evidence is growing include…
  - drastic changes in ocean circulation patterns, with large impacts on regional climates and on fisheries;
  - rapid increases in sea level (2-4 meters per century?) from melting, slumping, disintegration of Greenland & Antarctic ice sheets;
  - accelerated emissions of CO_2 and CH_4 from warming northern soil & melting permafrost, sharply increasing the pace of expected impacts and the possibilities for unexpected ones.

Atlantic "conveyor" behavior

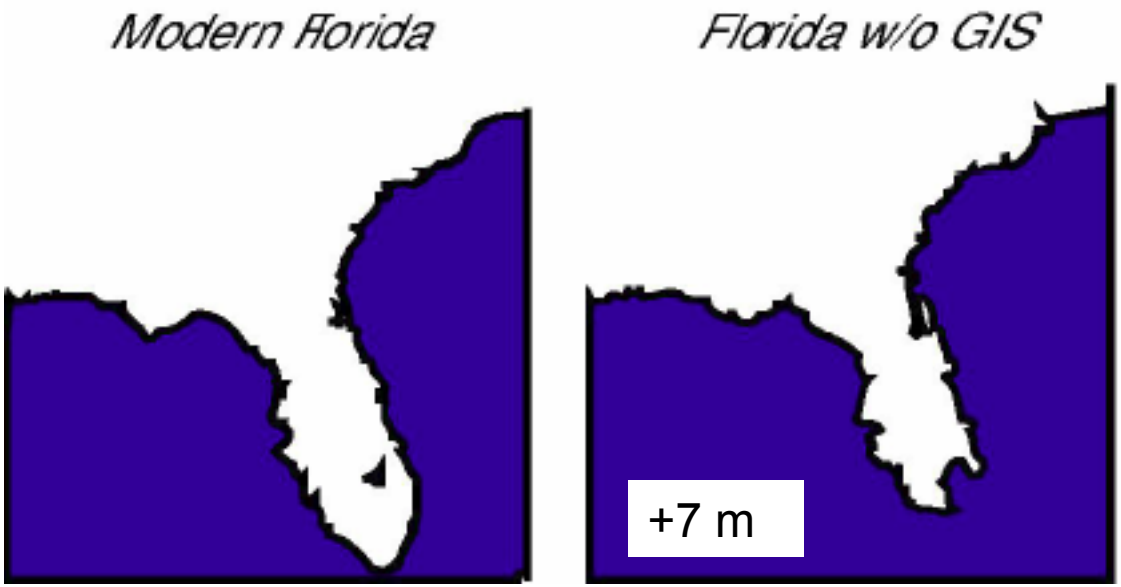


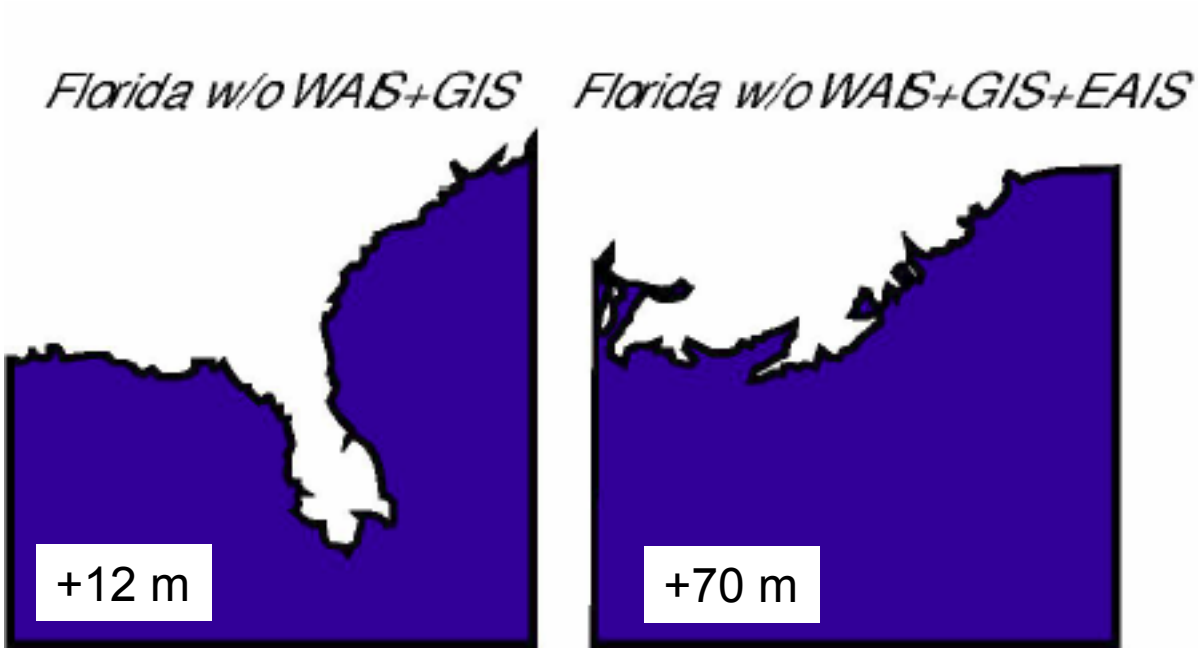
Theory & models predict that global warming will slow the conveyor. Recent measurements suggest northward heat transport by the conveyor may already have slowed by 25%

NATURE, 12-01-05

Greenland, Antarctica, & future sea level

- Recent observations of accelerating ice loss from Greenland & instability in West Antarctic Sheet, plus paleoclimate evidence, indicate rapid sea level rise from warming is possible.
- All the ice on Greenland ≈ 7 m increase in sea level; ice in West Antarctic Ice Sheet ≈ 5 m.
- Rates at which this ice could become sea water are still highly uncertain, but 12 m in 350-500 years is possible (~3 m per century); some think even faster is possible (Hansen 2005).
- East Antarctic Ice Sheet could add another 60 m, presumably only over many centuries…but recent surprises indicate science uncertain here.



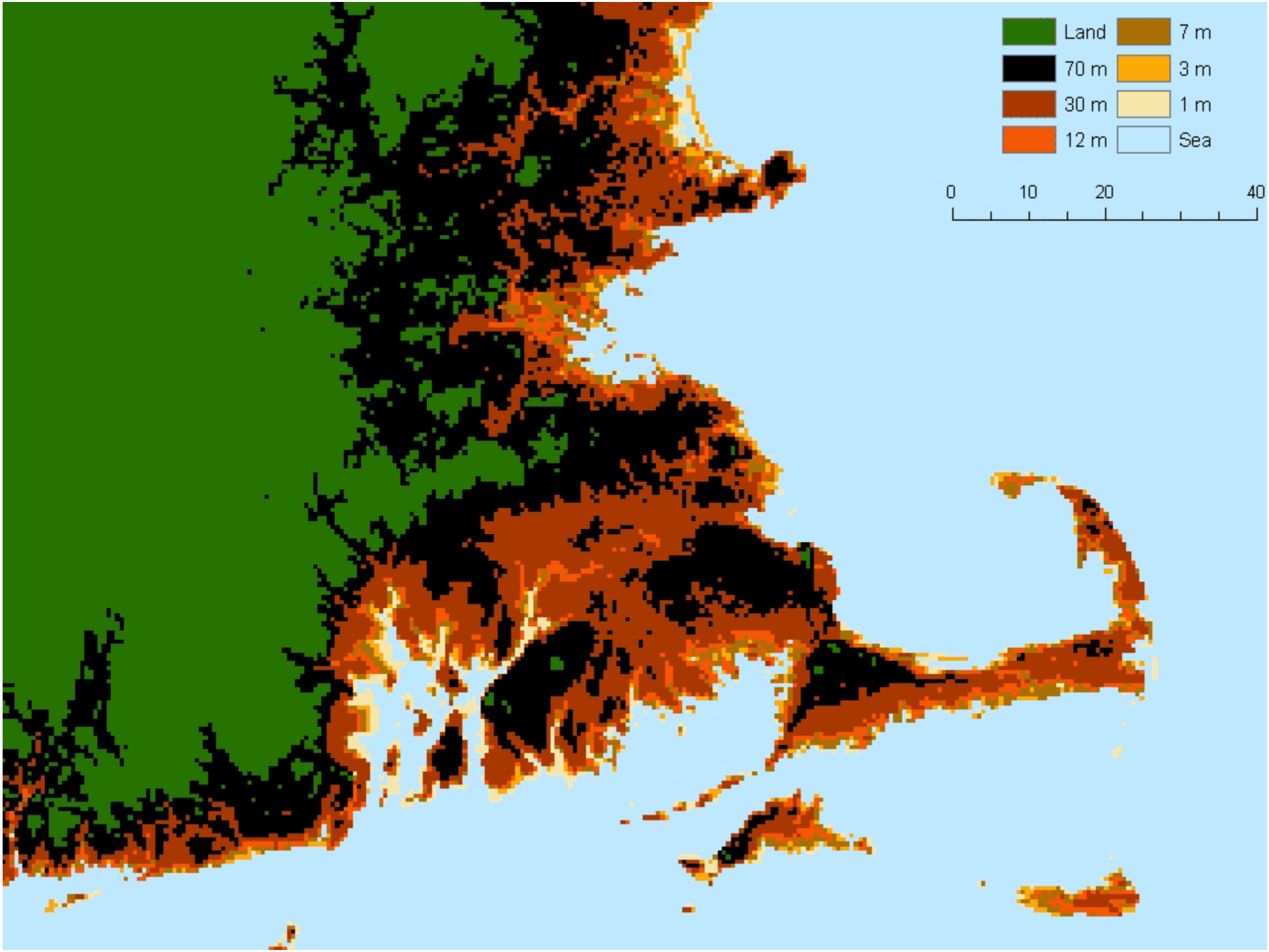


GIS = Greenland Ice Sheet

WAIS = West Antarctic Ice Sheet

EAIS = East Antarctic Ice Sheet

From a presentation by Richard B. Alley, U of Pennsylvania (with permission)


Land
7 m
70 m
3 m
30 m
1 m
12 m
Sea
0
10
20
40

The choices

Facing these dangers, we have 3 options:

- Mitigation, meaning measures to reduce the pace & magnitude of the changes in global climate being caused by human activities.
- Adaptation, meaning measures to reduce the adverse impacts on human well-being resulting from the changes in climate that do occur.
- Suffering the adverse impacts that are not avoided by either mitigation or adaptation.

The choices (concluded)

Mitigation and adaptation are <u>both</u> essential.

- Human-caused climate change is already occurring.
- Adaptation efforts are already taking place and must be expanded.
- But adaptation becomes costlier and less effective as the magnitude of climate changes grows.
- The greater the amount of mitigation that can be achieved at affordable cost, the smaller the burdens placed on adaptation and the smaller the suffering.

The remainder of this tutorial focuses mainly on mitigation: the size of the need, the available approaches, and the policy levers and prospects.

Mitigation by managing forests & soils

- Reduce emissions of CO_2 from deforestation in the tropics.

  "Avoided deforestation" depends on figuring out how owners of forest land – individuals, firms, countries – can be paid <u>not</u> to deforest, reflecting the value to society of keeping the forests intact.

- Accelerate reforestation and afforestation in regions where this is practicable.
- Improve management of agricultural soils to increase carbon storage.

  The last two could take up ~20% of atmospheric CO_2 buildup expected in 21st century under "business as usual".

Mitigation by reducing emissions of CH_4 & soot

- Anthropogenic methane (CH_4) comes 30% from energy systems, 30% from livestock, 25% from agriculture, 15% from landfills & waste treatment.
  - Technical means exist for reducing all of these.
  - Methane's relatively short atmospheric lifetime means emissions reductions translate quickly into reduced concentrations, thus reduced forcing.
- Soot comes from 2-stroke & diesel engines as well as from traditional uses of biomass fuels, agricultural burning, and forest fires.
  - The engine and biomass fuels emissions are amenable to sharp reduction by technical means.
  - The very short atmospheric lifetime of soot (days to weeks) means emissions reductions translate quickly into reduced forcing.

Mitigation by geo-engineering

- Increasing surface reflectivity to cool the Earth
  - Humans have done this inadvertently by deforestation, desertification, but more is undesirable.
  - Reflectivity of man-made surfaces (buildings, roads) can be increased, but global impact is limited by small fraction of land surface used for these purposes (~2%).
  - Large-scale alteration of reflectivity of oceans would be expected to have undesired climatological & ecological side effects.
- Increasing the atmosphere's reflectivity by injecting reflecting particles into the stratosphere might be affordable (& reversible), but would be likely to deplete stratospheric ozone.
- Placing reflecting materials or mirrors in Earth orbit (or at the Lagrangian equilibration point between the Sun and the Earth) would be staggeringly expensive.

Mitigation by reducing CO_2 emissions from energy systems

The emissions arise from a 4-fold product…

$$C = P \times GDP / P \times E / GDP \times C / E$$

where C = carbon content of emitted CO_2 (kilograms), and the four contributing factors are

P = population, persons

GDP / P = economic activity per person, $/pers

E / GDP = energy intensity of economic activity, GJ/$

C / E = carbon intensity of energy supply, kg/GJ

For example, in the year 2000, the world figures were…

6.1×10^9 pers x $7400/pers x 0.01 GJ/$ x 14 kgC/GJ

= 6.4×10^{12} kgC = 6.4 billion tonnes C

What happens to these factors on the "business as usual" path?

	2000	2050	2100
Population, billions	6.1	9	10
Economy, trillion 2000$	45	150	480
Energy, exajoules	450	900	1800
Fossil C in CO_2, gigatons	6.4	14	21

Corresponds to 2.4%/yr avg growth of real GDP, 1.0%/yr decline in energy intensity of GDP, 0.2%/yr decline in C intensity of energy supply.

Where's the leverage for reductions in these?

POPULATION

Lower is better for lots of reasons: 8 billion people in 2100 is preferable by far to 10 billion.

Reduced growth can be achieved by measures that are attractive in their own right (e.g., education, opportunity, health care, reproductive rights for women).

GDP PER PERSON

This is not a lever that most people want to use, because higher is generally accepted to be better.

But we're not getting rich as fast as we think if GDP growth comes at the expense of the environmental underpinnings of well-being.

Internalizing environmental costs of economic growth (including those of climate change) may slow that growth a bit...but not much.

Some lifestyle changes in industrialized countries could increase quality of life even though they reduced GDP.

Leverage against CO_2 emissions (continued)

ENERGY INTENSITY OF GDP

Getting more GDP out of less energy – i.e. increasing energy efficiency – has been a long-term trend.

It could be accelerated. It entails more efficient cars, trucks, planes, buildings, appliances, manufacturing processes. This opportunity offers the largest, cheapest, fastest leverage on carbon emissions.

CARBON INTENSITY OF ENERGY SUPPY

This ratio too has been falling, but more slowly than energy intensity of GDP. Reducing it entails changing…

- **the mix of fossil & non-fossil energy sources (most importantly more renewables and/or nuclear)**
- **and/or the characteristics of fossil-fuel technologies (most importantly with carbon capture & sequestration).**

Reducing E/GDP: Transportation

- Oil used as transport fuel ≈ 25% of global CO_2 from fossil-fuel combustion
- Growth in these uses can be reduced by…
  - increasing the efficiency of cars, trucks, buses, trains, aircraft
  - increasing the load factors of these (e.g., passengers per vehicle per trip)
  - mode switching (e.g., cars → buses, trucks → trains)
  - urban & economic planning that affects living & production patterns so as to reduce commuting and freight transport

Reducing E/GDP: Buildings

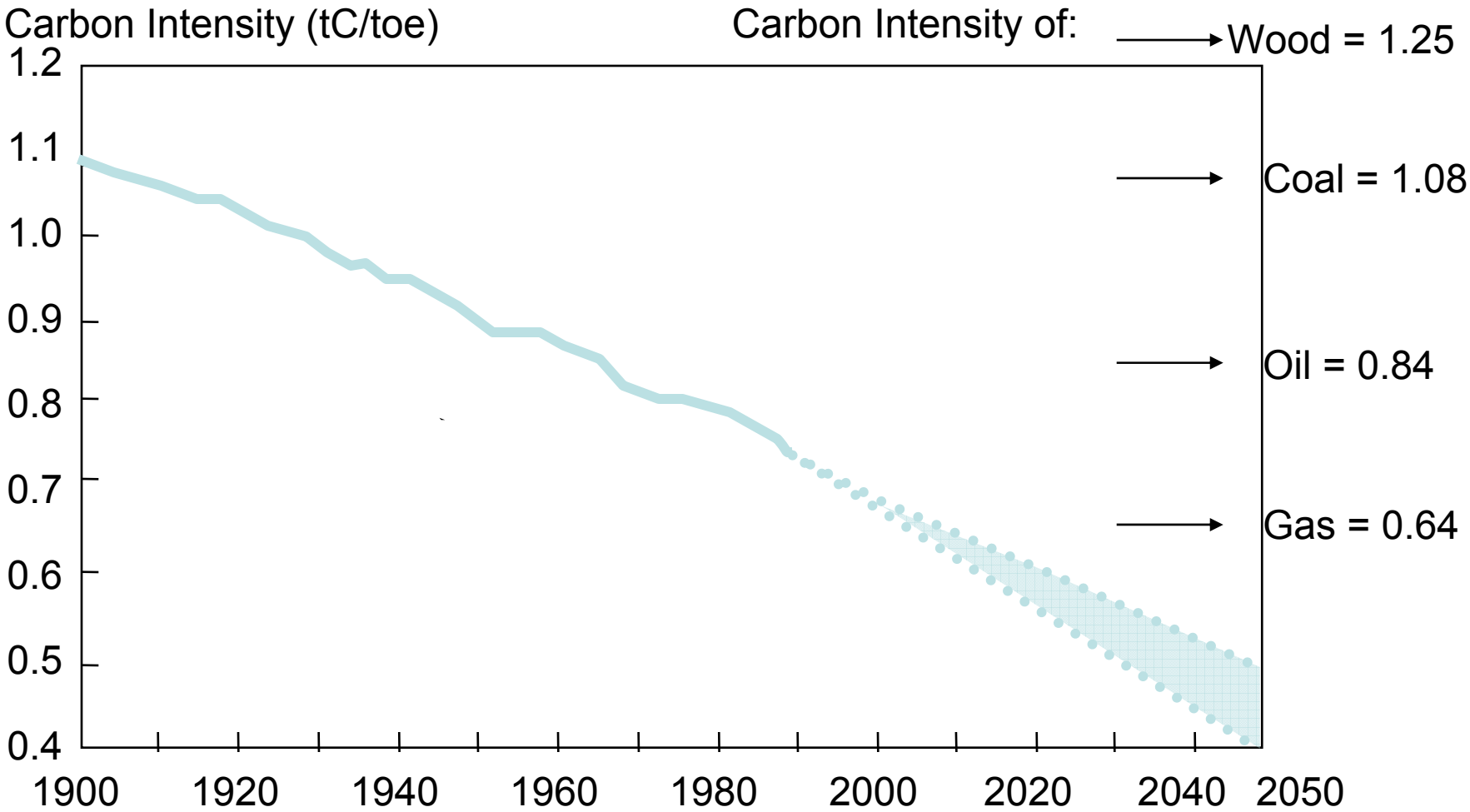
- Heating, cooling , refrigeration, lighting, office equipment ≈ 33% of global CO_2 from fossil-fuel combustion.
- Energy used for these purposes can be reduced by…
  - improvements in building envelopes (wall & roof insulation, high-performance windows)
  - improved building orientation, shading, passive energy storage;
  - increased efficiency of heating & cooling (improved furnaces, air conditioners, ground-water heat pumps)
  - increased efficiency of lighting, refrigerators, computers, other appliances

Reducing E/GDP: Industry

- Industrial energy use ≈ 40% of global CO_2 from fossil-fuel combustion.
- Biggest users include oil refining, plastics, fertilizers, iron & steel, aluminum, cement, pulp & paper.
- Energy used for these purposes can be reduced by…
  - improved efficiency of electric motors & individual industrial processes
  - increased use of on-site combined heat & power (CHP)
  - increased recycling of energy-intensive materials
  - shift in composition of industrial activity from materials-intensive to knowledge- and information-intensive goods & services

C/E: History and BAU projections

Carbon Intensity of World Primary Energy, 1900-2050



Source: National Academy of Engineering, 1997

C/E: Will running out of fossil fuel take care of it?

- Combustion of conventional fossil fuels yields about

  15 million tonnes C in CO_2 per EJ of natural gas

  20 million tonnes C in CO_2 per EJ of petroleum

  25 million tonnes C in CO_2 per EJ of coal

  1 tonne of C makes 3.67 tonnes of CO_2

- Remaining ultimately recoverable resources would yield

  200+ billion tonnes of C in CO_2 from natural gas

  300+ billion tonnes of C in CO_2 from petroleum

  4,000 billion tonnes of C in CO_2 from coal

Current C content of the atmosphere (380 ppmv) = 800 billion tonnes C in CO_2, an increase of about 215 billion tonnes C since 1750. About half of added CO_2 now stays in atmosphere; if this remains so, adding 700 billion more tonnes of C in CO_2 will get us to 2X 1750 concentration.

There is more than enough conventional fossil fuel to double, even triple & quadruple, the pre-industrial atmospheric concentration of carbon dioxide.

Reducing C/E going forward

HERE THE POSSIBILITIES ARE…

- Increasing the efficiency of conversion of fossil-fuels to end-use energy forms (most importantly electricity)

  Potential is limited because conversion efficiencies are constrained by thermodynamics and already high.

- Switching from high C/E to low C/E fossil fuels (coal to oil & natural gas, oil to natural gas)

  Potential is limited because oil & gas are much less abundant than coal (unless unconventional gas resources become practical)

- CO_2 capture & sequestration (CCS) when fossil-fuels are converted or burned

- Switching from fossil to non-fossil primary energy sources (renewables & geothermal, nuclear)

What's a suitable target for CO_2 reductions?

- The climate-policy aim negotiated in the process of formulating the UN Framework Convention on Climate Change was…

  "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

- There was no formal consensus at that time about what level is "dangerous" in this sense.

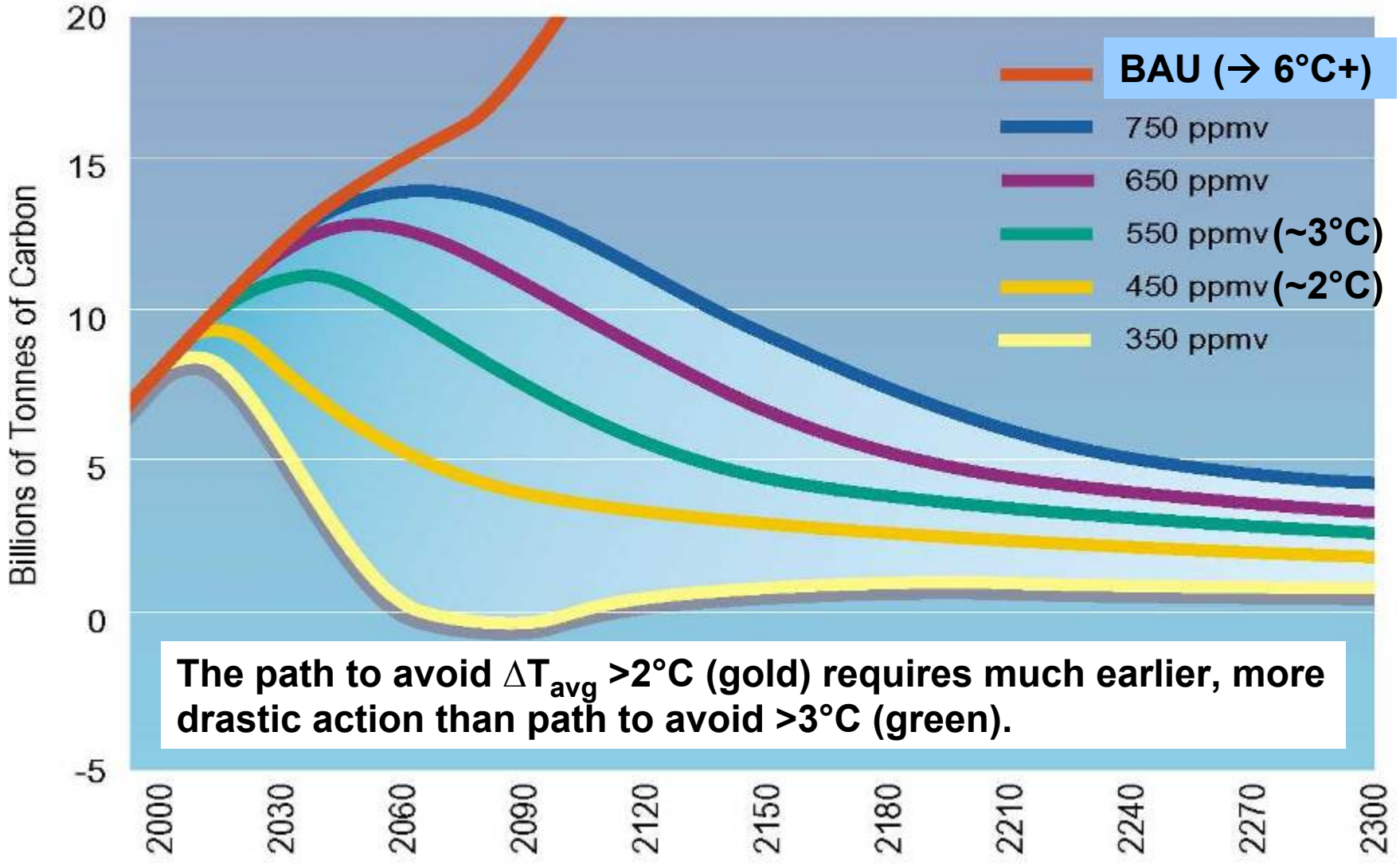
Suitable CO_2 target? (continued)

- There is still no formal consensus.
- But it's increasingly clear that the current level of anthropogenic interference is dangerous:
  - Significant impacts in terms of floods, droughts, wildfires, species, melting ice already evident at ~0.8°C above pre-industrial $T_{avg.}$
  - Current GHG concentrations commit us to ~0.6°C more.

Suitable CO_2 target? (continued)

- It is now entirely plausible that…
  - ΔT_{avg} ~ 1.5°C will mean the end of coral reefs & polar bears
  - ΔT_{avg} ~ 2°C will mean catastrophic melting of Greenland & Antarctic ice, with commitment to multi-meter rises in sea level
  - ΔT_{avg} ~ 2.5°C will sharply reduce global crop yields
- Thus stopping at 2x pre-industrial CO_2 (550 ppmv, corresponding to ~3°C), once thought a reason-able target by many) <u>may not be good enough</u>.
- Many analysts & groups now conclude that prudence requires aiming not to exceed 2°C.

Future BAU emissions path compared to paths for stabilizing CO2 concentration to limit $\Delta T_{average}$



The path to avoid ΔT_{avg} >2°C (gold) requires much earlier, more drastic action than path to avoid >3°C (green).

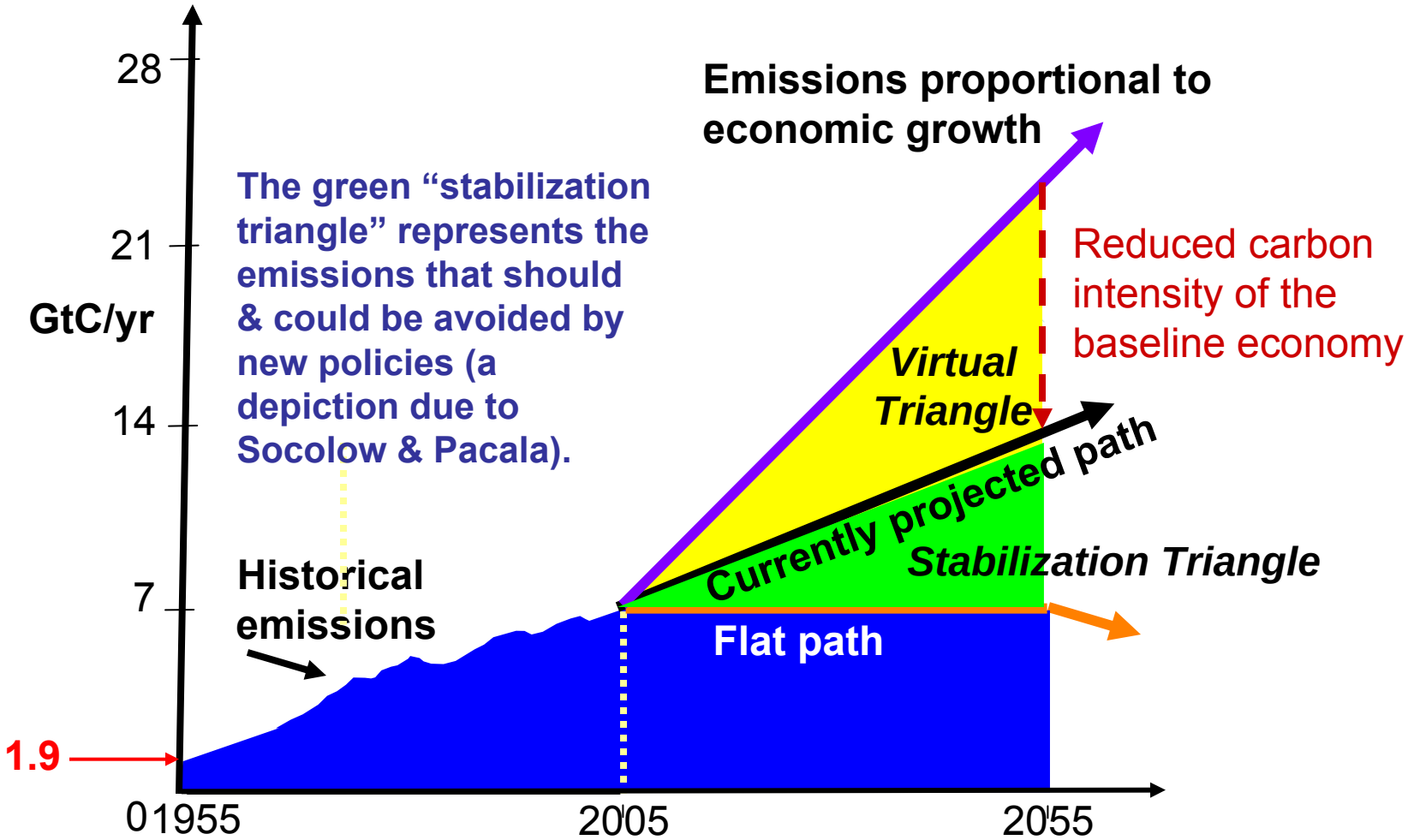
Thought experiment: How much carbon-free energy needed to stabilize CO_2 at 550 ppm_v?

Carbon-free energy in 2000 (from renewables and nuclear energy) ≈ 100 exajoules/year. (Fossil fuels ≈ 350 EJ/yr)

With BAU economic growth, the future need for C-free energy (renewables, nuclear, & advanced fossil with CO_2 sequestration) depends on rate of improvement of energy efficiency as follows:

C-free energy (exajoules) in	2050	2100
	---	---
E/GDP falls 1%/yr (BAU)	600	1500
E/GDP falls 1.5%/yr	350	800
E/GCP falls 2.0%/yr	180	350

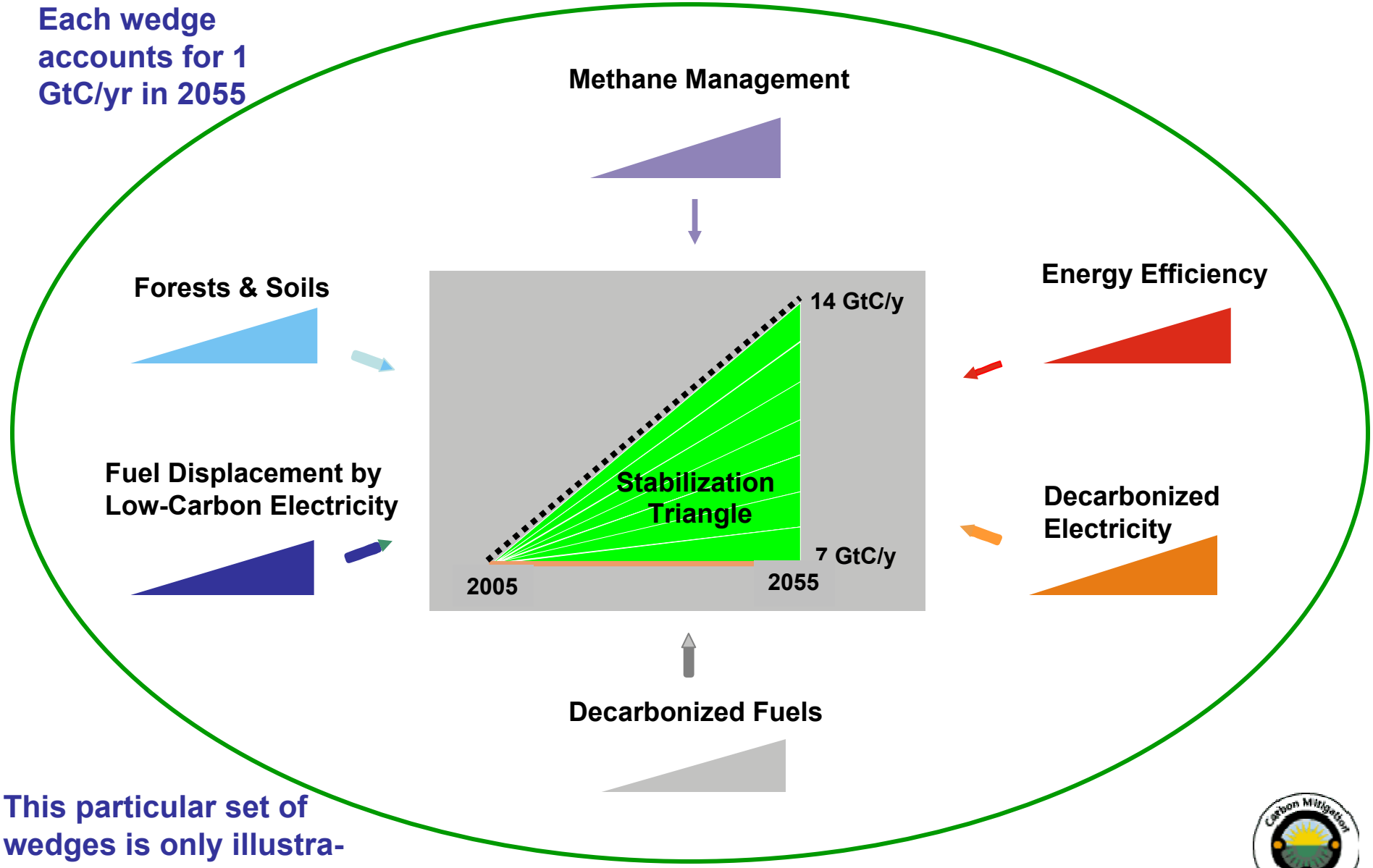
Stabilizing at 450-500 ppmv would be possible if emissions were flat for ~50 years, then declined.



The virtual triangle results more from structural shifts in the economy (toward services) and less from the carbon-saving activity required to fill the stabilization triangle.

The triangle can be filled by a portfolio of 7 wedges

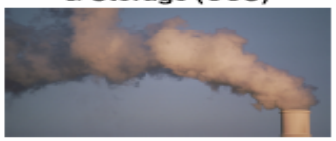
Each wedge accounts for 1 GtC/yr in 2055



This particular set of wedges is only illustrative, not prescriptive.

There are more than 7 wedges to choose from: Here are 15 candidates.

CO_2 Capture & Storage (CCS)



CO_2 capture:

1. Introduce CCS at 800 GW coal or 1600 GW natural gas plants (1100 GW coal today)
2. Introduce CCS at plants producing 250 MtH_2/yr from coal or 500 MtH_2/yr from natural gas (40 MtH_2/yr today)
3. Introduce CCS at synfuels plants producing 30 mbd from coal (200x Sasol)

H_2 safety, infrastructure

Geologic storage:
Create 3500 Sleipners

Durable storage

Wind and Solar

4. Add 2 million 1-MW-peak windmills (50 times current level) on 30 Mha, displacing coal electricity
5. Add 2000 GW-peak PV plants (700 times current level) on 2 Mha, displacing coal electricity

6. Add 4 million windmills or 4000 GW-peak PV plants generating 200 MtH_2/yr, displacing gasoline hybrid cars

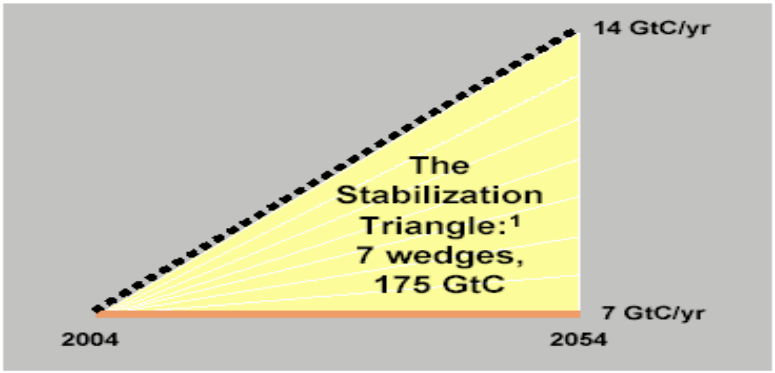
Energy storage, H_2 safety, infrastructure
PV production cost

Energy Efficiency & Conservation

Increase economy-wide emissions/GDP reduction by additional 0.15%/yr (e.g. increase US goal of 1.96%/yr to 2.11%/yr):

8. Increase fuel economy for 2 billion cars from 30 to 60 mpg
9. Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles/yr
10. Cut carbon emissions in buildings/appliances by 1/4 over 2054 projection
11. Produce twice today's coal output at 60% efficiency instead of 40% (compare with 32% today)

Weak incentives, urban design, lifestyle changes



Forests & Soils

14. Decrease tropical deforestation to zero instead of 0.5 GtC/yr, and establish 300 Mha of new tree plantations (twice current level)
15. Implement conservation tillage on all cropland (10 times current level)

Competing land use, verification, reversibility

Biomass Fuel

7. Add 50 times current US and Brazil ethanol production on 250 Mha (1/6 world cropland)

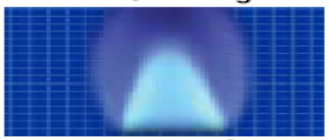
Biodiversity, competing land use

Nuclear Fission

13. Add 700 GW nuclear plants (compare with 350 GW today) replacing coal

Nuclear proliferation, terrorism, waste

Fuel Switching



12. Replace 1400 GW coal plants with natural gas plants (compare with 350 GW natural gas today)

Competing demands for natural gas

Beyond 2054

More wedges will be needed to maintain the trajectory established by the stabilization triangle, and scaling up the above technologies are unlikely to be enough to satisfy growing energy demand. Therefore, it is imperative that advanced technologies, including **artificial photosynthesis, satellite solar power, nuclear fusion,** and **geoengineering strategies** be developed now,[3] so that the second and subsequent "runners" have the necessary tools to do their jobs.

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Policy options for promoting mitigation

Measures to affect choices among available technologies

- analysis of and education about the options
- correction of perverse incentives
- lowering bureaucratic barriers
- financing for targeted options
- performance & portfolio standards
- subsidies for targeted options
- emission cap & trade programs
- taxes on carbon or energy

These are listed in order of increasing intrusiveness & political difficulty. But combinations that don't include one of the last two are almost certain to be insufficient.

Measures to improve mix of available technologies

- improving capabilities for RD&D
- encouraging RD&D with tax policy & other policies
- funding the conduct of RD&D
- promoting niche & pre-commercial deployment
- international transfer of resulting technologies

Policy options embraced to date

- The Kyoto Protocol
  - a landmark as a negotiated global commitment to move forward to address the problem
  - but limited in time frame, magnitude of required reductions, and participation
- The EU carbon trading system
  - implemented starting in January 2005, embracing 12,000 installations accounting for almost half of EU carbon emissions
  - C trading price reached $100/tC, but has recently fallen amid loss of confidence about monitoring, cheating
- Non-federal jurisdictions in the United States
  - USA has not ratified Kyoto; federal climate policy consists only of research, incentives, and modest “voluntary” targets.
  - But 28 states have climate-action plans, 21 have renewable portfolio standards, 234 cities have embraced Kyoto targets, many major corporations are acting.
  - US Senate endorsed mandatory, national GHG restraints in 6/05.

Corporate Commitments and Results

bp

10% reduction
$650 million saved

DUPONT

69% reduction
$2 billion saved

LAFARGE

10% reduction
"It's made us more competitive"

CINERGY

5% reduction

Entergy

Absolute cap

3M

35% reduction
$200 million saved

TOYOTA

19% reduction

ALCAN

10% reduction

GM

72% reduction

ALCOA

25% reduction
$100 million saved

SUNCOR ENERGY

6% reduction

IBM

65% reduction
$791 million saved

nike

13% reduction

GE

1% reduction
$1.5 billion clean tech R&D

9% reduction

United Technologies

37% reduction

Kodak

17% reduction

Polaroid

25% reduction

Sense of the Senate Resolution, 6-22-05

It is the sense of the Senate that Congress should enact a comprehensive and effective national program of mandatory, market-based limits and incentives on emissions of green-house gases that slow, stop, and reverse the growth of such emissions at a rate and in a manner that--

(1) will not significantly harm the United States economy; and

(2) will encourage comparable action by other nations that are major trading partners and key contributors to global emissions.

Policy recommendations (my own)

- Pursue a new global framework for mitigation and adaptation in the post-Kyoto period

  It must include mandatory, economy-wide reductions in GHG emissions below BAU everywhere, and it needs to be equitable, achievable, and adequate to the magnitude of the challenge.

- Pursue "win-win" technical and policy measures

  Pursue most vigorously those measures that address economic, social, and non-climate environmental goals as well as climate.

- Increase investments in energy-technology innovation

  A tripling to quadrupling of government investments is warranted worldwide, along with increased incentives for innovation in the private sector.

- Expand international cooperation on energy-technology innovation

  Cooperation is needed to reduce costs & spread benefits in implementing climate-friendly technologies in the interest of the whole world.

A few references…

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