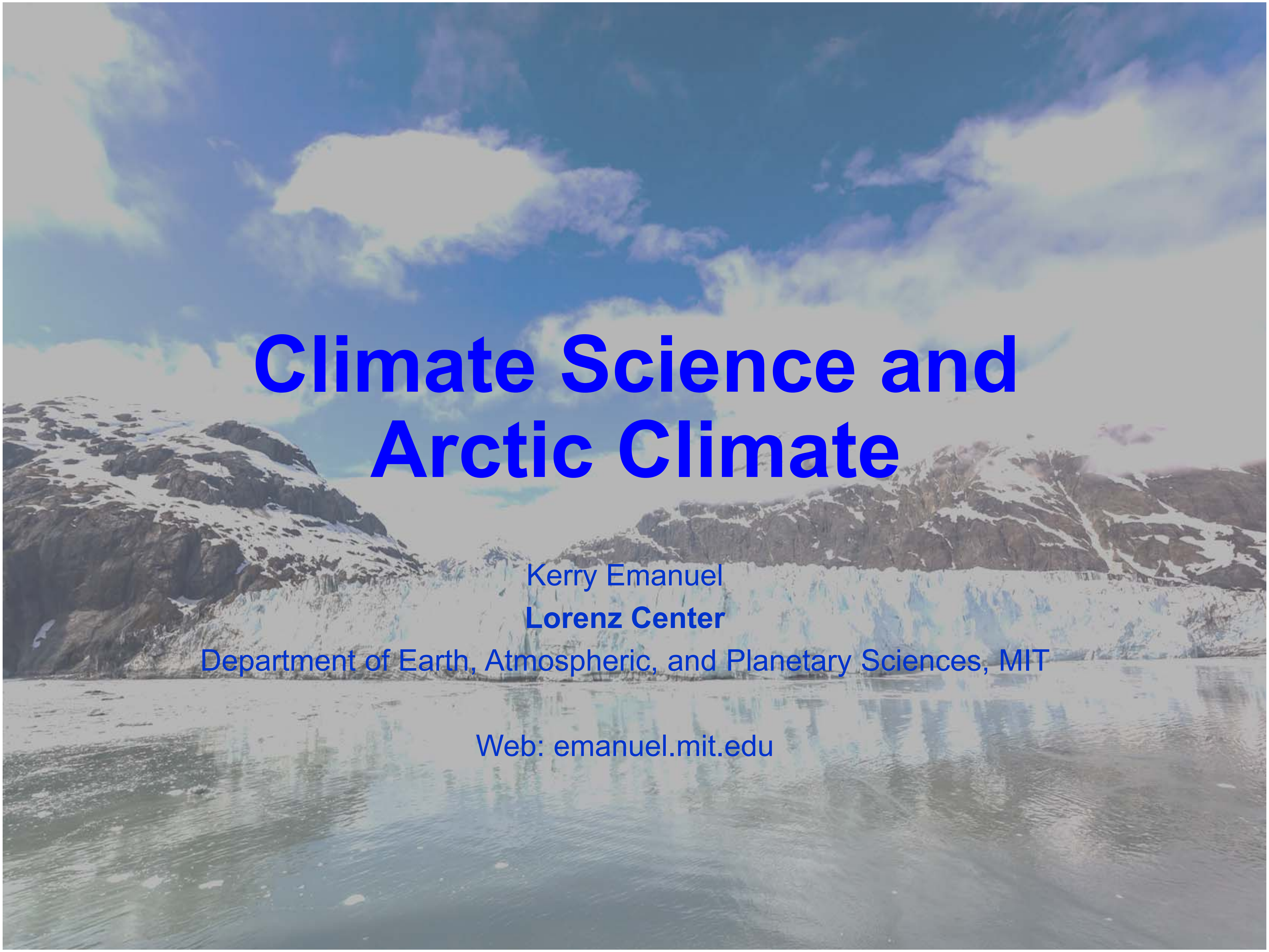


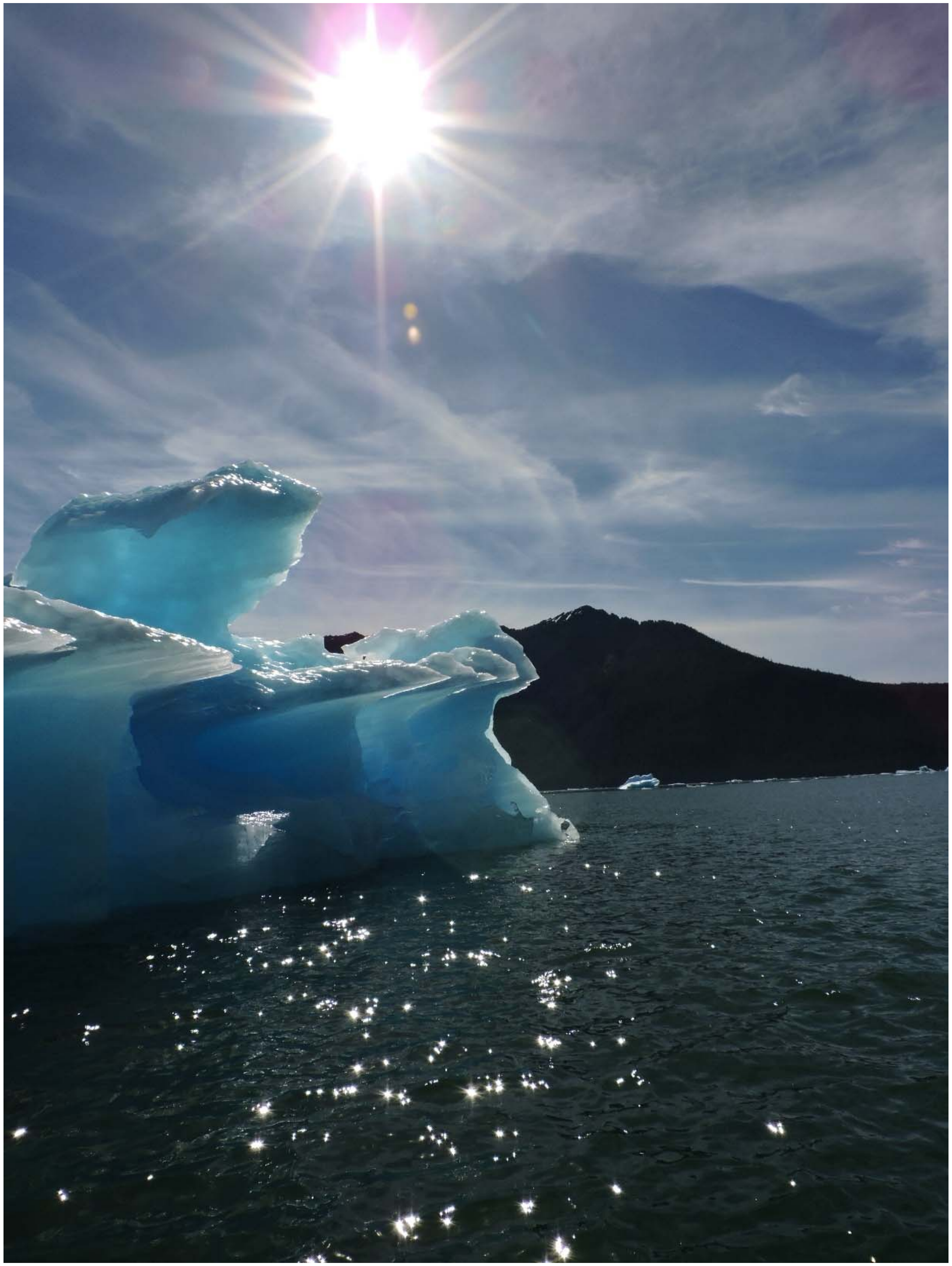
Climate Science and Arctic Climate

Kerry Emanuel

Lorenz Center

Department of Earth, Atmospheric, and Planetary Sciences, MIT

Web: emanuel.mit.edu

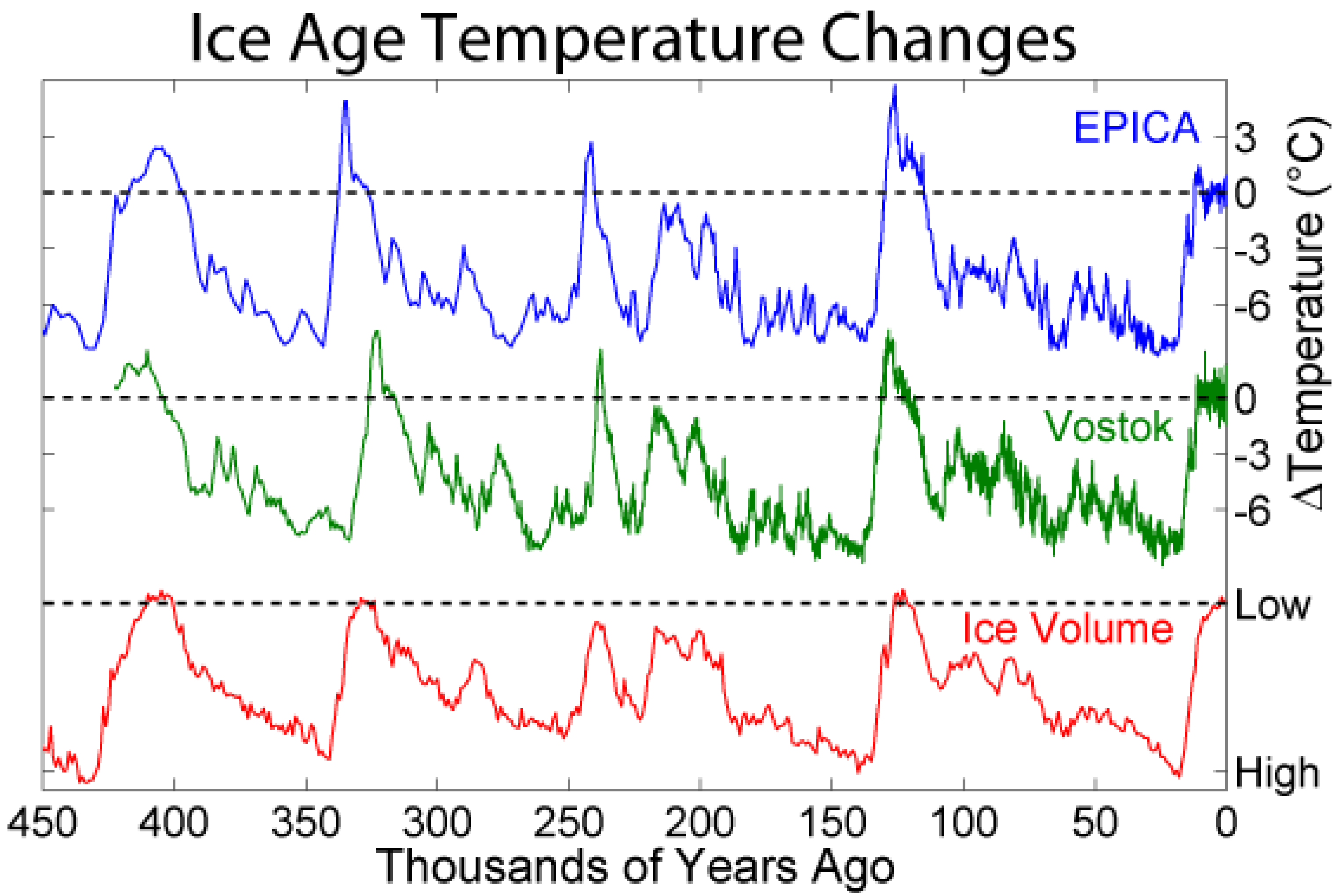


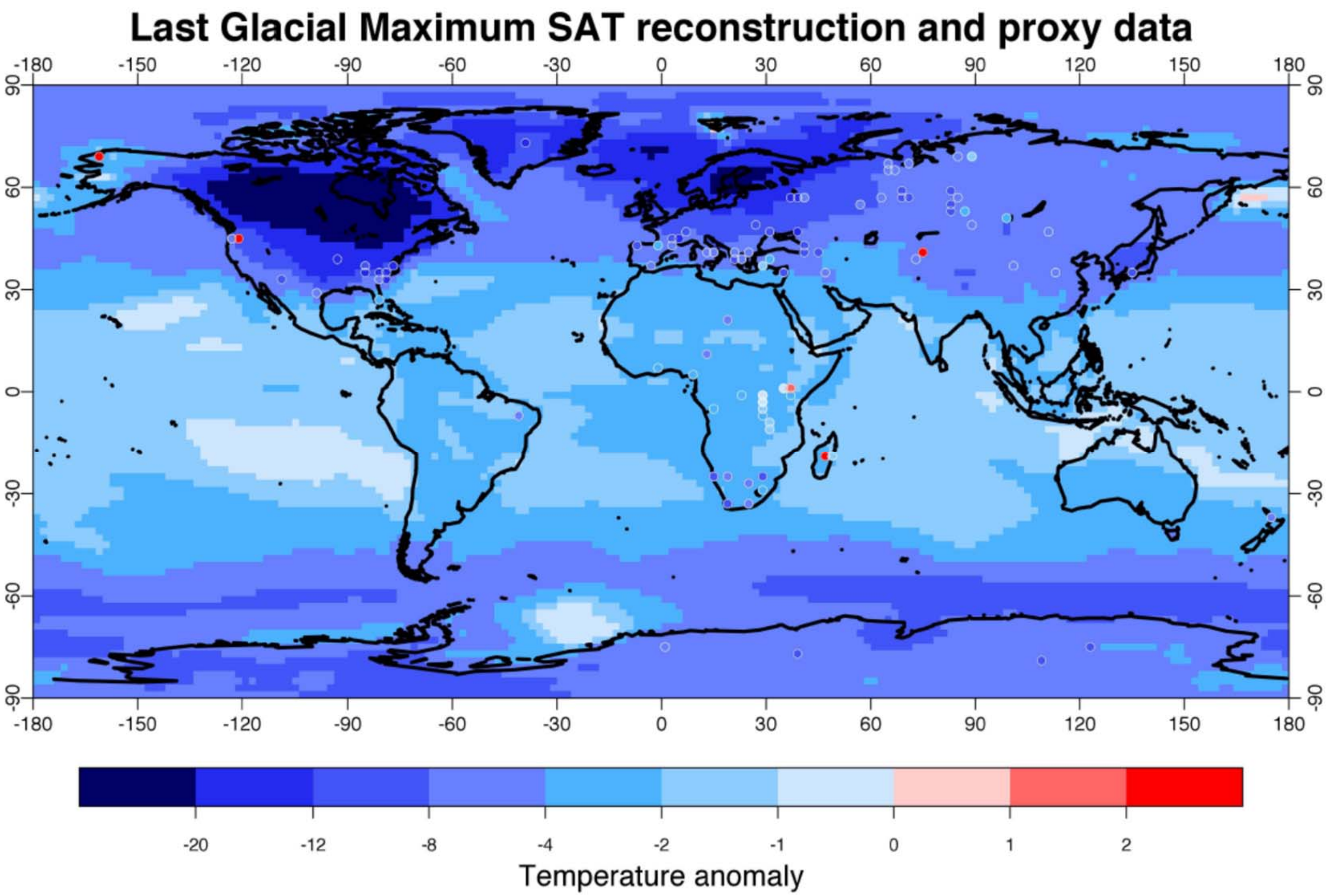
Frederick
Sound,
Alaska

Main Topics:

- Climate science is among the more fascinating topics in earth sciences
- Earth's climate is stable within certain limits, but sensitive to change in forcing within those limits. The Arctic is particularly sensitive
- Climate science has a long and illustrious history
- The idea that we are altering climate is based on simple physics, simple models, and complex models
- Human activities can and do have a strong effect on climate
- We are beginning to quantify some climate-related risks
- Where there is risk there is also opportunity

Last 450 Thousand Years

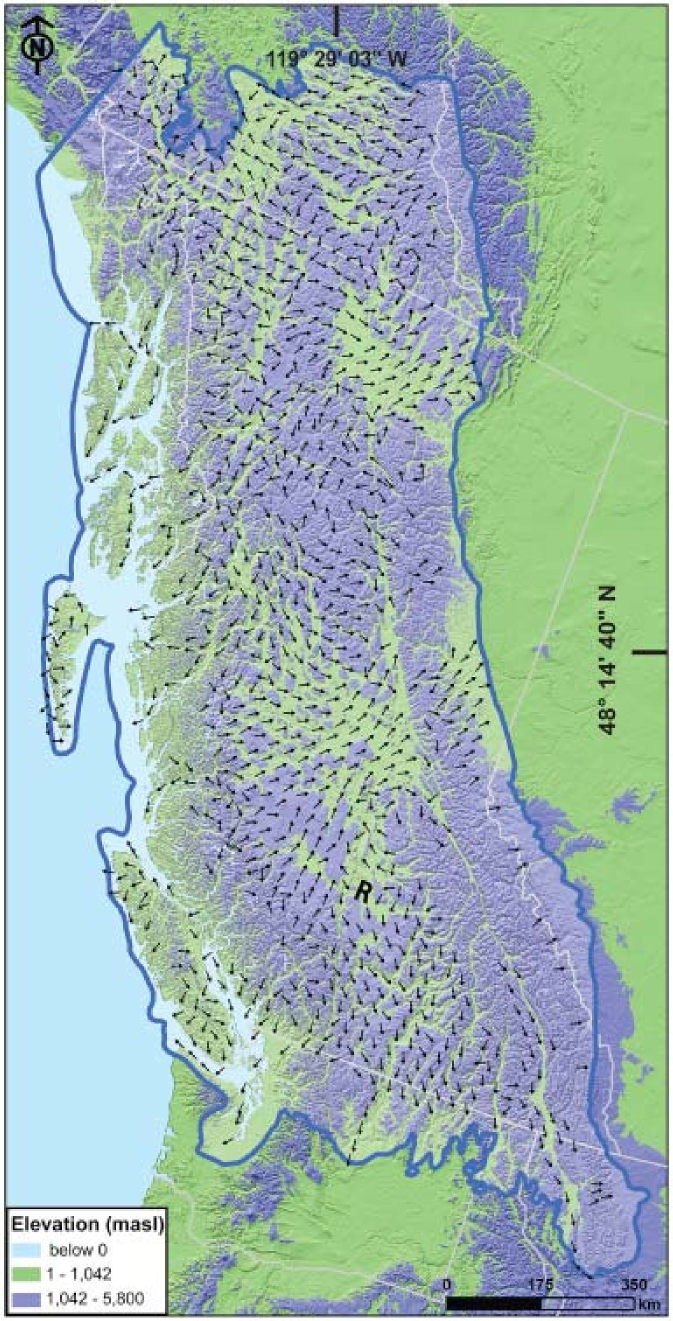




Source: Annan and Hargreaves, *Clim. Past*, **9,** 367–376, 2013

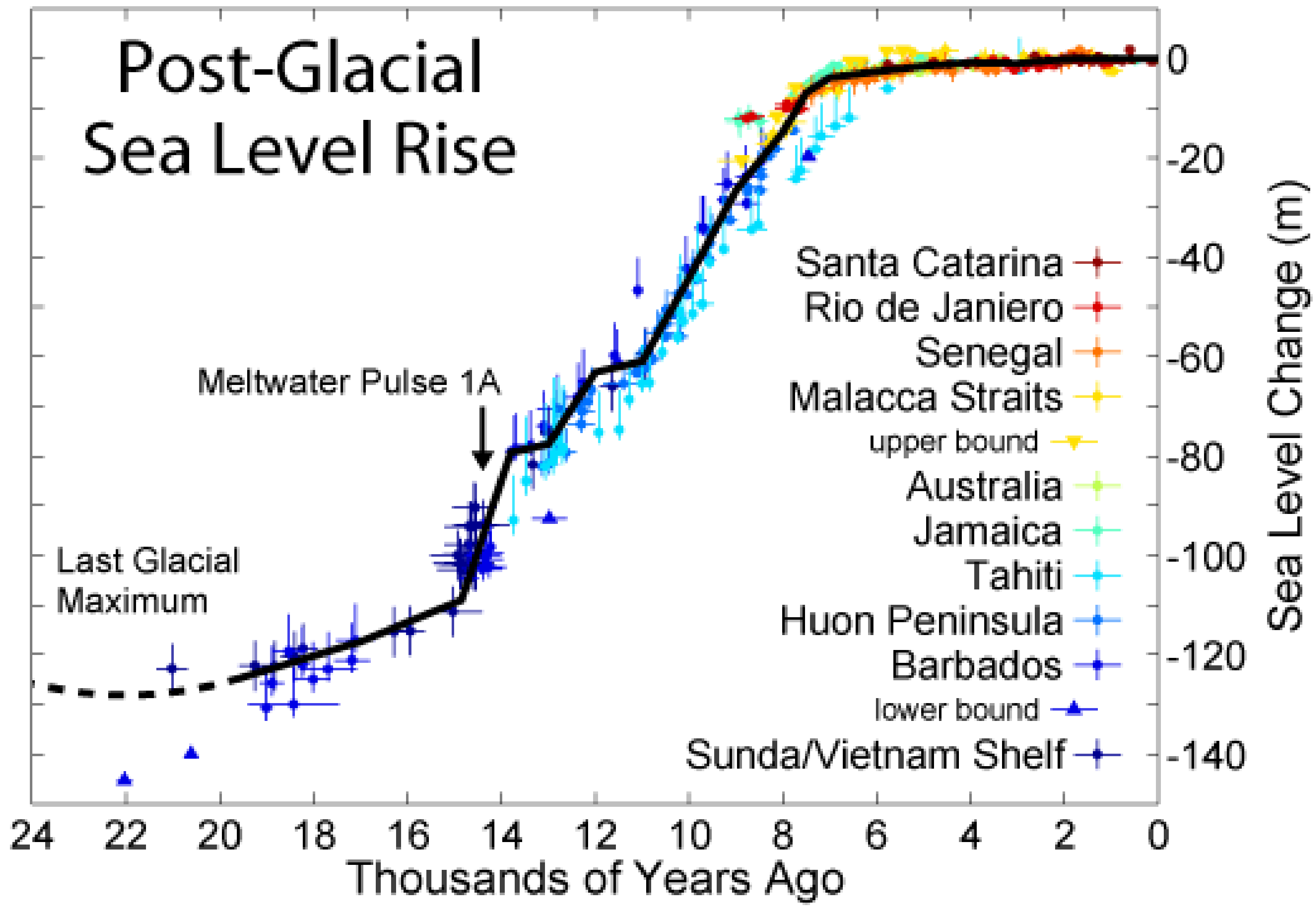
We are here

~ 20,000
years before
present



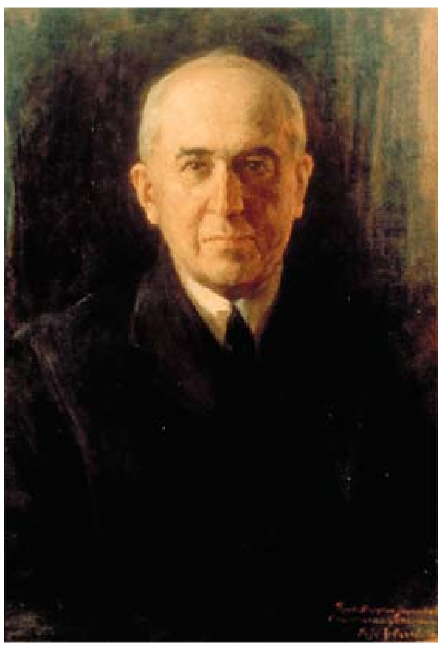
Flow directions in Cordilleran Ice Sheet, ~ 13,000 years ago

From Eyles et al, *Quaternary Science Reviews*, 2018

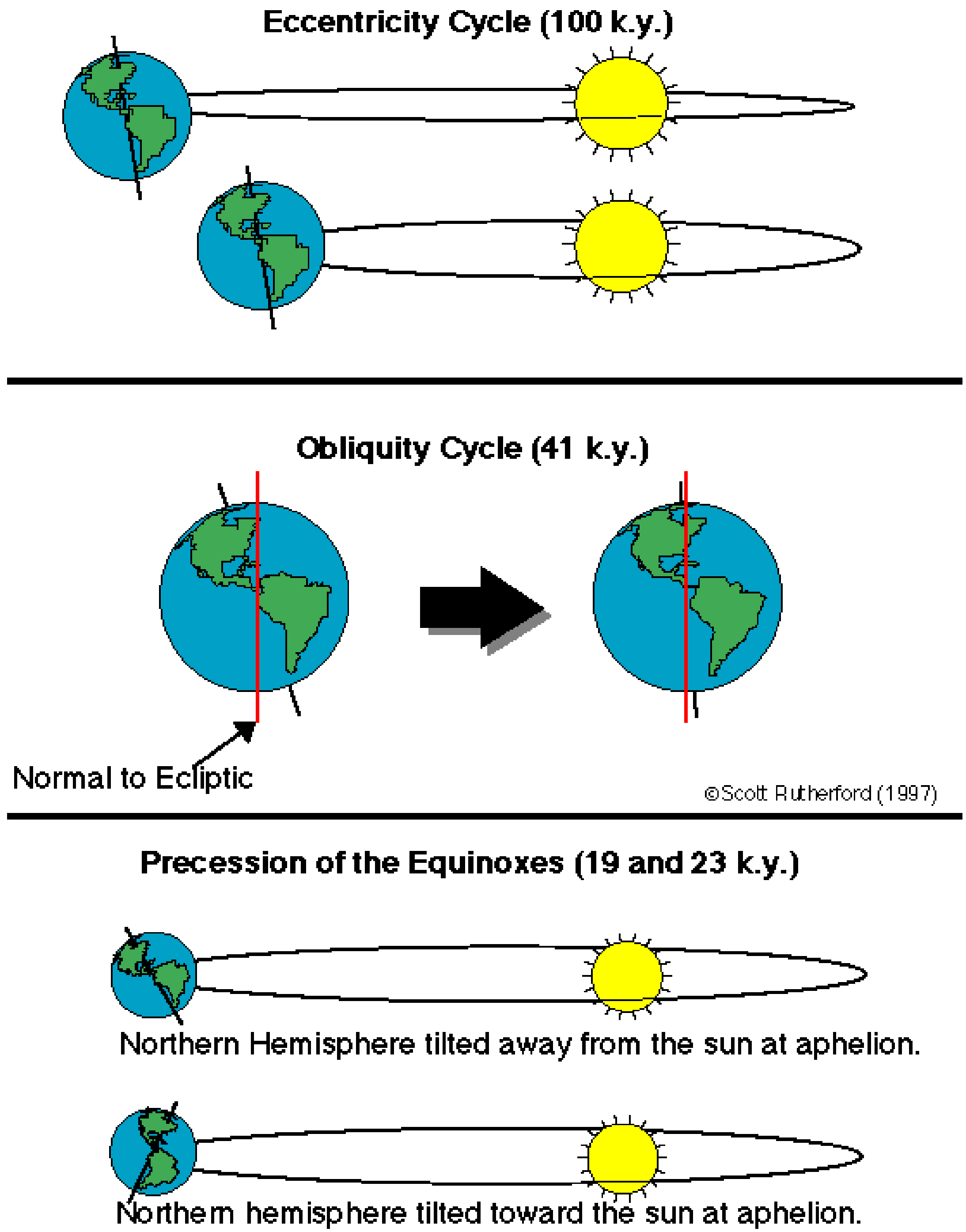


- Polar radiative forcing: 10 W/m^2 (4 W/m^2 for 2 x CO_2)
- Global mean temperature fluctuation: ~5 C

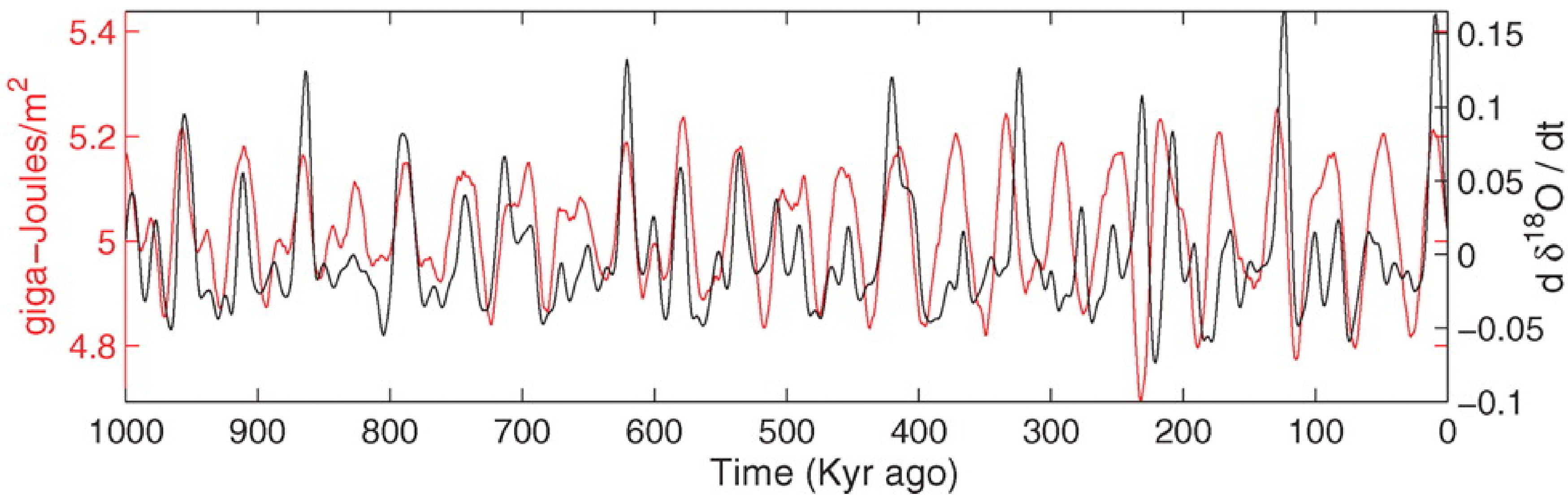
Climate Forcing by Orbital Variations (1912)



Milutin Milanković, 1879-1958



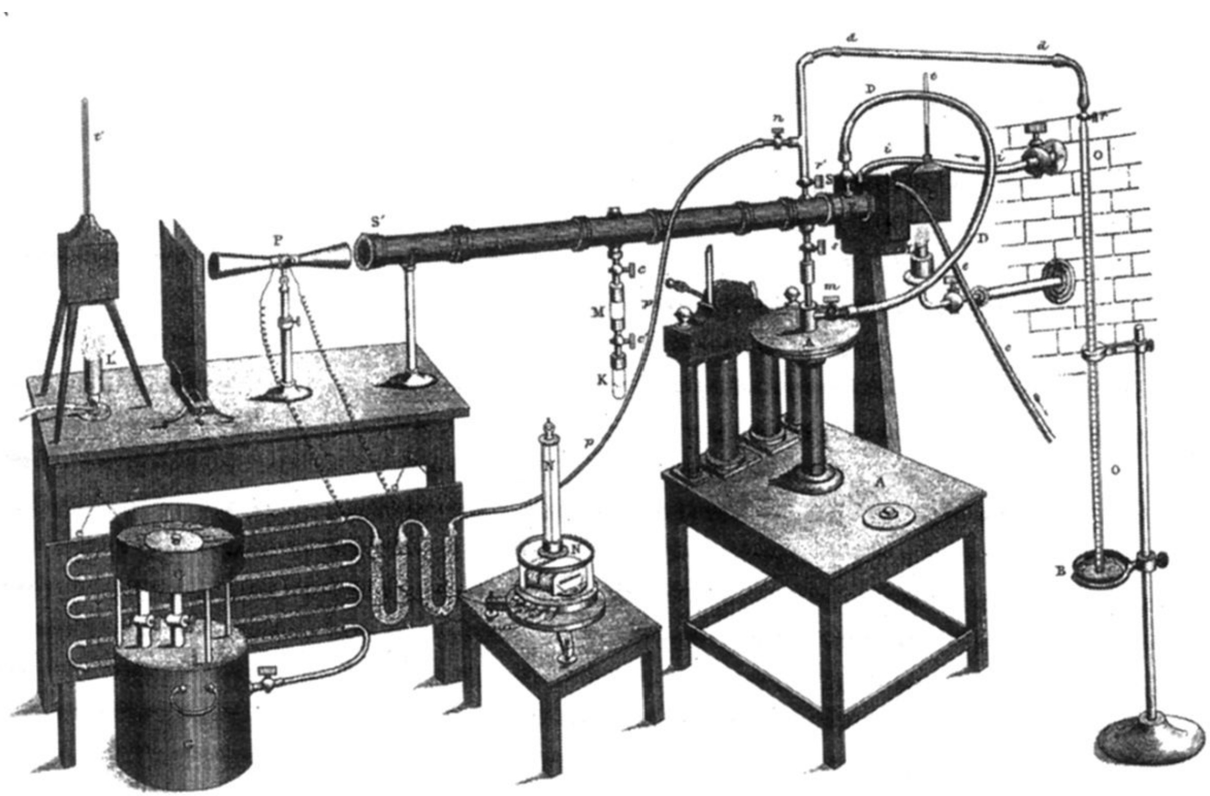
Strong Correlation between High Latitude Summer Insolation and Ice Volume



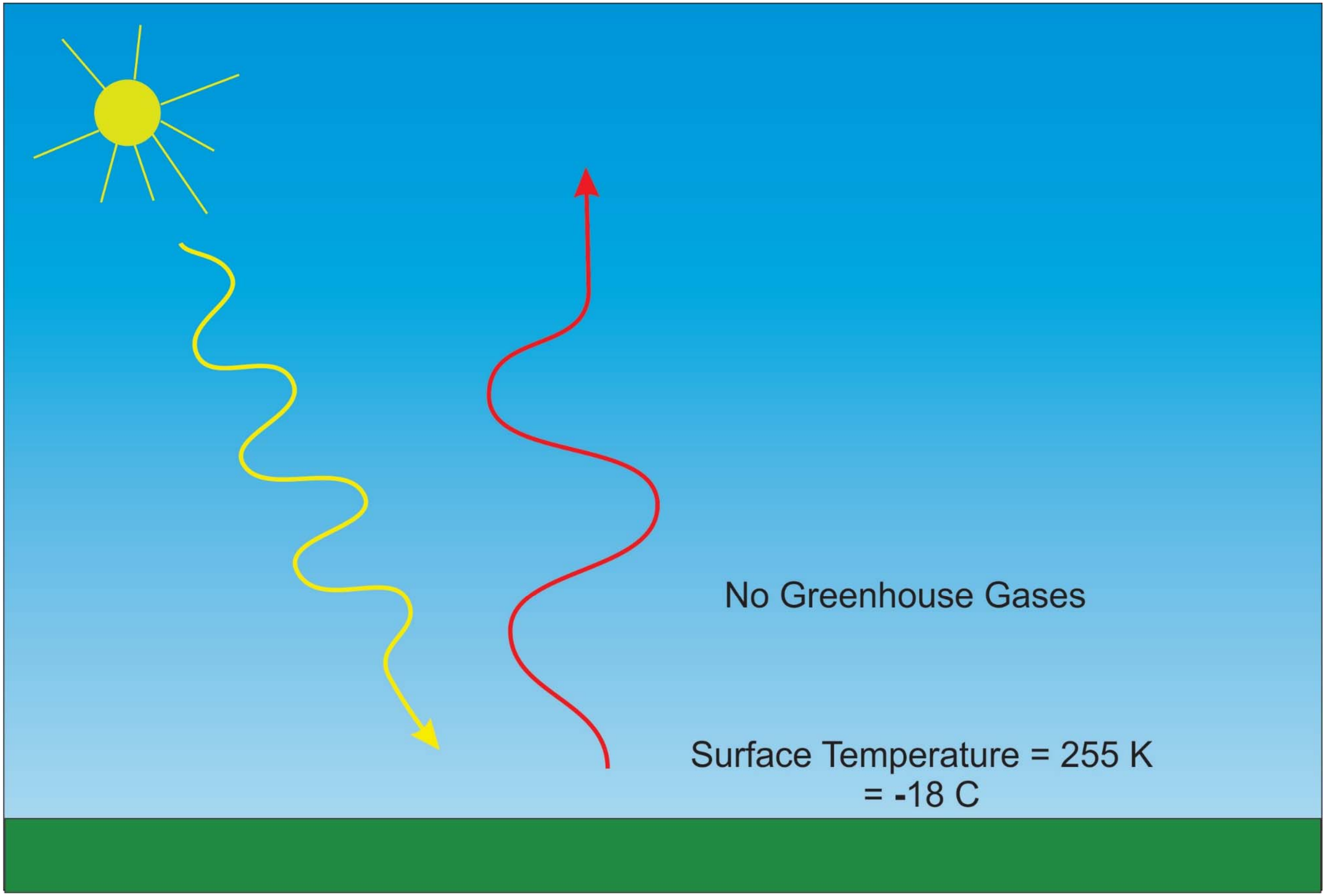
Black: Time rate of change of ice volume

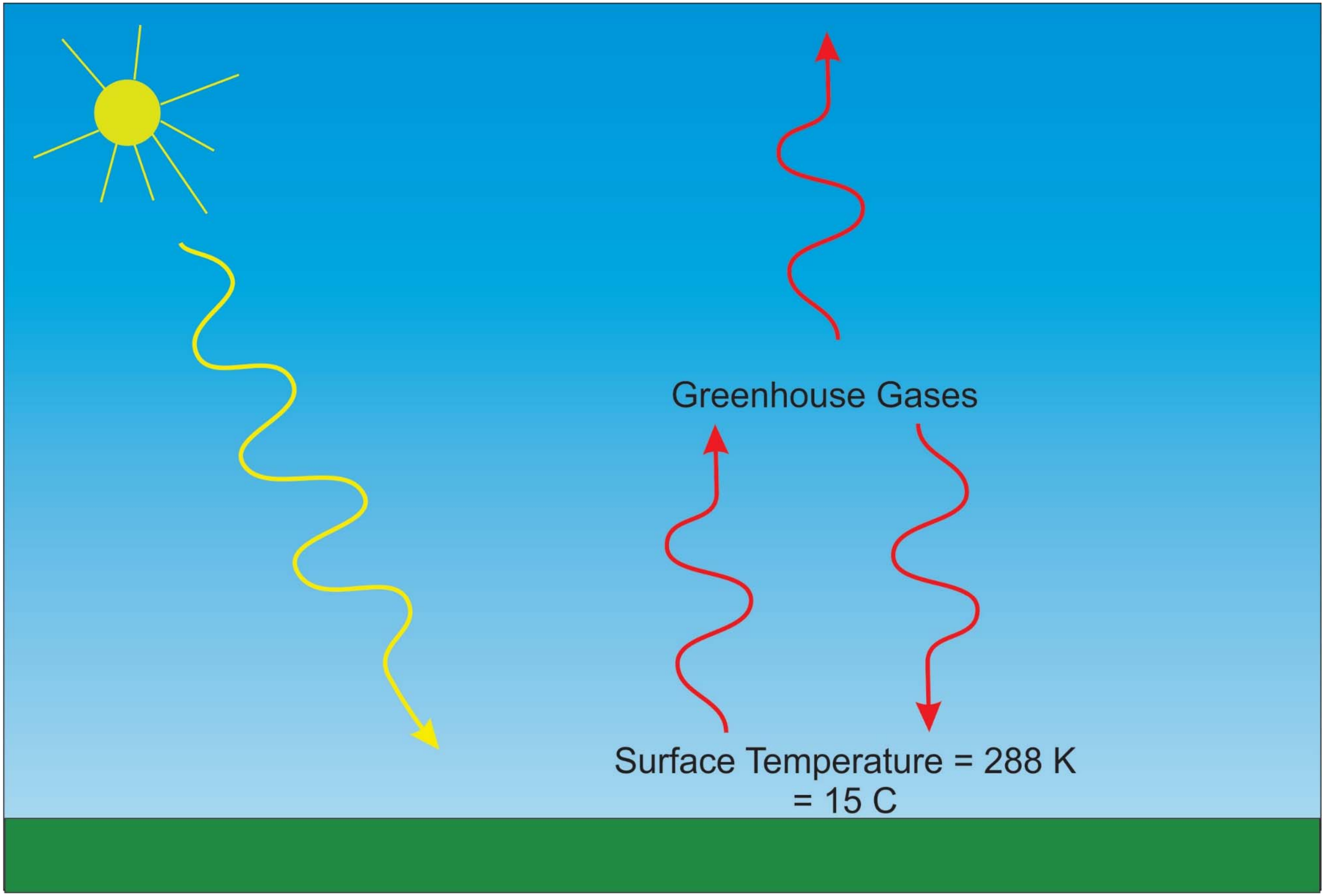
Red: Summer high latitude sunlight

P. Huybers, *Science*, 2006



John Tyndall
(1820-1893)


No Greenhouse Gases
Surface Temperature = 255 K
= -18 C

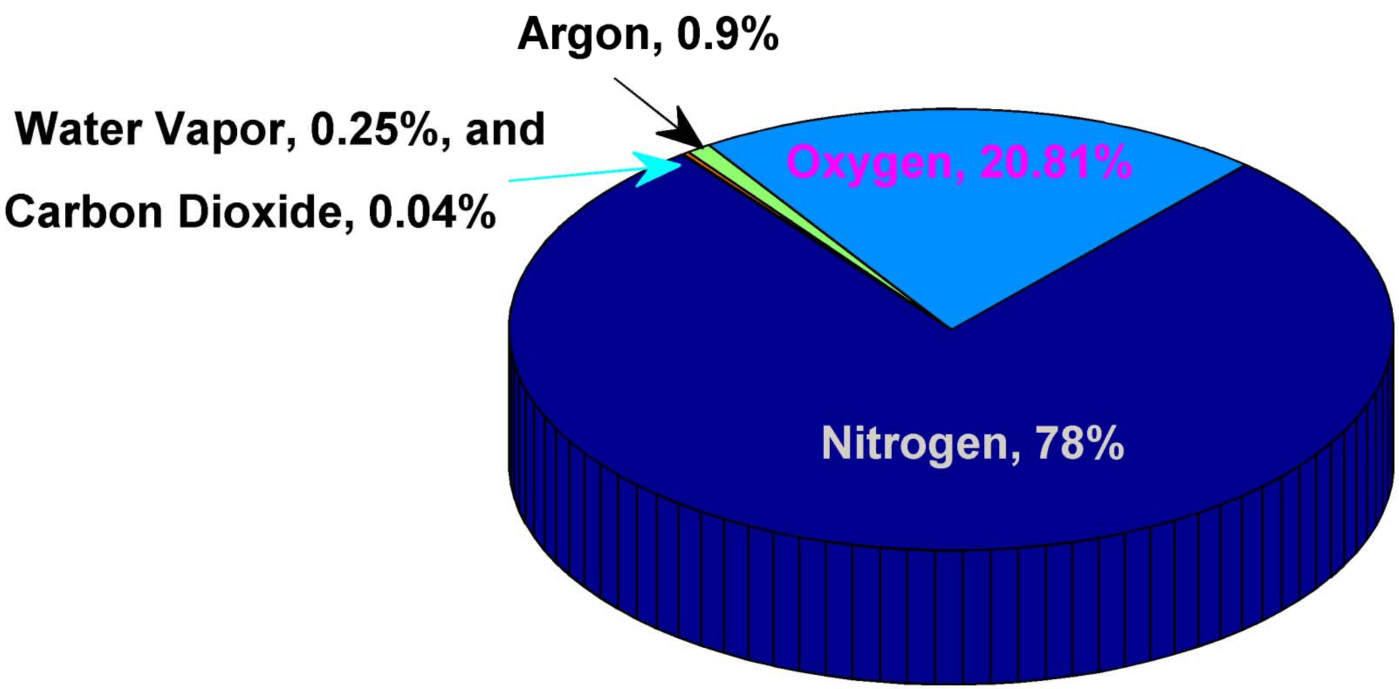

Greenhouse Gases
Surface Temperature = 288 K
= 15 C

Tyndall's Essential Results:

- **Oxygen (O_2), nitrogen (N_2), and argon (Ar), though they make up ~99% of the atmosphere, are almost entirely transparent to solar and terrestrial radiation**

- **Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), and a handful of other trace gases make the lower atmosphere nearly opaque to infrared radiation, though still largely transparent to solar radiation (but clouds have strong effects on radiation at all wavelengths). Together they increase the Earth's surface temperature from about 0^{o}F to around 60^{o}F.**

Atmospheric Composition



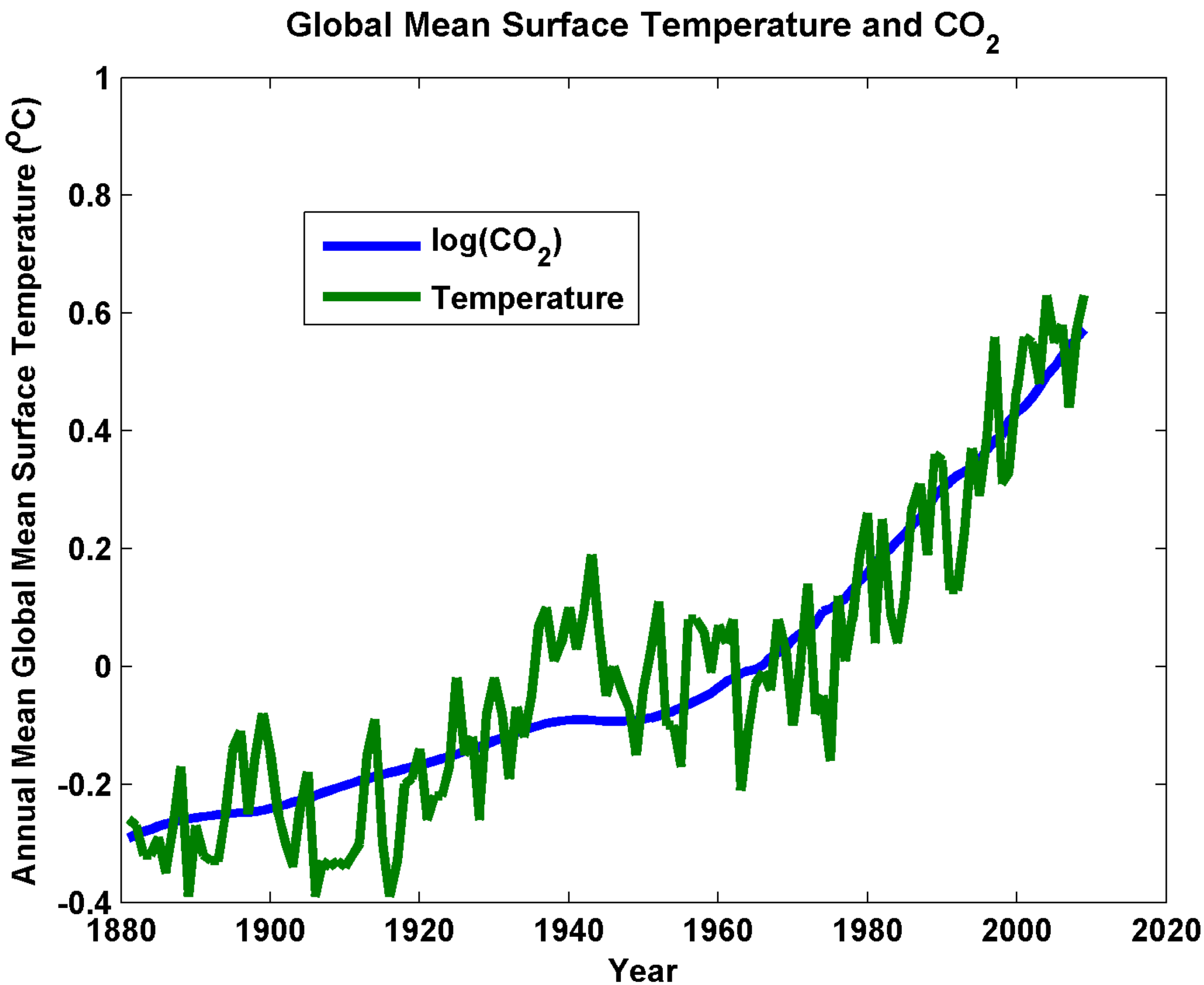
The orange sliver makes the difference between a mean surface temperature of 0°F and of 60°F.

- **Water Vapor (H_2O), about 0.25% of the mass of the atmosphere, is the most important greenhouse gas, but responds to atmospheric temperature change on a time scale of about 2 weeks**

- **Climate is therefore strongly influenced by long-lived greenhouse gases (e.g. CO_2, CH_4, N_2O) that together comprise about 0.04% of the mass of the atmosphere. Concentration of CO_2 has increased by 43% since the dawn of the industrial revolution**

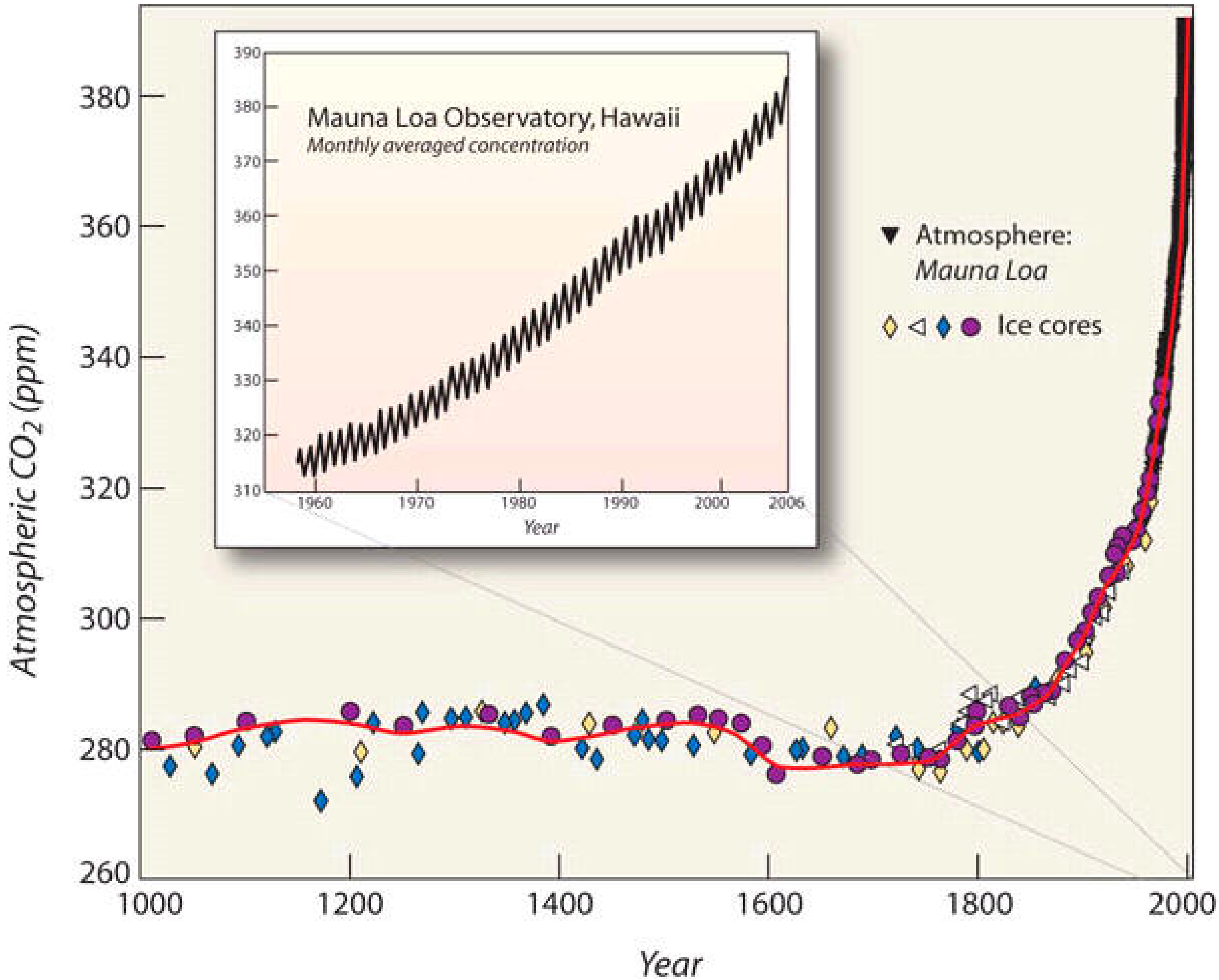
Svante Arrhenius, 1859-1927

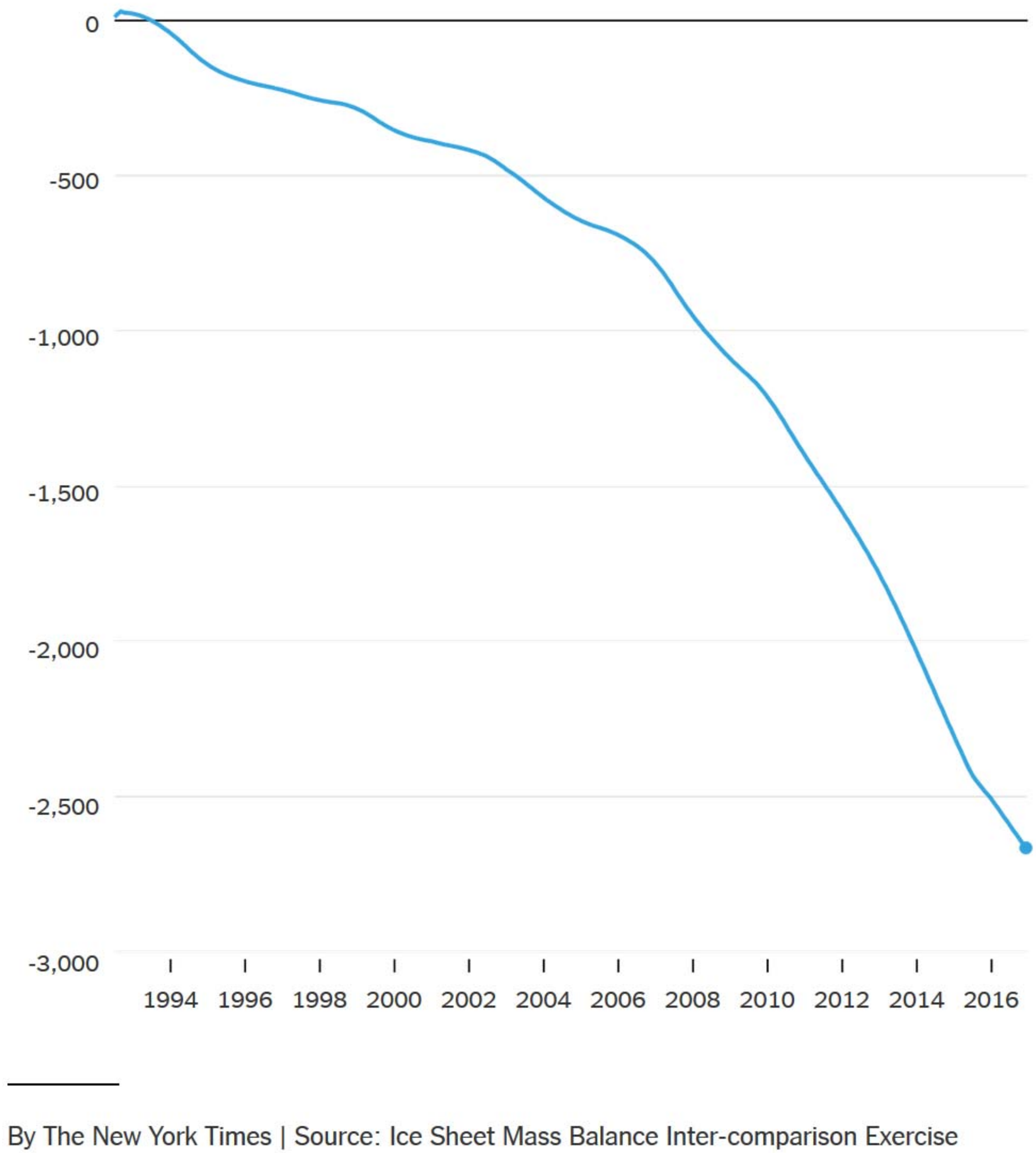
"Any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°." – *Världarnas utveckling (*Worlds in the Making), 1906



Global Mean Surface Temperature and CO_2
log(CO_2)
Temperature
Annual Mean Global Mean Surface Temperature (°C)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1880
1900
1920
1940
1960
1980
2000
2020
Year

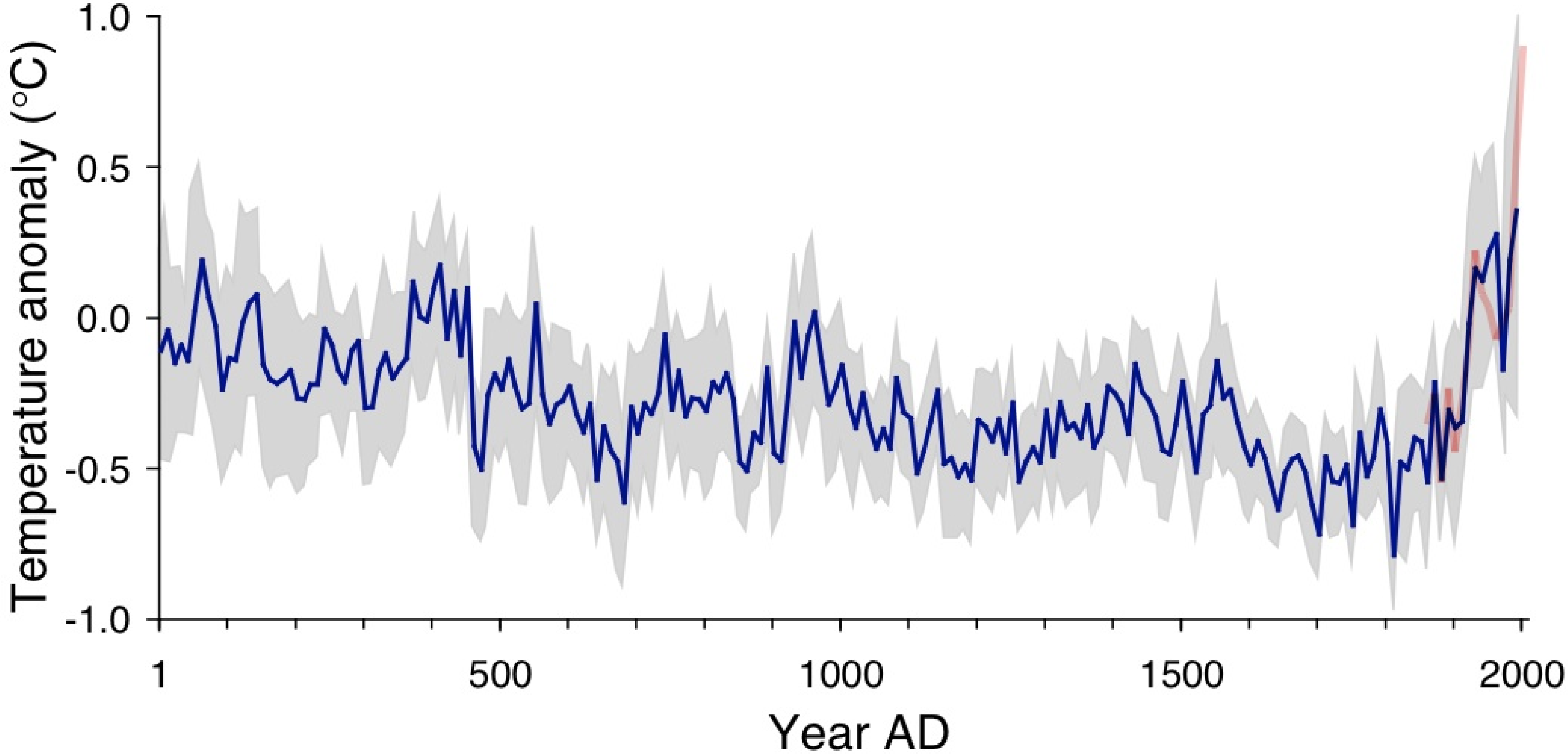
Atmospheric CO_2 Variations Since 1000 AD





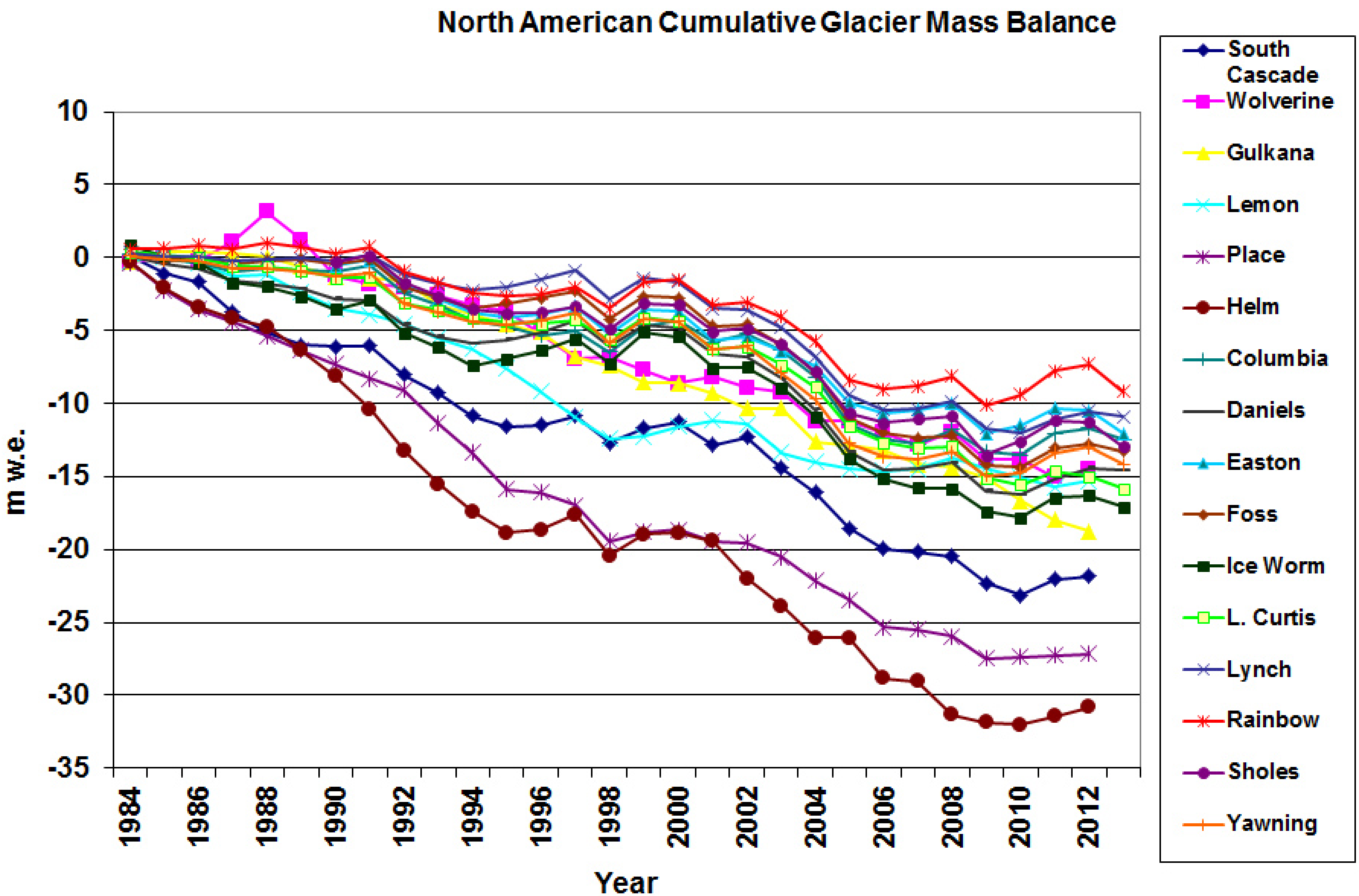
Cumulative change in Antarctic mass since 1992 (gigatons)

Arctic air temperature change reconstructed (blue), observed (red)



The long-term cooling trend in the Arctic was reversed during recent decades. The blue line shows the estimated Arctic average summer temperature over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings. The shaded area represents variability among the 23 sites use for the reconstruction. The red line shows the recent warming based on instrumental temperatures. From Kaufman et al. (2009).

Climate Change in Alaska



North American glacier mass balance.
Image courtesy of Mauri Pelto

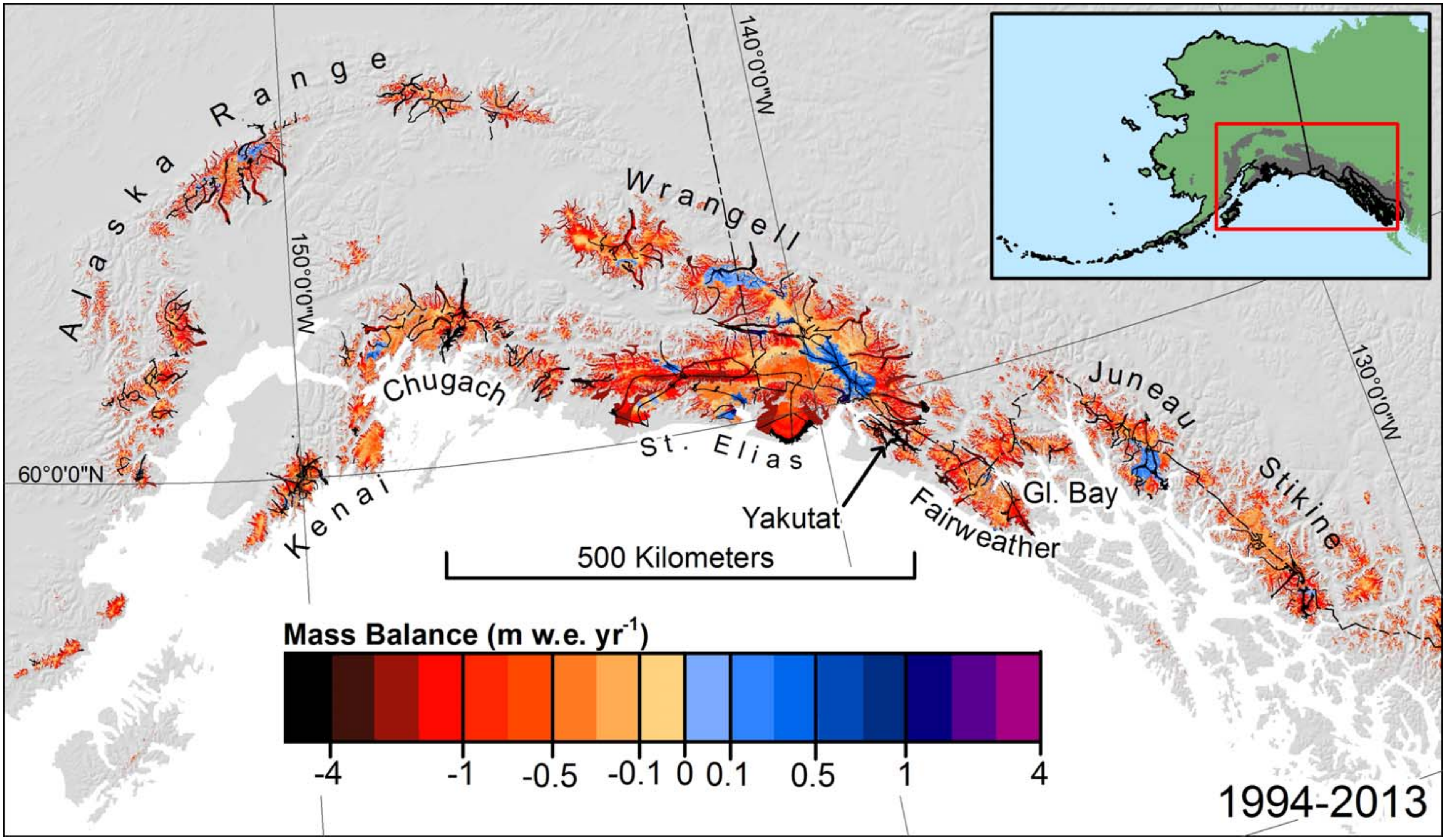
Alaska’s Columbia Glacier

2009

2015

McCarty Glacier, Alaska

1909 2004

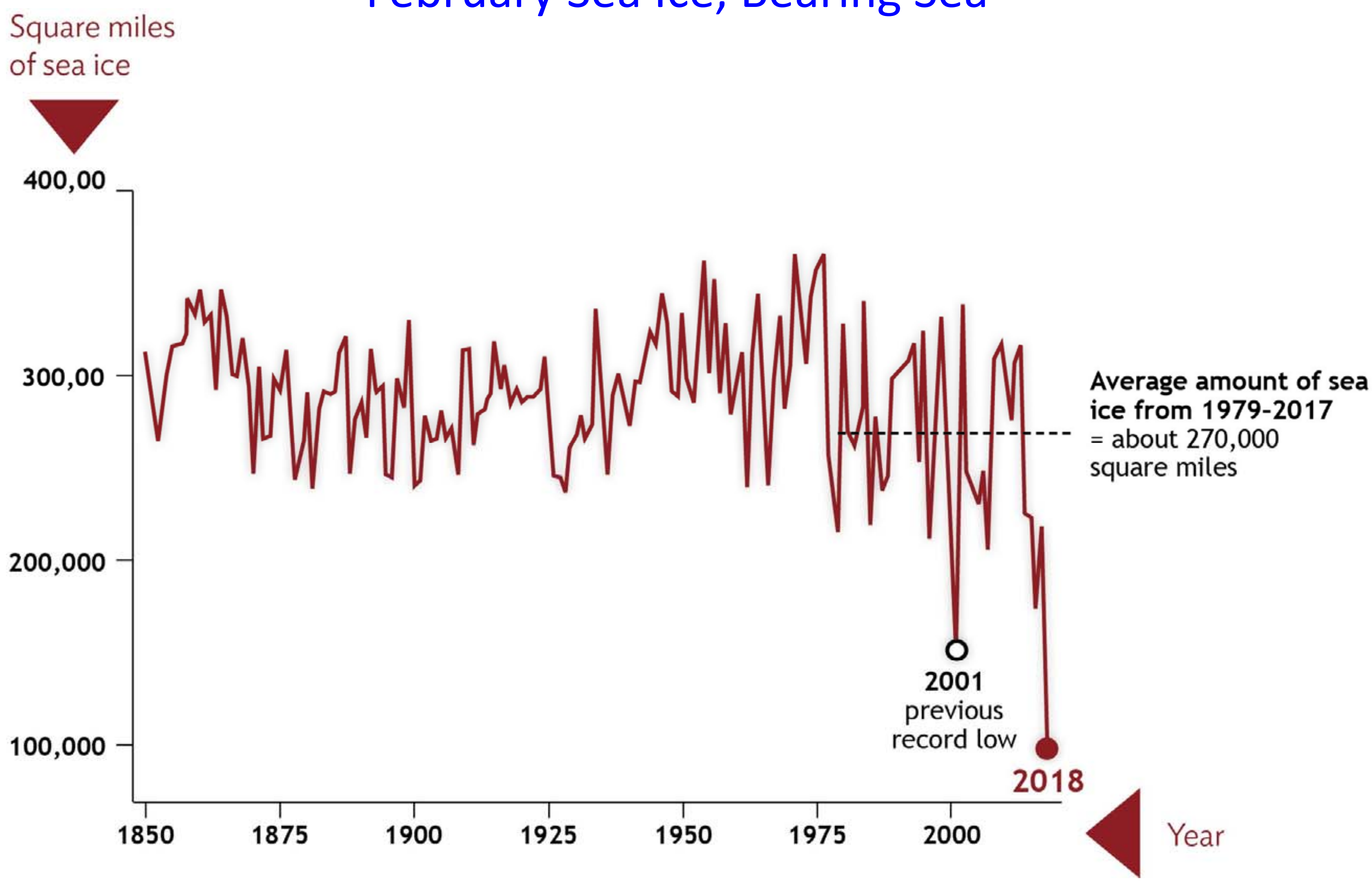


Alaska Range
Wrangell
Chugach
St. Elias
Kenai
Yakutat
Fairweather
Gl. Bay
Juneau
Stikine
140°0'0"W
150°0'0"W
130°0'0"W
60°0'0"N
500 Kilometers
Mass Balance (m w.e. yr-1)
-4
-1
-0.5
-0.1
0
0.1
0.5
1
4
1994-2013

Thawing Permafrost

A railroad in Alaska (left) and building (right), both buckled due to thawing permafrost. Image credit: (left) NASA and U.S. Geological Survey, (right) Vladimir Romanovsky, Geophysical Institute, University of Alaska Fairbanks.

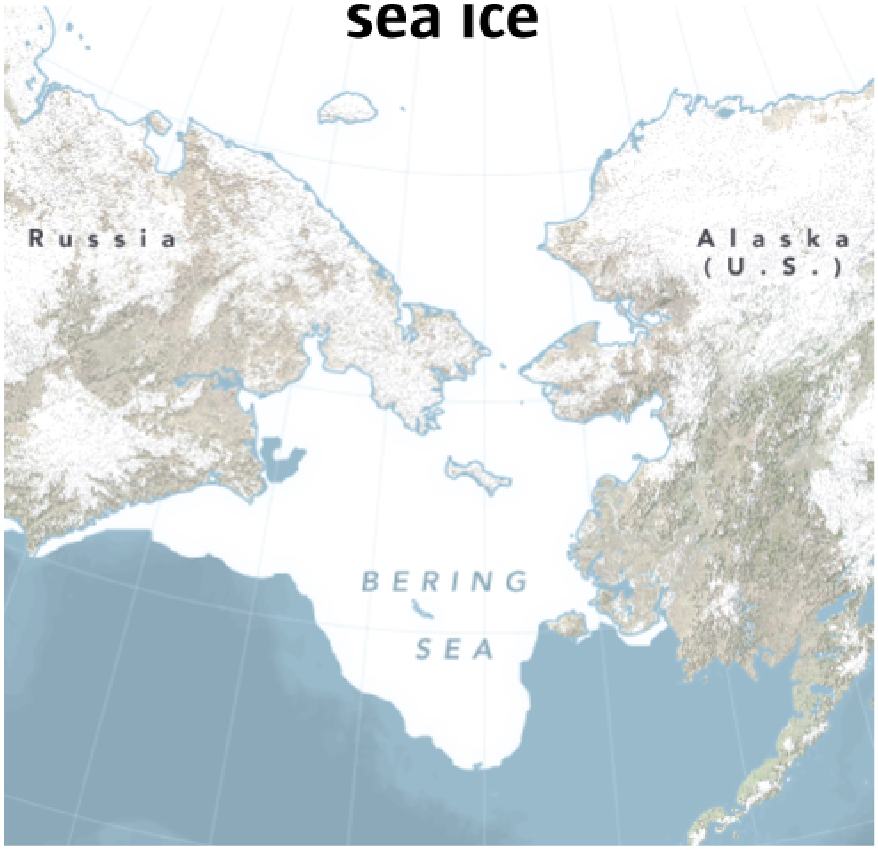
February Sea Ice, Bearing Sea



The record low February sea-ice extent in the Bering Sea, off the coast of Alaska, compared with the 168-year historic record. *Credit*: Zachary Labe, University of California-Irvine and Heather McFarland, University of Alaska

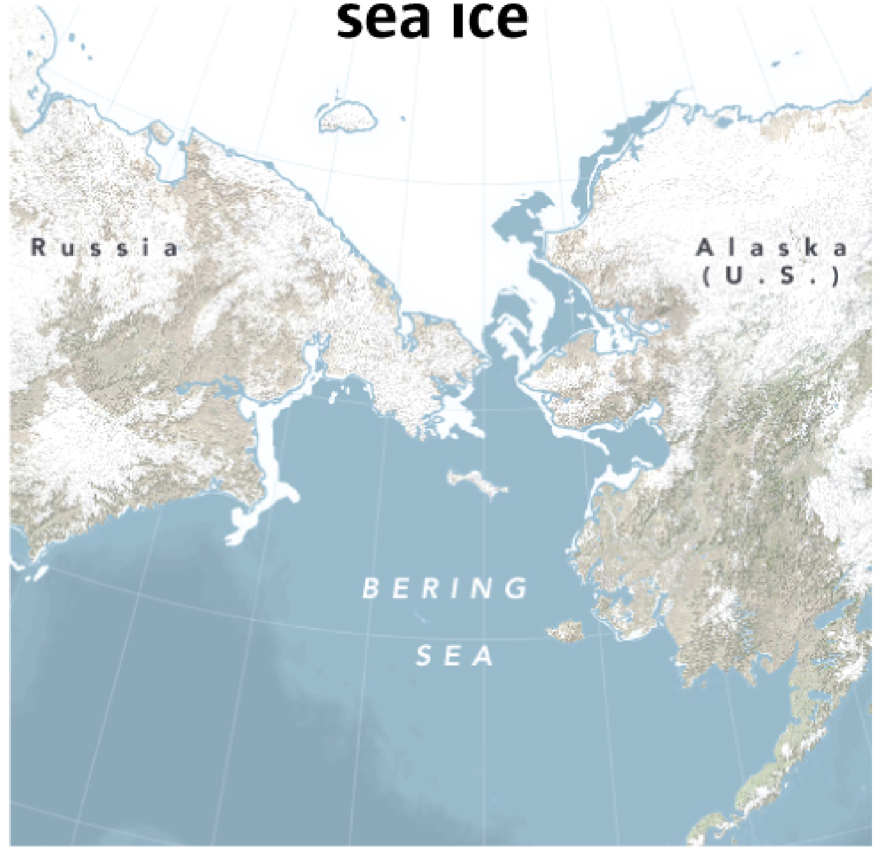
April 29, 2013

Normal sea ice



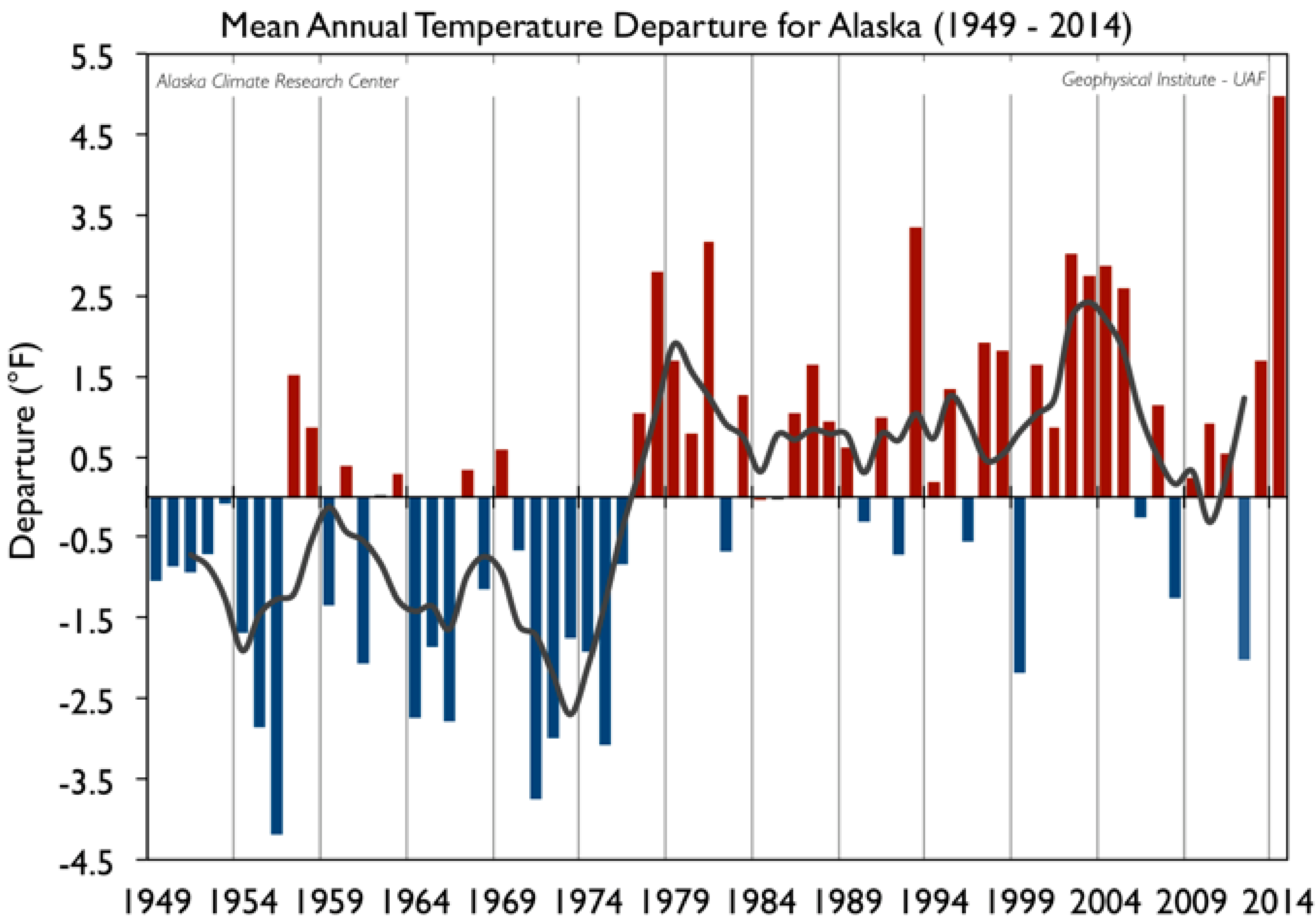
April 29, 2018

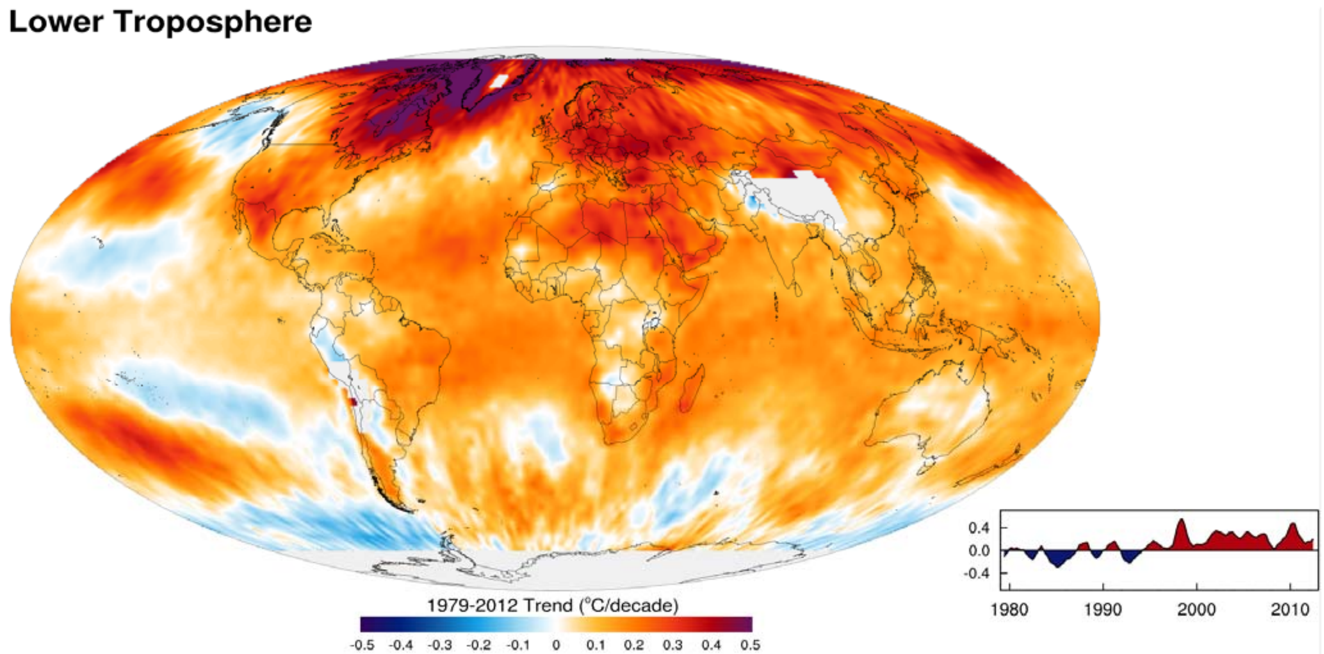
Extremely low sea ice



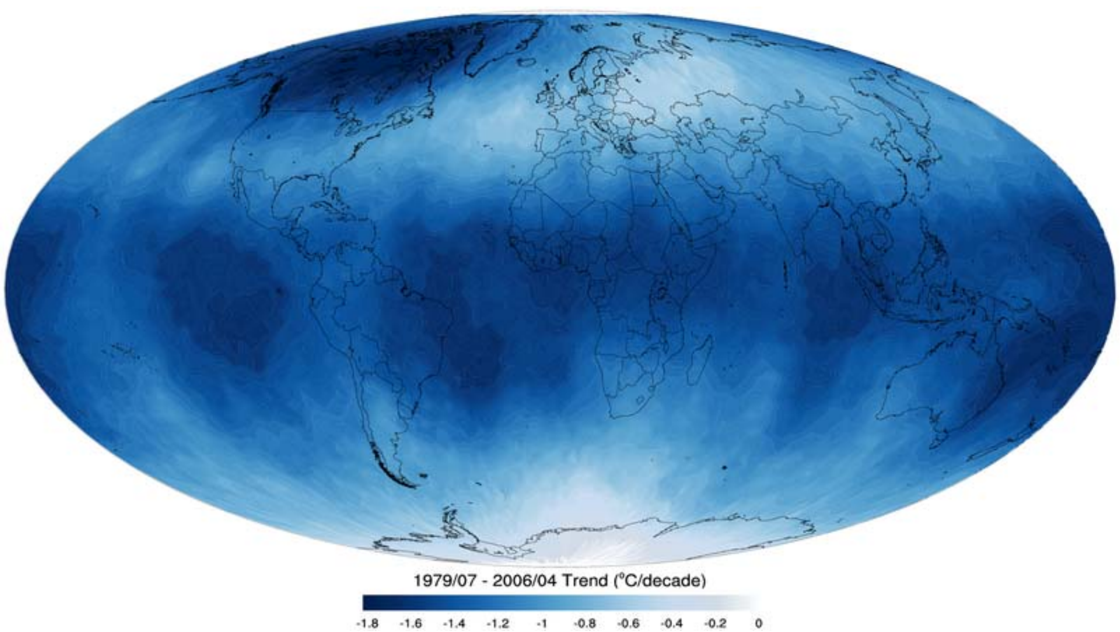
Source: NASA, earthobservatory.nasa.gov

MARK NOWLIN / THE SEATTLE TIMES

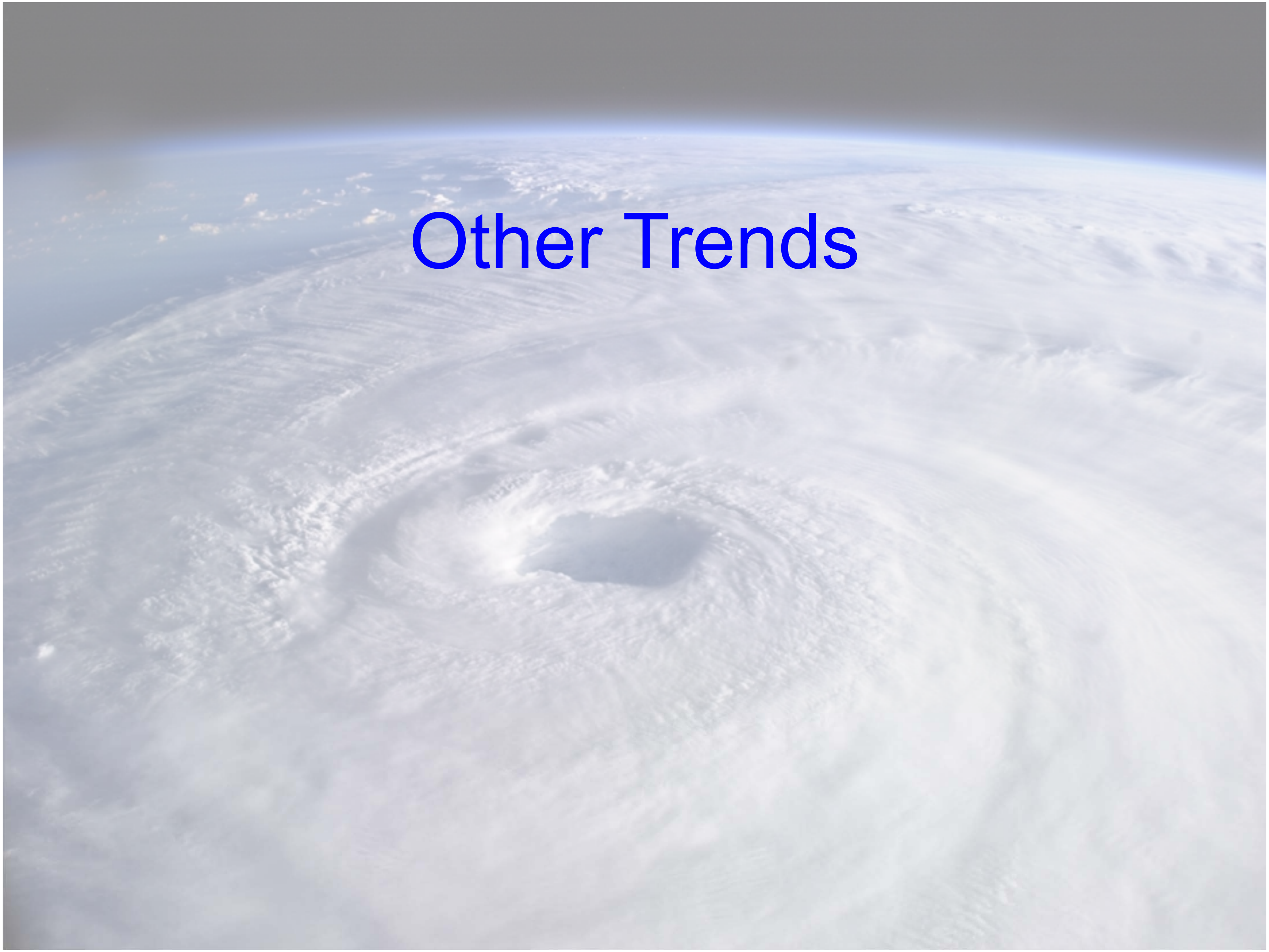

Mean Annual Temperature Departure for Alaska (1949 - 2014)
Alaska Climate Research Center
Geophysical Institute - UAF
Departure (°F)
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
-4.5
1949
1954
1959
1964
1969
1974
1979
1984
1989
1994
1999
2004
2009
2014



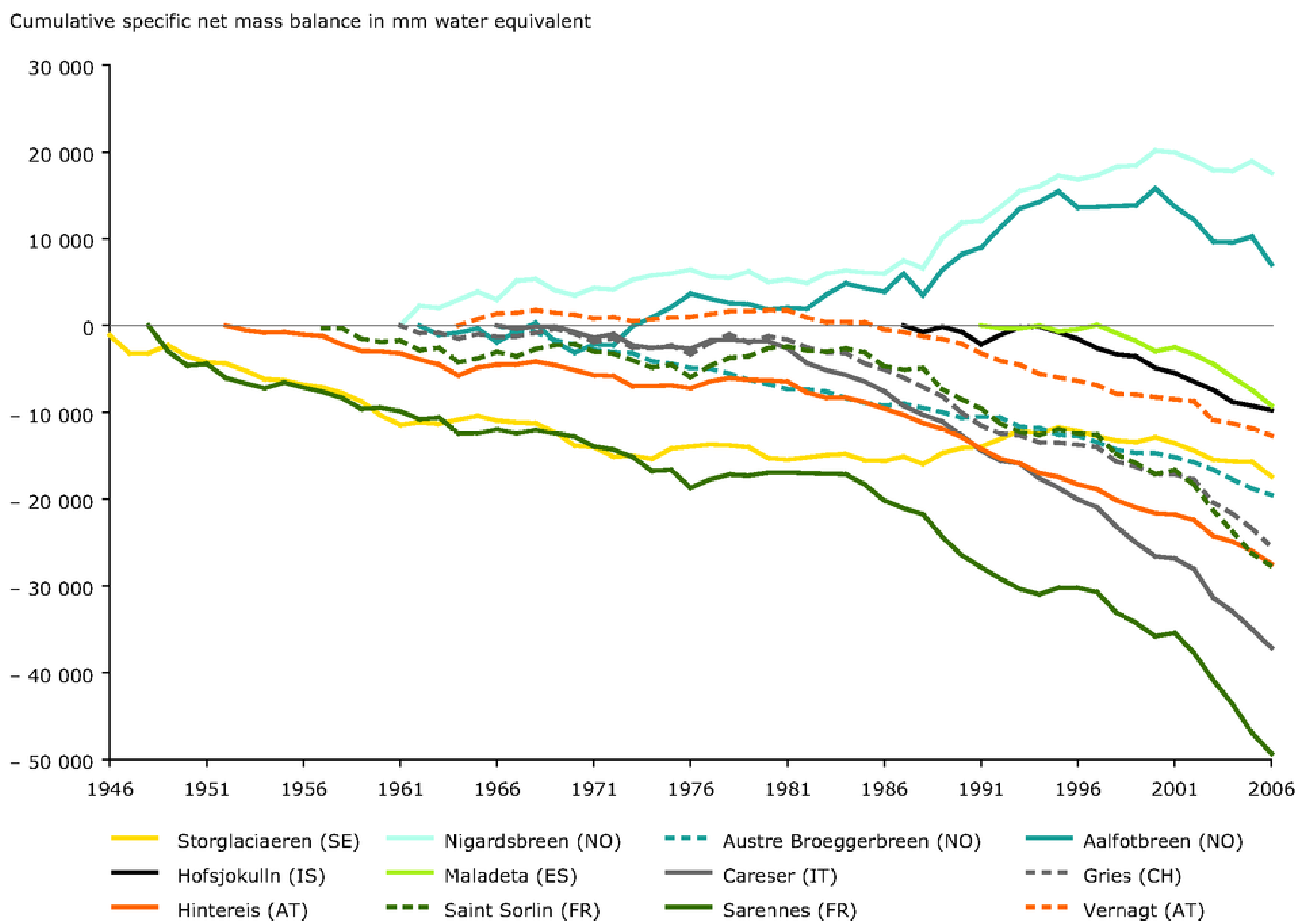
Tropospheric temperature trend from 1979-2012 based on satellite measurements (RSS)



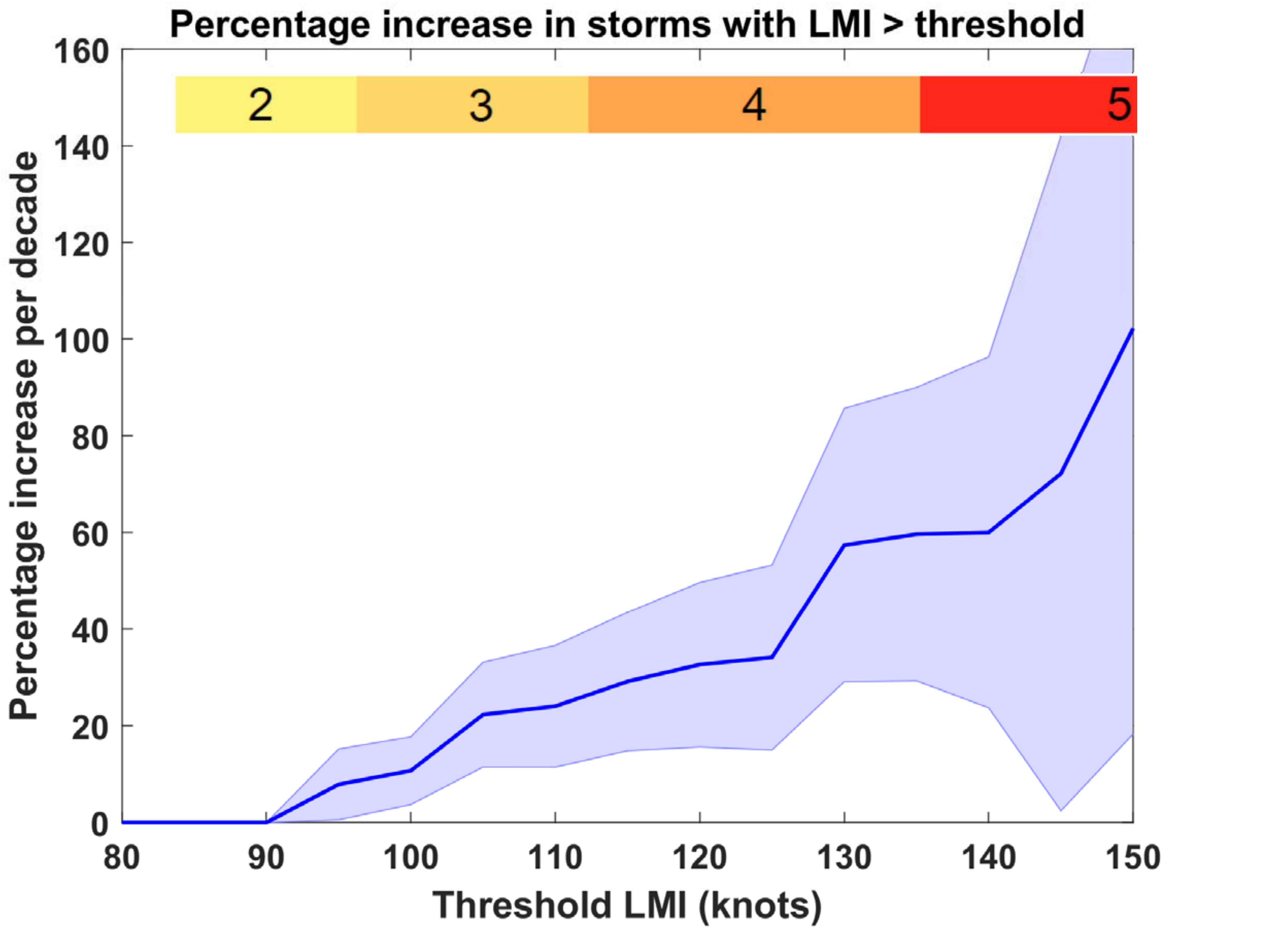
Top of the stratosphere (TTS) 1979-2006 temperature trend.

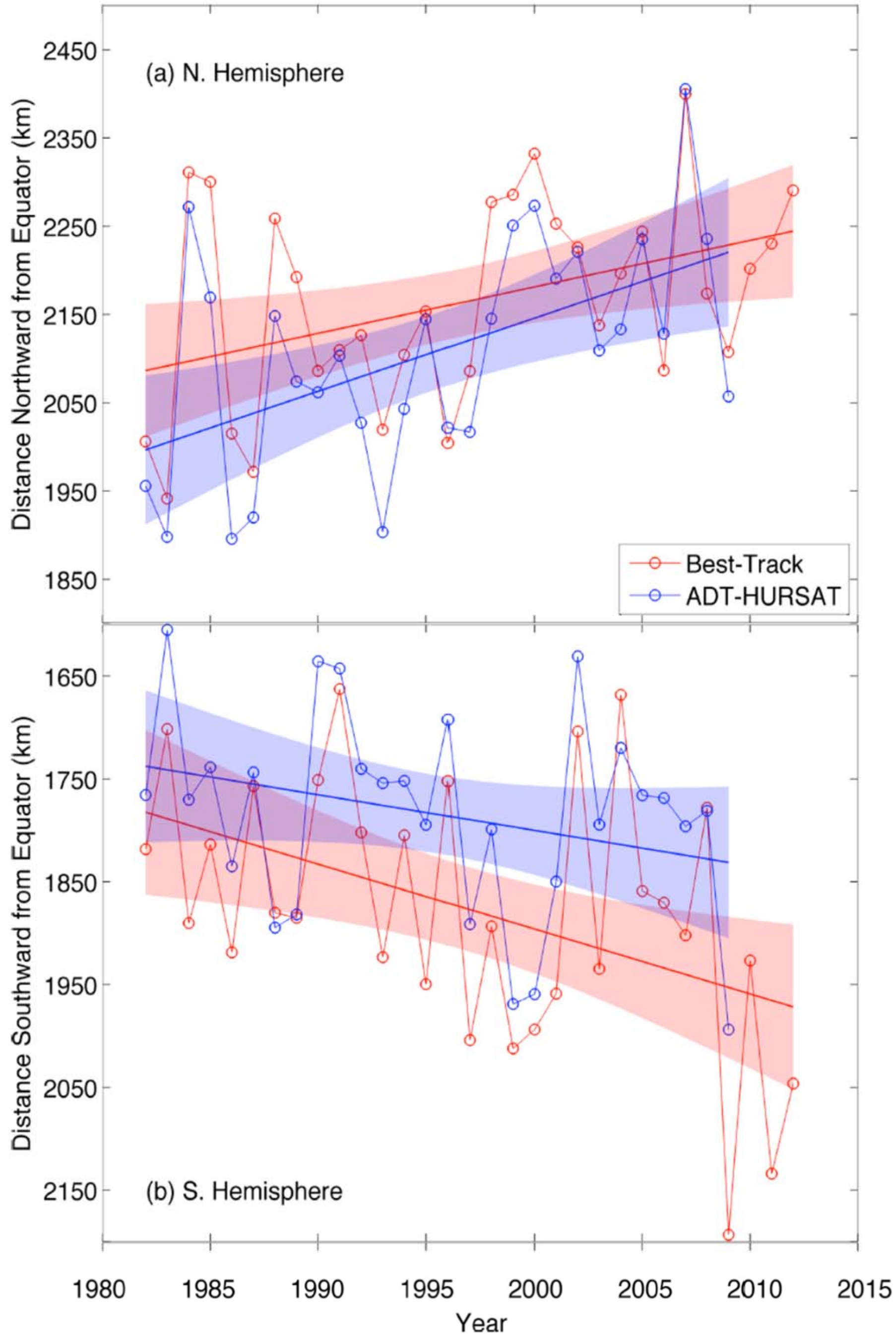

Other Trends

European Alpine Glaciers



Trends in Global Tropical Cyclone Frequency Over Threshold Intensities, from Historical TC Data, 1980-2016. Trends Shown Only When $p < 0.05$.



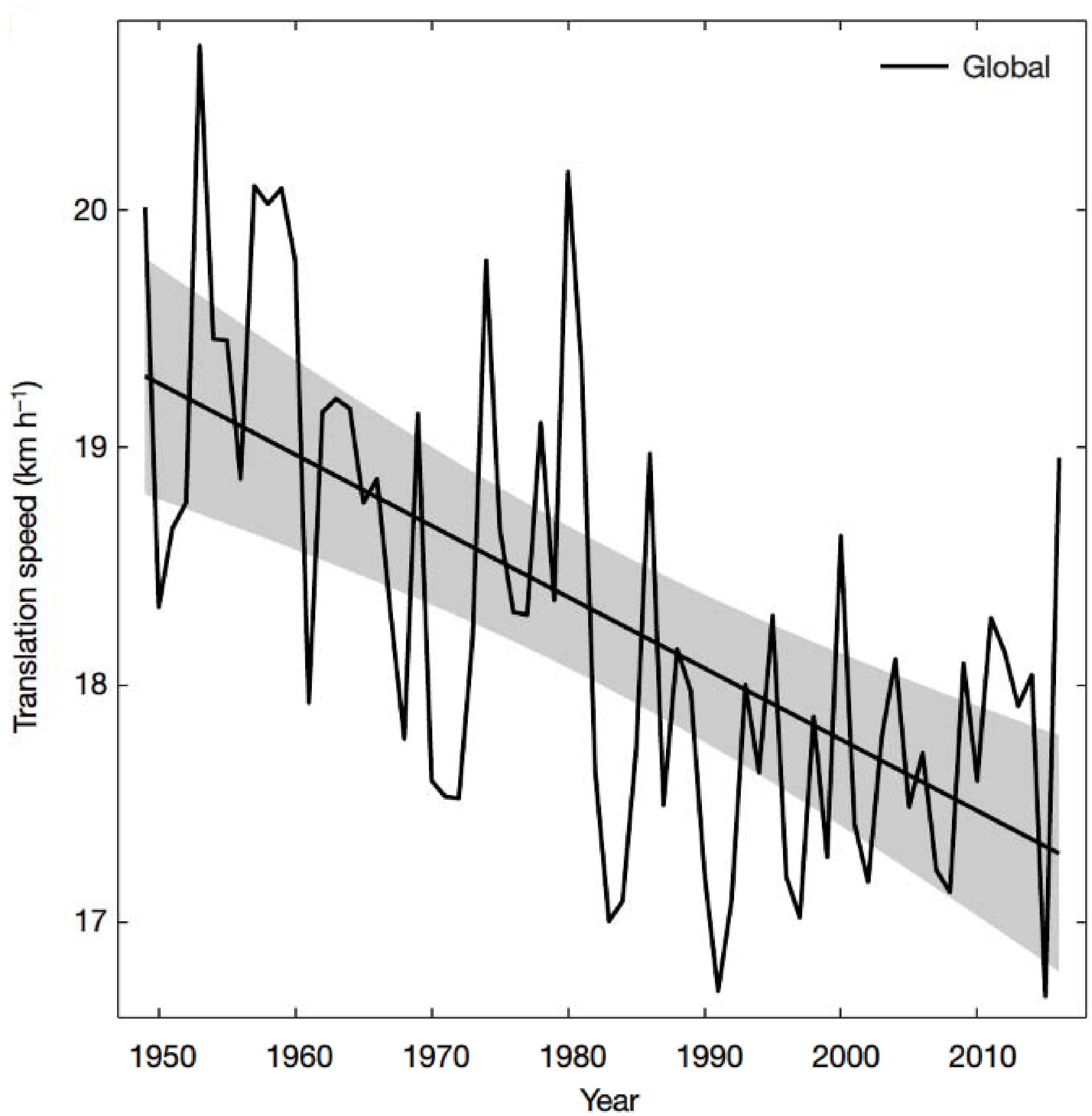


Hurricanes are reaching peak intensity at higher latitudes

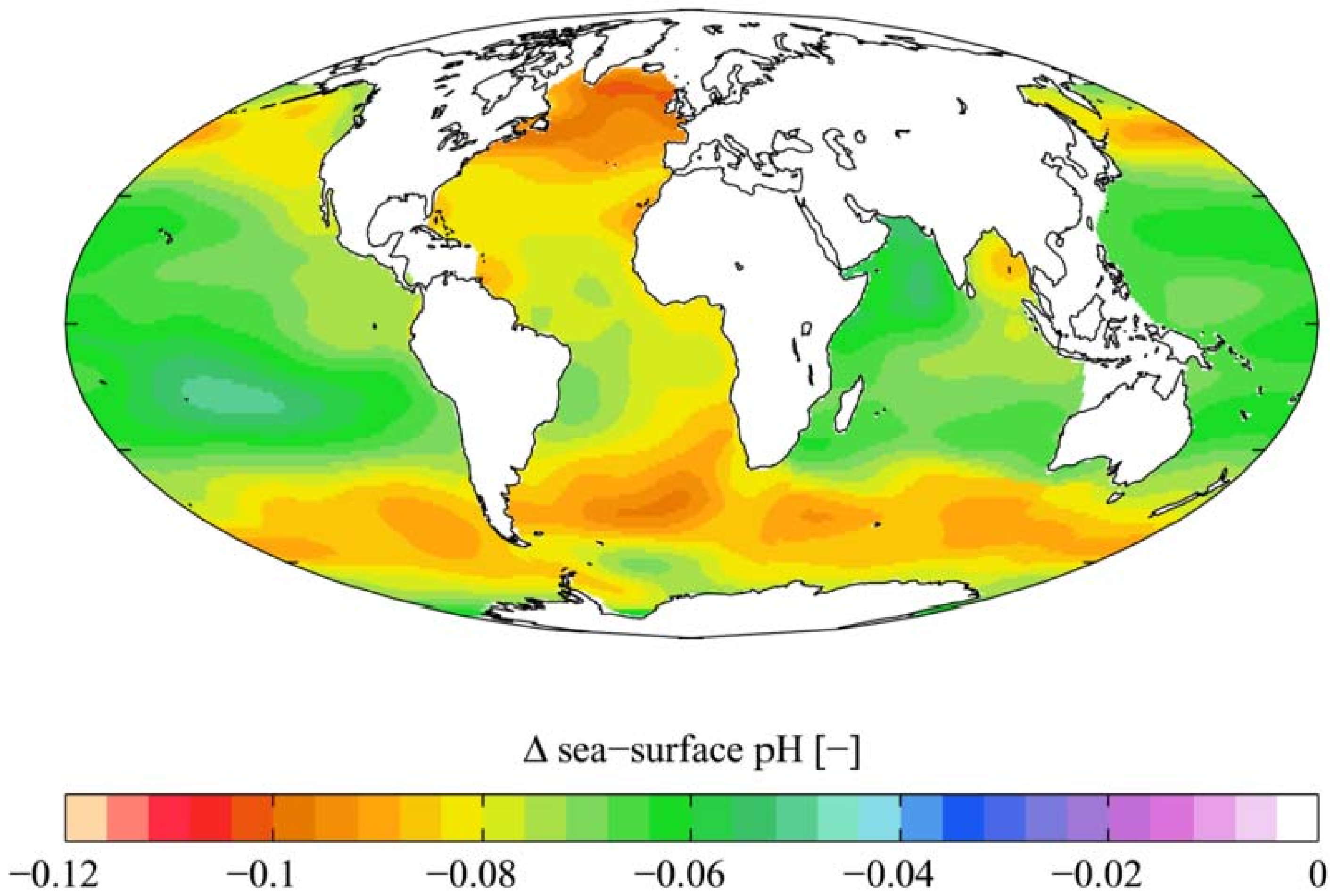
Time series of the latitudes at which tropical cyclones reach maximum intensity.

From *Kossin et al. (2014)*

Tropical Cyclones are Slowing Down (Kossin, Nature, 2018)



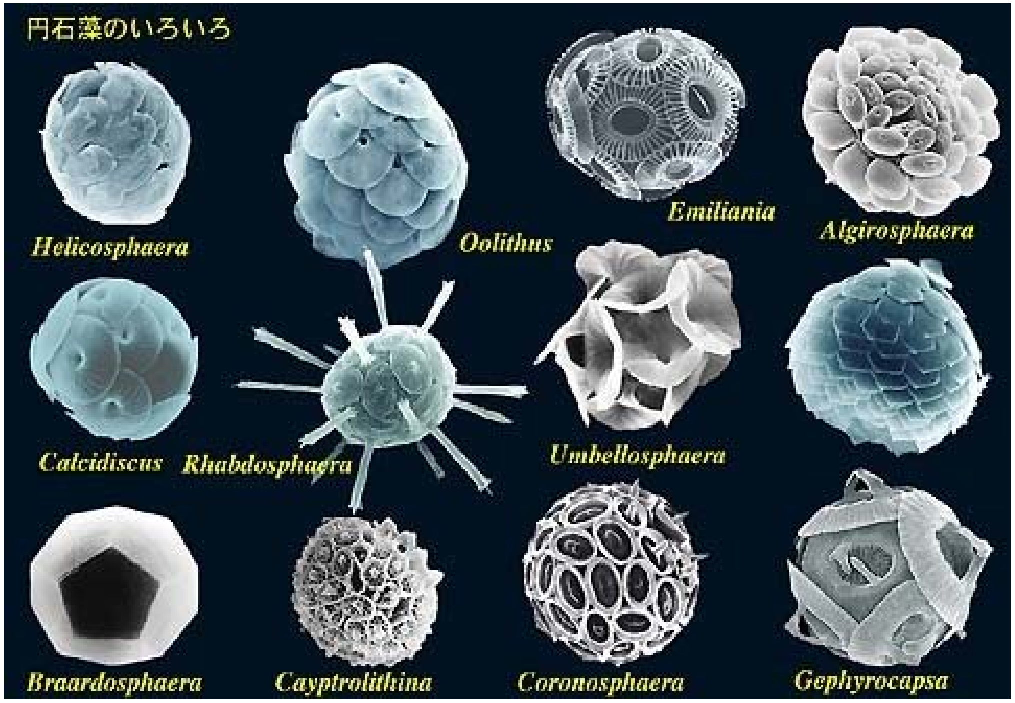
The Oceans Are Becoming More Acidic



- Acidification through CO_2 threatens marine life

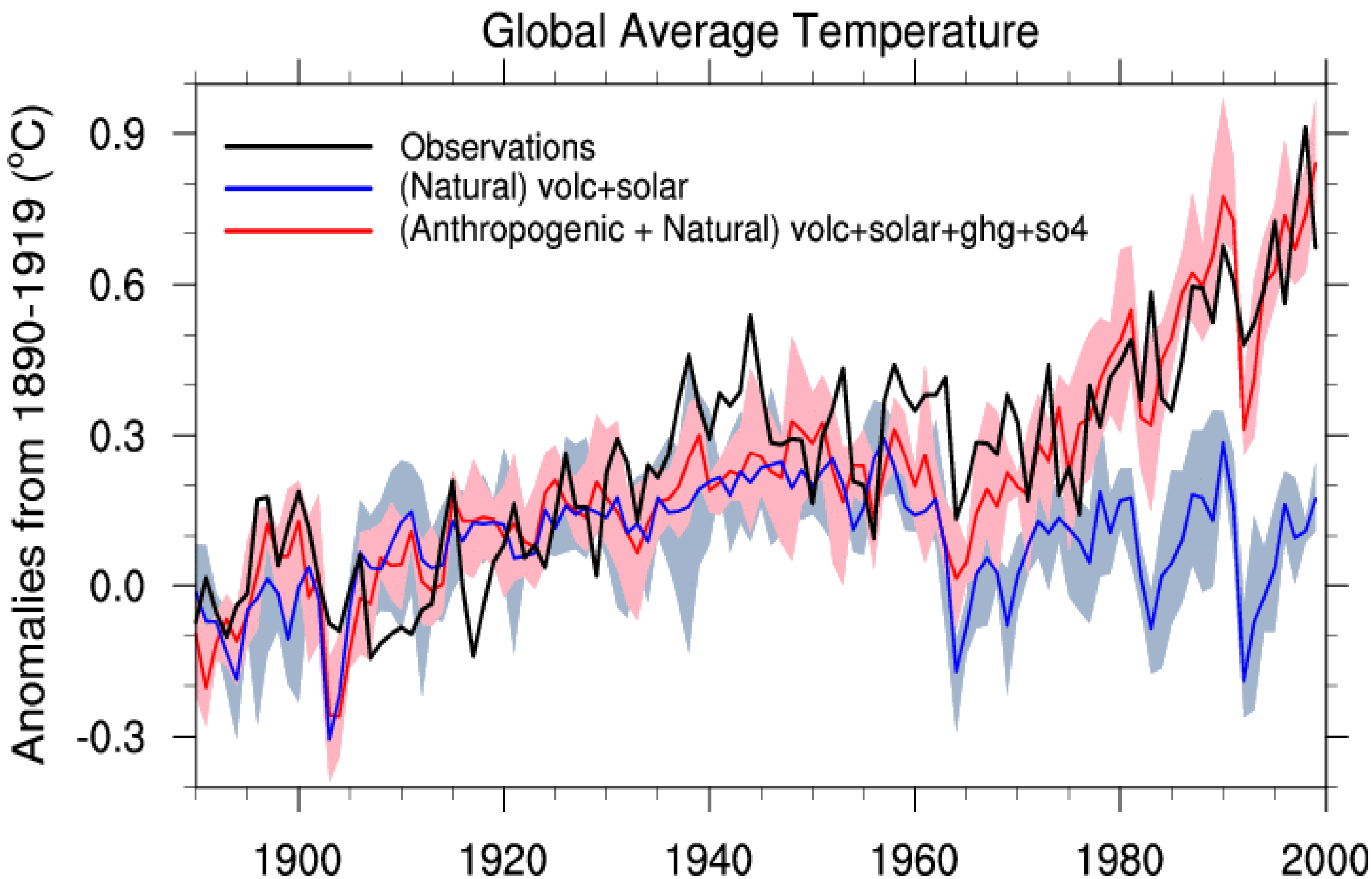
Plankton

Coral Reefs



Global Climate Models

20th Century With and Without Human Influences



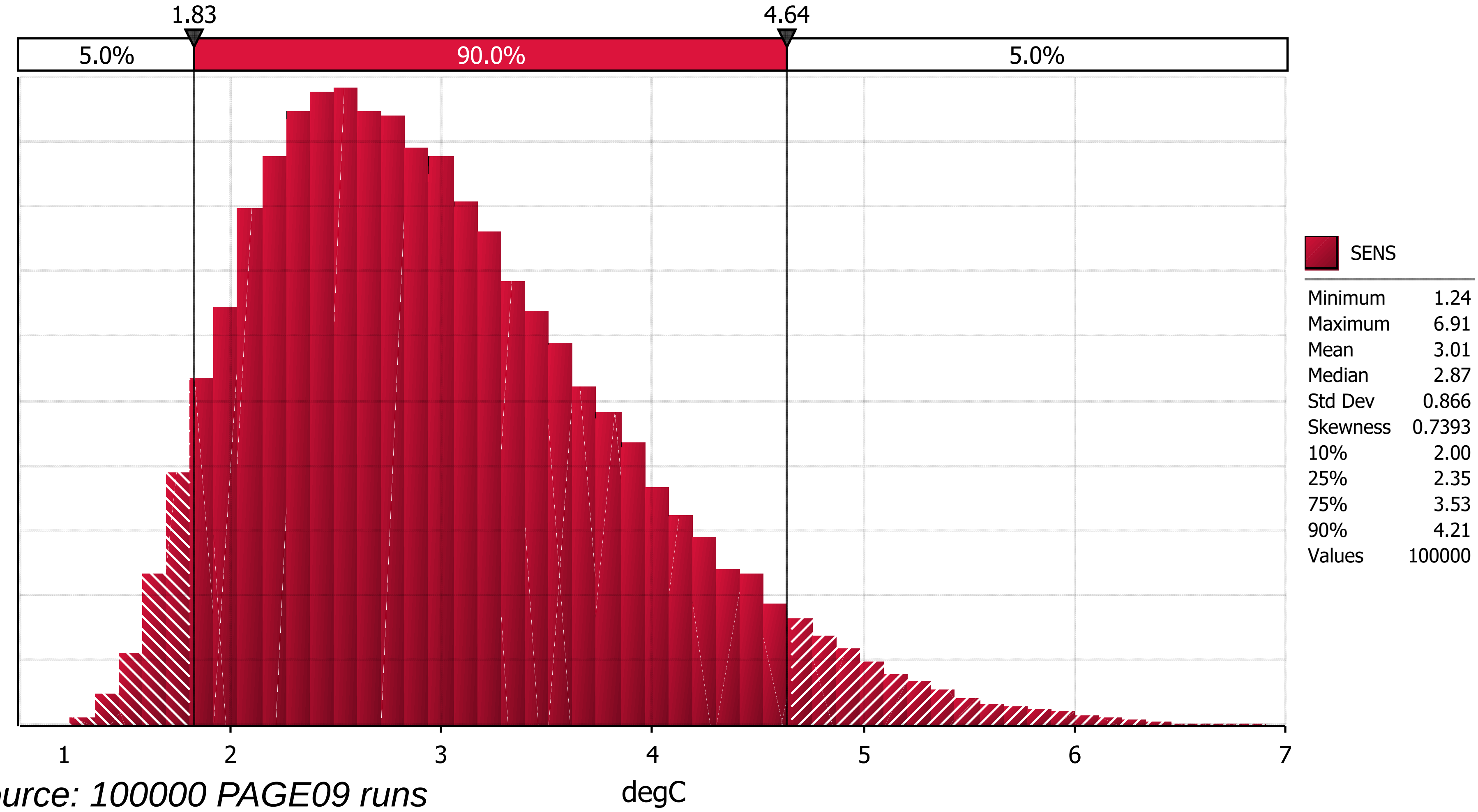
Based on 4-member PCM ensembles, Meehl et al., *J. Climate*, 2004

The Future

Sources of Uncertainty

- Cloud Feedback
- Water Vapor Feedback
- Ocean Response
- Aerosols

Estimate of how much global climate will warm as a result of doubling CO_2: a probability distribution



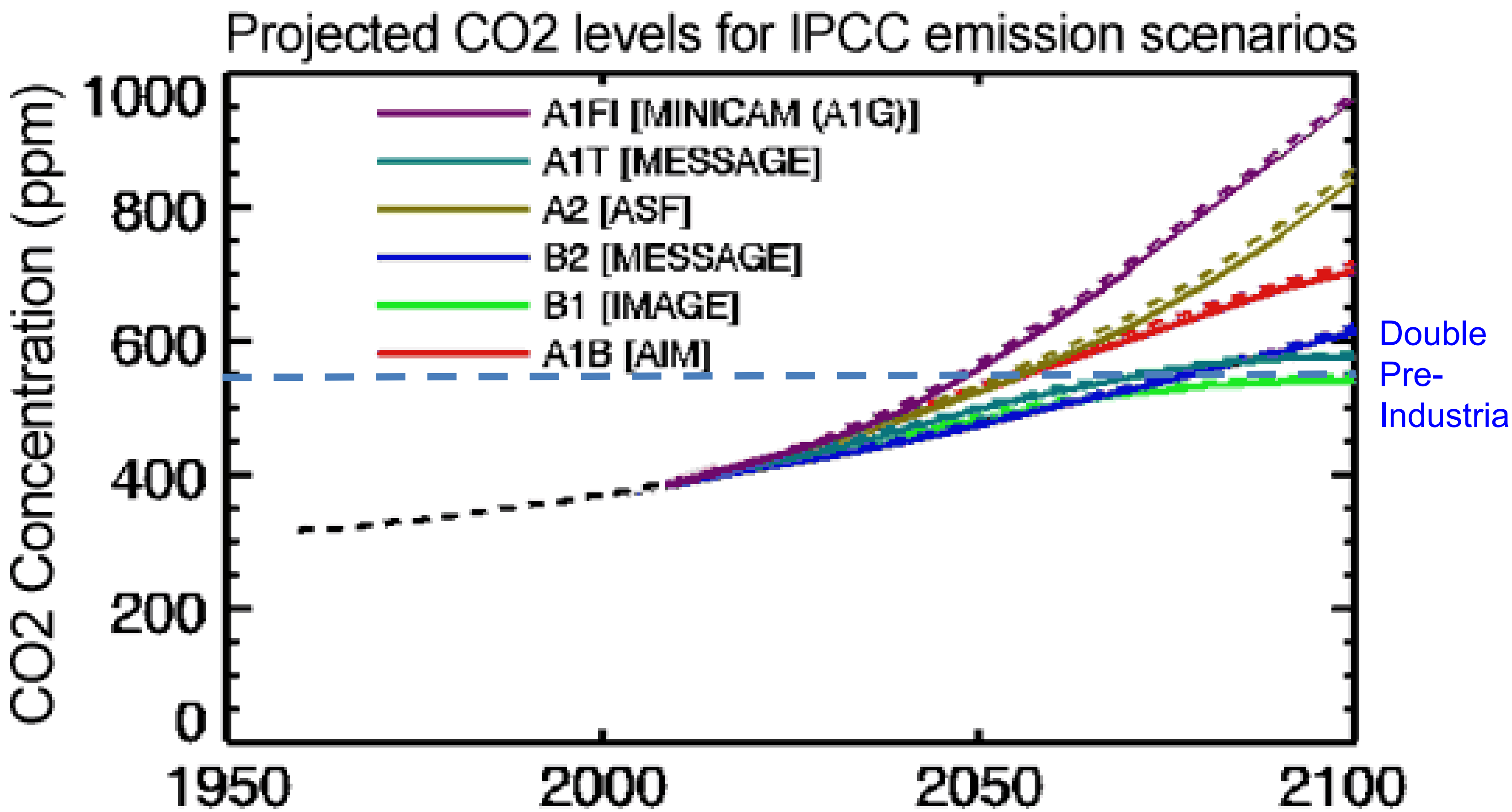
Source: 100000 PAGE09 runs

SEI

ClimateCost

Chris Hope, U. Cambridge
courtesy Tim Palmer

CO_2 Will Go Well Beyond Doubling

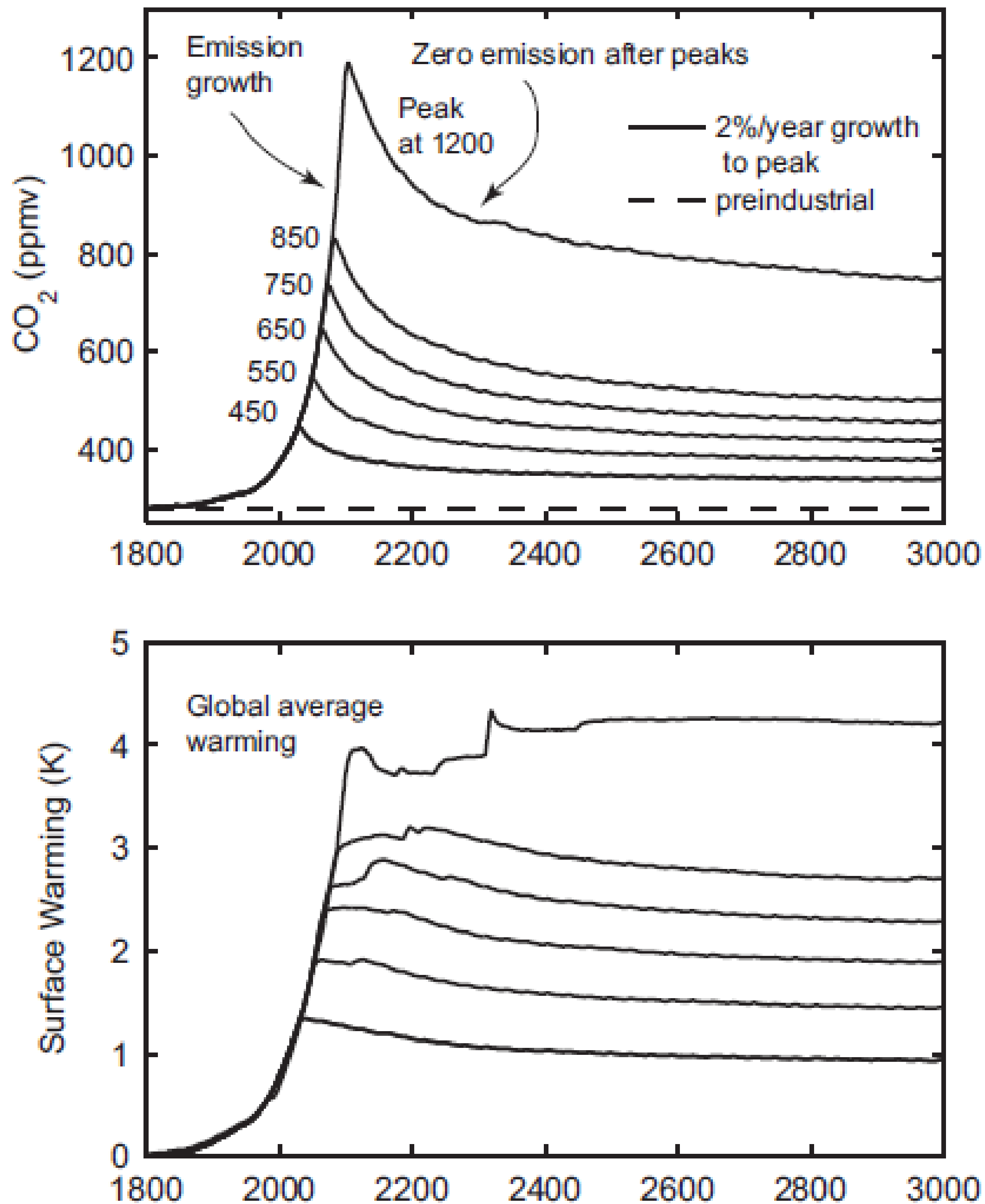


IPCC 2007: Doubling CO_2 will lead to an increase in mean global surface temperature of 2 to 4.5 °C.

Atmospheric CO_2 assuming that emissions stop altogether after peak concentrations

Global mean surface temperature corresponding to atmospheric CO_2 above

Courtesy Susan Solomon



Known Risks

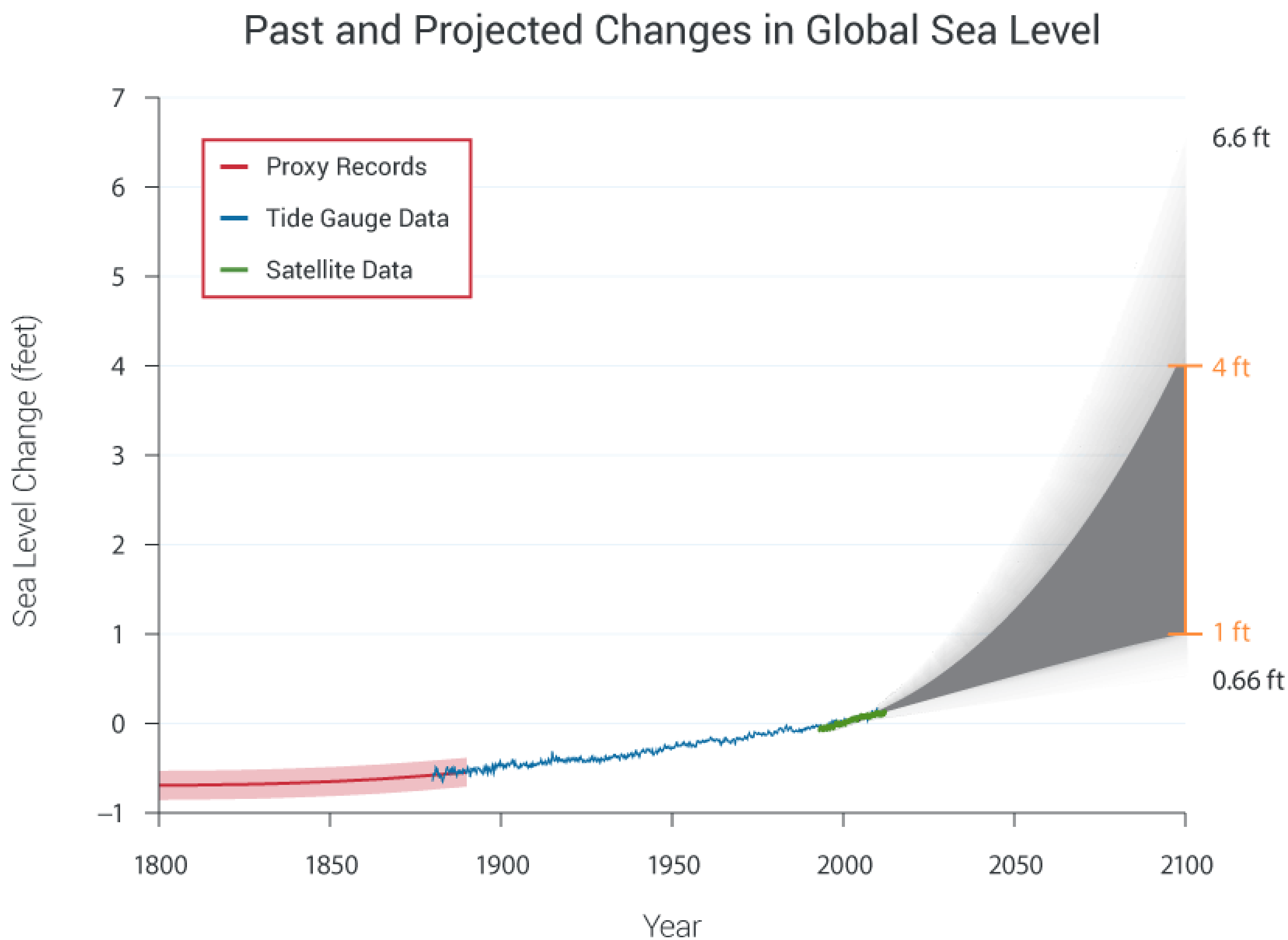
- Increasing sea level
- Increasing hydrological events… droughts and floods
- Increasing incidence of high category hurricanes and associated storm surges and freshwater flooding
- More heat stress and other health risks
- Armed conflict

Benefits

- Some increase in plant productivity
- Reduction in health problems related to cold weather

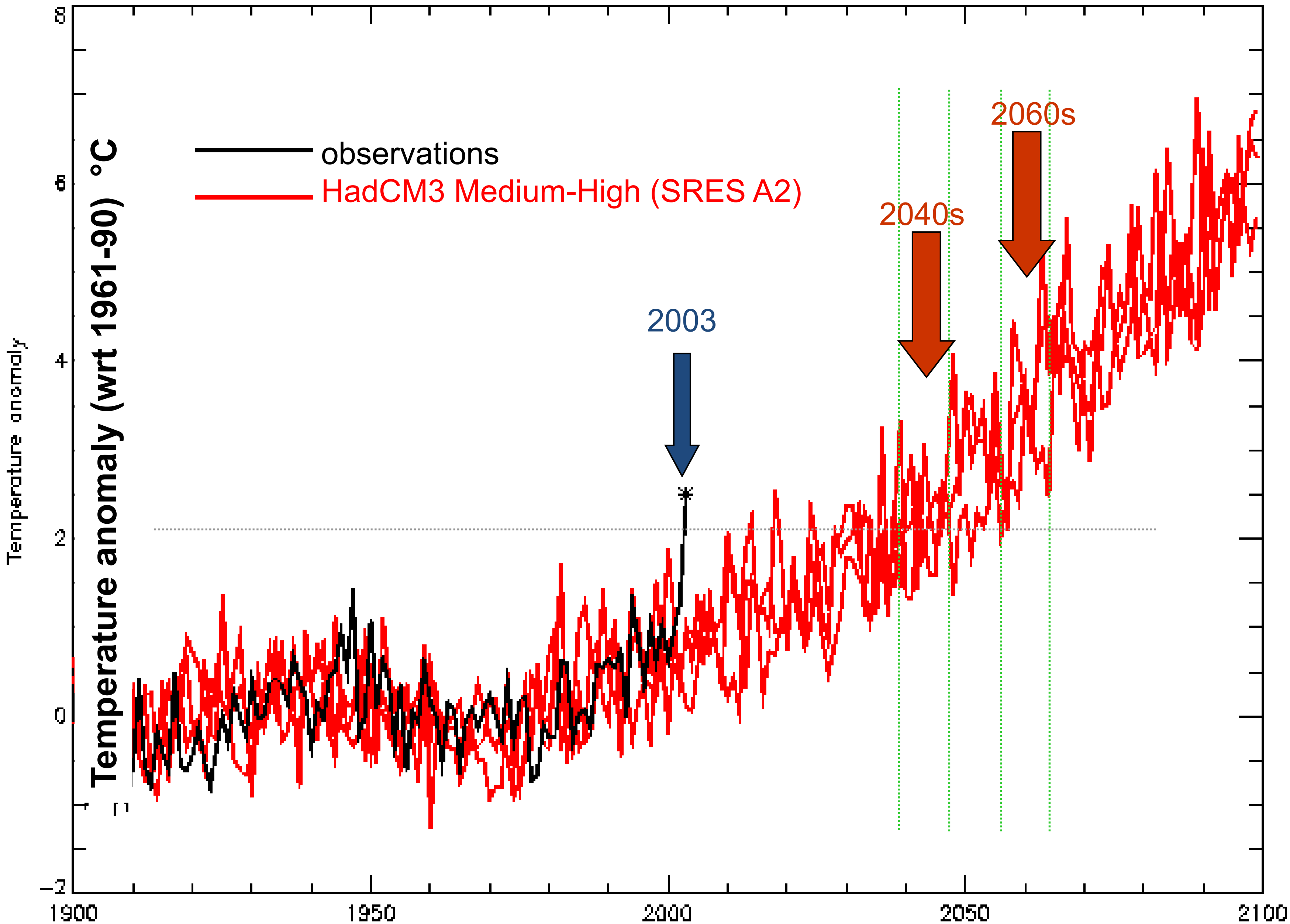
“Taken as a whole, the range of published evidence indicates that the net damage costs of climate change are likely to be significant and to increase over time.”

- Intergovernmental Panel on Climate Change

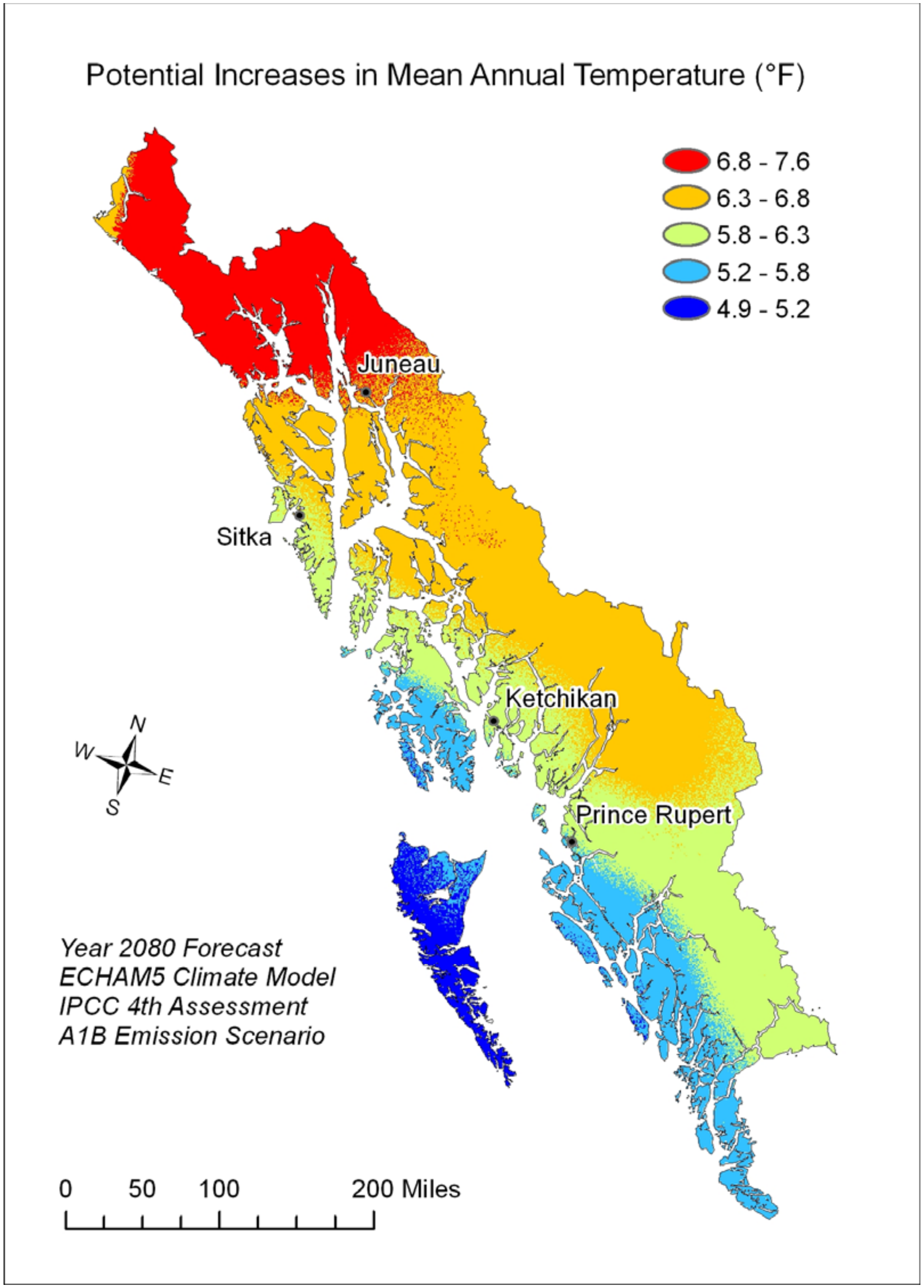

Past and Projected Changes in Global Sea Level
Proxy Records
Tide Gauge Data
Satellite Data
Sea Level Change (feet)
7
6
5
4
3
2
1
0
–1
1800
1850
1900
1950
2000
2050
2100
Year
6.6 ft
4 ft
1 ft
0.66 ft

Heat

Heat Waves



observations
HadCM3 Medium-High (SRES A2)
Temperature anomaly (wrt 1961-90) °C
Temperature anomaly
2003
2040s
2060s
8
6
4
2
0
−2
1900
1950
2000
2050
2100



Potential Increases in Mean Annual Temperature (°F)
6.8 - 7.6
6.3 - 6.8
5.8 - 6.3
5.2 - 5.8
4.9 - 5.2
Juneau
Sitka
Ketchikan
Prince Rupert
N
W
E
S
Year 2080 Forecast
ECHAM5 Climate Model
IPCC 4th Assessment
A1B Emission Scenario
0 50 100 200 Miles

Hydrological Extremes

- Rainfall intensity (how hard it rains when/where it is raining) scales with the Clausius-Clapeyron equation, doubling for every 10^o C temperature increase

- Wet places get wetter, dry places get drier; incidence of both floods and droughts increases

- Large potential effects on food and water supplies; major national security issue

Hydrological Extremes Increase with Temperature

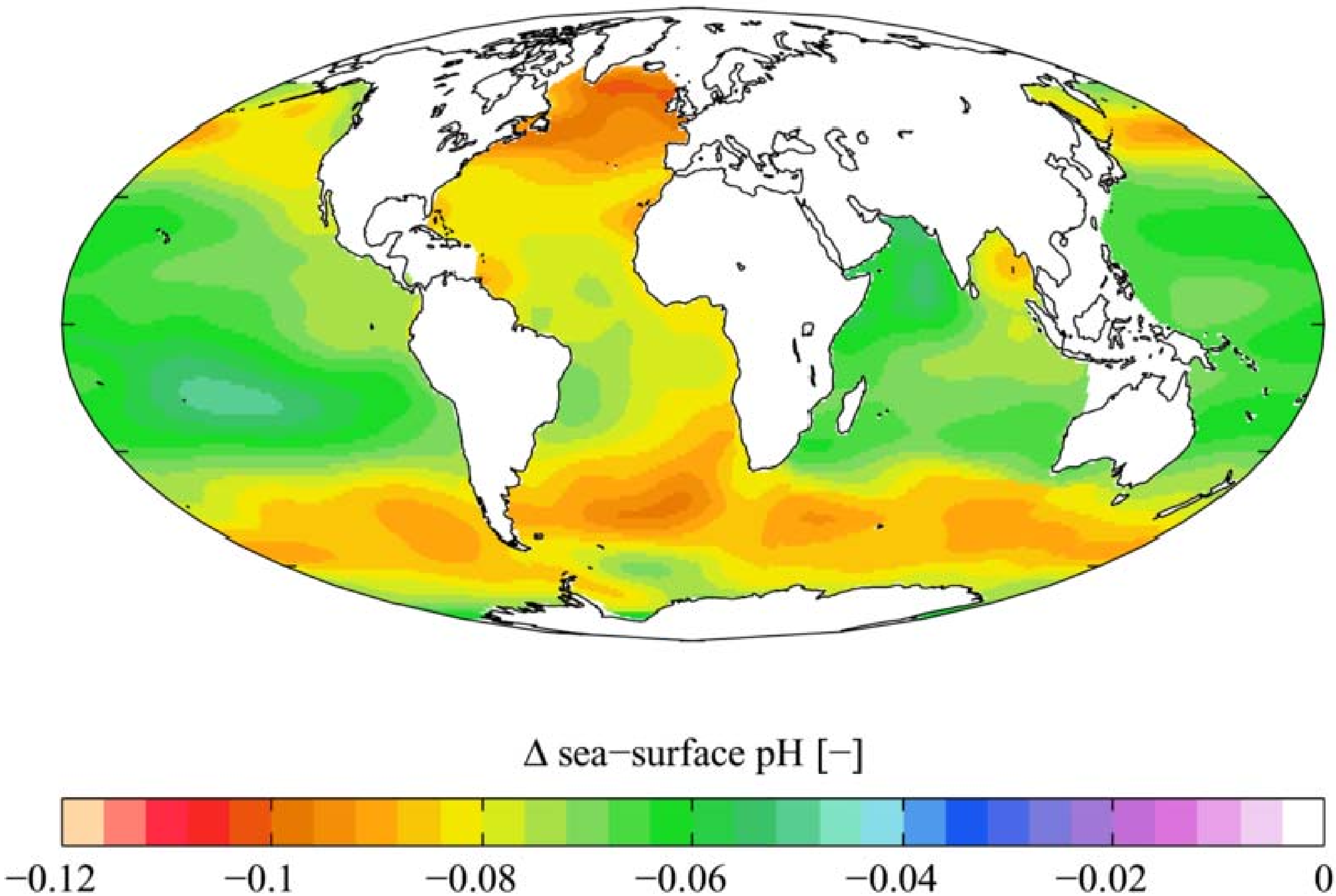
Floods

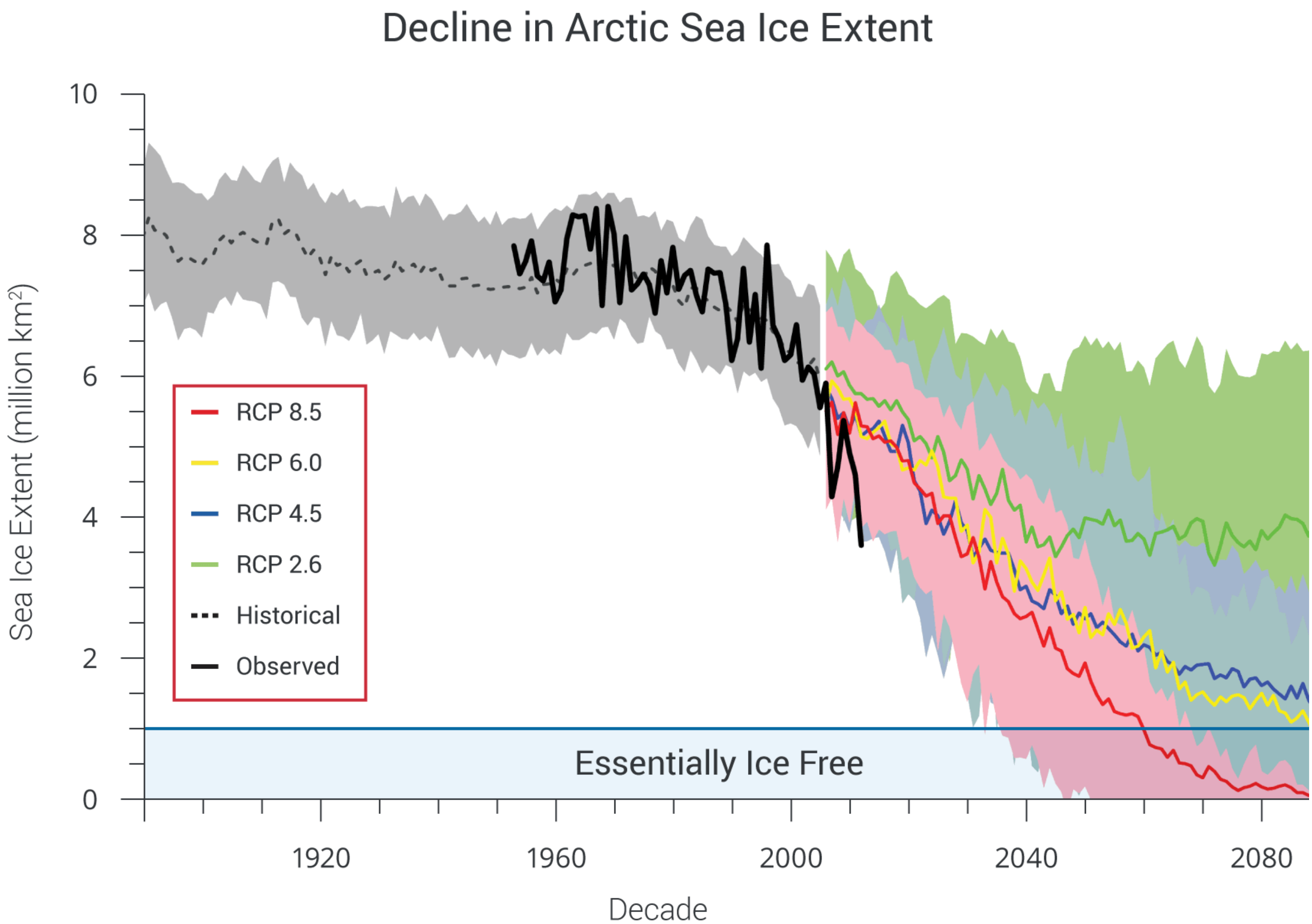
Drought

“Climate change could have significant geopolitical impacts around the world, contributing to poverty, environmental degradation, and the further weakening of fragile governments. Climate change will contribute to food and water scarcity, will increase the spread of disease, and may spur or exacerbate mass migration.”

-- Quadrennial Defense Review, U.S. Department of Defense, February, 2010

Ocean Acidification



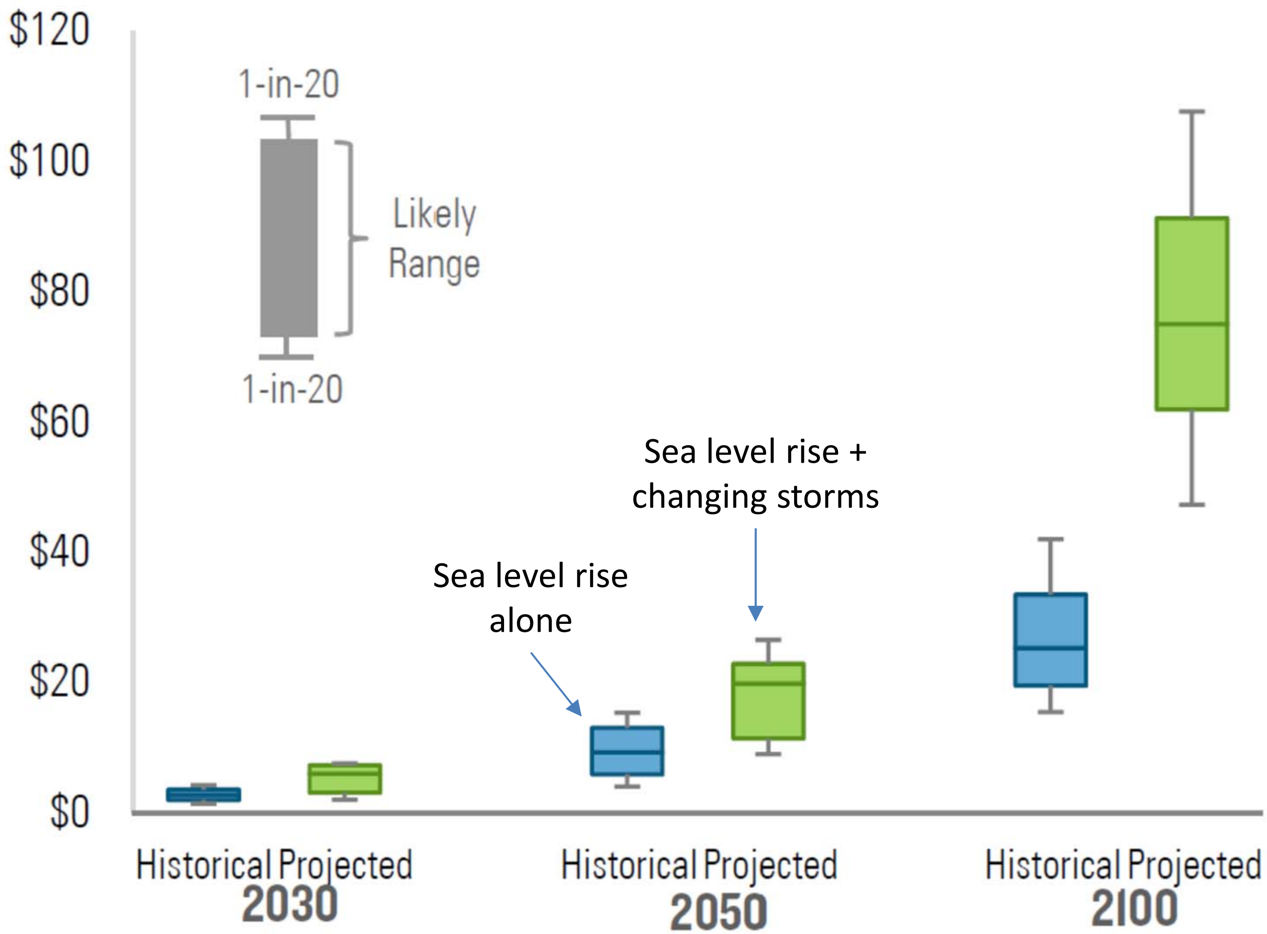


Decline in Arctic Sea Ice Extent
Sea Ice Extent (million km²)
10
8
6
4
2
0
1920
1960
2000
2040
2080
Decade
RCP 8.5
RCP 6.0
RCP 4.5
RCP 2.6
Historical
Observed
Essentially Ice Free

Hurricanes

Figure 11.17: Increase in average annual losses with historical and projected hurricane activity

Billion 2011 USD, RCP 8.5 ensemble tropical cyclone activity projections from Emanuel (2013)

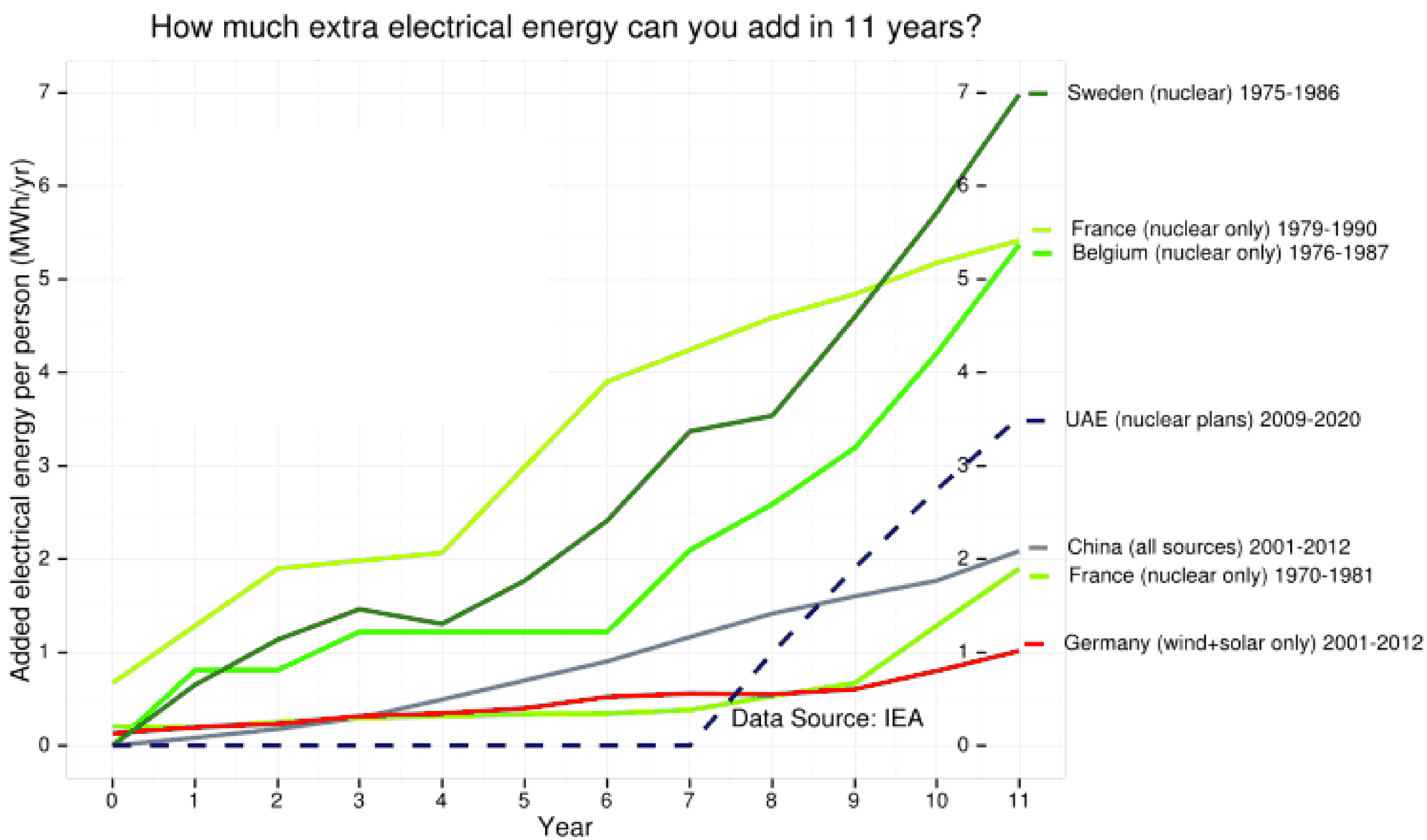


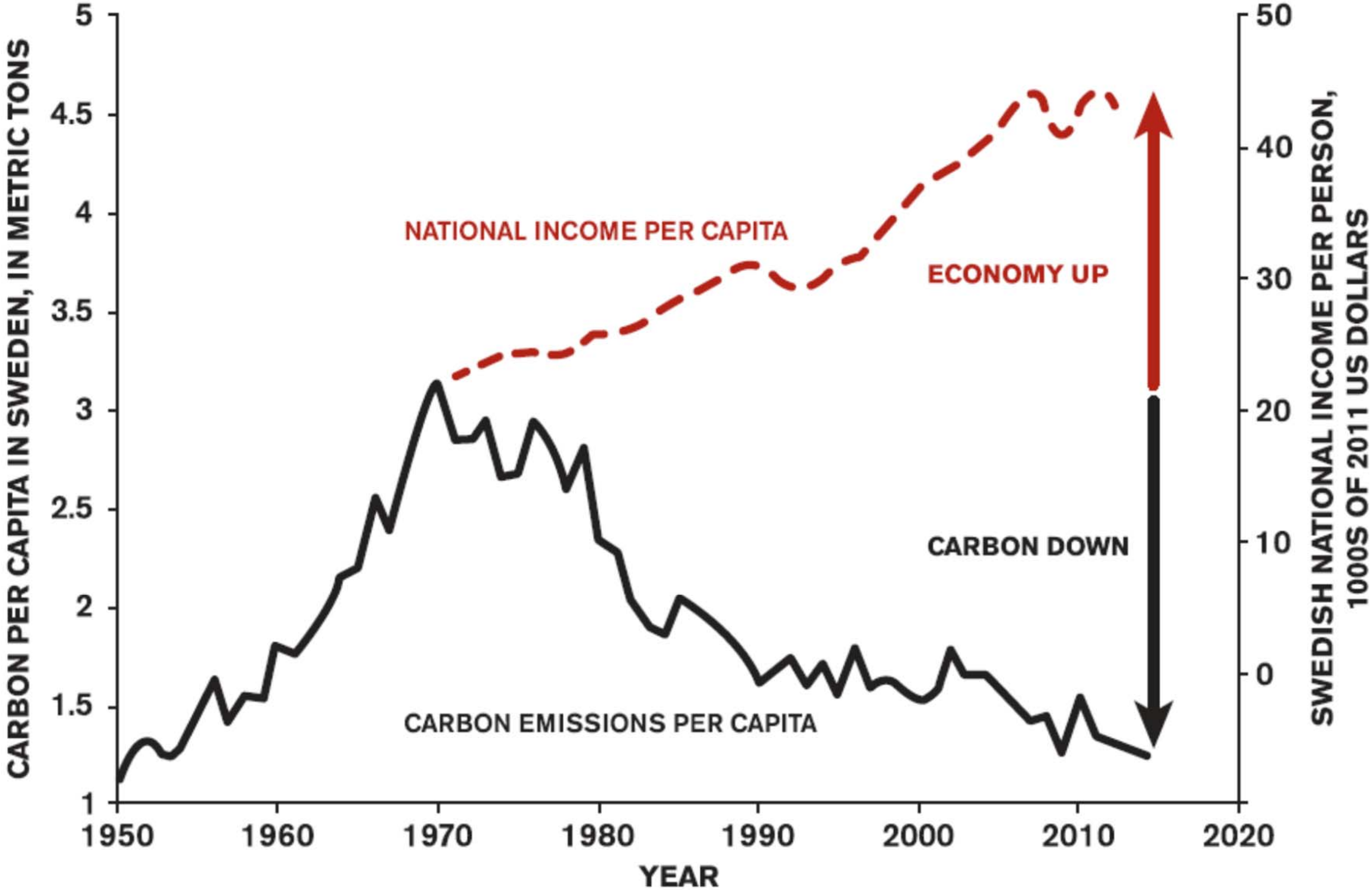
From: *American Climate Prospectus Economic Risks in the United States*

Solutions and Opportunities

- Renewables (solar and wind)
  - Might provide up to 30% of current power needs
  - Limited by intermittency and lack of storage
- Carbon Capture and Sequestration
  - Currently would add ~$200/ton to energy costs
  - Reasonable prospects for reducing this to ~$100/ton
  - Currently little incentive to develop this
- Nuclear fission and fusion

Ramping up Fission Power





NATIONAL INCOME PER CAPITA
ECONOMY UP
CARBON DOWN
CARBON EMISSIONS PER CAPITA
CARBON PER CAPITA IN SWEDEN, IN METRIC TONS
SWEDISH NATIONAL INCOME PER PERSON, 1000S OF 2011 US DOLLARS
YEAR
5
4.5
4
3.5
3
2.5
2
1.5
1
50
40
30
20
10
0
1950
1960
1970
1980
1990
2000
2010
2020

Summary of Main Points

- Several aspects of climate science are well established
- Earth's climate is strongly bounded but shows strong sensitivity within the bounds
- Climate science dates back well into the 19^{th} century and is well established

Summary of Main Points

- Earth's greenhouse effect triples the amount of radiation absorbed by the surface though it is regulated by trace gases comprising no more than 0.04% of the mass of the atmosphere. The concentration of CO_2 has increased by ~45% since the dawn of the industrial revolution

- Beginning with the calculations of Arrhenius more than 100 years ago, simple models predict an increase in global mean surface temperature of around 3 ^oC for each doubling of CO_2. These are consistent with the results of global climate models

- Long atmospheric lifetime (~1000 years) of CO_2 limits window of time in which serious risks could be curtailed

Summary of Main Points

- Solar, wind, and especially fission can replace existing power generation infrastructure in 10-20 years
- We will eventually need to do this anyway. Why not start now?
- Real world economics: 20 years from now, will we be selling clean energy technology to China and India, or buying it from them?