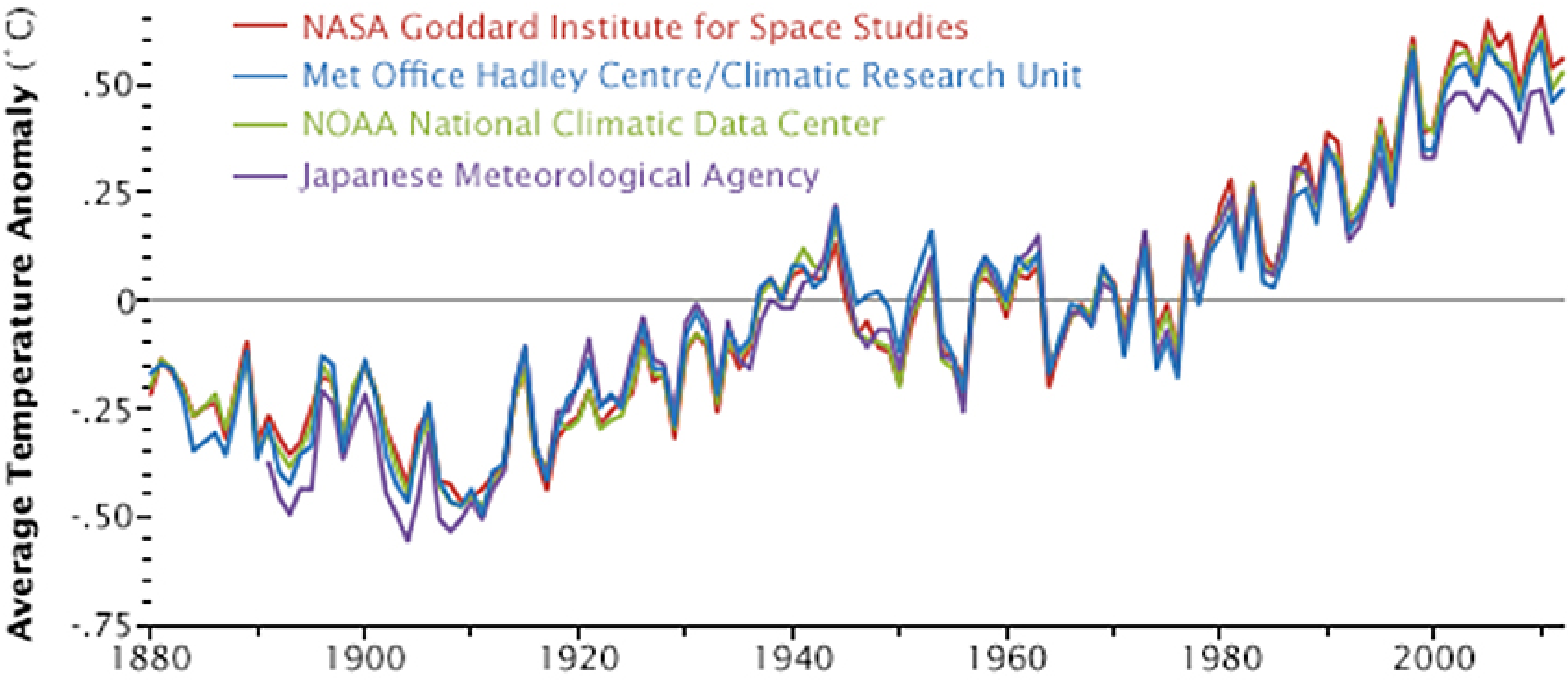
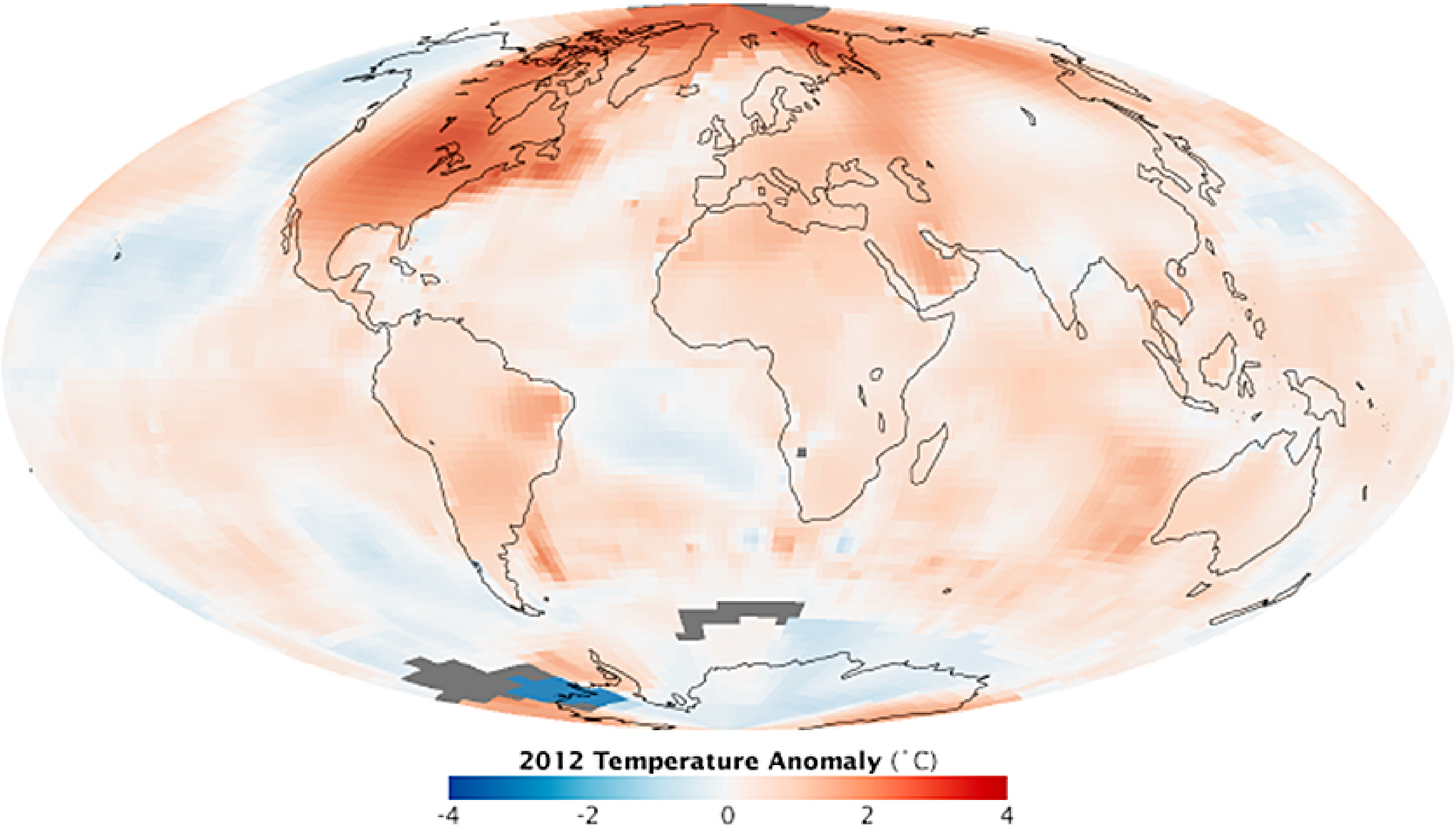
# Hot Topics in Climate 2: Climate Models & The Cryosphere

Warren Wiscombe
NASA Goddard

# The missing temperature plots 1: Global-average anomaly, 1880-2012



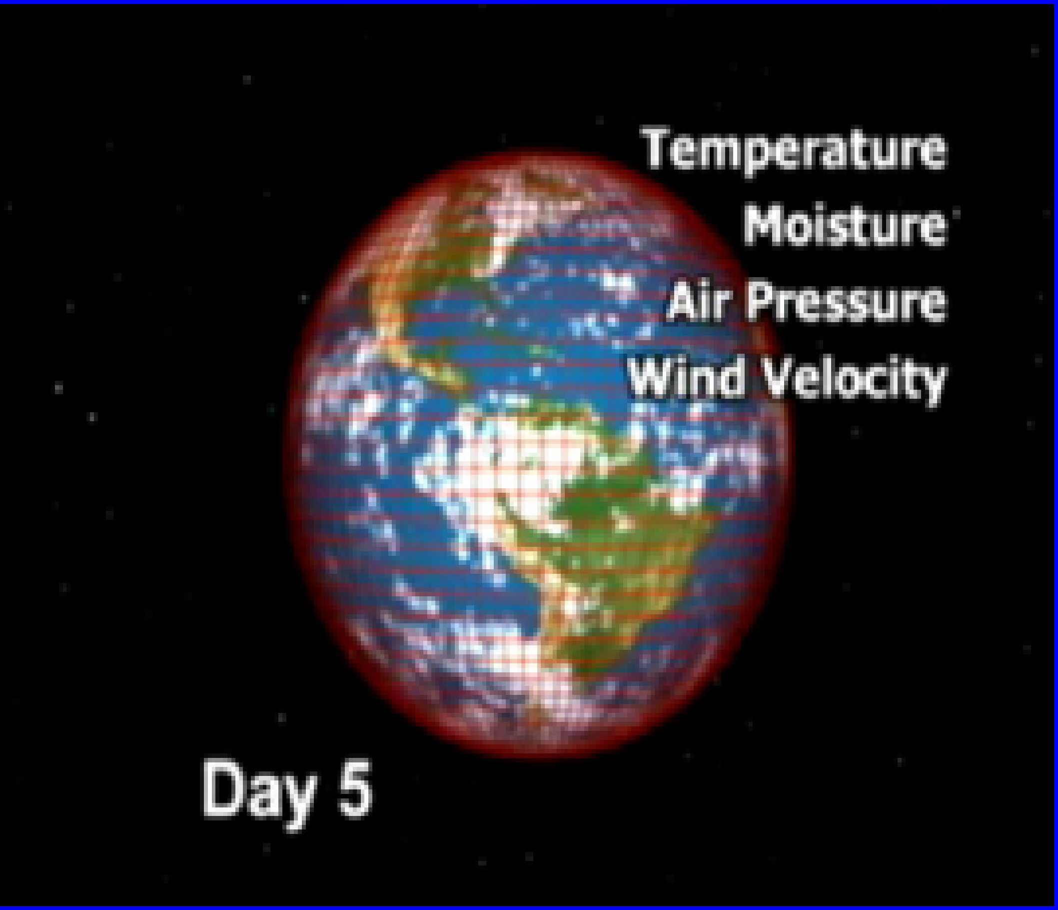
# The missing temperature plots 2: 2012 anomaly relative to 30-yr mean



# Climate Modeling

**Movie: Intro to climate modeling (4 min)**

# Variables in a climate model




Solve "primitive equations"

PDEs for conservation of mass, momentum, energy, + gas law

Cloud liquid water added recently

# THEMES in climate modeling

Bad models?

Models vs. theories

Models have emergent behavior.

Problem: it takes > 10 yr to verify a 10-yr forecast

Trenberth bet in 2010 that current IPCC models would have larger uncertainties due to adding more complexity (like aerosol effect on clouds, permafrost and CO2 fertilization).

# THEMES in climate modeling

Climate modeling is counter-intuitive: as knowledge increases, so does uncertainty.

'Idealized emissions scenarios': lead to projections, not predictions or forecasts

Rather than rely on these scenarios, modest predictions are possible because "the amount of warming that will take place up to 2030 is largely dependent on greenhouse gases that have already been released into the air"

# Climate modeling pyramid in 1987

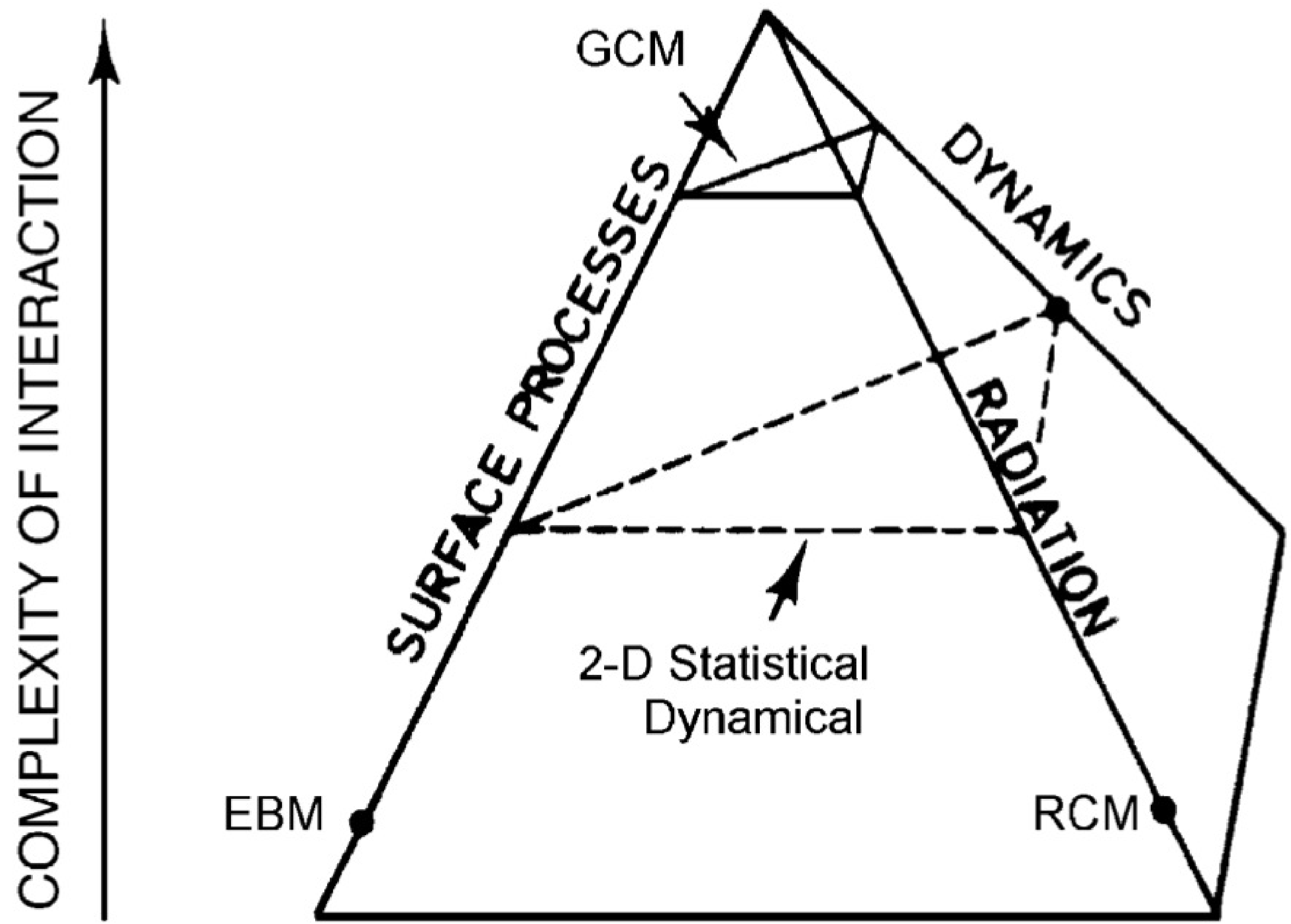



**Fig. 2.** The climate modeling pyramid. Adapted from Henderson-Sellers and McGuffie (1987)

# Climate model classification circa 2000

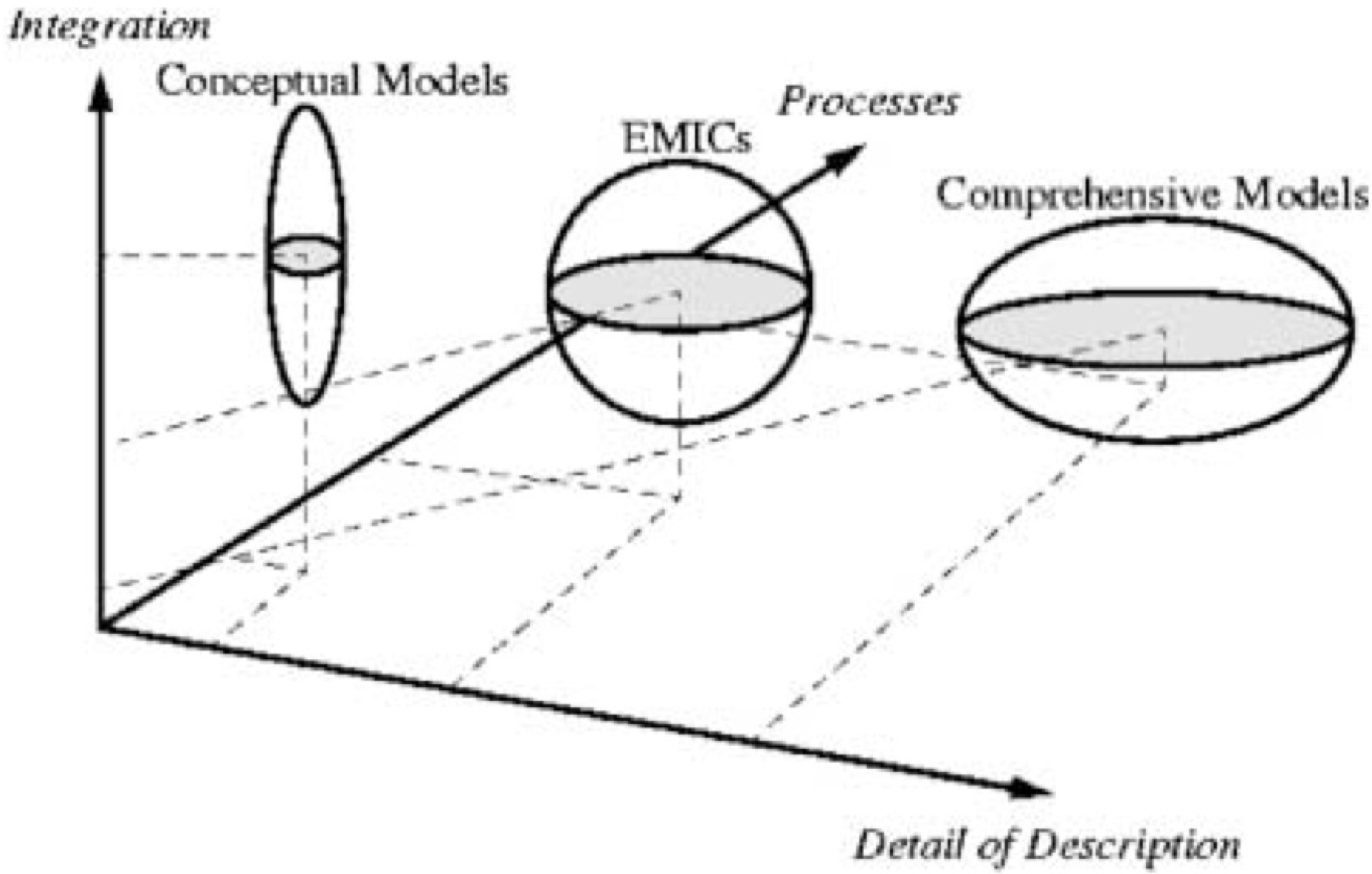
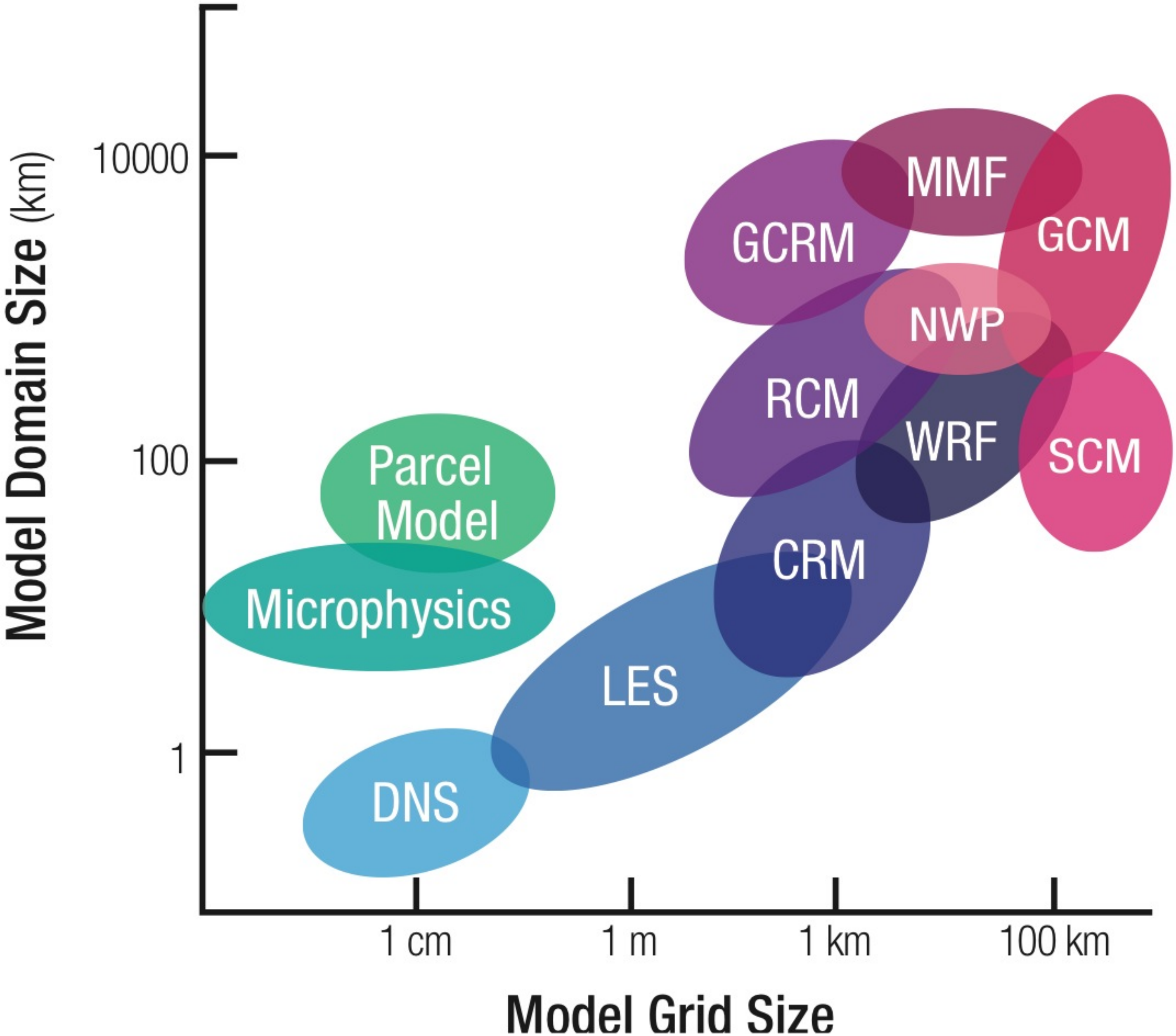



**Fig. 1.** Pictorial definition of EMICs. Adapted from Claussen (2000)

# Types of models




DNS=Direct Numerical Simulation

LES=Large Eddy Simulation

CRM = Cloud-Resolving Model

WRF = Weather Research and Forecast Model

GCM = Global Climate Model

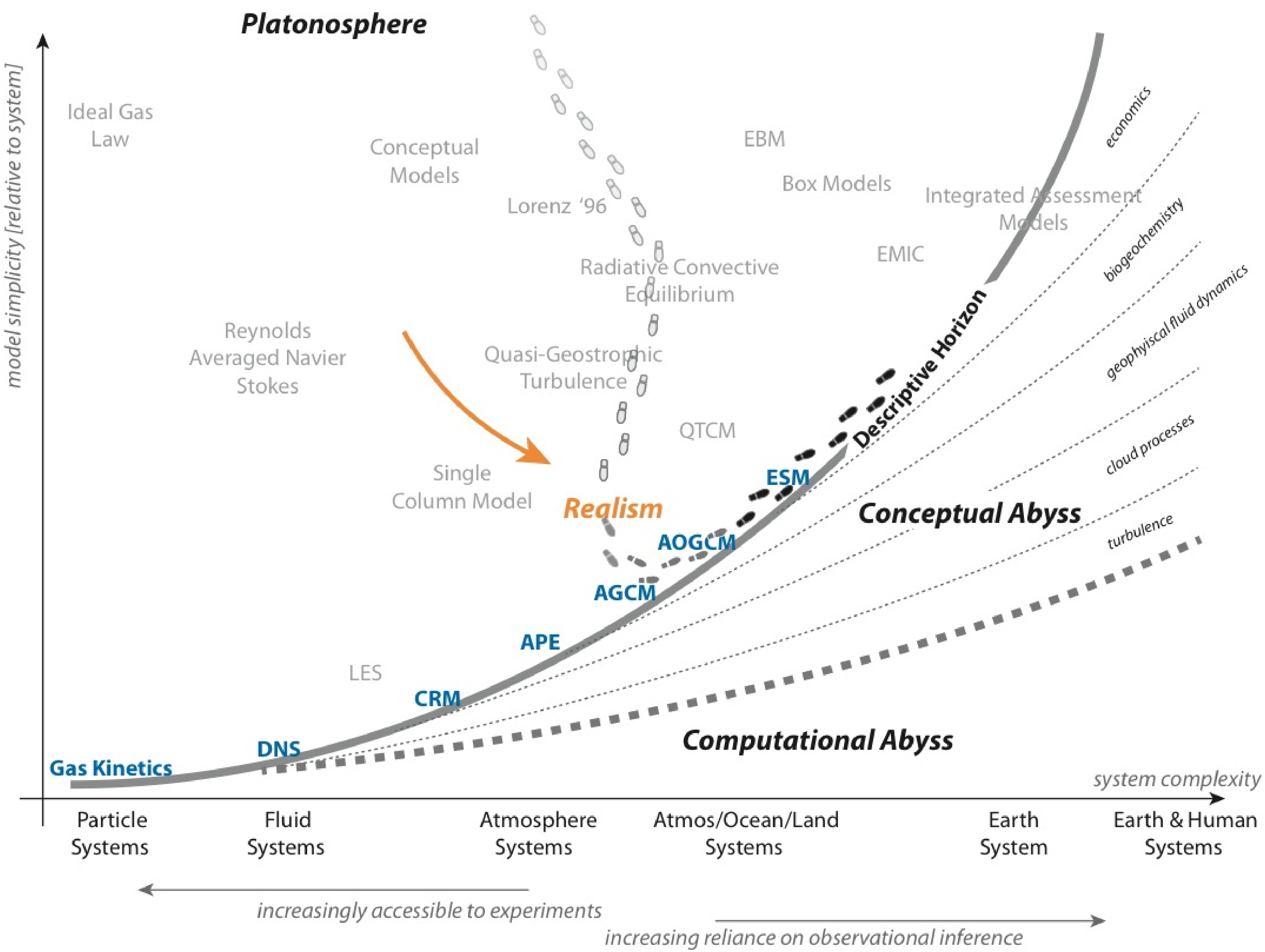
RCM = Regional Climate Model

GCRM = Global CRM

NWP = Numerical Weather Forecasting

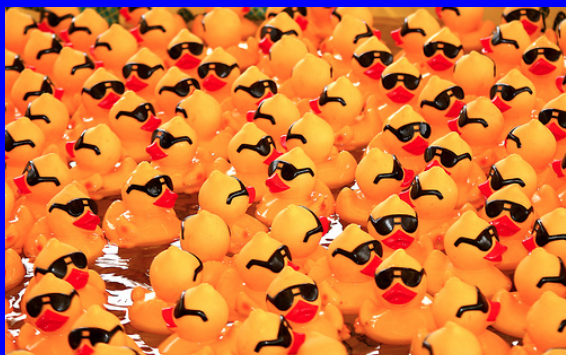
SCM = Single Column Model

# The imprints of our efforts (toward a widening abyss)



# There are ways to find robust behavior and make progress despite the difficulty of the problem

Perturb Physics

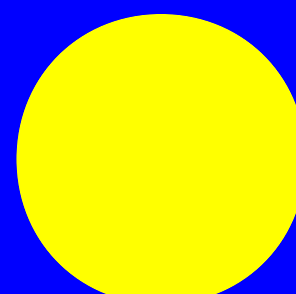


GCM

Multiple GCMs

Check with fancy model

Find a simple story/physics



Dorian Abbott

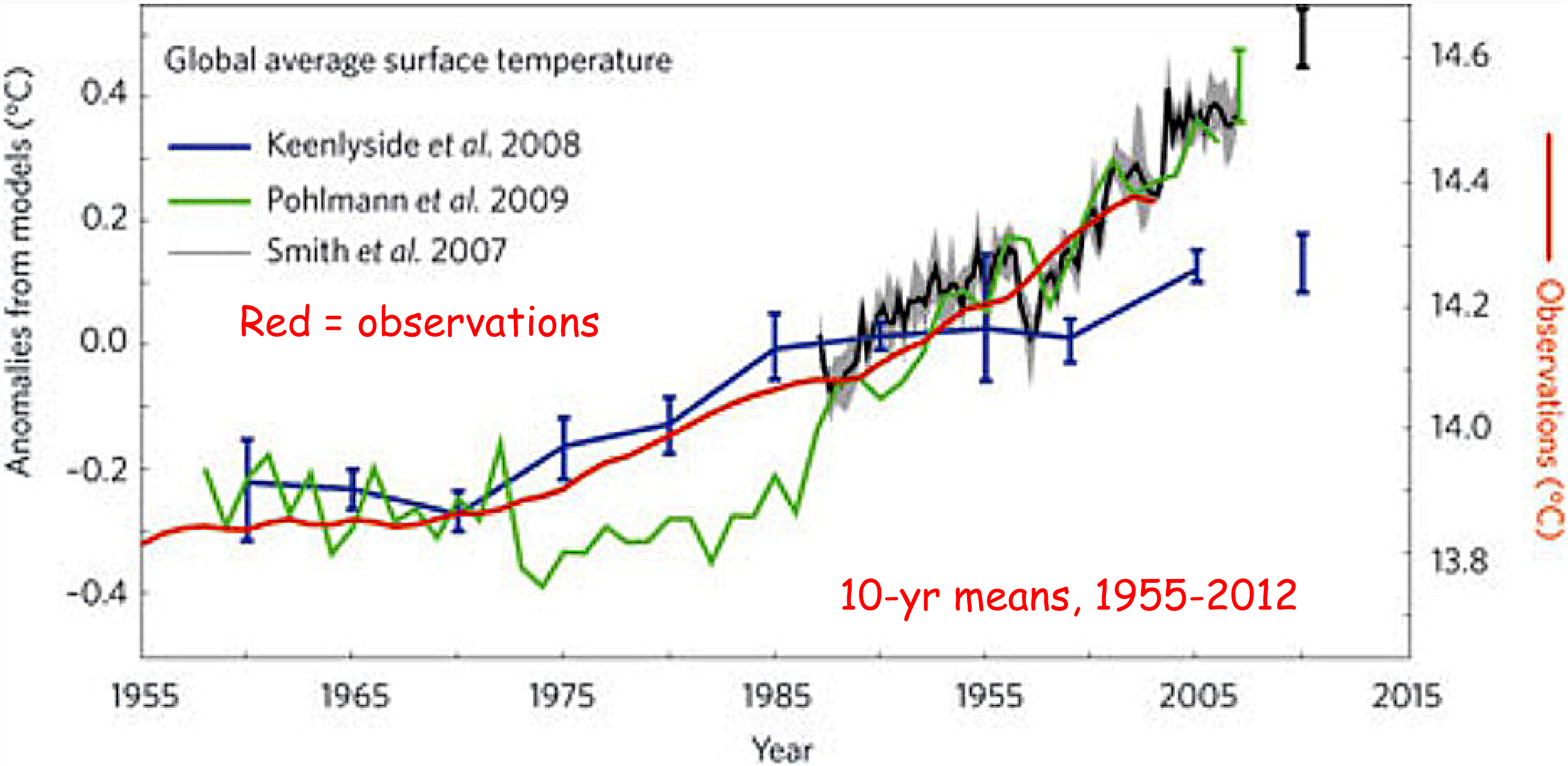
# Climate modeling is NOT like weather forecasting

Unlike a weather prediction, climate models are not initialized with the current or past state of the climate system, as derived from observations.

Instead, they begin with arbitrary climatic conditions and examine only the change in projected climate.

The actual initial states of climate models differ quite a lot. IPCC doesn't show them.

# Climate models are just beginning to try to produce true fore/hindcasts




Trenberth, 2010

# Are climate models getting better?
# Reichler & Kim (BAMS 2008) found YES

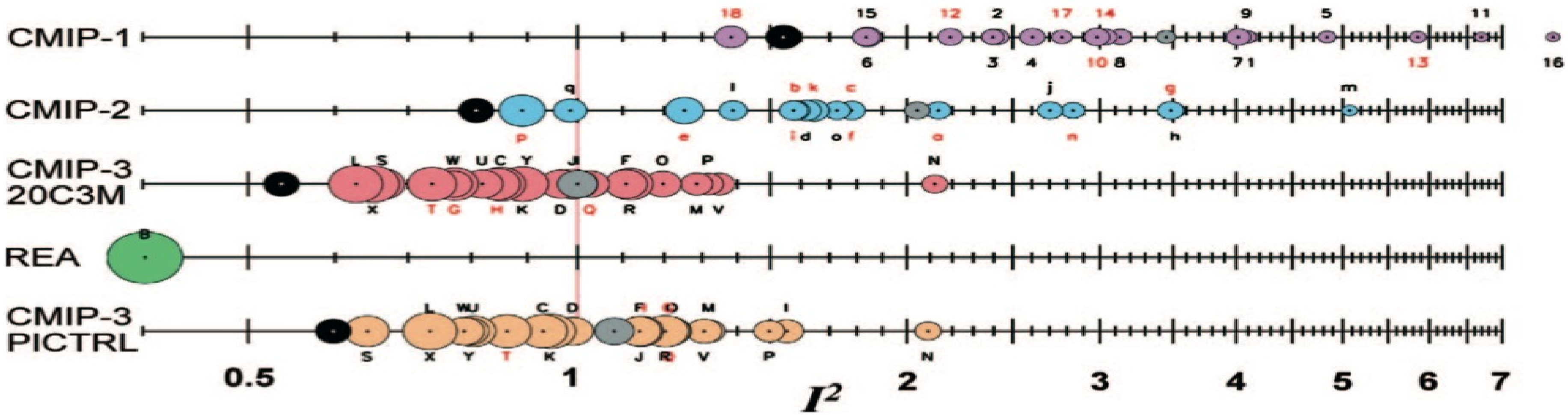



FIG. 1. Performance index $I^2$ for individual models (circles) and model generations (rows). Best performing models have low $I^2$ values and are located toward the left. Circle sizes indicate the length of the 95% confidence intervals. Letters and numbers identify individual models (see supplemental online material at doi:10.1175/BAMS-89-3-Reichler); flux-corrected models are labeled in red. Grey circles show the average $I^2$ of all models within one model group. Black circles indicate the $I^2$ of the multimodel mean taken over one model group. The green circle (REA) corresponds to the $I^2$ of the NCEP/NCAR reanalyses. Last row (PICTRL) shows $I^2$ for the preindustrial control experiment of the CMIP-3 project.

CMIP = Climate Model Intercompar'n Project (start 1994)
Index compares grab bag of predicted var's to current climate
Index > 1 for underperforming (bad?) models
Better resolution and parameterizations led to better results
Black circles = multi-model means (green = observ'ns)

# Kerry Emanuel video on climate (24 min)

https://alum.mit.edu/learn/facultyforum/online/climate-research?destination=node/20702

Starts with Arrhenius and ends with need for going back to basics in climate modeling
--emphasizing basic understanding over black box simulation

# Professor Kerry Emanuel of MIT

"Climate Research: Time for a New Direction

Research aimed at predicting future climate activity has primarily focused on exceptionally large and complex numerical models. While this approach has provided some quantitative estimates of climate change, those predictions can vary greatly from one model to the next and produce significant uncertainties in the projected outcome. Attempts to reduce these uncertainties have largely failed."

# Stevens/Bony paper says STOP adding more complexity and get hydrological cycle right

CLIMATE CHANGE

## What Are Climate Models Missing?

**A better representation of the coupling between atmospheric water and circulation is necessary to reduce imprecision in climate model projections.**

**Bjorn Stevens[1] and Sandrine Bony[2]**

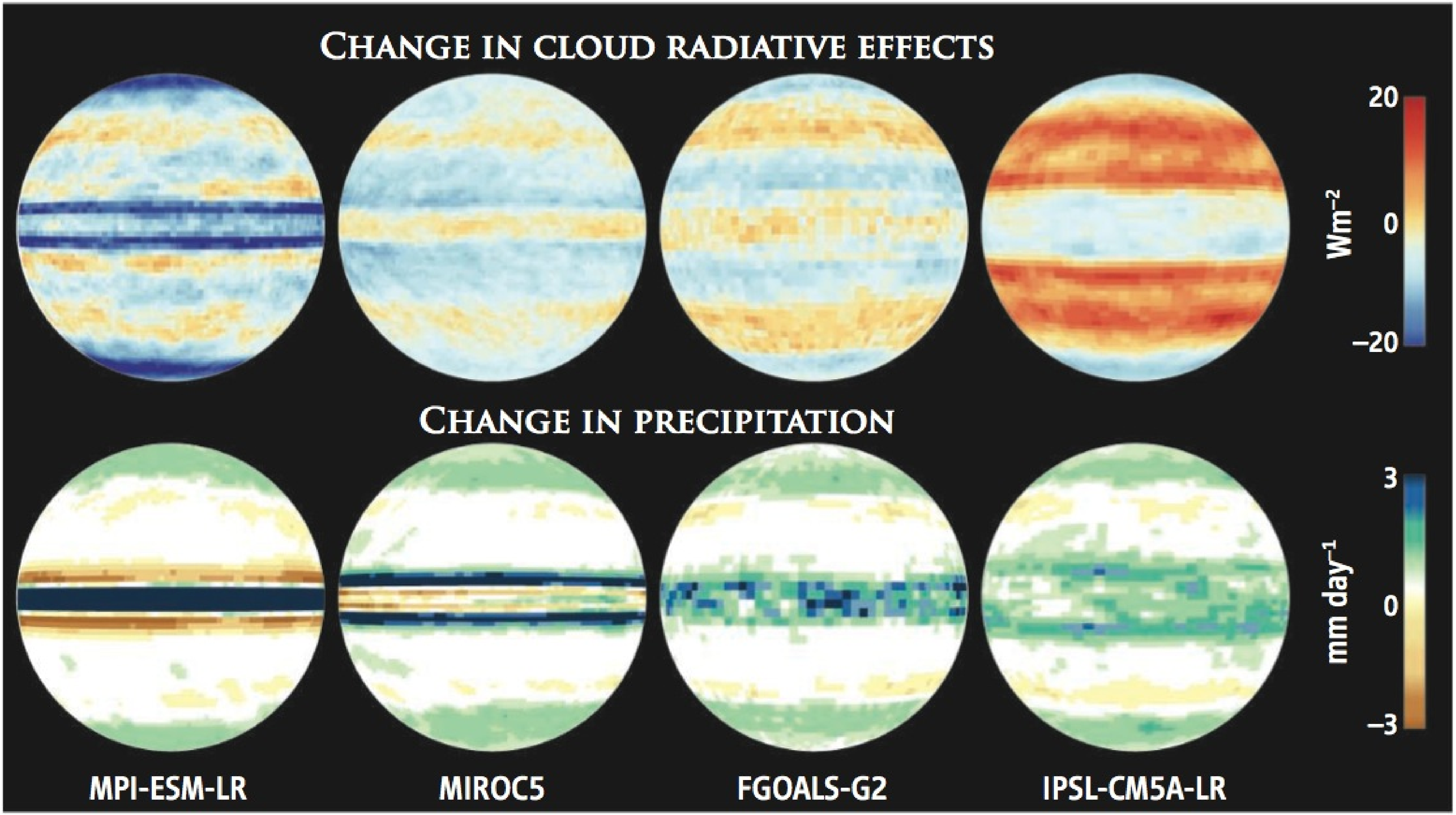
Fifty years ago, Joseph Smagorinsky published a landmark paper (*1*) describing numerical experiments using the primitive equations (a set of fluid equations that describe global atmospheric flows). In so doing, he introduced what later became known as a General Circulation Model (GCM). GCMs have come to provide a compelling framework for coupling the atmospheric circulation to a great variety of processes. Although early GCMs could only consider a small subset of these processes, it was widely appreciated that a more comprehensive treatment was necessary to adequately represent the drivers of the circulation. But how comprehensive this treatment must be was unclear and, as Smagorinsky realized (*2*), could only be determined through numerical experimentation. These types of experiments have since shown that an adequate description of basic processes like cloud formation, moist convection, and mixing is what climate models miss most.

[1]Max Planck Institute for Meteorology, Bundesstraße 53, 20146 Hamburg Germany. [2]Laboratoire de Météorologie Dynamique–Institut Pierre Simon Laplace, CNRS, Université Pierre et Marie Curie, Paris, France. E-mail: bjorn.stevens@mpimet.mpg.de

**From GCMs to Earth System Models**

Smagorinsky's GCM was designed around the premise that studies of the general circulation required a model capable of resolving the heat transport from the equator to the poles. Its formulation was the next logical step in a program of hierarchical model development best known for its pioneering contributions to numerical weather prediction (*3*). The work paved the way for fundamental studies of the atmospheric general circulation, and hence Earth's climate.

Over the past half century, many of these studies have focused on the types of numerical experiments anticipated by Smagorinsky. Beginning with basic processes like moist convection and cloud formation, which have long been appreciated as central to the energetics of the troposphere, a long succession of processes and couplings have been added to primitive-equation descriptions of the atmospheric general circulation. In so doing, GCMs have gradually morphed into Global Climate Models, and with the more recent incorporation of models of the biosphere and the associated cycles of important chemical nutrients, Earth System Models (*4*, *5*).

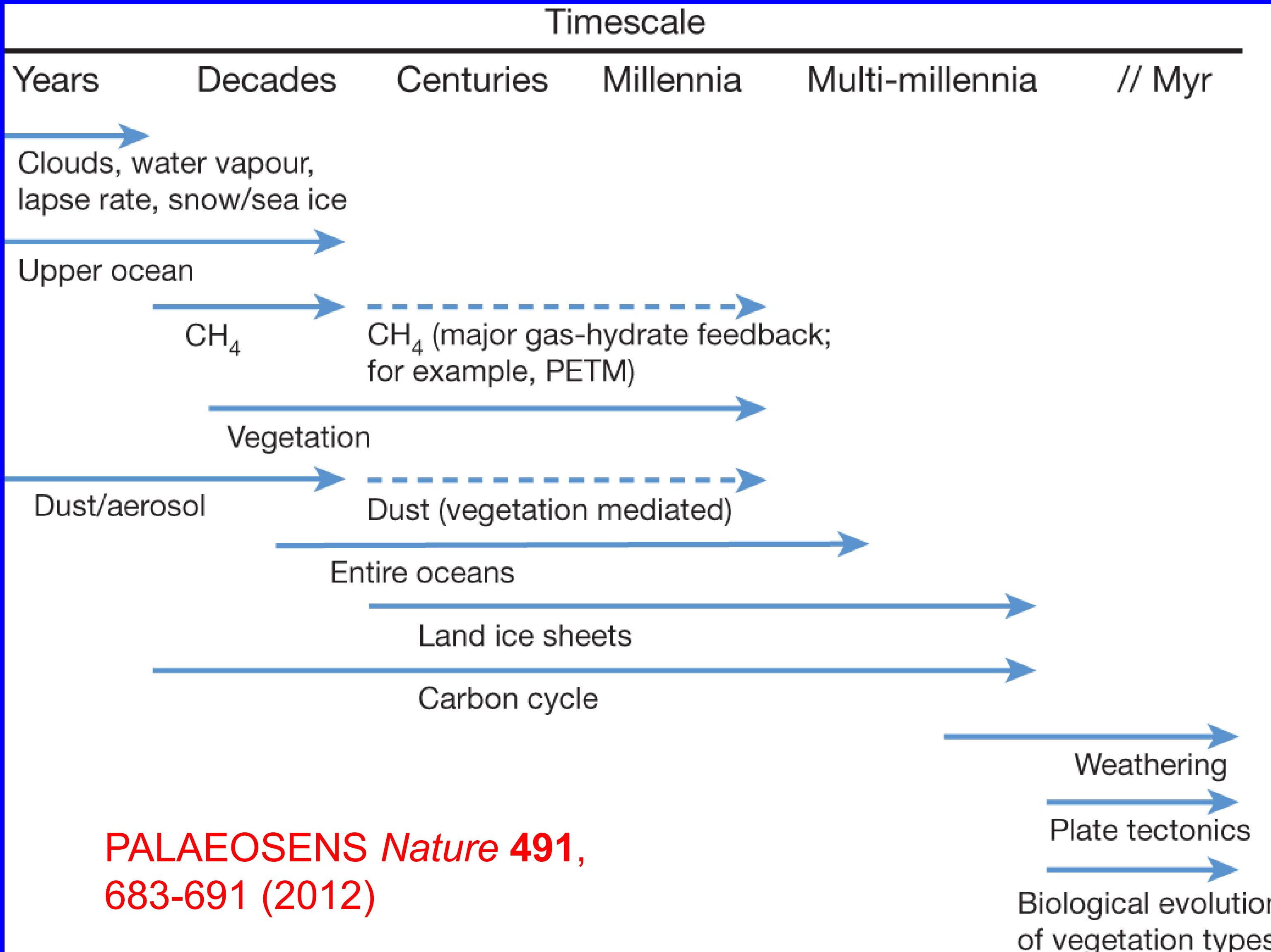



**Wide variation.** The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures.

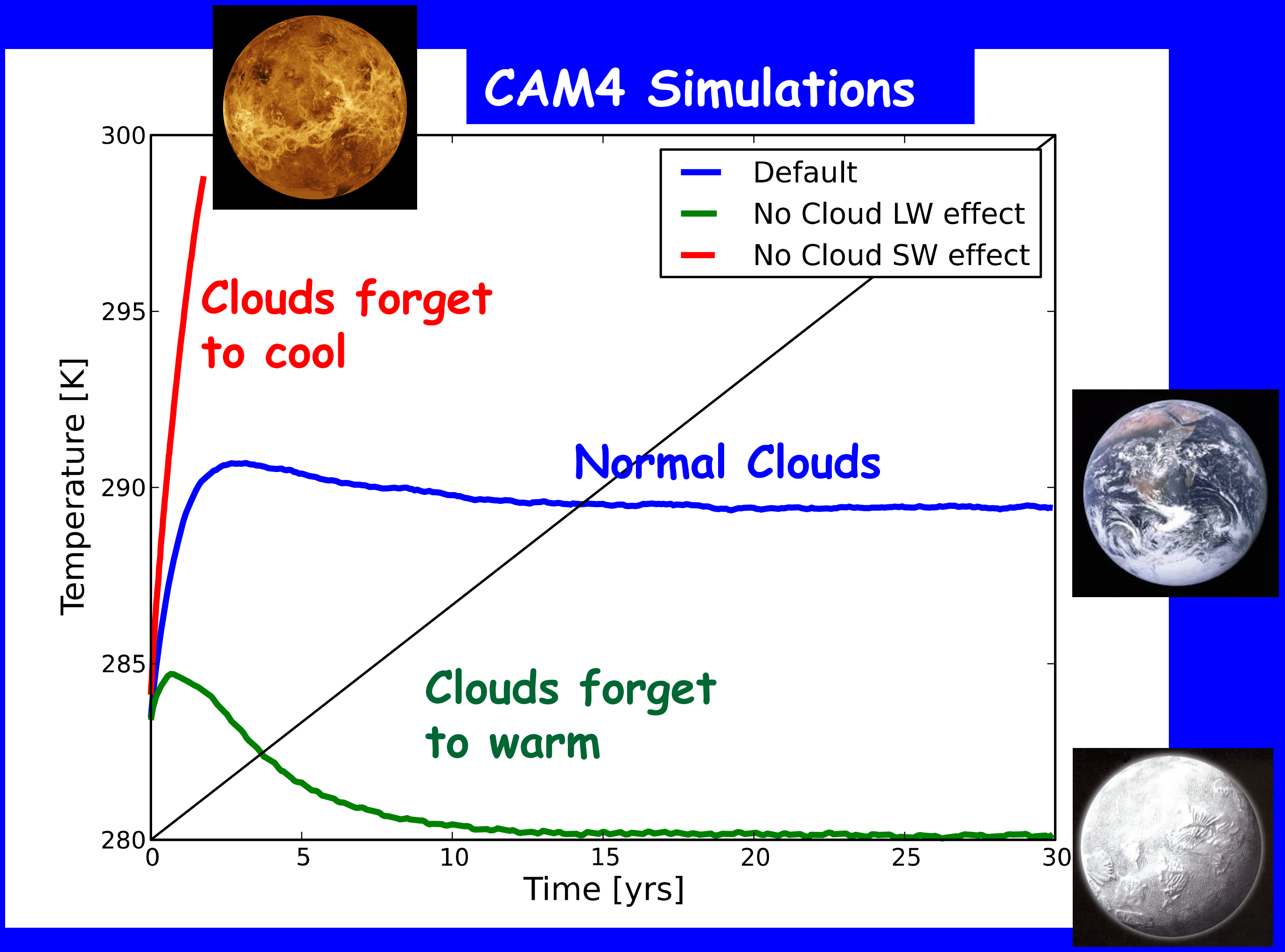
# What drives modelers crazy?

- clouds (a feedback)
- precipitation
- aerosols (a forcing)
- known unknown feedbacks
  - permafrost
  - ocean thermohaline circulation
- unknown unknown feedbacks
  - esp. over long timescales

# Typical timescales of different feedbacks relevant to equilibrium climate sensitivity



# Cloud shortwave reflection and infrared absorption are critical for determining planetary climate



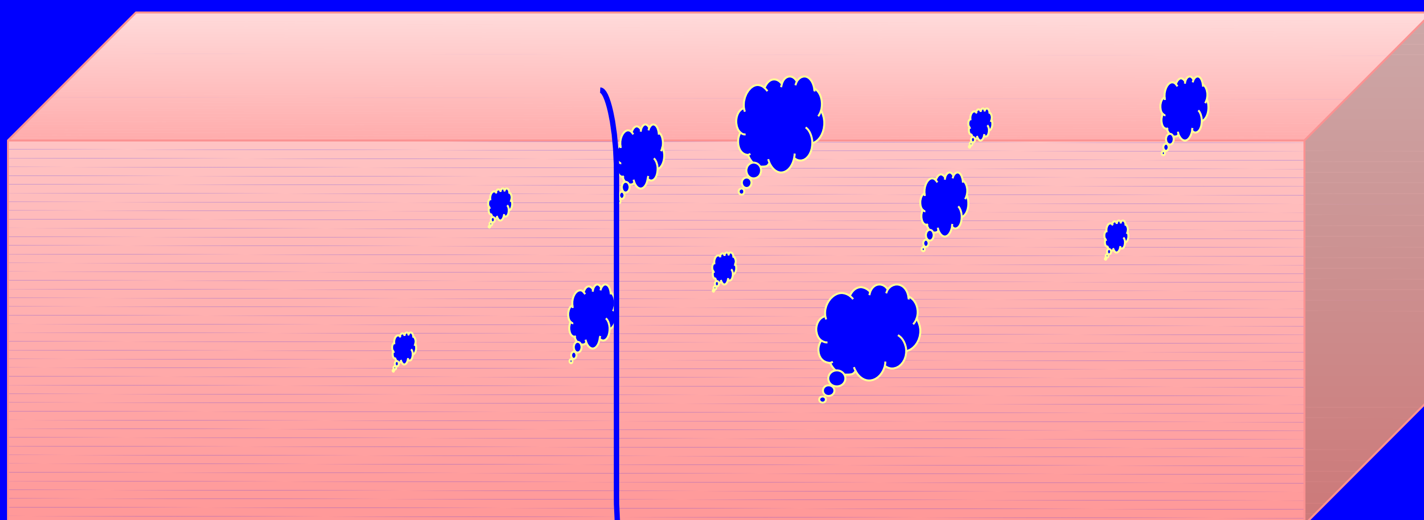

Thanks to Daniel Koll

Cloud processes are not resolved by GCMs, and therefore require parameterization in terms of resolved variables

Cloud microphysics scale: ≈10-6-10-3 m

## GCM gridbox

Cloud size: ≈101-103 m



≈103 m

≈105 m

# What drives modelers crazy? – 2

Regional climate change

Multiple equilibria?

Why is Earth's albedo 0.3?  Is it stable?

Which ensemble member are we on?

1940 to 1975 cooling (tuned with aerosols)

Dimming and brightening of sunlight@surface

# What drives modelers crazy? – 3

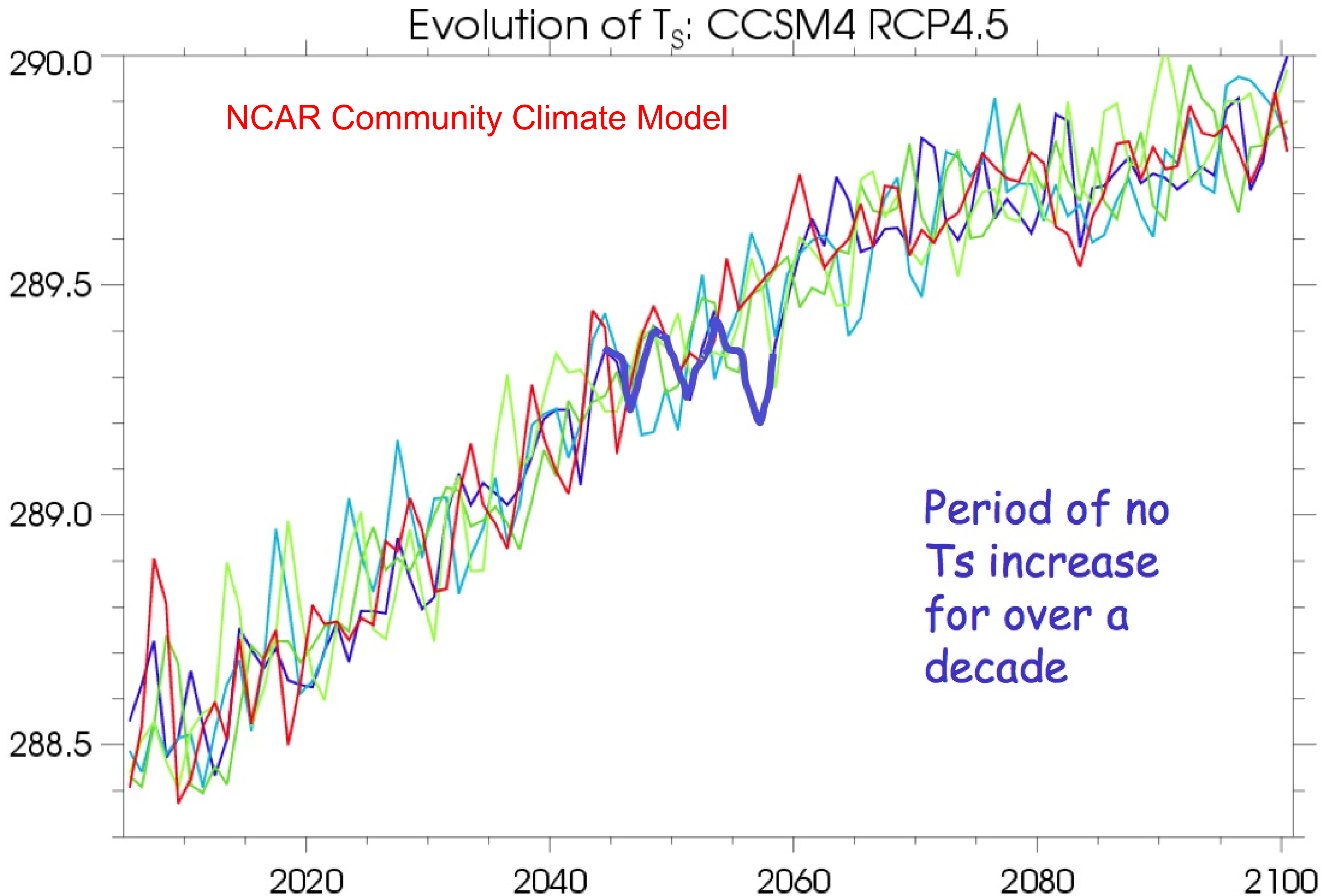
Internal variability:

* El Nino / La Nina

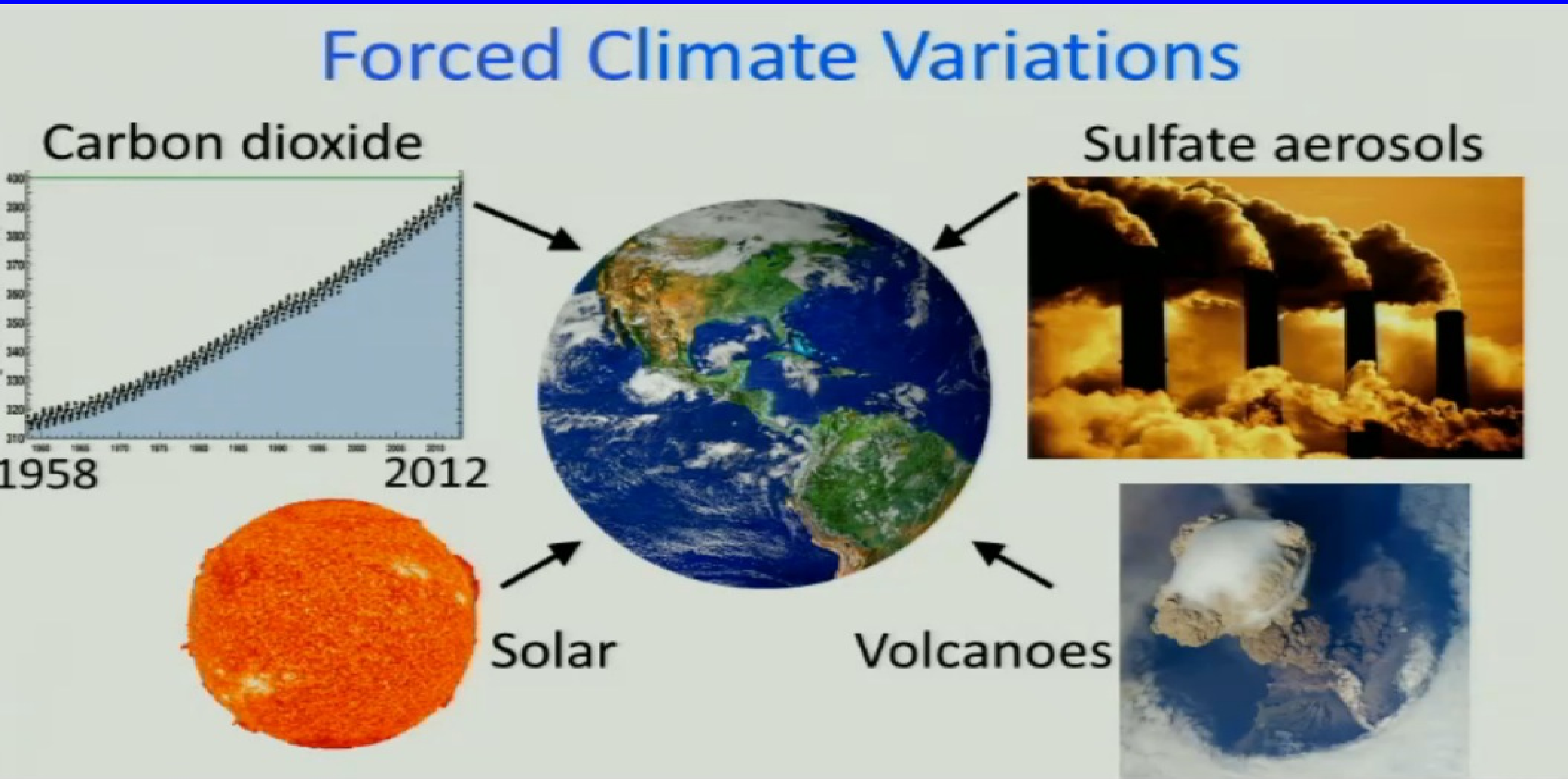
* Madden-Julian Oscillation

* other oscillations (vacillations, really)
  - Arctic
  - Pacific Decadal
  - Atlantic

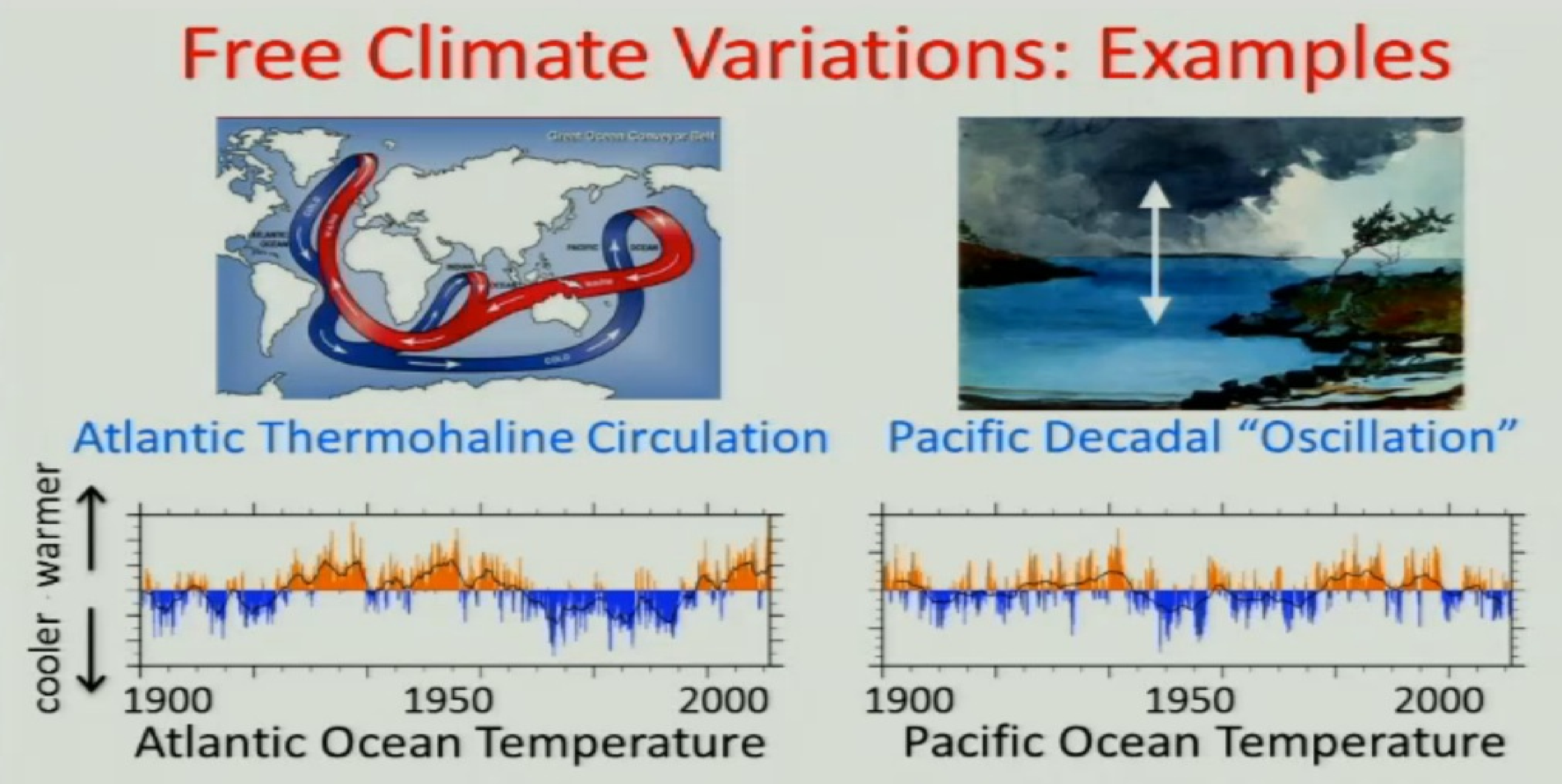
# Global warming hiatuses in models: who knew?



# Forced climate variations are the goal

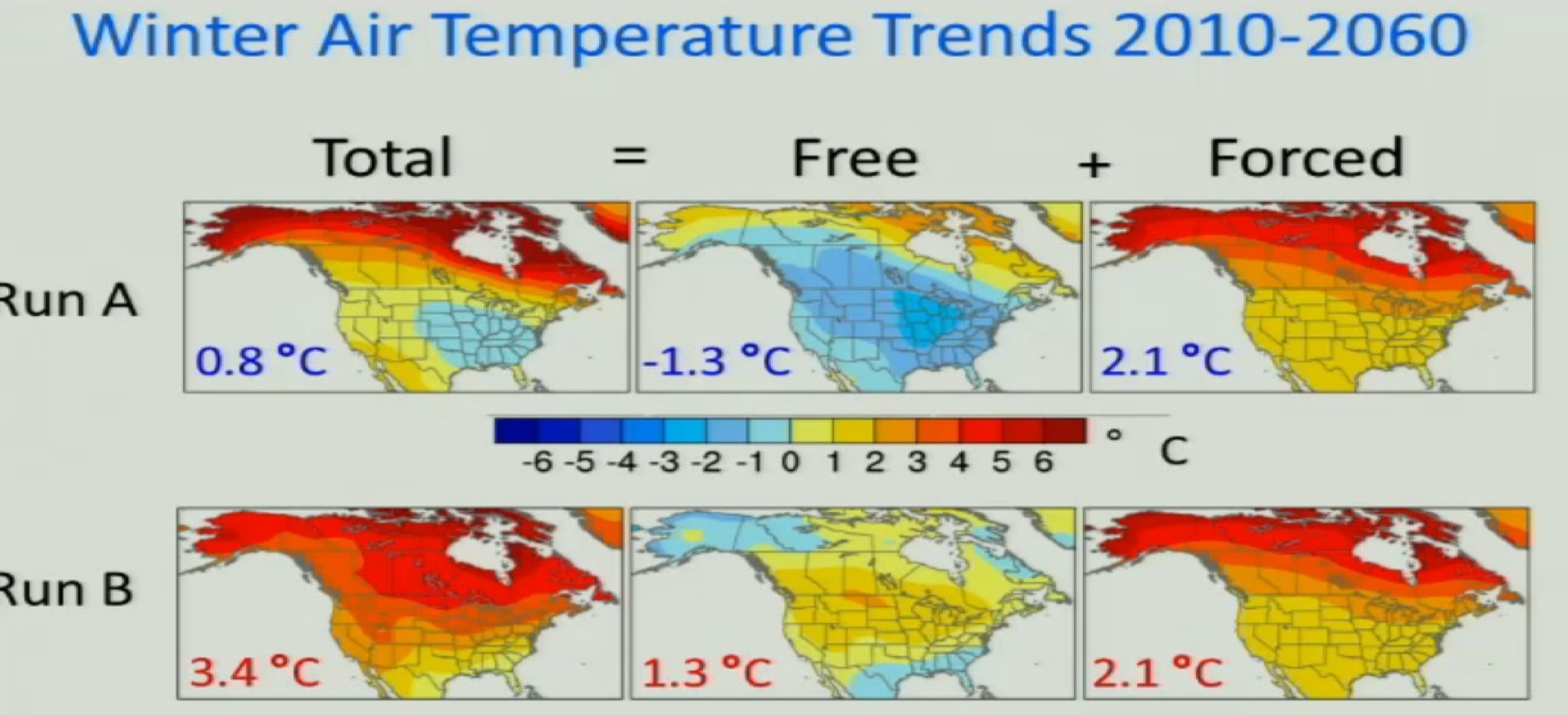


# Free climate variations are what you get



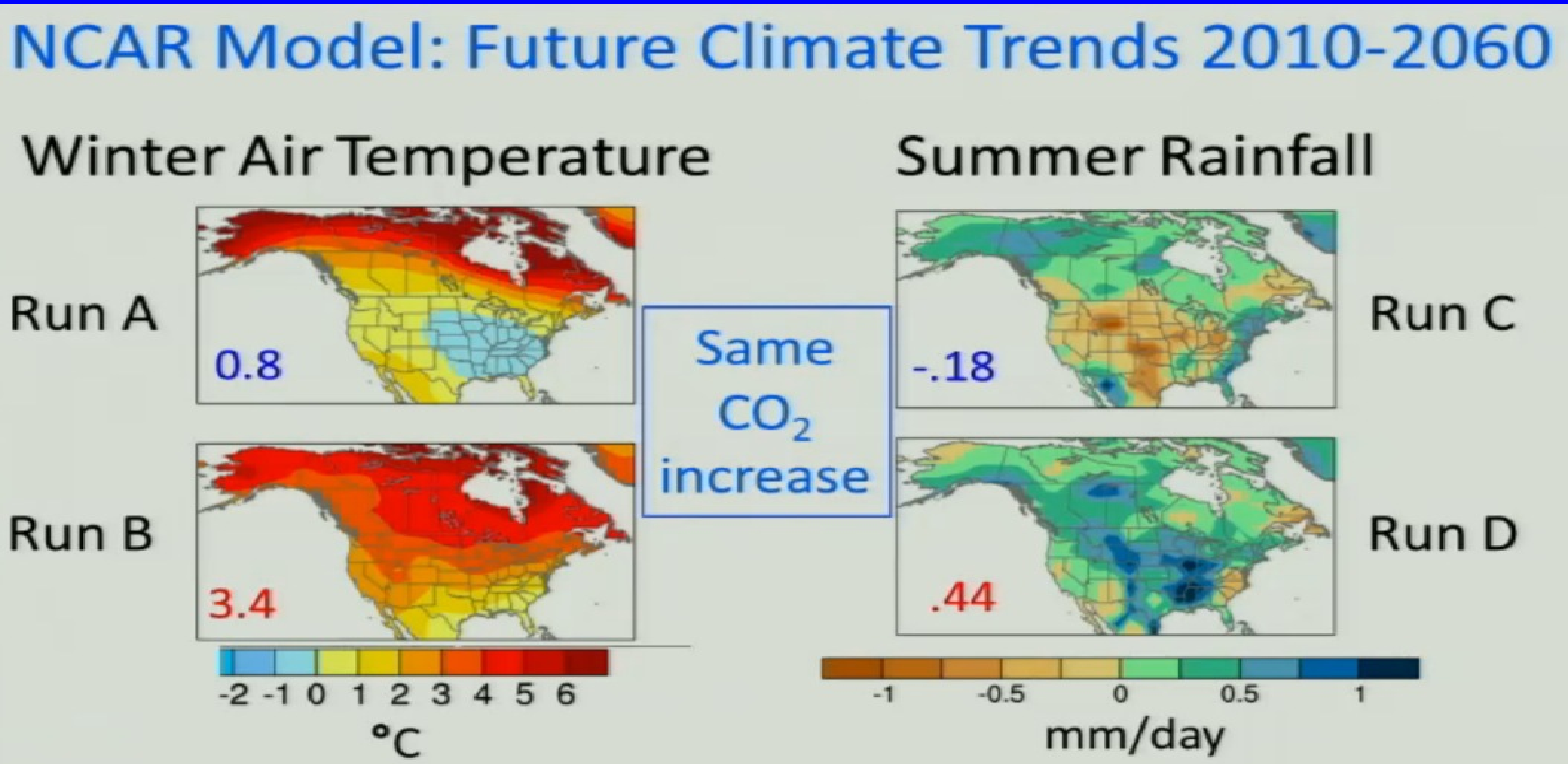
# 40 identical experiments with NCAR CCSM3 for 2000-2060 with CO2 and sulfate aerosol forcing

Winter air temperature trends

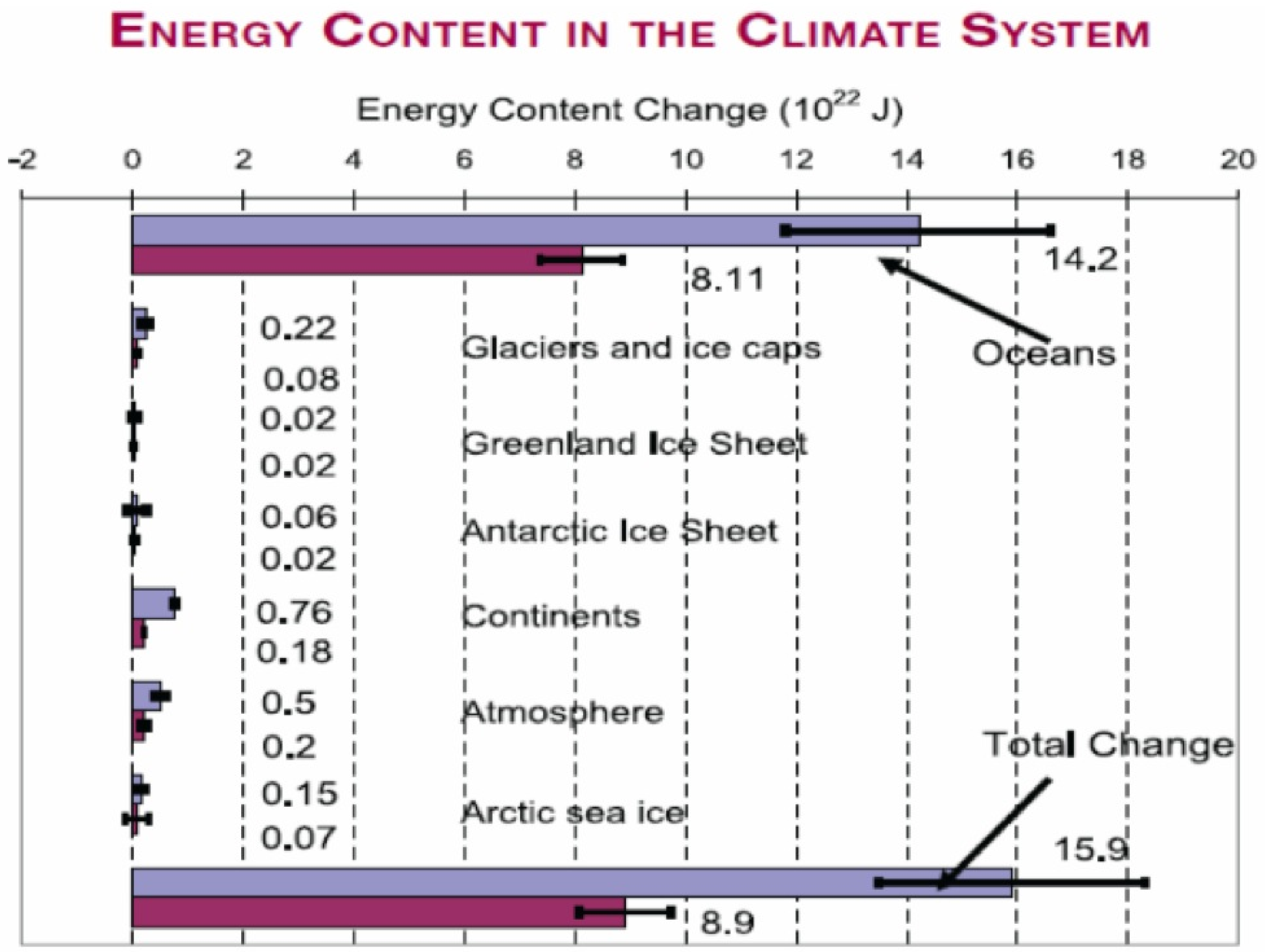



Deser 2013

# It matters which ensemble member you are on!



# Where does the extra energy from rising CO2 go? Bet on the oceans!

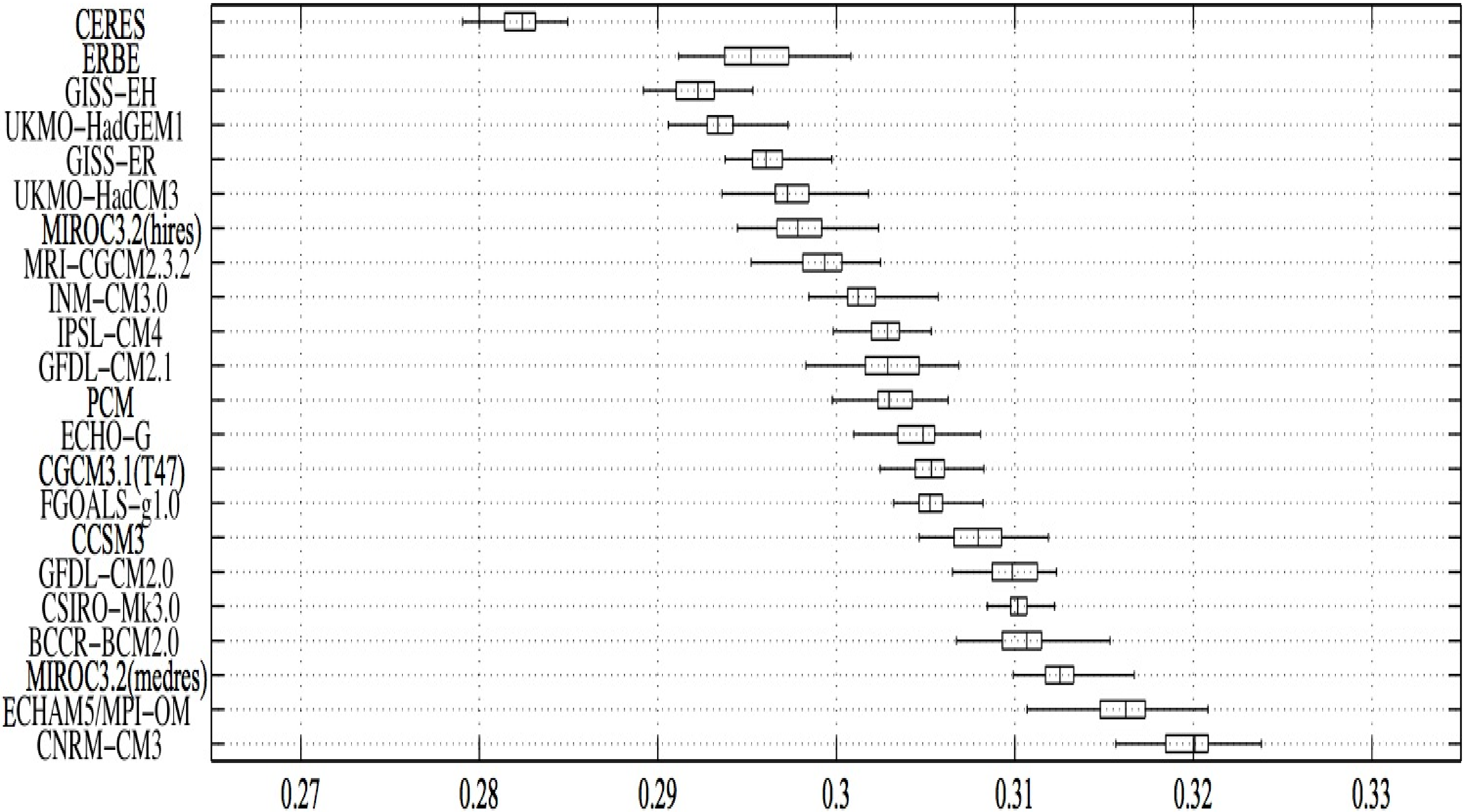



from IPCC, Trenberth

Blue= 1961 to 2003

Burgundy= 1993 to 2003

# Bender 2005: model disparity in Earth albedo



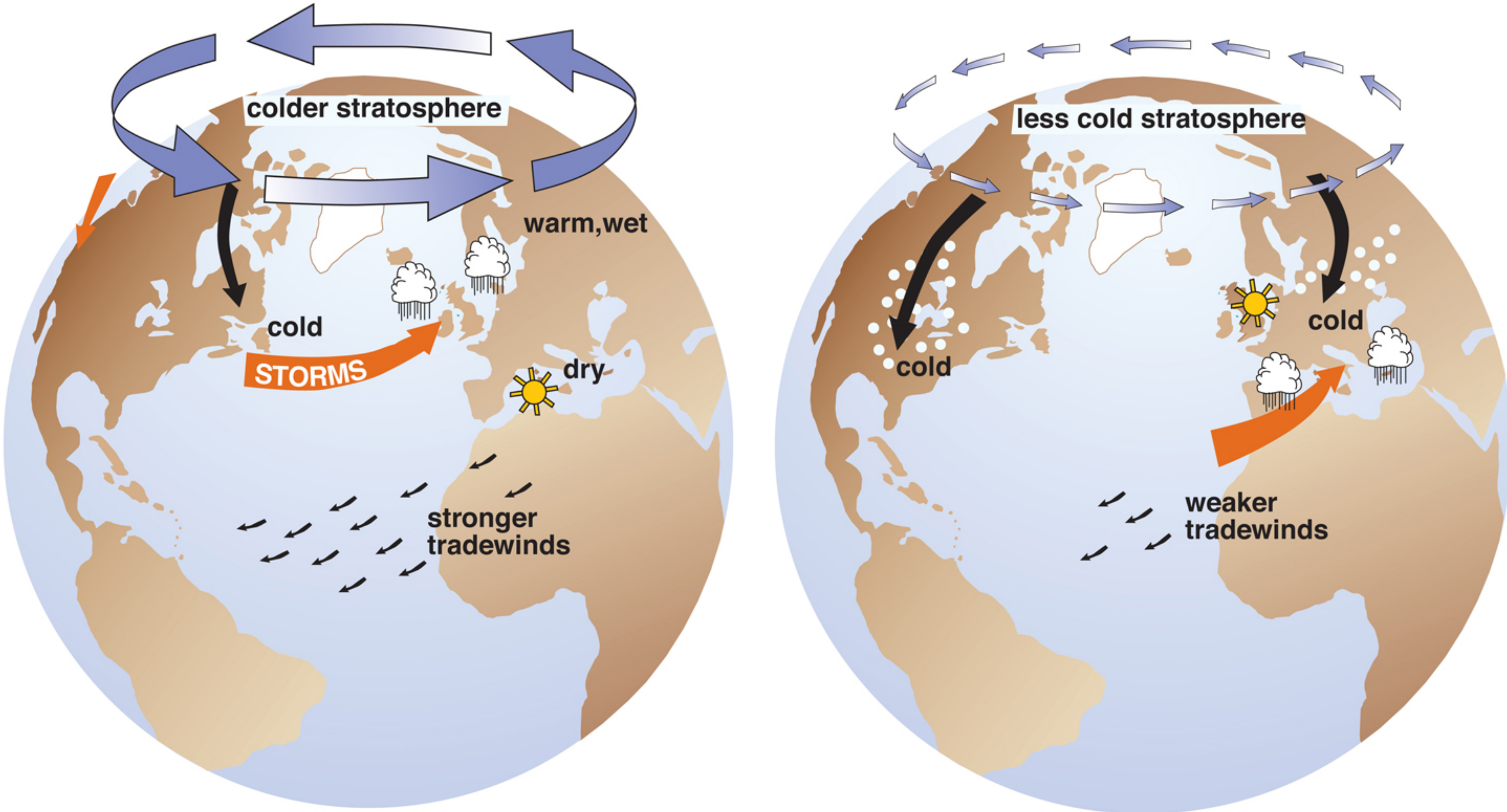
# Arctic Oscillation (AO)

= an opposing pattern of pressure between the Arctic and northern middle latitudes

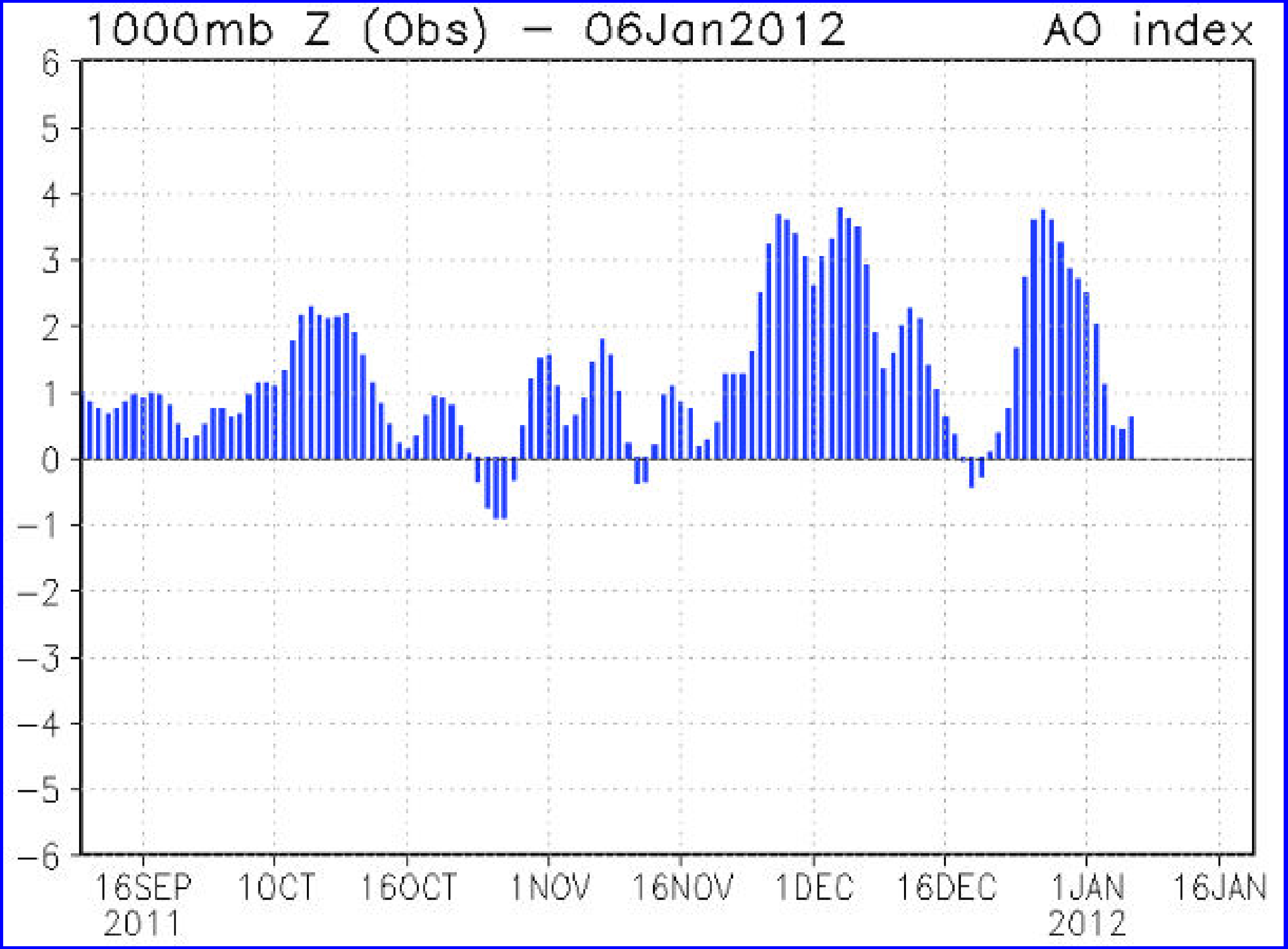
From 1970s to mid-1990s, AO tended to lock into positive phase.

However, since then (as before 1970) has alternated between positive and negative, with record negative phase in 2009-2010 winter.

# Arctic Oscillation (AO)



# Arctic Oscillation Index, Winter 2011



# Regional climate change forecasts?

NEWS&**ANALYSIS**

GLOBAL CHANGE

## Forecasting Regional Climate Change Flunks Its First Test

The strengthening greenhouse is warming the world, but what about your backyard, or at least your region? It's hard to say, climate researchers concede. Modelers have sharpened their tools enough to project declining grape yields in a warmer, drier California wine country and to forecast that the Mediterranean region will be getting drier in coming decades. But just how reliable such localized projections might be remains unclear.

Now, a group of global, rather than regional, modelers has tested a widely used

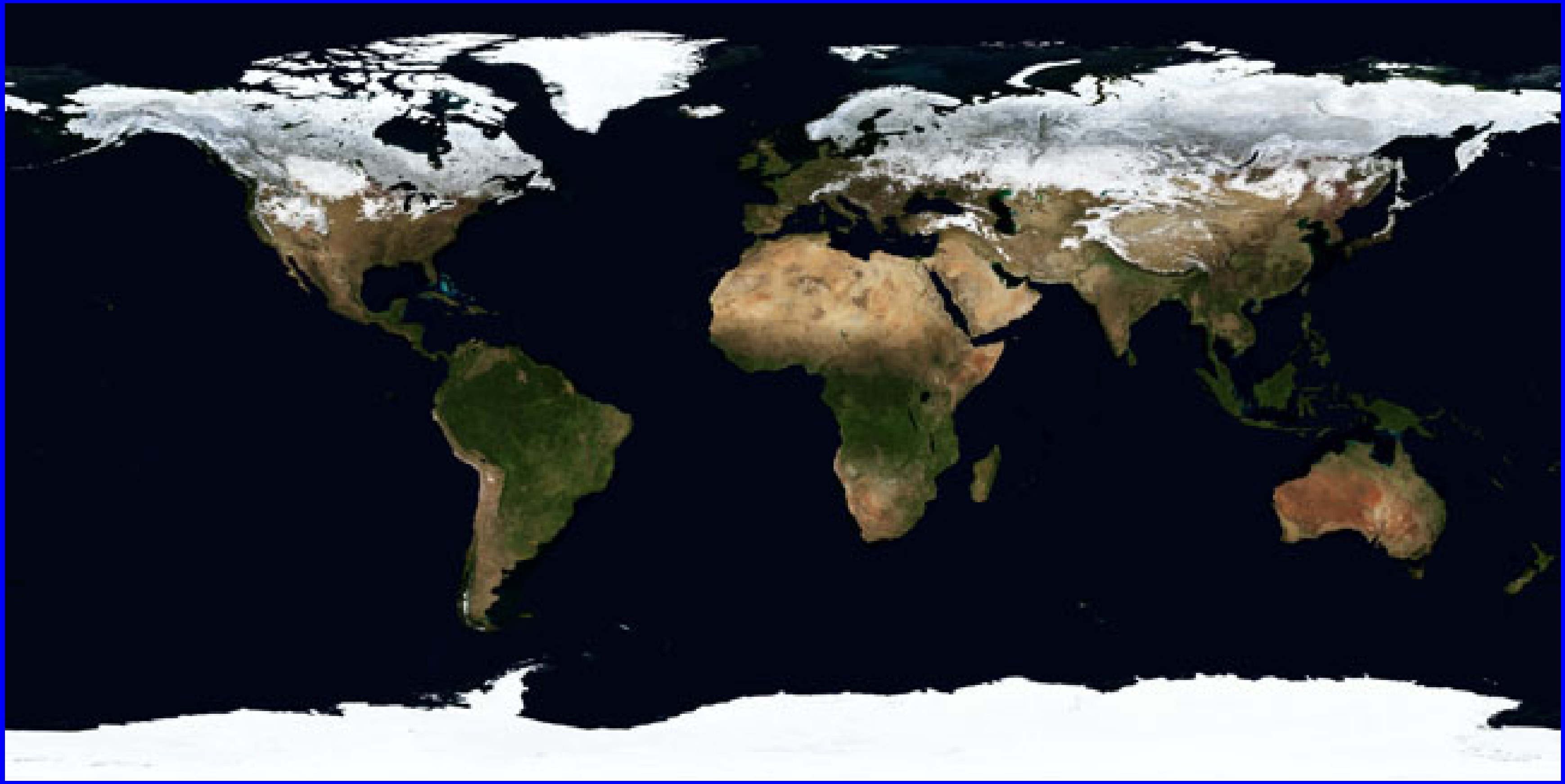
provide detailed, reliable climate projections for, say, West Texas versus East Texas. So modelers began embedding a detailed, higher resolution climate model spanning, for example, much of North America, in a global climate model. The global model would calculate broad changes and feed them into the embedded regional model, which would then compute more-detailed (and, presumably, more-accurate) simulations of smaller atmospheric features, such as storms and fronts, as well as better rendering of the atmospheric

WRF did not shine. "Skill capturing climatology does not translate into skill capturing climate change," Shindell concludes, echoing the group's paper of late last year in the *Journal of Geophysical Research: Atmospheres*. "There is modest improvement over the [global] model, but it's not so large." And most of that improvement came only when the global model was periodically allowed to "nudge" the wandering regional model back toward a more realistic broad-scale pattern of climate.

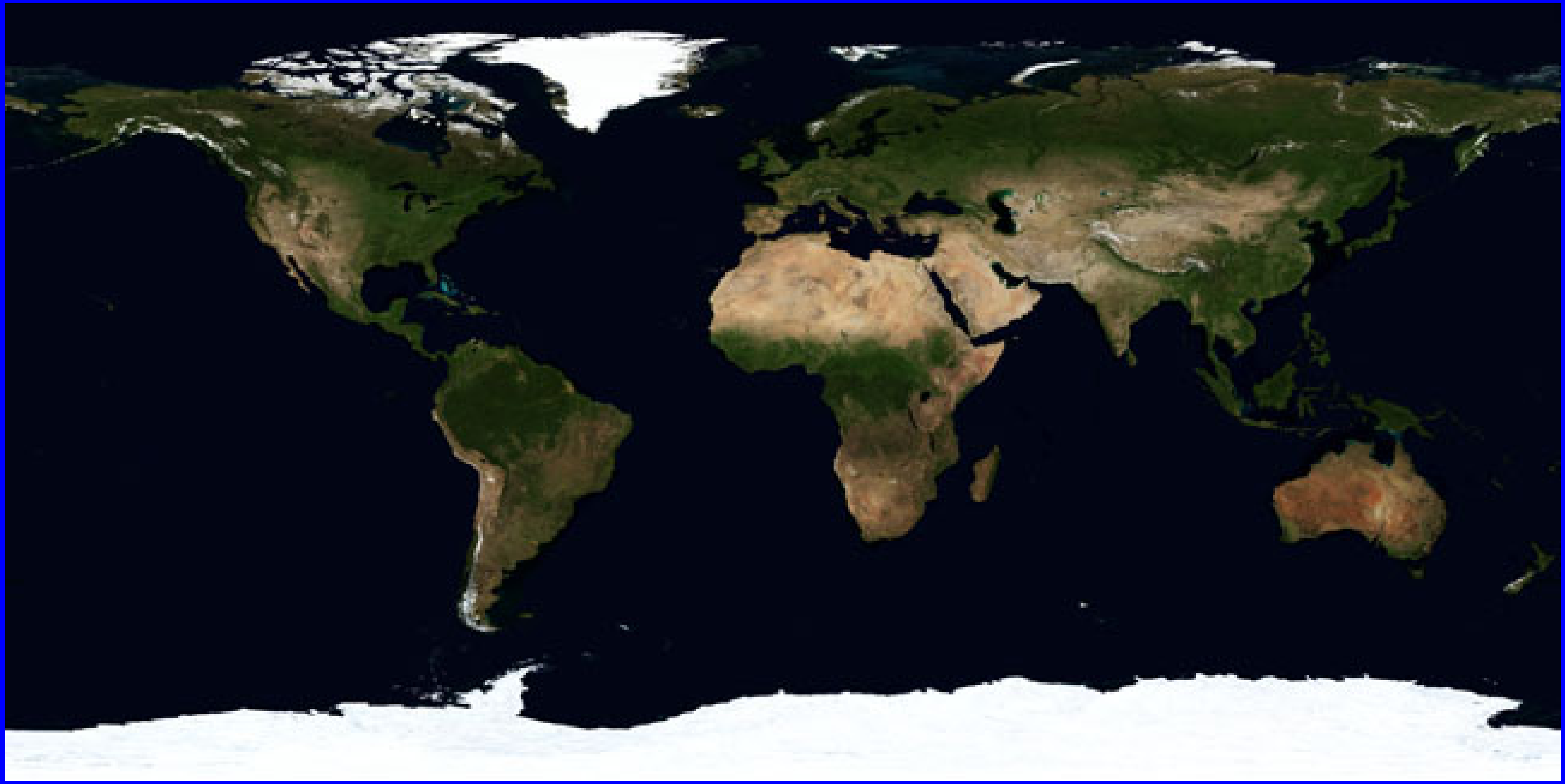
Kerr, Science, 8 Feb 2013

# Cryosphere

# Ice on Land Today – January



# Ice on Land Today – July



# The Two Basic Climate States: Nonglacial and Glacial

Glacial states : multiple expansions of continental ice sheets into midlatitudes

- last tens of thousands of years
- occasional abrupt climate change

Continental drift, sea level change, and CO2 all contributed to planetary temperature shifts on the million-yr timescale

# Evidence of glacials

U-shaped valleys

Till

Striations

Erratics

# Fluctuations of ice sheets in last 3M yr

correlate with Earth-orbit-induced changes in solar radiation distribution with latitude.

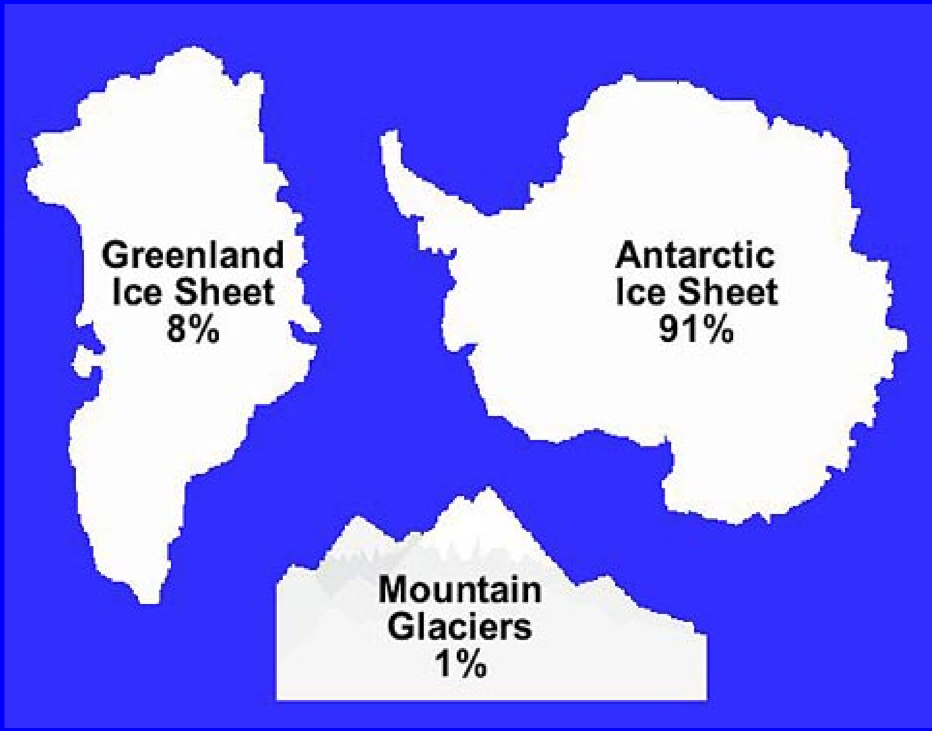
Terrestrial feedbacks (ice sheet dynamics, ocean temperatures, CO2) modulate the orbital signal.

# How much ice?

Greenland and Antarctica contain enough water to raise sea level by over 73 m.

Measurements of ice elevation and volume were poorly known until IceSAT and GRACE.

(Older satellites missed poles.)



# Ice and Snow Strongly Affect Climate

During Northern Hemisphere winter, they

- blanket up to 15% of the Earth's surface,
- reflect up to 80% of sunlight back to space.

During Southern Hemisphere winter, they cover only 8% of the surface, . . .

but their influence is far larger than their areal coverage would indicate.

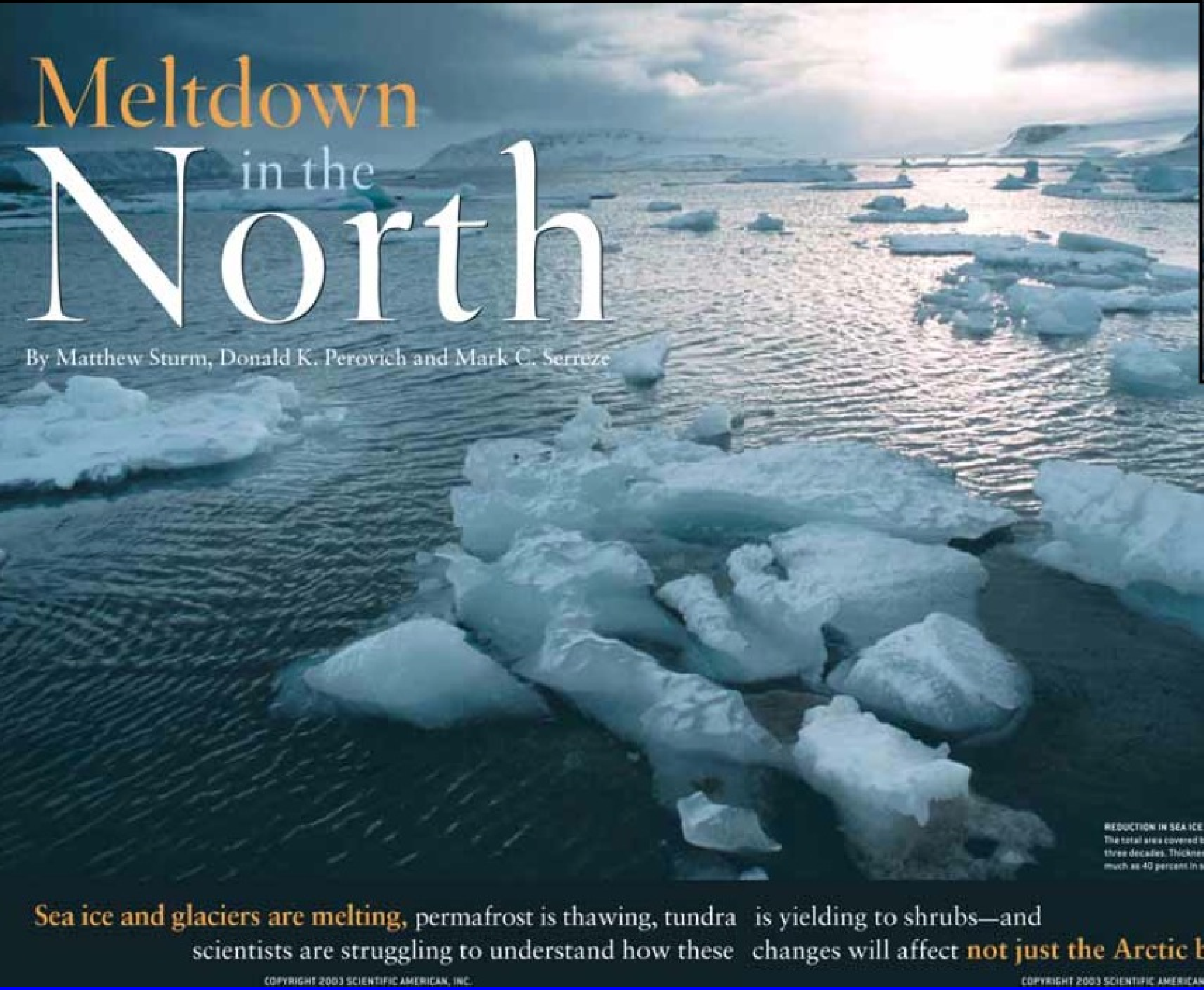
# Global Warming and the Cryosphere

Ice-albedo feedback

Meltback of sea ice would increase ocean heat flux to atmosphere, again amplifying the warming.

It would also increase vapor flux to atmosphere, which might enhance clouds.  What would that do?

Climate Models (not all...) have been predicting amplified Arctic warming since Manabe in late 1960's. But...the observational data were too sparse to tell.


Meltdown
in the
North
By Matthew Sturm, Donald K. Perovich and Mark C. Serreze
REDUCTION IN SEA ICE is one of the most striking measures of change in the Arctic. The total area covered by sea ice has shrunk by 3 percent during each of the past three decades. Thickness has decreased even more over this same period—as much as 40 percent in some places. The image shows the Arctic Ocean near Russia.
Sea ice and glaciers are melting, permafrost is thawing, tundra is yielding to shrubs—and scientists are struggling to understand how these changes will affect not just the Arctic but the entire planet
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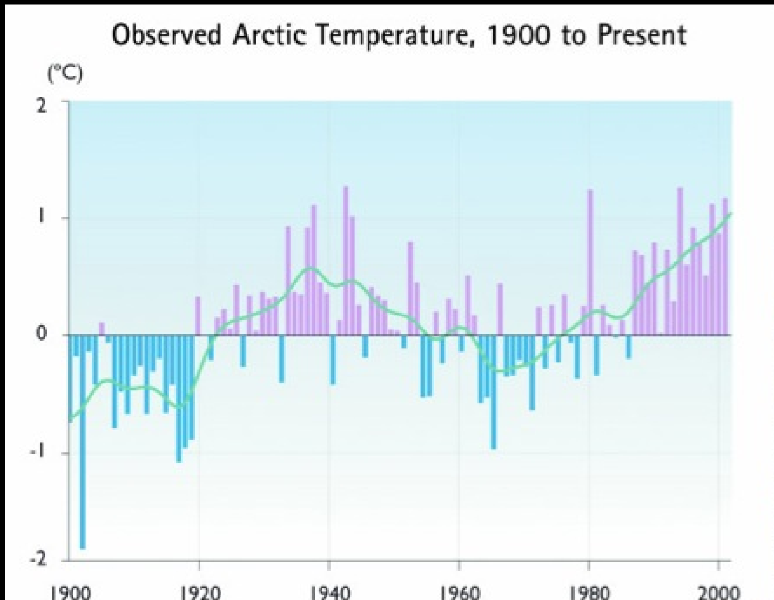
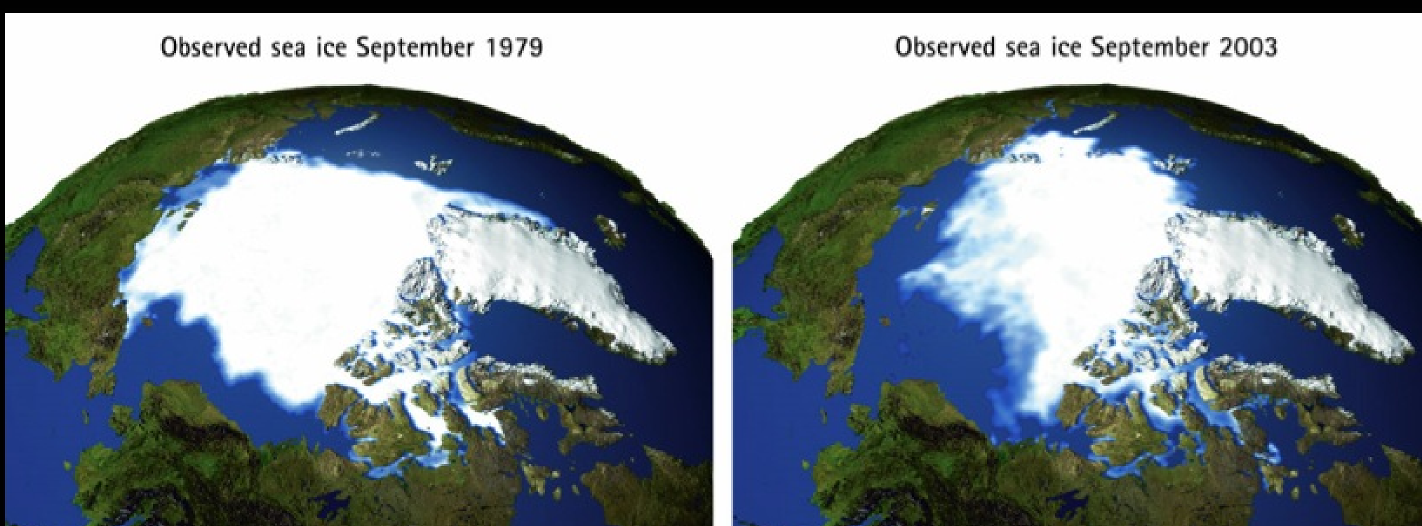
Science
30 August 2002
Polar
Science

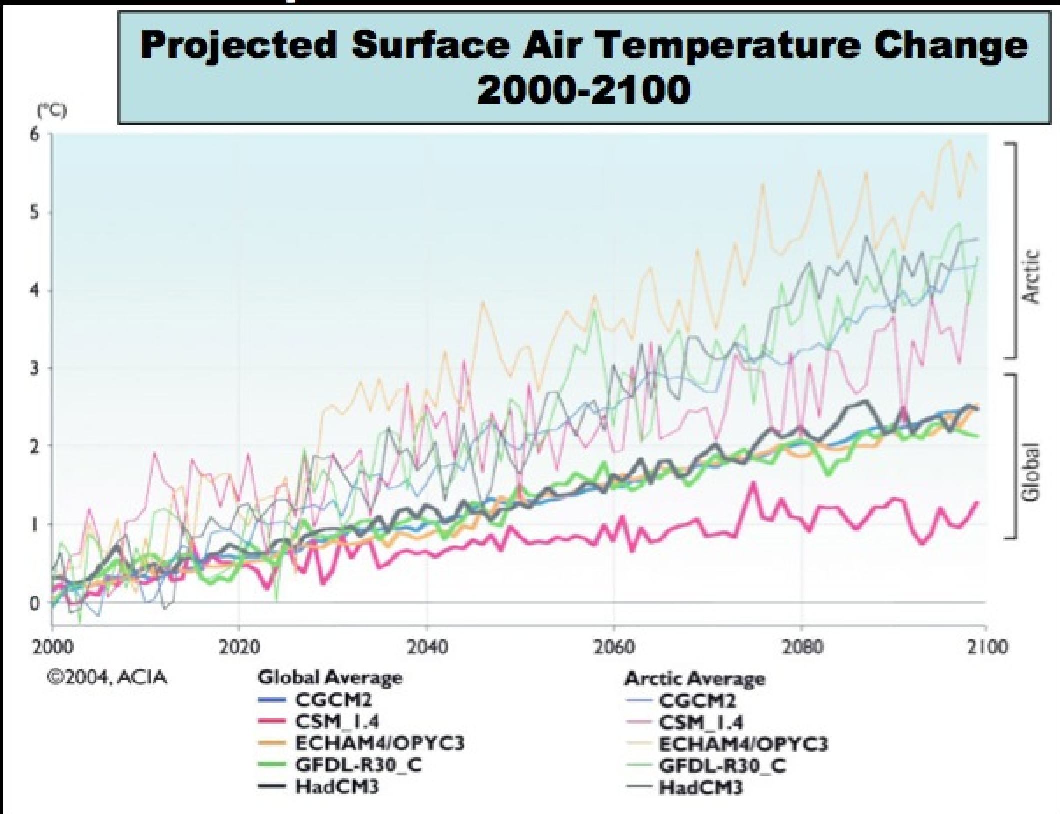
# *Arctic warming is currently underway...*

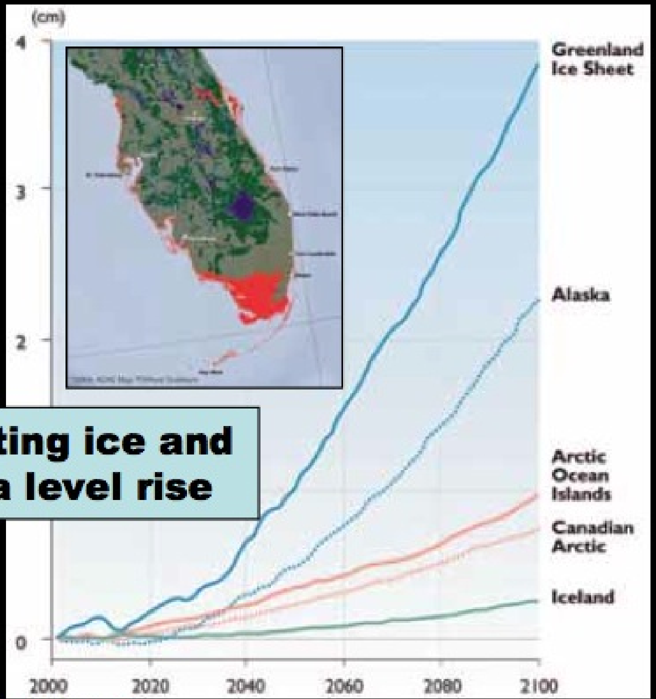




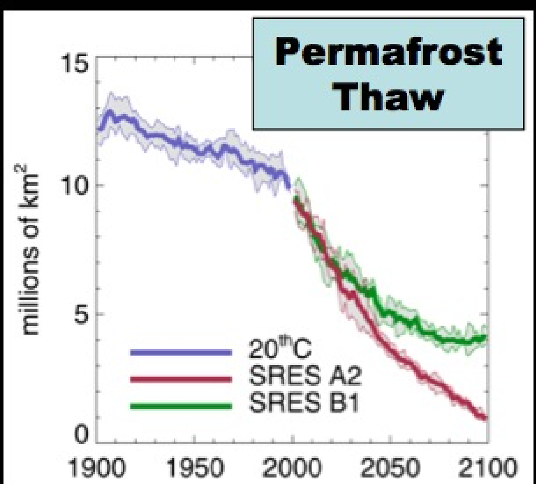



# Models predict even more warming in this century...

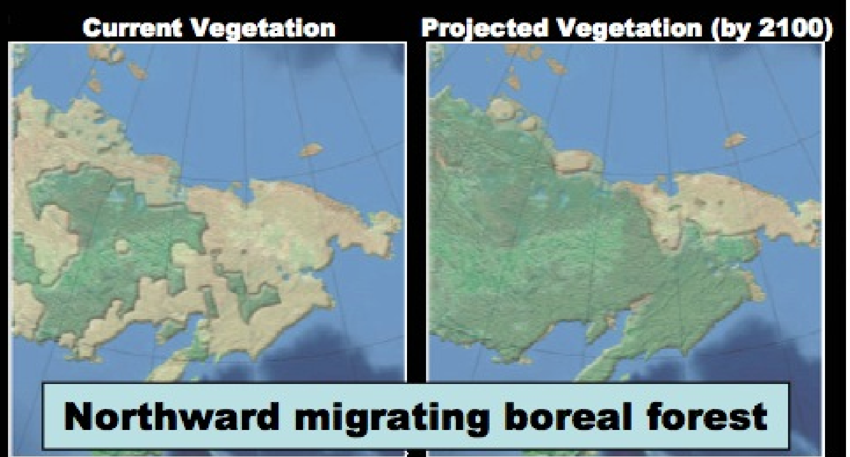


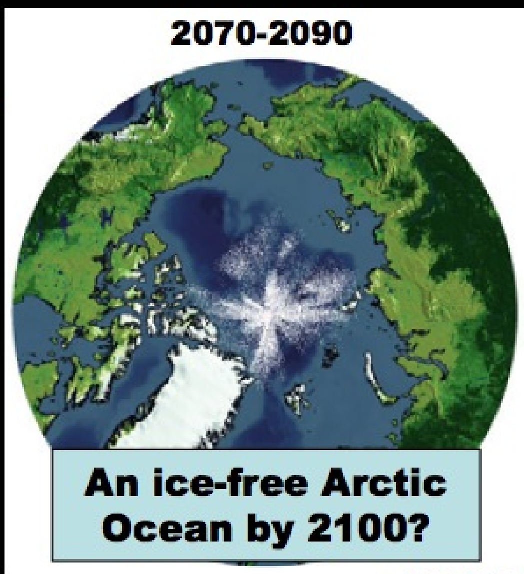

*ACIA (2004)*




*Lawrence & Slater (2005)*




©2004, ACIA/ map ©Clifford Grabhorn




*ACIA (2004)*

# SHEBA, 1998: early warning of Arctic sea ice collapse

- the first extensive sea ice experiment ...
  - since AIDJEX in 1972, in which I was involved
- icebreaker, frozen for a yr in Arctic ice
- helicopter, aircraft, under-ice robot surveys
- confirmed what U.S. nuclear submarines had seen: dramatic thinning of pack ice

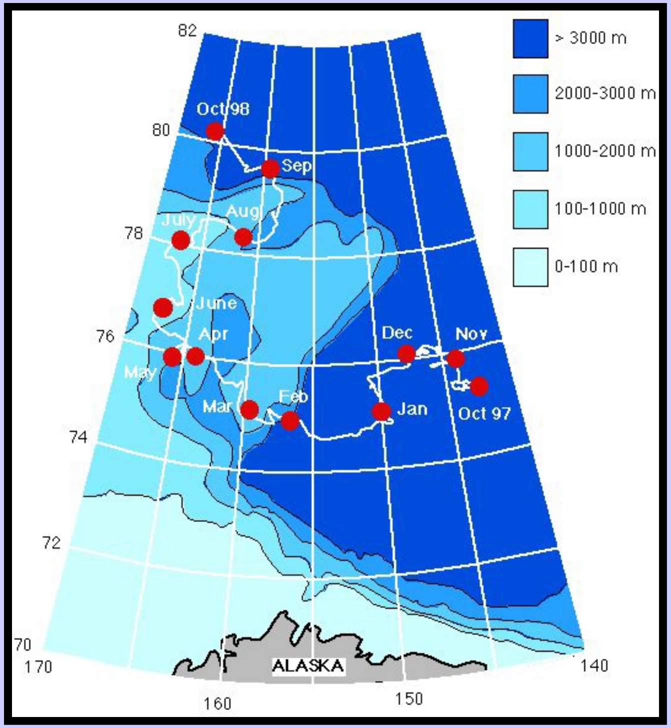
# SHEBA

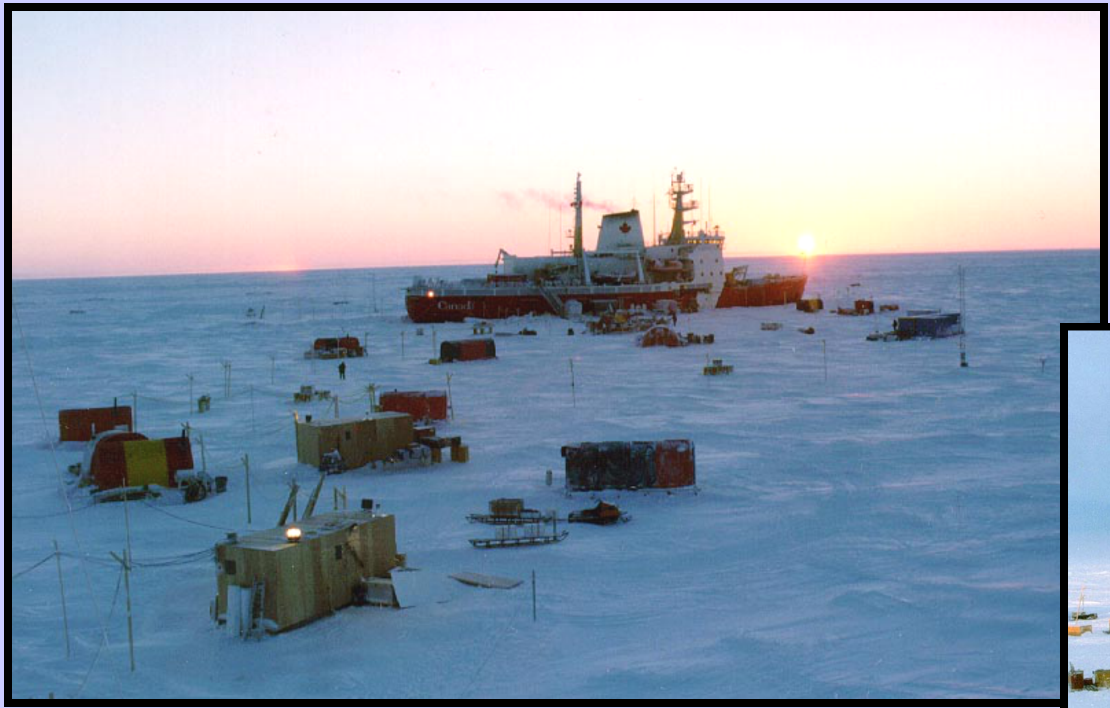
## The Surface Heat Budget of the Arctic Ocean

- Major climate change initiative
- NSF, ONR funded
- SHEBA team
  - ~ 150 researchers
  - ~ 20 institutions
- Collaborate with other groups
  - ARM, FIRE, SCICEX

# Ice Station SHEBA

- Year long drift
- CCGC Des Groseilliers
- 2 Oct 1997: 75 N, 142 W
- 11 Oct 1998: 80 N, 166 W
- Total drift ~ 2800 km
- Displacement ~ 800 km



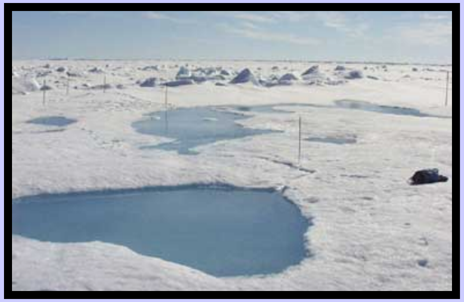



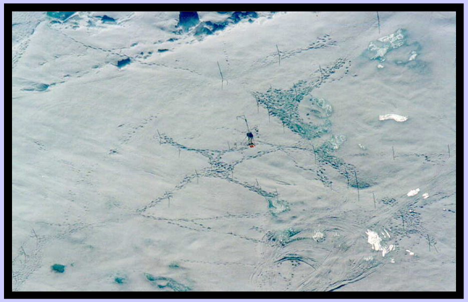
# Seasonal evolution

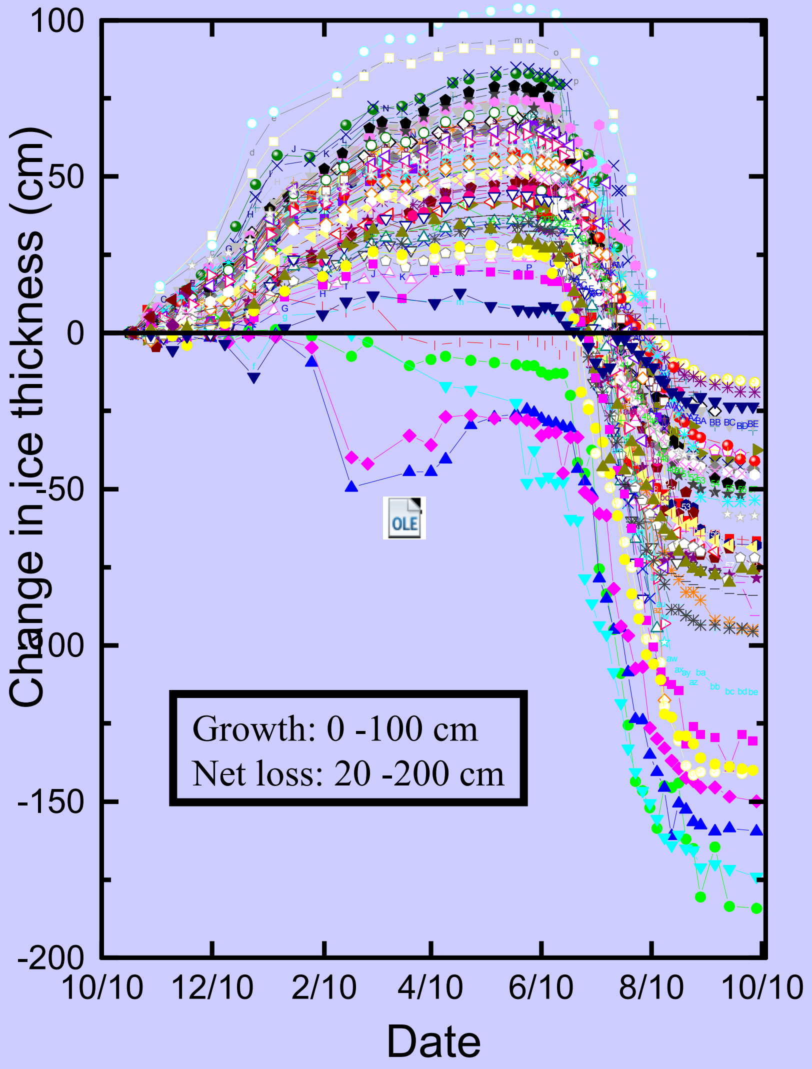
April 17

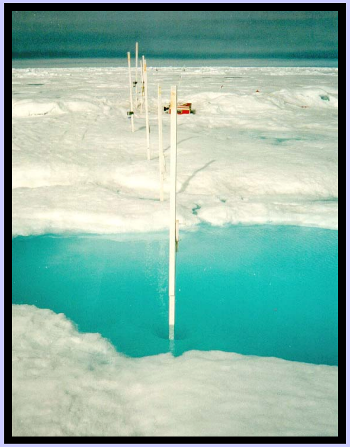
August 8

# Net mass loss during SHEBA year!

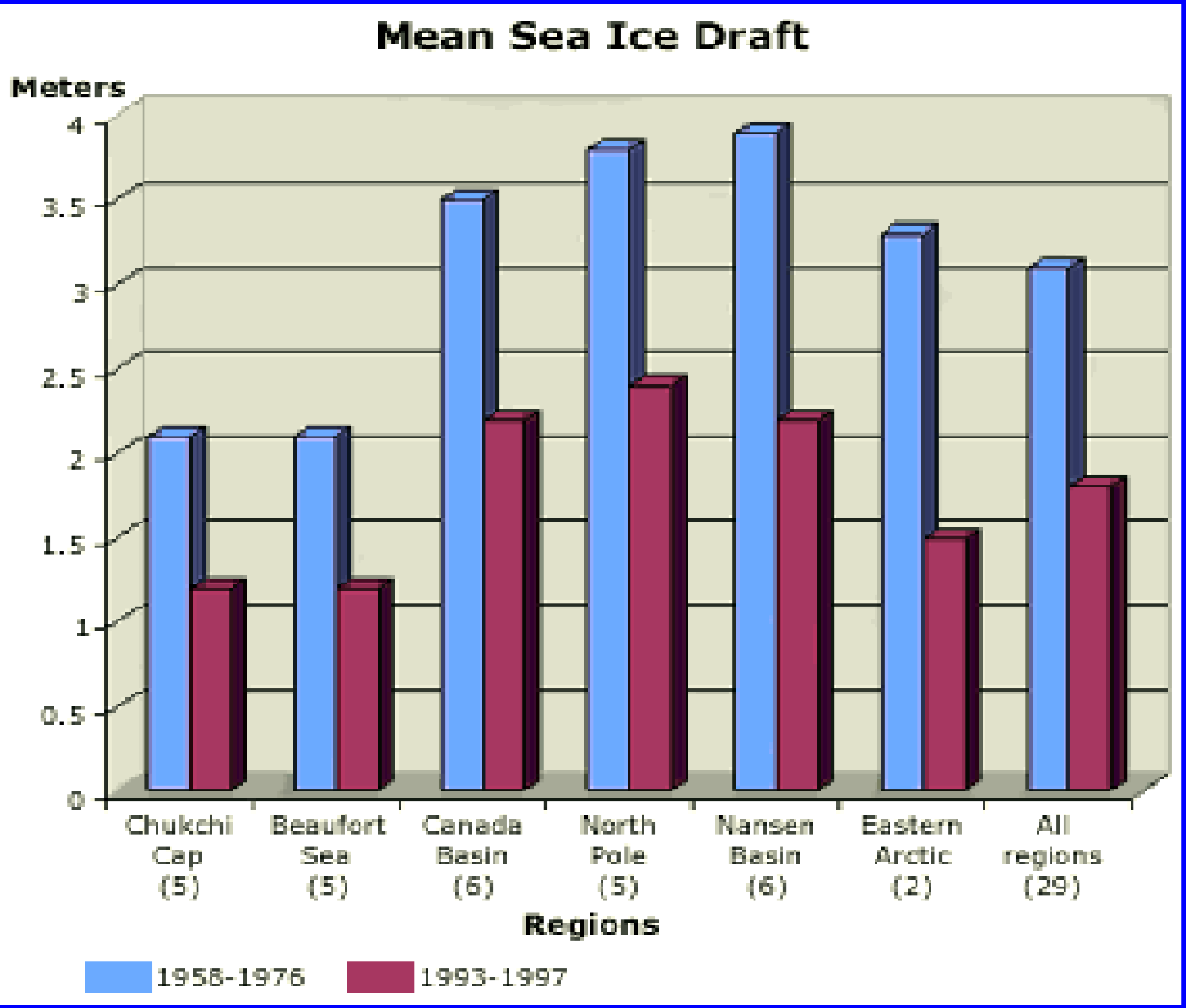






# Sea ice thickness, 1955-76 vs 1993-97




Nuclear submarines measured it, but it was a Cold War secret!

Declassified in mid-90s.

# International Polar Year: 50th Anniversary of International Geophysical Year (IGY)

# News on the Antarctic Warming Front

Earth's fastest warming trend on Antarctic Peninsula: 2.5C in 50 yr

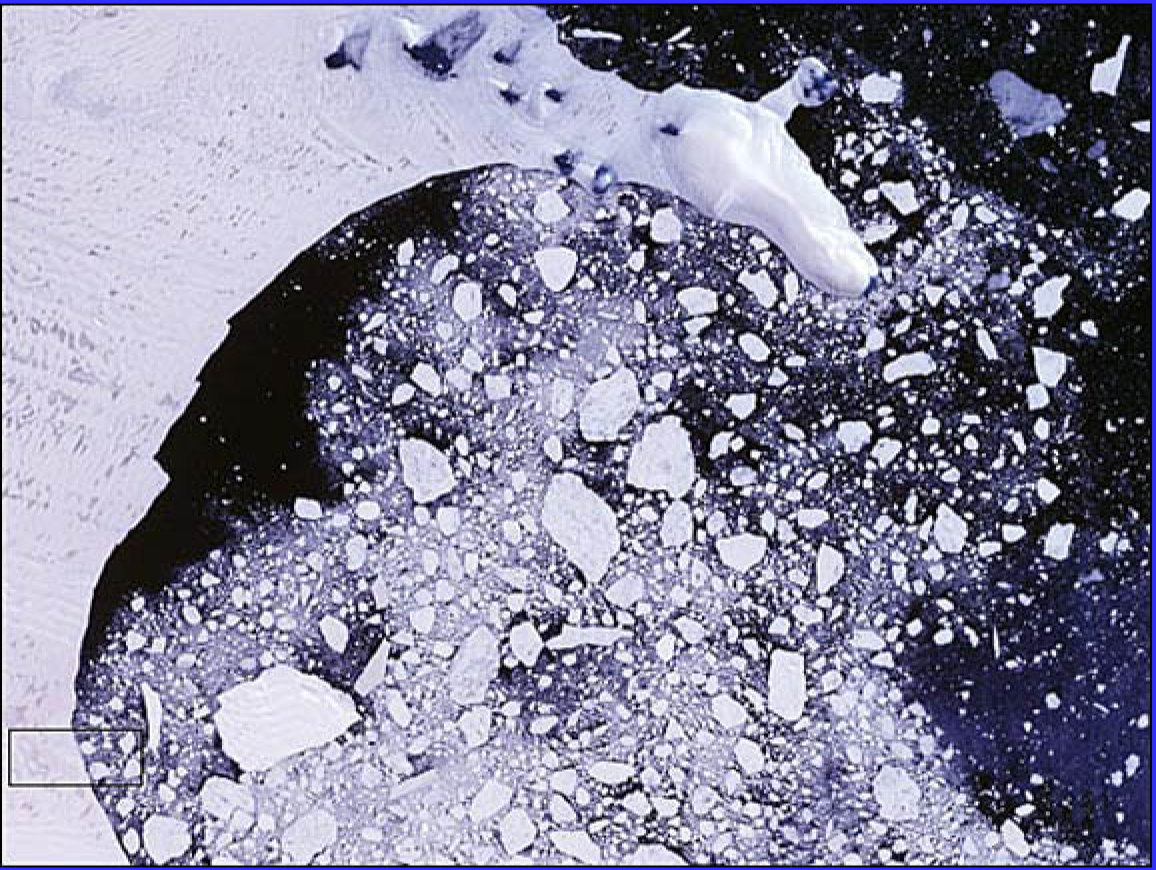
But Antarctica as a whole is not warming

Antarctic sea ice area not decreasing

Some huge West Antarctic outflow ice streams are accelerating and slumping

Some monster Antarctic icebergs have calved recently... but our history is short.

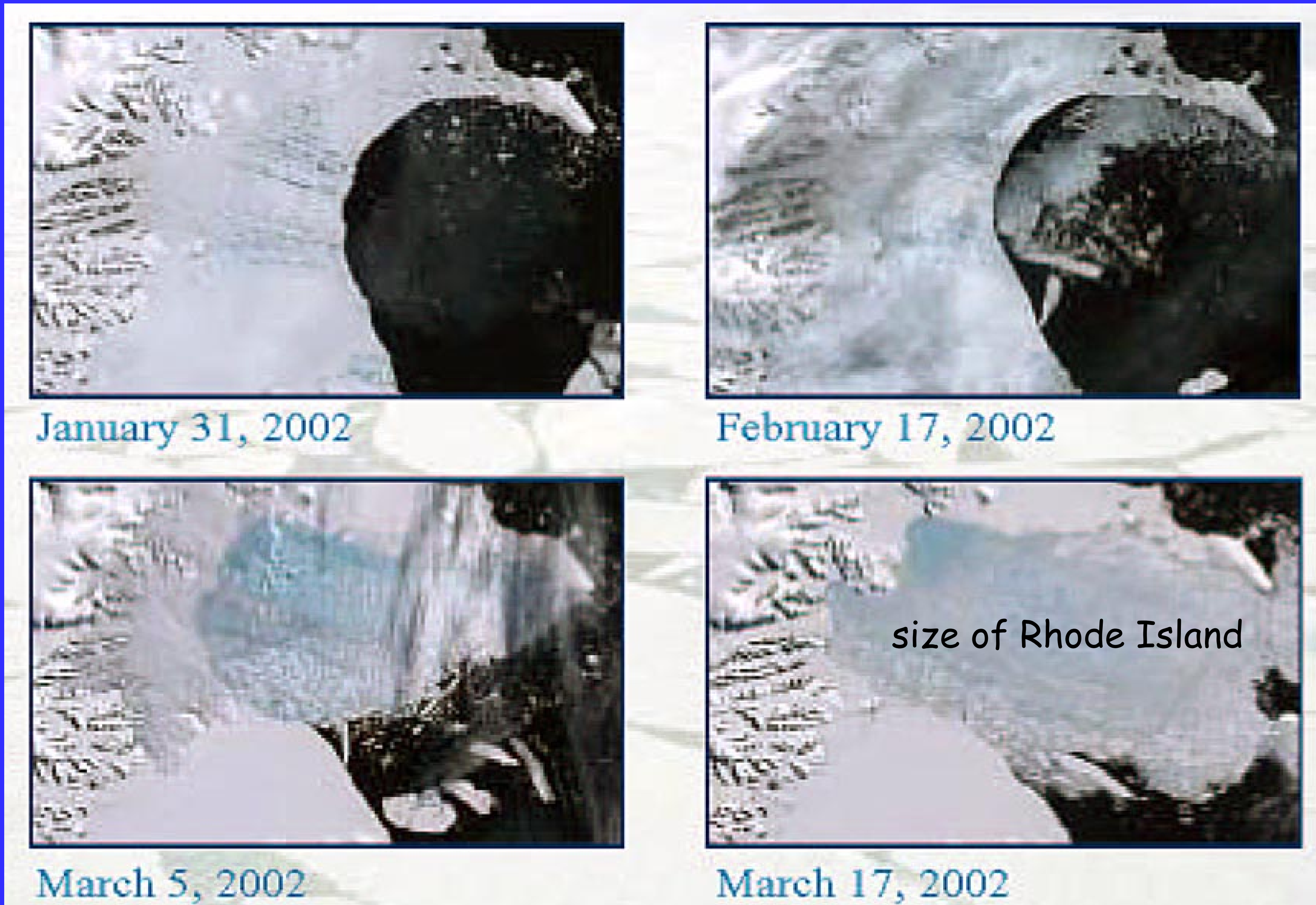
# Collapsing Larsen-B Ice Shelf, Antarctic Peninsula

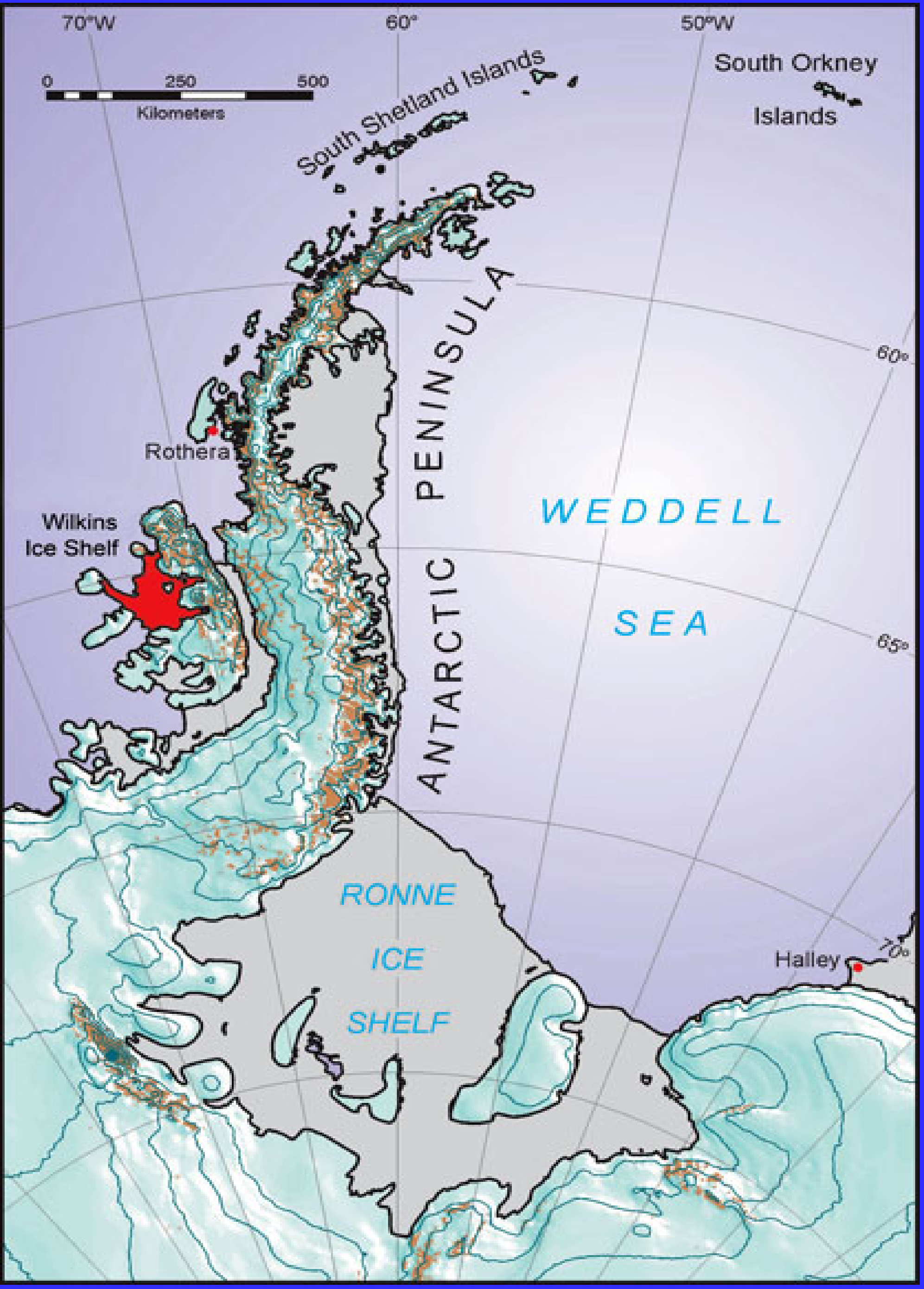


21 Feb 2000 Landsat 7 image

On northern thumb of Antarctica, warming surface temperatures created melt ponds on the surface. Surface water filled crevasses, then froze, cracking the ice entirely through.

# Larsen-B Ice Shelf Collapse






# Wilkins Ice Shelf Collapse, Feb 2008

# Wilkins Ice Shelf Collapse, Feb 2008

# News on the Arctic warming front

40% thinning, Arctic sea ice, 1950s to 2007

10%/decade reduction in surface area, sea ice

0.6C/decade temperature increase since 1960s in high northern latitudes

Greenland warming has finally surpassed the warmth of the 1930s.

Greenland melted all over, July 2012.

# IPY Movie:  Changes in the Arctic

# Themes from movie

GLIMS glaciers:  97% shrinking

Arctic sea ice shrinking

Permafrost

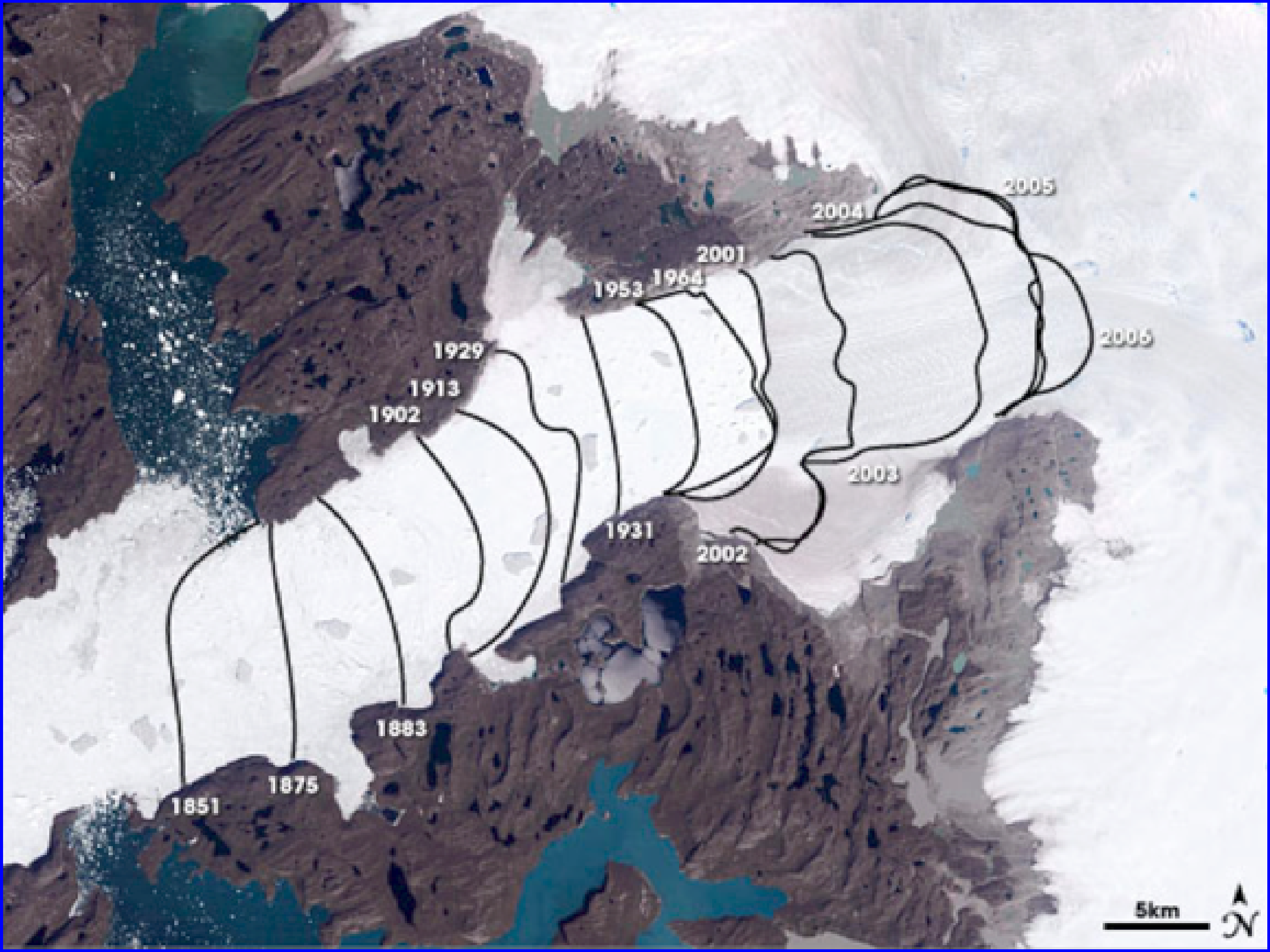
Greenland;  Jacobshaven retreat accelerating

Snow cover;  water storage

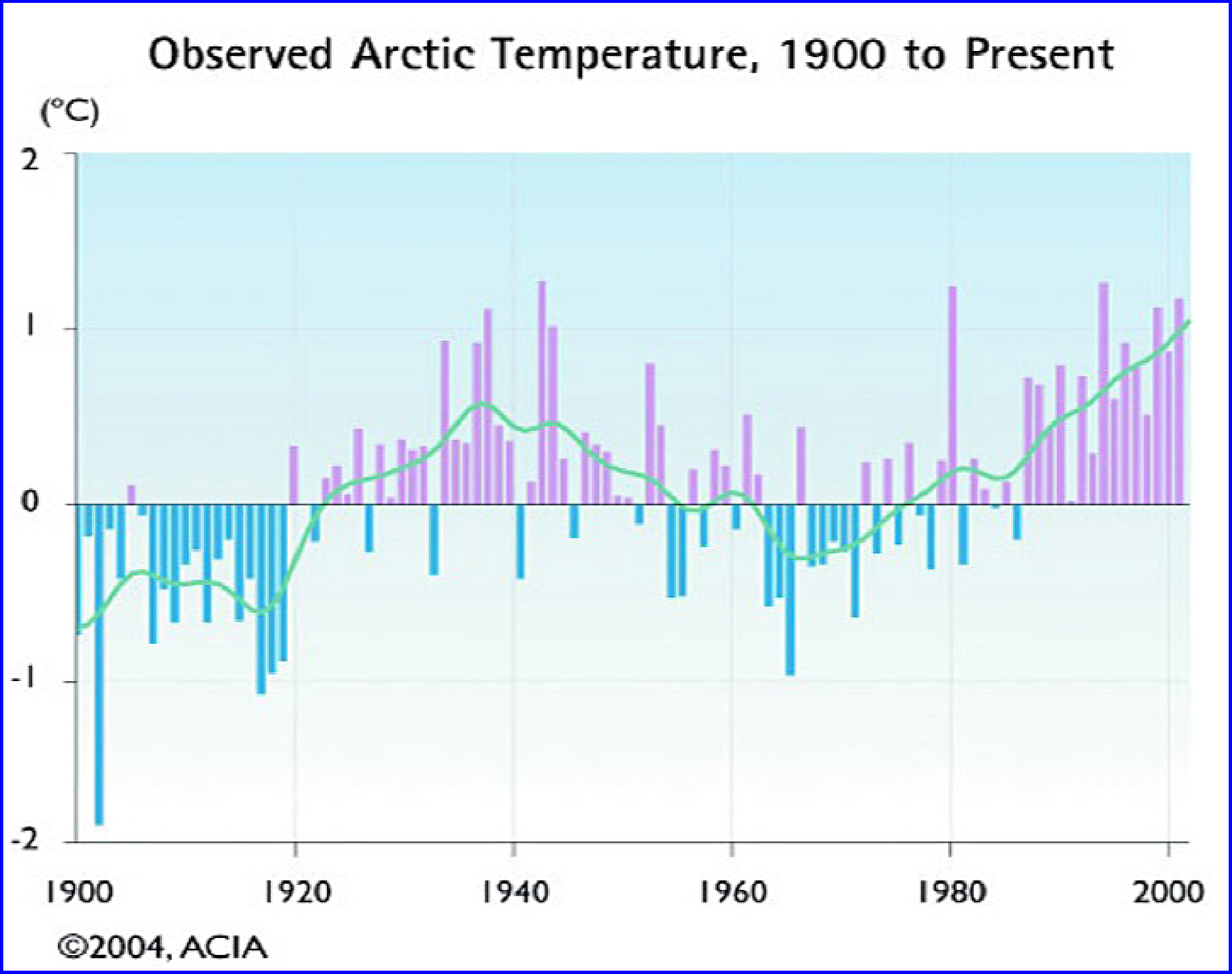
Colorado: green 2003, drought 2004 + fires

Snow/ice keep Earth cool

# Jacobshavn Glacier retreat to 2006



# Arctic avg temp change, 1900 to 2000



# Observed Arctic climate change fingerprints

Polar amplification: Arctic air temp's rising 2-3x faster than rest of world

Arctic sea ice thickness, extent collapsing

Arctic glaciers retreating

Shrubs expanding, tree line moving north

Tundra shifting from CO2 sink to source

Permafrost temp's rising

# Global Land Ice Meas't from Space (GLIMS)

160,000 glaciers

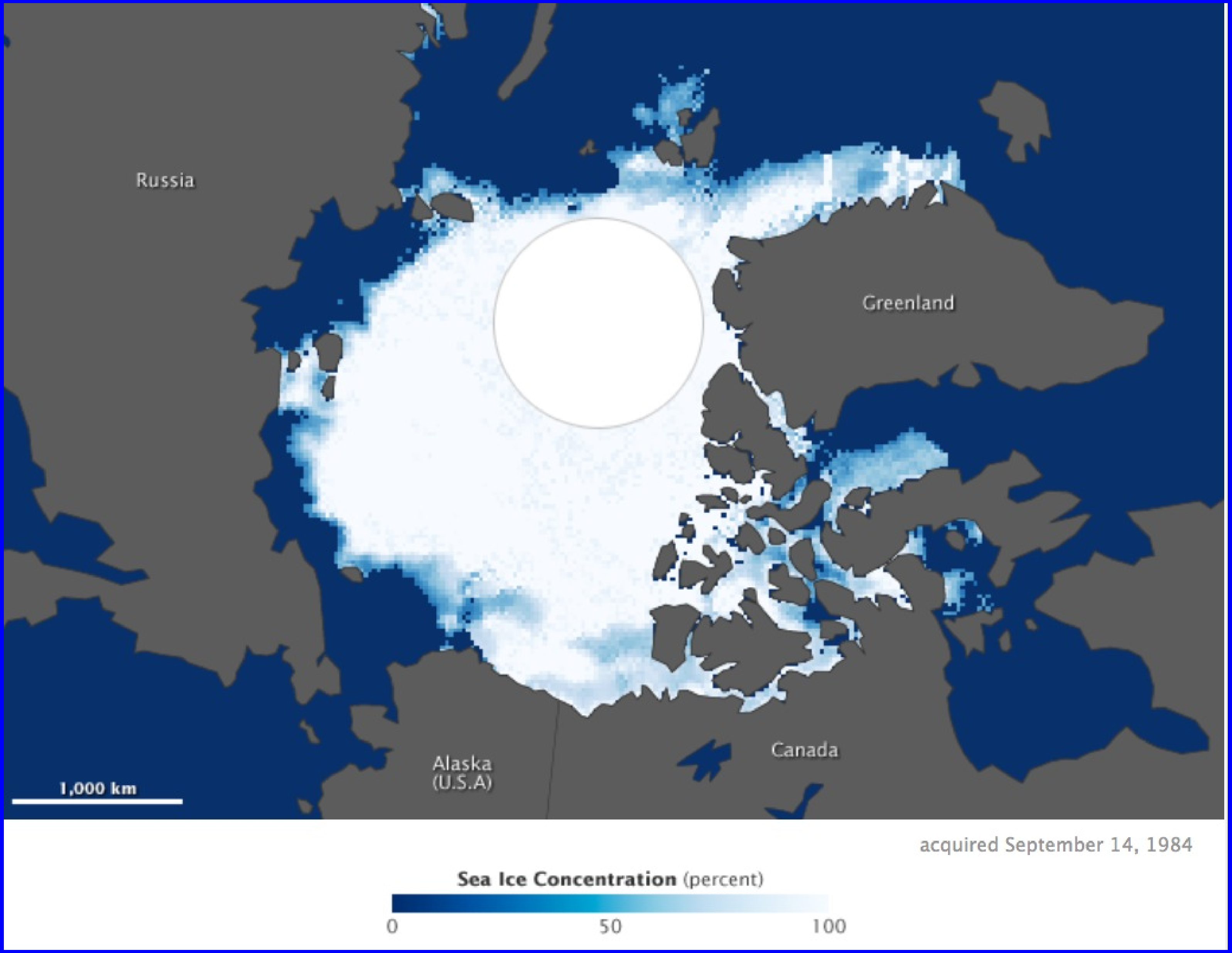
Vast majority not monitored on ground

GLIMS uses mainly ASTER data

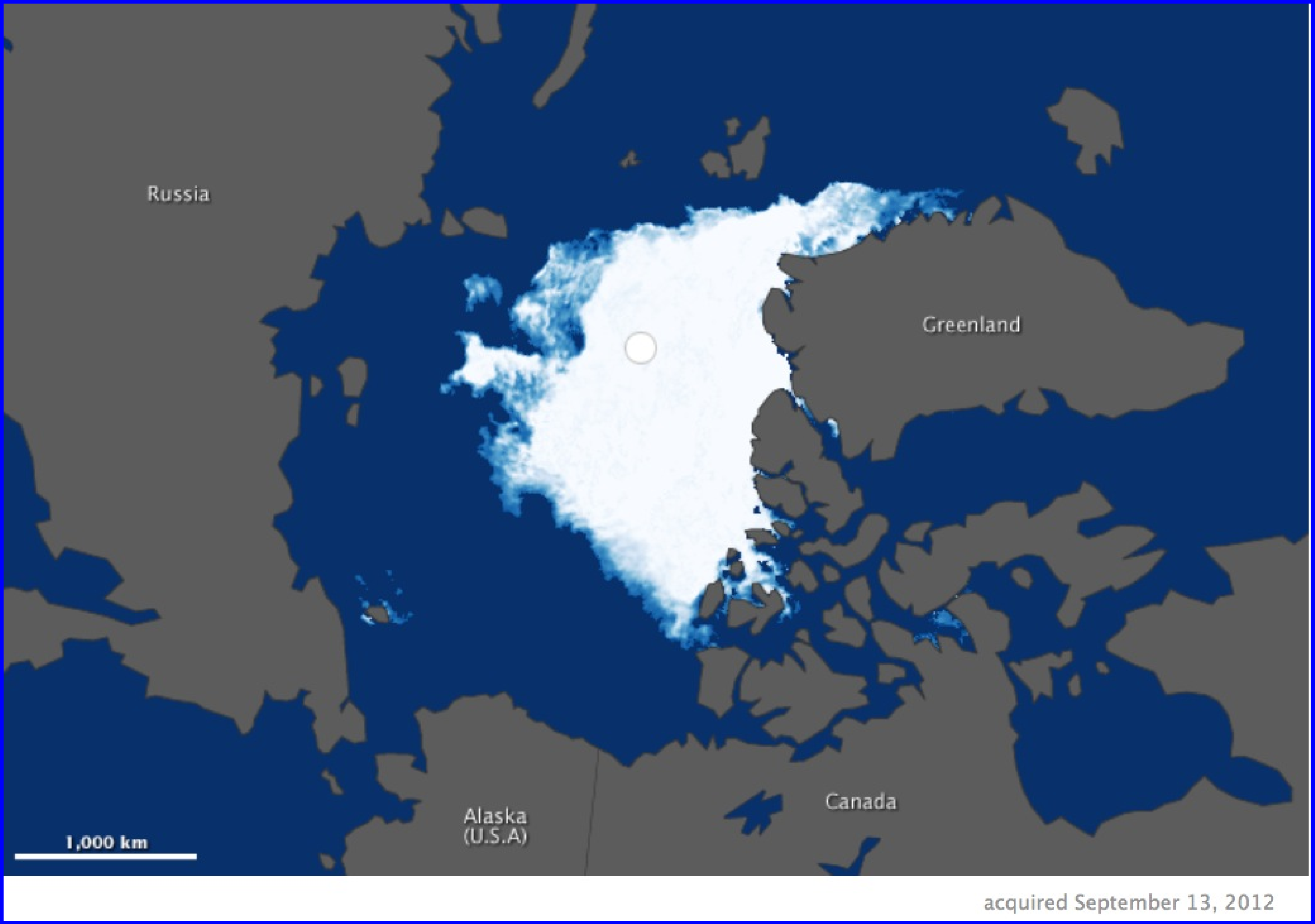
Over half of glaciers now outlined

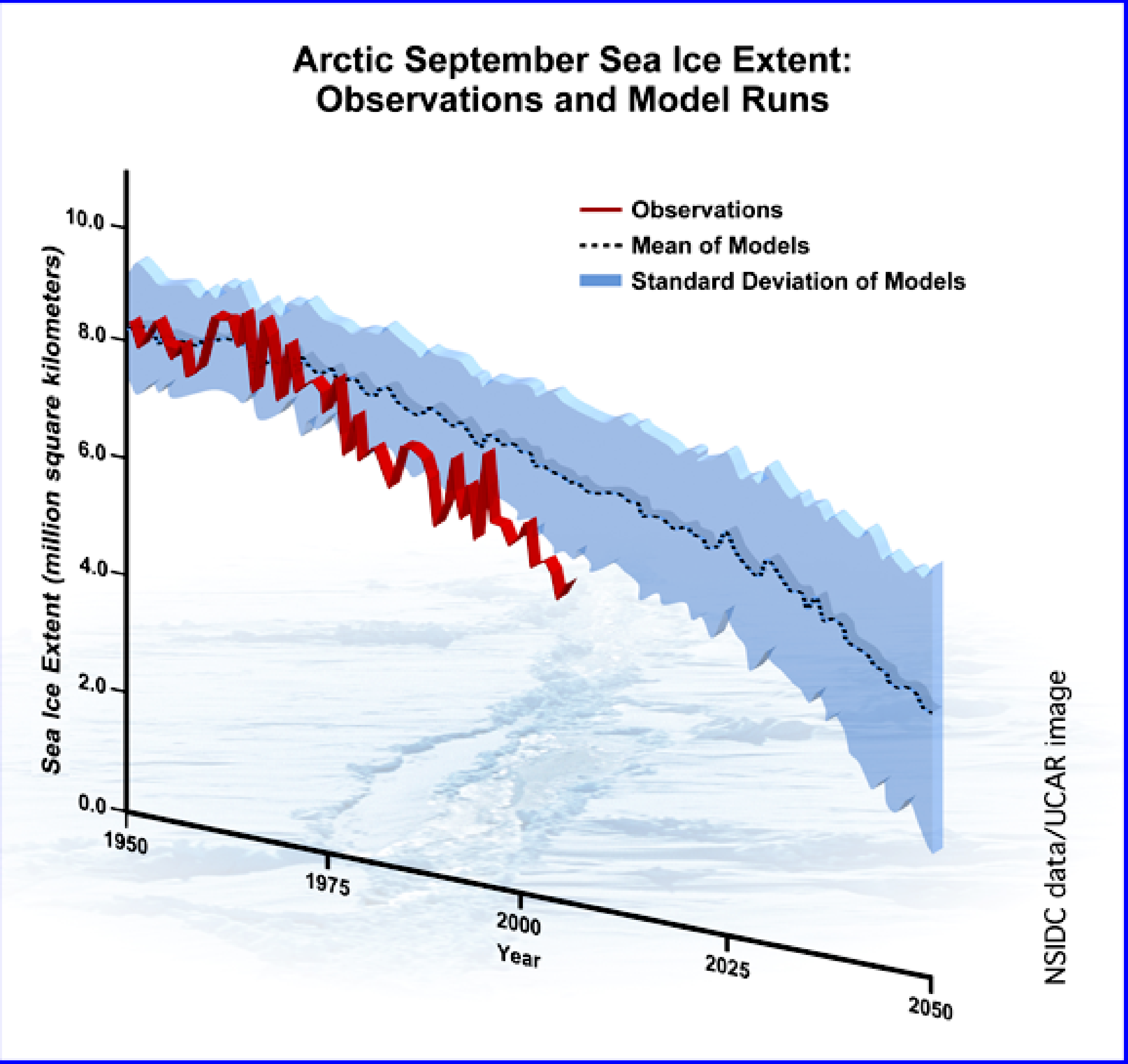
Many errors, eg stopping at political boundary

# Rapidly declining sea ice minimum – 1984



# Rapidly declining sea ice minimum – 2012



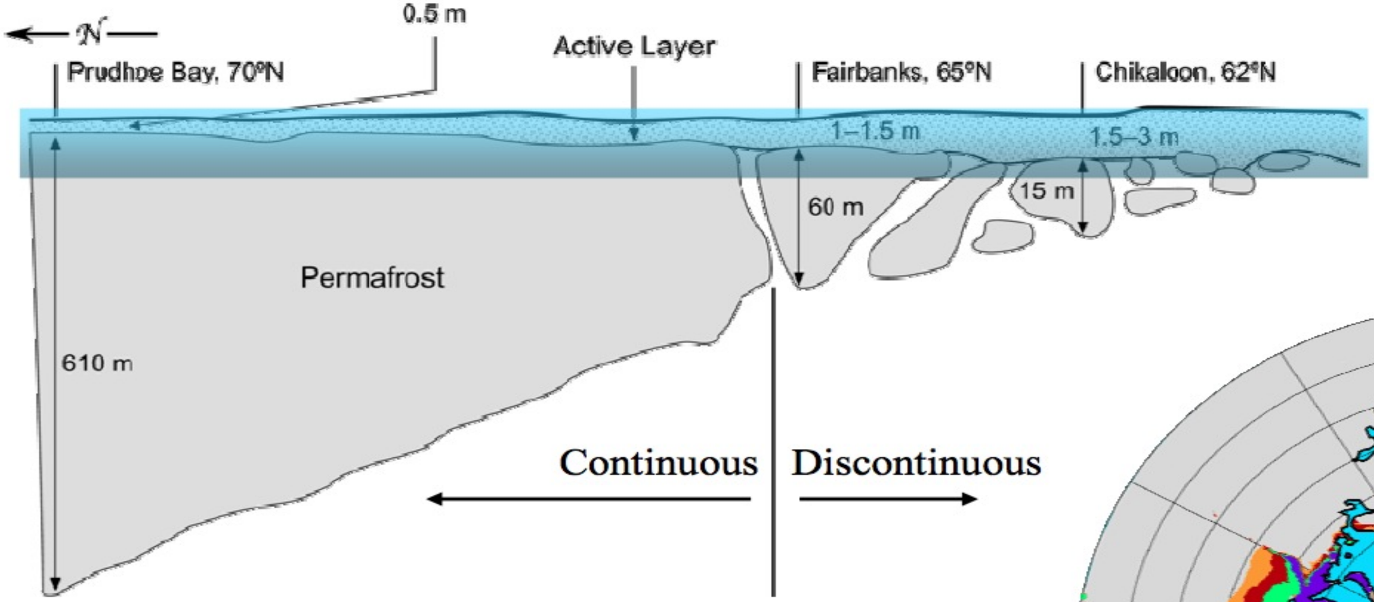



18 IPCC models, 2007

No summer ice by 2030?

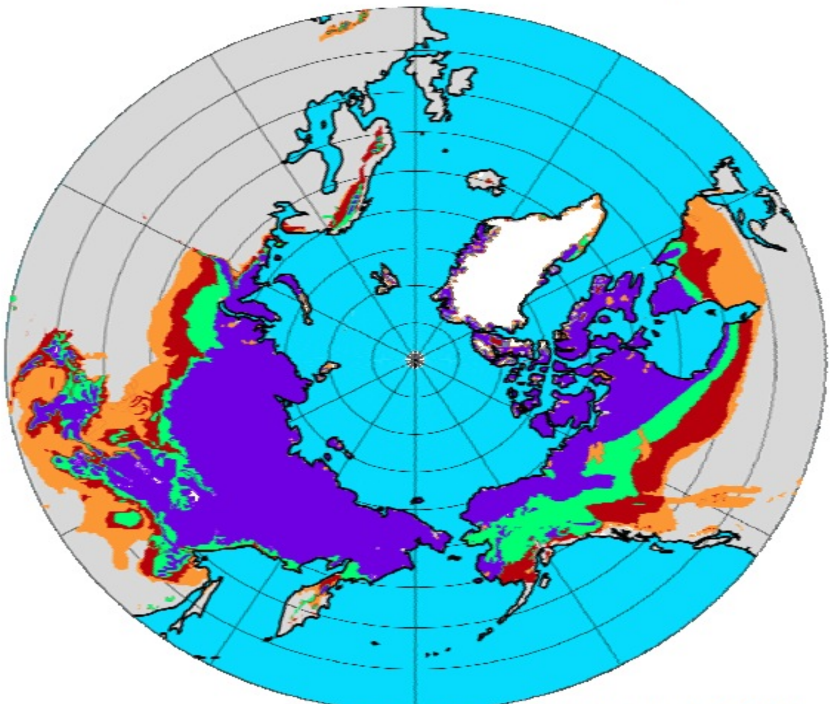
# Permafrost: soil/rock below 0C for 2+ yr

## Permafrost:
Soil or rock that remains below freezing for two or more years



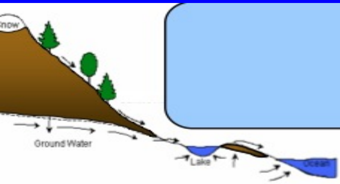

IPA Permafrost Distribution Map

- Continuous (90 – 100% coverage)
- Discontinuous (50 – 90%)
- Sporadic (10 – 50%)
- Isolated (0 – 10%)

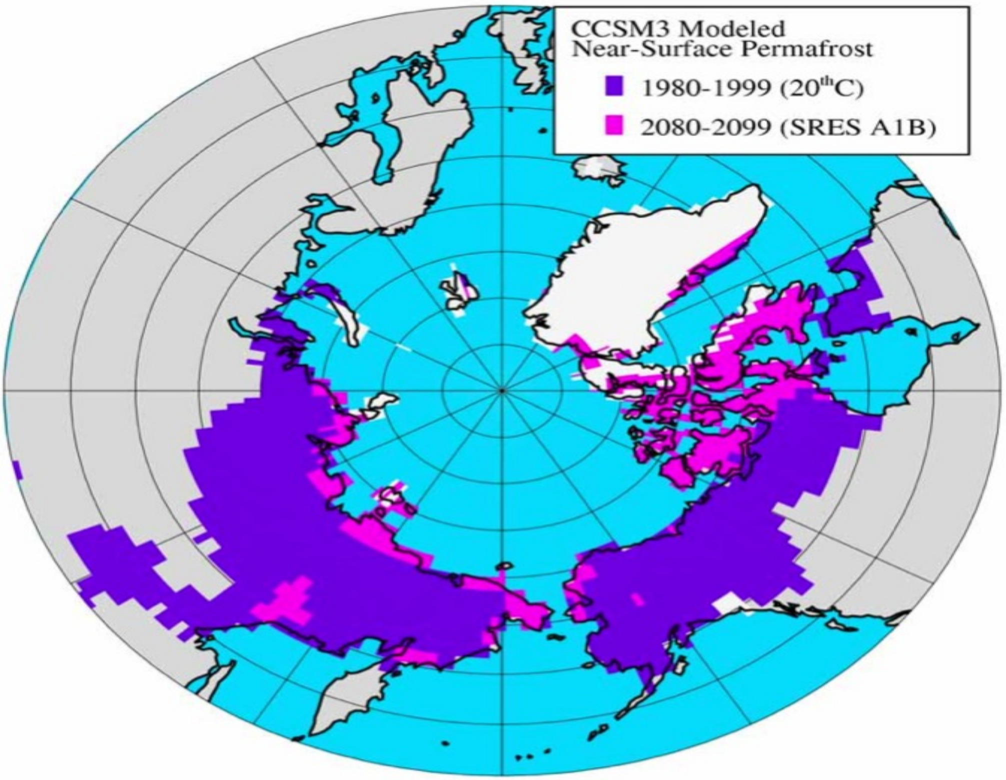


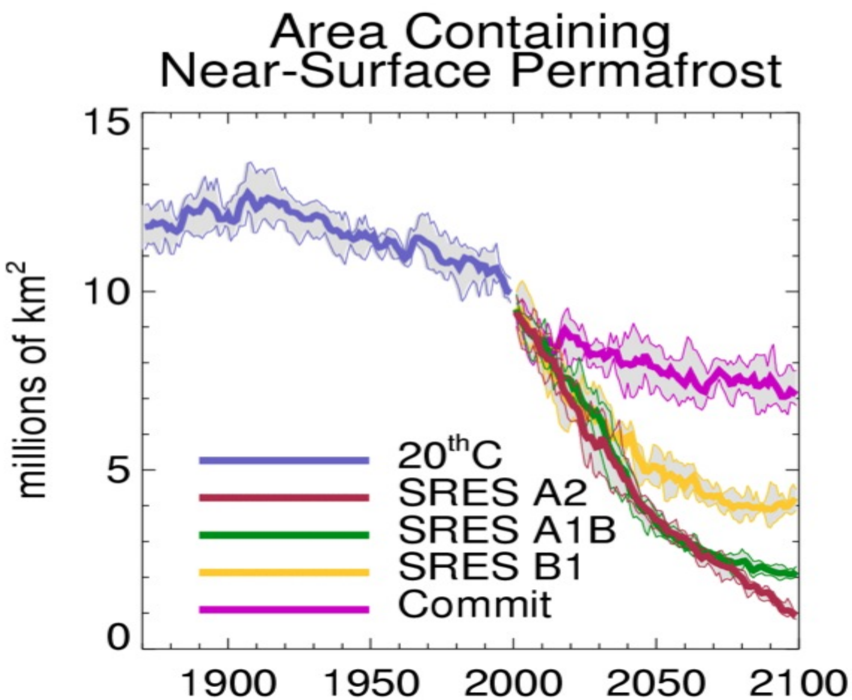
Brown et al. 1998

# NCAR CCSM3 model projections, permafrost

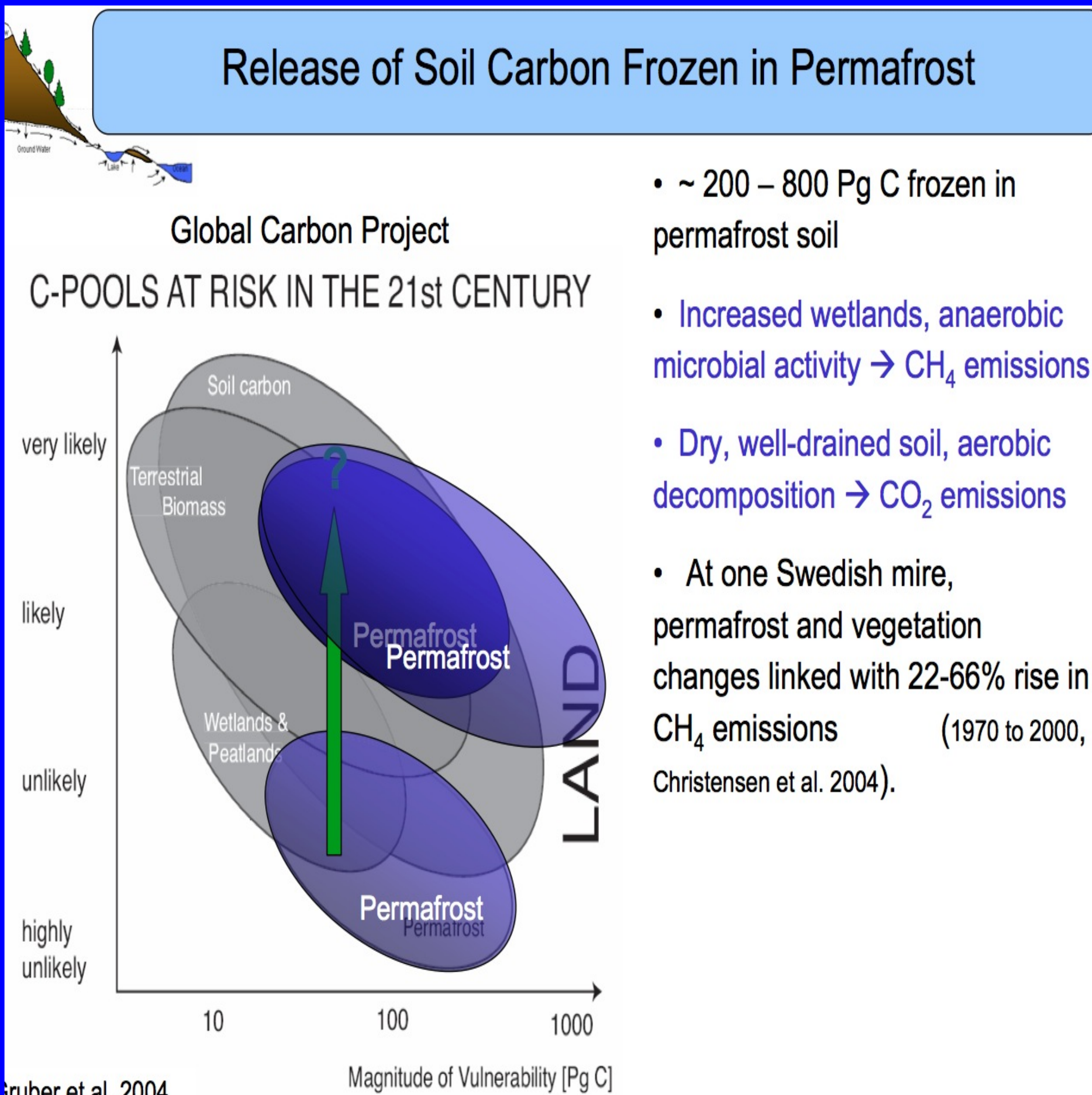



## CCSM3 Projections of Degradation of Near-Surface Permafrost



# Release of carbon stored in permafrost




200 – 800 Pg C

More wetlands → CH4

More drylands → CO2

At one Swedish bog, ~50% rise in CH4, 1970 to 2000

# Background