Recent Developments in Climate Change Modeling

Warren M. Washington
National Center for Atmospheric Research

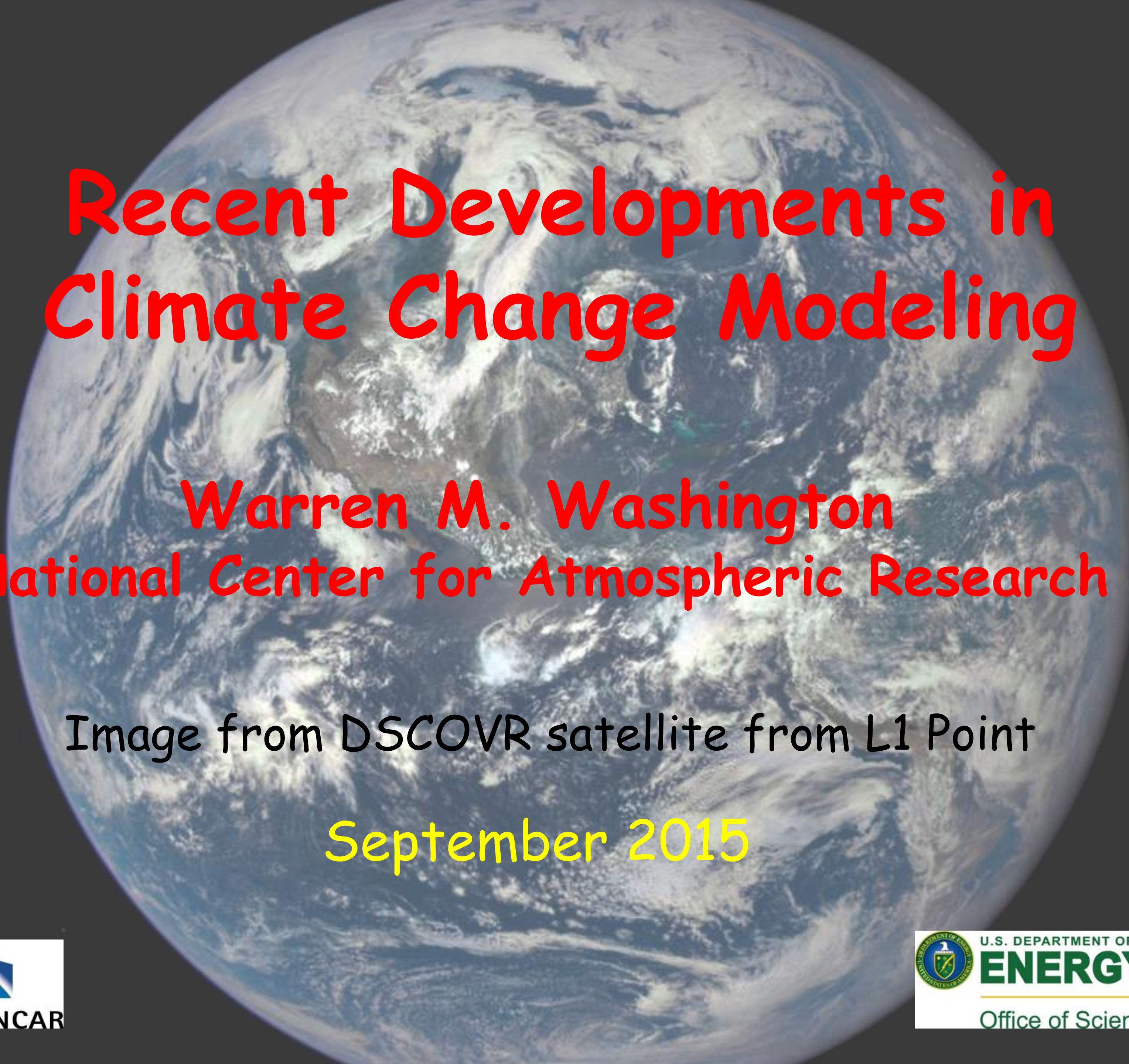


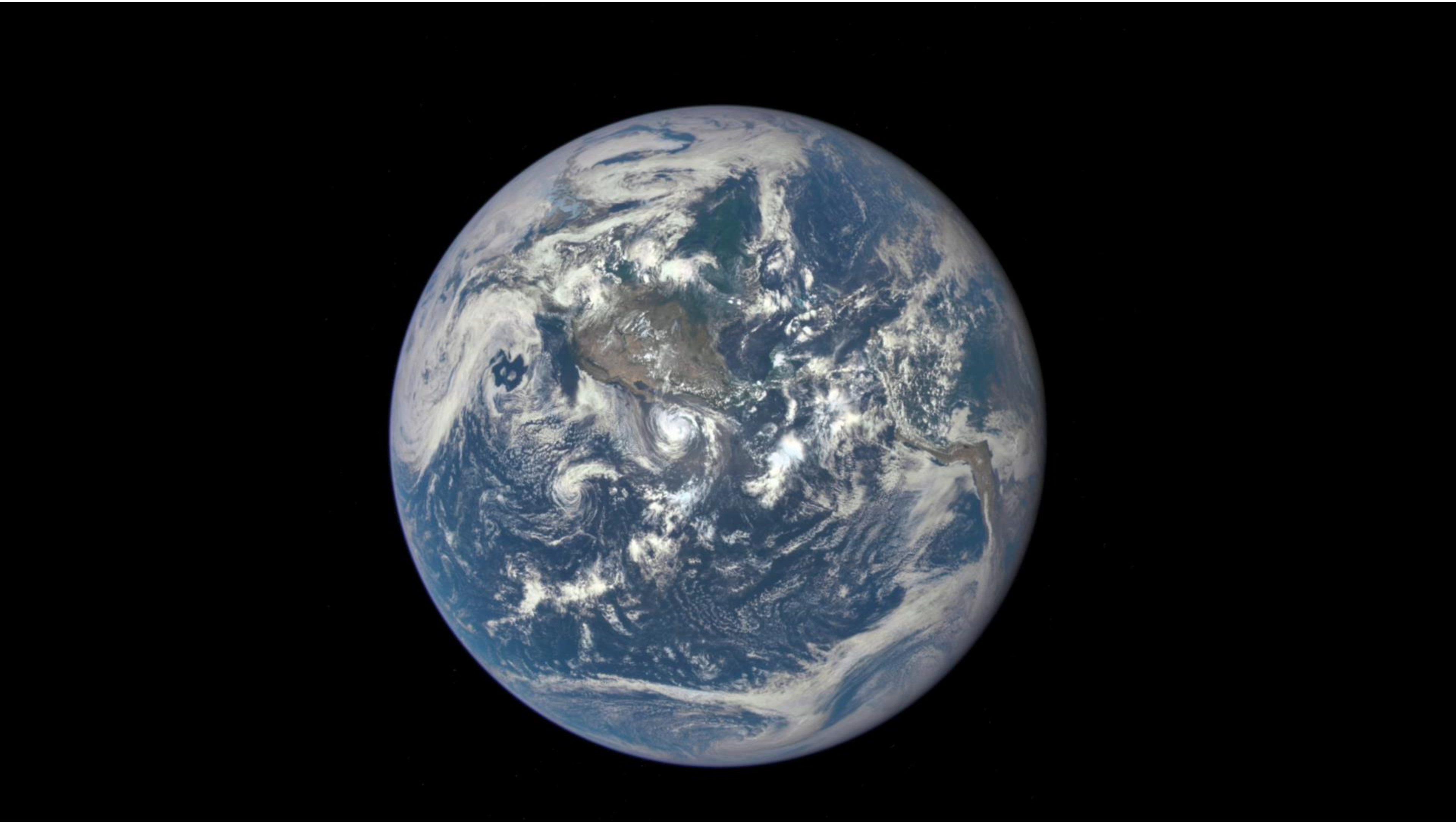
Image from DSCOVR satellite from L1 Point

September 2015

NCAR

U.S. DEPARTMENT OF ENERGY
Office of Science

NASA's new DSCOVR satellite



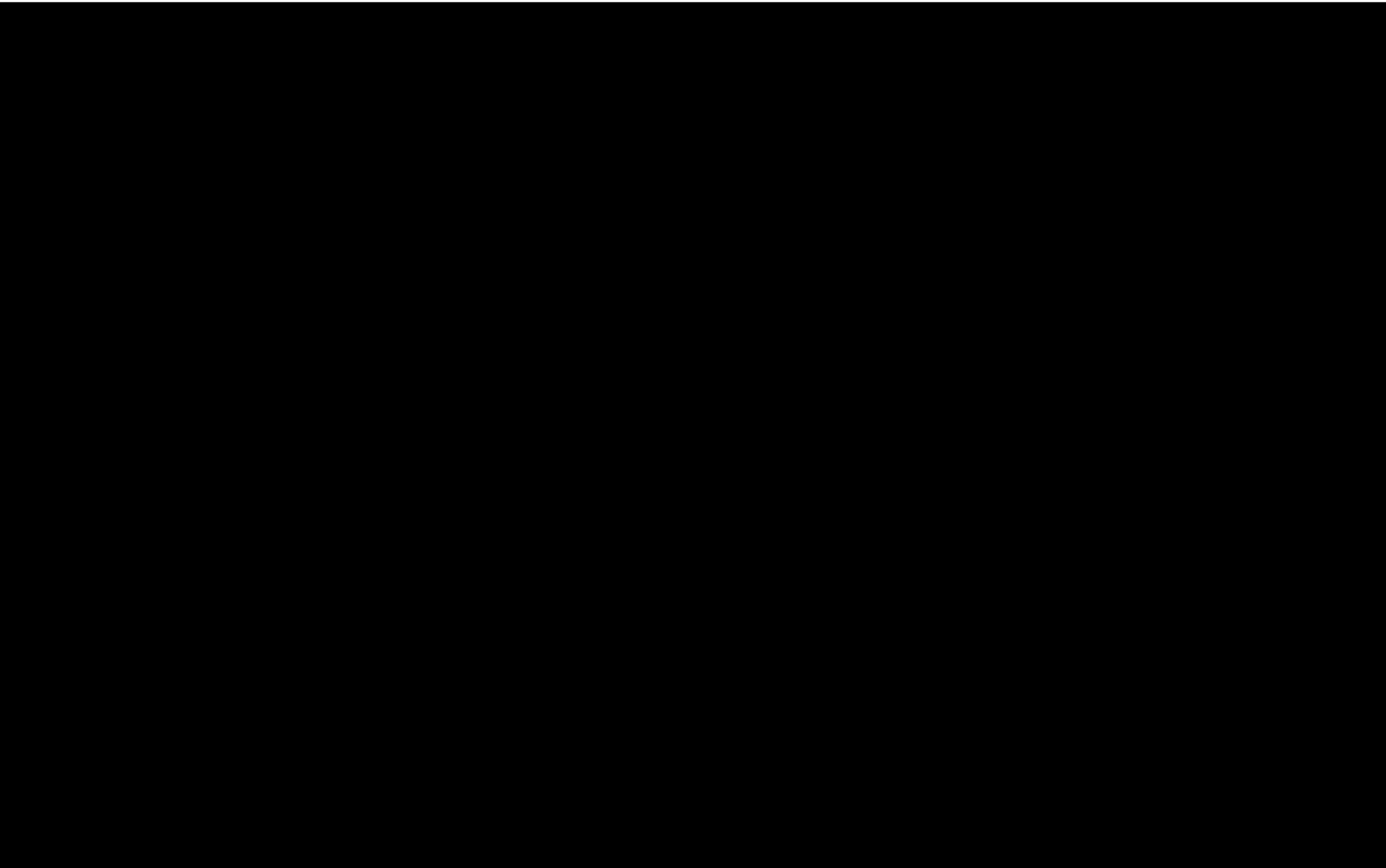
Overview

- Brief history of climate modeling and its future
- Brief discussion of computational methods
- What is in the present models
- What are climate change simulations telling us.
- Paris meeting on cutting GHG emissions

The next NASA satellite videos give insight to how the climate is changing and the interaction of vegetation on the carbon cycle.

Credit to the NASA Aqua instrument:
Tom Pagano and colleagues at JPL

The atmospheric carbon dioxide and vegetation connection!



The Climate and Earth System Modeling Story

Laws of Physics, Chemistry, and Biology

- Equations govern the dynamics of atmosphere, ocean, vegetation, and sea ice
- Equations put into a form that can be solved on modern supercomputer systems
- Physical processes such as precipitation, radiation (solar and terrestrial), vegetation, boundary transfers of heat, momentum, and moisture at earth's surface are included
- Forcings: Greenhouse gases (GHGs), Volcanic, Solar variations

Mathematical equations (known since 1904)

Eqs. of Momentum

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial\lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial\phi} + F_\phi$$

Hydrostatic

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

Conservation of mass

$$\frac{\partial\rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(\rho u) + \frac{\partial}{\partial\phi}(\rho v\cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

First law of thermodynamics

$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

Gas law

$$p = \rho RT$$

$(u, v, w, \rho, p, \text{and } T)$,

Late 1950s and Early 1960s Climate Modeling groups

GFDL

S. Manabe
J. Smagorinsky

UCLA

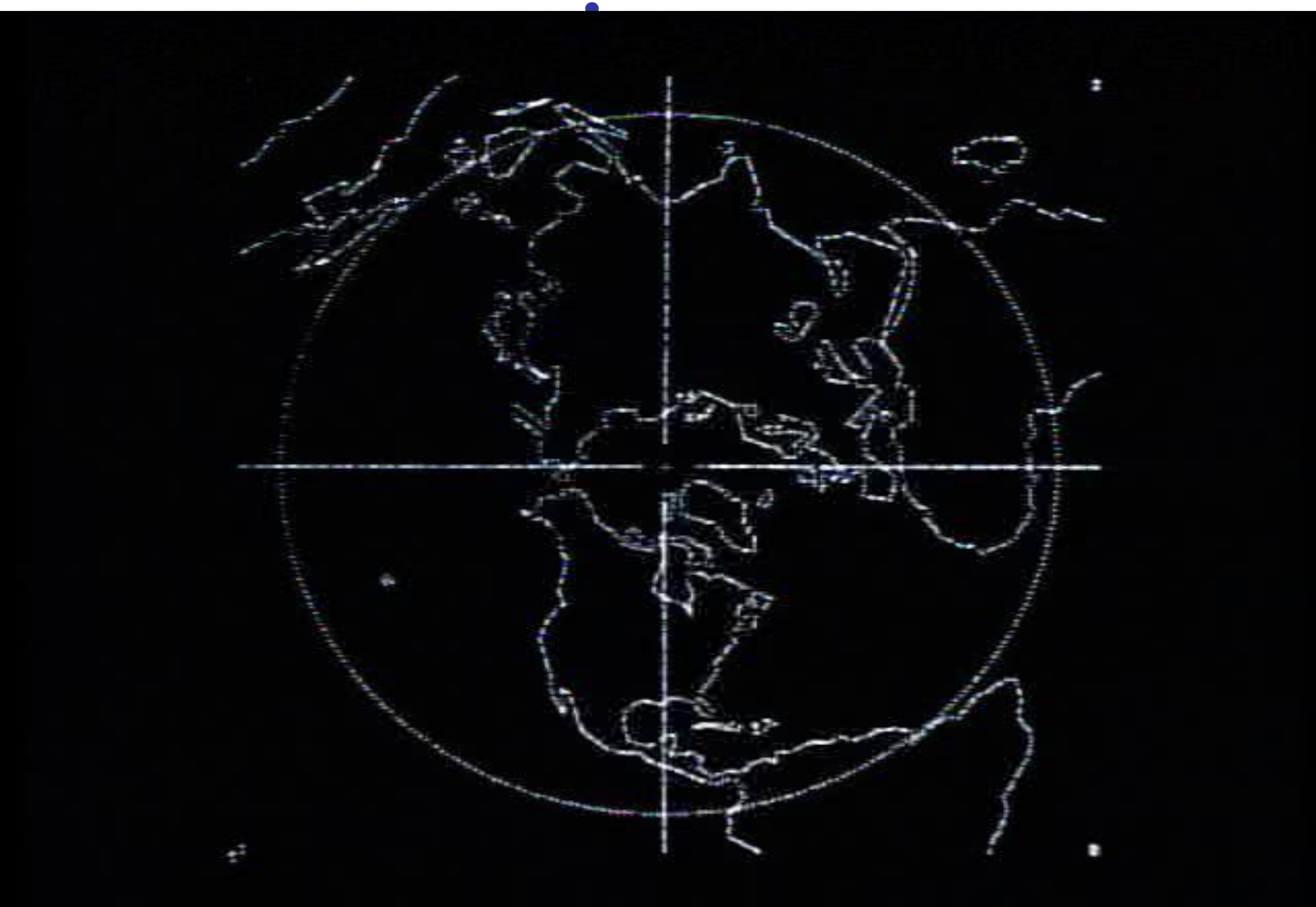
Y. Mintz
A. Arakawa

LLNL
& NCAR

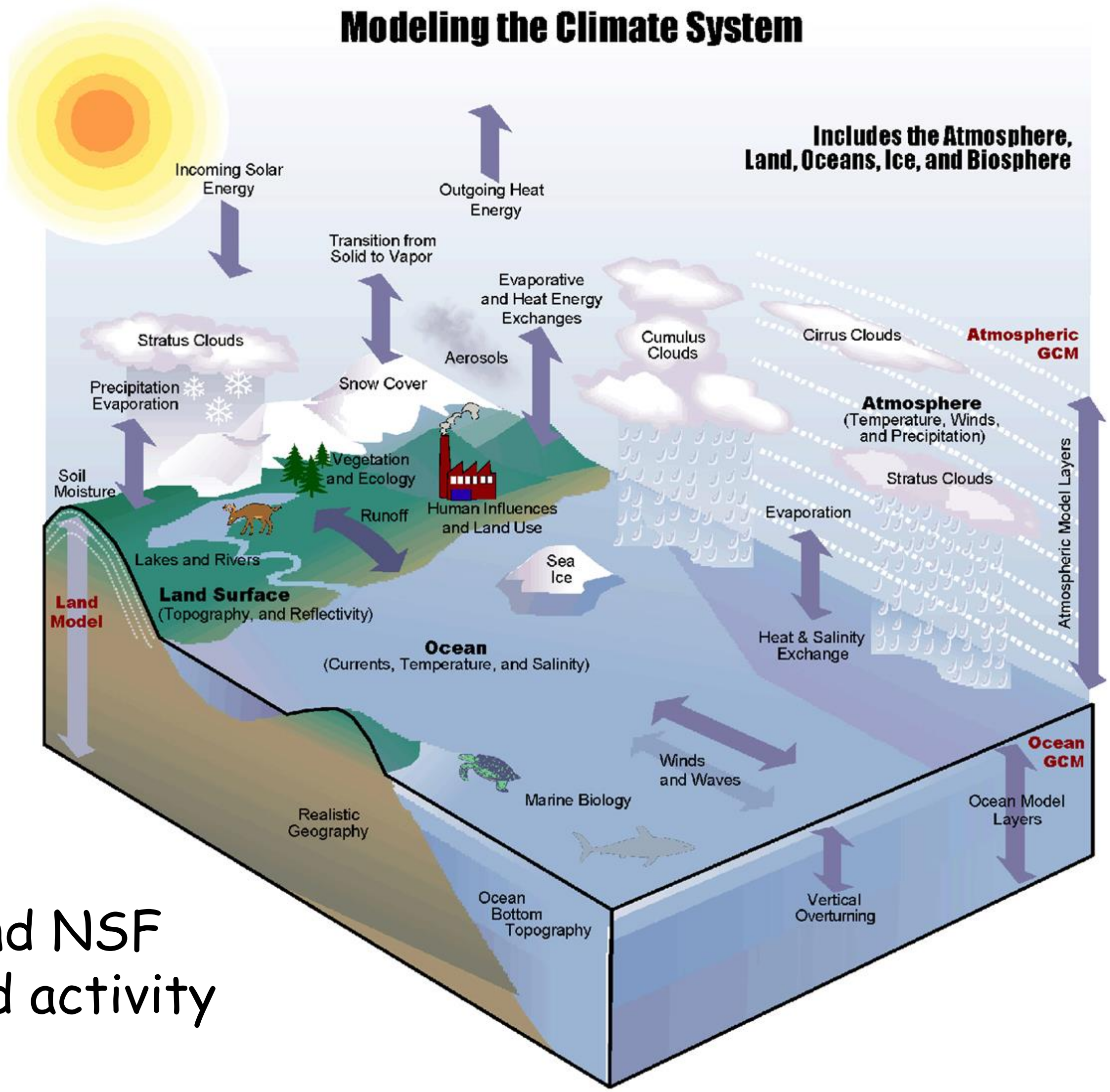
C. Leith

A. Kasahara
W. Washington

From Dave Randall

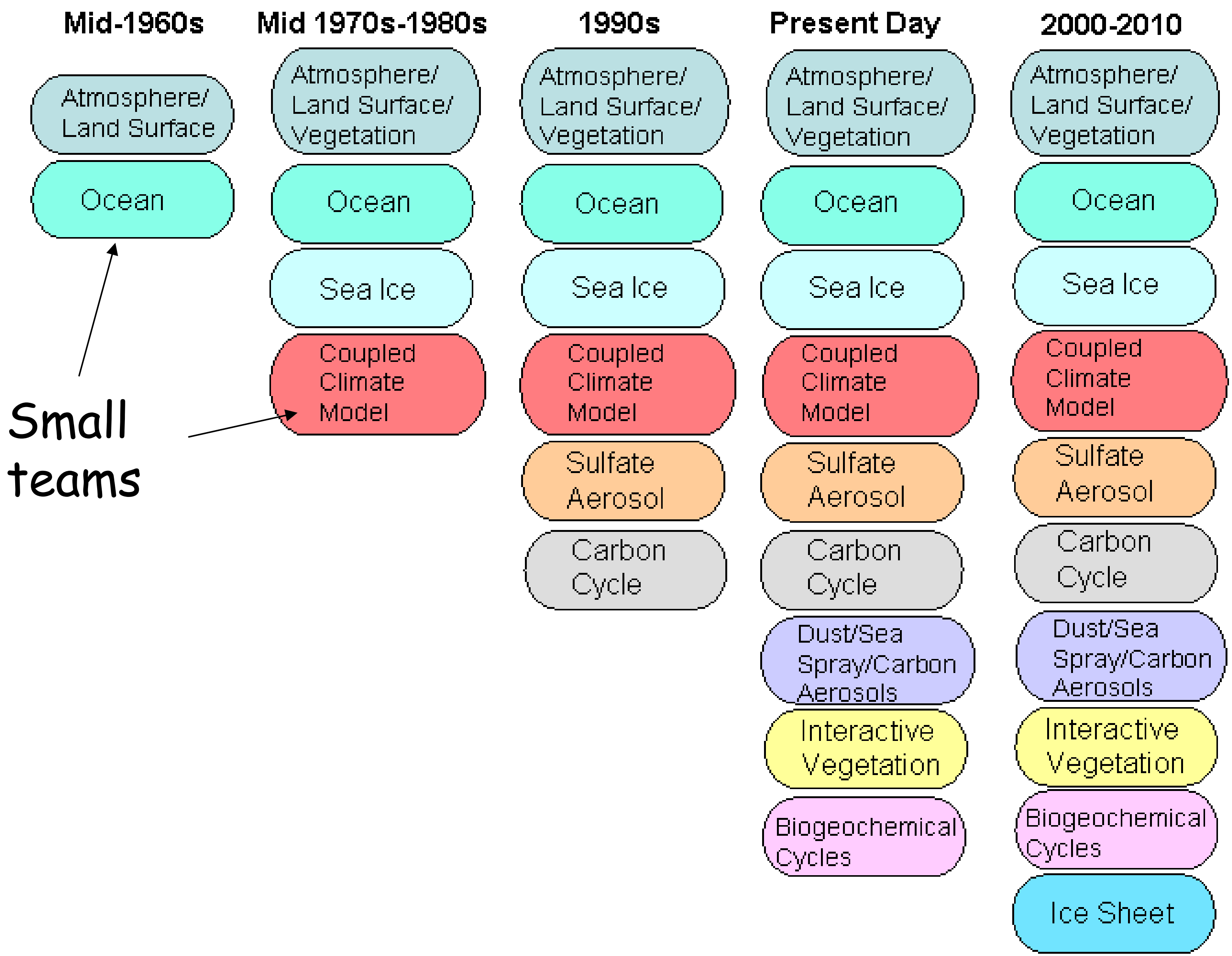


The Community Earth System Model (CESM) is becoming more complete



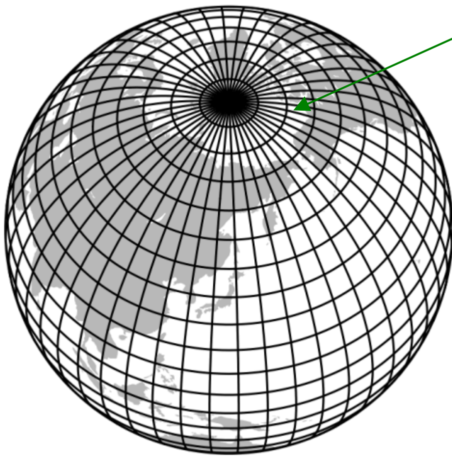
A DOE and NSF supported activity

Timeline of Climate Model Development



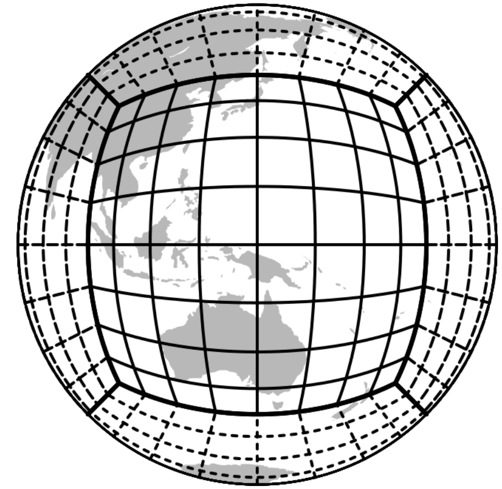
Atmospheric Grids

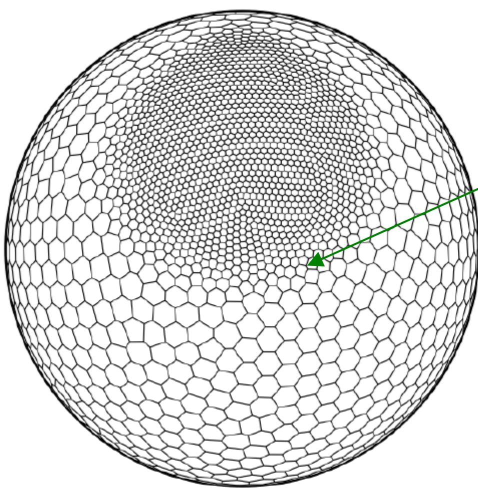
LATITUDE-LONGITUDE GRID



Problem near the poles
where longitudes converge

CUBED SPHERE GRID

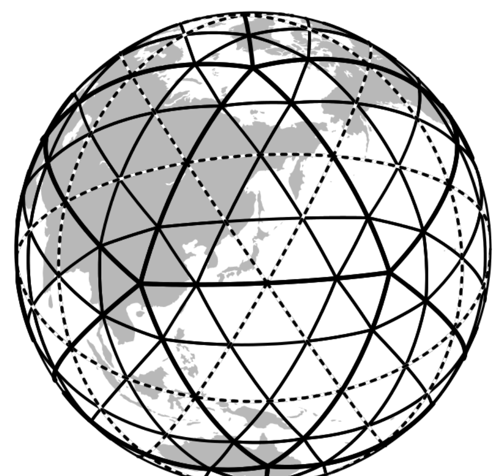




Regional focus

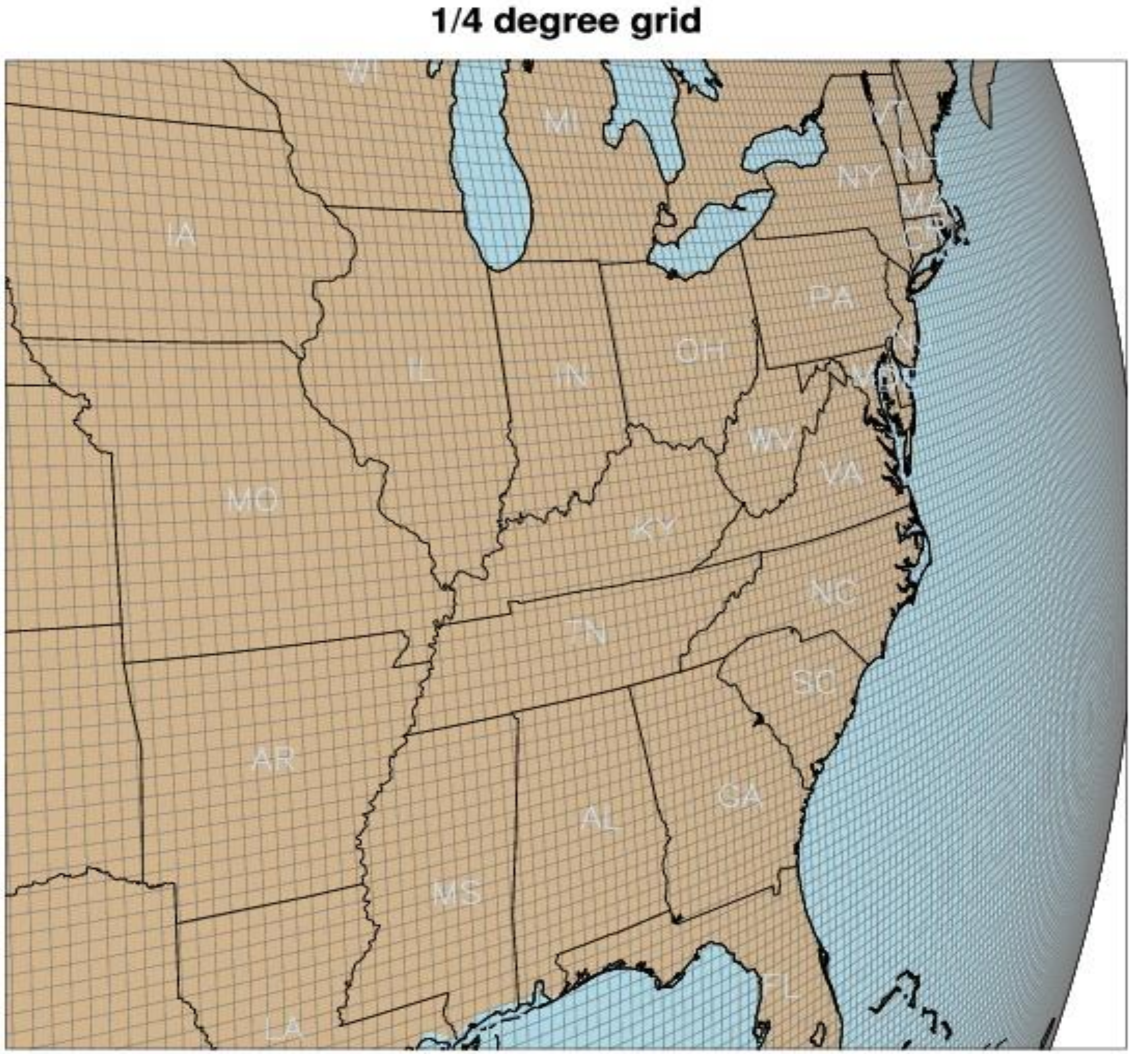
Figure V.1. A variable resolution grid based on a Spherical Centroidal Voronoi Tesselation.

SPHERICAL GEODESIC
OR ICOSAHEDRAL GRID



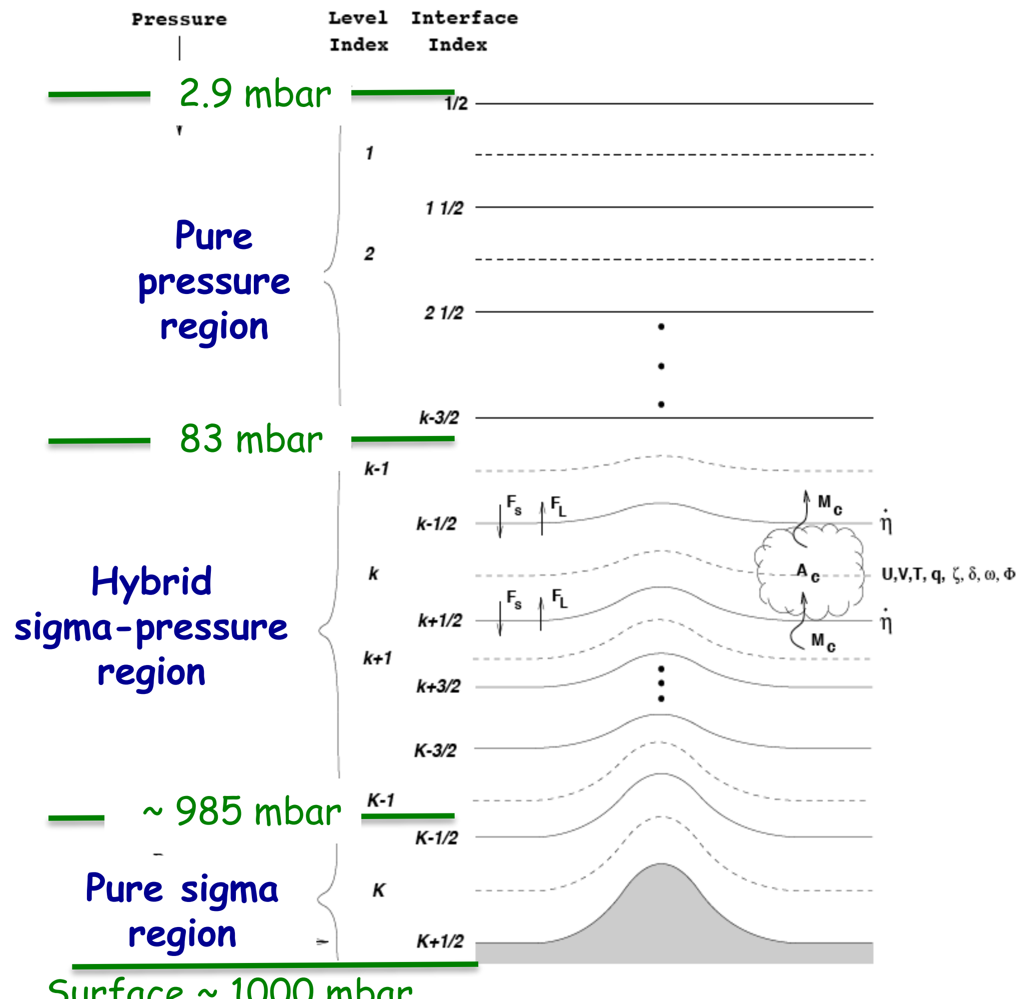
From C. Hannay, NCAR

Part of the global grid (25 km) for the next IPCC simulations



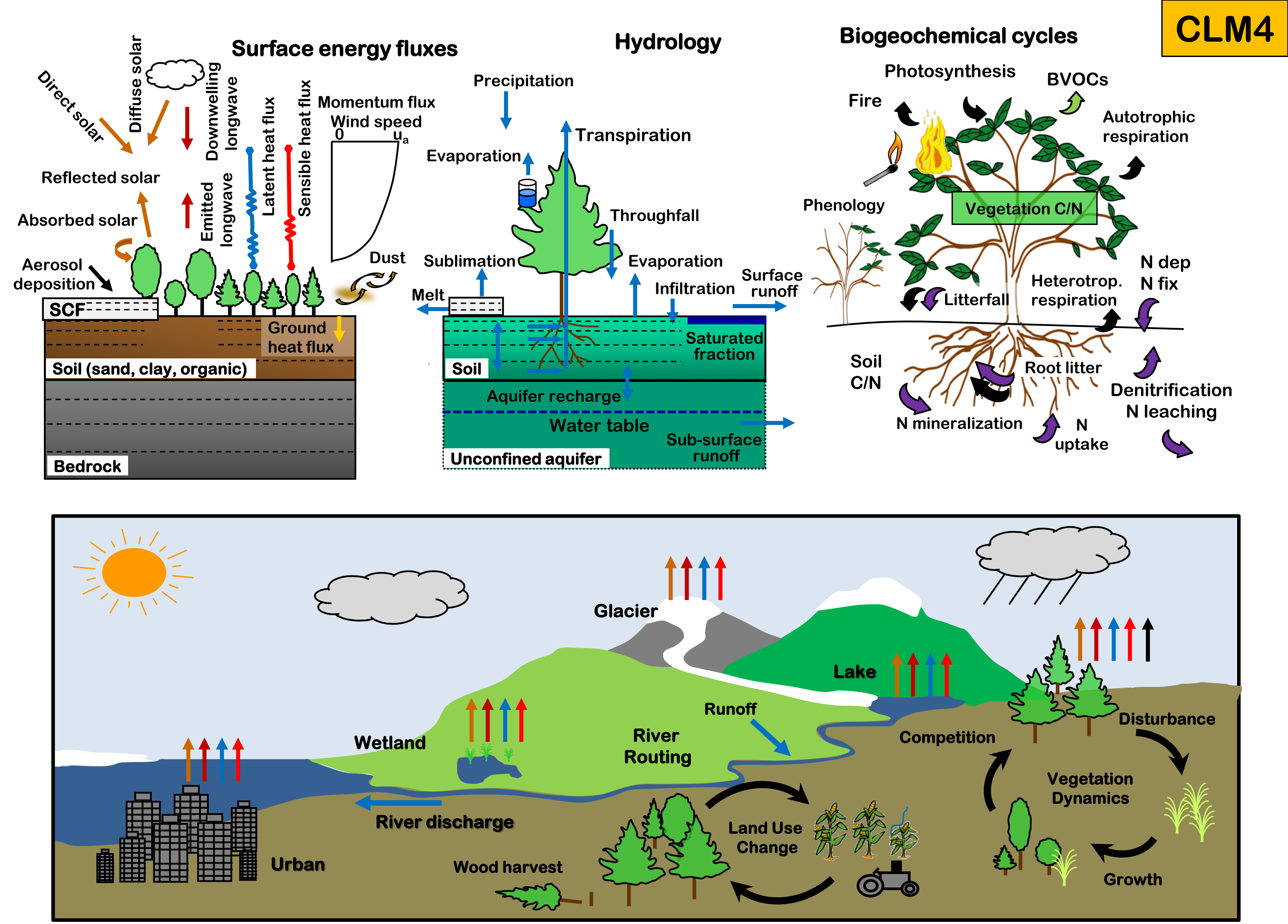
Vertical Grid

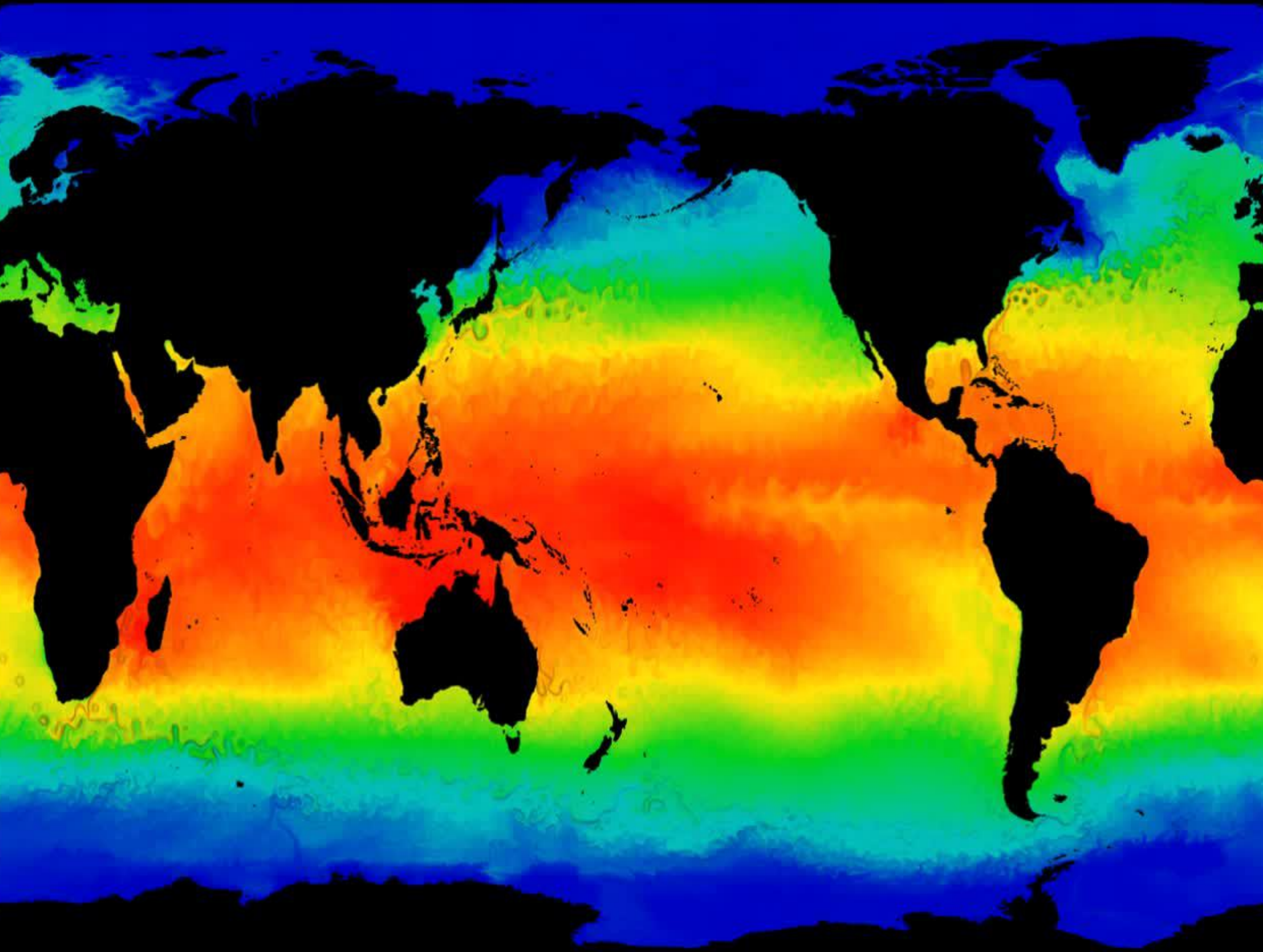
- Vertical resolution is also important for quality of simulations
- Levels are not equally spaced (levels are closer near surface and near tropopause where rapid changes occurs)
- In CAM*: "hybrid" coordinate
  - bottom: sigma coordinate (follows topography)
  - top: pressure coordinate
  - middle: hybrid sigma-pressure



Vertical level structure of CAM 4.0

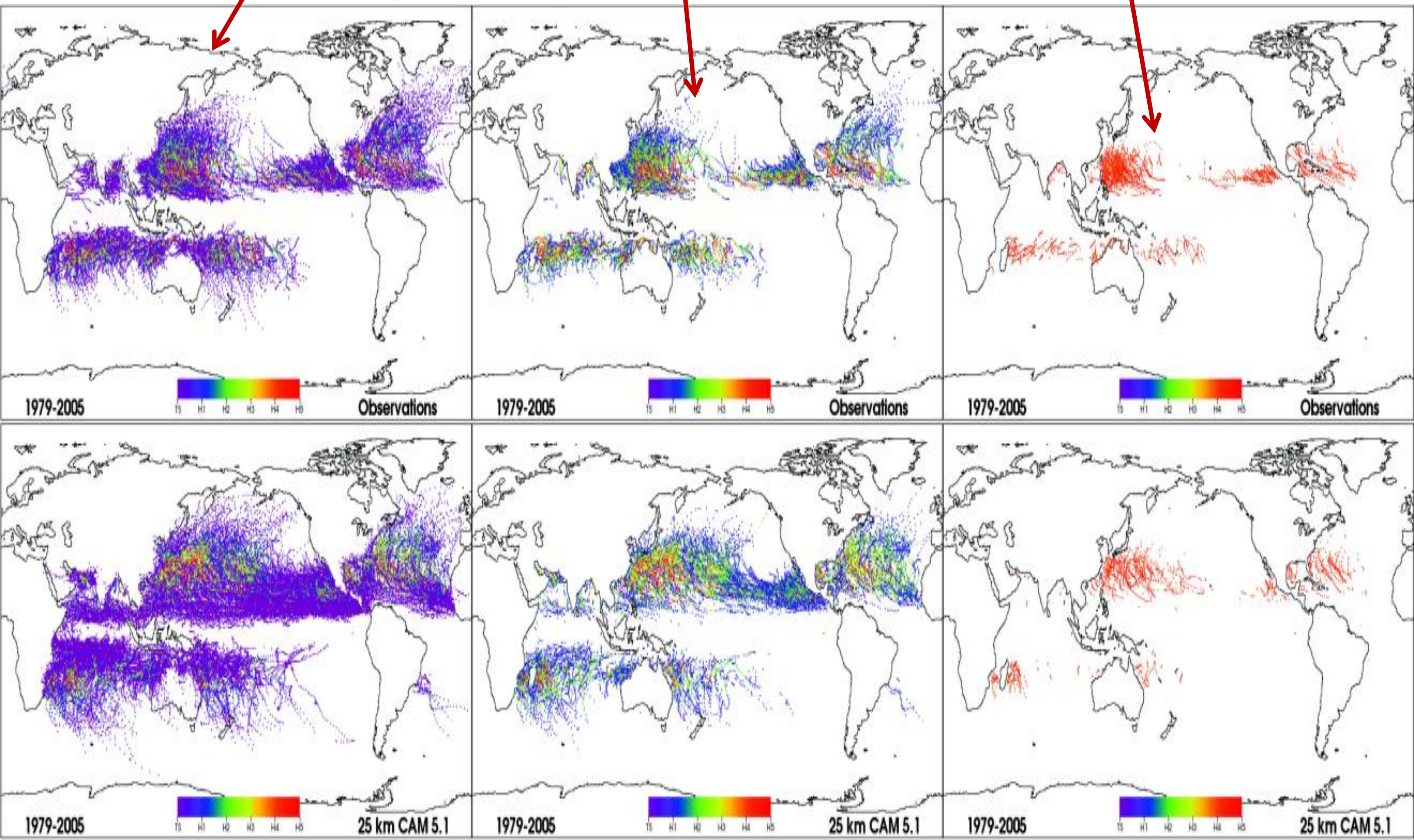
*CESM Atmospheric Model


CLM4
Surface energy fluxes
Direct solar
Diffuse solar
Downwelling longwave
Reflected solar
Absorbed solar
Emitted longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
0
u_a
Aerosol deposition
SCF
Dust
Ground heat flux
Soil (sand, clay, organic)
Bedrock
Hydrology
Precipitation
Transpiration
Evaporation
Throughfall
Sublimation
Evaporation
Melt
Infiltration
Surface runoff
Saturated fraction
Soil
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Biogeochemical cycles
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
Litterfall
Heterotrop. respiration
N dep
N fix
Soil C/N
Root litter
Denitrification
N leaching
N mineralization
N uptake
Glacier
Lake
Wetland
Runoff
River Routing
Competition
Disturbance
Vegetation Dynamics
Growth
River discharge
Land Use Change
Urban
Wood harvest

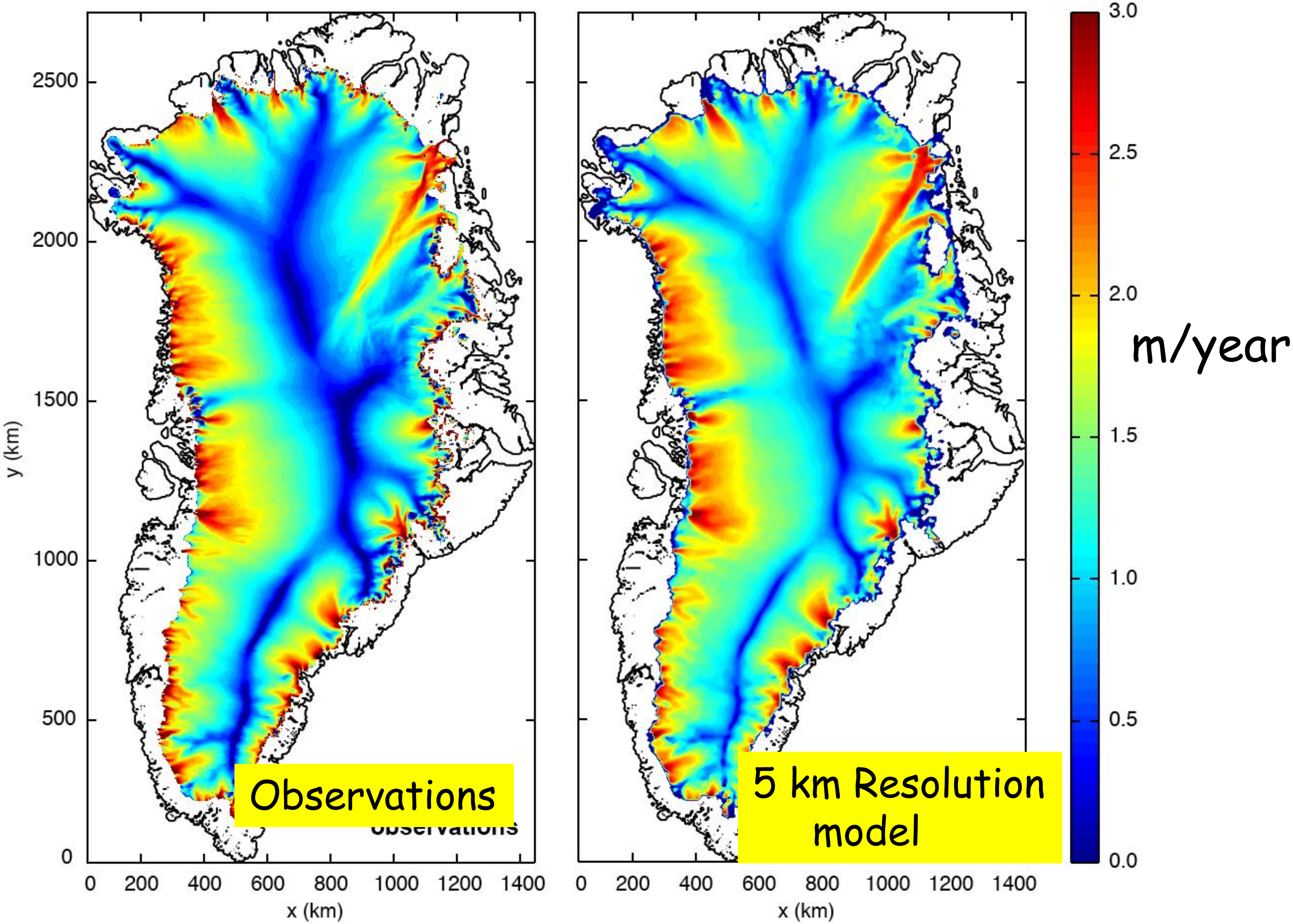


NASA/Goddard
animation showing key tropospheric aerosols in a 10 km resolution model:
Organic and black aerosols, dust, sulfates, and
sea salt aerosols

Tropical storms, hurricanes, and intense hurricanes for high resolution (25 km) atmospheric model(CAM5) M. Wehner, DOE LBL



Velocities

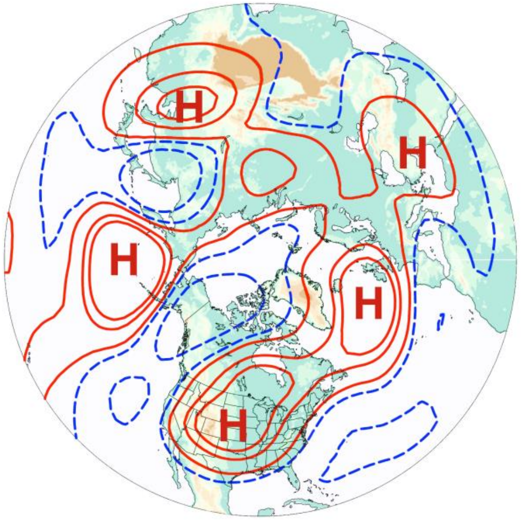


Price, Lipscomb et al, DOE/LANL, 2010

Examples of Climate Change Studies

- 20^{th} and 21^{st} century simulations for IPCC
- Single forcing simulations
- Hurricane and tropical storm changes (First time simulated and used in assessments)
- Closing Bering strait
- Heat waves, etc.
- Model development for both specified ocean temperature and fully coupled model

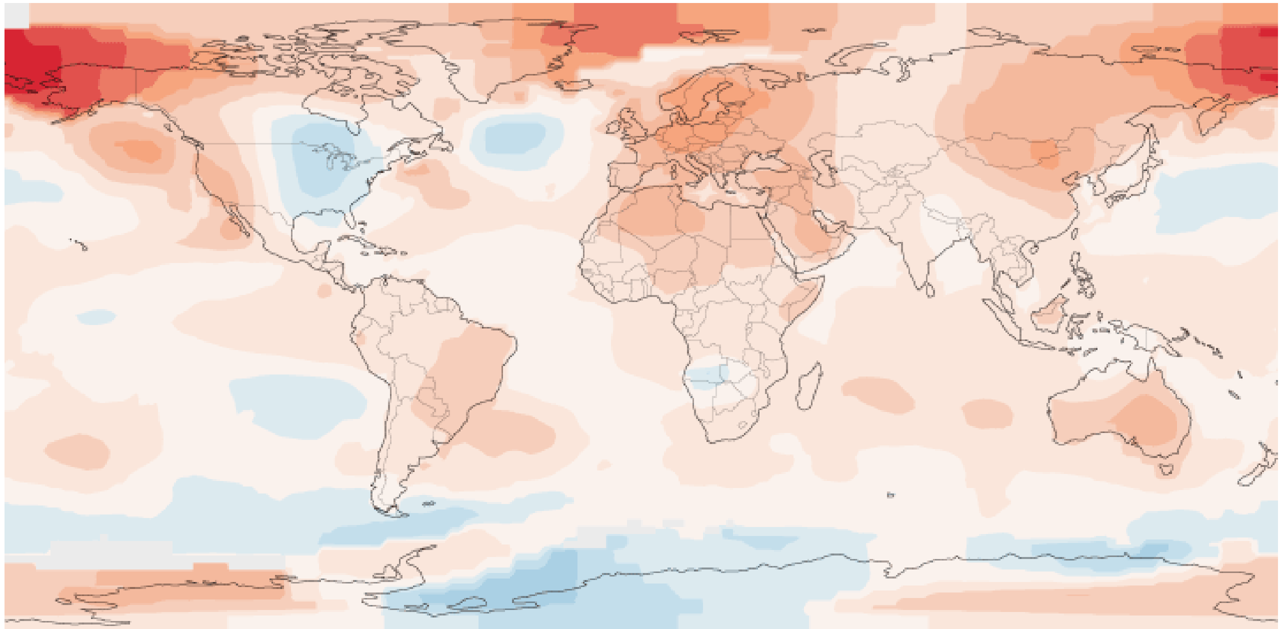
Probability of US heat Waves Affected by a Subseasonal Planetary Wave Pattern: Prediction 15-20 days in Advance



Haiyan Teng, Grant Branstator, Hailan Wang, Jerry Meehl, and Warren Washington, (2013) Nature Geoscience

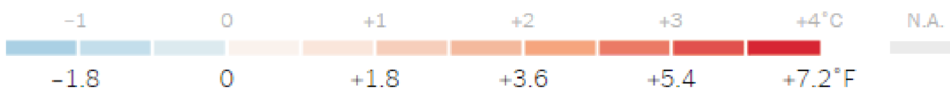
The Warmest Year on Record

Parts of the eastern United States were cooler than average last year, but globally 2014 was the warmest year in recorded history.



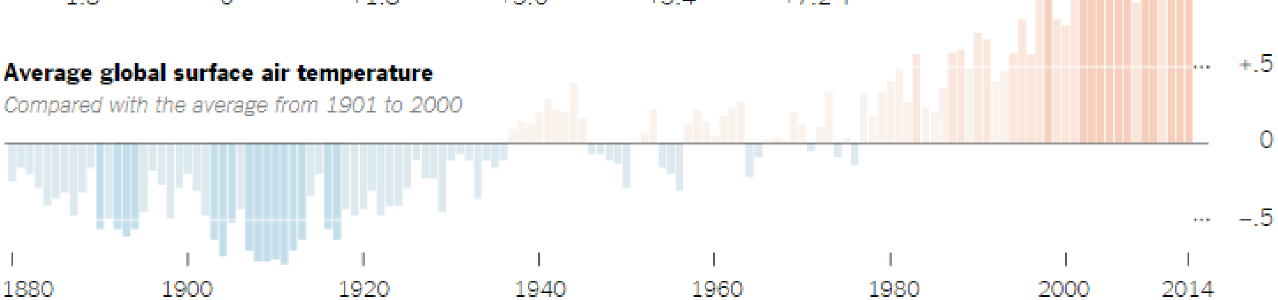
How far above or below average temperatures were in 2014

Compared with the average from 1951 to '80



Average global surface air temperature

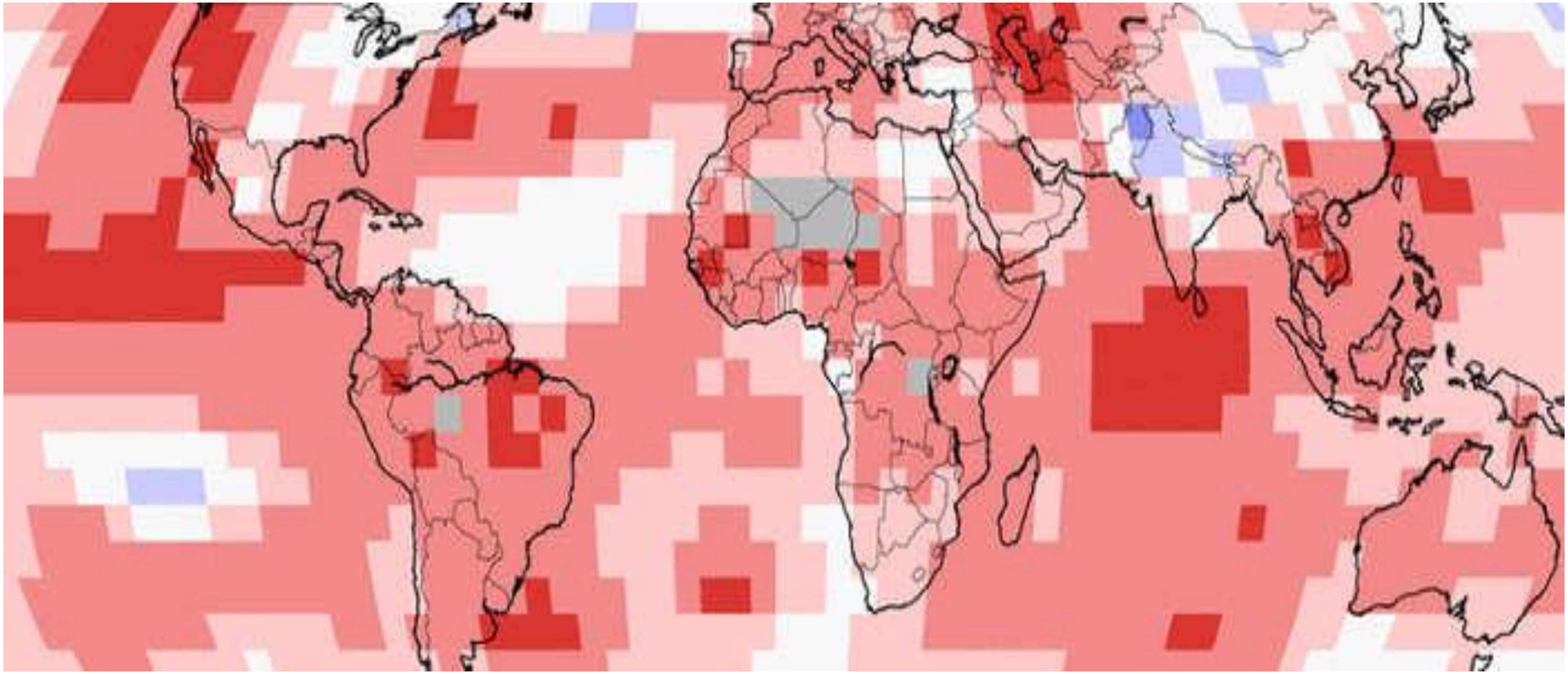
Compared with the average from 1901 to 2000

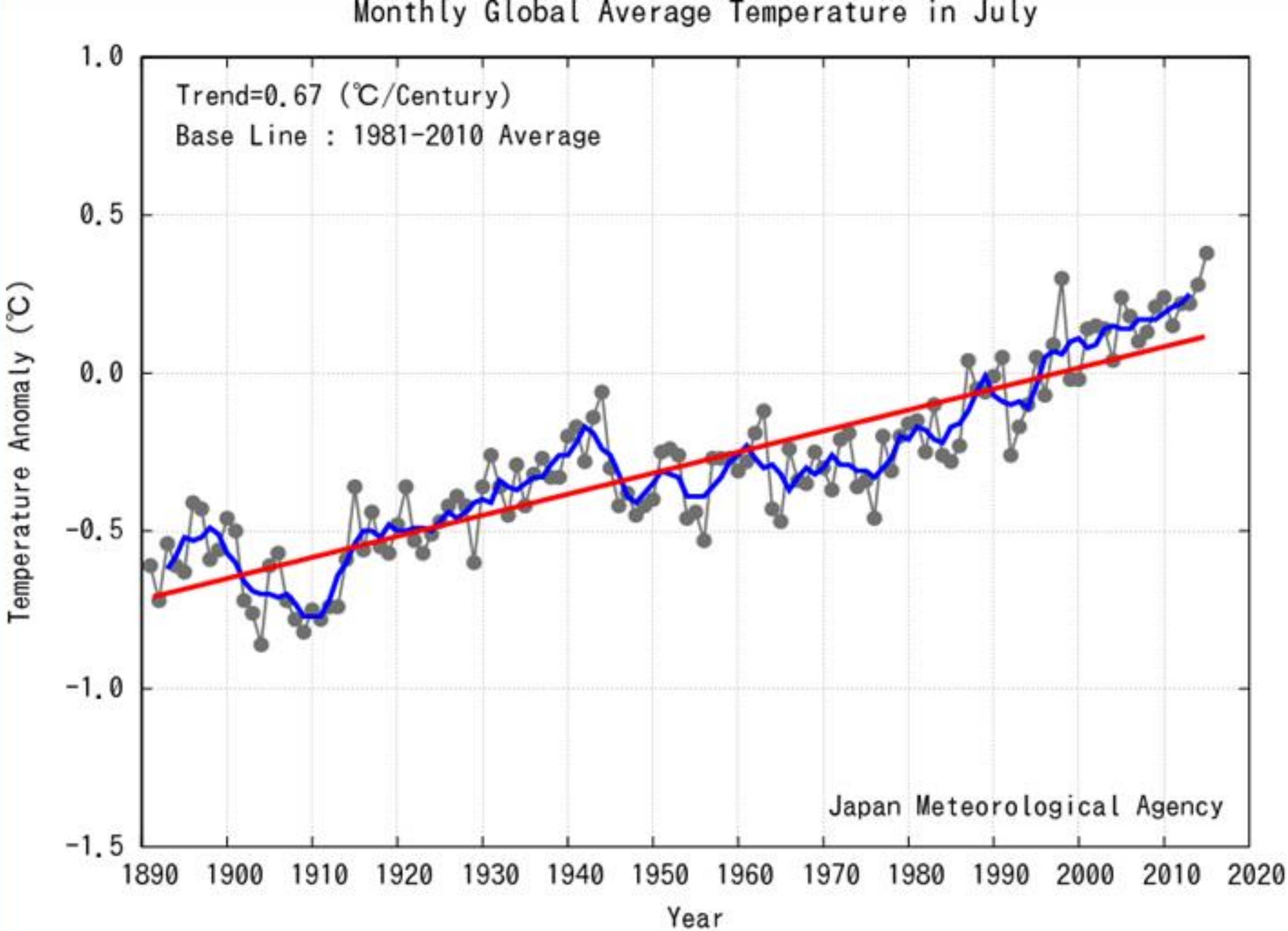


Sources: NASA; National Oceanic and Atmospheric Administration

By The New York Times

First 6 months of 2015 are warmest ever in recorded history



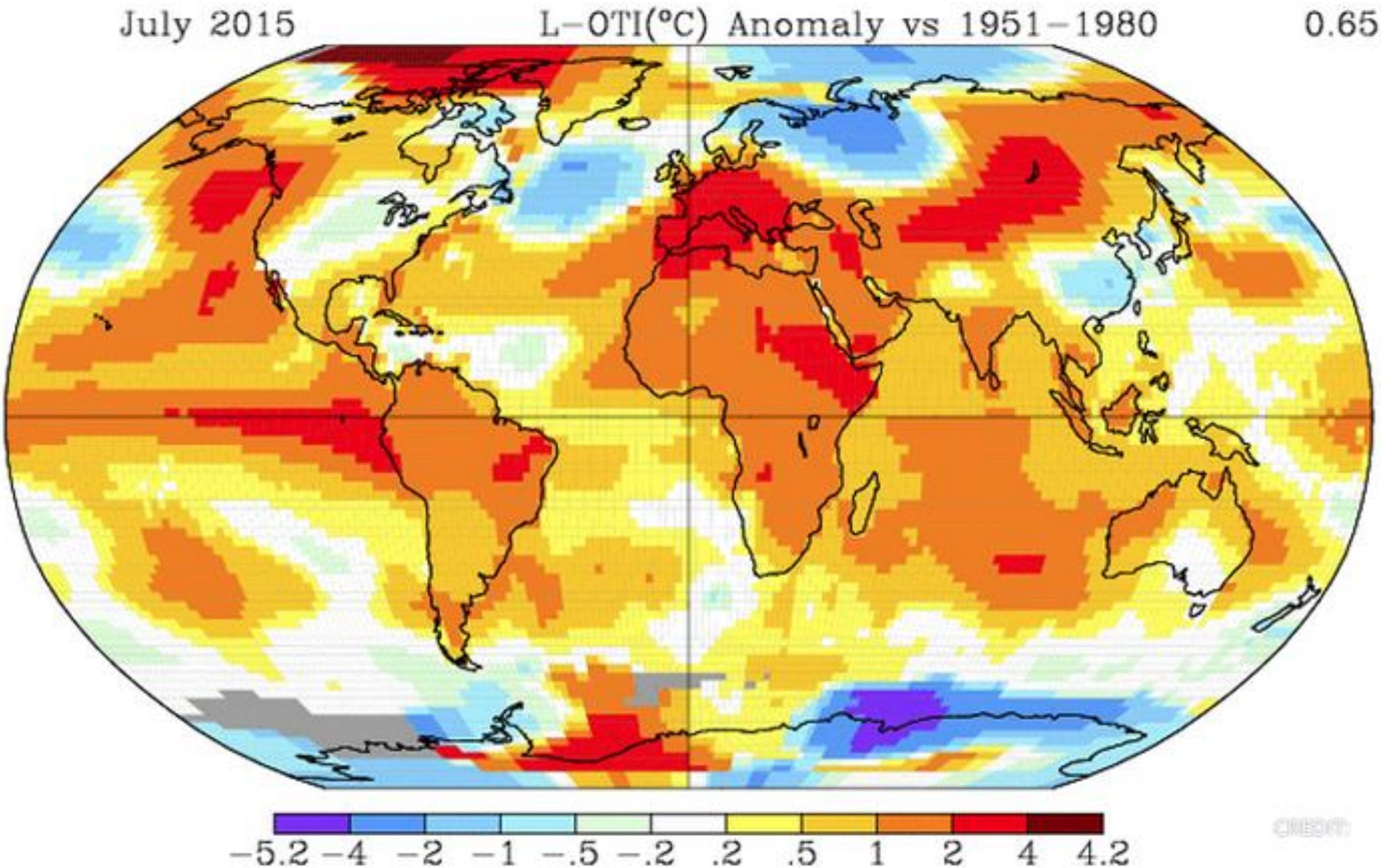


Anomalies are deviation from baseline (1981-2010 Average).

The black thin line indicates surface temperature anomaly of each year.

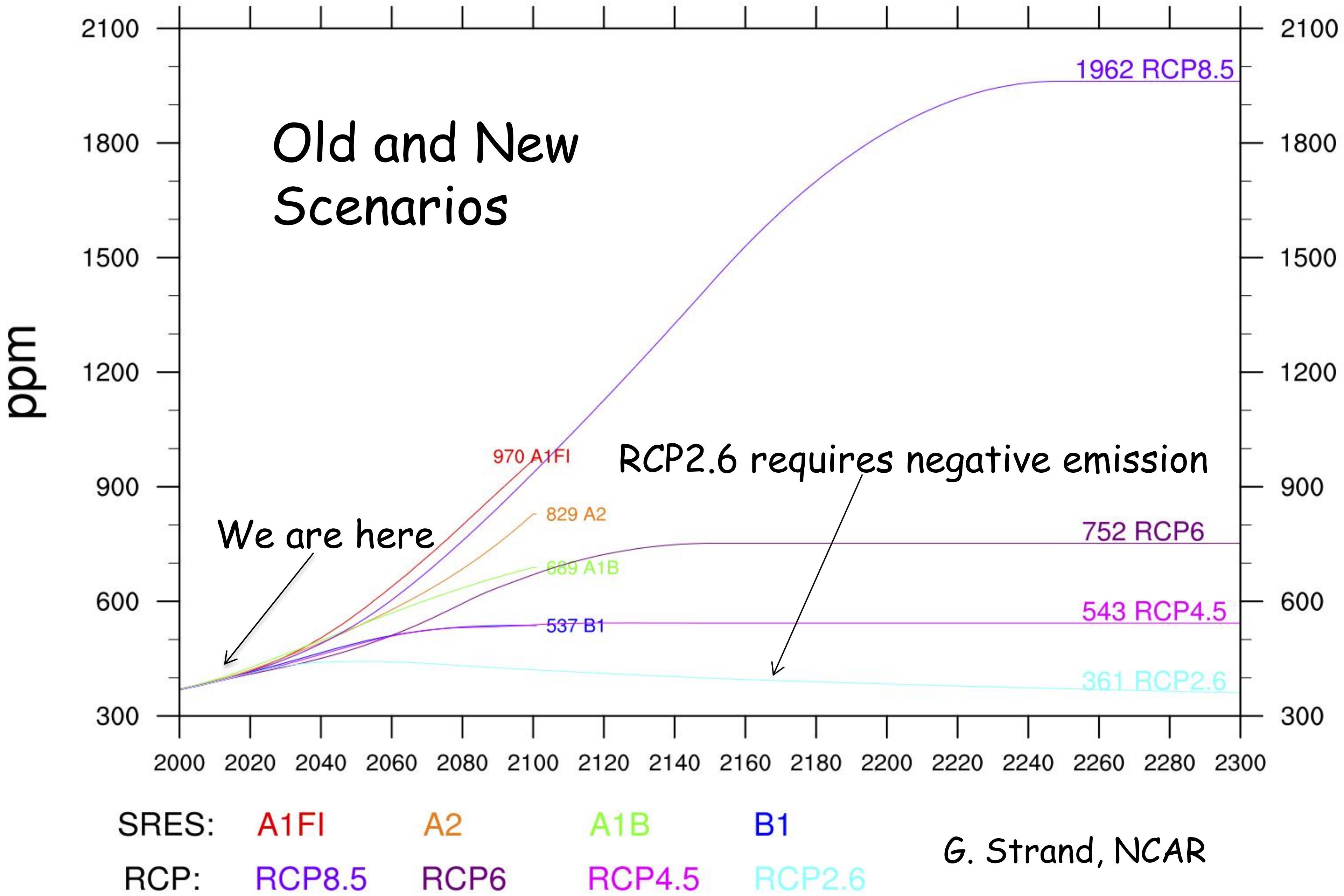
The blue line indicates their 5-year running mean.

The red line indicates the long-term linear trend.



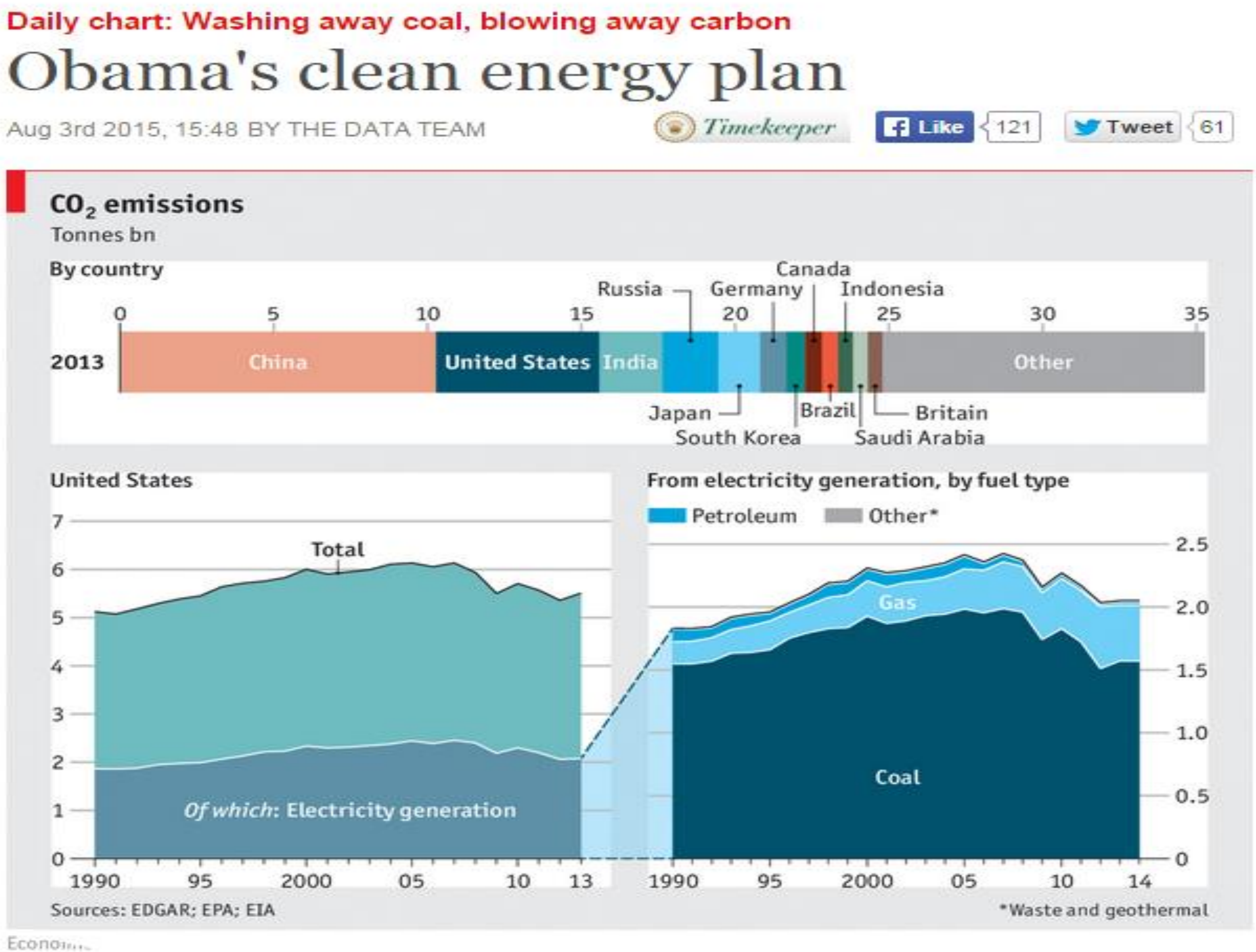
Global temperatures in July vs. 1951-1980 average. Via NASA.

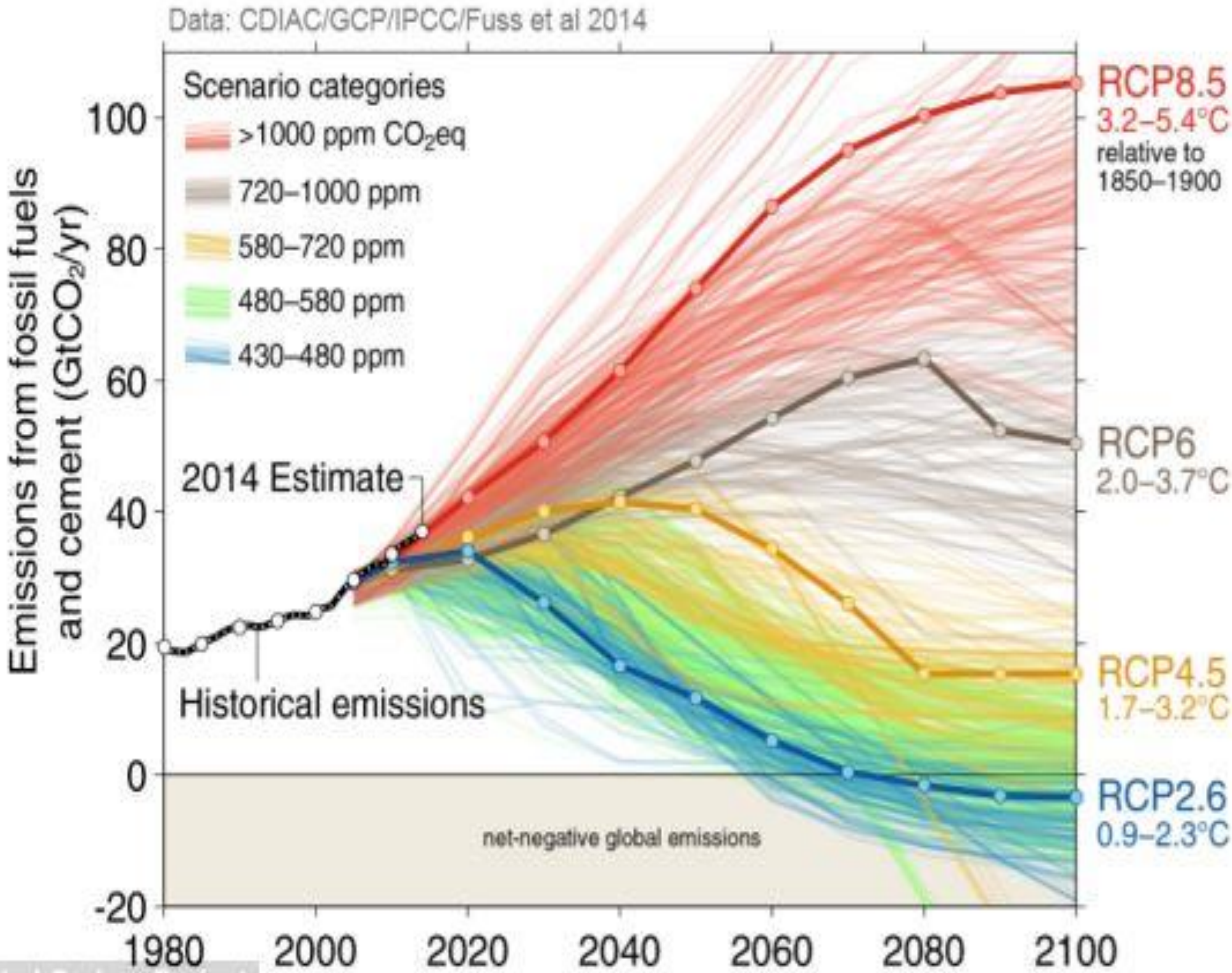
CO_2 concentrations



G. Strand, NCAR

CO2 Emissions (from Economist)





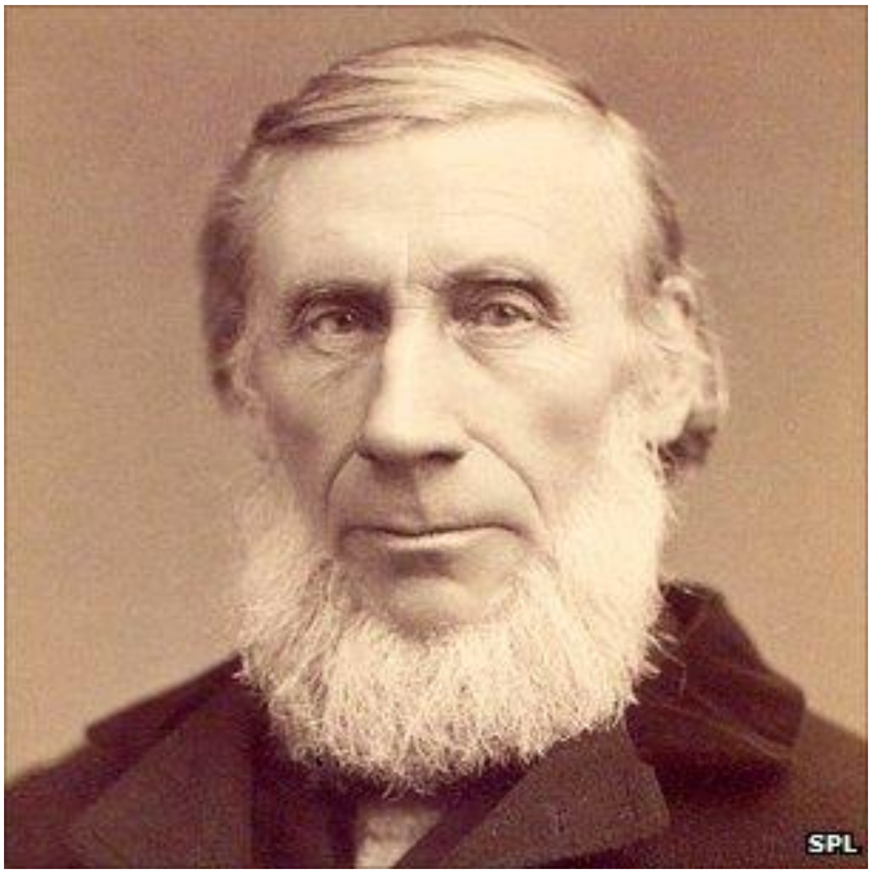
Data: CDIAC/GCP/IPCC/Fuss et al 2014
Scenario categories
>1000 ppm CO_2eq
720–1000 ppm
580–720 ppm
480–580 ppm
430–480 ppm
Emissions from fossil fuels and cement ($GtCO_2$/yr)
100
80
60
40
20
0
-20
2014 Estimate
Historical emissions
net-negative global emissions
1980
2000
2020
2040
2060
2080
2100
RCP8.5
3.2–5.4°C
relative to 1850–1900
RCP6
2.0–3.7°C
RCP4.5
1.7–3.2°C
RCP2.6
0.9–2.3°C

Next animation prepared by Tim Scheitin (CISL) which shows the difference in total water vapor between present and end of this century.

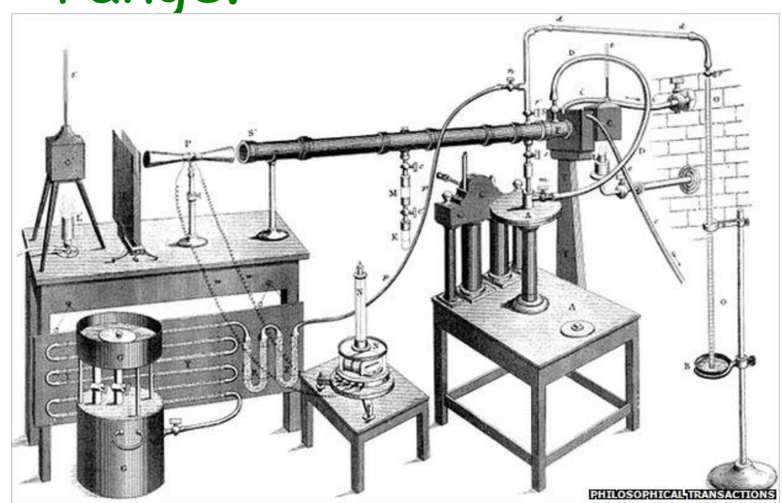
Climate Change:

A High Resolution Atmospheric Model (0.25 degree) with Specified Ocean Temperatures and Sea Ice

Tyndall started all this in 1861



- John Tyndall (British) showed that triatomic molecules like CO_2 and H_2O absorbed and emitted infrared radiation in the Earth's temperature range.



The End

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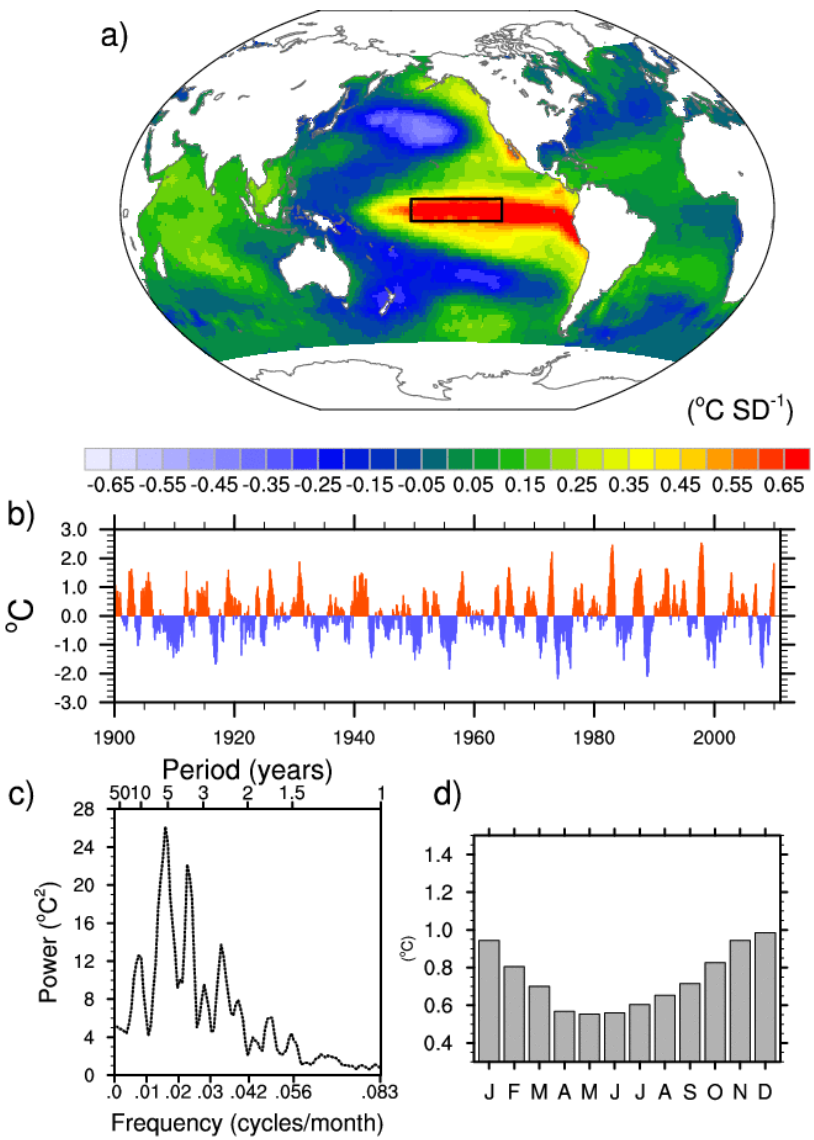
Special thanks to the
Department of Energy, Office of Science (BER),
the National Science Foundation (NSF), and OSTP
The computer time all these studies and model simulations
came from NSF and DOE supercomputer systems.

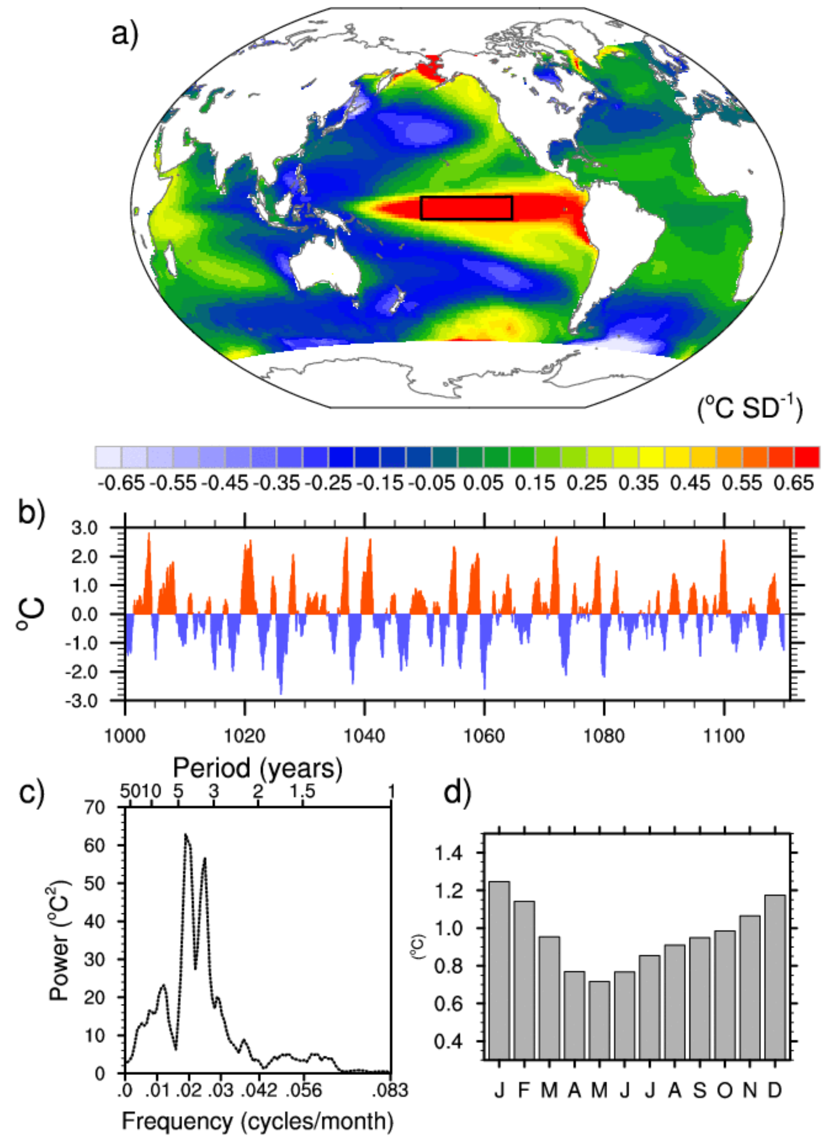

Mauna Loa, Hawaii
(MLO)

Leading Mode of Global SST Variability
Seasonal Capability (Neale, NCAR)

Observations



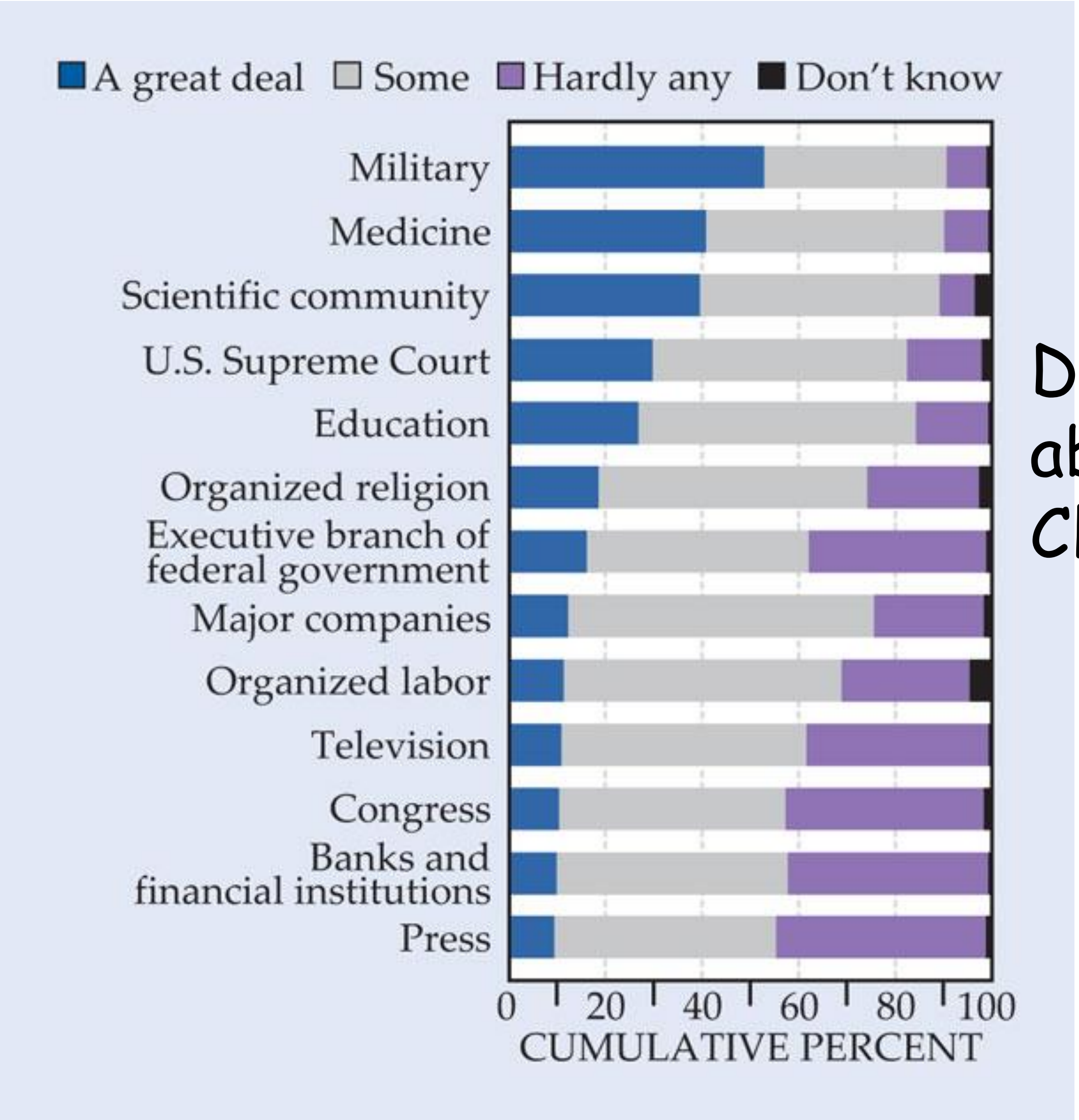
CCSM4



Climate and Earth System models have and continue to contribute to understanding and predicting the climate system. They allow the science community to determine objectively the possible impacts of climate change on food production, flooding, drought, sea level rise, and health as well as decision support. Higher resolution and more complete models will help.

From Istockphoto.com

Professions: Public Trust



Debate in Congress about the President's Climate Action Plan

From National Science Board S & E Indicators (2012)

Genesis of U.S. Global Change Program

White House Cabinet meeting on climate change in 1990

President George H. W. Bush

John Sununu, Chief of Staff

We installed a climate model in The White House!

Allan Bromley, President's Science Advisor

Convinced the cabinet about climate change.

We have loss the bipartisan approach.

U.S. Global Change Research Program

$2.7 Billon over 12 agencies

Thomas R. Armstrong, PhD

Executive Director, USGCRP

Office of Science and Technology Policy

Executive Office of the President

Washington, DC

www.globalchange.gov

I chaired the Review Committee for the National Academies

Slides provided by Thomas Armstrong

Global Change Research Act

Global Change Research Act of 1190 (P.L. 101-606)

Act at *http://www.globalchange.gov/about/program-structure/global-change-research-act*

Called for a "comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change"

OMB/OSTP FY 14 S&T Memo:
Guidance to the Agencies

Memo at *http://www.whitehouse.gov/sites/default/files/omb/memoranda/2012/m-12-15.pdf*

"Emphasize research that advances understanding of vulnerabilities in human and natural systems and their relationships to climate extremes, thresholds, and tipping points"

Passed by bipartisan Congress

National Climate Assessment released on May 6, 2014 at the White House

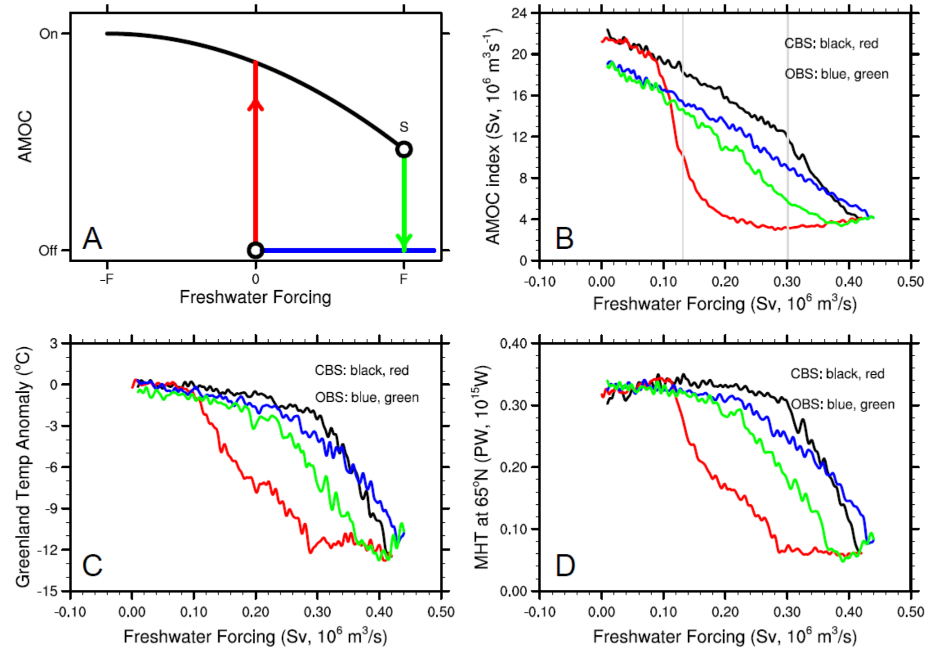
Role of the Bering Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability

Objective

Study the influence of the Bering Strait opening/closure on the hysteresis of the Atlantic meridional overturning circulation (AMOC) and abrupt climate change

Approach

- CCSM3 is used as the primary tool.
- Two simulations have done under present-day climate boundary conditions with everything is identical except one with an open Bering Strait and the other has a closed one.
- Freshwater is slowly added into the North Atlantic until the AMOC collapses, then freshwater water is slowly reduced until the AMOC restarts again. The simulations run 4400 years each at NERSC.

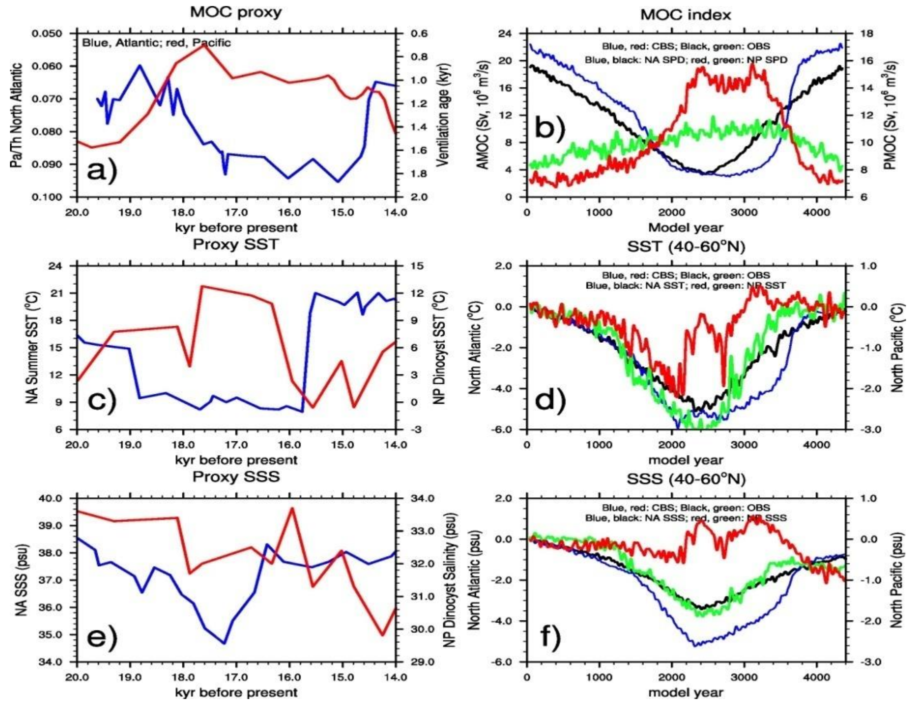


Impact

- Our results suggest that AMOC hysteresis only exists when Bering Strait is closed. Thus abrupt climate changes occur only in glacial time.
- This could have broad impact on both past and future climate studies.

Hu, A, G. A. Meehl, W. Han, A. Timmermann, B. Otto-Bliesner, Z. Liu, W. M. Washington, W. Large, A. Abe-Ouchi, M. Kimoto, K. Lambeck and B. Wu, 2012, **Role of the Berig Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability**, *PNAS*, doi:10.1073/pnas.1116014109. (Highlighted by PNAS and receivedsignificant media attention)

The Pacific-Atlantic Seesaw and the Bering Strait



Objective

Study the influence of the Bering Strait opening/closure on the Pacific-Atlantic climate response to a collapse of the Atlantic meridional overturning circulation (AMOC)

Approach

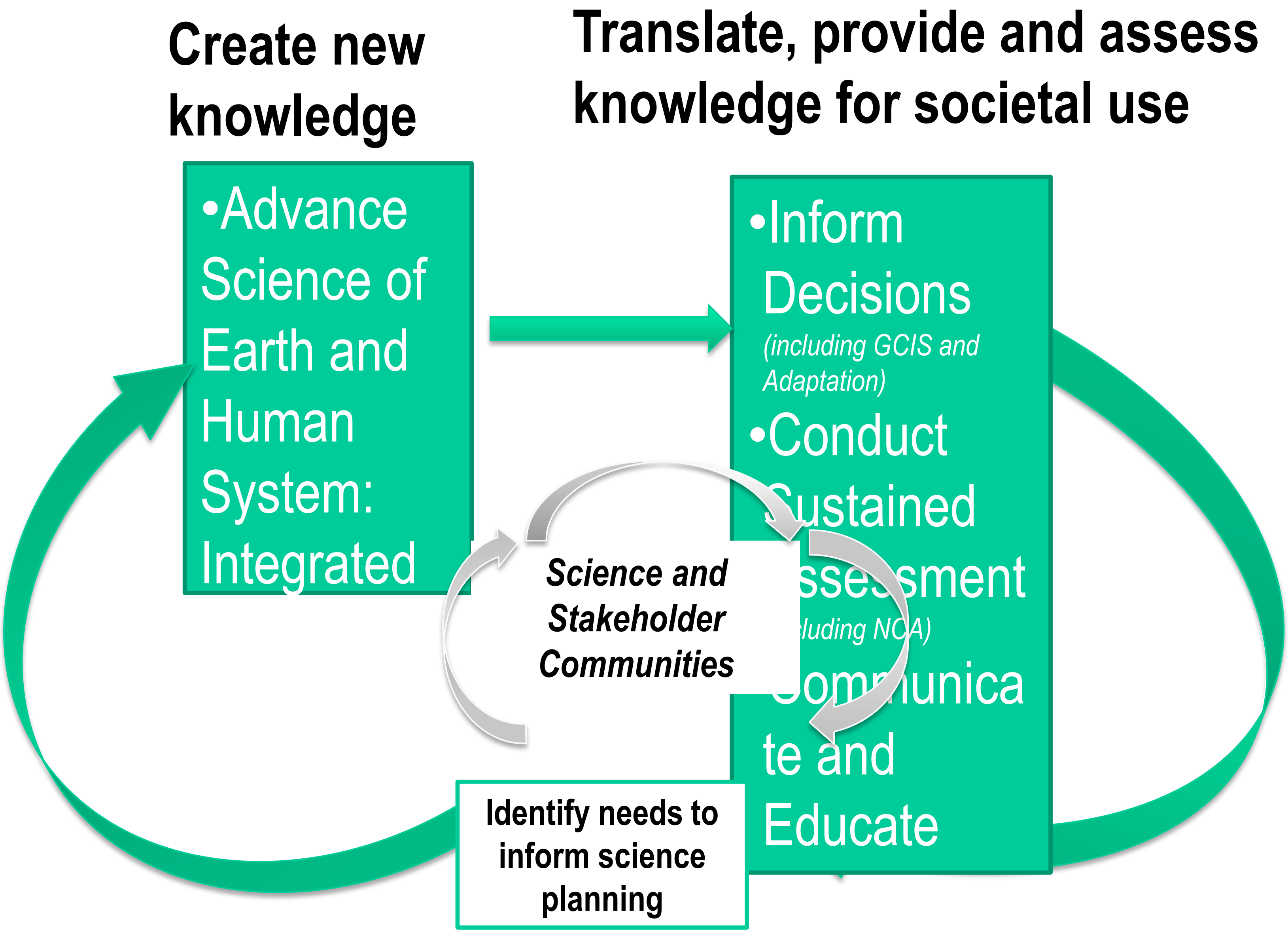
- CCSM3 is used as the primary tool.
- Two simulations have done under present-day climate boundary conditions with everything is identical except one with an open Bering Strait and the other has a closed one.
- Freshwater is slowly added into the North Atlantic until the AMOC collapses, then freshwater water is slowly reduced until the AMOC restarts again.

Impact

- Our results suggest that a seesaw-like climate change due to an AMOC collapse can only occur with a closed Bering Strait.
- This could have broad impact on both past and future climate studies.

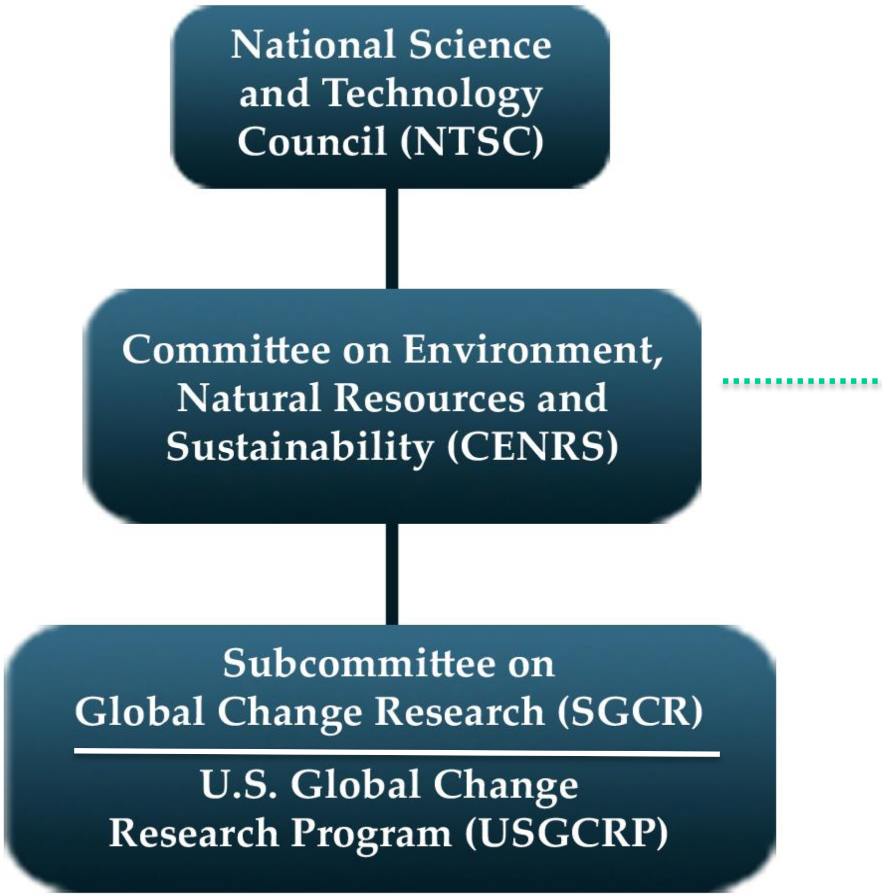
Hu, A, G. A. Meehl, W. Han, A. Abe-Ouchi, C. Morrill, Y. Okazaki, and M.O. Chikamoto, 2012, **The Pacific-Atlantic seesaw and the Bering Strait**, *Geophys. Res. Lett.*, L03702,doi:10.1029/2011GL050567. (Chosen to be AGU Research Spotlight)

USGCRP Research Enterprise



USGCRP in the Federal Context

Principals: *http://globalchange.gov/about/program-structure/officials*



CENRS Sub-Committees, WGs, & Task Forces
Air Quality Research (AQRS)
Critical and Strategic Mineral Supply Chains (CSMSC)
Interagency Arctic Research Policy Committee Interagency Working Group (IARPC)
Integration of Science and Technology for Sustainability Task Force
National Earth Observations Task Force (NEO)
Disaster Reduction (SDR)
Ecological Services (SES)
Global Change Research (SGCR)
Ocean Science & Technology (SOST)
Water Availability & Quality (SWAQ)
Toxics & Risks (T&R)
US Group on Earth Observations (USGEO)

Research Goals U.S. Global Change Research Program

- Goal 1. Advance science: Earth system understanding, science of adaptation and mitigation, observations, modeling, sharing information
- Goal 2. Inform decisions: Scientific basis to inform, adaptation and mitigation decisions
- Goal 3. Conduct sustained assessments: build capacity that improves Nation's ability to understand, anticipate, and respond
- Goal 4. Communicate and educate: Advance communication and educate the public, improve the understanding of global change, develop future scientific workforce

The USGCRP Strategic Plan
Outcomes and Priorities Activities

Outcomes

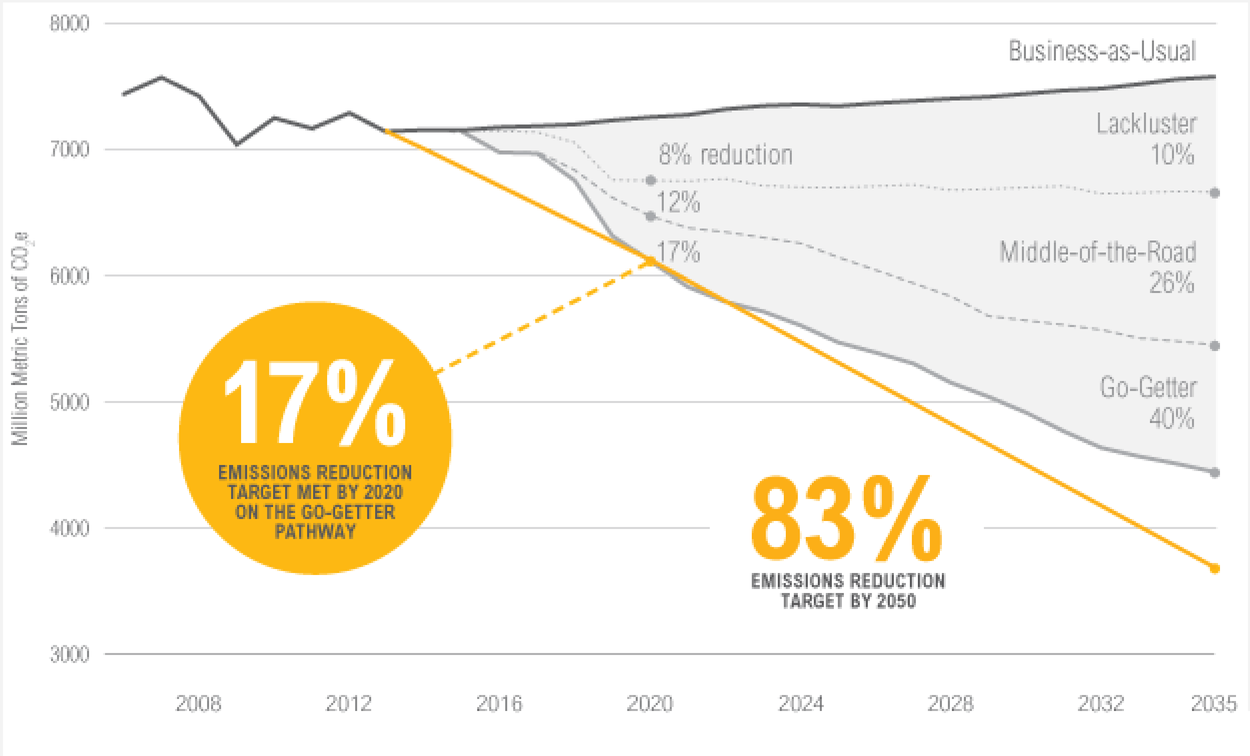
- Providing Knowledge on Scales Appropriate for Decision Making
- Incorporating Social and Biological Sciences
- Enabling Responses to Global Change via Iterative Risk Management

Priorities Activities

- Enhance Information Management and Sharing
- Enable new capabilities for Integrated Observations and Modeling
- Increase Proactive Engagement and Partnerships
- Leverage International Investments & Leadership
- Develop the Scientific Workforce for the Future

The Obama Administration committed in 2009 to reduce U.S. greenhouse gas emissions 17 percent below 2005 levels by 2020. **While the Administration is not currently on track to meet this goal, it can pursue a suite of policies even without new legislation. If pursued with "go-getter" level ambition, those policies can achieve the 17 percent commitment.** Below we look at four possible emissions scenarios. Click through each scenario to learn more. *(States can also play a role in achieving the 17 percent target, but these actions are not incorporated into this infographic.)*

Business-as-Usual   Lackluster   Middle-of-the-Road   Go-Getter   2050



Source: Can the U.S. Get There from Here? Using Existing Federal Laws and State Action to Reduce Greenhouse Gas Emissions

WORLD RESOURCES INSTITUTE