Introduction to the Community Earth System Model

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Outline

- An Overview of the CESM Model
- Science Highlights
  - Using different CESM configurations to investigate climate variability and change
- Some New Developments and Directions

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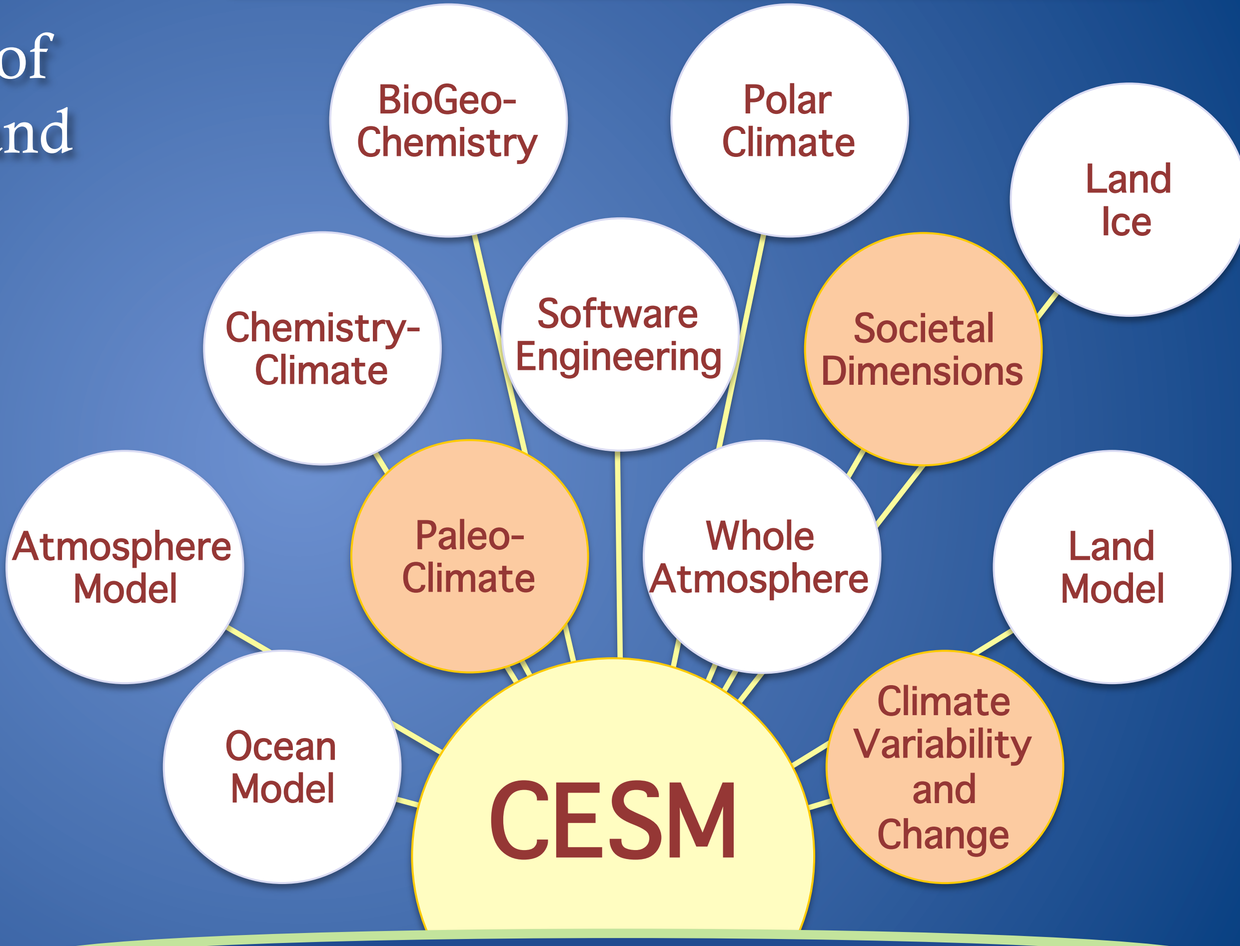
CESM Project

CESM Advisory Board

CESM Scientific Steering Committee

Based on 20+ Years of Model development and application



CESM is primarily sponsored by the National Science Foundation and the Department of Energy

Most working groups have winter/spring meetings. Annual meeting in June.

http://www.cesm.ucar.edu/management

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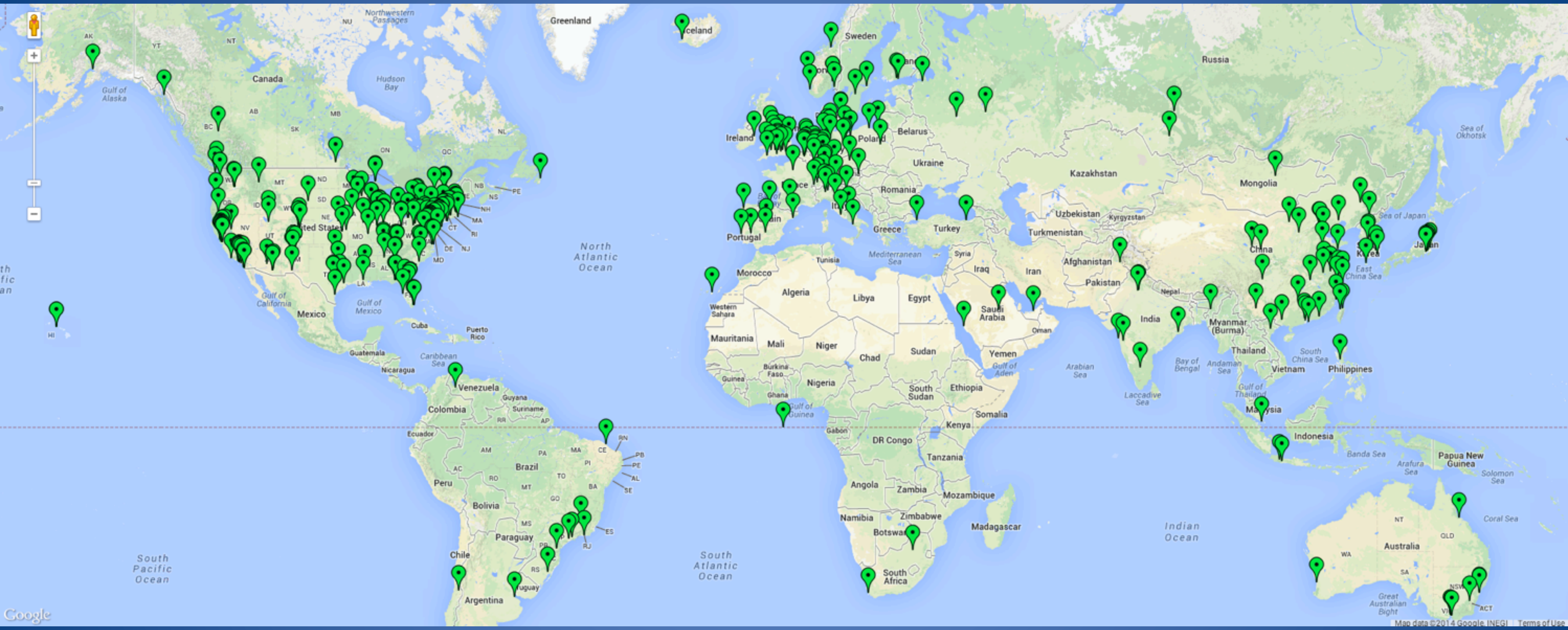
A truly global community



Download of release version since 2010

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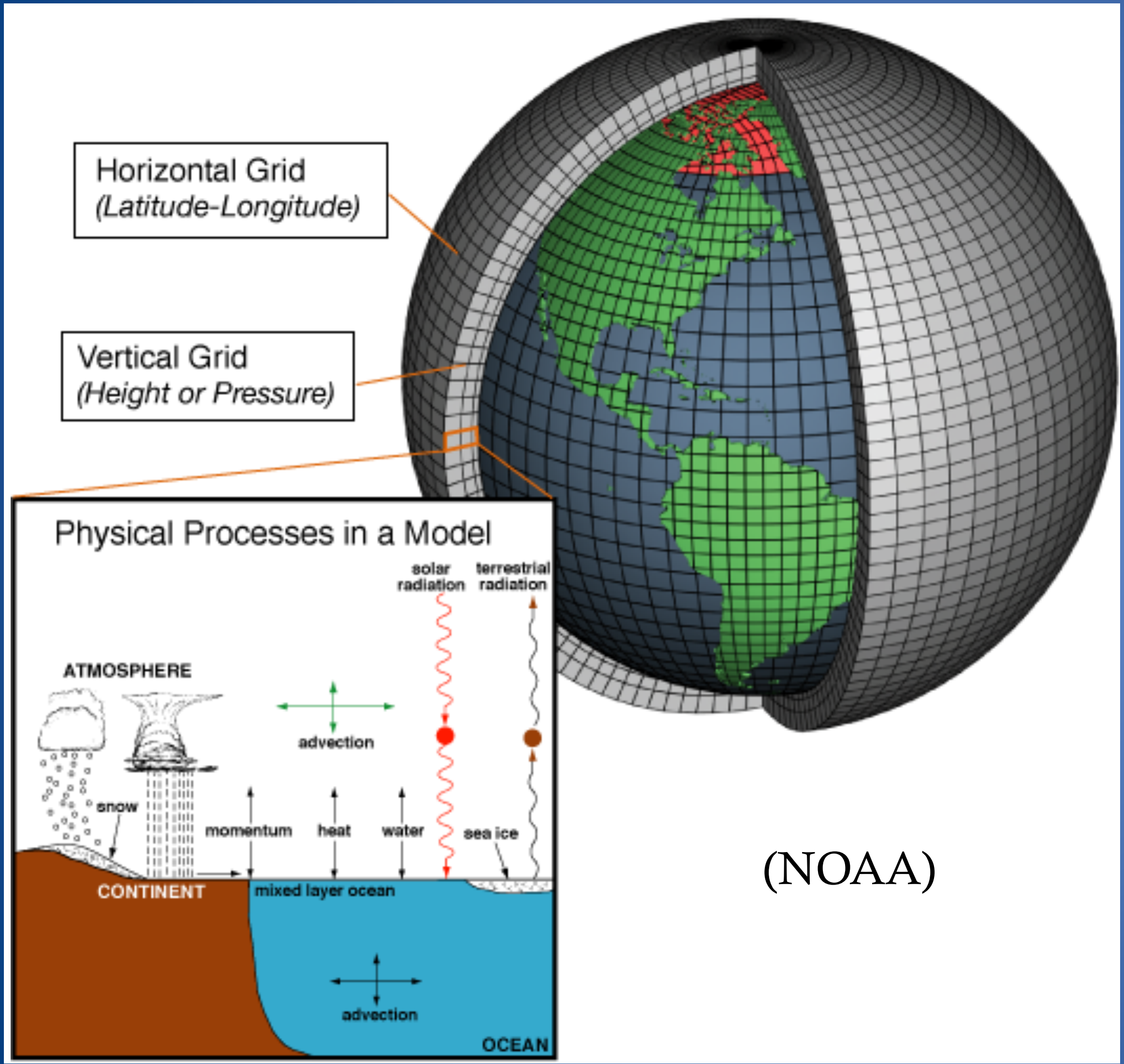
Community Earth System Model



(NOAA)

- Systems of differential equations that describe fluid motion, radiative transfer, chemical composition, etc.
- Planet divided into 3-dimensional grid to solve the equations
- Atmosphere and land traditionally on same horizontal grid
- Similarly for ocean/sea-ice
- Sub-gridscale processes are parameterized

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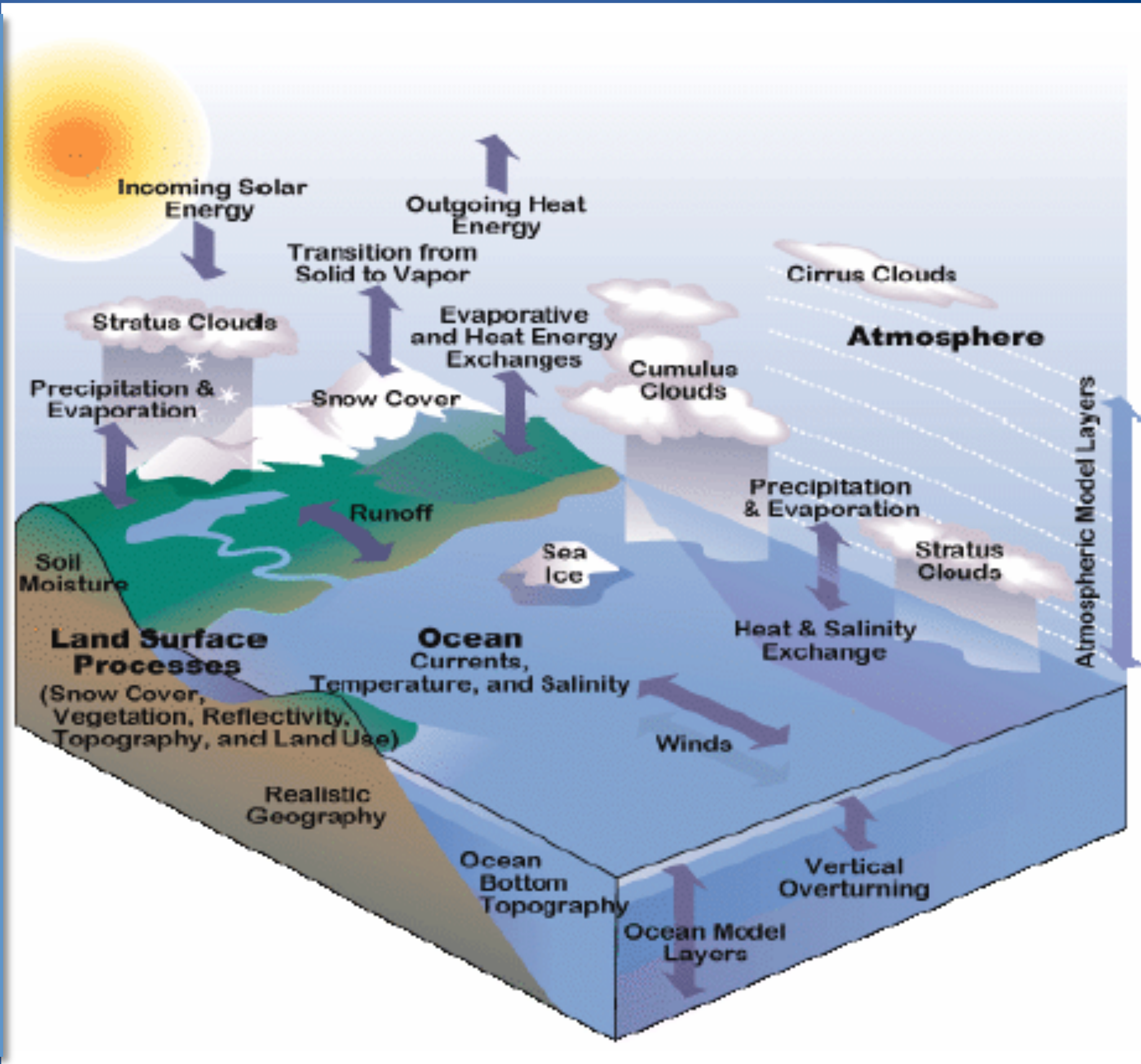
Coupled Climate Models

- Include atmosphere, ocean, land, & sea ice components
- Conservative exchange of momentum, heat, water and chemical constituents across components
- Can apply changes in external forcing – solar input, GHGs, volcanic eruptions
- Provide a virtual laboratory for experimentation



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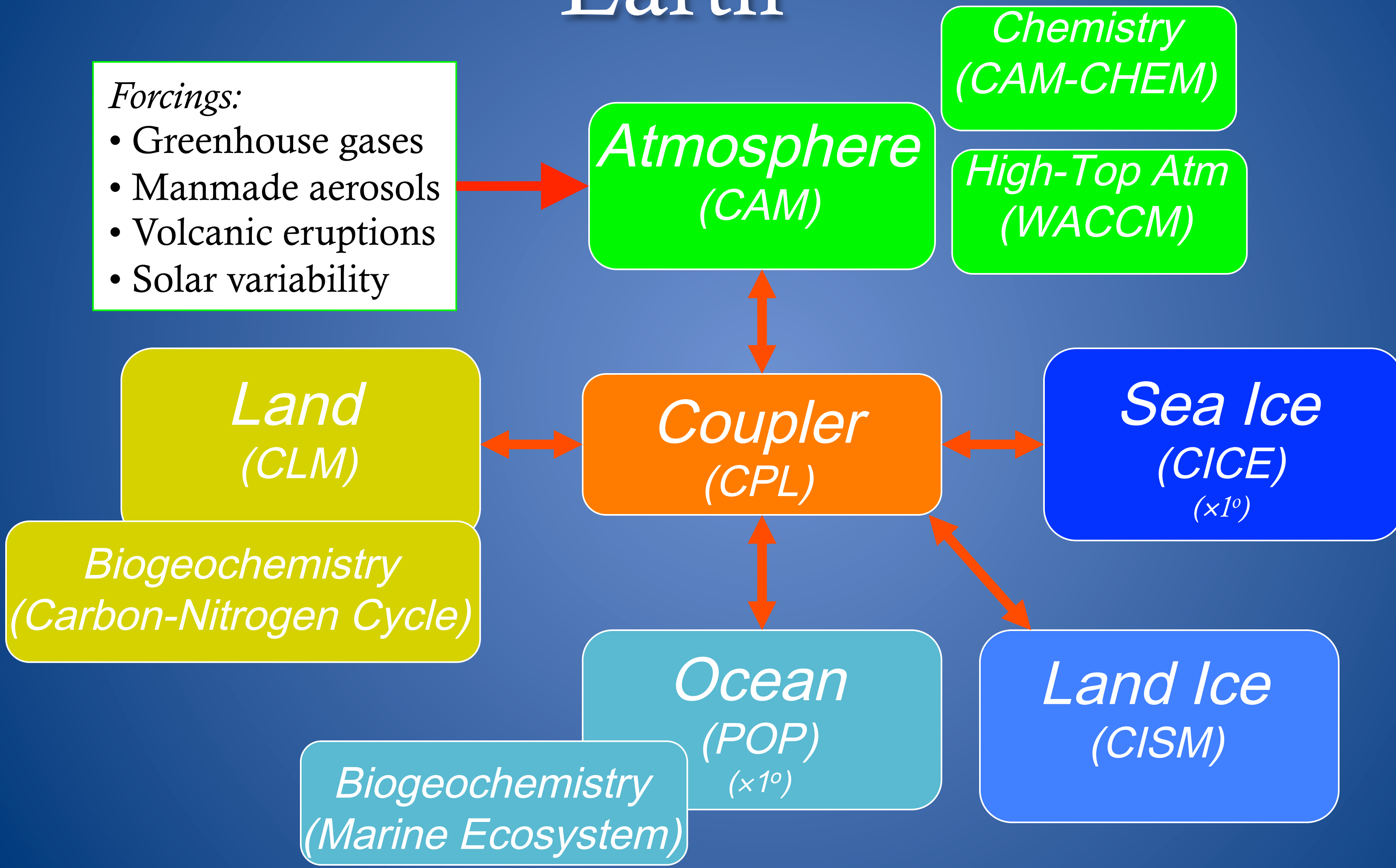
Community ~~Climate~~ Earth System Model



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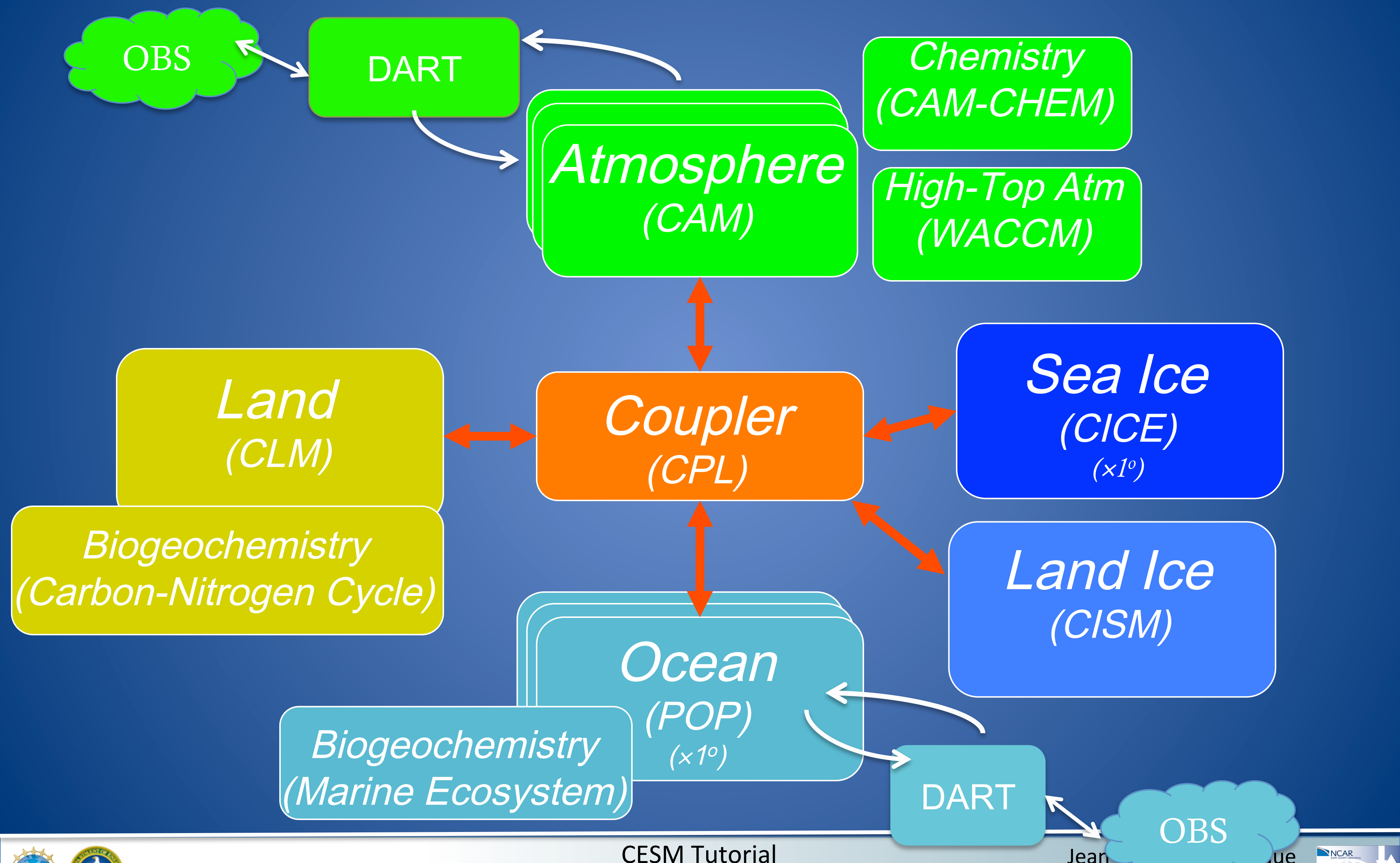
Community Earth System Model



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Notes on CESM Configurations

- All component models can be active
- All component models can be replaced with "data models"
  - These read in relevant fields for model forcing (for example the datm used in an ocean-only run may read in NCEP for forcing)
  - The ocean model can also be replaced with a slab model
- Numerous options are available within components
  - Can be chosen with namelist options
  - For example different sea ice albedo formulations, etc.
- Increasing number of supported component sets available (including ability to run 20^{th} & 21^{st} century runs)

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CESM Model Releases

- Targeting annual (May/June) releases
- Configurations in multiple categories
  - Scientifically vetted (with runs/"assessment")
  - Functionally vetted (routine testing)
  - Development only (no testing; use at own risk)
- Webpage with "scientifically supported" compsets: http://www2.cesm.ucar.edu/models/scientifically-supported
- New bulletin board (DiscussCESM Forum) for updates on releases and other model support – encourage subscription

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CESM Community Integrations

- CESM integrations with broad cross-working group science applications
- Results are/will be made available in timely fashion to scientific community via ESG

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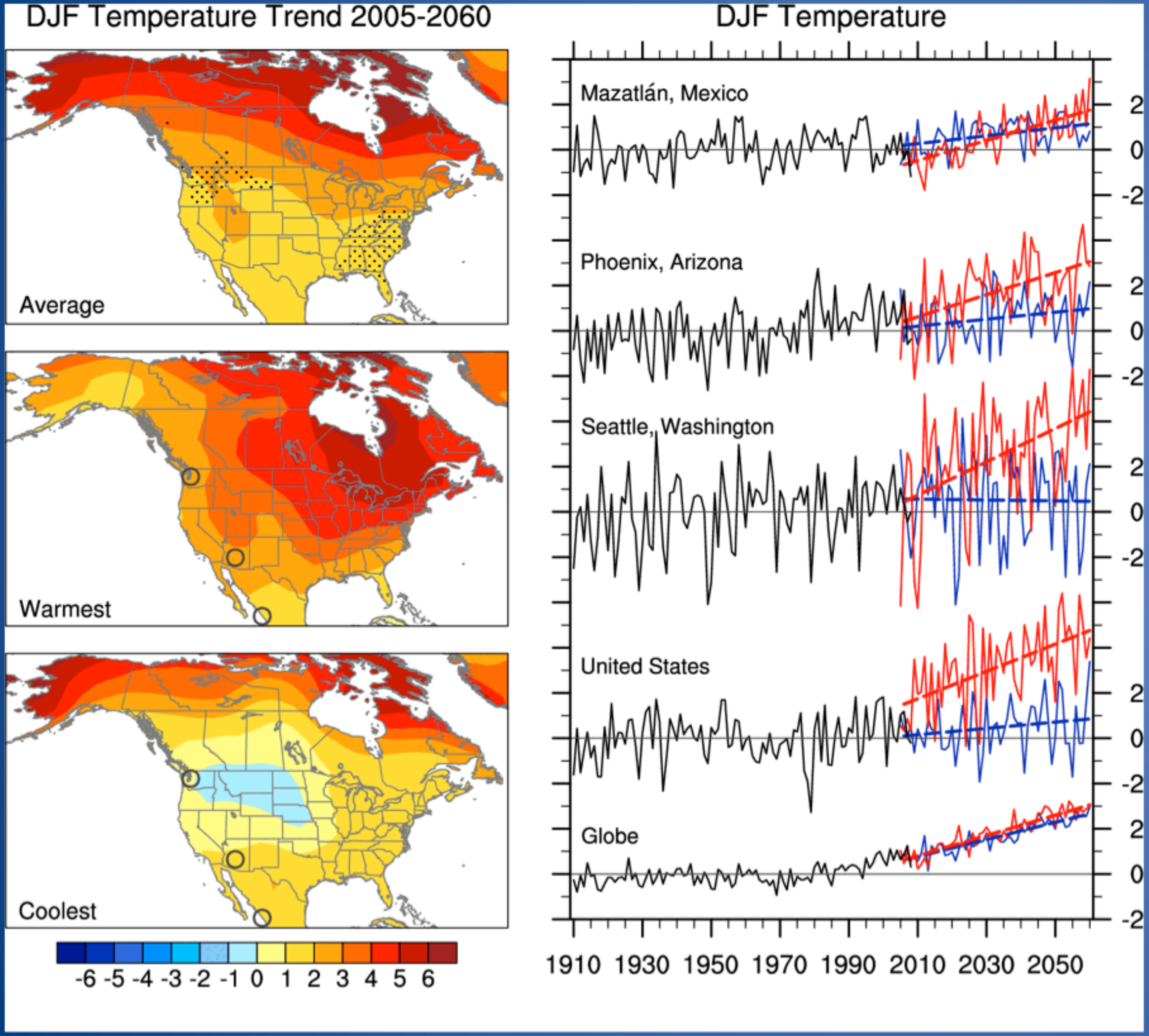
Community Integrations - Large Ensemble
Science Motivation



From Deser et al., 2012, Nature Climate Change

Purpose:

- To robustly determine simulated natural variability
- To assess climate extremes and their changing likelihood
- To investigate detection/attribution of climate changes in the 20th-21st centuries

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Large Ensemble Experimental Design

- CESM1-CAM5-BGC 1 degree
- Long control simulation (1500+ years)
- One member 1850-2080
- 29 members 1920-2080 (20 extended to 2100)
- 7-10 additional members being run in Toronto (Paul Kushner's group)
- BAMS paper submitted
- Data publicly available on ESG

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LE Data Access

- CESM-LE website = where you can learn about the experiment, see diagnostics etc. http://www2.cesm.ucar.edu/models/experiments/LENS/
- ESG = where you can get all data https://www.earthsystemgrid.org
- Also: /glade/p/cesm0005 partition for users with yellowstone access

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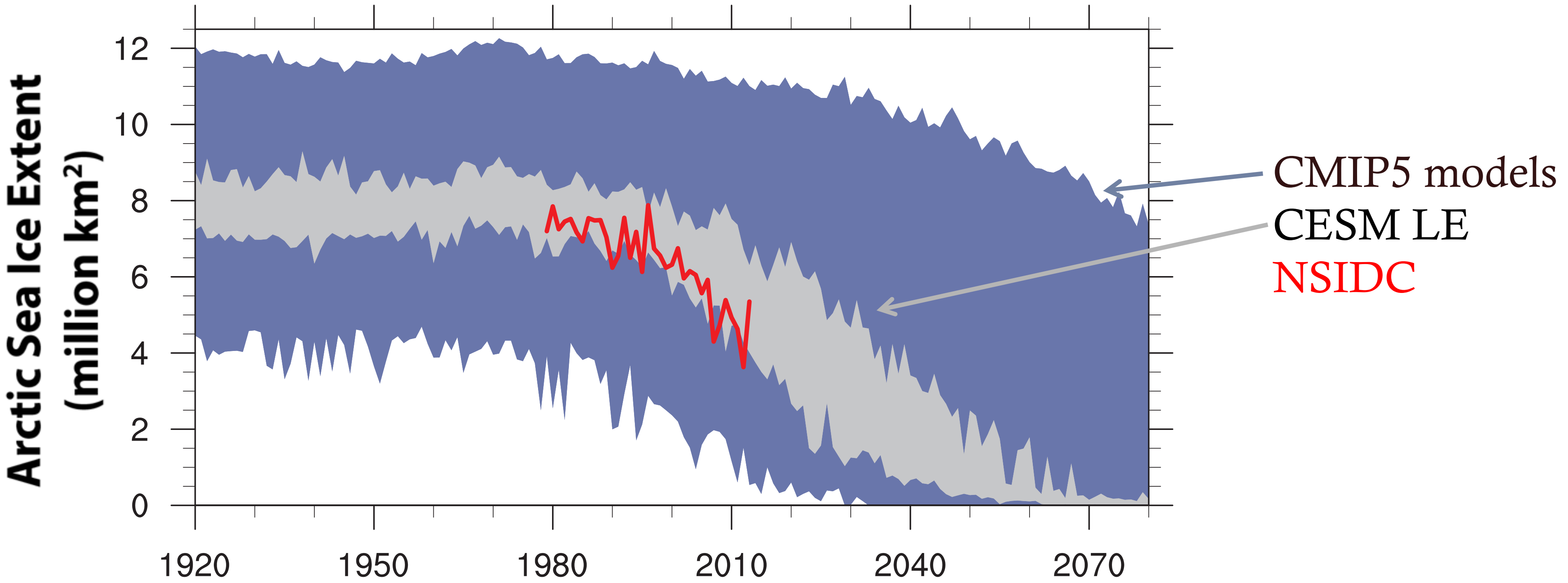
September sea ice extent



Slide courtesy of A. Jahn
CMIP5 data courtesy of A. Barrett and J. Stroeve (NSIDC)

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What can we learn from comparing observed and modeled September sea ice trends?

1. Observed sea ice loss cannot be explained by natural variability alone.

2. Individual ensemble members can reproduce the observed ice loss, but the ensemble spread is large.

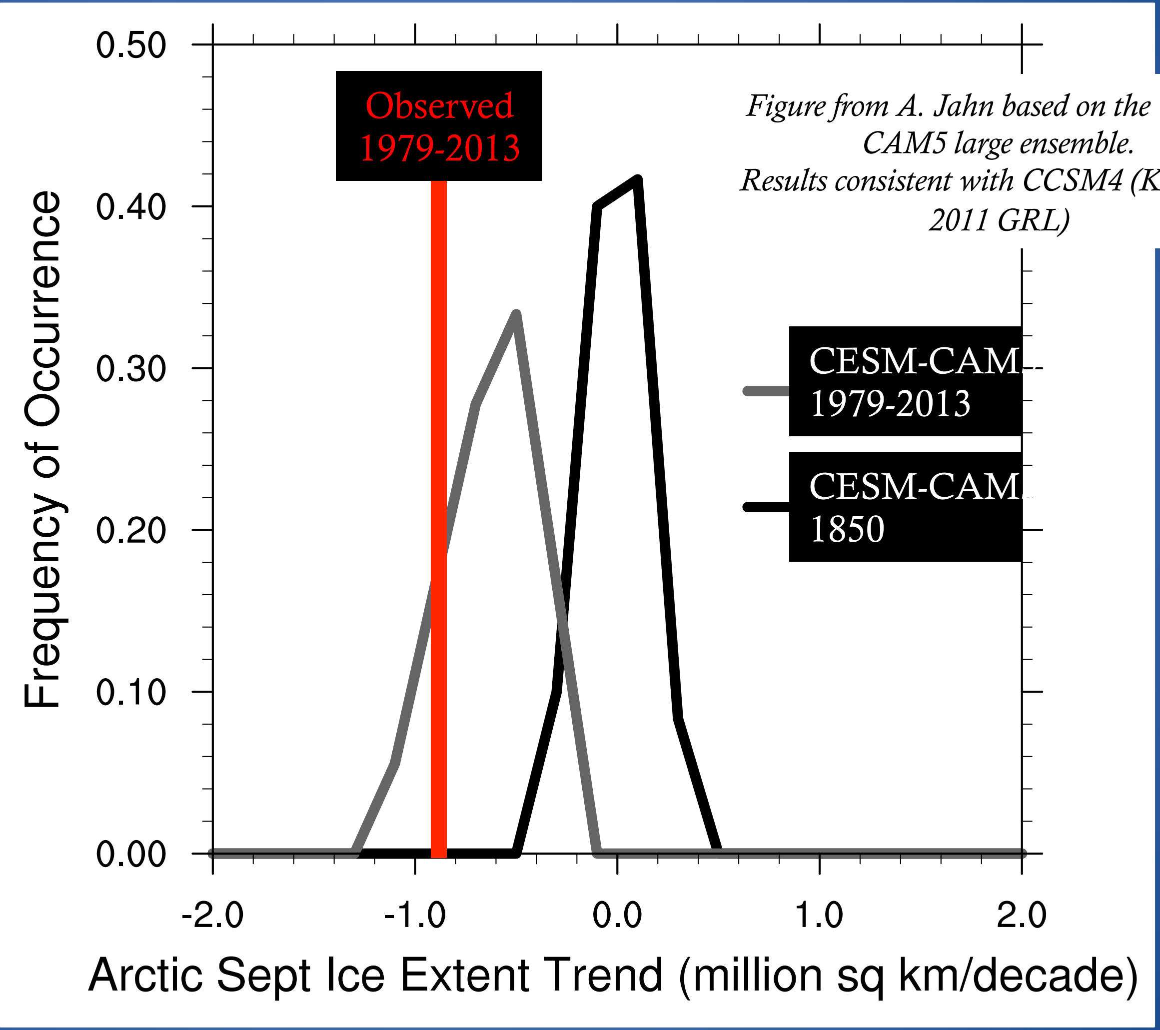

Figure from A. Jahn based on the CESM-CAM5 large ensemble. Results consistent with CCSM4 (Kay et al. 2011 GRL)

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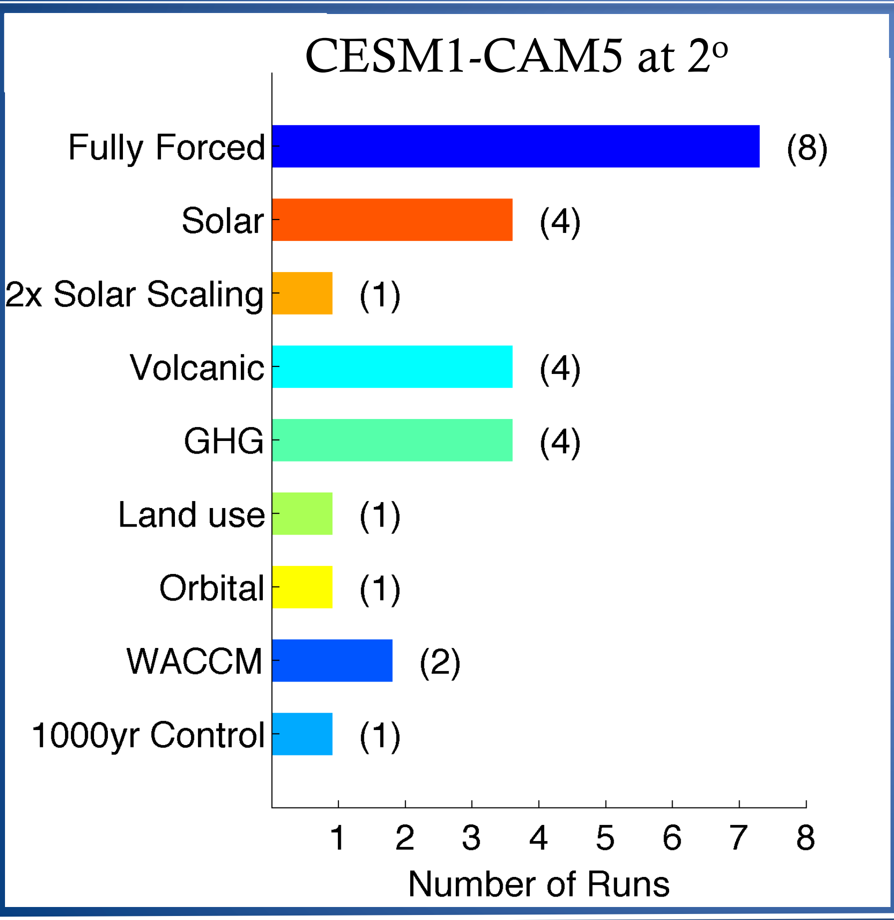
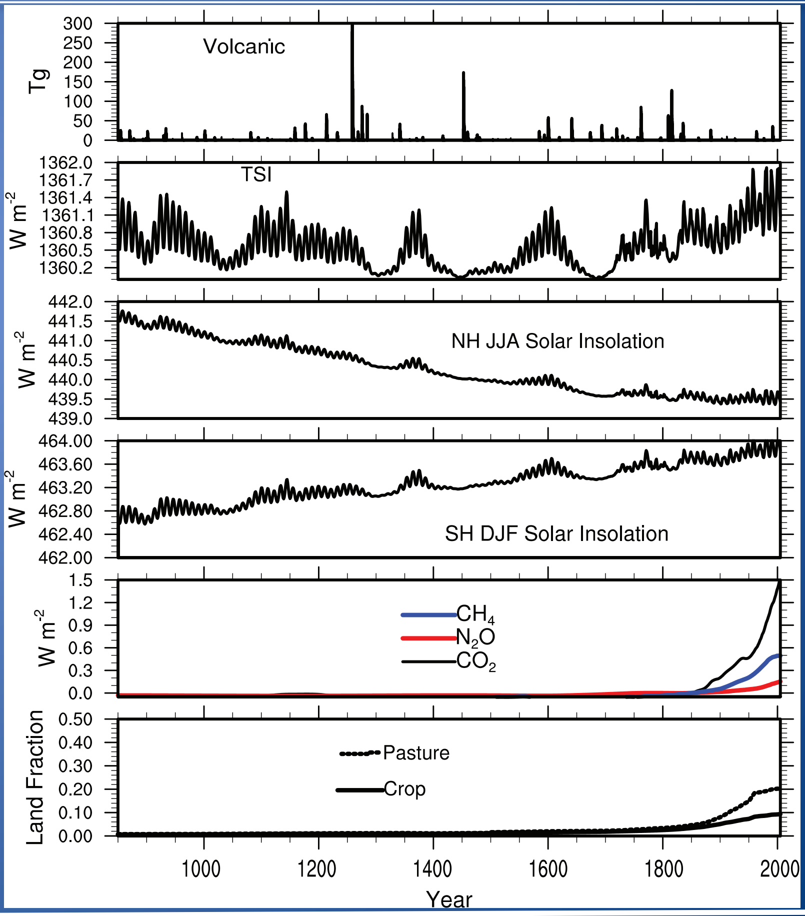
Community Integrations: Last Millennium Ensemble

- Motivation: To assess and attribute climate variations over the last millennium
- Simulations from 850-2005; ensembles of fully-forced + single forcing CESM-CAM5 experiments (23) and fully-forced WACCM runs (2)
- CESM1-CAM5 2-degree pre-industrial control integration will also be available





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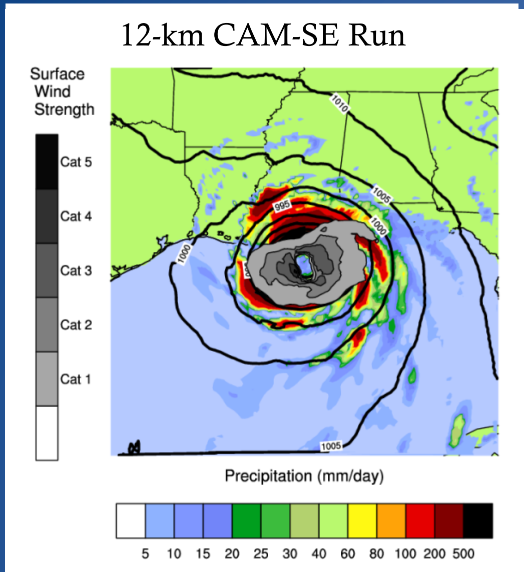
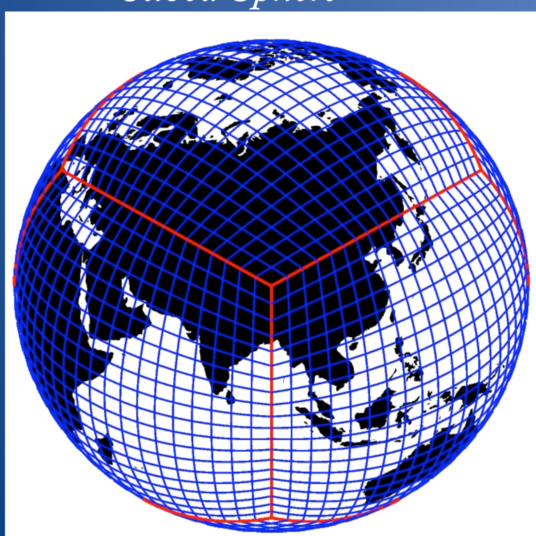
Community Integrations – High Resolution Control

Tropical Cyclones



Cubed Sphere



- Fully coupled configuration
  - 25km CAM5-SE
  - 1-degree ocean
- Multi-century integration

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CESM2 targets and timeline

- CESM2 release June 2016
- 2 main target configurations for CMIP6
  - 1-degree CAM5.5 (FV or SE)
    - ➡ for BGC/Chemistry/WACCM/Paleo/…
  - ¼-degree CAM6-SE
- CAM5.5 to be finalized by winter AMWG and released by June 2015 to allow for testing and development of other components

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Science Highlights

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CCSM4/CESM1 J. Climate Special Collections

- >50 Papers available via AMS early-online release
- Document major model components and numerous aspects of simulated variability and change from all CESM configurations

AMERICAN METEOROLOGICAL SOCIETY
AMS Journals Online

CCSM4 Special Collection

Theme Description:

This collection consists of papers analyzing results from the recently completed and released Community Climate System Model, version 4; see http://www.cesm.ucar.edu/models/ccsm4.0/. The coupled simulations range from runs of past paleoclimates, a long preindustrial control forced by 1850 conditions, an ensemble of 20th century runs, and four ensembles of the future climate using different Representative Concentration Pathways.

CESM1 Special Collection

Theme Description:

The second part of this collection has papers analyzing results from the recently completed and released Community Earth System Model, version 1; see http://www.cesm.ucar.edu/models/cesm1.0/. The new components that are available which turn it into an Earth System Model are: carbon cycle modules in the land, ocean, and atmosphere components; an interactive chemistry component in the atmosphere; a version of the atmosphere that reaches into the upper stratosphere, called WACCM; and a completely new land ice component. In addition, an updated version of the atmosphere component, CAM5, is available, which uses several new parameterizations, and can simulate the indirect effects of aerosols.

The CCSM4/CESM1 Special Collection organizers are:

Peter Gent, Past Chairman of the CCSM Project SSC (gent@ucar.edu)
Jim Hurrell, Chairman of the CCSM Project SSC (jhurrell@ucar.edu)

Semyon A. Grodsky, James A. Carton, Sumant Nigam, Yuko M. Okumura, **Tropical Atlantic Biases in CCSM4.** *Journal of Climate*, early online release.
Abstract . PDF (1250 KB)

Gerald A. Meehl, Warren M. Washington, Julie M. Arblaster, Aixue Hu, Haiyan Teng, Claudia Tebaldi, Ben Sanderson, Jean-Francois Lamarque, Andrew Conley, Warren G. Strand, James B. White III. **Climate system response to external forcings and climate change projections in CCSM4.** *Journal of Climate*, early online release.
Abstract . PDF (9088 KB)

C. M. Bitz, K. M. Shell, P. R. Gent, D. Bailey, G. Danabasoglu, K. C. Armour, M. M. Holland, J. T. Kiehl, **Climate Sensitivity of the Community Climate System Model Version 4.** *Journal of Climate*, early online release.
Abstract . PDF (2920 KB)

Keith Oleson, **Contrasts between urban and rural climate in CCSM4 CMIP5 climate change scenarios**. *Journal of Climate*, early online release.
Abstract . PDF (4067 KB)

Alexandra Jahn, Kara Sterling, Marika M. Holland, Jennifer E. Kay, James A. Maslanik, Cecilia M. Bitz, David A. Bailey, Julienne Stroeve, Elizabeth C. Hunke, William H. Lipscomb, Daniel A.

http://journals.ametsoc.org/page/CCSM4/CESM1

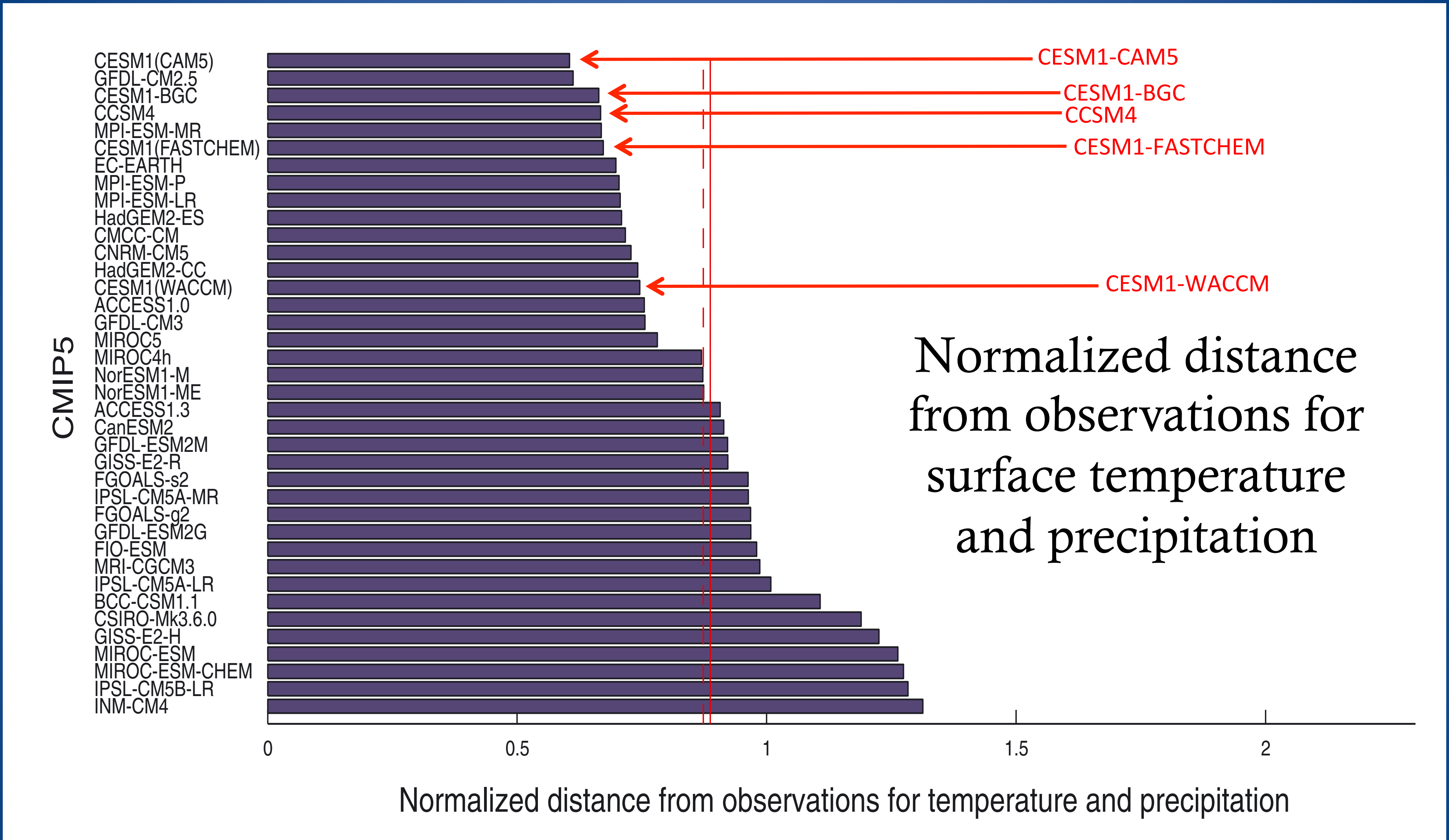
Figure courtesy of Steve Ghan and DOE Graphics team

BAMS Article:

The Community Earth System Model: A Framework for Collaborative Research

J.W. Hurrell, M.M. Holland, P.R. Gent, S. Ghan, J.E. Kay, P.J. Kushner, J.-F. Lamarque, W.G. Large, D. Lawrence, K. Lindsay, W.H. Lipscomb, M.C. Long, N. Mahowald, D.R. Marsh, R.B. Neale, P. Rash, S. Vavrus, M. Vertenstein, D. Bader, W.D. Collins, J.J. Hack, J. Kiehl, S. Marshall, available online

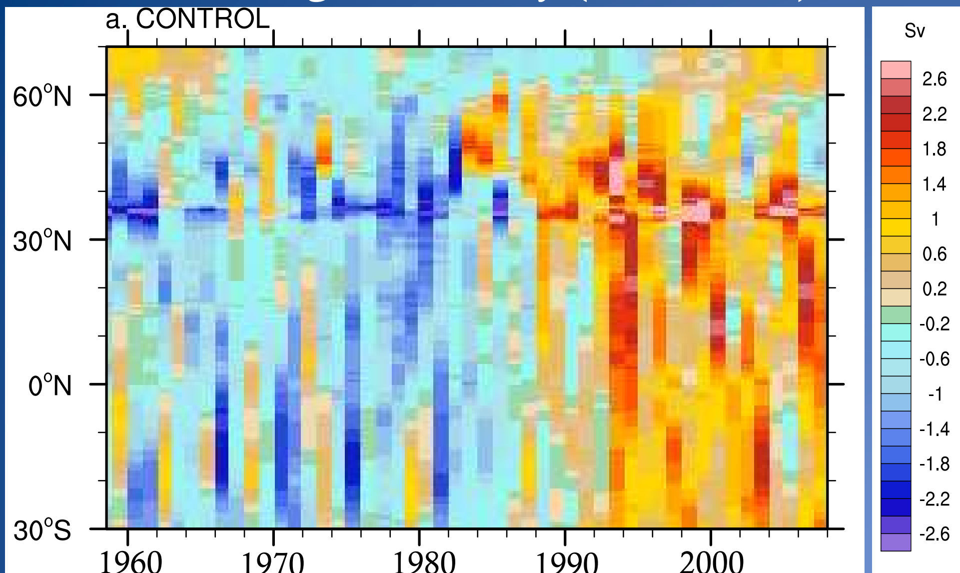
CMIP5 Model Intercomparison

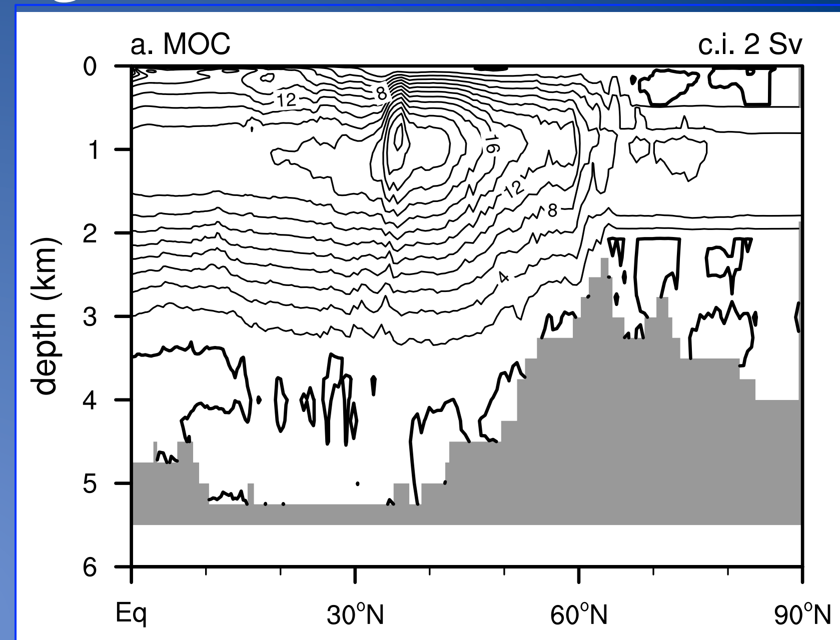


(Knutti, Masson, Gettelman, GRL, 2013)

Atlantic Meridional Overturning Circulation Variations

AMOC strength anomaly (1958-2008)

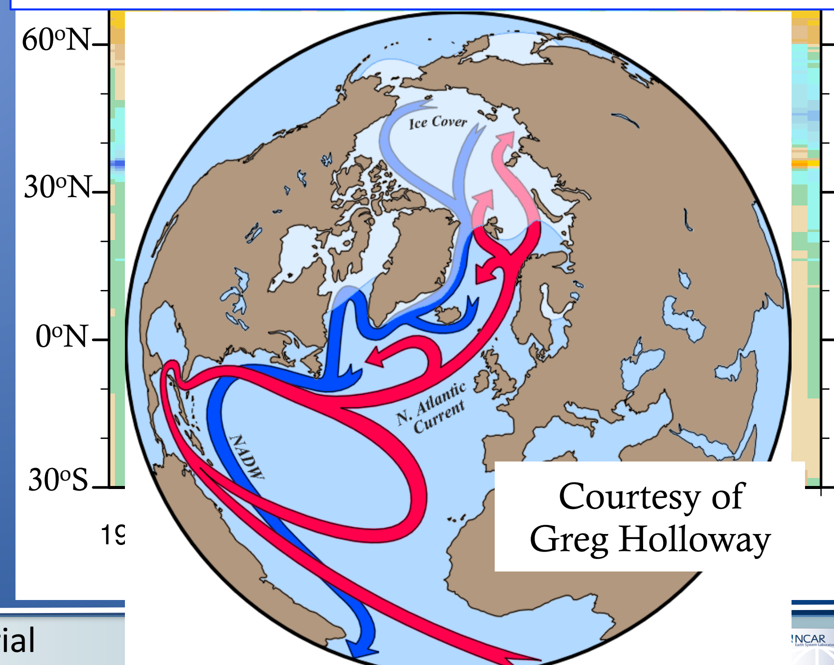




<u>CESM Ocean-Ice (CORE-II) experiments</u>

- AMOC variations well approximated by a linear superposition of momentum and buoyancy forced anomalies
- Buoyancy forcing explains decadal variations, with Labrador Sea turbulent forcing mostly responsible

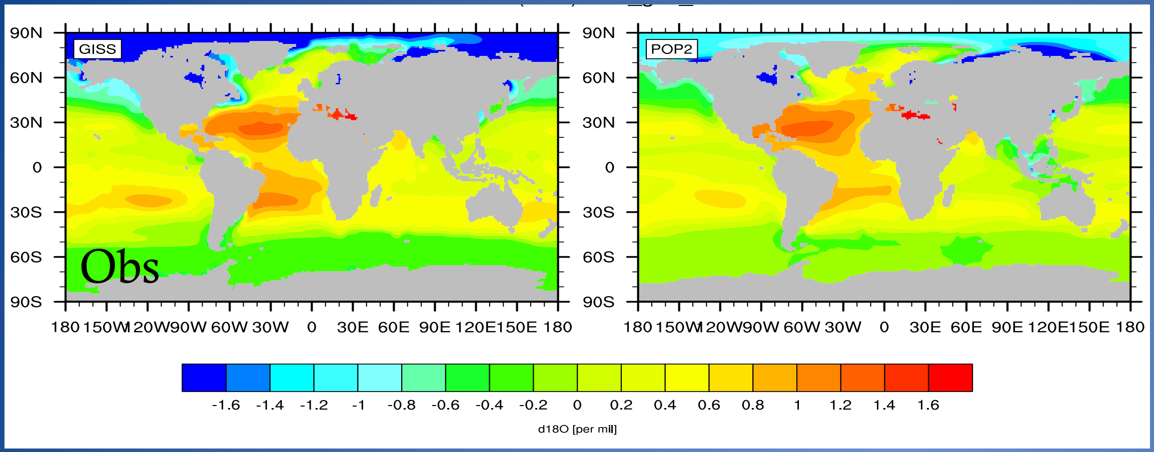
Yeager and Danabasoglu (2013)



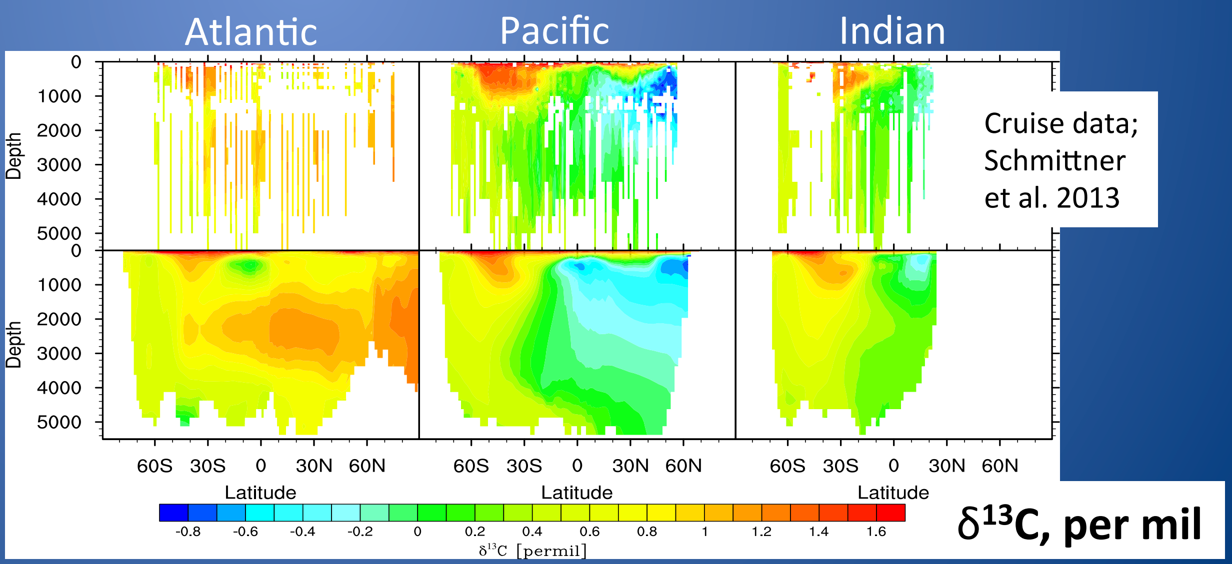
Courtesy of Greg Holloway

Results from the isotope enabled CESM

Surface water isotope ($\delta^{18}O$, per mil) distribution



Zonal carbon isotope ($\delta^{13}C$) distribution



Slide courtesy of A. Jahn, E. Brady
The iCESM project is funded by DOE, Office of Science

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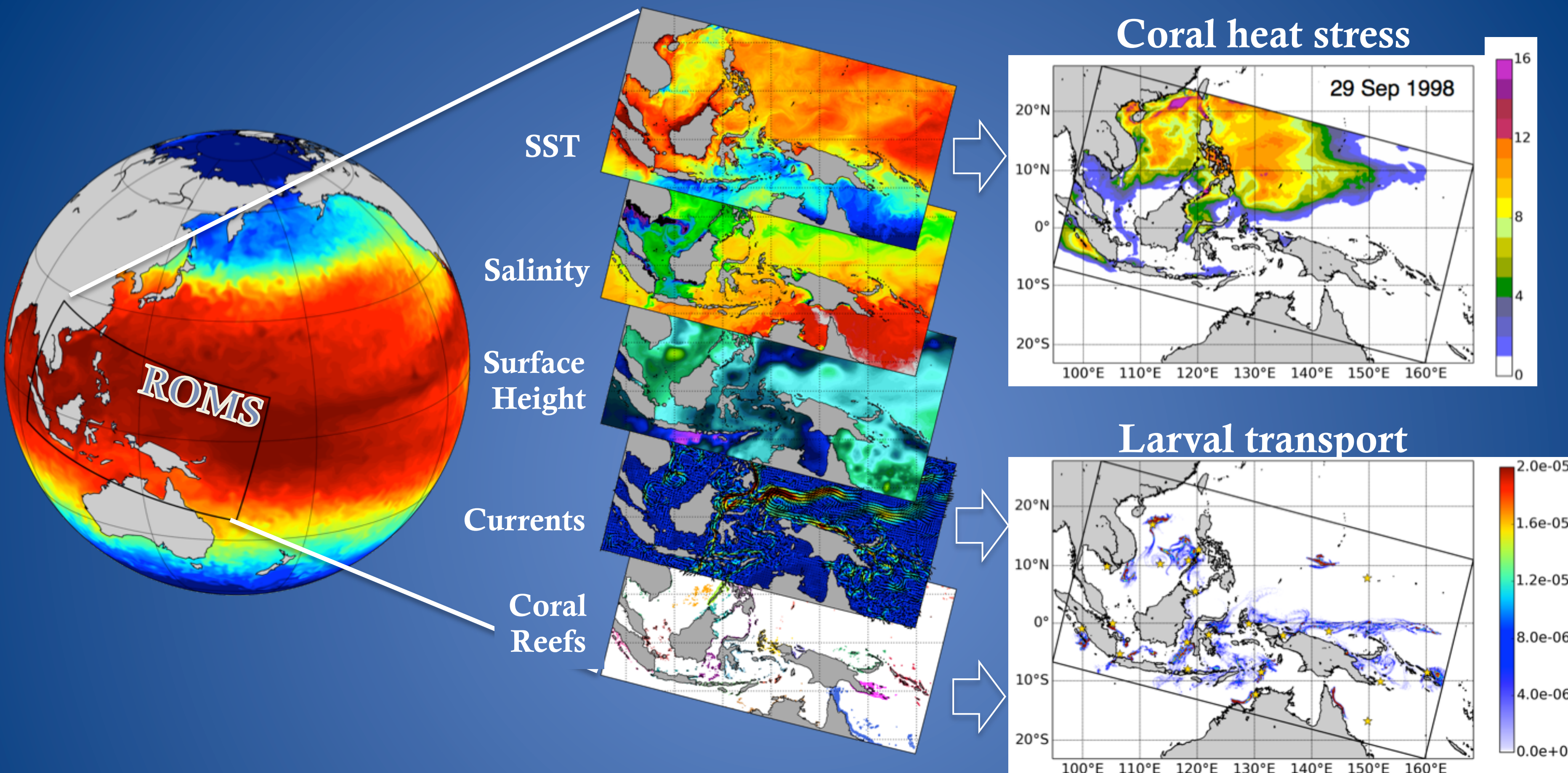
Using CESM output in marine ecosystem research



Goal: How will climate change affect marine ecosystems in the western tropical Pacific?

Method: Dynamical downscaling of CESM using a 5-km Regional Ocean Model System (ROMS)

Results: Identify regions for conservation: low heat stress, important sources/sinks of larvae

Coral Triangle Project: J. Kleypas, F. Castruccio, D. Thompson, E. Curchitser (Rutgers), and The Nature Conservancy. *See the posters by Castruccio and Thompson.*

Sponsors: NSF, Rutgers Univ., and NCAR ISP and ASP programs

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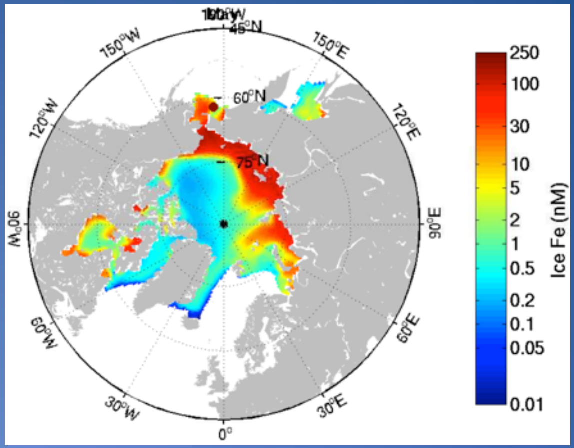
Impact of Sea Ice on the Marine Iron Cycle and Ecosystems

Motivation

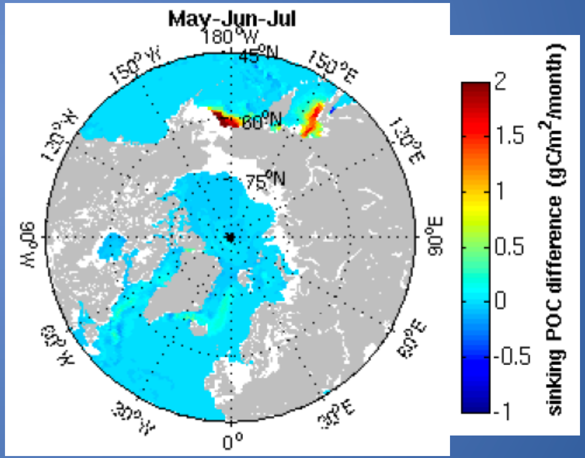
- **<u>Iron is a key nutrient for phytoplankton growth in the surface ocean</u>**. At high latitudes, the iron cycle is closely related to the dynamics of sea ice. Iron sequestration in ice needs to be considered in simulations of the iron cycle and marine ecosystems.

Approach

- Iron is incorporated in CICE4 as a passive tracer.
- **<u>Iron cycles between seawater and ice</u>**.
- Three sources of iron are considered for iron accumulation in sea ice: atmospheric deposition, seawater iron, and suspended sediments in shallow regions.



Simulated iron concentration in sea ice in Arctic spring



Impact of sea ice iron on biological carbon export

Slide courtesy of S. Wang (LANL)

Results

- Sea ice shifts the timing and location of iron supplied to high latitude surface waters.
- Simulated surface iron distributions are improved in the Arctic.
- **<u>Iron released from melting ice increases phytoplankton production in spring and summer</u>.**

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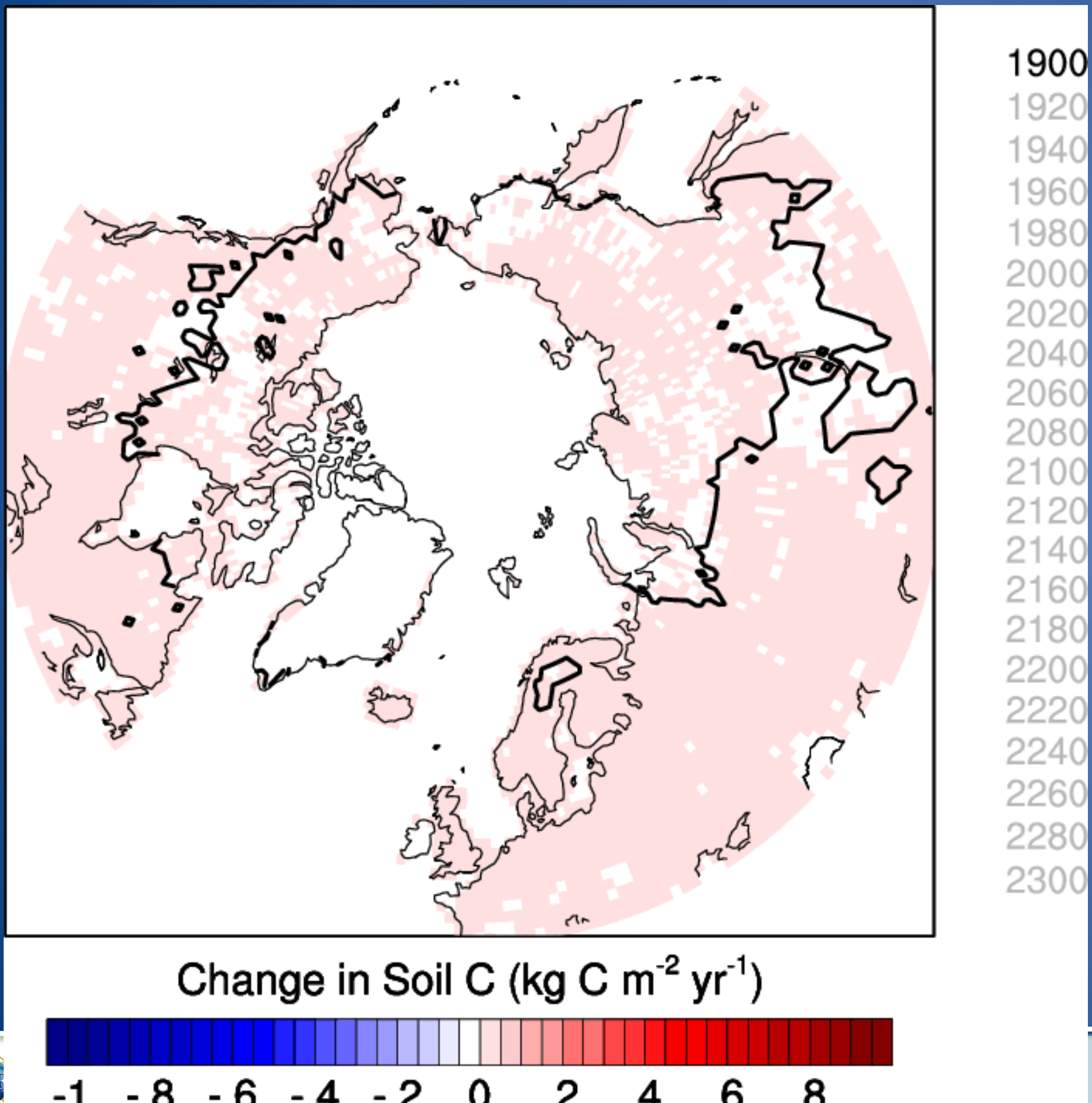
Projected soil C emissions follow retreating permafrost boundary (black line) and persist long after permafrost has thawed



CLM4.5BGC forced with RCP8.5 climate projections

- 17 – 42 Pg of 'deep' C lost by 2100
- 103 – 252 PgC by 2300
- Many potentially important processes still not included or poorly understood

Koven et al., 2014 (submitted)

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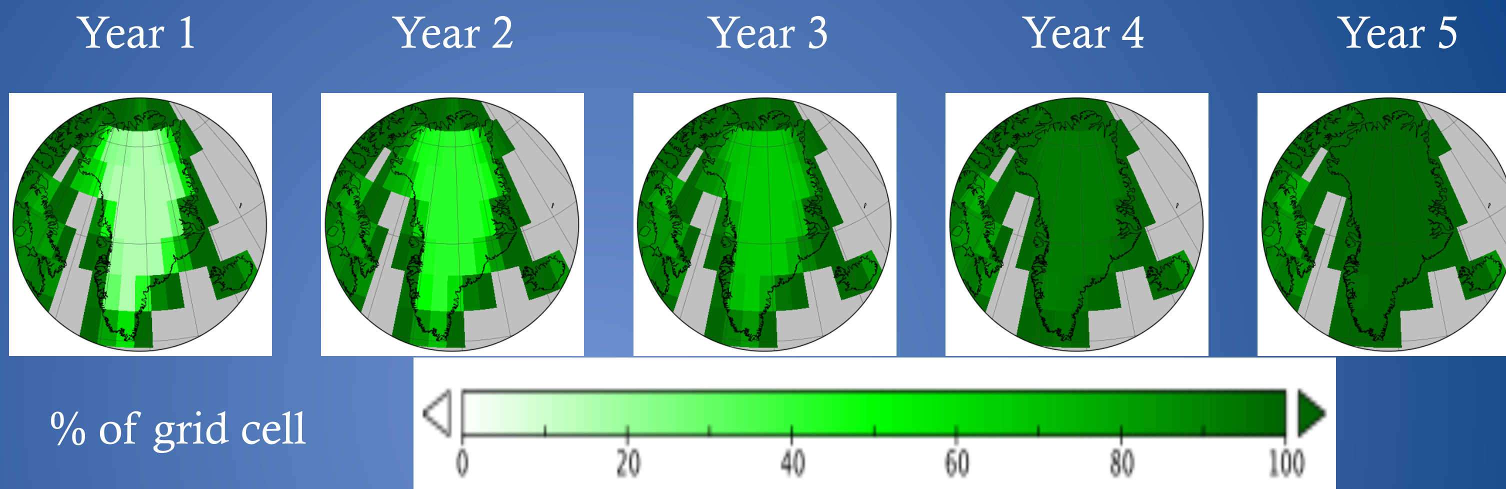
Ice-sheet coupling with dynamic landunits

Fast deglaciation experiment: 100% to 0% in 5 years

Vegetation area
(1.0 – glacier area)



% of grid cell

Ice sheets can now be coupled interactively in CESM:

- CISM sends ice-sheet extent and elevation to CLM via coupler
- Dynamic landunits in CLM: As ice sheets retreat, glaciated regions are replaced by vegetation
- CAM lower surface responds to evolving ice topography
- This will allow multi-century deglaciation experiments

Slide courtesy of B. Sacks and J. Fyke

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4-mode version of Modal Aerosol Module (MAM4)

Aitken
- number
- sulfate
- secondary OM
- sea salt

Accumulation
- number
- sulfate
- secondary OM
- primary OM
- BC
- soil dust
- sea salt

Coarse
- number
- soil dust
- sea salt
- sulfate

coagulation
condensation

Primary Carbon
- number
- primary OM
- BC

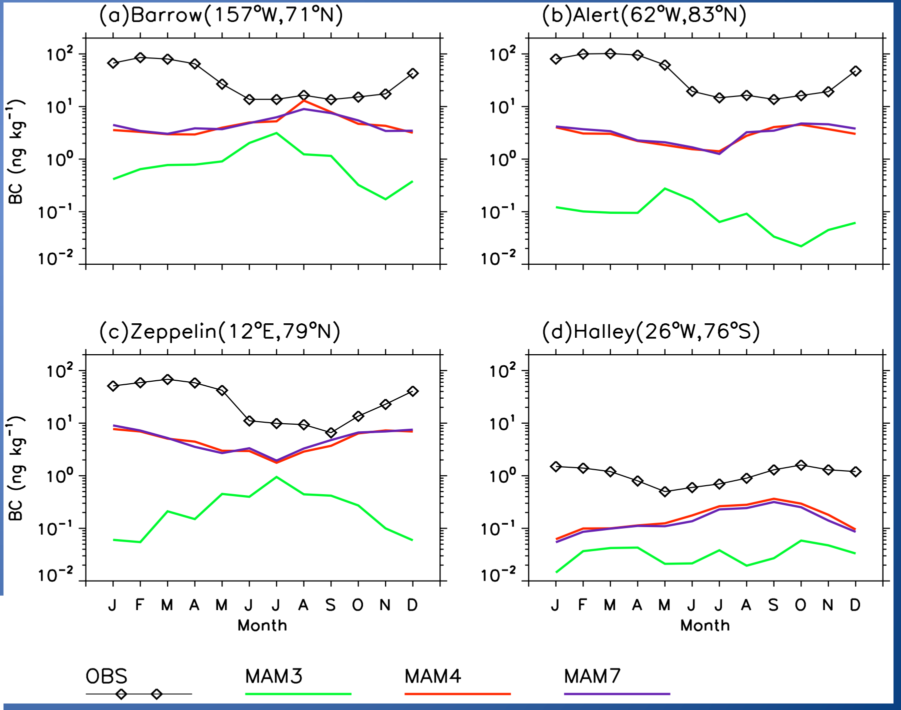
All modes log-normal with prescribed width.

Total transported aerosol tracers: **18**

Cloud-borne aerosol and aerosol water predicted but not transported.

Adding the primary carbon mode to MAM3 increases run time ~10%. RESTOM change: 0.06 W m^{-2}

MAM4 significantly increases (and improves) BC concentration in Arctic compared to MAM3 (and agrees with MAM7). The remaining underestimation of BC concentration in Arctic in MAM4 is very likely due to wet scavenging by precipitation and/or emissions.



Comparison of model results (MAM3, MAM4, MAM7) with seasonal BC observations at surface in high latitudes

Liu et al., in prep, (2014)

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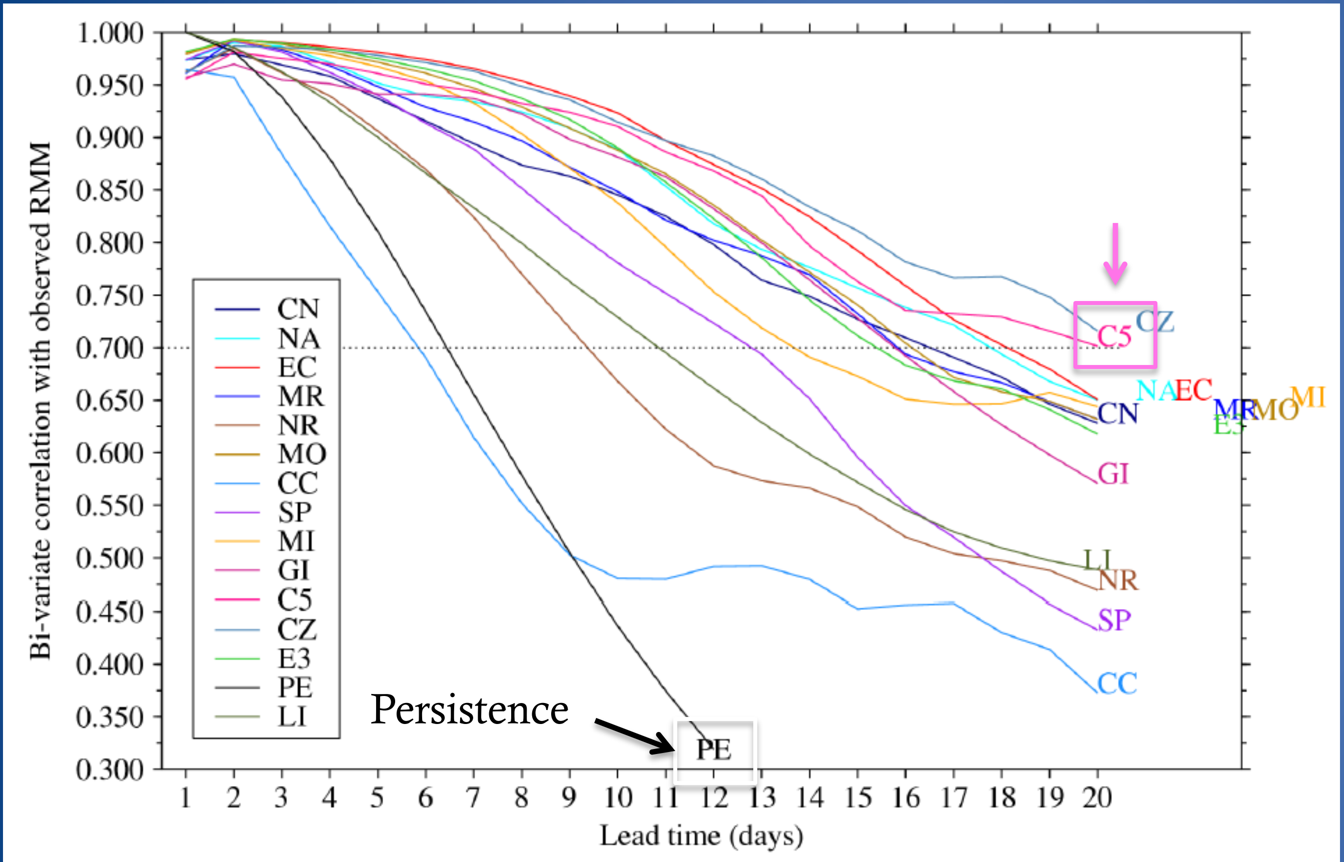
Madden Julian Oscillation (MJO) Hindcasts



Initial forecast mode (CAPT)

During MJO-DYNAMO Campaign

Combined bivariate mode of MJO variability

CAM5 only model to retain skill out to 20 days.

Top performer among participating CMIP5 models.

Courtesy: Nick Klingaman, U. Reading, UK

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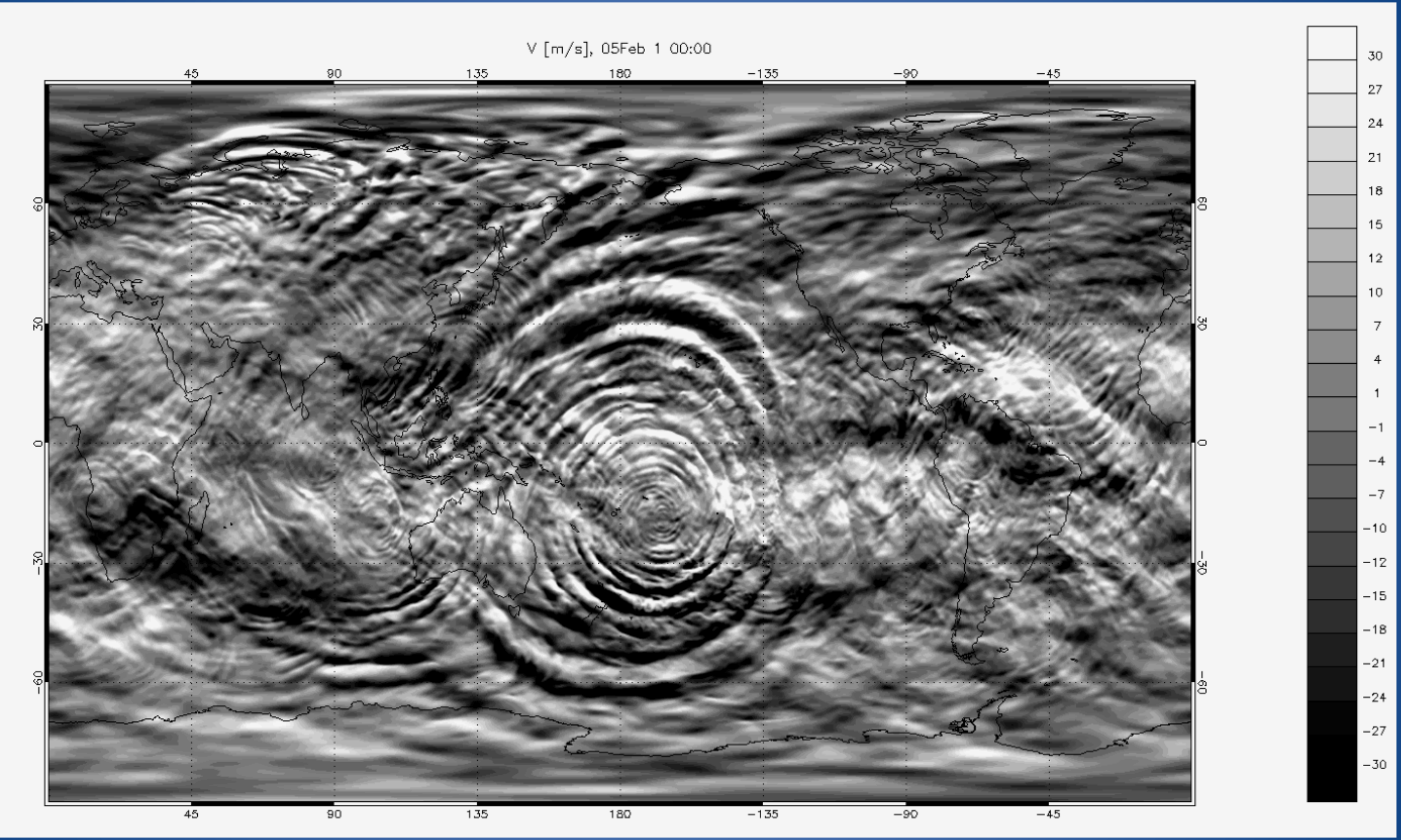
WACCM5-High Res (ne120: ≈25km) Meridional Wind at ~110km:

Space Weather Driven by Tropospheric Weather



Slice courtesy of Hanli Liu

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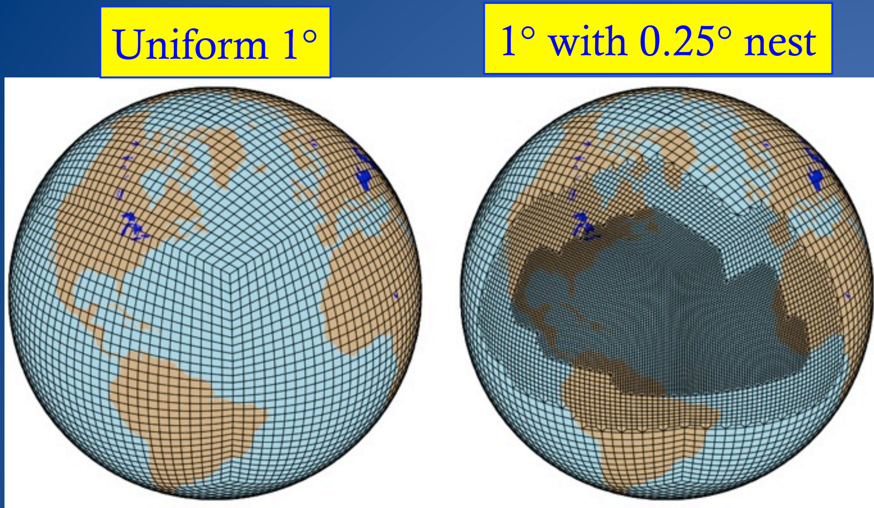
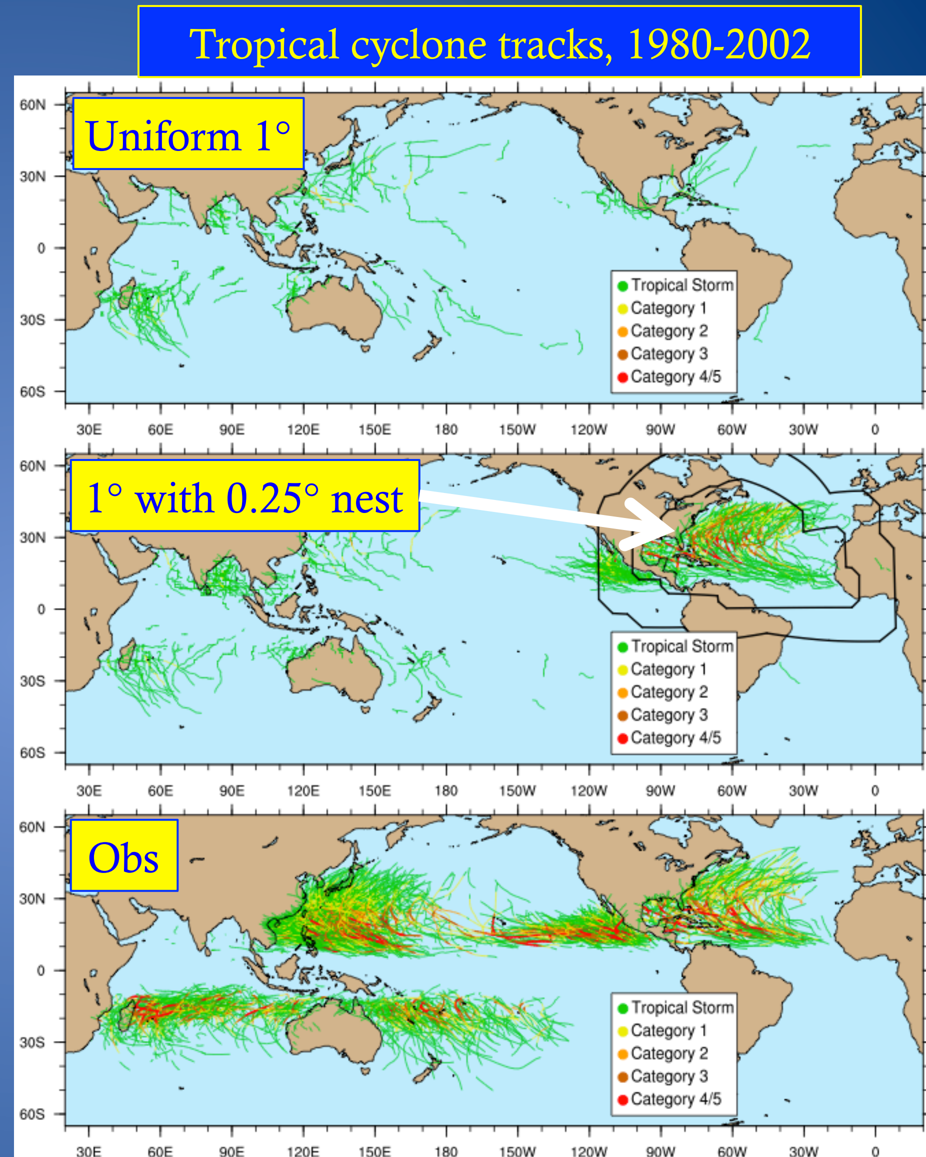
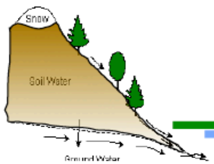




- Variable-resolution CAM-SE (CAM5) simulations -> dramatically improved tropical cyclone representation at regional scale
- 0.25° nest produces realistic storm counts/intensities in North Atlantic at 1/6th compute cost of globally-uniform 0.25° mesh

Courtesy: Colin Zarzycki, U. Mich.

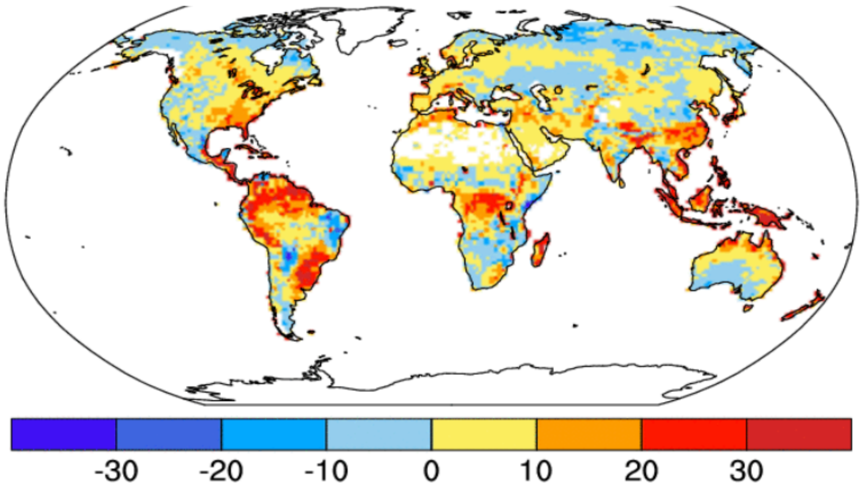


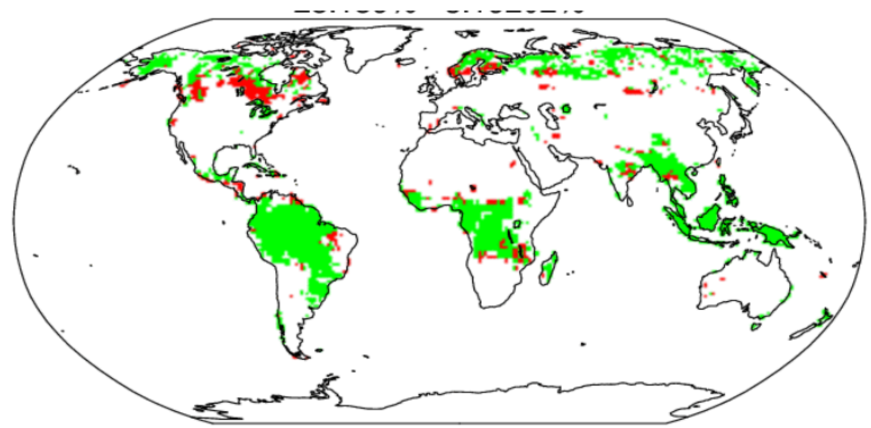
Reduced biases in CLM4.5

ANN Latent Heat bias (obs: FLUXNET MTE)

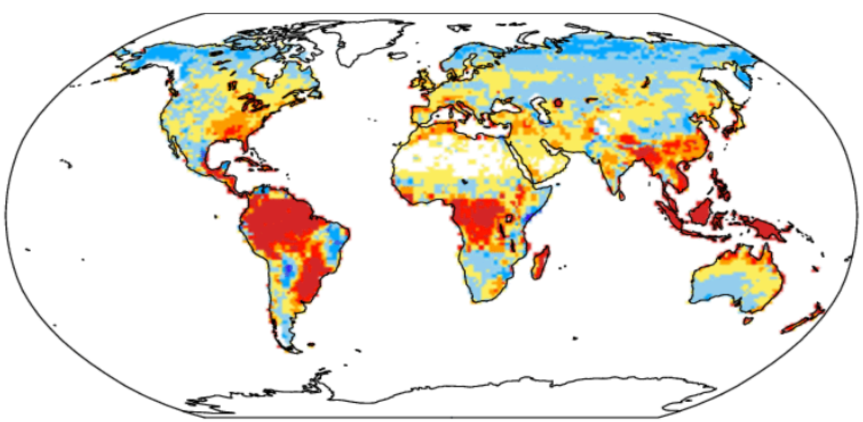
Green: Improved in CLM4.5
Red: Degraded in CLM4.5

CLM4.5BGC





CLM4CN



	CLM4	CLM4.5
LH ($W\ m^{-2}$)	8.9	5.9
GPP ($gC\ m^{-2}\ d^{-1}$)	0.41	0.07
Albedo (%)	-0.41	-0.52

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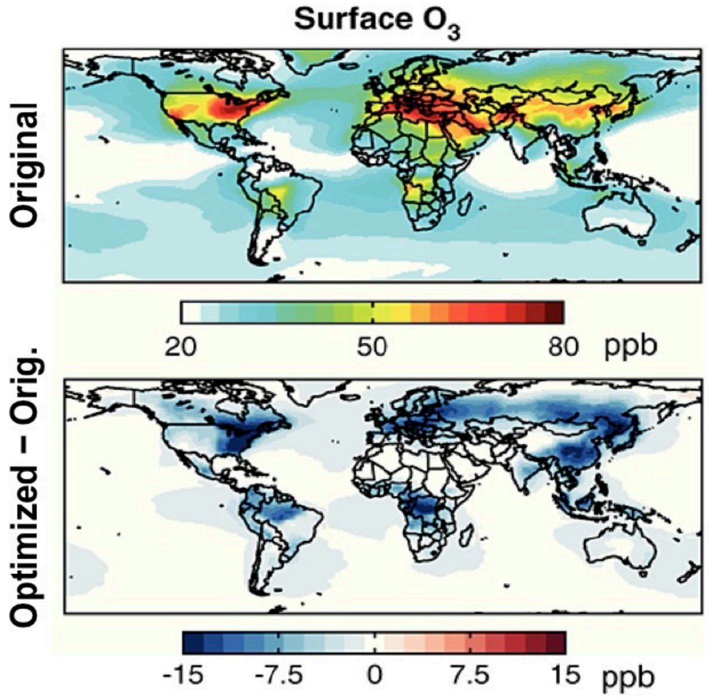
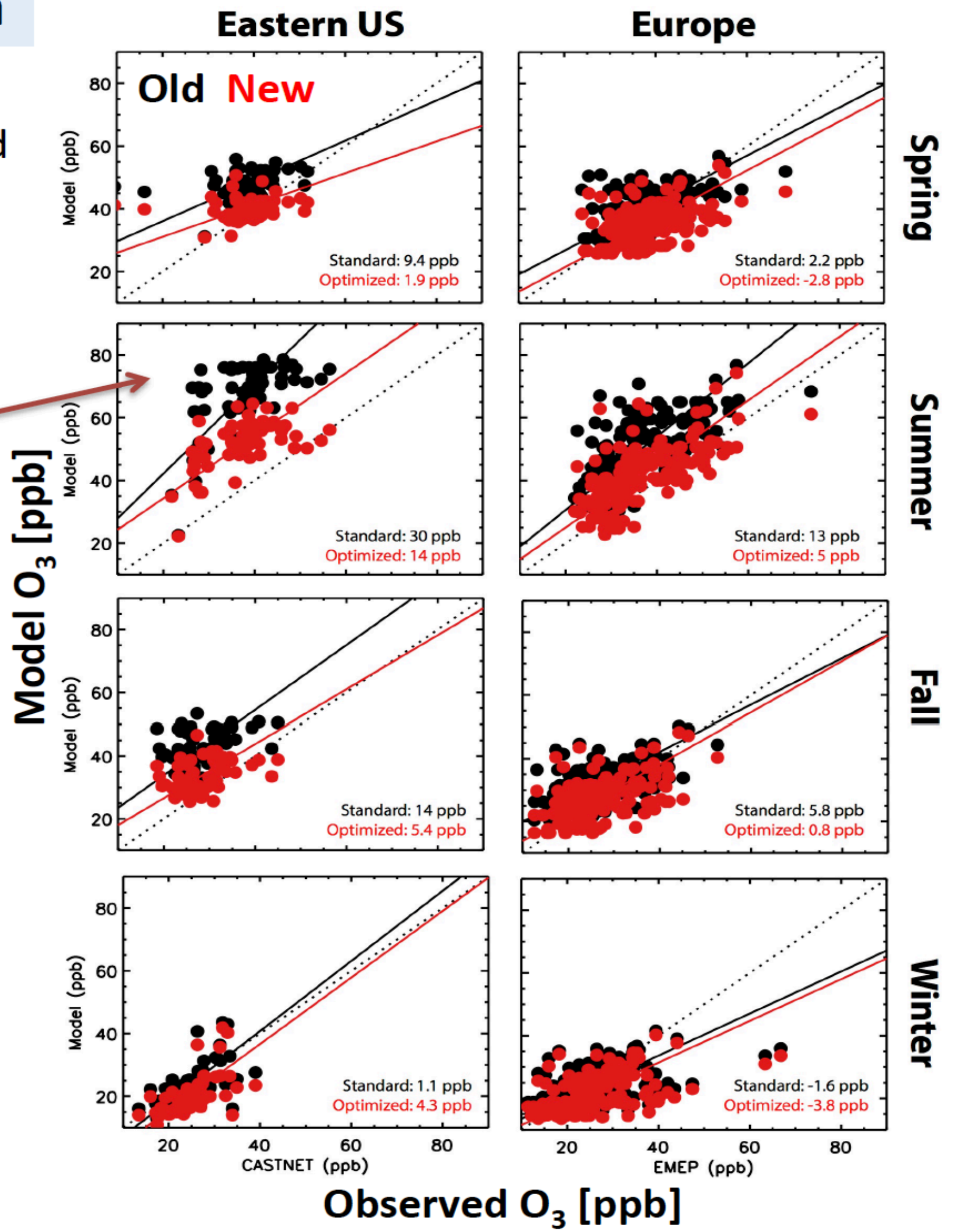
Ozone Dry Deposition Correction

- Dry deposition parameterization in MOZART and CAM-chem lacked coupling of leaf and stomatal vegetation resistances to LAI
- Correcting this and optimizing to observations improves model surface ozone

Summer U.S. bias reduced (30 to 14 ppb)





M. Val Martin, et al., GRL, 2014

Future Directions and Remaining Challenges

A need for continued scientific understanding and model improvements

Investigation of small-scale phenomena

Incorporation of New Capabilities

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an example CESM model hierarchy

SIMPLICITY

+ a fully coupled CMIP-class atmos-ocean-land-sea-ice model
+ an atmosphere only model (w/ slab ocean or spec'd SSTs)
+ an aquaplanet atmosphere w/ slab ocean (Lee et al. 2008)
+ a dry dynamical core (see Held & Suarez 1994)
+ a shallow water model on the sphere
+ a single-column model

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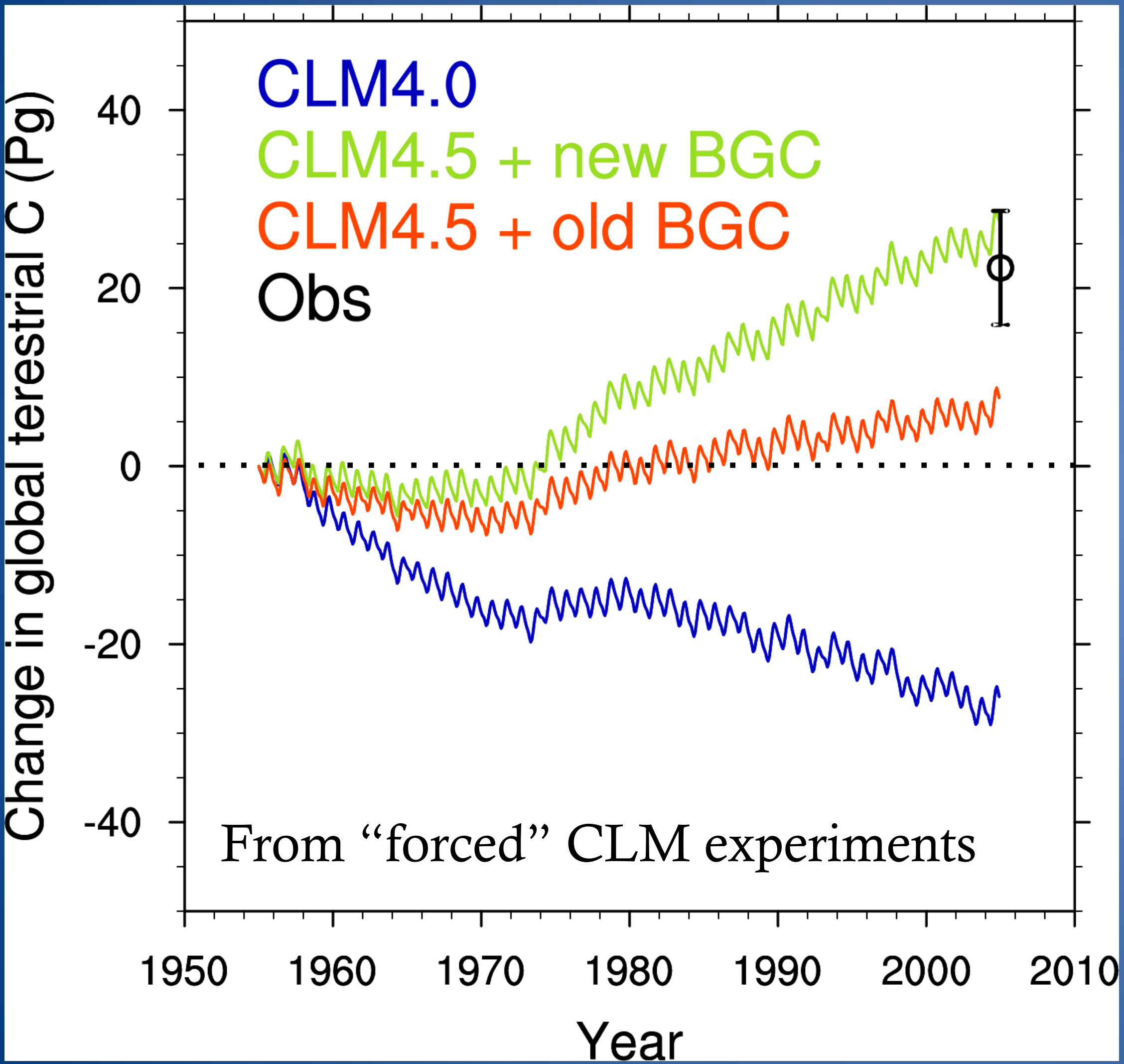
Changes in the Global Terrestrial Carbon Budget



Accumulated carbon from
- losses due to land cover change,
- gains due to CO_2 fertilization
- regional losses or gains due to climate-carbon feedbacks.

More realistic land carbon uptake results from reduced N-limitation on CO_2 fertilization.

Koven et al., 2013

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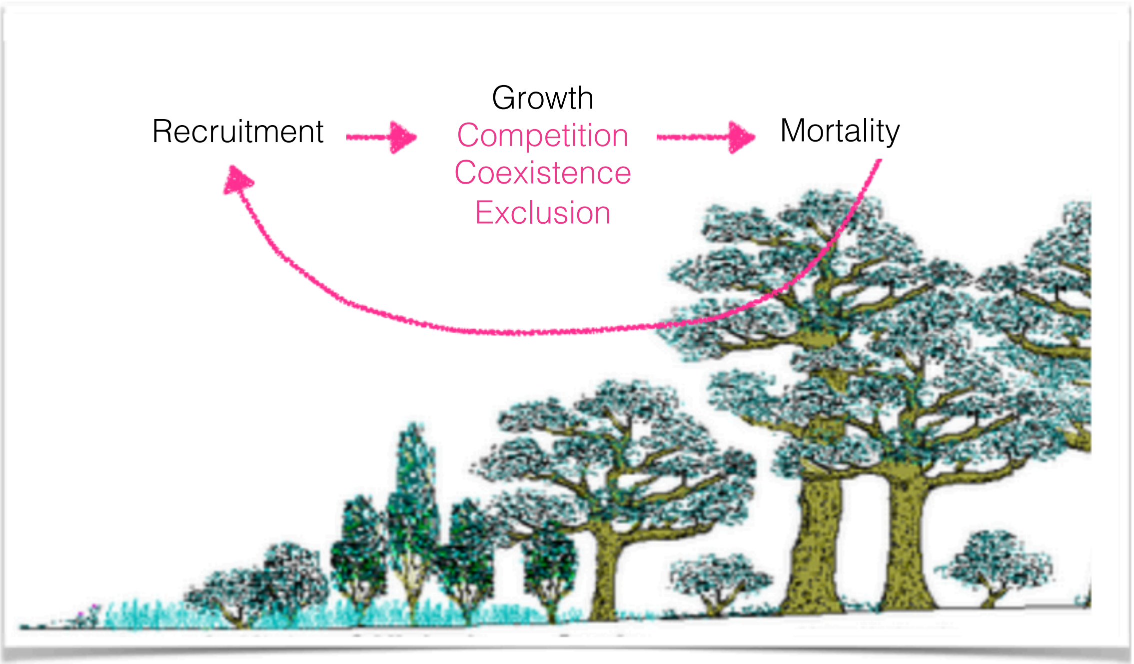
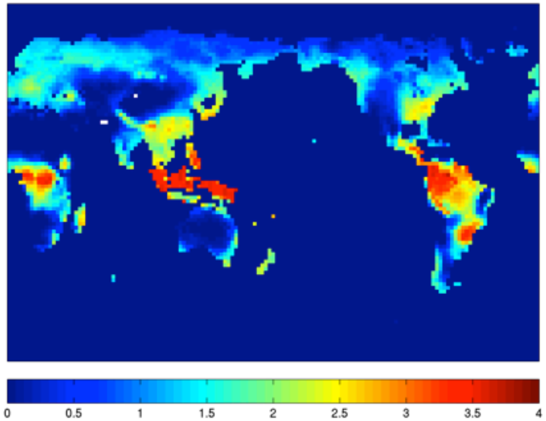
CLM(ED) ecosystem demography

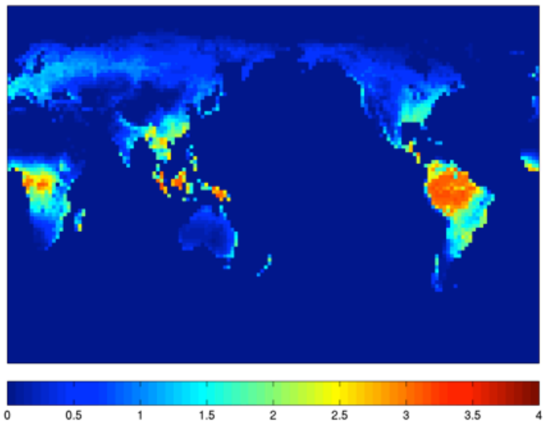
- Next-generation biogeophysical and biogeochemical core for the CLM
  - Landscape structured according to disturbance history.
  - Height resolved competition between plants for light.
- Plant distribution emerges from plant functional properties.



Gross Photosynthesis: CLM(ED) v0.0



Gross Photosynthesis: FLUXNET product



KgC m^{-2} yr^{-1}

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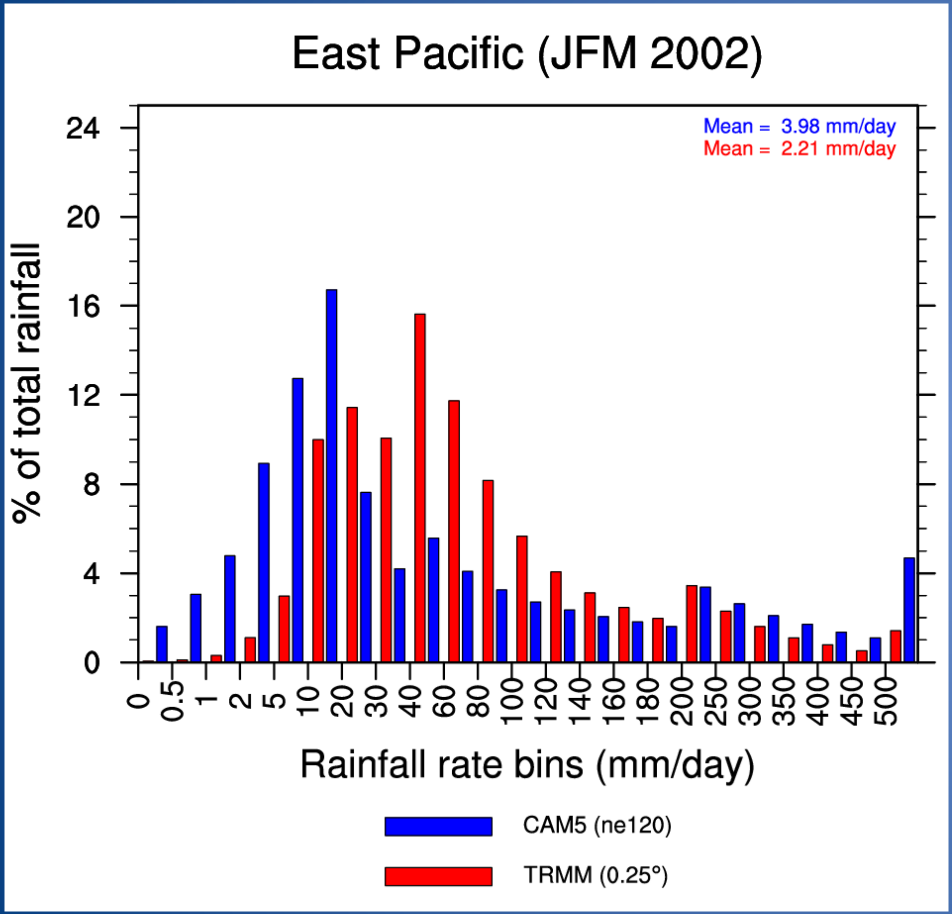
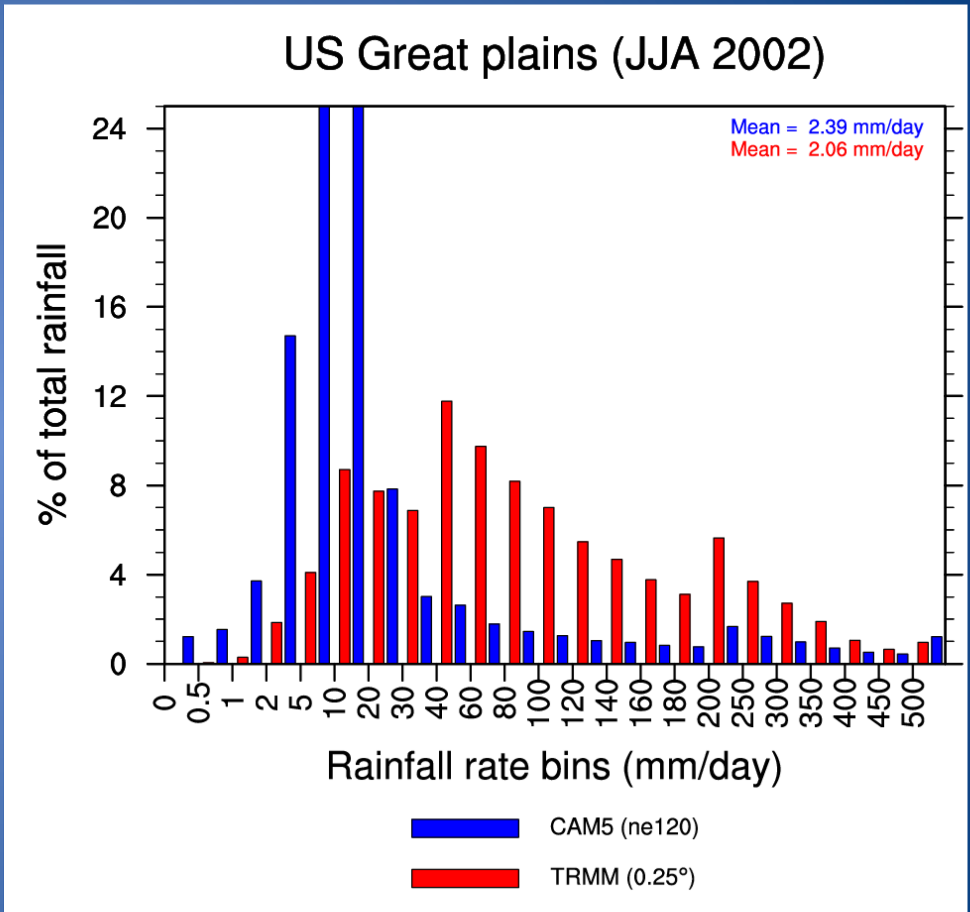
Bias Example: Rainfall frequency

Common bias for many regions: Too much light rainfall, not enough heavy





Courtesy of Rich Neale

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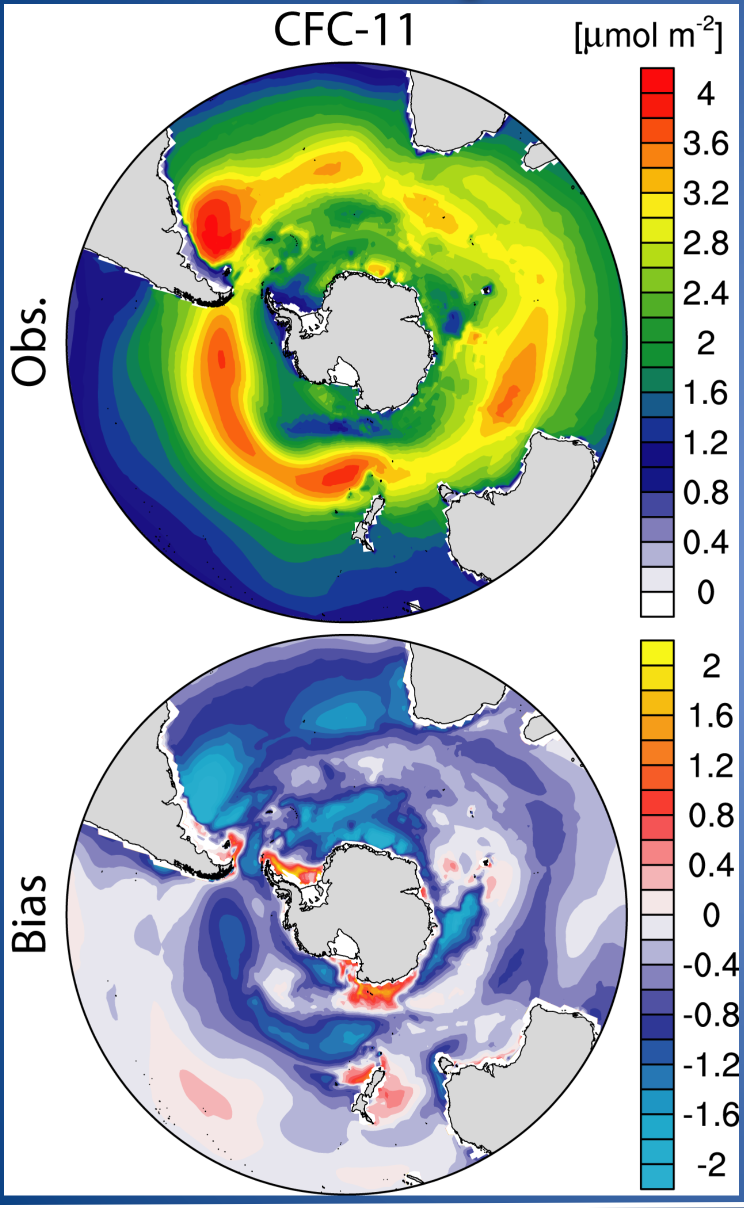
Bias Example: Southern Ocean Ventilation



CESM1-CAM5 20th Century Simulation

Comparisons of simulated and observed ocean CFCs

Indicate too little Southern Ocean uptake

Has implications for simulated ocean heat and carbon uptake

Courtesy of Matt Long

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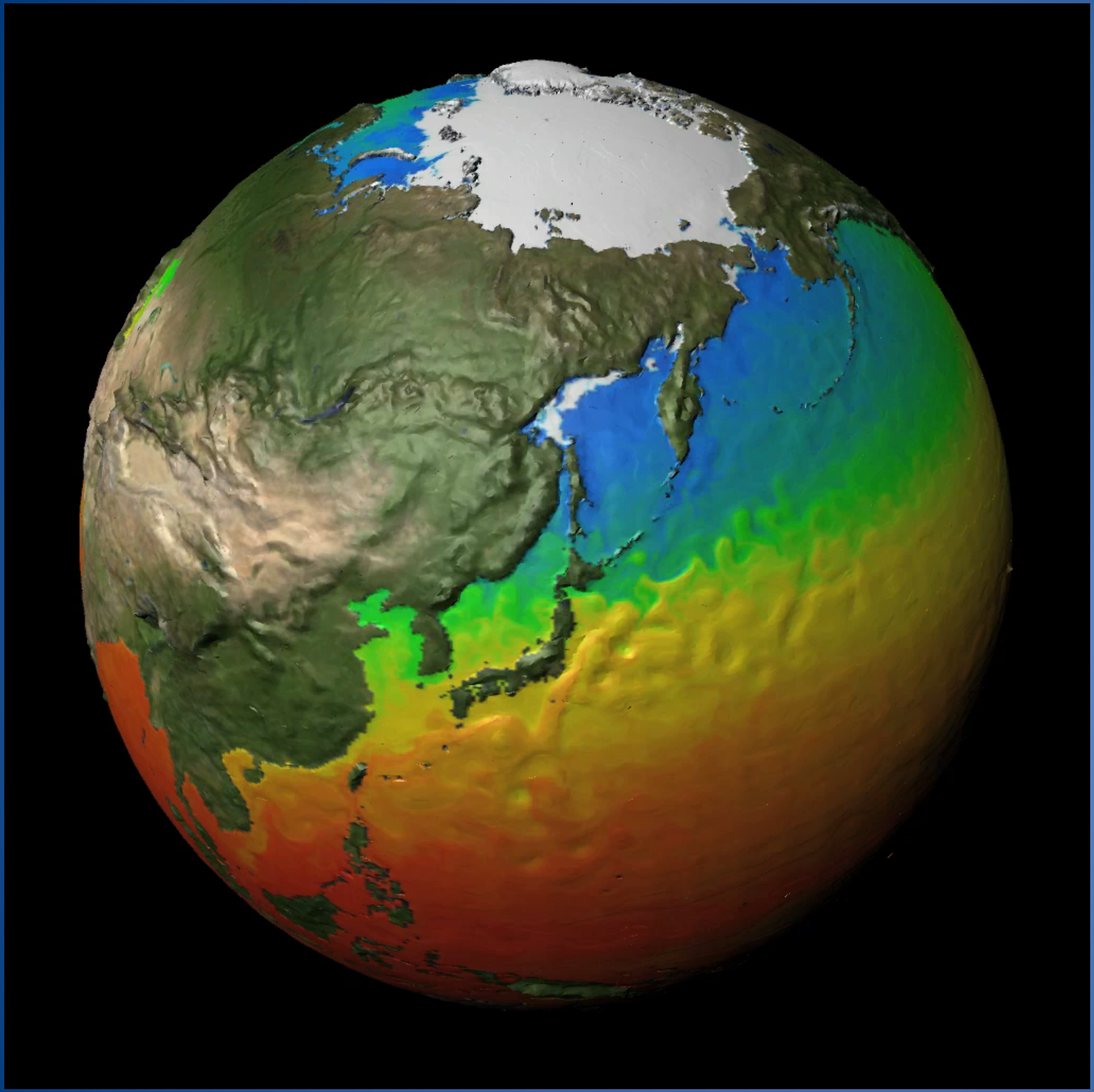
Future Directions: Study of High Resolution Phenomena



- Fully coupled CESM1-CAM5-SE simulations with a 25km atmosphere and 0.1° ocean
- 60 years in length

- Yellowstone-NWSC Accelerated Science Discovery Run
- Project support from DOE-BER and NSF

Courtesy of Justin Small, Tim Scheitlin

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And More…

All component models incorporating improved parameterizations and processes

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In summary:

- CESM is a flexible, extensible and well supported community tool
- CESM applications continue to increase
- Numerous CESM simulations are currently available through CMIP5 for analysis; additional community runs becoming available
- Model developments and improvements are ongoing

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Questions? Comments?

Purple: precipitation

Slide courtesy of R. Knutti and O. Stebler

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