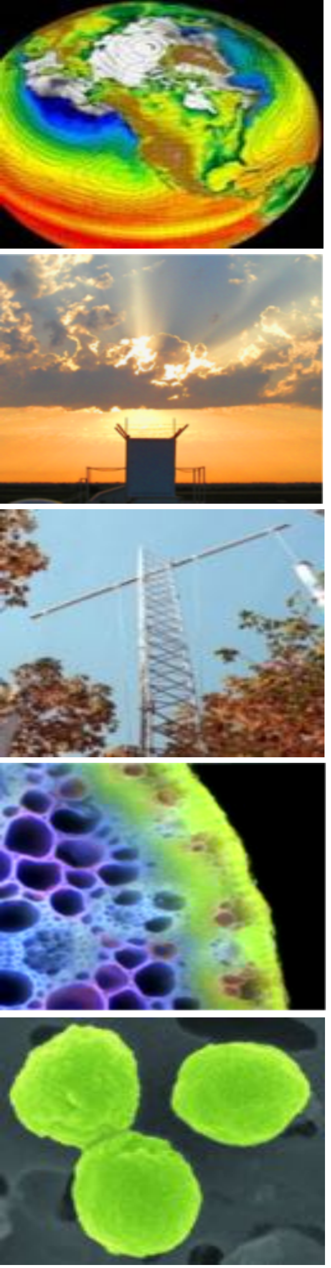


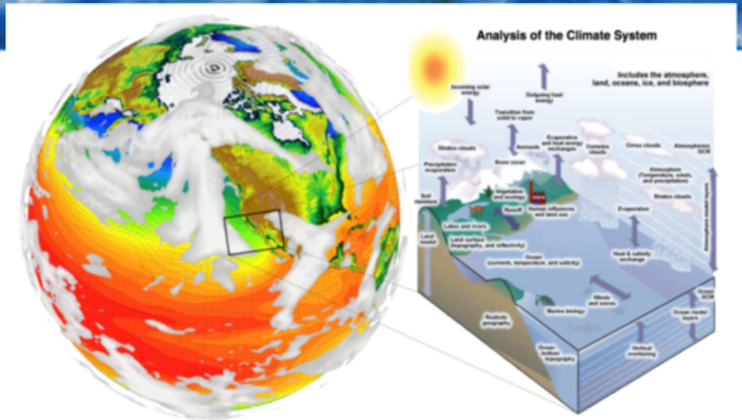
DOE’s Modeling Capabilities

Renu Joseph, Corinne Hartin, Sally McFarlane

Earth and Environmental Systems Modeling, CESD

June 5th, 2019

Climate and Environmental Sciences Division



Atmospheric Science

- Atmospheric Radiation Measurement Climate Research Facility
- Atmospheric System Research

Earth and Environmental Systems Modeling

- ❖ Earth System Model Development
- ❖ Regional and Global Model Analysis
- ❖ Multisector Dynamics

Environmental System Science

- ❖ Terrestrial Ecosystem Science
- ❖ Subsurface Biogeochemical Research
- Environmental Molecular Sciences Laboratory

Data Informatics

Budget is Roughly Divided Equally Among the Three Groups

Additionally, in FY19: Initiating 2 new coastal projects

Capabilities with respect to some challenges for initialized prediction/projection

- The need for a computationally efficient Earth System Model
- Understanding of Earth system model biases, internal variability, and change

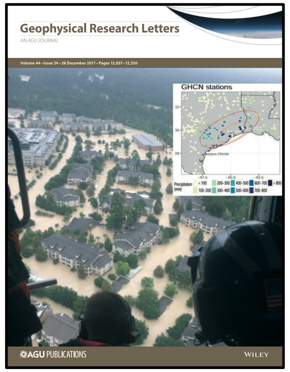
- Methods to initialize
- The possible sources of prediction skill in initialized predictions

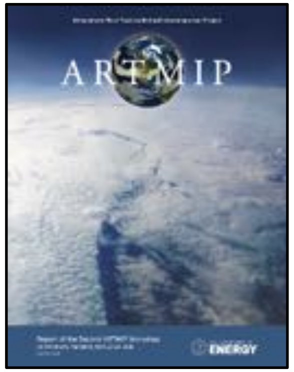
Regional and Global Model Analysis (RGMA) Overview

Goal: To enhance predictive and process level understanding of Variability and Change in the Earth system by advancing capabilities to design, evaluate, diagnose, and analyze global and regional earth system models informed by observations

- Primary Model we focus on is the E3SM – Energy Exascale Earth System Model
- Multi-Model approaches and also a use of a hierarchy of models of varying levels of varying complexity to address the relevant science questions

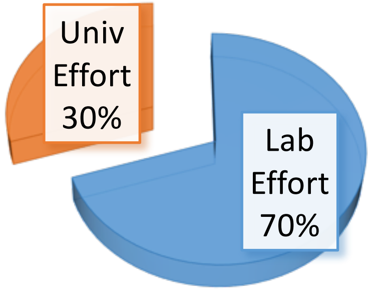
- University Projects
- 5 SFA
- 2 CA

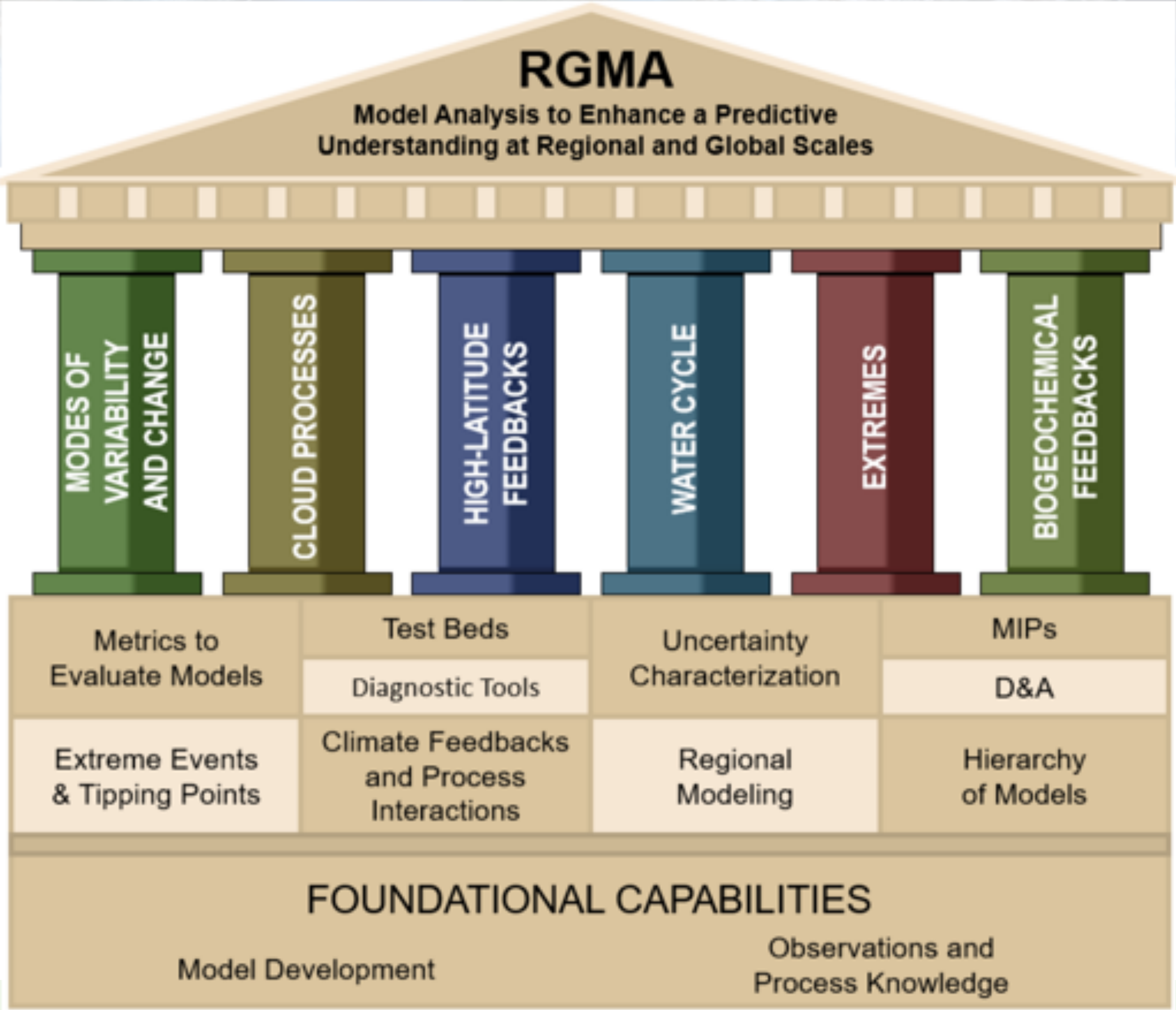




Roughly 120 publications/year

APPROX FUNDING DISTRIBUTION




RGMA
Model Analysis to Enhance a Predictive Understanding at Regional and Global Scales
MODES OF VARIABILITY AND CHANGE
CLOUD PROCESSES
HIGH-LATITUDE FEEDBACKS
WATER CYCLE
EXTREMES
BIOGEOCHEMICAL FEEDBACKS
Metrics to Evaluate Models
Test Beds
Diagnostic Tools
Uncertainty Characterization
MIPs
D&A
Extreme Events & Tipping Points
Climate Feedbacks and Process Interactions
Regional Modeling
Hierarchy of Models
FOUNDATIONAL CAPABILITIES
Model Development
Observations and Process Knowledge

Regional and Global Model Analysis (RGMA)

Renu Joseph, Renu.Joseph@science.doe.gov

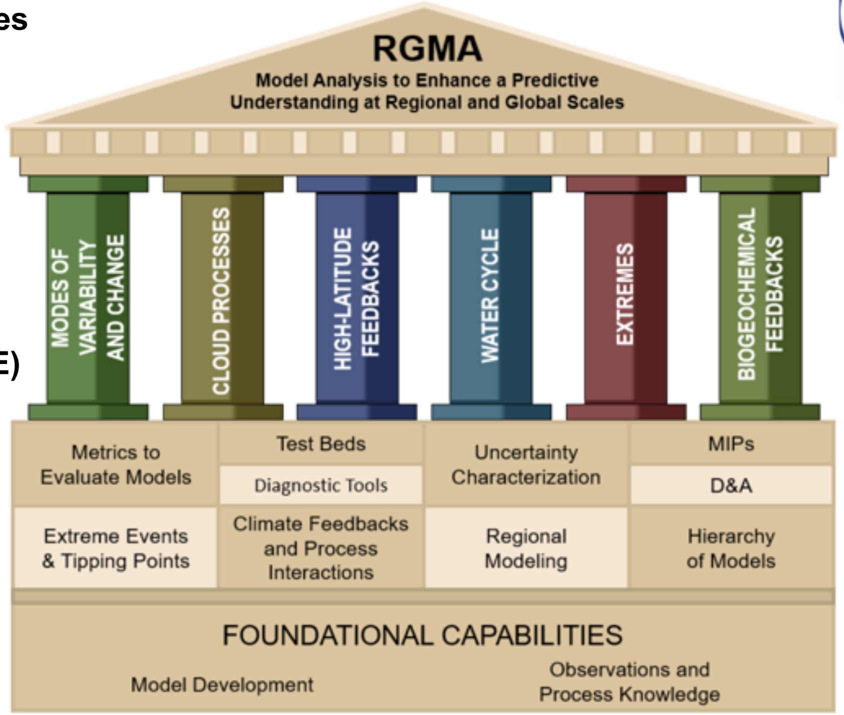
Water Cycle and Climate Extremes Modeling (WACCEM)

Calibrated and Systematic Characterization, Attribution, and Detection of Extremes (CASCADE)

RUBISCO

Reducing Uncertainty in Biogeo-chemical Interactions Through Synthesis and Computation (RUBISCO)

High-Latitude Application and Testing (HiLAT)



Program for Climate Model Diagnosis & Intercomparison – Cloud Process Research (PCMDI-CPR)

Cooperative Agreement To Analyze variability, change and predictability in the earth SysTem (CATALYST)

An Integrated Evaluation of Earth System Simulations relevant to Energy-Water-Land

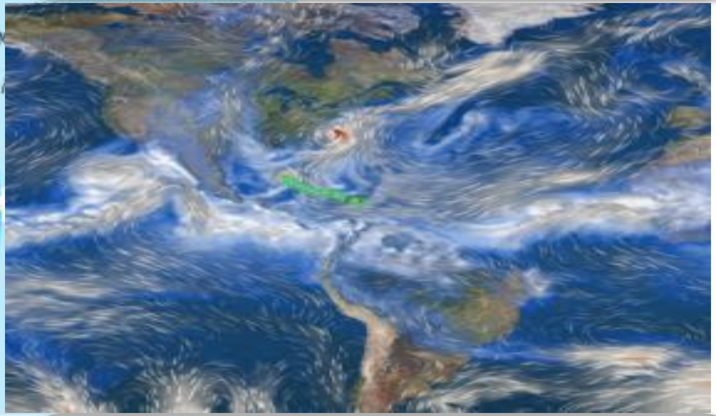
RGMA FY18 University Projects & in FY19 will be making more from FOA 1862

Science Themes	University Projects
Water Cycle Extremes	• Boos- **Monsoon Extremes**: Impacts, Metrics, and Synoptic-Scale Drivers • Kooperman- Simulating Extreme Precipitation in the United States in the E3SM: Investigating the Importance of Representing Convective Intensity Versus Dynamic Structure • Kim- **Madden-Julian Oscillation**, **Tropical Cyclones**, and Precipitation Extremes in E3SM
Cloud Processes	
Variability & Change	• Kirtman- **Decadal Prediction and Predictability of Extremes** in Ocean Eddy Resolving Coupled Models • DiLorenzo- Mechanisms of **Pacific Decadal Variability** in ESMs: The Roles of Stochastic Forcing, Feedbacks and External Forcing • Kwon- The **Atlantic Multi-decadal Oscillation** – Key drivers and Climate Impacts • Cheng- Arctic freshwater pathways and their impact on North Atlantic deep water formation in a hierarchy of models
High Latitude Feedbacks	• Magnusdottir- Reducing Uncertainty of Polar to Mid-latitude Linkages using DOE's E3SM in a Coordinated Model-Experiment Setting
Analysis of BGC Feedbacks	

Calibrated And Systematic Characterization, Attribution and Detection of Extremes (CASCADE)

- Tools for characterizing extremes in the obs. record: climextRemes, fastKDE, TECA
- Participation in ARTMIP
- Studies documenting changes in extremes

- Studies on drivers of tropical cyclone variability
- Focus on compound extremes: droughts and heatwaves
- Approach uses observations and simulation hierarchies

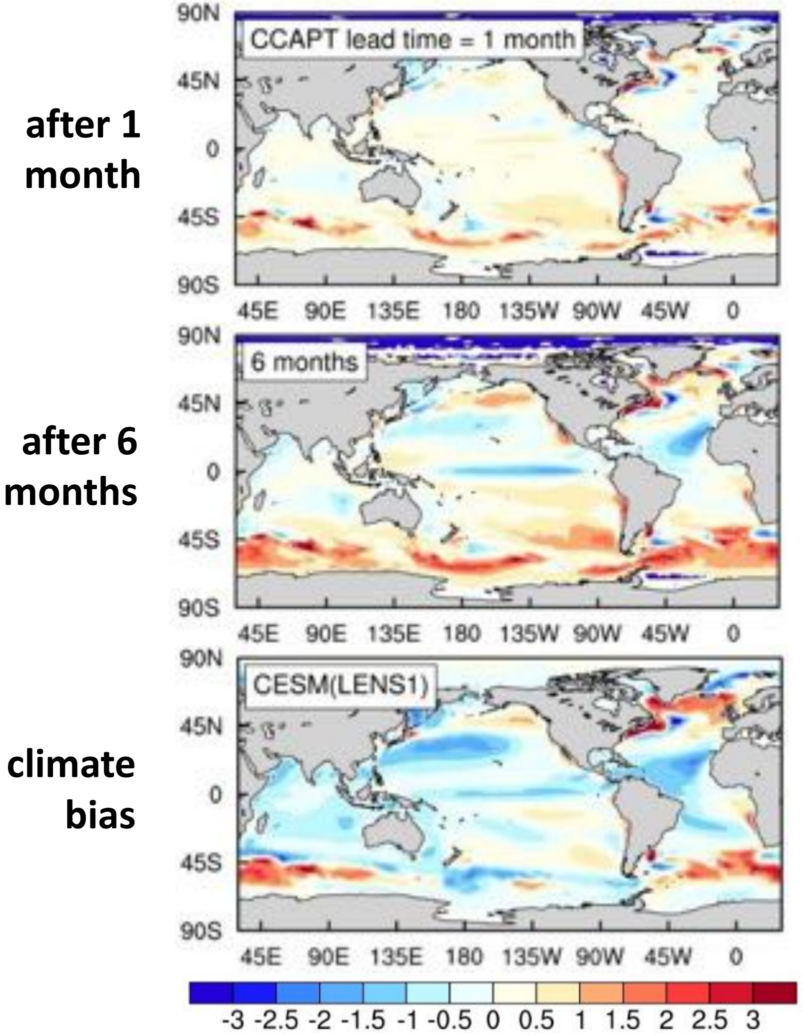


- Has used CESM extensively in C20C + D&A
- Studies attributing changes in extremes

- First-ever perturbed parameter ensemble for D&A: a public dataset
- Studies on effect of ocean variability on estimated risk ratios

Diagnosing Causes of Sea Surface Temperature Biases with Initialized Coupled Models ("Coupled CAPT")

SST biases in CESM1



Hsi-Yen Ma, Angela Cheska Siongco, and Stephen Klein

PCMDI

Results:

- Experiments with CESM1 show that SST errors after only 6 months of integration started from an observed state resemble climatological SST errors
- This is also true for other models we have studied (CanCM3/4, CCSM4)

Implication:

- Careful analysis of the growth of SST errors in initialized simulations may help pinpoint the causes of climatological SST errors and help answer:
- Are SST errors due to poor modeling of ocean processes or atmospheric forcing (wind stress, heat flux, water flux, etc.)?

DOE Support of Arctic Decadal Prediction and Predictability

Rationale

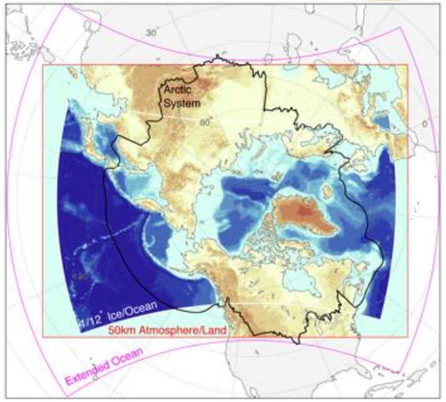
- A case study on Arctic prediction and predictability using the Regional Arctic System Model (RASM) for dynamical downscaling of the CESM initialized decadal predictability large ensemble (DPLE);
- Not accomplished before, in part due to the (i) lack of ‘right tools’ and (ii) computer resource limitations;
- RASM offers such an opportunity in terms of tools and the emerging Exascale capability reduces the past resource limitations.

Science Questions

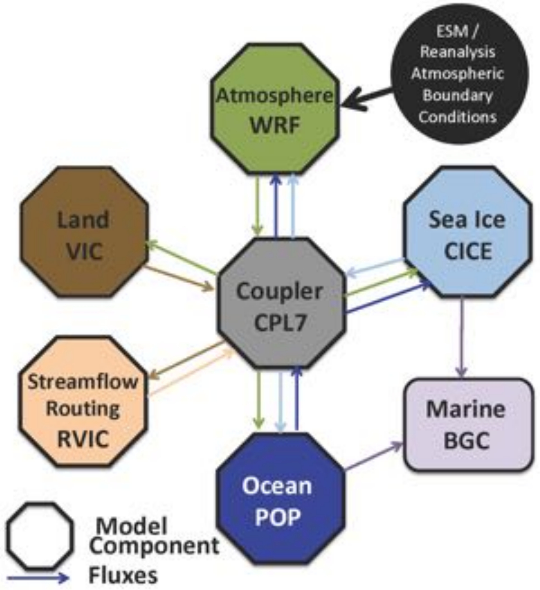
- What are the timescales of predictability of Arctic change?
- What is the sensitivity of Arctic predictability to the representation of critical processes and coupling channels governing Arctic climate variability and trends?
- Are there measurable gains in long-term Arctic prediction from dynamical downscaling relative to regional Arctic predictability in Earth System Models?

Regional Arctic System Model (RASM) Overview

RASM 1.0 (RBR)	Code	Configuration: Pan-Arctic domain including all sea ice covered ocean in the NH (down to ~30°N in N. Pacific and ~45°N in N. Atlantic)
Atmosphere	WRF3	50km/ 25km, 40 levels
Land	VIC	50km/ 25km, 3 Soil Layers
Ocean	POP2	1/12˚ (~9km) & 1/48˚ (~2.4km) 45 / 60 levels (20m@5m/100m@5m)
Sea ice	CICE5	1/12˚/1/48˚, 5 thickness categories Anistropic(EAP)/Isotropic(EVP) rheology
Coupler	CPL7x	Flux exchange every 20/10 min, inertial resolving w/ minimized lags



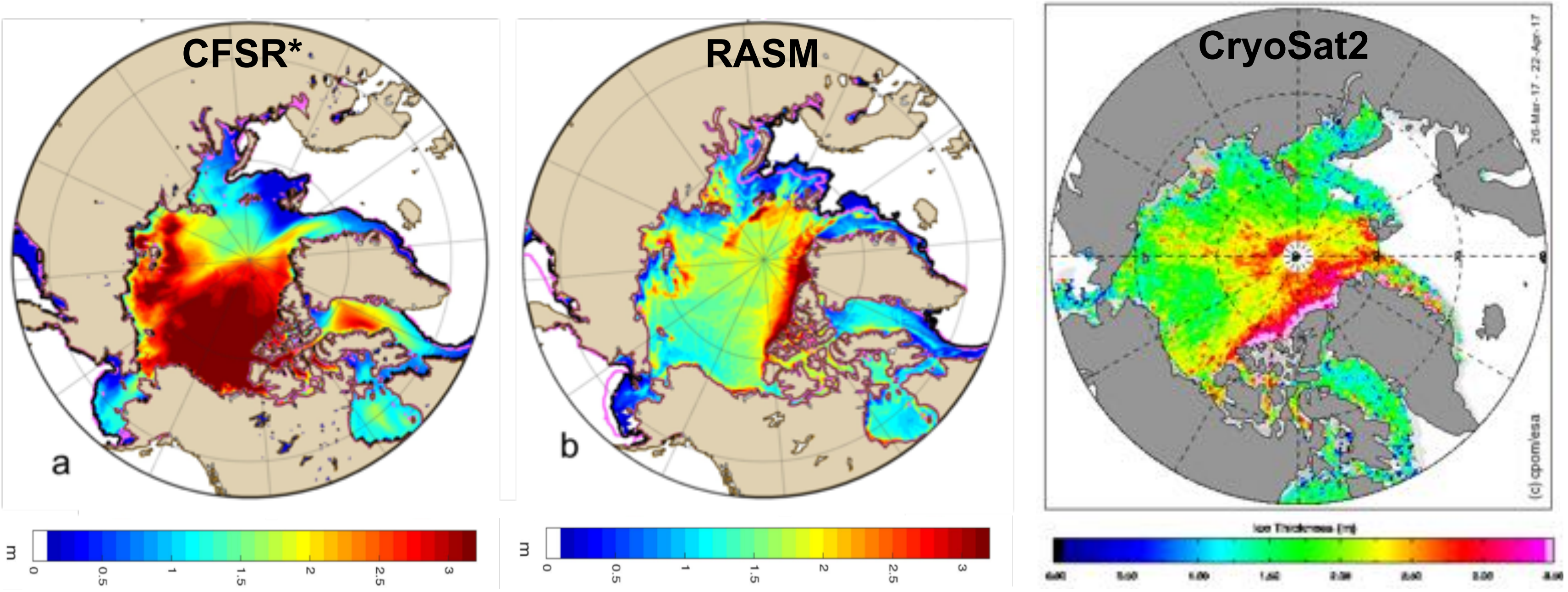
RASM Wiring Diagram



RBR9: fully coupled model as above;
RASM-G: POP + CICE + CPL7 + CORE2/JRA55 (atm+runoff)

Dynamical Downscaling - Initial Value Problem

Dynamical downscaling of the CFSR reanalysis using RASM produces much more realistic sea ice thickness distribution, relative to CryoSat2 estimates.



The sea ice thickness distribution (m) and extent on April 1, 2017 from:

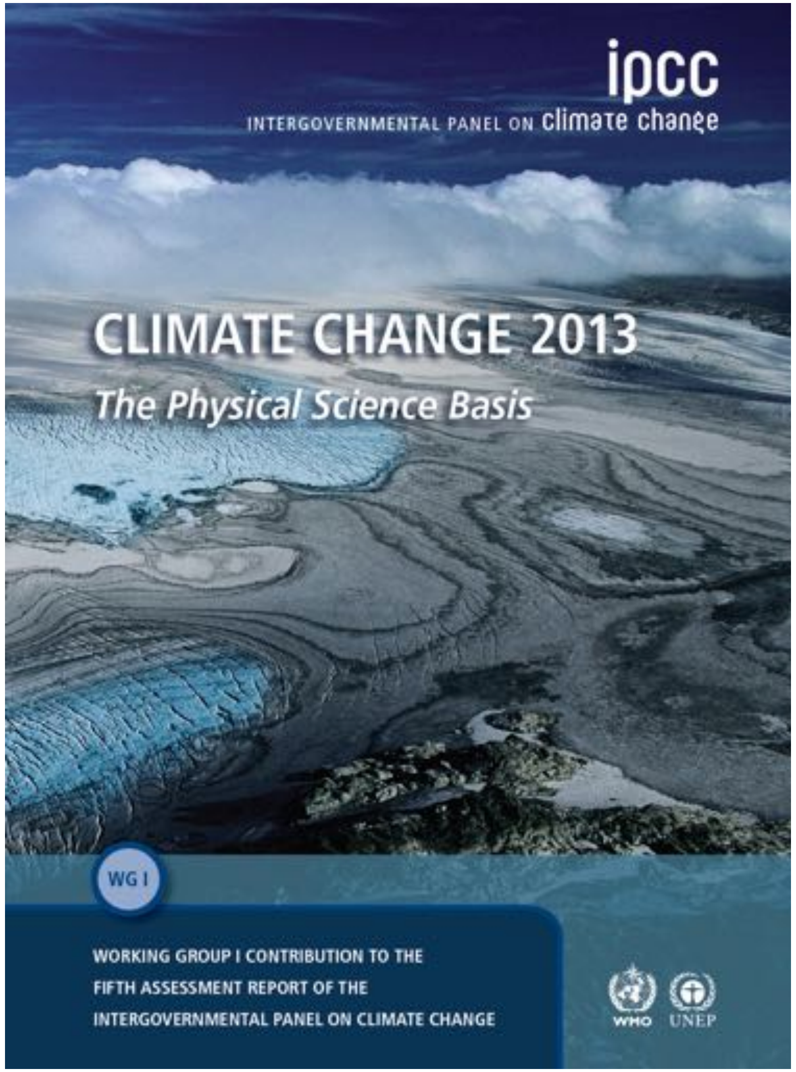
(a) CFSR (where sea ice concentration is assimilated),

(b) RASM forced with CFSR from 1979, and

(c) CryoSat2 (28-day composite of 26 Mar-22 Apr, 2017.

The black / purple contours represent the respective model / observed ice extent (i.e. 15% concentration) for the same day in (a) and (b).

First results from initialized decadal climate predictions were assessed in the IPCC AR5 by DOE-funded PIs



11

Near-term Climate Change: Projections and Predictability

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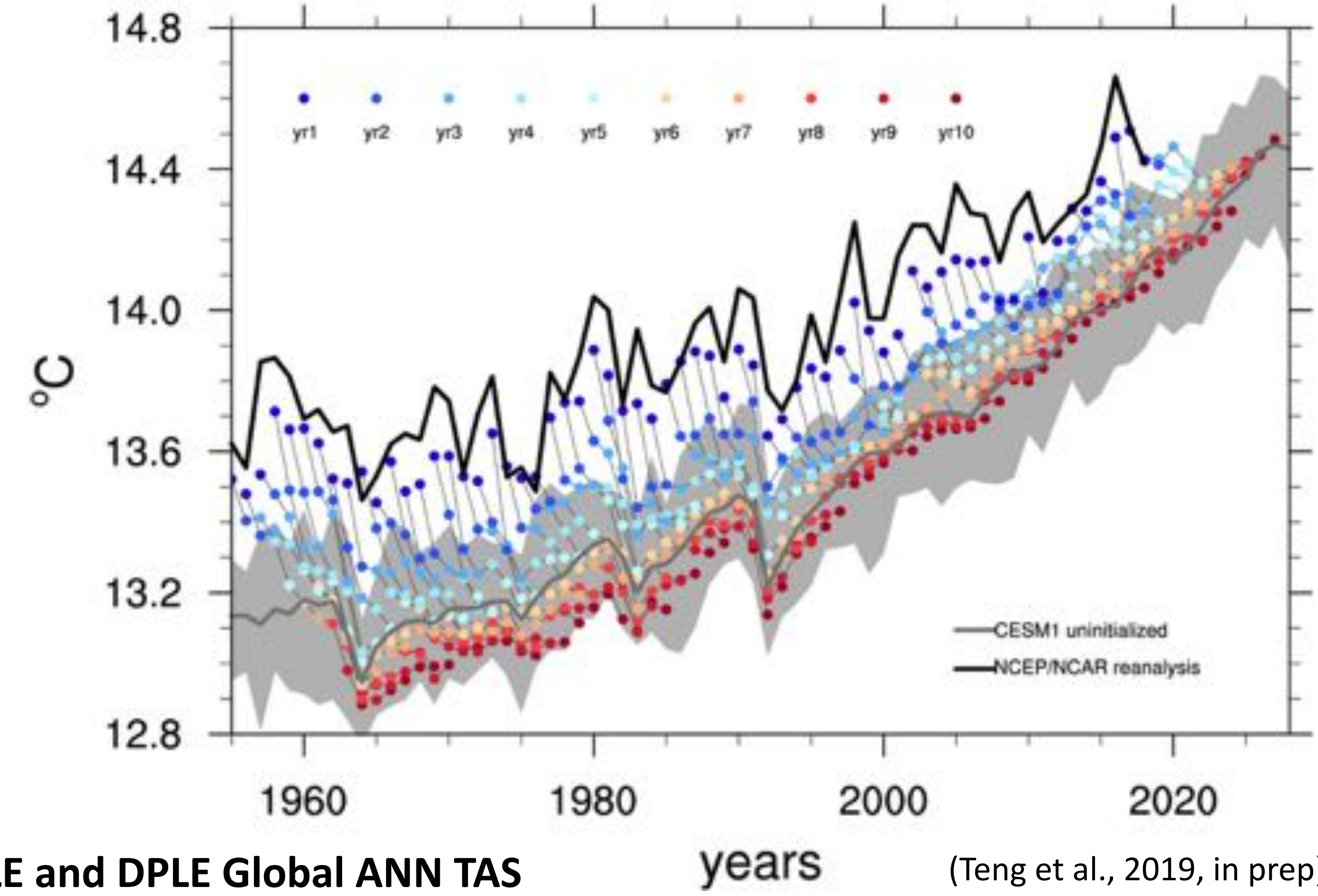
Pascale Delecluse (France), Tim Palmer (UK), Theodore Shepherd (Canada), Francis Zwiers (Canada)

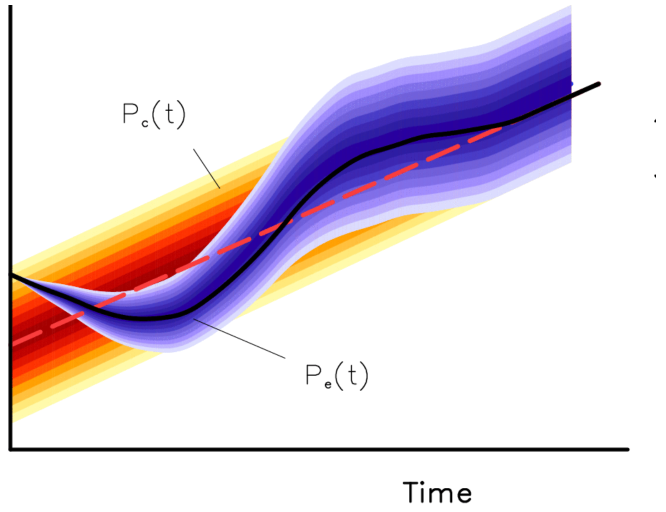
Model error and bias adjustment

The model initial states (blue dots) are close to the observations (black line); the predictions drift (progression of blue dots to red dots) toward the uninitialized state (red line); bias adjustment techniques must then be applied to correct for this drift that is the result of model error



CESM1 LE and DPLE Global ANN TAS

(Teng et al., 2019, in prep)



An ensemble of predictions (blue lines at left) evolve from the initial state with processes and mechanisms that produce climate states that evolve with time until the initial state effects transition into the externally forced response (orange shading)

CESM2/E3SM collaboration on decadal climate prediction

Address initialization, drift, model error, prediction skill, and processes and mechanisms we hope to predict

- CATALYST (NCAR/CGD) and Ben Kirtman's group, U. Miami

Science questions:

1. What differences in ocean initial states occur between CESM2 (with pop ocean) and E3SM (with mpas ocean) from the same CORE-forced-style hindcast initialization?
2. What are the model drifts resulting from the two different initialization techniques, and how does that factor into bias adjustment?
3. What differences in hindcast skill arise from models with two different types of ocean but more similar atmospheres? (and how does that relate to 1 above)
4. What processes and mechanisms can be identified as important in the two respective models in producing hindcast skill (or lack thereof)?

Experiments:

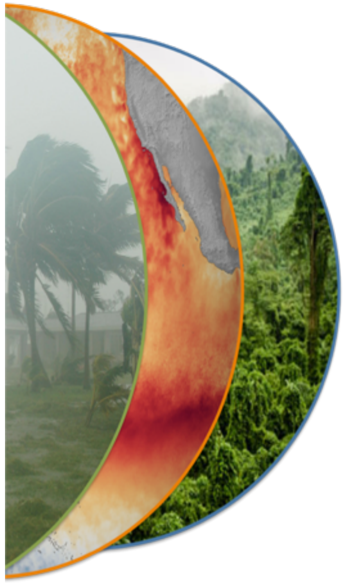
1. CORE-forced-style (JRA) hindcast initialization with CESM2 and E3SMv1 (both at 1 degree)
2. Initialized 10 member ensemble 5-year hindcasts for limited number of start years (1980, 1985, 1990, 1995, 2000, 2005, 2010, 2015, 2016, 2017, 2018) with CESM2 and E3SMv1 (both at 1 degree)

Features:

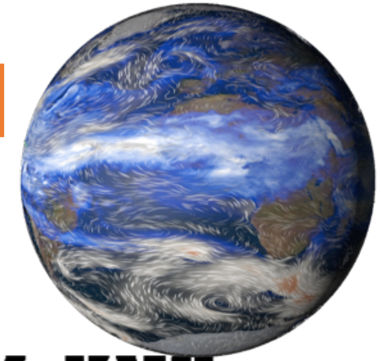
- Collaboration across CESM2 and E3SMv1, NCAR and DOE, in a decadal climate prediction project

CMEC - Coordinated Model Evaluation Capabilities (CMEC) for Historical Simulations **Joint Analysis of Variability, Extremes and BGC**

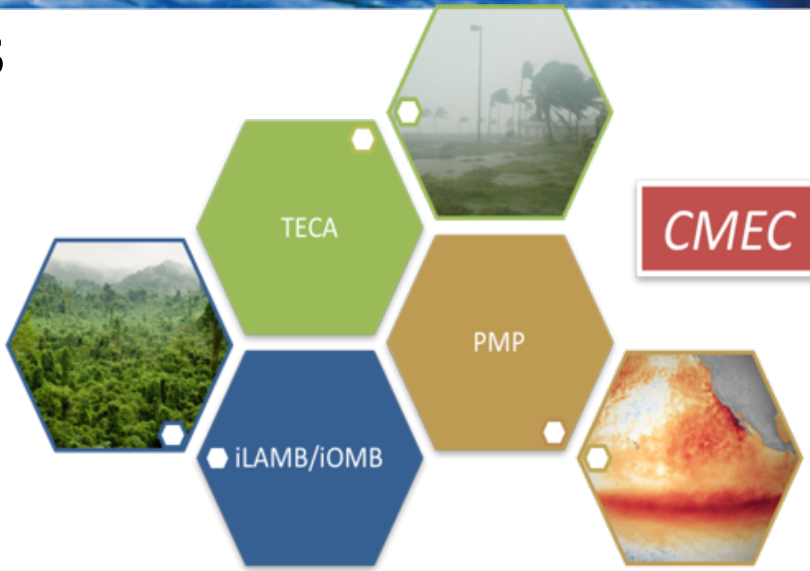
Integrated Tools and Science for Event Analysis



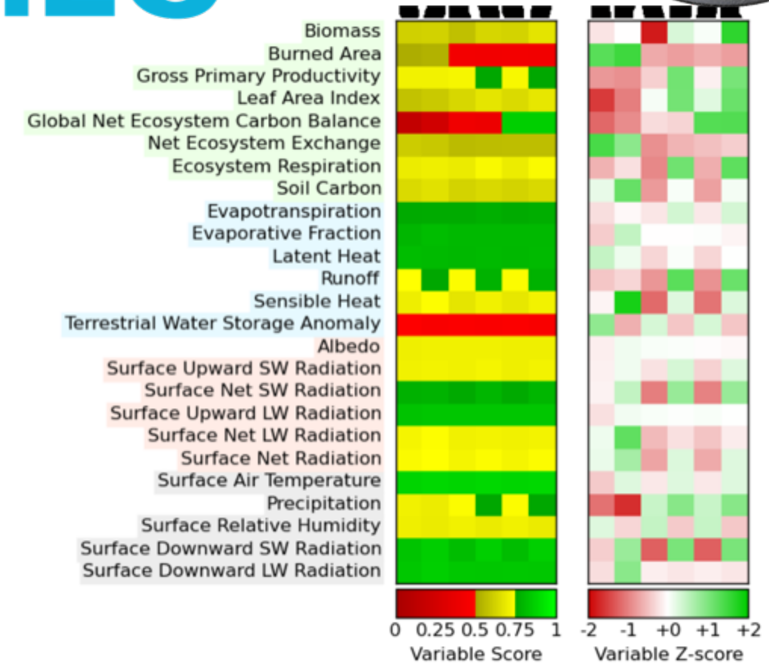
TECA



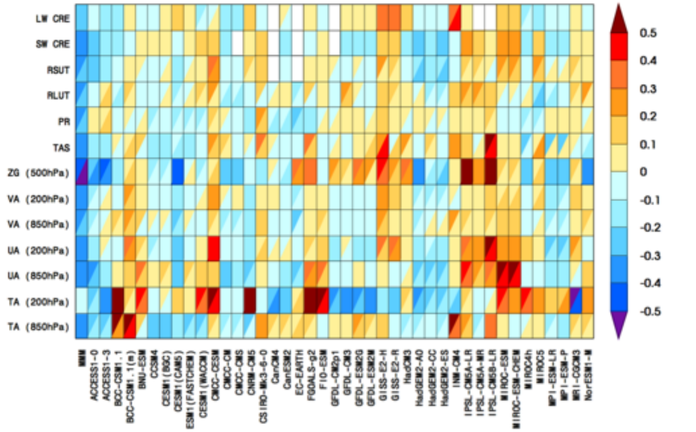
CMEC



ILAMB



PMP



RGMA (Model Analysis Program Area) Summary

- 6 Science Topics
- 5 lab efforts (SFA's or Science Focus Areas)
- Multiple university Projects from FY18 and will choose some in FY19
- 3 Cooperative Agreements
  - 2 of them being combined into one HyperFACETS
- All these efforts were encouraged to work in a multimodel framework that includes E3SM and CESM
- **Coordination with RGMA** across long-term (lab and CA) and short-term University projects
- **Coordination across Program Areas** and Programs within DOE
- Metrics being developed in all these projects will contribute to a **Coordinated Model Evaluation Capability**
- 2 new initiatives across the 3 modeling program areas (Development, Analysis, Mutisecter Dynamics) and the Data Program
- **Coordination across agencies** (with NSF, NOAA, NASA, and ONR)

E3SM strategies defined by goals and vision

Goals

Understand Earth system variability and change

Simulations, predictions, and projections to support DOE's energy mission

Prepare for and overcome the disruptive transition to next era of computing

Vision

Develop Earth system models that address the grand challenge of actionable predictions of Earth system variability and change, with an emphasis on the most critical scientific questions facing the nation and DOE

Strategies

- Push the high-resolution frontier of Earth system modeling
- Represent natural, managed and manmade systems across scales
- Quantify uncertainty using ensemble modeling

Earth system science  Computational science

Three overarching science drivers

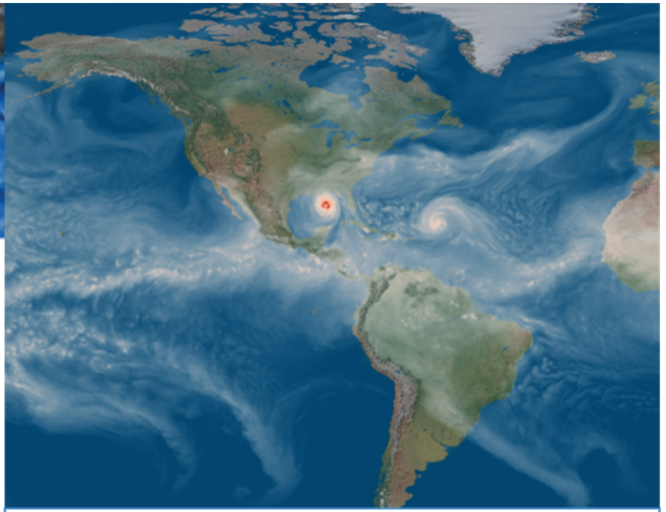
U.S. energy sector is vulnerable to:

- Decreasing water availability
- More intense storm events and flooding
- Increasing temperatures
- Sea level rise

- **Water cycle:** How does the hydrological cycle interact with the rest of the human-Earth system on local to global scales to determine water availability and water cycle extremes?
- **Biogeochemistry:** How does the biogeochemical cycle interact with other Earth system components to influence energy-sector decisions?
- **Cryosphere systems:** How do rapid changes in cryospheric systems evolve with the Earth system and contribute to sea level rise and increased coastal vulnerability?

Challenge: water cycle, biogeochemistry, and cryosphere systems interactions cannot be ignored for predictions or projections at longer time scales

E3SM Overview

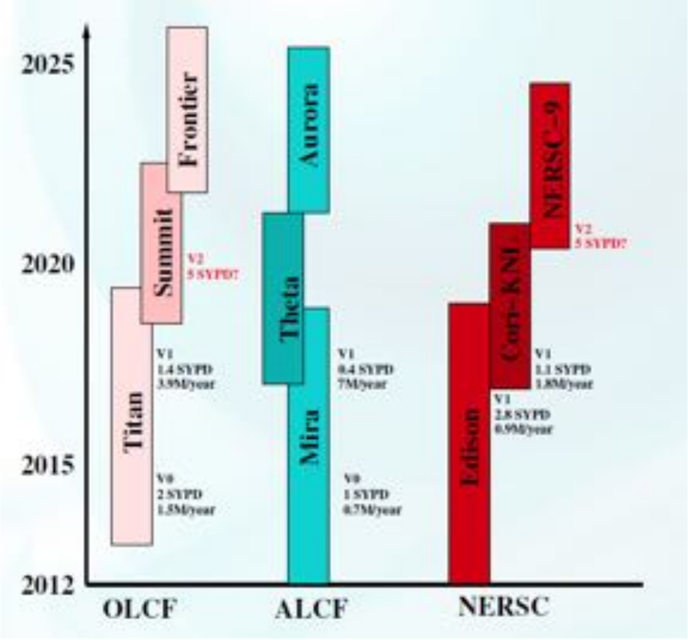


Hurricanes in E3SM, ¼ degree

- DOE - Office of Science coupled Earth system model
- Simulates the coupled Earth system at high resolution (about 25km), with variable-resolution options in all components. Aim is for 3km atmosphere in 6-10 years.
- Model configurations based on calculated trade-off between resolution, processes included, and length of simulation
- Developed for DOE science involving water cycle, biogeochemistry and ocean-cryosphere
- Designed to use all DOE High-Performance Computers – multiple challenging architectures. This effort aims to break ground for the broader community!

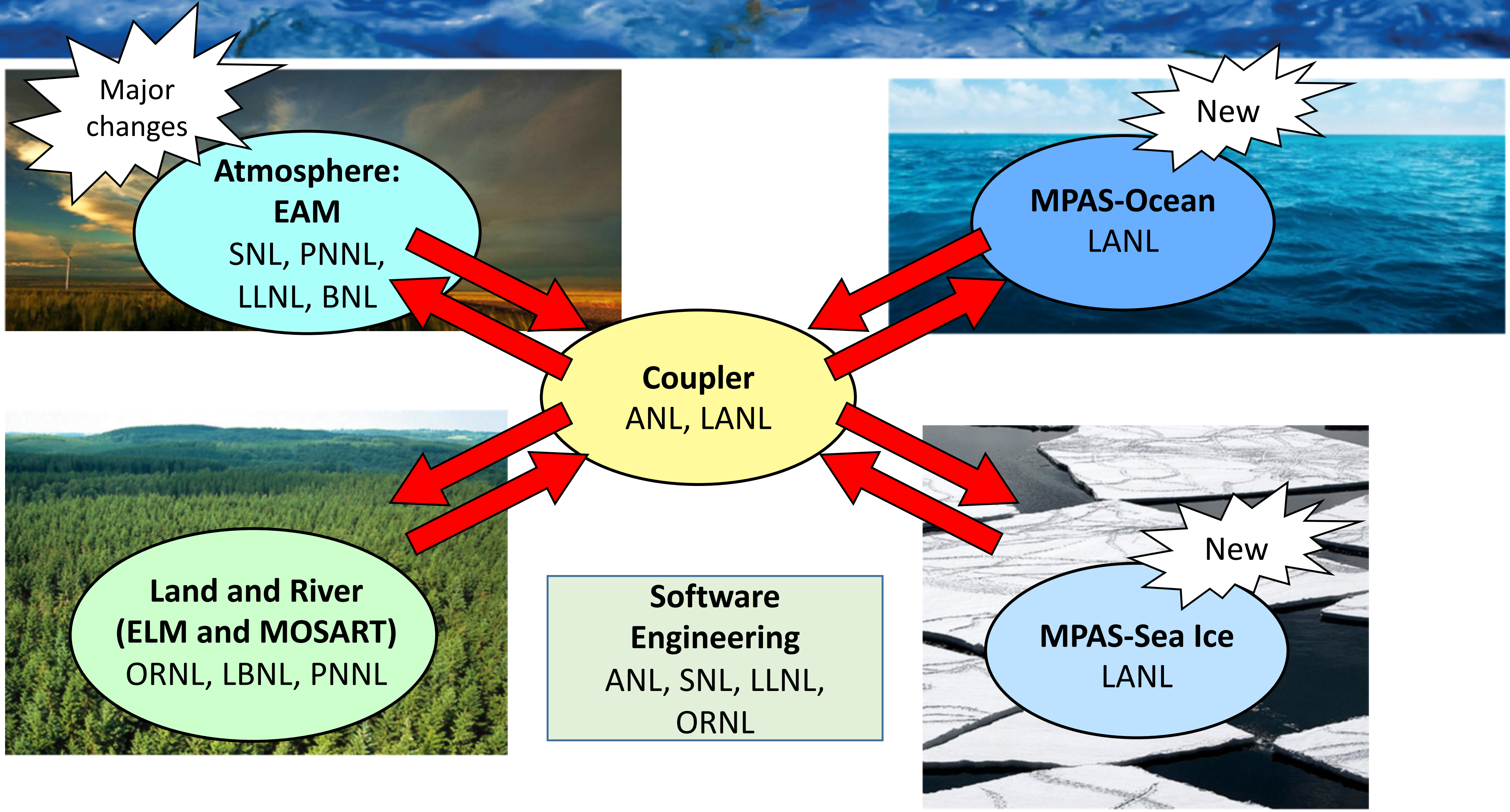
<u>Programmatics</u>

- Version 1 (v1) was released in April 2018: includes code, output, analysis tools
- Project code is Open-Development: https://github.com/E3SM-Project/E3SM
- E3SM Project is now 4 years old, now developing versions v2-v4
- Project website: https://E3SM.org
- E3SM Project is central to an extensive “ecosystem” of related projects



DOE – HPC timeline

What's new in E3SMv1?



piControl

- **Overall performance**
- Better than **CMIP5** mean (...but comparing a newer model against older ones).
- Quite good for v1 (at least we think)

Global seasonal RMS relative to ensemble

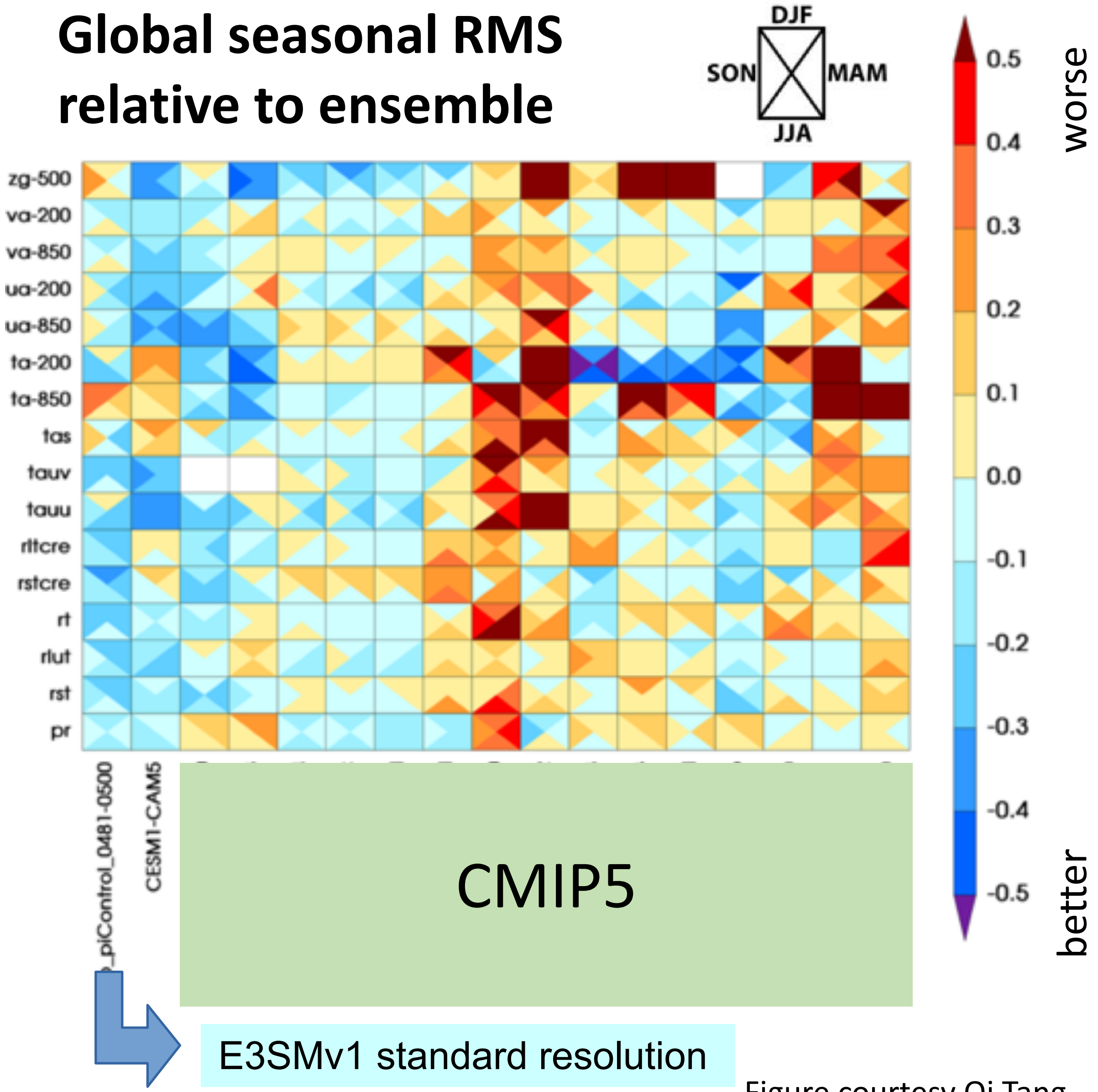
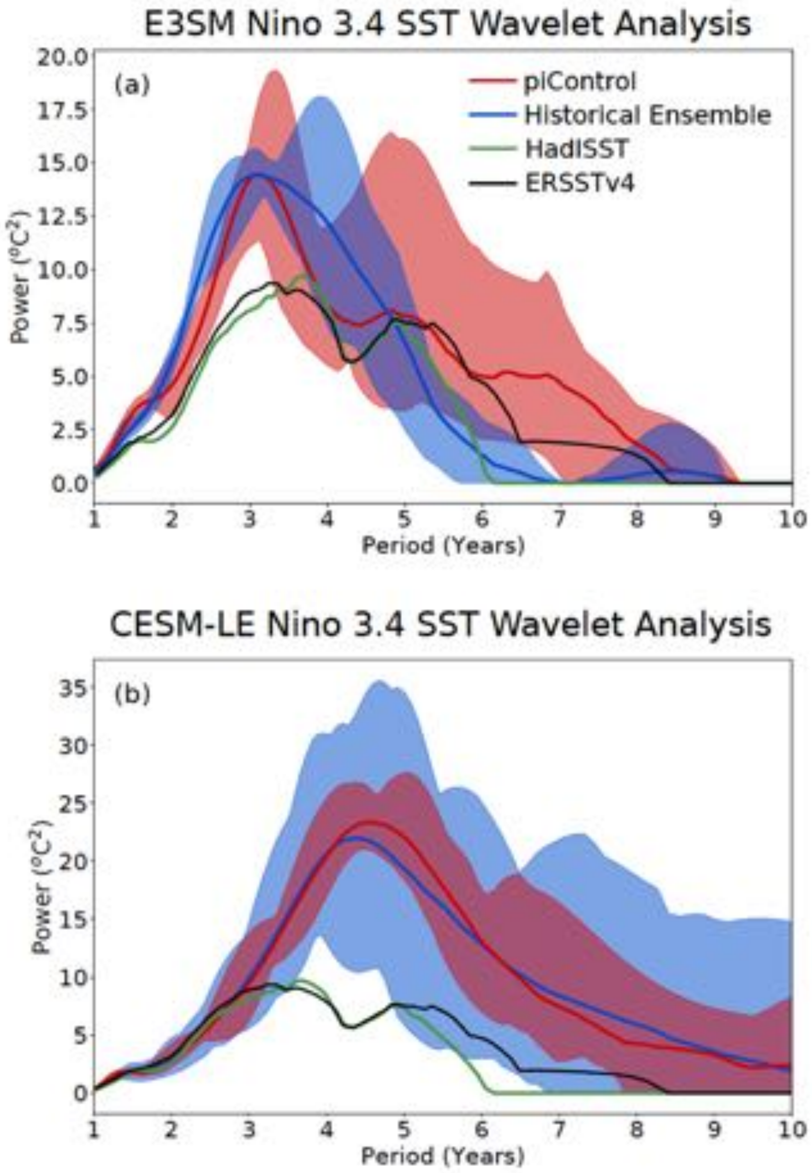


Figure courtesy Qi Tang

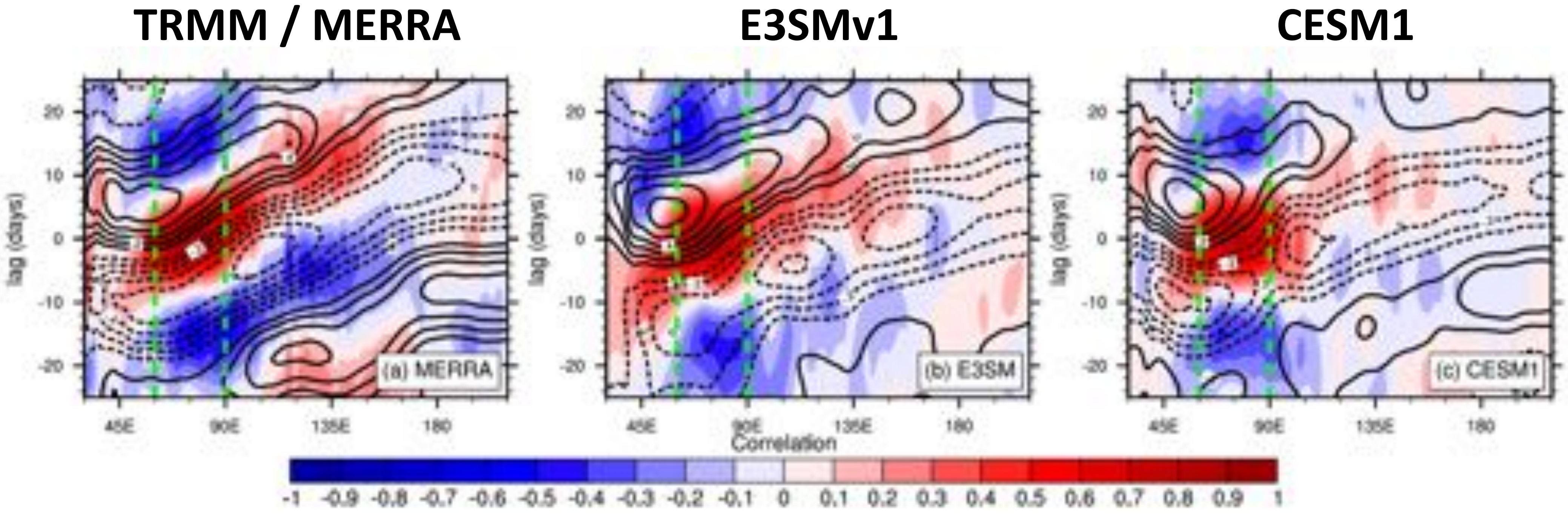
PCMDI Metrics Package (PMP); Gleckler et al. (2008, 2016)

ENSO (Nino3.4)

- Morlet wavelet (degree 6) of
  - piControl – subset into 5 100 year intervals
  - Historical ensemble
- E3SM has variability similar to reanalysis products.
  - Too much variability near 3 year period.
  - Long term modulation of ENSO evident in piControl
- Power spectrum improved compared to CESM-LE



Madden Julian Oscillation (MJO)

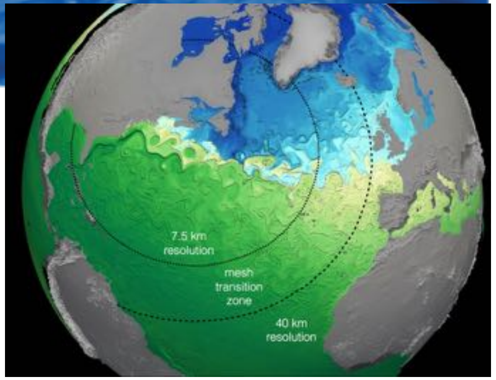


Tropical lag correlation (averaged 10N-10S) of precipitation (colors) and 850-mb zonal wind (lines) with precipitation.

- E3SMv1 simulated **MJO** closer to data than CESM1.
- Biases in Pacific propagation remain

Figure courtesy Rich Neale (NCAR)

Energy Exascale Earth System Model

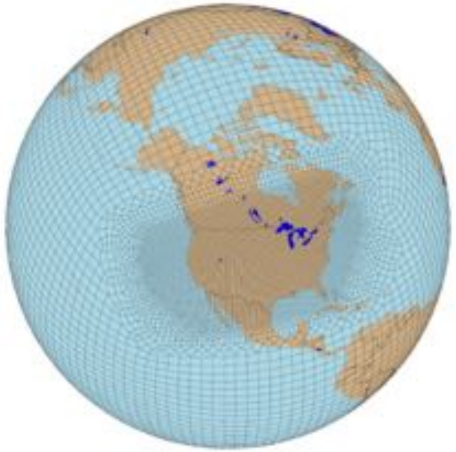


Programmatics:

- Version 1 was released in April, 2018: includes code, output, analysis tools
- The Project code is now Open-Development: https://github.com/E3SM-Project/E3SM
- New project website: https://E3SM.org
- Phase 2 of the project was reviewed May 14-16, 2018

Simulation progress (v1):

- The lower resolution (100km) coupled system behaves well and many simulations are completed. Coupled biogeochemical simulations (with more processes and tracers) are nearly ready to begin.
- High-resolution (25 km) tuning nearly completed, production simulations imminent



Phase 2 high-level plans (v2-v3-v4)

- Regional refinement over North America, focus on Energy-relevant science (e.g. water management, land-use, crops)
- V3-v4 will ultimately target very high-resolution (3km) atmospheric version with simpler physics and strong scaling on DOE computers
- Ongoing work, with variable mesh around Antarctica, to determine AIS instabilities and SLR

Community engagement

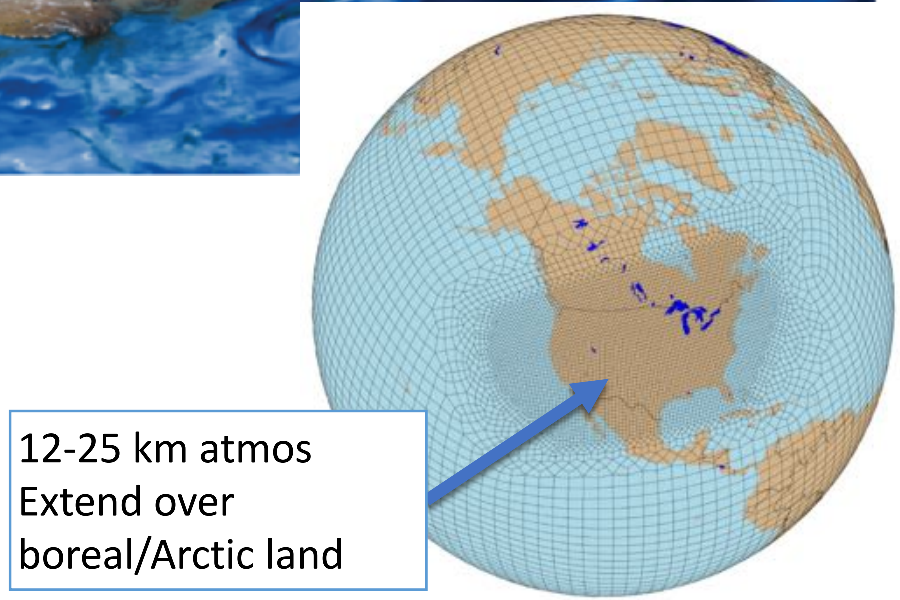
- Several new University and DOE-Laboratory projects, including SciDAC projects, will use E3SM. On-line training provided early this fall.

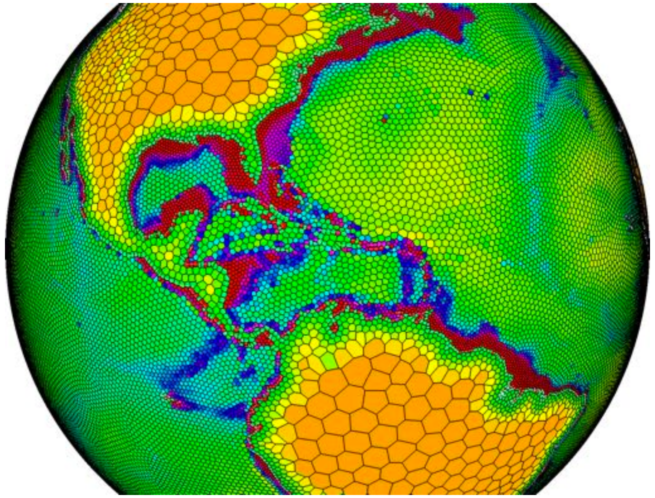
SciDAC projects will contribute mainly to v4-v5

E3SM Energy Exascale Earth System Model

E3SM v2 and v3 plans

- Version 2 (Release in 2021)
- Focus on improving computational aspects of project
- Science and developments will focus on North America
- Regionally refined North America
- Science:
  - Moisture transport to the Arctic; Effects of Arctic changes on lower latitude extremes
  - Vegetation changes; effects of surface heterogeneity
  - Effects of freshwater shifts on the AMOC
- Version 3 (Release in 2024) Goals and features
- Understand evolving hydrology over continental regions
- Effects of energy and land-use on carbon cycle and water
- Nonhydrostatic dynamical core in atmosphere (1/8 deg atmos)
- Land subgrid hierarchical structure
- Terrestrial-aquatic interfaces
- Groundwater
- Coastal processes – targeted regional refinement, estuary modeling, tides, storm-surge,watershed impacts
- Ice sheet improvements (with SciDAC project)





M. Gunzburger

The Simple Cloud-Resolving E3SM Atmosphere Model - SCREAM

Motivation

- Cloud-resolving simulations (with $\Delta x \approx 3$ km) avoid the need for convection parameterizations, which are a major source of climate change uncertainty (Figure).

Approach

- By leveraging DOE's world-leading investments in hardware and software, we are building the world's fastest global cloud-resolving model.
- Running a full non-hydrostatic dynamical core with increasing resolution from 25km (E3SMv1) to 3km.

Impact

- This research is pushing the boundaries of both science and computing.
- The goal is to have a fully tested model in 3 years which will become the default E3SM atmosphere model in 5-10 years.

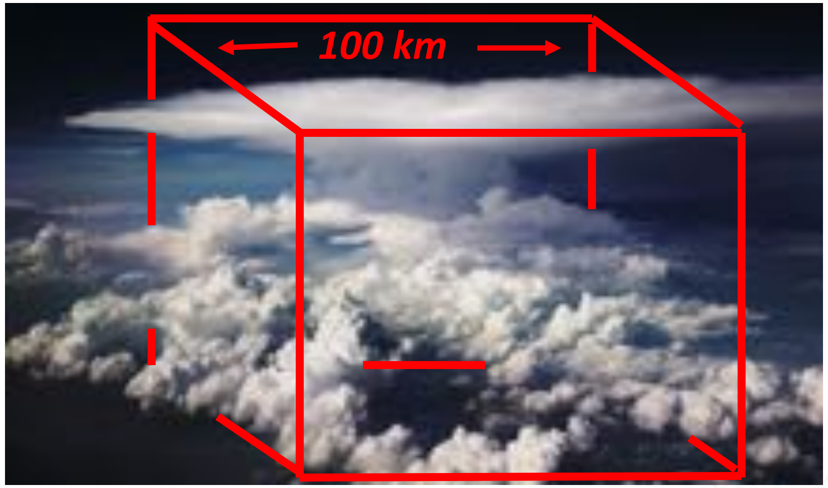
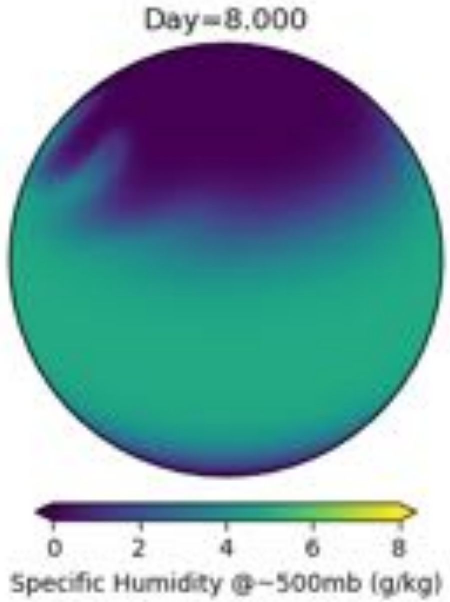


Figure: How do we parameterize this sub-grid variability?
Movie: Water vapor concentration at 500 mb from an idealized baroclinic instability simulation at 3 km resolution.



New Modeling Framework Represents Aerosols at Cloud Scale

Objective

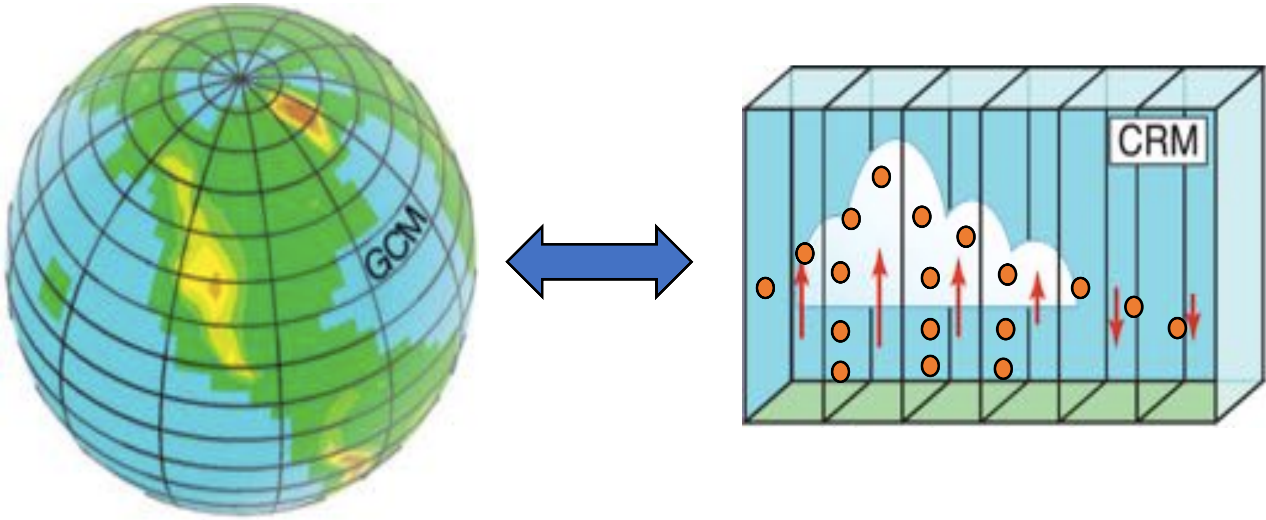
- Most global climate models (GCMs) cannot resolve the important aerosol processes that are related to clouds and occur at cloud scale. This makes it difficult to predict the aerosol change and aerosol effects on climate.
- Develop a multi-scale modeling framework (MMF), which embeds a cloud resolving model (CRM) into each GCM grid column to resolve the cloud formation

Approach

- Apply all cloud-related aerosol processes within grid cells of each cloud resolving model (CRM) embedded in the global climate model (GCM) grid
- Compare simulations of the new MMF with those using aerosols parameterized in GCM grids and observations

Impact

- The new MMF increases black carbon aerosols and decreases sea-salt aerosols compared to the old MMF that parameterized aerosols at GCM grids
- The new aerosol treatment improves many aspects of simulated aerosols
- Aerosol differences produce little impact on cloud formation or aerosol radiative forcing



The diagram for the new MMF. Within each GCM grid column (left), one CRM (right) is used to explicitly represent clouds and precipitation. In addition, cloud-related aerosol processes are explicitly indicated on the CRM grid.

G. Lin, S.J. Ghan, M. Wang, P-L MA, R. C. Easter, M. Ovchinnikov, J. Fan, K. Zhang, H. Wang, D. Chand, and Y. Qian, "Development and Evaluation of an Explicit Treatment of Aerosol Processes at Cloud Scale Within a Multi-scale Modeling Framework (MMF)". *Journal of Advances in Modeling Earth Systems* 10(7):1663-1679. DOI: 10.1029/2018MS001287.

Thank You

And a new research thrust with MSD, RGMA, and ESM…
The Integrated Coast: Systems, Dynamics, & Evolution

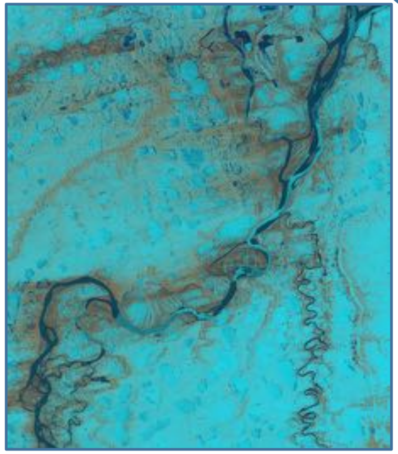
Arctic Change with Implications for Resources and Development

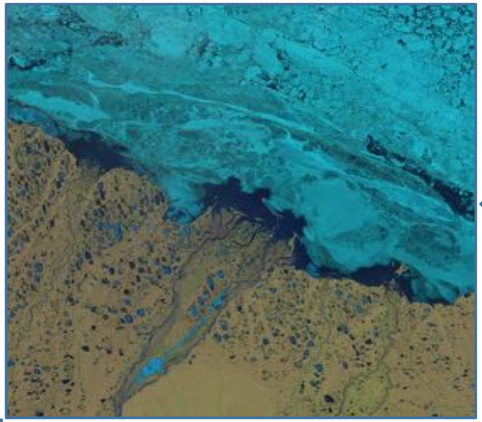
Lab-led, multi-institutional effort (40% or more external) ~ $2.5M/yr over three years
Collaboration involving RGMA (Joseph-POC), MD (Vallario), ESM (McFarlane), and Data (Hnilo)

Quantifying the coupled dynamics of the changing Land-Ocean-Sea ice interface

How changes in watershed permafrost and hydrology

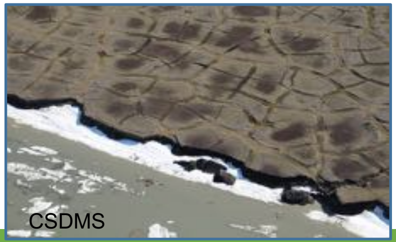
Influence riverine fluxes

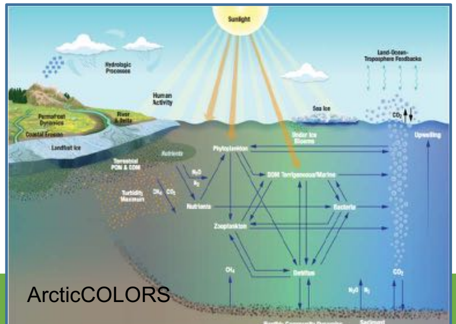




How changes in landfast ice and open

Influence wave dynamics, coastal erosion, biogeochemistry and transportation



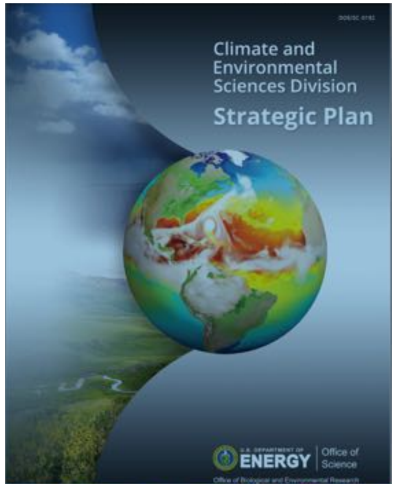


How best to initialize?

- **Hindcast initialization (used by NCAR)**
  - run the ocean model with the observed time evolution of forcing from the atmosphere through the 20th and early 21st centuries, and repeat this five times; the atmospheric observations will be imprinted on the upper ocean and provide initial states that are part observations and part remaining model systemic errors; the assumption is that, taking into account the latter, there will be less initial drift than if the entire model was initialized exactly with observations
- **Reanalysis initialization ("brute force" used by Ben Kirtman)**
  - Take ocean reanalyses from NOAA and put them directly into the ocean model; do the same for atmosphere and land surface; therefore, the initial state of the model is exactly that from observations (as represented by reanalysis products); drift could be large as the model immediately drifts toward its systematic error state, but this is now being evaluated in comparison to the hindcast initialization drifts from NCAR

CESD: Mission and Vision

- **CESD's Mission** is to enhance the seasonal to multi-decadal scale predictability of the Earth system using long-term field experiments, DOE user facilities, <u>modeling and simulation, uncertainty characterization, best-in-class computing, process research, and data analytics</u> and management in order to inform the development of advanced solutions to the Nation's energy challenges.



- **CESD's Vision**: An improved capability for earth system prediction on seasonal to multi-decadal time scales to inform the development of resilient U.S. energy strategies.