Accelerated Climate Model for Energy

Translating Process Understanding to Improve Climate Models
GFDL, October 15, 2015

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Ocean, Cryosphere: Todd Ringler, Steve Price, Phil Jones

Land: Peter Thornton, Bill Riley, Charlie Koven

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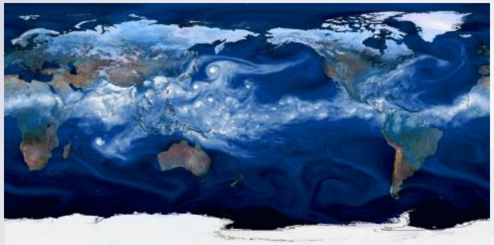
ACME Overview

- ACME is a modeling project launched by DOE in July 2014 to develop a branch of the CESM to
  - ❖ Advance a set of science questions that demand major computational power and advanced software
  - ❖ Provide the high resolution coupled climate simulations (15-25 km), with adaptable grids <10 km
  - ❖ Focus on near-term time horizon: 1970-2050
  - ❖ Design codes to effectively utilize next and successive generations DOE Leadership Class computers, both hybrid and multi-core, through exascale
- The project was based on a consolidation of previous DOE Laboratory model development projects, and includes 8 DOE Laboratories and 6 non-Laboratory institutions; over 100 people.
- The project is initially supported for 3 years and is structured around
  A) 3 Science drivers and <u>questions</u>
  C) Experiments to answer questions
  D) <u>New developments</u>
- While testing is part of the plan, <u>CPT-type work</u> is always needed!

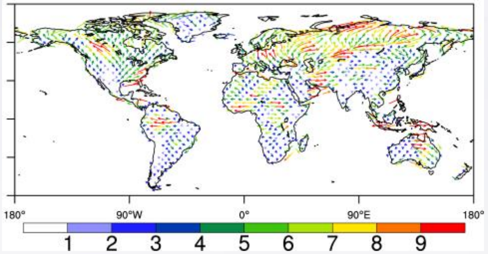
Climate Science Drivers and Questions

Water cycle: How do the hydrological cycle and water resources interact with the climate system on local to global scales?



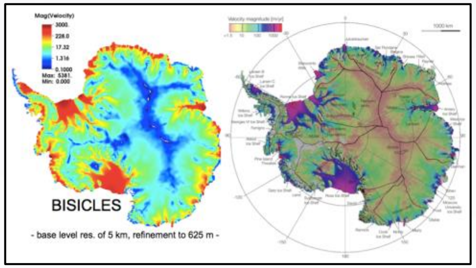
What are the processes and factors governing precipitation and the water cycle today and how will precipitation evolve over the next 40 years?

Biogeochemistry: How do biogeochemical cycles interact with global climate change?



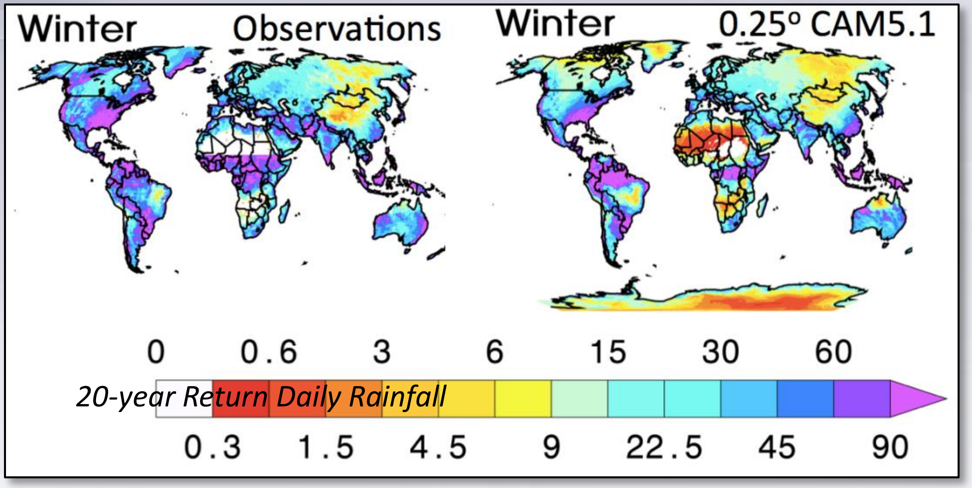
What are the contributions and feedbacks from natural and managed systems to current greenhouse gas fluxes, and how will those factors and associated fluxes evolve in the future?

Cryosphere-Ocean: How do rapid changes in cryospheric systems interact with the climate system?



What is the long-term, committed Antarctic Ice Sheet contribution to sea level rise (SLR) from climate change during1970–2050?

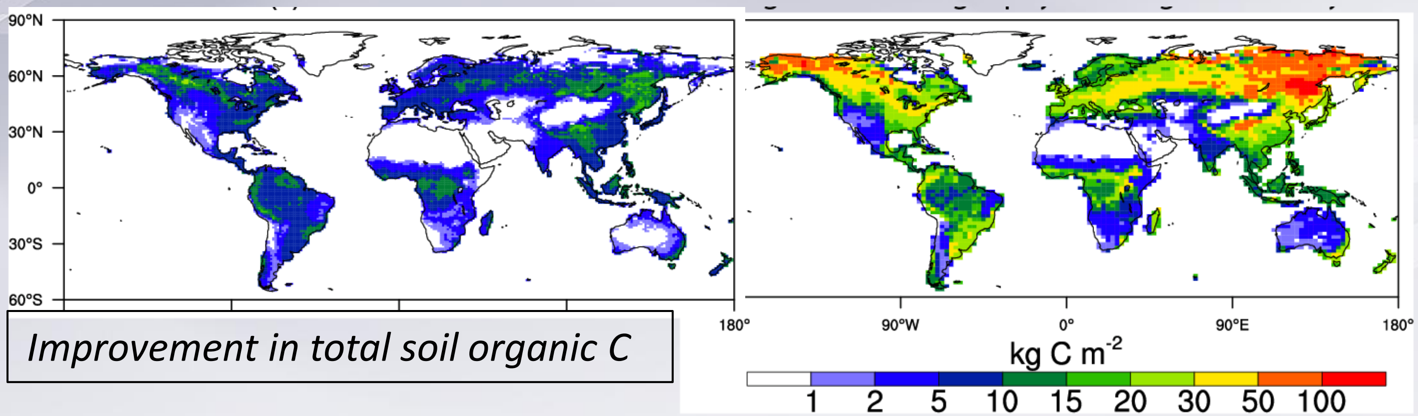
Water Cycle Experiments



Near-term: How will more realistic portrayals of features in the water cycle (resolution, clouds, aerosols, snowpack, river routing, land use) affect river flow and associated freshwater supplies at the watershed scale?

Simulations: High-res (0.25-deg, eddying ocean)

Biogeochemical Experiments



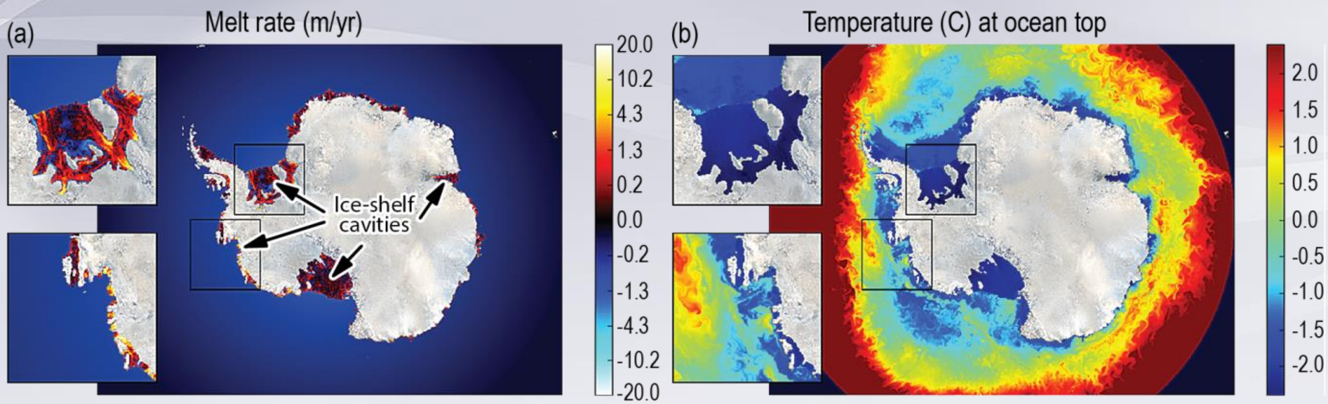
Improvement in total soil organic C

Near-term: How do carbon, nitrogen, and phosphorus cycles regulate climate system feedbacks, and how sensitive are these feedbacks to model structural uncertainty?

Simulations: Simulation plan includes

1. Fixed-forcing control simulations, using pre-industrial (circa 1850 AD) boundary conditions
2. Transient-forcing control simulations, using historical forcings
3. Fixed-forcing C-N-P simulations
4. Transient-forcing C-N-P simulations

Cryospheric Experiments



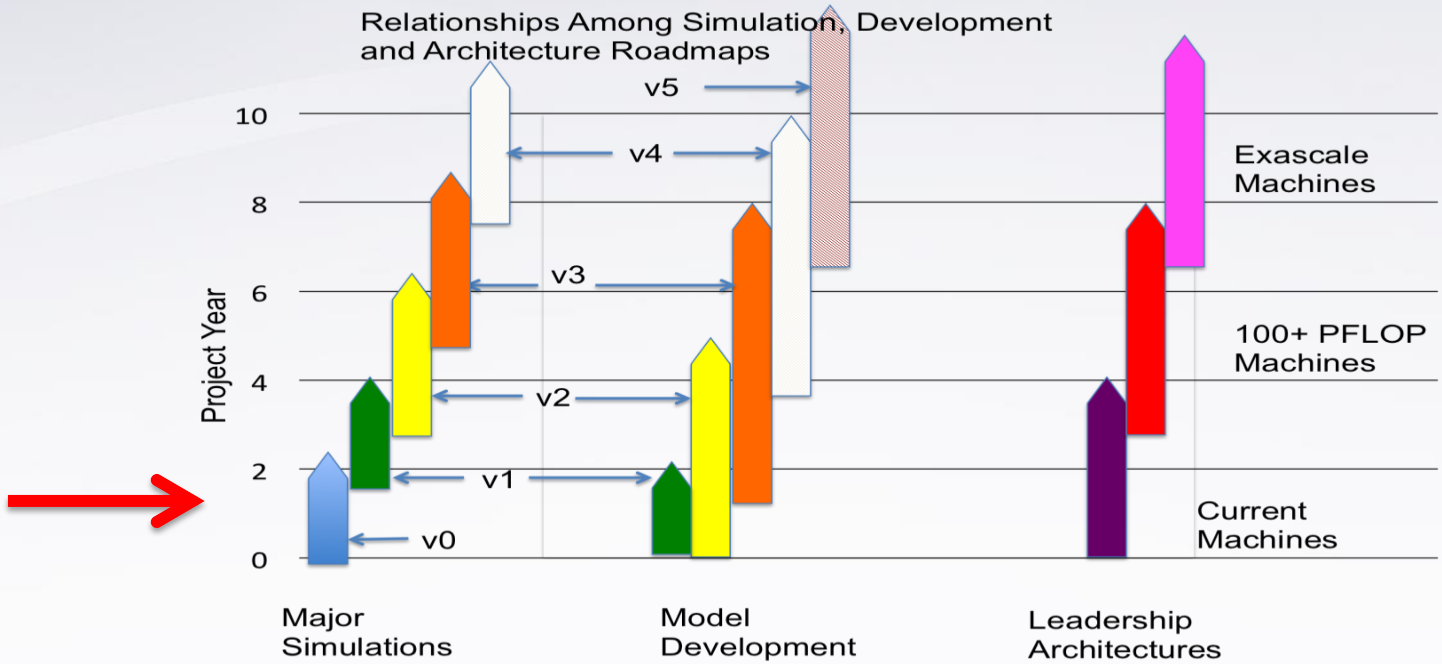
Near-term: Could a dynamical instability in the Antarctic Ice Sheet be triggered within the next 40 years?

Simulations: Simulation plan focuses on

1. Rigorous testing of the ice sheet and its interactions with the atmosphere, underlying continent, ocean, and sea ice
2. Transient fully coupled simulation from 1970 to 2050.

ACME timeline and plan

- v0 model – CESM 1 (CAM-SE, POP, CICE, CLM)
- v1 model – CAM-SE, MPAS-O, MPAS-CiCE, ACME Land ice, CLM variant Land/Terrestrial BGC
- v1 frozen Nov 1, 2015, V&V, simulations -> release 2017
- v2 under development now…



Atmosphere

Developments
CPT ideas
DOE activities

Atmosphere Developments

CAM-SE dynamical core standard

- Development resolution 100km, 30L/64L/72L
- Production resolution 25km; 72 layers, top at ~60km
- Subgrid orographic treatment for atmosphere and land (v2)
- Non-hydrostatic CAM-SE (v3?)

Aerosols and clouds

- New convection scheme (CLUBB or UNICON)
- Ice nucleation improvements
  - pre-existing ice crystals on aerosol activation
  - vertical velocity dependence ice
- Aerosol deposition on ice and snow
- Convective aerosol transport, activation, removal
- 4th mode for black carbon; Sulfuric acid, nucleation; SOA’s
- Ocean aerosols: organics, DMS with ocean BGC

Diagnostics

- COSP simulator (V1.4); New aerosol-CALIPSO simulator
- In-Situ Diagnostics

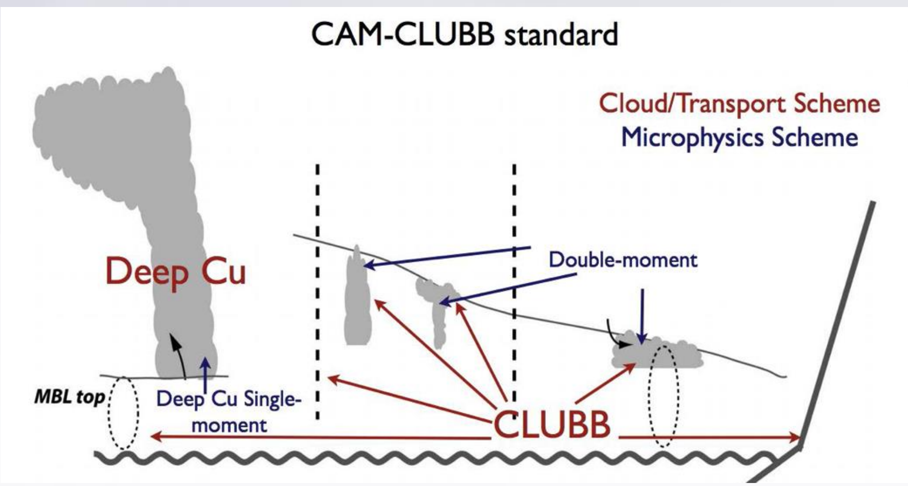
CPT1: ACME Shares Many Common Errors in Climate Models

- Double ITCZ, weak MJO, problems capturing amplitude and phase of diurnal cycle of precipitation over land
- Failure in capturing transition from shallow to deep convection over land; and in cloud regime transition along a Pacific cross-section from stratocumulus, to cumulus and to deep convection (GPCI).
- Too much light rain and too little heavy rain
- "Too few, too bright" problem in simulated clouds
- Mixed-phase clouds problems

CPT2: New Convection Schemes

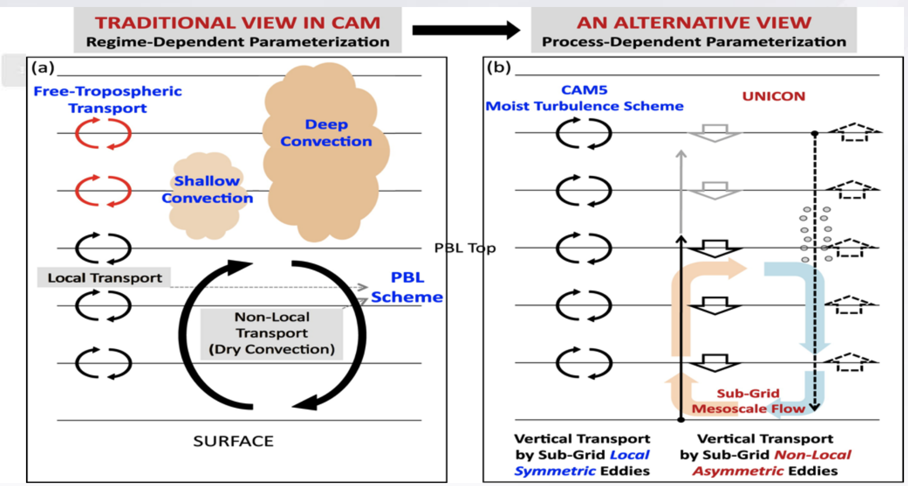
- **CLUBB + MG2 (Andrew Gettelman, Pete Bogenshutz, Vince Larson)**
- **UNICON (Sungsu Park)**
- **ZM variants (Guang Zhang, Rich Neale)**

CLUBB



Thanks Pete Bogenschutz

UNICON

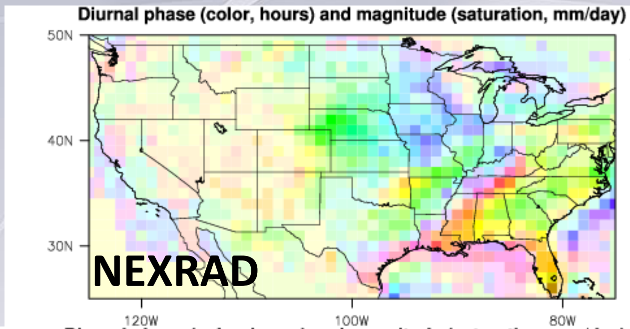


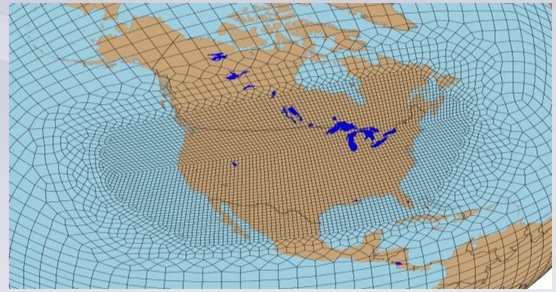
Thanks Sungsu Park

UNICON and CLUBB treat different physical processes in a unified way and are some sort of scale-aware parameterizations.

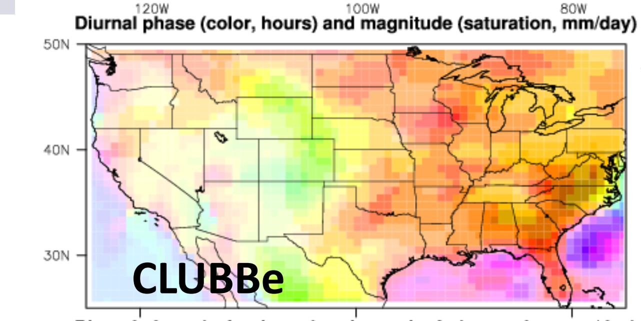
CPT3: Diurnal Cycle of Precipitation: Regional Refinement (RRM) improves!

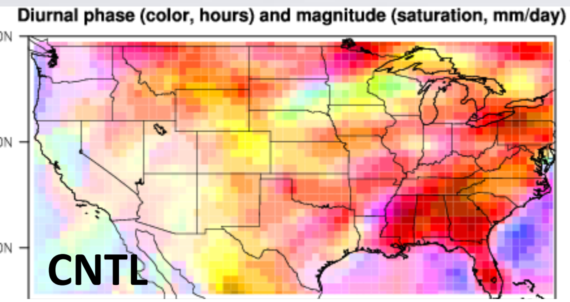
April-July AMIP 2011

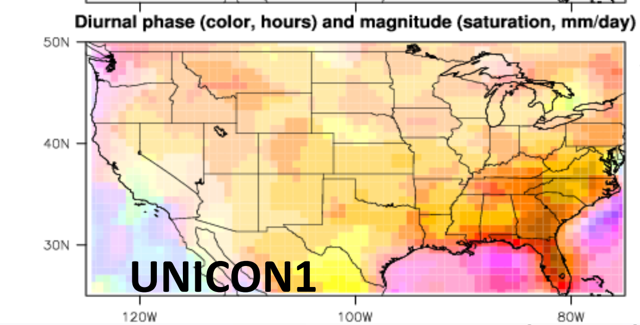


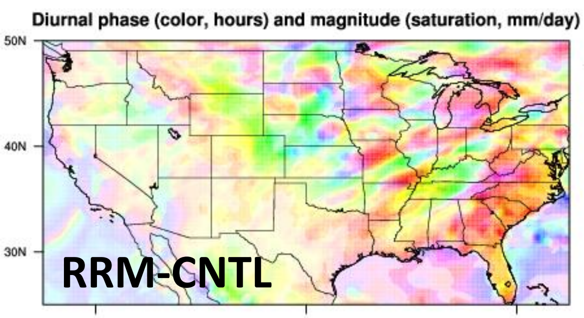


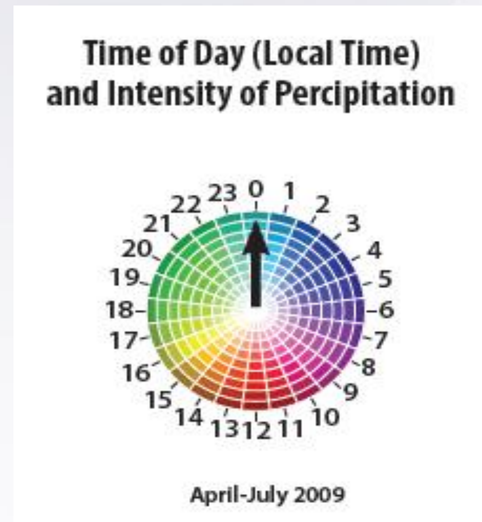
Regional Refined Model (RRM) over CONUS







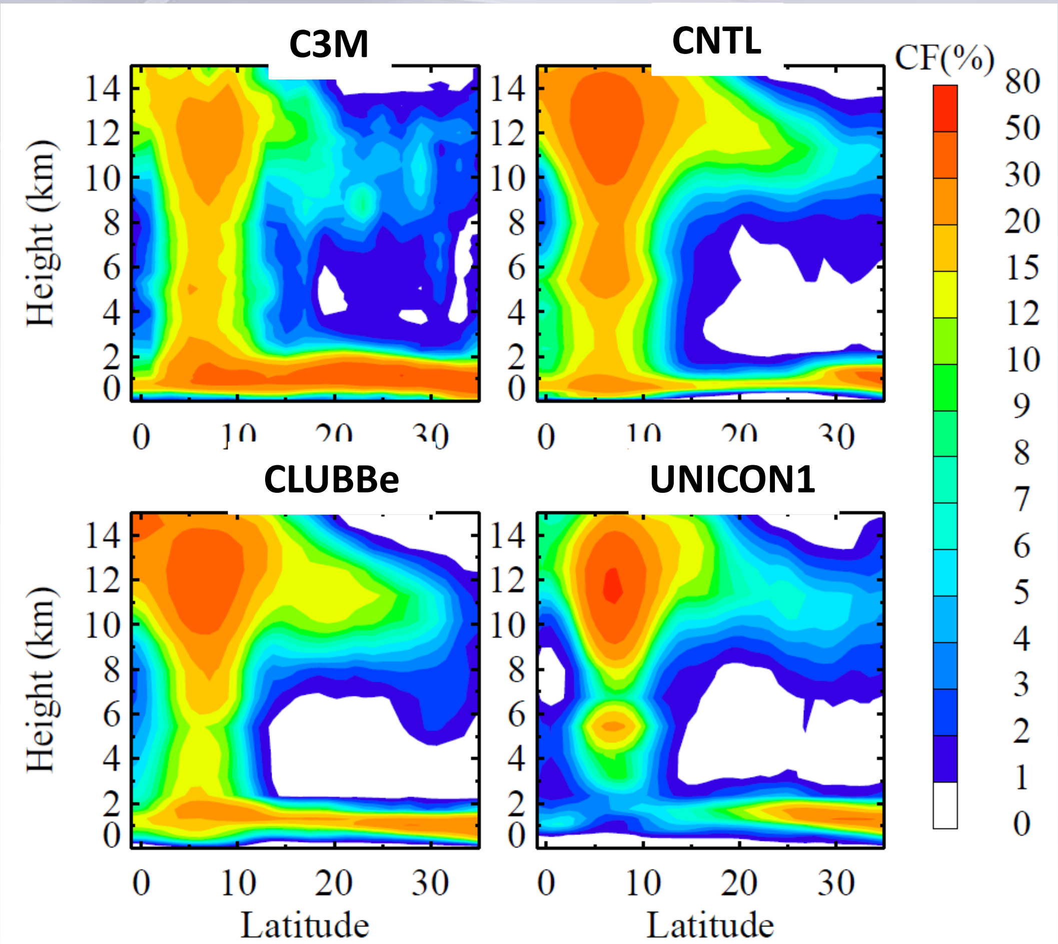




Regional Refined Model (RRM) simulation over CONUS nudged to analysis data to simulate the meteorology of the day

CPT4: StCu-Cu Transition

Cloud Transition Along the GPCI Transect JJA 2008-2012



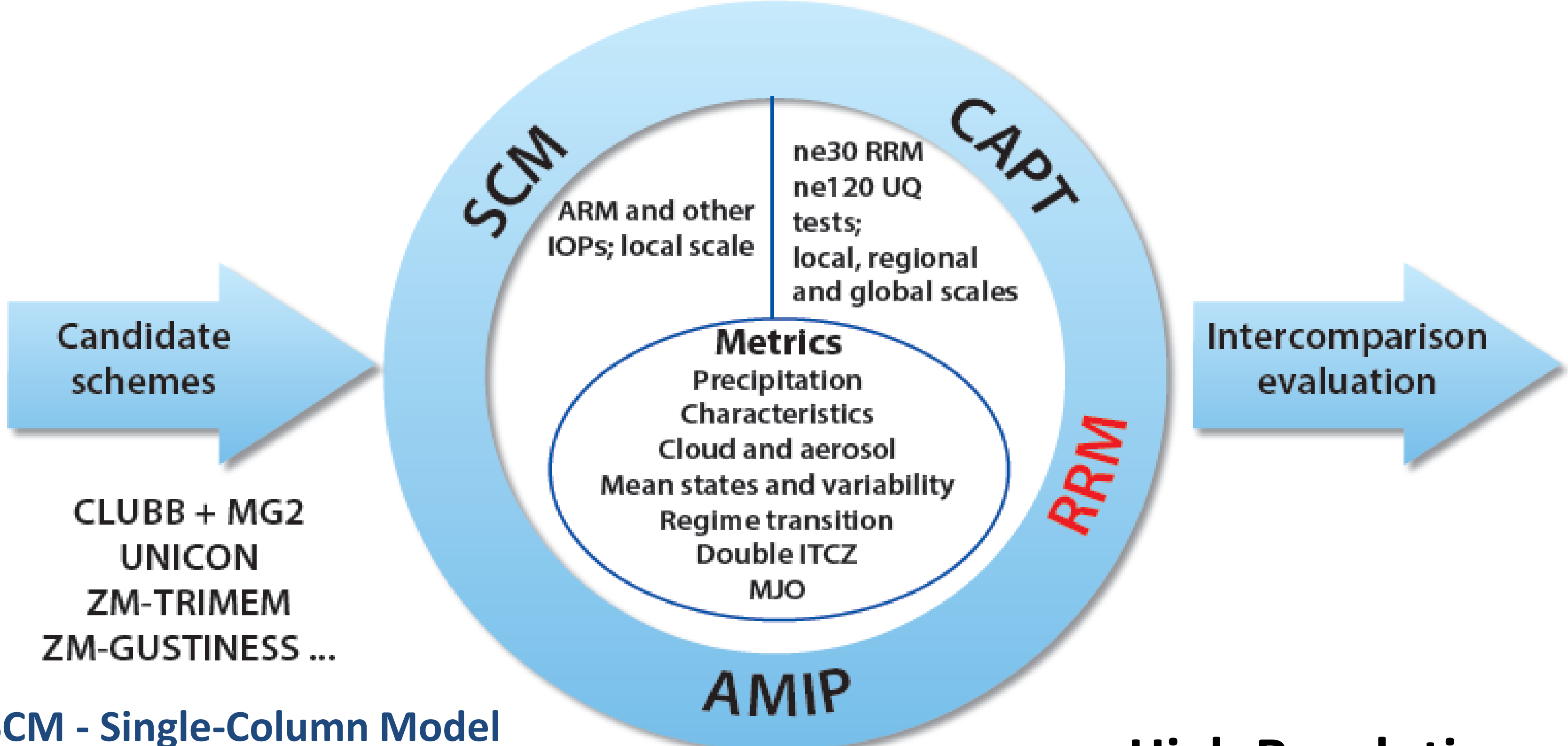
CNTL:
Overproduces high cloud over the whole GPCI. Underproduces low cloud over Cu and Dc zone; Cu depth too shallow.

CLUBB:
Some improvements are seen in low clouds

UNICON:
Improves high and low clouds over Sc and Cu regime; Mid-cld over Dc regimes become worse; possibly related to over-precipitating.

GPCI: GCSS/WGNE Pacific Cross-section Intercomparison project

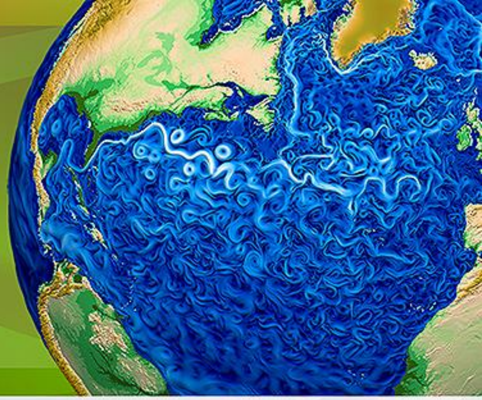
DOE: Process Model tools Used in Developing New Parameterizations (Convection) for ACME



SCM - Single-Column Model
(LES: Large-Eddy Simulation models)
CAPT - Cloud-Associated Parameterization Testbed
RRM - Regional Refined Model
AMIP - Free run with specified SST and Sea Ice
Short ensemble UQ – Model tuning

High Resolution:
ne30L30 –> ne120L60+

ACME
Accelerated Climate Modeling for Energy



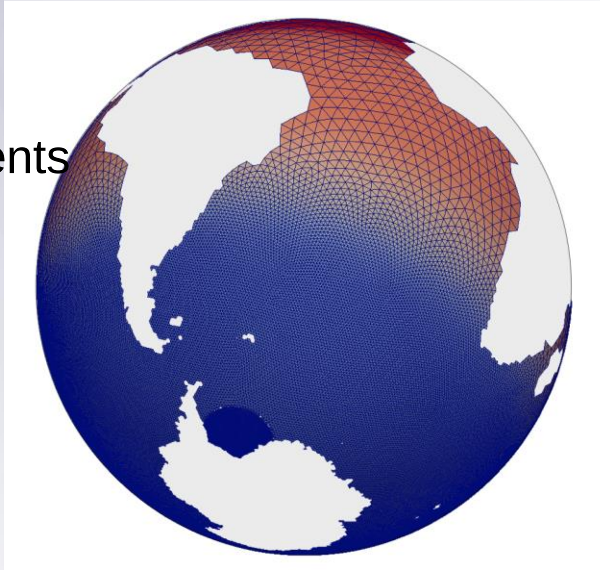
Ocean and Cryosphere

Developments
CPT ideas
DOE activity

ACME Ocean and Ice Developments

MPAS-Ocean

- Hi-res: 15-5km RRS, 100 vert levels
- Eddy resolving, down to 1-5km in selected embayments
- BGC: (One-degree equivalent mesh)
- All ocean parameterizations, Cvmix
- Hybrid-vertical (v2)
- New scale-dependent eddy treatment (v2)

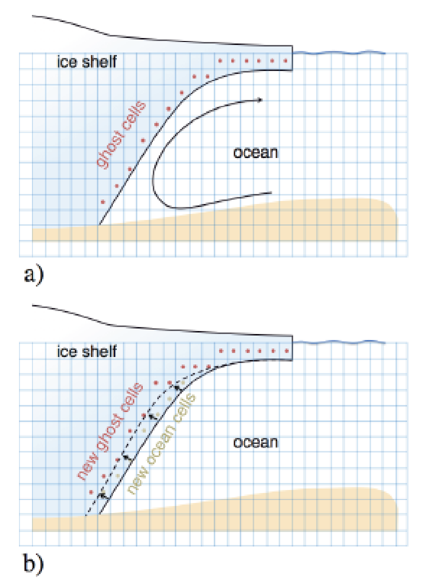


MPAS-Sea-Ice

- Elastic-Viscous-Plastic
- CICE5 physics (melt ponds, mushy layer; snow-on-ice (v2))
- BGC

MPAS-Land-Ice

- Antarctic grid (variable-mesh)
- SMB in land model
- Shelf-ocean coupling
- Moving grounding line, ice shelf boundaries
- Calving; Basal hydrology (v2)



CPT1: Coastal Ocean/Atmosphere Biases

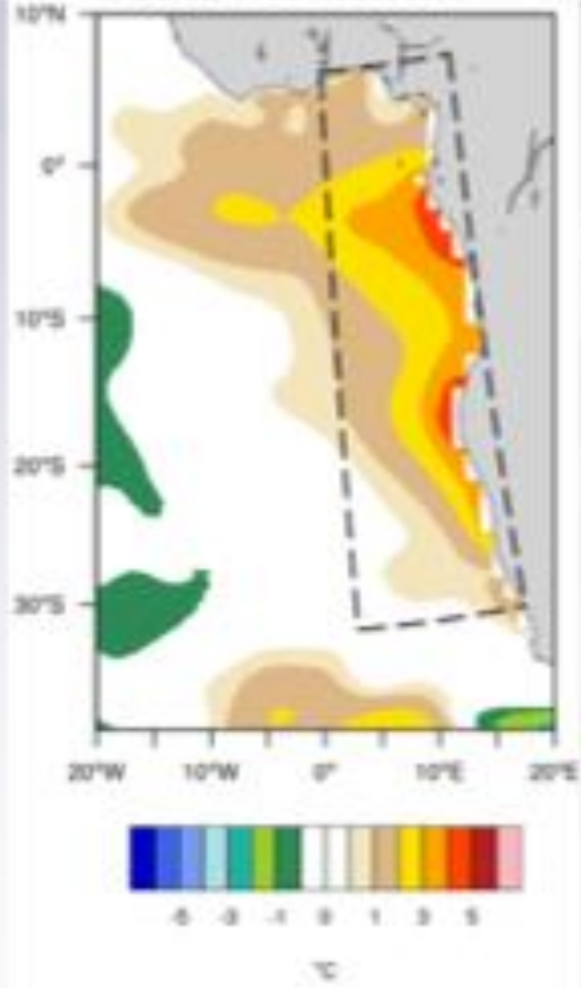
Biases in atmosphere and ocean coupling along the west coast North and South America and Africa remain ubiquitous in climate models[1].

These are coupled ocean-atmosphere phenomena.

Multiscale modeling approaches in the atmosphere and ocean, along with improved in-situ and remote sensing, might warrant another attempt at remedying these biases.

ACME v2 will likely include configurations with enhanced resolution for atmosphere and ocean along some coastal regions.

SST bias



from Small et al. 2015

[1]Griffies, S. M., Biastoch, A., Böning, C., Bryan, F., Danabasoglu, G., Chassignet, E. P., et al. (2009). Coordinated Ocean-ice Reference Experiments (COREs). Ocean Modelling, 26(1-2), 1–46. http://doi.org/10.1016/j.ocemod.2008.08.007

Small, R. Justin, et al. "THE BENGUELA UPWELLING SYSTEM: QUANTIFYING THE SENSITIVITY TO RESOLUTION AND COASTAL WIND REPRESENTATION IN A GLOBAL CLIMATE MODEL." *Journal of Climate* 2015 (2015).

CPT2: Water Mass Transformation around Antarctica

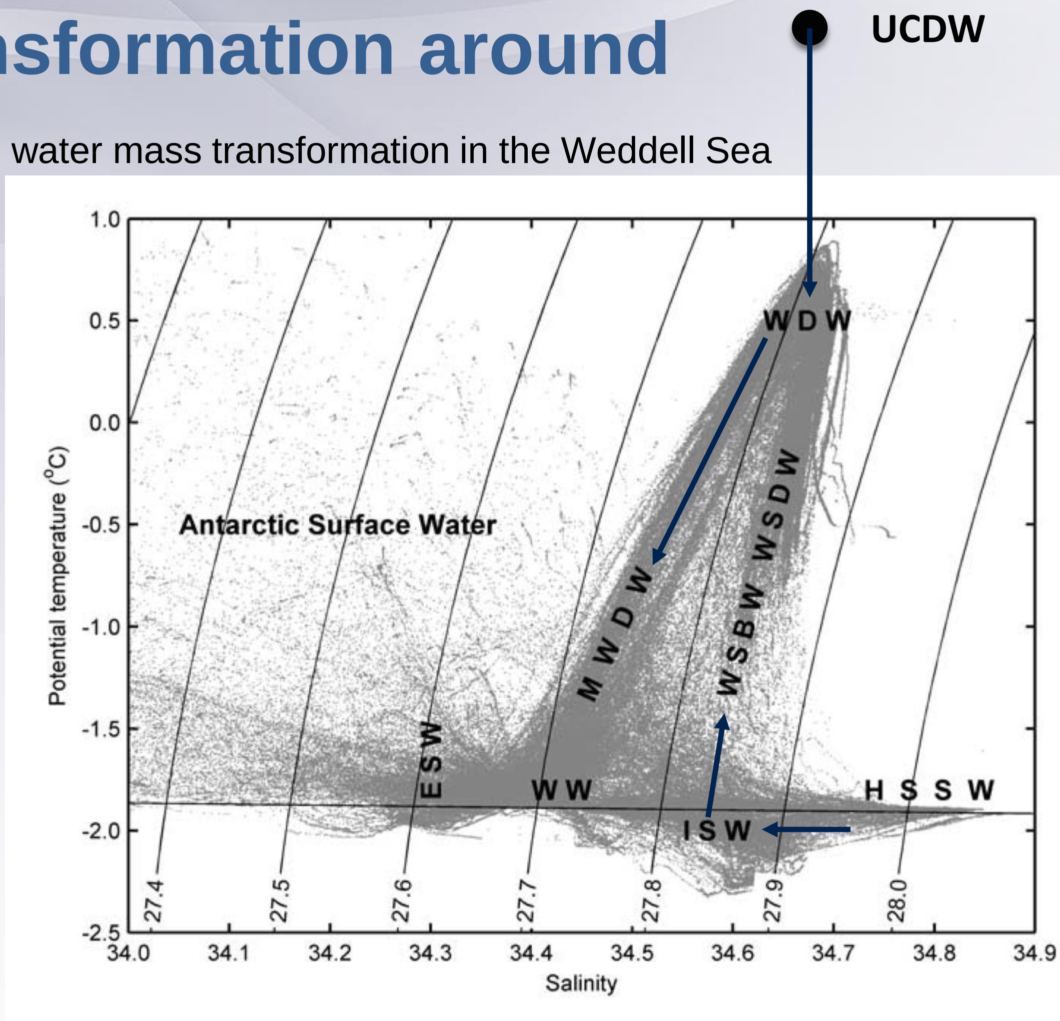
The ocean, sea-ice and land-ice systems are all critical to water mass transformation and deep water creation around Antarctica.

The input (Upper Circumpolar Deep Water: UCDW) is a potentially strong driver of rapid sea-level rise.

The output (Weddell Sea Deep Water) is a large contributor to Antarctic Bottom Water.

A CPT focused on water mass transformation in the Weddell, Ross or Amundsen Sea could provide critical information for coupled climate simulations (and sea-level estimates)

water mass transformation in the Weddell Sea



Nicholls, K. W., Østerhus, S., Makinson, K., Gammelsrød, T., & Fahrbach, E. (2009). Ice-ocean processes over the continental shelf of the southern Weddell Sea, Antarctica: A review. Reviews of Geophysics, 47(3), RG3003. doi:10.1029/2007RG000250

CPT3: Snow on Sea Ice

snow depth measurements using a magnaprobe on sea ice just offshore from Barrow AK

photo courtesy of Andrew Roberts

Snow processes on sea ice are the largest source of uncertainty in current sea-ice models.

Improved snow modeling in ACME v2 will include blowing, compaction and metamorphosis of snow due to both wet and dry processes.

Snow modelers and field experts are already beginning to organize around this topic. EOS summary of workshop to appear.

Multiple agencies are already engaged on this topic. The CPT framework is a great vehicle to solidify and propel the effort forward.

CPT3: Cryological Iron Cycle

Iron dictates carbon draw-down over the Southern Ocean, but it is sequestered in sea ice for much of the year.

The biology and chemistry involved in its retention is not well understood but includes interactions among the sea ice physical system of brine channels and ice algal geocycling.

As the critical nutrient for the southern hemisphere ecosystem, iron must be included in biogeochemical models coupled into full earth system simulations.

A CPT could clarify the critical processes involved in (SH) iron cycling

brine channels provide pathways to connect sea-ice sequestered iron to the open ocean.

CPT4: Land Ice Discharge

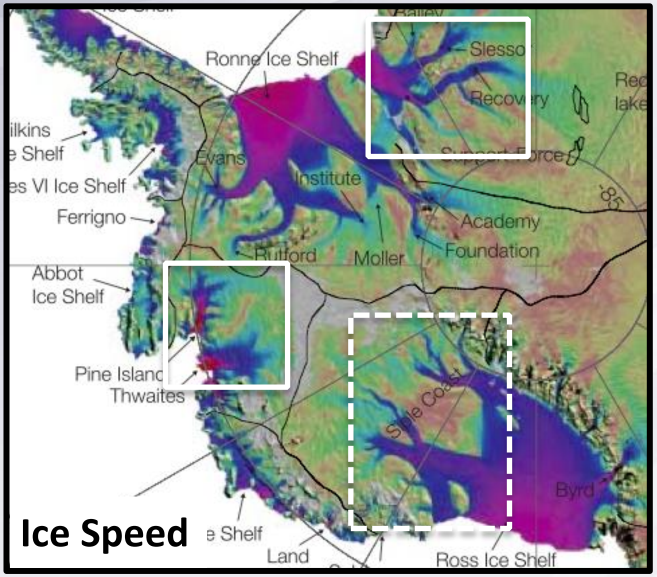
Discharge from ice sheets (solid & liquid) is becoming the dominant source of sea-level rise and impacts the ocean fresh water budget and water mass formation.

Ice sheet discharge depends strongly on:

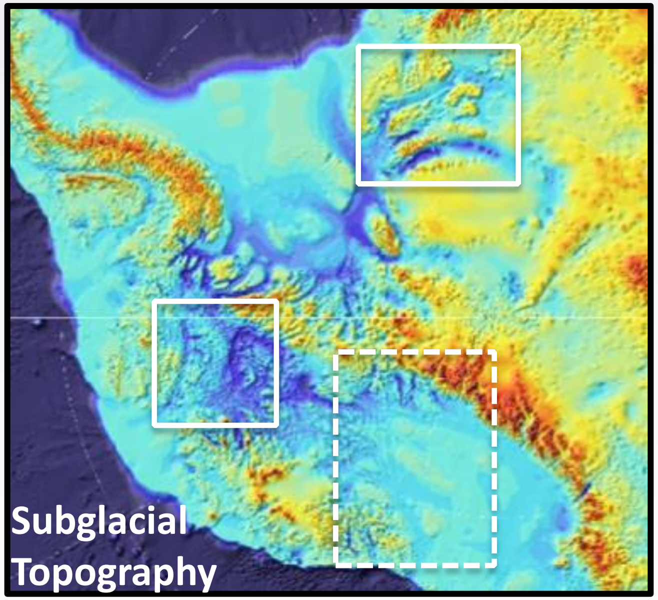
- subglacial topography (solid boxes at right)
- subglacial processes (dashed boxes at right)

Accurate modeling of ice sheet discharge requires:

- continued improvements in topographic mapping
- improved observations and models of subglacial processes (e.g., subglacial hydrology)
- improved treatments of ice sheet model initial conditions (e.g., spin-up vs. data assimilation)



Rignot et al., (*Science*, **333**, 2011)



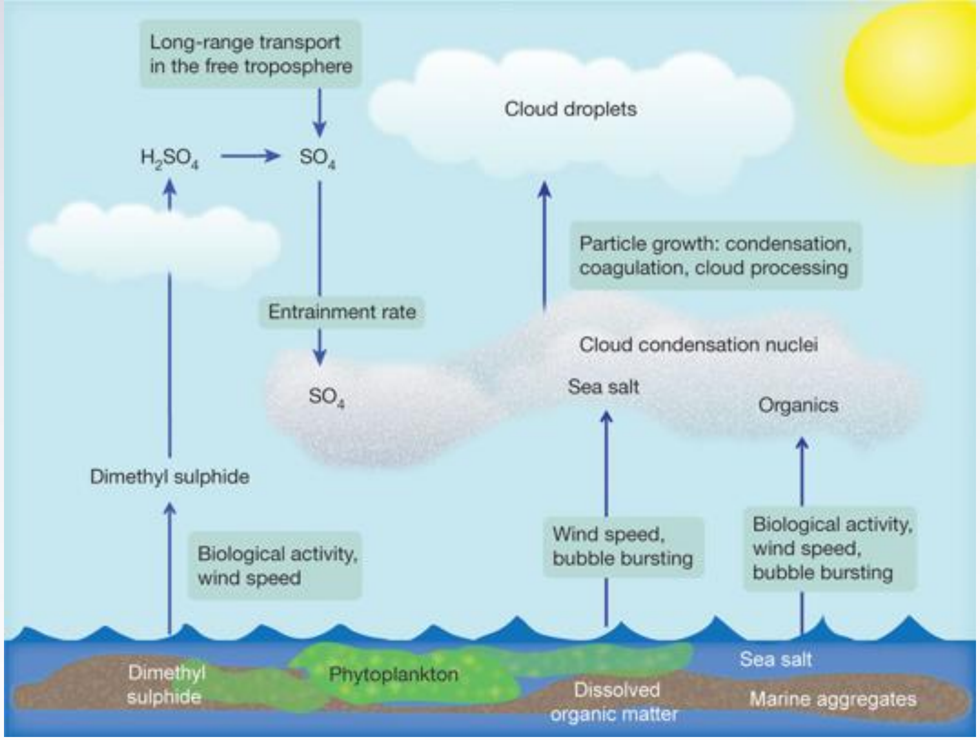
Fretwell et al., (*The Cryos.*, **7**, 2013)

CPT5: Marine Biogenic Aerosols and cloud effects

Away from land masses, especially above the Southern Ocean, marine biogenic aerosols are a major source of cloud condensation nuclei.

The biological and chemical sources and sinks for marine aerosols need to be tested in order to reduce uncertainties.

Effects of marine biogenic aerosols on cold cloud processes may be unique in SH



PK Quinn & TS Bates *Nature* **480**, 51-56 (2011) doi:10.1038/nature10580

DOE: Ocean Mixed-Layer Biases

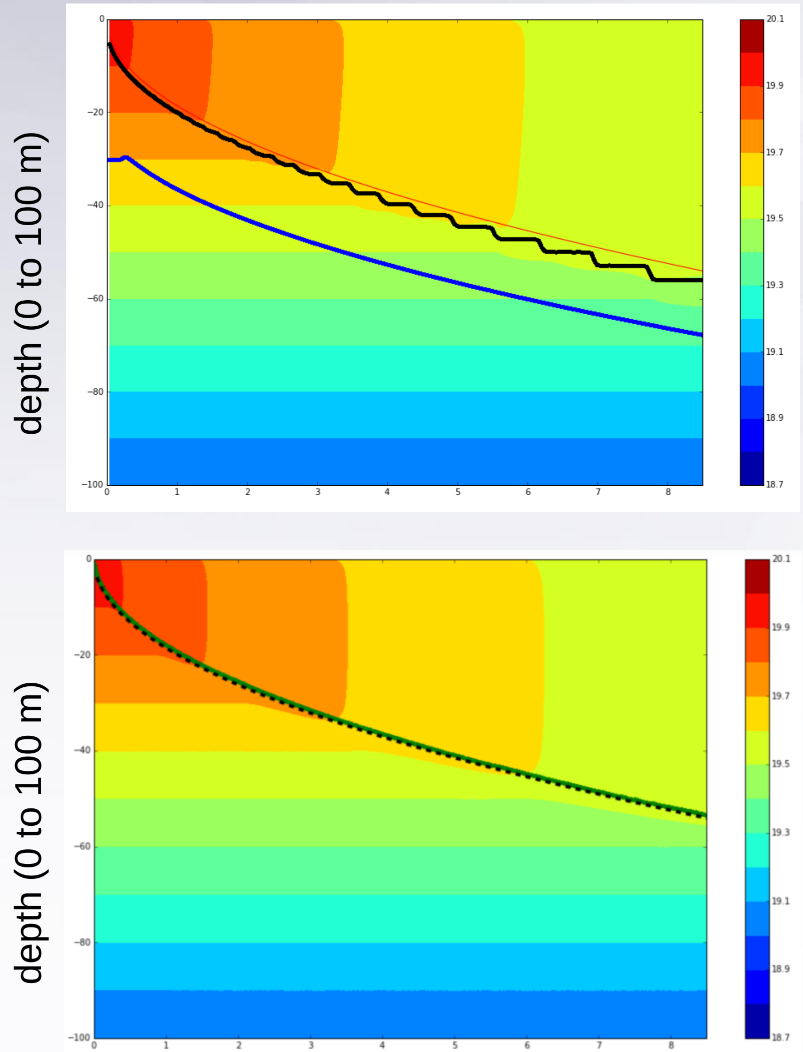
Mixed layer processes mediate the transport of heat, carbon and biogeochemical constituents across the ocean-atmosphere interface

Biases in seasonal and climatological mixed-layer depth are widespread.

NCAR and LANL are teaming to use LES and MPAS-O to understand and correct processes leading to the Southern Ocean mixed-layer biases.

Additional work within a CPT may be appropriate.

temperature
top: MPAS/KPP-CVMix
bottom: NCAR LES



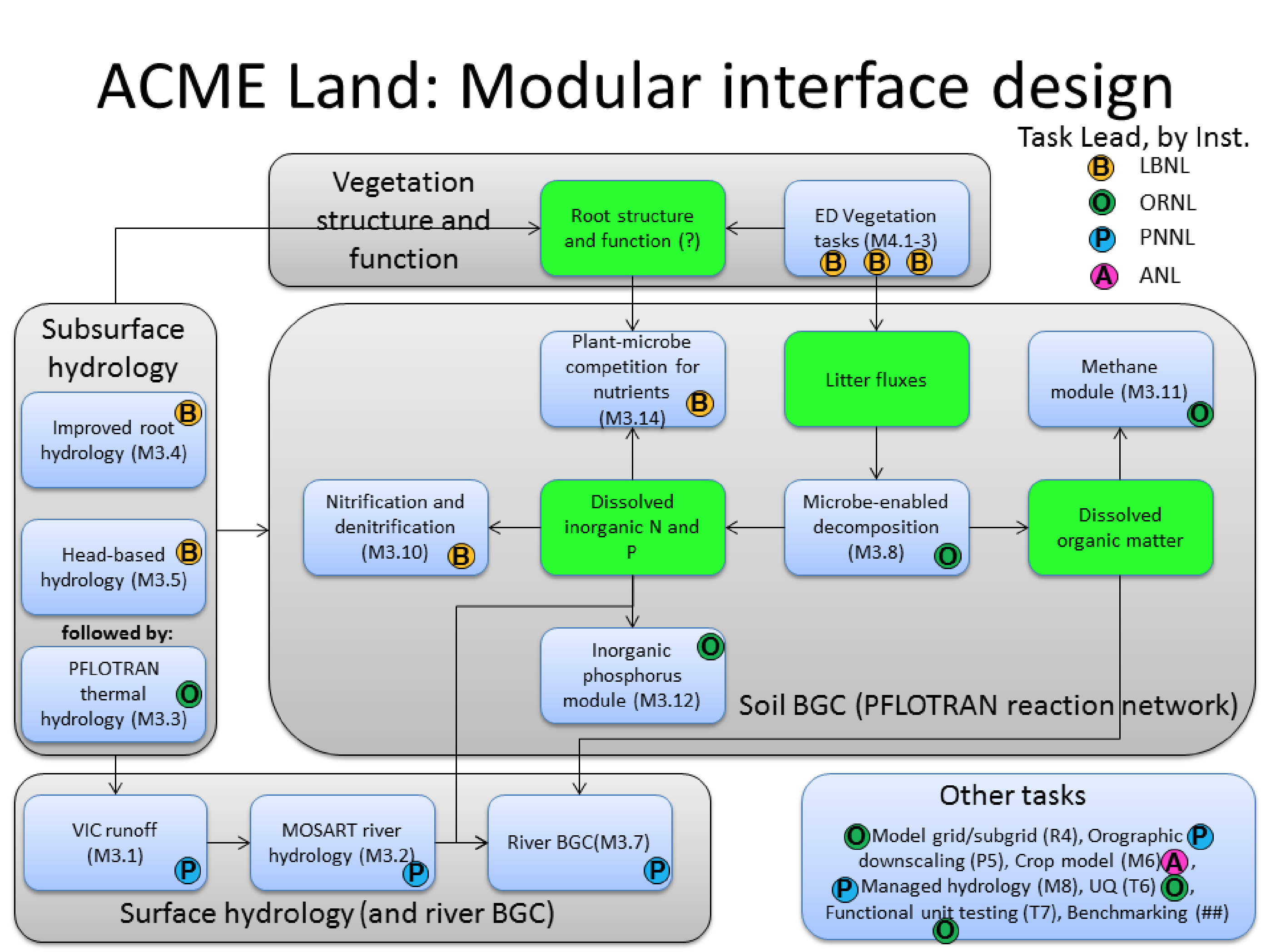
time (0 to 10 days)

Land

Developments
CPT ideas
DOE activities

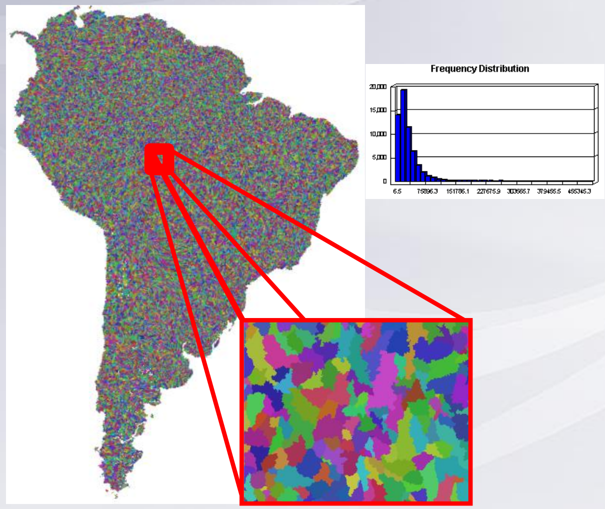
Overview of V1 & V2 ACME-LM (ALM) Development Activities

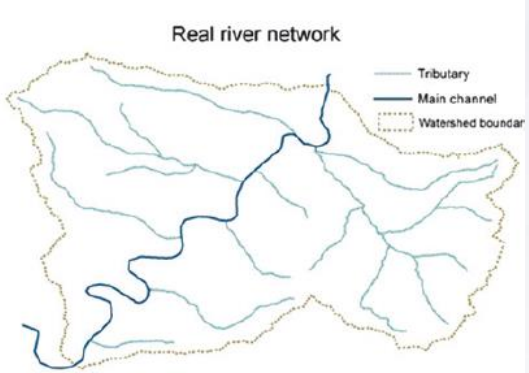
- Hydrology and thermal
- Soil BGC
- Plants



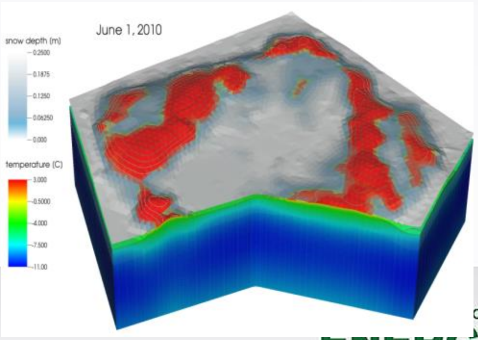
Hydrology and Thermal

- V1
  - Watershed delineation, topo-units
  - MOSART water (including inundation), temperature, and BGC
  - Variably Saturated Flow Model (VSFM)
  - Water management effects
- V2
  - PFLOTRAN (in 1D)
  - Explicit root and plant hydrology





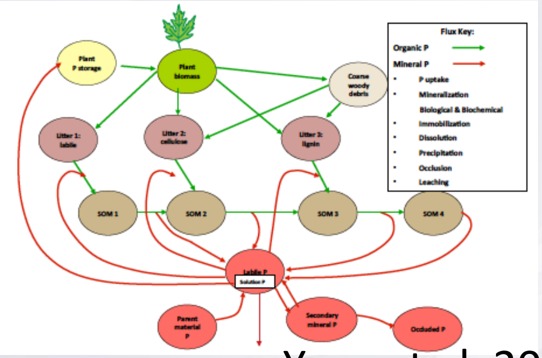
Li et al. (2013)



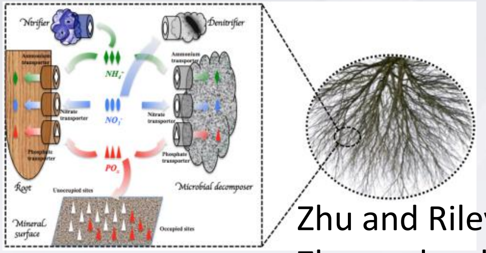
3-D thermal hydrology (Coon et al.)

Soil BGC

- V1
  - Representation of P dynamics (*2)
  - Competition representation for nutrients (N, P)
  - Dynamic allocation
  - Vertically-resolved reactive transport (BeTR), leaching
- V2
  - Explicit microbial processes, N cycle
    - PFLOTRAN

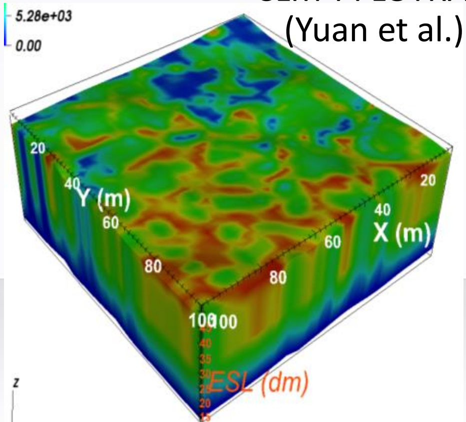


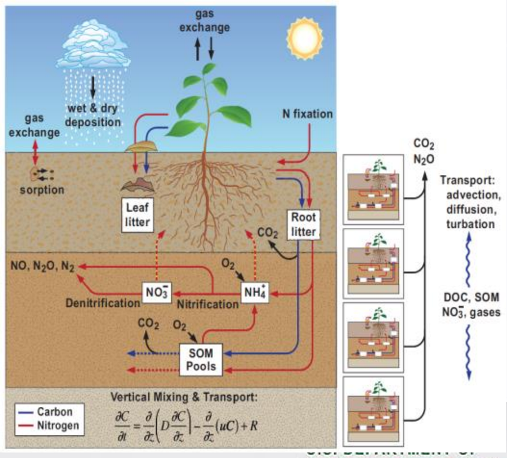
Yang et al. 2014



Zhu and Riley 2015; Zhu et al. sub.

CLM-PFLOTRAN (Yuan et al.)

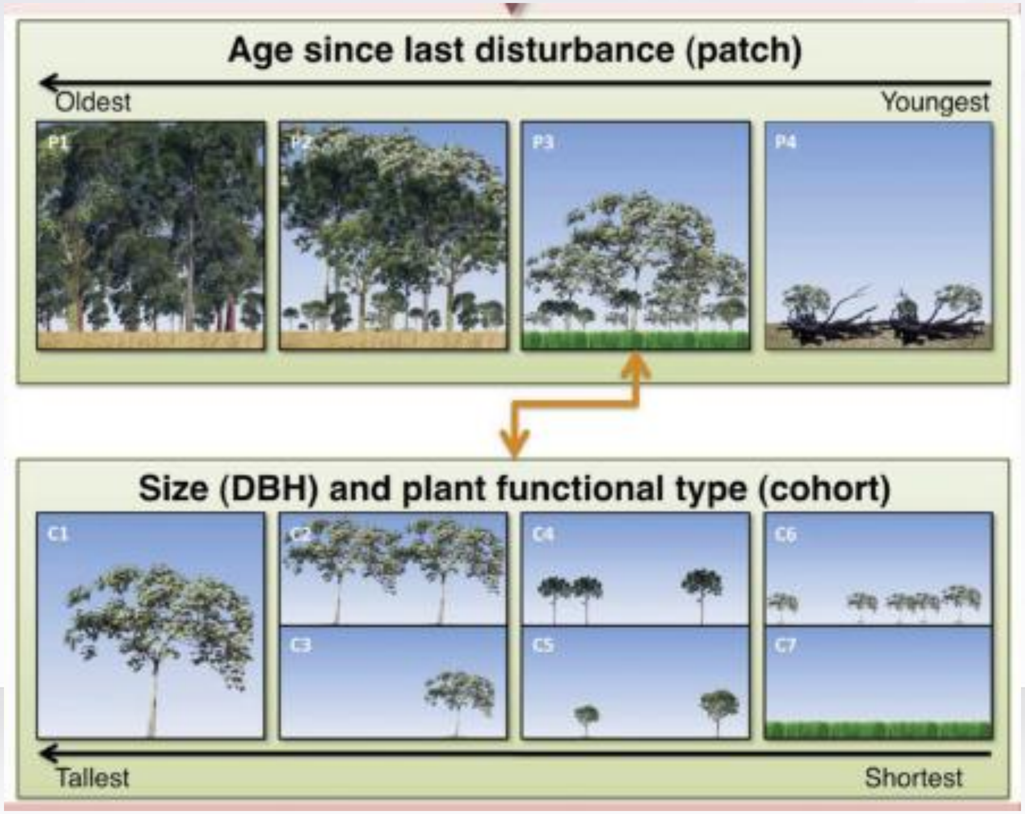




Tang et al. 2013

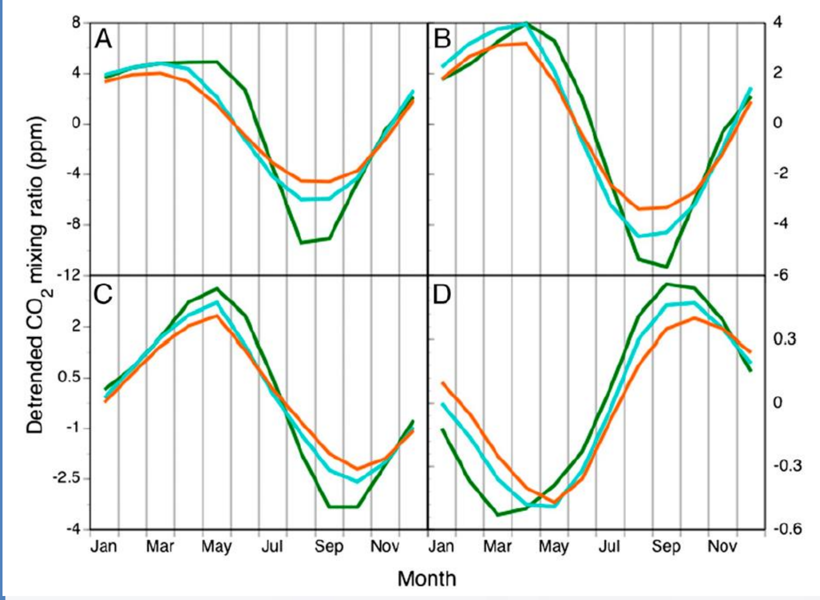
Vegetation

- V1
  - Root and leaf traits for nutrient acquisition and use
  - New Crops
- V2
  - ED model (Ecosystem Demography)
  - Coupling of soil BGC into ED



CPT- Land #1:Underpredicted seasonal cycle amplitude of $[CO_2]_{atm}$

- Common ESM bias: either low bias in NH photosynthesis or a high bias in NH summer ecosystem respiration
- Sensitive to controls on phenology, reflects uncertainty in carbon and nutrient allocation to storage pools.
- ACME-LM processes to address: plant storage pools for carbon and nutrients; plant traits; plant and microbe competition for soil minerals; microbial biomass pools and dynamics
- Large-scale (stand-level or larger) studies examining the mechanisms controlling carbon and nutrient storage at different points in the seasonal cycle, different stages of stand development, different nutrient limitation conditions



Example of how phenology of leaf traits directly influences seasonal cycle of atmospheric CO_2 at four sites: green=observed, orange=no phenology, cyan=with phenology. (From Bauerle et al., 2012)

CPT-Land #2 – Terrestrial-aquatic interfaces

Estuaries and coastal hydrology and biogeochemistry

- Motivation
  - Large carbon, N, and P fluxes from terrestrial systems to coastal margins, affect ocean BGC and net GHG exchanges
- New and planned ACME work
  - MOSART river hydrology (Li et al. 2013) and BGC
  - Land leaching improvements (Riley and Zhu 2015), integration of BeTR reactive transport to resolve fluxes into river (Tang et al. 2013; Tang et al. in prep)
  - Coupling MOSART biogeochemistry with BeTR land fluxes
- CPT on coastal margin BGC processes

CPT-Land #3: Agriculture modeling

Motivation

- Large N_2O and leaching sources, water use, soil C storage and net GHG exchanges, biofuels

New and planned ACME work

- Improvements to the crop model (Drewniak at ANL)
- BeTR reactive transport for leaching and vertically-resolved soil C transformations (Tang et al. 2013; Tang et al. in prep)
- Improvements to N and P cycling (Zhu and Riley 2015; Zhu et al. 2015; Zhu and Riley submitted; Yang et al.)

CPT to test

- Multi-nutrient, multi-consumer competition
- More crops and phenotypes
- Field-scale heterogeneity, connections to groundwater and rivers

DOE: NGEE – Arctic

Supported by DOE-TES program

Goal: Advance the predictive understanding of the structure and function of Arctic terrestrial ecosystems in response to climate change.

Objective: Develop a process-rich ecosystem model in which the evolution of *Arctic ecosystems* in a changing climate can be modeled at the scale of a high resolution Earth system model (ESM) grid cell (i.e., approximately 30x30 km grid size).

- Phase 1 (2012-2015) field and laboratory research and modeling focused on characterizing ice-wedge polygons, thaw lakes, and drained thaw lake basins in Barrow
- Phase 2 (2012-2015) Second site at Seward Peninsula that is more evolved to study transitional ecosystems, warm, discontinuous permafrost, higher annual precipitation, and well-defined watersheds with strong topographic gradients

Will coordinate with other activities such as NASA-ABOVE

Next-Generation Ecosystem Experiments: Arctic
Ecosystem Processes
Modeling, Prediction
Systems Understanding

ENERGY

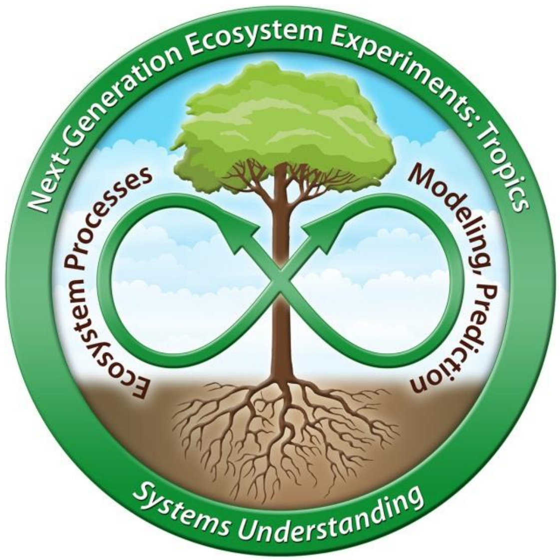
DOE: NGEE – Tropics

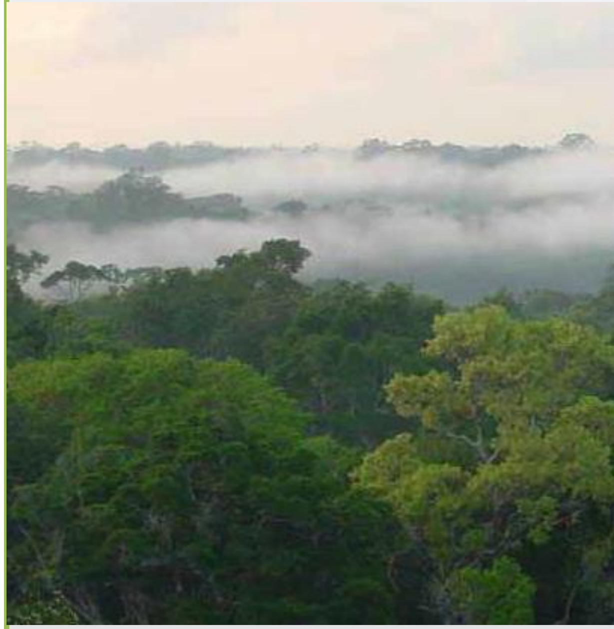
Supported by DOE-TES program

Goal: Improve our understanding of ecosystem-climate feedbacks due to changes in precipitation, temperature, nutrient cycling and disturbance in tropical forests.

NGEE-Tropics field activities organized around testbeds as a central organizing principle

- model informed field study that results in iterative refinement of high resolution predictive models.
- be based on field studies in the most climate sensitive tropical geographies that provides a high scientific return on investment.
- Manaus: coupled water and carbon cycles
- Puerto Rico: nutrients and secondary forest growth
- Panama: plant trait variation across precipitation gradient
- Pan-tropical: demography and functional trait variation across ForestGEO and GEM networks





ACME Information

http://climatemodeling.science.energy.gov/projects/accelerated-climate-modeling-energy