Introduction to the Community Earth System Model

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Evolution of climate modeling

Growth of Climate Modeling

- Atmospheric/Land Surface/Vegetation
- Ocean
- Coupled Climate Model
- Sea Ice
- Sulfate Aerosol
- Biogeochemical Cycles
- Carbon Cycle
- Ice Sheet
- Marine Ecosystems
- Upper Atmosphere
- Atmospheric Chemistry
- Dust/Sea Spray/Carbon Aerosols
- Interactive Vegetation

60s  70s  80s  90s  00s  10s
Carbon cycle in the Earth System

IPCC AR5 Ch.6
Processes in the CESM land model

- Human systems
- Urban
- Wood harvest
- River discharge
- Flooding
- Wetland
- River Routing
- Runoff
- Glacier
- Water systems
- CO2 BVOCs Soil NOx
- Disturbance
- Vegetation Dynamics
- Growth
- Ecosystem
- Land Use Change
- Irrigation
- Crops
- Biogeochemical cycles
- CH4
- Processes in the CESM land model
Current processes in CLM

**Surface energy fluxes**
- Radiation
  - Direct solar
  - Diffuse solar
- Reflected solar
- Absorbed solar
- Aerosol deposition

**Hydrology**
- Precipitation
- Momentum flux
  - Wind speed
  - Momentum
- Evaporation
- Transpiration
- Sublimation
- Evaporation
- Infiltration
- Surface runoff

**Soil**
- Saturated fraction
- Aquifer recharge
- Water table
- Unconfined aquifer

**Biogeochemical cycles**
- Photosynthesis
- BVOCs
- Heterotrophic respiration
- Autotrophic respiration
- N uptake
- N mineralization
- Denitrification
- N leaching
- CH₄
- N₂O

**Hydrology details**
- Surface energy fluxes:
  - Latent heat flux
  - Sensible heat flux
- Soil (sand, clay, organic)
- Bedrock

**Hydrology fluxes**
- Ground heat flux
- Surface energy fluxes:
  - Downwelling longwave
  - Emitted longwave
- Wind speed
- Momentum
- Radiation

**Surface water**
- Throughfall
- Infiltration
- Surface runoff
- Melt
- Sublimation

**Bedrock**
- Aquifer recharge
- Water table
- Sub-surface runoff

**Soil water**
- Saturated fraction
- Aquifer recharge
- Water table

**Unconfined aquifer**
- Surface runoff

**Processes in CLM**
- Radiation
- Heat
- Momentum
- Soil (sand, clay, organic)
- Bedrock
Current processes in CLM

Biogeochemical cycles

Photosynthesis
BVOCs
Fire
Autotrophic respiration

Vegetation C/N

Heterotrophic respiration

Litterfall

Root litter

Soil C/N

Denitrification

$\text{N}_2\text{O}$

$\text{CH}_4$

$\text{N}_{\text{dep}}$

$\text{N}_{\text{fix}}$

$\text{N}_{\text{uptake}}$

$\text{N}_{\text{leaching}}$

$\text{N}_{\text{mineralization}}$

Lamarque et al., 2013

$\text{mg}(\text{N})/\text{m}^2/\text{yr}$
Earth System Model

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

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60s  70s  80s  90s  00s  10s

Complexity
Resolution
Resources
Ensemble size

Initial condition uncertainty
Analysis
Time
Forecast uncertainty

Probability of precipitation (%)
Internal variability and ensemble

30 Runs
1920-2080

Same forcing
Same initial conditions except round-off error to initial air temps

Slide from C. Deser

Panels show 1979-2012 DJF surface temperature trends for 9 ensemble members, the ensemble mean, and observations.
BAMS Article:

The Community Earth System Model: A Framework for Collaborative Research


Figure courtesy of Steve Ghan and DOE Graphics team
How to build an improved model

- Model development
- Model evaluation
  - Provision of datasets
  - Provision of analysis tools (diagnostics)
- Simulation analysis
- Publish results from numerical experiments
CESM1 vs CMIP5 models

The deeper blue, the better the model is

IPCC AR5
Ch. 9
Others. Some models have evolved strongly from CMIP3 to CMIP5, whereas in other centers much of the effort has gone into additional components. Shared code or concepts may lead to similarity of the output, but the degree depends of course on what effect the shared code has on the simulated field and less on the amount of code. For example, a shared atmosphere produces more similarity than a shared ocean when looking at a precipitation field. Similarity may also arise from "fitting" to common data sets (see below). Shared code and data sets reduce the effective degrees of freedom in a multimodel ensemble. 

The detailed steps from one model version to the next are often not obvious. Exceptions are the MIROC model [Watanabe et al., 2012] and the evolution from the NCAR CCSM4 (CAM4) to CESM1 (CAM5), which is documented in detail by Gettelman et al. [2012] and illustrates steps between CESM with two different versions of the atmosphere model: CAM4 and CAM5. Gettelman et al. [2012] created an ensemble of different experiments to step from CAM4 to CAM5, by sequentially adding new microphysics (micro), macrophysics (macro), radiation (rad), aerosols (aero), planetary boundary layer (pbl), and finally the shallow convection scheme to reach CAM5 (all runs labeled CAM5). As discussed by Gettelman et al. [2012], the biggest change in climate sensitivity results from the change to the shallow convection scheme, which increases shortwave cloud feedbacks. As is clear from the tree shown in Figure 2a, the CAM5 experiments cluster together, with three single perturbation experiments similar to the base CAM5 experiment. The sequential changes between CAM4 and CAM5 also cluster together (with macro, rad, aero, and pbl added in that order). The micro1–3 series represent different tuning adjustments to get a better radiation balance (micro3 is in approximate balance). The same is true for the pbl1–2 experiments. Experiment CAM4_2 was run with different sea ice albedo specified at the surface, which may partially explain the separation. Thus, the CAM5 experiments cluster, and there is a break point in the differences. The perturbation experiments also cluster, with some of the single perturbation (tuning) experiments closest together. In general, the CAM models with the most similar physics packages cluster closest together. 

Normalized distance from observations for temperature and precipitation

(Knutti, Masson, Gettelman, GRL, 2013)
Impact of CLM4.5 model changes on historical global terrestrial carbon trajectory

In CLM4.5, land is a C sink over latter half of 20th C, as observed.
Model Development Process

- Model release (CESM1/CLM4)
- Detailed model assessment (identify strengths and weaknesses)
- LMWG members develop parameterizations or add features
- Present ideas/results at LMWG meetings
- Publish papers
- Evaluate competing parameterizations
- Plans for next (and next next) model version discussed at LMWG meetings
- Build and test beta version of offline model
- Finalize and test within CESM
- Use model for scientific studies
- Document; Control integrations; Model release (CESM2/CLM5)
- Observations
## Evolution of CAM

<table>
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<th>CAM4</th>
<th>CAM5.1 CESM1.0.3</th>
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- New parameterization/dynamics

[http://www.cesm.ucar.edu/working_groups/Atmosphere/development/cam6/CAM5.5_panel_rec_Jun15.pdf](http://www.cesm.ucar.edu/working_groups/Atmosphere/development/cam6/CAM5.5_panel_rec_Jun15.pdf)
[http://www.cesm.ucar.edu/working_groups/Atmosphere/development/cam6/cam5.5-process/](http://www.cesm.ucar.edu/working_groups/Atmosphere/development/cam6/cam5.5-process/)
Community Earth System Model v2

Forcings:
- Greenhouse gases
- Manmade aerosols
- Volcanic eruptions
- Solar variability

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Chemistry

Biogeochemistry
(Carbon-Nitrogen Cycles)

Biogeochemistry
(Marine ecosystems)

Land Ice

Atmosphere Model

Ice Sheet Model

Ocean Model

Climate Variability and Change

Paleo-Climate

Whole Atmosphere

Societal Dimensions

Software Engineering

Chemistry-Climate

Polar Climate

Land Model

http://www.cesm.ucar.edu/management
Some numbers on CESM

- 0.25°, 1°, 2° resolutions, +regional-refinement
- 30 minute time step (for 1° and 2°)
- 32 atmosphere levels (72 for WACCM)
- 60 ocean levels (0.1° or 1°)
- 25 ground layers
- ~5 million grid boxes at 1° resolution
- >1.5 million lines of computer code
- Data archived (monthly, daily, hourly) for hundreds of geophysical fields
- Utilized by hundreds of scientists all around the world
CESM supports a range of climate science goals through a *Single Model Code Base*.

- **Desktop**: Single column / Coarse resolution: Physics development
- **Small cluster**: Lower resolution: Paleo/Large Ensemble University research
- **HPC**: Higher resolution: CMIP Breakthrough ASD

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Graphical representations of precipitation rate and model outputs are shown for each computing level.
STATUS OF CESM2
Current status

- CESM2- (new or significantly updated component)
  - Atmosphere: CAM6 (WACCM and chemistry)
  - Land: CLM5 (incl. MOSART)
  - Sea-ice: CICE5
  - Land-ice: CISM2
  - Ocean: POP2 with improved mixing and BGC
  - Infrastructure: CIME

- Many (many!) stand-alone and coupled simulations (mostly 1850 control) started in November 2015
  - http://www.cesm.ucar.edu/working_groups/Atmosphere/development/cesm1_5/ (password protected)
  - Significant optimization (in collaboration with CISL) to get approx. 20 simulated years per day for CESM2 with 1-degree resolution and 32 levels (on Yellowstone)
CESM2: 20th century smoke test (Feb. 2017)

125 configuration provides a reasonable simulation of the 20th century TS evolution.
Changes beyond simulation #125 (slide from Feb 2017)

• Results from CESM2 simulation #125 released to community February 9. Results shown here come mostly from that configuration

• Changes for final version:
  – Subgrid topography representation around Greenland (different scale due to very strong winds)
  – Caspian sea: from ocean model to land model (lake)
  – Update to land vegetation parameters (little climate impact expected, mostly for carbon-cycle improvements)
  – CMIP6 emissions
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CMIP5 vs CMIP6 emissions: global TS
APPLICATIONS
Stratospheric dynamics
CESM2 Regional refinement

Regional-refinement in CAM6 (AMIP) with the Spectral Element (SE) and MPAS dynamical cores (effort led by A. Gettelman and C. Zarzycki)

Precipitable water Sept 23-Oct 3, 111 km -> 14 km

Slide from C. Zarzycki
Questions? Comments?

Movie from M. Long and T. Scheitlin
Questions?
Comments?