The Community Earth System Model (CESM)

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with thanks to Jim Hurrell and Peter Gent

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What is the Community Earth System Model (CESM) Project?

- Project to develop and utilize a comprehensive model to:
  - Investigate and predict seasonal and interannual variability in the climate
  - Explore the history of Earth’s climate
  - Estimate future of environment for policy formulation
- Collaborations are critical:
  - Developed jointly by NCAR, National Labs and Universities
- Provide support for climate modeling:
  - fully documented and freely available model (portable)
  - model data
  - training
Why so much effort to keep improving our collective ability to model Earth’s climate?

“Prediction is [very] difficult, especially of the future” (Niels Bohr)
Community Earth System Model (CESM1)

Core is a Coupled Ocean-Atmosphere-Land-Sea Ice model (CCSM4)

- 0.5°, 1°, 2°, T31 resolutions
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~5 million grid boxes at 1°
- ~1.5 million lines of computer code
- Archive data (monthly, daily, hourly) for hundreds of geophysical fields (over 250 in land model alone)
CCSM4: 1° resolution; $T_{surf}$, clouds, P

animation courtesy ETH Zurich
History of Climate Model to Earth System Model Development

http://www.aip.org/history/climate/GCM.htm

Mid-1960s: Atmosphere/Land Surface/Vegetation
- Ocean
- Sea Ice
- Coupled Climate Model

Mid-1970s-1980s: Atmosphere/Land Surface/Vegetation
- Ocean
- Sea Ice
- Coupled Climate Model

1990s: Atmosphere/Land Surface/Vegetation
- Ocean
- Sea Ice
- Sulfate Aerosol
- Carbon Cycle
- Dust/Sea Spray/Carbon Aerosols
- Interactive Vegetation
- Biogeochemical Cycles

2000s: Atmosphere/Land Surface/Vegetation
- Ocean
- Sea Ice
- Sulfate Aerosol
- Carbon Cycle
- Dust/Sea Spray/Carbon Aerosols
- Interactive Vegetation
- Biogeochemical Cycles

2010: Atmosphere/Land Surface/Vegetation
- Ocean
- Sea Ice
- Sulfate Aerosol
- Carbon Cycle
- Dust/Sea Spray/Carbon Aerosols
- Interactive Vegetation
- Biogeochemical Cycles
- Ice Sheet

Individual PIs

Small Teams

Large Teams

Distributed, Interdisciplinary, Interagency Teams
Configuration of CCSM4

- **Atmosphere**: CAM 4
- **Land**: CLM 4
- **Coupler**: CPL 7
- **Sea Ice**: CICE 4
- **Ocean**: POP 2

The diagram illustrates the configuration of the Community Climate System Model (CCSM4), showing the interconnections between the atmosphere, land, coupler, sea ice, and ocean components.
CESM1 (Coupled modeling framework)

Atmosphere
CAM 4, CAM5, WACCM,
Fast Chem, Full Chem

Land
CLM 4
SP, CN, CNDV

Coupler
CPL 7

Sea Ice
CICE 4

Land ice
CISM

Ocean
POP 2
Ecosys
CESM1 (Coupled modeling framework)

- Atmosphere:
  - CAM 4, CAM5, WACCM, Fast Chem, Full Chem

- Land:
  - CLM 4
  - SP, CN, CNDV

- Land ice:
  - CISM

- Coupler:
  - CPL 7

- Sea Ice:
  - CSIM 4

- Ocean:
  - POP 2
  - Ecosys
CESM Structure

- CESM Advisory Board
- CESM Scientific Steering Committee
- CESM Management
- Working Groups
  - Development
  - Application
- Atm Model
- Ocean Model
- Land Model
- Polar Climate
- BioGeo Chem
- Chem-Climate
- WACCM
- Land Ice

CCSM is primarily sponsored by the National Science Foundation and the Department of Energy.
CESM: A Community Resource

Model data: Over 3,000 sites from 130+ countries
> 230 Tb since 2005
Model code: Over 1100 downloads since April 2010

Courtesy Gary Strand
CMIP-5 Simulations

• CESM and partners will make a major contribution to IPCC AR5 through simulations performed with CCSM4.0 and CESM1.0

• CMIP-5 Experimental Design (Taylor et al. 2009):
  A set of coordinated climate model experiments to:
  ✓ address outstanding scientific questions from AR4
  ✓ improve understanding of climate variability/change
  ✓ provide estimates of future climate change useful to those considering its possible consequences

• CMIP-5 is a 5-year experimental design, but a significant fraction of the experiments will be done in time to be included in AR5
  ✓ Initialized decadal prediction and long-term climate change
  ✓ Includes carbon cycle, paleoclimate, whole atmosphere, and land ice
CMIP5 Long-term Climate Change Experiments

- All Core + Most Tier completed at NCAR (> 11M GAU used) (~500 Tb history output)
- Began in Sept 2009
- Experiments with:
  - CAM4
  - CAM5
  - CAM-CHEM
  - WACCM
- 1,000 yr controls
- Ensembles:
  - Historical
  - RCPs
- High-frequency output
  - Control
  - Historical
  - RCPs
Have GCMs actually been getting any better?

Reichler et al., 2008, BAMS
Selected Results

• Pre-industrial controls (CCSM4 and CESM1)
  ✓ 1850 conditions, multi-century, mostly 1° resolution
  ✓ some comparisons to 1870 CCSM3 (T85)

• 20th century transient simulations
  ✓ 1850-2005, some ensembles, mostly 1° resolution
  ✓ some comparisons to CCSM3 (1870-1999; T85)

• Observations (best available, common periods)

• Mean and Variability

• Good and Bad

• Details and more results in CCSM4 and CESM1
  Journal of Climate Special Collections (~65 papers)
SST Biases

CCSM3 (Pre-Industrial)
- Mean = -0.76°C
- RMS = 1.57°C

CCSM4 (2°)
- Mean = 0.30°C
- RMS = 1.46°C

CCSM4 (1°)
- Mean = 0.07°C
- RMS = 1.11°C

Overall reduction SST bias, all basins
Equatorial Pacific SST
(Late 20th Century)
Equatorial Pacific SST
(Late 20th Century)
Incoming Shortwave Radiation
(Differences from SHEBA Observations)

CCSM3 (1980-1999)
* SHEBA Observations

CCSM3 bias compensated by unrealistically low ice albedos
Antarctic sea ice cover
(Late 20th Century)

CCSM4

JAS

JFM

Too extensive, similar to CCSM3
Land water storage (MAM-SON)

GRACE satellite measures small changes in gravity which on seasonal timescales are due to variations in mean soil and snow water content. CLM4 has improved capacity to store water from one season to the next.
Land surface temperature (annual)

(Differences from Observations: 1950-99)

\( T_{\text{air}} \) RMSE: CCSM3
3.01°C

\( T_{\text{air}} \) RMSE: CCSM4
2.71°C

\( T_{\text{air}} \) RMSE: CCSM4 vs CCSM3
27.1% (+) 12.9% (–)

\( T_{\text{air}} \) ANN Mean Bias: CCSM3
-0.28°C

\( T_{\text{air}} \) ANN Mean Bias: CCSM4
-0.17°C

\( T_{\text{air}} \) ANN Mean Bias: CCSM4 vs CCSM3
27.7% (+) 28.3% (–)
Total Precipitation (Annual)

CCSM4 (1 deg)

Average = 2.96  Min. = 0.06  Max. = 20.34

CCSM4 (2 deg)

Average = 2.89  Min. = 0.05  Max. = 13.92

Observed

Average = 2.69  Min. = 0.03  Max. = 11.39

CCSM3 (T85)

Average = 2.80  Min. = 0.01  Max. = 13.80

mm/day
Total Precipitation Difference (Annual)

Ave. = 0.20  RMSE = 1.27  Min. = -5.65  Max. = 6.30

Ave. = 0.11  RMSE = 1.29  Min. = -6.57  Max. = 7.28
Total Precipitation Difference (Annual)

CCSM4 (1 deg)
Ave. = 0.28  RMSE = 1.10  Min. = -6.24  Max. = 9.94

CCSM4 (2 deg)
Ave. = 0.20  RMSE = 1.27  Min. = -5.65  Max. = 6.30

CCSM3 (T85)
Ave. = 0.11  RMSE = 1.29  Min. = -6.57  Max. = 7.28

-8 -6 -4 -3 -2 -1 -0.5 0 0.5 1 2 3 4 6 8 mm/day
Total Precipitation Difference (Annual)
Tropical Land Precipitation
(Frequency of Daily Rate)

CCSM3: too few strong rainfall events

CCSM4: more realistic extremes
High Latitude SLP (DJF)

- Observed
- CCSM3
- CCSM4

Systematic Reduction in North Atlantic and North Pacific biases
High Latitude SLP (DJF)

Observed

CCSM3

Systematic Reduction in North Atlantic and North Pacific biases

CESM (CAM5)
Variability
Leading Mode of Global SST Variability

**Observations**

- a) Global SST Variability map (°C SD⁻¹)
- b) Time series of SST anomalies
- c) Power spectrum of SST anomalies

**CCSM3**

- a) Global SST Variability map (°C SD⁻¹)
- b) Time series of SST anomalies
- c) Power spectrum of SST anomalies

**Period (years)**

- Frequency (cycles/month)

- Power (°C²)
Leading Mode of Global SST Variability

Observations

CCSM4
North Atlantic Variability

Observations

CCSM4

NAO
Intraseasonal Variability

Lag correlation of 20-100 day band pass filtered precipitation and 850-mb zonal wind

Observed
(GPCP,ERA40)

CCSM4

CCSM3 (T85)
20th Century and Future Climate
Global Temperature
(1850-2005)

- CCSM4.0: 1.2°C
- CESM1.0 (WACCM): 0.8°C
- Observations

Timeline: 1880 to 2000
Equilibrium Climate Sensitivity

3.20°C in CCSM4 at 1°; 2.86°C in CCSM3 at T85

Due primarily to decline in negative lapse-rate feedback and an increase in positive shortwave cloud feedback.
Representative Concentration Pathways (RCP)
Simulation of the 20th and 21st Centuries

Annual Global Mean Surface T (°C)
(anomaly from 1980-99)

RCP8.5
RCP6.0
RCP4.5
RCP2.6
20th Century

20C 005
20C 006
20th Century Surface Temperature Change

Ave. = 0.73

CCSM4 (1 deg)

Ave. = 0.72

CCSM4 (2 deg)

Ave. = 0.48

OBSERVATIONS

Warming too strong in CCSM4.0
Projected # of Days of Extreme Heat (RCP8.5)

Peacock, 2011
September Arctic Sea Ice Extent

<table>
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<tr>
<th>Year</th>
<th>SSM/I Observations</th>
<th>1979-2005 Trend (10^6 km² per decade)</th>
<th>1979-2005 Std Dev (10^6 km²)</th>
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<tr>
<td>2000</td>
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Seasonally Frozen Ground


CCSM4_RCP8.5 (2080-2099)

CCSM4_RCP2.6 (2080-2099)
Earth System Model
Features of CESM1
Anthropogenic Aerosol Affects: CESM1 (CAM5)  
(late 20th century relative to pre-industrial climate)

- Increased aerosol burdens in SE Asia, Europe, NE North America, Brazil
- Increased cloud droplet number concentration; strongest over land
- Increased numbers of smaller drops; thus brighter low clouds with more liquid

Low cloud affects: net cooling over 20th century
20th Century Surface Temperature Change

Ave. = 0.48

weaker warming in CESM1.0 (CAM5) –
Note preliminary version of CAM5
New Capability: Urban Modeling

- CLM4 includes a representation of urban processes; global simulation of urban environments incl. T of cities.

- The UHI describes the fact that urban areas are generally warmer than surrounding rural areas.

- More directly evaluate projected changes in urban heat stress

CESM1.0 (BGC) Simulations

Surface CO₂ Concentration

Cumulative CO₂ Surface Flux

Fossil Fuel Emissions
Net
Ocean
Land (No LCLUC)
Land

OBS

500+ yr Pre-industrial Control

1850-2005
Paleoclimate: Late Permian continents

The map shows the Pangea supercontinent and the Panthalassic Ocean, with the continents in their Late Permian configuration.
Simulation with CCSM3: Ocean barotropic streamfunction (Kiehl and Shields, 2005)
An ice sheet model in CESM

• Community Ice Sheet Model (Glimmer-CISM)
  • Currently Glimmer-CISM 1.6 (shallow-ice dynamics)
  • Glimmer-CISM 2.0 (higher-order dynamics) to be added soon
  • Greenland grids at 5, 10, and 20 km are supported.

• CESM also includes a new surface mass balance scheme for ice sheets in CLM.
  • The surface mass balance is computed on the global land grid, then sent to Glimmer-CISM and downscaled to the local ice sheet grid.

Left: Greenland SMB from CESM: CLM on 1° grid forced by CAM output, downscaled to 10-km ice sheet grid

Right: Greenland SMB from high-resolution regional climate model (RACMO; Ettema et al. 2009)

Red = net accumulation
Blue = net ablation
Superfast Chemistry in CESM
Final Thoughts
Some Upcoming Challenges

- Incorporation of vast array of new capabilities and parameterizations provided by the community (e.g., isotopes, super-parameterization – embedded cloud resolving model, global methane cycle, …)
- Regional refined grids (NRCM and static regionally refined meshes)
- Extending data assimilation capability
- Incorporation of hooks for human dimensions
- Improved validation metrics, benchmarking
- Post-processing – data management
Thanks and Get Involved!

- CESM Workshop every June in Breckenridge
- Working group meetings in Winter every year
  - Model development discussions
- Download and analyze CESM output
  - CCSM4 CMIP5 data will be posted to Earth System Grid ~May 25
- Download and run the model and do great science with it!
- Sign up for CESM and/or Working group email lists (see www.cesm.ucar.edu)
CSM 1 was the first climate model to produce a non-drifting control run without “flux corrections”
Decadal Forecasts

• For forecasts need to initialize the ocean component.

• Use an ocean and sea ice hindcast from 1950 – 2005 forced by best estimate of atm forcing from reanalysis.

• Run ocean component alone forced by atm reanalysis, but assimilating ocean temp and salinity observations.

• This is new, and more deep ocean obs after ~2003 from ARGO floats trying to initialize N Atlantic MOC.
Atlantic MOC in CCSM4
(Late 20th Century)

No Overflows

With Overflows

CCSM3

Sv

mean = 1.41°C
rms = 1.49°C

mean = 1.07°C
rms = 1.18°C

T (2649 m)
Land ice sheet model development

A CESM release later in 2010 will include Glimmer-CISM 2.0, with “higher-order” ice dynamics valid in all parts of an ice sheet (including ice streams, ice shelves).

Left: Greenland surface velocities (on a log scale) from a higher-order version of Glimmer-CISM

Right: Target velocities based on observations

Red = fast (~3 km/yr)
Blue = slow (~30 m/yr)
Initialized (Decadal) Predictions with CCSM4

North Atlantic SST RMS Error (North of 30°N)

Persistence of large-scale SST bias reduction

Steve Yeager et al. (2010)