Introduction to the Community Earth System Model

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CESM Chief Scientist
Purpose of Earth System Modeling

- To provide scientific understanding of observed climate change (historical, paleo)
- To simulate future climate change and its impacts
- Builds on our process understanding from observations and highly-detailed models (large-eddy simulations, chemical master mechanism, …)

High-resolution (25 km atmosphere, 0.1° ocean) coupled simulation captures short-term variability (hurricanes) and seasonal variations (sea-ice)

From J. Small
CESM Project

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
A truly global community

Locations of released version downloads since 2010
Community Earth System Model

- 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

(NOAA)
Current structure of CESM

Forcings:
- Greenhouse gases
- Manmade aerosols
- Volcanic eruptions
- Solar variability
- Land-use change

CESM contains a hierarchy of models that can be configured for specific scientific explorations: single column, aquaplanet, dynamical cores, ocean-only, …
Community Earth System Model (CESM1)

- 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

CESM2 will be released in December 2016
Science Highlights
Mechanisms of Climate Variations on Decadal to Century timescale

Figure courtesy of Steve Ghan and DOE Graphics team

BAMS Article:
The Community Earth System Model: A Framework for Collaborative Research
Internal variability and ensemble

40+ runs
1920-2100

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

Slide from C. Deser
Internal variability and ensemble

From J. Kay and C. Deser

Slide from C. Deser
Internal variability and ensemble

Panels show 1979-2012 DJF surface temperature trends for 9 ensemble members, the ensemble mean, and observations.
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)
Carbon cycle in the Earth System

Atmosphere: 589 ± 240 (average atmospheric increase: 4 (PgC yr⁻¹))

Net ocean flux: 2.3 ± 0.7

Ocean-atmosphere gas exchange: 80 ± 20

Net land flux: 2.6 ± 1.2

Freshwater outgassing: 10

Volcanism: 0.1

Rock weathering: 0.3

Wet deposition: 0.7

Net land use change: 1.1 ± 0.8

Gross photosynthesis: 123 ± 108.9 + 14.1

Total respiration and fire: 118.7 ± 107.2 + 11.6

Export from soils to rivers: 1.7

Export from vegetation to soils: 0.7

CO₂ storage in ocean sediments: 1.750

Fossil fuel reserves: Gas: 383-1135, Oil: 173-264, Coal: 446-541

Fossil fuel reserves: Gas: 0.365 ± 0.3

Units: Fluxes: (PgC yr⁻¹), Stocks: (PgC)

IPCC AR5 Ch.6
Timescales in carbon pools

Atmosphere

Volcanism

Weathering

Gas exchange

Surface ocean from 1-10 yrs

Deep sea from 100-2000 yrs

Sediments >10,000 yrs

IPCC AR5 Ch.6

Fossil fuel emissions

Respiration

Photosynthesis from 1-100 yrs

Vegetation from 10-500 yrs

Soils

Rocks Earth crust

Fossil fuel reserves

CESM Tutorial August 2016

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Processes in the CESM land model

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

Biogeochemical cycles

Photosynthesis

BVOCs

Fire

Autotrophic respiration

Litterfall

Heterotrophic respiration

Root litter

N mineralization

N uptake

Denitrification

N leaching

Vegetation C/N

N dep

N fix

Vegetation C/N

mg(N)/m²/yr

Lamarque et al., 2013

Radiation

Heat

Momentum

Surface energy fluxes

Soil (sand, clay, organic)

Dust

SCF

Surface water

Bedrock

Evaporation

Melt

Sublimation

Throughfall

Infiltration

Surface runoff

Sub-surface runoff

Aquifer recharge

Water table

Unconfined

Ground heat flux

Sensible heat flux

Latent heat flux

Wind speed

u₀

Momentum flux

Current processes in CLM

CESM Tutorial August 2016

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$\text{CO}_2$ over historical period in CESM1

Mauna Loa

Keppel-Aleks et al., 2013
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
BRACE: Benefits of Reduced Anthropogenic Climate Change

- Explore differences in physical and societal impacts between RCP8.5 and RCP4.5 using CESM ensembles
- 21 papers, special issue of *Climatic Change* (in progress)
- 50+ participants, from NCAR and 18 other institutions

Avoided Impacts

- Health
- Ag. and Land use
- Heat extremes
- Tropical cyclones
- Drought
- Sea-level rise
Decadal prediction

Predicted rate of global warming from 2013 initial year greater than during early-2000s slowdown and greater than uninitialized:

Observed 2001-2014: 
+0.08±0.05°C/decade

Predicted 2013-2022: 
+0.22±0.13°C/decade

Uninitialized 2013-2022: 
+0.14±0.12°C/decade

(Meehl et al., 2016, Nature Communications)
With funding from DOE RGCM program
ROAD TO CESM2
Where we were in Feb. 2016

• 4-day all-WGs meeting in Boulder
• Had generated 100+ year control and 20th century simulation w/ intermediate configurations
• Identified 3 main areas of strong concern
  – > Amazon precipitation
  – > Surface wind over ice sheet
  – > Arctic ocean warming at depth
Amazon problem
Parameter and physics exploration – Amazon DJF Rainfall

Amazon - (15S-5N; 290W-310E)

- PRECT (TRMM) - mm/day
- TREFHT (LEGATES) - K

mm/day

- Observed
- CESM1.5 (79)
- CESM1.5 (66)
- CESM1.5 (41)
- CESM1.5 (28)
- CESM1 (LENS)
Reduced surface biases for ice sheets

- CESM2 can now generate a realistic surface mass balance for either Greenland or Antarctica.
  - However, surface melting is sensitive to snow physics. Still working on uniform physics that gives good results for both ice sheets.
- Surface winds over both ice sheets are much improved.
- CAM still generates too much liquid precipitation in cold regions.

10 m wind speed (m/s) over the Greenland ice sheet.

Left: Run 36, with turbulent mountain stress.

Right: Run 79, with Beljaars form drag.

Far right: RACMO2.3 regional model.
Prognostic stratospheric aerosols with volcanic SO$_2$ database match lidar observations much better than existing climatologies.
Overall score

ANN: SPACE–TIME

Reference Grids Used

Black: Large Ensemble
Red: CESM2

RMSE Bias
- 1.00 1.00
- 0.86 0.72

0 = Sea Level Pressure (ERAi)
1 = SW Cloud Forcing (CERES–EBAF)
2 = LW Cloud Forcing (CERES–EBAF)
3 = Land Rainfall (30N–30S, GPCP)
4 = Ocean Rainfall (30N–30S, GPCP)
5 = Land 2–m Temperature (Wilmott)
6 = Pacific Surface Stress (5N–5S,ERS)
7 = Zonal Wind (300mb, ERAi)
8 = Relative Humidity (ERAi)
9 = Temperature (ERAi)
Where we are now:

• Nearing completion of ALL components
• Targeted coupled issues identified in Feb.
✓ CESM2 is improved over LENS
• Additional work going on
  ➢ Secondary-organic aerosols
  ➢ Land optimization
Amazonia Latent Heat Climatology

- **Optimal (predicted)**
- **Default**
- **Observations (FLUXNET)**

Latent Heat (Wm$^{-2}$)

J F M A M J

LHflx change from default (Wm$^{-2}$)

- **High**
- **Low**

CLM5 parameters:

- **cn_s1**
- **cn_s2**
- **minpsi_hr**
- **k_nitr_max**
- **FUN_fracfixers**
- **leafcn**
- **froot_leaf**
- **grperc**
- **Latent Heat (Wm$^{-2}$)**
- **mbbopt**
- **ekn_active**
- **denitrif_respiration_coefficient**
- **denitrif_respiration_exponent**
- **pot_hmn_ign_counts_alpha**
- **upplim_destruct_metamorph**
- **r_mort**
- **slatop**
- **baseflow_scalar**

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  - Secondary-organic aerosols
  - Land optimization
  - Performance optimization (20+ sYPD!)
  - …
Sea-ice issue in very recent experiments
Timeline until release

- **Feb 2016**
  - WG meetings
  - All WGs define
    - final additions
    - timeline

- **Mar. 1 2016**
  - CESM2 Sessions at Breckenridge

- **June 2016**
  - Definition of CESM2

- **Jul. 1 2016**
  - Code Freeze
  - Code available through developers’ access
  - Document impacts in coupled simulations

- **Sep. 1 2016**
  - CESM2.0 Release
    - Full release, incl. WACCMX and simpler models
    - CMIP6 1°

- **Dec 2016**
  - Start CMIP6 simulations
CESM Model 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

• Bulletin board (DiscussCESM Forum) for updates on releases and other model support – encourage subscription
Future Directions and Remaining Challenges

A need for continued scientific understanding and model improvements
Investigation of small-scale phenomena
Incorporation of New Capabilities
Bias Example: Southern Ocean Ventilation

Comparisons of simulated and observed ocean CFCs Indicate too little Southern Ocean uptake Has implications for simulated ocean heat and carbon uptake

CESM1-CAM5 20th Century Simulation

Courtesy of Matt Long
Air-sea exchange of CO$_2$

Air-sea exchange:

\[ J_{CO_2} = (1 - A_{ice}) \kappa \alpha (pCO_2^{sw} - pCO_2^{atm}) \]
\[ = (1 - A_{ice}) \kappa \alpha \Delta pCO_2 \]

where

\( k \) = piston velocity (empirical), and
\( \alpha \) = solubility, \( f(T, S) \)

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Slide courtesy of M. Long
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.

Recruitment → Growth → Competition → Coexistence → Exclusion → Mortality
High resolution: Regionally refined grids

- 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
- Challenges: Streamlining generation of new grids; Ensuring that physics parameterizations work across resolutions

Slide from Colin Zarzycki
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

NCAR is sponsored by the National Science Foundation
Questions? Comments?

Purple: precipitation

Slide courtesy of R. Knutti and O. Stebler