Benefits and Challenges of High-Resolution Global Climate Simulations and Prediction

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Complexity of Climate System

To accurately simulate and predict climate change, an Earth system modeling approach is required to represent complex interactions among different components of the Earth system.

Community Earth System Model (CESM)

- Land Biogeochemistry
- Atmosphere (temperature, winds and precipitation)
- Coupler CIMES
- Ocean (POP2)
- Marine Biogeochemistry (MARBL)
- River Runoff (MOSART)
- Sea Ice (CICE)
- Land Ice (CISM2)

Intergovernmental Panel for Climate Change (IPCC) Assessment Report

> 1.5 million lines
> 5 million cells at 1º

https://nordicesmhub.github.io/containers/01-introduction/
Multi-scale Nature of Climate System

Lifetimes and sizes of atmospheric phenomena

- **CLIMATE PREDICTION**
  - 1000 yr
- **LONG RANGE FORECASTING (SEASONAL TO INTERANNUAL CLIMATE PREDICTION)**
  - 100 yr
  - 1 year
- **EXTENDED-RANGE WEATHER FORECASTING**
  - 1 month
- **WEATHER FORECASTING**
  - 1 week
- **NOWCASTING**
  - 1 hour

Current Climate Models

Atmosphere

Ocean

https://ceoa.oregonstate.edu/file/webspacetimescalesgif
Long Time Scales of Climate Change

Preindustrial Simulation
Constant GHG forcing at PI level (278 ppm)

Historical Simulation
Observed GHG forcing

Future Simulation
Future Scenario

PI-CTRL
RCP2.6
RCP4.5
RCP6.0
RCP8.5
IPCC Climate Simulations

Coupled Model Intercomparison Project (CMIP):

- Ensemble of atmospheric model intercomparison project (AMIP) simulations (5-40 x 40 years ~200 years)
- Preindustrial control simulations (1850 climate forcing) (~1,000 years)
- Ensemble of 1850-2100 historical and future climate simulations under different emission scenarios (i.e. RCP/SSP1 2.6, RCP/SSP2 4.5 ... RCP/SSP5 8.5) (5-40 x 250 years x 5 ~ 6,000 years)
- 1%/yr CO2 increase - transient climate sensitivity experiment (~150 years)
- Abrupt 4 x CO2 - equilibrium climate sensitivity experiment (~150 years)

Total simulation years:

~ 10,000 years

Computational Resources:

~ 100 million core hrs for IPCC-class Earth system model simulations with 1º (~100 km) atmosphere & ocean resolution

Participants for CMIP Phase 6 (2017-2020):

~ 33 models for CMIP6, from US, China, UK, Australia, Canada, Germany, Japan, India, Italy, France, Russia, South Korea, Brazil ...
IPCC-Class climate models are capable of simulating and projecting 1) global-mean surface temperature (GMST) changes, 2) large-scale warming patterns, 3) large-scale weather pattern changes and 4) other large scale climate phenomena, such as El Niño-Southern Oscillation.

Projected Change in Temperatures by 2090
- If CO₂ emissions peak by 2020 and drop to zero by 2080 (RCP 2.6)
- If CO₂ emissions triple by 2080 (RCP 8.5)

https://commons.wikimedia.org/wiki/File:Projected_Change_in_Temperatures_by_2090.png
What are the limitations of IPCC-Class Climate Models?

At ~100 km horizontal resolutions, IPCC-Class climate models lack capability of simulating and projecting changes in weather extremes, such as tropical cyclones, and changes in regional ocean environments, such as coastal sea-level rise, coastal upwelling, as well as many other small-scale regional phenomena ...

Figure Source: Fu et al. (2017)
IPCC-Class vs. Eddy-Resolving Ocean Simulations

Mesoscale Eddy-Resolving (~10 km)  IPCC-Class (~100 km)
Moores Law for IPCC Climate Models

• A complete set of CMIP simulations at TC permitting (~25 km) atmosphere resolution and mesoscale-eddy-resolving (~10 km) ocean resolution (hereafter high-resolution) represents a major step forward in climate modeling community

• Our team (TAMU, NCAR and our international partners) is among the first to complete such a high-resolution set

• Completed simulations so far include
  o 1950-2005 AMIP simulations
  o 650 years of preindustrial climate simulation
  o Ensemble of 3 historical and future climate simulations (1850-2100) under RCP8.5 and one under RCP2.6
  o 1%/yr CO2 increase - transient climate sensitivity experiment (150 years)
  o Abrupt 4 x CO2 - equilibrium climate sensitivity experiment (150 years)
  o Ensemble of decadal prediction simulations

25 out of 35 CMIP6 models are running at ~100 km resolution (only 4 at ~50 km or finer with one at ~25 km), coarser than the anticipated ~50 km resolution

Anticipated resolution ~50 km for CMIP6

HighResMIP (smaller numbers of participating models and much shorter integration period)
Transition from Low- to High-Resolution Models

• In order to run high-resolution climate models efficiently, we need to reformulate the models for massively parallel computer architectures, such as Frontera.

• For low-resolution CESM, the atmosphere model (CAM) is discretized on the traditional regular latitude-longitude grid:
  o CAM-EUL: Spherical harmonics based spectral transform method (dominated for over 40 years)
  o CAM-FV: Finite-volume method (the work-horse for CMIP5/6 simulations)

• These traditional numerical methods are not “trivially” amenable for massive parallel computer systems because they require non-local communication:
  o Legendre transform
  o “Polar filters” (due to convergence of the meridians near the poles)

Peter Lauritzen: https://www.cesm.ucar.edu/events/tutorials/2019/files/Lecture2-lauritzen.pdf
Reformulation of CAM for massively parallel Computer Architectures

- Instead of the traditional regular latitude-longitude grid, we need 1) quasi-uniform grid and 2) local numerical method, and non-local communication is not required.

- **CAM-SE**
  - Spectral element method
  - Discretized on cubed-sphere (uniform resolution or conforming mesh-refinement) and highly scalable
  - 1/4° “work-horse” for high-resolution CESM

- **MPAS (Model for Prediction Across Scales)**
  - Finite-volume unstructured
  - Centroidal Voronoi tessellation of the sphere
  - Fully compressible nonhydrostatic
  - Being integrated into CESM

Peter Lauritzen: https://www.cesm.ucar.edu/events/tutorials/2019/files/Lecture2-lauritzen.pdf
CAM Scalability

High-Resolution CAM

CAM-SE has superior scalability compared to CAM-FV and CAM-EUL. CAM-SE is used for the high-resolution CESM simulations.

High-Resolution CAM-SE on Frontera

CAM-SE achieves a benchmark of 20 simulation years per day on 1,500 Frontera nodes (84,000 cores).

https://www.cesm.ucar.edu/events/tutorials/2019/files/Lecture2-lauritzen.pdf
Ocean Component - POP2

- Finite difference code on Arakawa B-grid
- Vertical level- (z-) coordinate
- Horizontal orthogonal curvilinear tripole grid with displaced poles (two north poles on land) to avoid numerical instability
- Implicit free-surface method for barotropic mode, which requires solving an elliptic system of equations that scales poorly
- A preconditioned Chebyshev-type iterative method (P-CSI) is implemented to speed up the barotropic solver (Hu et al. 2015)
- CICE and POP2 Halo-update routines are optimized (Kim and Dehnis, 2018)

Hu et al. (2015)

High-Resolution CESM on TACC Systems

- High-resolution CESM shows an excellent scalability up to ~800 nodes (~45,000 cores) on Frontera
- POP2 does not scale beyond 800 nodes
- High-frequency IO significantly deteriorates the CESM performance (by ~40%)
- 6 ypd performance on Frontera is among the best that we have seen for this class of climate models on any HPCs
- High-resolution CESM is ~92 times more costly than standard CESM
Global Tropical Cyclones

(a) Global TC Tracks OBS 1950-2018 (global mean: 82.4)

NIO(4.8)  WNP(25.7)  ENP(16.1)  NTA(12.4)

SIO(15.7)  STP(9.5)  STA(0.0)

(b) Global TC Tracks HR 1950-2018 (global mean: 111.5)

NIO(8.2)  WNP(25.0)  ENP(27.0)  NTA(6.5)

SIO(24.3)  STP(19.4)  STA(1.1)

(c) Global TC Tracks LR 1950-2018 (global mean: 24.6)

NIO(2.0)  WNP(6.2)  ENP(3.6)  NTA(0.5)

SIO(8.4)  STP(3.7)  STA(0.2)

Courtesy of Dan Fu

Chang et al 2020
Projected Tropical Cyclones Changes

- Projected TC change in HR-CESM simulations shows an increase in TC activity in the Northwestern Pacific and India Subcontinent, but LR-CESM simulations do not project such an increase.
- HR-CESM simulations also project a 30% increase in TC-induced extreme rainfall compared to 15% increase in LR-CESM.
Future Projection of TC-rainfall over Land

Number of Major Hurricane

Accumulated TC-rainfall over land

Future minus Historical Period

Courtesy of Dan Fu
Atmospheric Rivers

Satellite Retrieved IWV (mm)

CESM-HR Simulated IWV (mm)

CESM-LR Simulated IWV (mm)

Courtesy of Xue Liu
Atmospheric River Induced Precipitation

Representation of Orography in Climate Models

The underestimated precipitation in low-resolution CESM is likely caused by
• weak atmospheric rivers
• poorly represented orography

Courtesy of Xue Liu

Projected Future Changes in Atmospheric Rivers

Courtesy of Xiaohui Ma
Coastal Ocean Upwelling

Upwelling along California Current System (CCS)

Ocean eastern boundary upwelling systems, like the CCS, are ocean’s most productive biomes, supporting one-fifth of the world’s wild marine fish harvest.
NSF Convergence Accelerator Track E:
Climate Change Adaptation Tools for California Current Fisheries (CATCCH)

CESM-HR with Ocean Biogeochemistry plus Fisheries

Decision Support System for Sustainable Future Fisheries

**Sustainable Blue**

- Earth system model predictions
  - Atmospheric CAM
  - Land CLM
  - Ocean Physics: POP
  - BGC: MARBL

- Social science activities

- Actionable Science & Management

**Fish model predictions using FEISTY**

- Micro & Macro Zoo
- Small Fish
- Medium Fish
- Large Fish

Based on Heath et al. (2020)

(courtesy of Fred Castruccio)

(courtesy of Jaison Kurian)
Storm-resolving Global Climate Models – A New Challenge

• Explicitly representing convection requires non-hydrostatic dynamics
• Horizontal resolutions < 4 km and vertical levels > 80
• ~200 times more costly than current high-resolution climate models (~0.25° & 30 vertical levels)
• 500 CPU-based nodes → ~1 simulation week per day
• GPU-based HPCs are expected to deliver a better performance (~3 simulation months per day)
• Not to expect ~1000-yr climate simulations in the near future

Stevens et al. 2019
Different CO2 Emission Scenarios in CMIP

CO2 at Mauna Loa now reaching 50% above pre-industrial levels

50% increase 417 ppm

Pre-industrial 278 ppm

Ice core data from MacFarling Meure et al. (2006), Mauna Loa data from the Scripps CO2 program. 2021 forecast from Met Office.
High-resolution simulations show better skills in capturing the strength and spatial distribution of winter extreme precipitation.

Decrease in extreme precipitation in southwest Texas in future.