GFDL’s Fourth Generation CM4.0 and ESM4.1

John P Dunne
AM4/OM4 substantively improved dynamics, physics, clouds, and radiation along with doubled resolution.

CM4.0 vastly improves SST, Southern Hemisphere sea ice, variability modes and teleconnections.

Overall, CM4.0 surface climate provides strong analysis framework.

ESM4.1 improves carbon, chemistry, dust and nitrogen interactions and captures most CM4.0 baseline simulations characteristics.

ESM4.1 provides for understanding forced response, feedbacks and impacts across climate, carbon, ecosystems, and air quality.
Development Activity On Many Fronts

• CM4.0 development foci included
  — Ocean cold bias and heat uptake without mesoscale formulation
  — Convergence of mean atmospheric fidelity at 1°
  — Boreal forests and snow masking for albedo seasonality
  — Understanding high climate sensitivity given moderate AM4 CESS Sensitivity
  — Sensitivity to parameterization of orographic drag
  — Southern Ocean Polynya/sudden warming

• ESM4.1 development foci included
  — Coupled carbon-chemistry
  — Atmospheric aerosol emission and deposition
  — Comprehensive earth system dust/iron representation
  — Vegetation and canopy competition, daily fire, and nitrogen cycling
  — Ocean eddy parameterization for midlatitude SSTs and water masses
  — Southern Ocean Polynya/sudden warming
CM4.0 (BLINGv2) and ESM4.1 (COBALTv2)

6 Tracer Biogeochemistry and Steady State Ecosystem

Gas exchange

- DIC
- O2
- Alk

Rivers

- PO4
- Fed

Light

Production

Large and Small Biomass

Scavenging

Calcite sinking and burial

Organic C sinking and burial

Burial and sediment storage (Table 1)

Deposition and Air-Sea Exchanges (Table 1)

River Inputs (Table 1)

Nitrogen
- Iron
- Lithogenic dust

Carbon
- Silicon
- Fluxes to DOM

Phosphorus
- Calcite, Aragonite
- Remineralization/dissolution

Geophysical Fluid Dynamics Laboratory Review
October 29-31, 2019
COBALT Builds upon ESM2 Generation Success in Resolving Energy Flows from Primary Production to Fish

• **Fidelity Highlights of GFDL 4th Generation Models**

• For further information, see:


Cloud and Radiation Improvement on Bias

<table>
<thead>
<tr>
<th>Model</th>
<th>Net Rad.TOA</th>
<th>SW Abs.</th>
<th>Outgoing LW</th>
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</thead>
<tbody>
<tr>
<td>CM3</td>
<td>ε=9.2</td>
<td>ε=13.5</td>
<td>ε=10.7</td>
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<tr>
<td>CM4.0</td>
<td>ε=7.3</td>
<td>ε=8.9</td>
<td>ε=6.2</td>
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<tr>
<td>ESM4.1</td>
<td>ε=7.6</td>
<td>ε=9.0</td>
<td>ε=6.4</td>
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</tbody>
</table>

\[ \epsilon = 9.2, \epsilon = 7.3, \epsilon = 7.6, \epsilon = 13.5, \epsilon = 8.9, \epsilon = 9.0, \epsilon = 10.7, \epsilon = 6.2, \epsilon = 6.4 \]
Vast Improvement in Sea Surface Temperature
Strong Improvement in Sea Surface Salinity

a) ESM2M: mean = -0.17 ppt, rms = 0.80 ppt
b) CM3: mean = -0.09 ppt, rms = 0.66 ppt
c) CM4.0: mean = 0.04 ppt, rms = 0.47 ppt
d) ESM4.0: mean = -0.01 ppt, rms = 0.47 ppt
Strong Improvement in Surface Climate Bias

CM3

CM4

ESM4

$\varepsilon = 1.8$

$\varepsilon = 1.5$

$\varepsilon = 1.3$

$\varepsilon = 9.2$

$\varepsilon = 7.1$

$\varepsilon = 7.7$
ESM4 eliminates Southern Ocean Wind Bias

![Diagram showing zonal average eastward wind stress over the Pacific (115E-100W) and annual average. The graph compares different datasets, including CM4 historical (1980-2014), ESM4 historical (1980-2014), CMIP5 (27 models, 1979-2008), MERRA, and ECMWF.]
Strongly Improved Regional Precipitation

Pacific Double ITCZ Challenge

Amazon Dry Bias

Previous models

Solid – North Amazon
Dash – South Amazon
Good Boundary Currents and Eddies at $\frac{1}{4}^\circ$
ENSO Terrific in CM4.0, less so in ESM4.1

NINO3 SSTA spectra

Zonal wind stress (mPa) regressed on NINO3 SSTA (°C)

(a) OBS
(ERA-Interim reanalysis (1980–2014))

(b) CM4.0 (1980–2014)

(c) ESM4.1 (1980–2014)
Improved SO Sea Ice Brings Complex Dynamics
Southern Ocean Sea Ice anomaly patterns reflect recharge and discharge of interior ocean heat.

See Liping Zhang’s Presentation for mechanisms!
CFCs Show CM4 Deep Mixing & ESM4 Polynya
Anthropogenic CO₂

Similar total uptake, more in North Atlantic in ESM4.1, more Southern Ocean in CM4.0

(Sabine et al. 2004)
Vastly Improved CO₂ Variability Over ESM2

Seasonal CO₂ Amplitude

ESM2G

\( \varepsilon = 3.3 \)

ESM4

\( \varepsilon = 1.6 \)

Interannual CO₂ Variability

ESM2G

\( \varepsilon = 0.6 \)

ESM4

\( \varepsilon = 0.2 \)
CM4.0 more recent NH warming than ESM4.1

a. Global Mean

b. Tropics Mean (30S - 30N)

c. N. Hemisphere Mean (Eq. - 90N)

d. S. Hemisphere Mean (90S - Eq.)
ESM4.1 Lower Climate Sensitivity than CM4.0

<table>
<thead>
<tr>
<th>°C</th>
<th>EM2M</th>
<th>CM3</th>
<th>CM4.0</th>
<th>ESM4.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCR</td>
<td>1.5</td>
<td>1.9</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>ECS</td>
<td>3.3</td>
<td>4.4</td>
<td>4.9</td>
<td>3.1</td>
</tr>
</tbody>
</table>

GFDL CMIP6 Projection Scenarios with Shared Socioeconomic Pathways (ESM4.1 – solid, CM4.0 – dash)
Lower sensitivity under 4xCO₂ in ESM4.1 than CM4.0

- Differences in pre-industrial control (ESM4.1 0.7°C warmer than CM4.0)
- Earth System feedbacks included in ESM4.1, but neglected in CM4.0
  - Greater temperature-dependence of sea salt emissions
  - Sea ice masking of marine aerosols (DMS, sea salt, organic carbon)
  - Temperature dependence of biogenic VOC emissions (source of secondary organic aerosols)
  - Interactive stratospheric ozone
  - Dust emissions from semiarid regions modulated through dynamic vegetation and hydrology
GFDL’s 4th Generation is a Major Advance

• AM4/OM4 substantively improved dynamics, physics, clouds, and radiation along with doubled resolution.
• CM4.0 vastly improves SST and Southern Hemisphere sea ice variability modes and teleconnections providing good surface climate as an analysis framework.
• ESM4 combines improved interactive carbon, chemistry, dust and other cycles:
  — Much improved representation of chemistry and aerosols than CM3
  — Much improved representation of Carbon cycle relative to EMS2
• ESM4.1 captures much of the baseline simulations characteristics of CM4.0 with different advantages for each.
• ESM4.1 provides for understanding of forced response, feedbacks, and impacts across climate, carbon, ecosystems, and air quality.
• Overall, these models have many novel emergent behaviors worth exploration.
• Extra Slides
### Ocean Resolution versus Comprehensiveness

<table>
<thead>
<tr>
<th>Component</th>
<th>CM4.0</th>
<th>ESM4.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Dynamics</td>
<td>100 km, 33 levels</td>
<td>100 km, 49 levels</td>
</tr>
<tr>
<td>Atmospheric Chemistry</td>
<td>aerosol (21 tracers)</td>
<td>aerosol+ozone (103 tracers)</td>
</tr>
<tr>
<td>MOM6 Ocean</td>
<td>1/4°, 75 hybrid levels, no mesoscale parameterization</td>
<td>1/2°, 75 hybrid levels with mesoscale eddy kinetic energy parameterization</td>
</tr>
<tr>
<td>Ocean BGC</td>
<td>BLINGv2 (6 tracers)</td>
<td>COBALTv2 (33 tracers)</td>
</tr>
<tr>
<td>Land physics</td>
<td>LM4.0????</td>
<td>LM4.1????</td>
</tr>
<tr>
<td>Land Ecosystem</td>
<td>Leaf canopy dynamics with annual fire model</td>
<td>Perfect Plasticity Approximation canopy dynamics with daily fire model</td>
</tr>
<tr>
<td>Dust</td>
<td>Emission areas prescribed from external map based on wind and soil moisture</td>
<td>Emissions fully interactive with vegetation dynamics (Evans et al)</td>
</tr>
<tr>
<td>Atmospheric CO2</td>
<td>Externally prescribed</td>
<td>Either interactive or restored to externally prescribed value</td>
</tr>
</tbody>
</table>
CM4 Mean State Plateau at 1° Atm

Net Rad. TOA

**CM4**

$\varepsilon = 7.3$

Ion = (0.,360.), lat = (-90.,90.)

r(Obs, Mod) = 0.99157

rmse = 7.27634

**CM4 ½° Atm**

$\varepsilon = 7.1$

Ion = (0.,360.), lat = (-90.,90.)

r(Obs, Mod) = 0.992016

rmse = 7.0808

Precipitation

**CM4**

$\varepsilon = 0.96$

Ion = (0.,360.), lat = (-90.,90.)

r(Obs, Mod) = 0.896014

rmse = 0.960098

**CM4 ½° Atm**

$\varepsilon = 0.96$

Ion = (0.,360.), lat = (-90.,90.)

r(Obs, Mod) = 0.907478

rmse = 0.963665
Evolution of Southern Ocean Polynya