The IITM Earth System Model: Development and Future Road Map

ESM Team: R. Krishnan, V. Prajeesh, D.C. Ayantika, N. Sandeep, S. Manmeet, M. Aditi and V. Ramesh

ICTP TTA: Monsoon in a changing climate, Italy, 31st-4th August 2017
Outline

- Climate Modeling: brief history
- Need for Improving Monsoon Simulation
- Overview of IITM-ESM
- Step towards Earth System Modeling framework
- Future Road Map
Manabe and Brian (1969)

Climate Calculations with a Combined Ocean-Atmosphere Model

- Sector model of 120\degree
- 1 atmospheric year coupled to
- 100 ocean years
- 1200h for 1 simulated year
- (0.02 SYPD) on Univac 1108

- Empirical evidence indicates that poleward heat transport by ocean currents is of same order of magnitude as poleward transport of energy in the atmosphere (Sverdrup, 1975)
- Serious attempt to calculate climate must take into account atmosphere and hydrosphere
Atmospheric response to doubled CO2

Manabe and Wetherald (1975): A foundational document of climate modeling

- Estimated the temperature changes resulting from doubling CO₂ concentration
- Simplified three-dimensional general circulation model.
- A limited computational domain, an idealized topography, no heat transport by ocean currents, and fixed cloudiness.
- The CO2 increase raises the temperature of the model troposphere and significantly increases the intensity of the hydrologic cycle
The Charney Report (1979)

“Carbon dioxide and climate: A Scientific Assessment.”

• Precursor to the IPCC Assessment Reports.
• Based on 5 model runs: 3 from Manabe (GFDL), 2 from Hansen (GISS).

• Conclusions:
  • Direct radiative effects due to doubling of CO2: 4 W/m2
  • Feedbacks: water vapor (Clausius-Clapeyron), snow-ice albedo feedback.
  • Cloud effects: “How important the cloud effects are, is, however, an extremely difficult question to answer. The cloud distribution is a property of the entire climate system, in which many other feedbacks are involved.”
  • “We believe, therefore, that the equilibrium surface warming will be in the range of 1.5-4.5C, with the most probable value near 3C.”
Climate Modeling Today...

IPCC AR5 SPM:

- Warming of the climate system is unequivocal
- Last three decades has been successively warmer than any preceding decade since 1850

IPCC AR5. 20th century warming cannot be explained without greenhouse gas forcings
Recent Climate Change Report

Observed change in average surface temperature 1901–2012

Planet has warmed by 0.85 K over 1880-2012
**Figure 10.7:** Global, land, ocean and continental annual mean temperatures for CMIP3 and CMIP5 historical (red) and historicalNat (blue) simulations (multi-model means shown as thick lines, and 5–95% ranges shown as thin light lines) and for HadCRUT4 (black). Mean temperatures are shown for Antarctica and six continental regions formed by combining the sub-continental scale regions defined by Seneviratne et al. (2012). Temperatures are shown with respect to 1880–1919 for all regions apart from Antarctica where temperatures are shown with respect to 1950–2010. Adapted from Jones et al. (2013).
Wide variations among CMIP5/CMIP3 models in capturing the South Asian monsoon.

Indian Land: CMIP5 vs Obs

ISM domain 15S-30N, 50E-120E

Realism of present-day climate simulation is an essential requirement for reliable assessment of future changes in monsoon.
Historical and SRES A1B projection of South Asian monsoon rainfall
[Turner and Annamalai, 2012]

• Observed data shows a negative trend in precipitation since 1950.
• Decadal variability dominates & considerable uncertainty in precipitation between the models
Temporal evolution of monsoon hydro-climatic signals

- Decreasing trend of monsoon precipitation during the later part of 20th century
- The aridity index (SPEI, Standard Precipitation-Evaporation Index) indicates a marked increase in propensity of monsoon droughts

Krishnan et al. 2016
Long-term trends in the Indian monsoon rainfall


Significant negative trends: Kerala, Jharkhand, Chattisgarh

The 142-yr (1871-2012) record of all-India monsoon rainfall indicates a 40% increase in the frequency of monsoon-droughts during the second half relative to the first half of the period.
Summer Monsoon Rainfall and Crop Production

Rainfall - 2009

Detrended All India Kharif Production Anomaly (NCC, IMD)
Impact of a severe drought on GDP remains 2 to 5% throughout, despite the substantial decrease in the contribution of agriculture to GDP over the five decades.

Two-thirds of the workforce is in agriculture

Gadgil and Gadgil (2006)
The observed linear trend shows widespread decrease in rainfall over the IGP and mountainous west-coast. The increasing trend over southeastern China and adjoining areas is also observed. The prominent drought over the Sahel region is also evident from the decreasing trend.
Most models show an intensified Asian monsoon rainfall,
There is substantial model spread.  
(Li and Ting, 2016)
Why there are uncertainty in regional precipitation response?

- In a warmer climate, as a consequence of the increase in tropospheric water vapor, the global hydrological cycle will become more intensified (Held and Soden 2006).

- The rate of precipitation increase is less than the rate of water vapor, and tropical atmospheric circulation weakens as climate warms (Vecchi and Soden 2007, Krishnan et al., 2015).

- The atmospheric circulation is the major source of uncertainty in regional rainfall projection (Xie et al. 2015).
Science of climate change
Detection, attribution & projection of global climate and regional monsoons

Roadmap for Earth System Model (ESM) development

• **Start with an atmosphere-ocean coupled model with realistic mean climate**
  – Fidelity in capturing the global and monsoon climate
  – Realistic representation of monsoon interannual variability
  – Features of ocean-atmosphere coupled interactions
  – ...

• **Include components / modules of the ESM**
  – Biogeochemistry
  – Interactive Sea-ice
  – Aerosol and Chemistry Transport
  – ...
Atmosphere: T126 spectral (~ 190 km), 64 vertical levels – ESMv1

Ocean: 0.5 deg grid, ~ 0.25 deg between 10N-10S, 40 vertical levels
The NCEP CFS Components

Atmospheric GFS (Global Forecast System) model
- T62; vertical: 64 sigma – pressure hybrid levels
- Model top 0.2 mb
- Revised Simplified Arakawa-Schubert convection (Han & Pan)
- Non-local PBL (Pan & Hong)
- SW radiation (Chou, modifications by Y. Hou)
- Prognostic cloud water (Moorthi, Hou & Zhao)
- LW radiation (GFDL, AER in operational wx model)
- Land surface processes (Noah land model)

Interactive Ocean: GFDL MOM4p1 (Modular Ocean Model-4p1)
- 1.0 deg poleward of 10°N and 10°S; and 0.33 deg near equator (10°S – 10°N)
- 50 levels
- Interactive sea-ice
- Interactive ocean biogeochemistry
Schematic of IITM ESM

GFS (Atmospheric Model) with NOAH Land Model

AO Coupler

Atm Grid

Sea Ice

GFDL MOM4p1 (Ocean Model) & SIS (Ice Model)

FMS coupler

Ocean

Fast loop

Slow loop

Scalability: 8 SYPD
The drift in surface temperature and SST is minimum in IITM ESMv1 (red line) compared to CFSv2 (blue line).

Significant reduction in cold SST bias in tropical IO and subtropical Pacific.
Coupled models drift towards a more equilibrated state. Initial rapid cooling of SST followed by warming trend. Significant subsurface drifts seen through multiple centuries of simulation. Vertical redistribution of heat with tendency of cooling in upper layers and warming in the sub-surface – Delworth et al. 2006
Precipitation (mm day$^{-1}$): JJAS mean

CFSv2 JJAS Precip (mm/day)

ESM JJAS Precip (mm/day)

TRMM JJAS Precip (mm/day)
Inter-annual variability
PDO - IITM ESM

(a) HadISST (EOF1) HadISST 30.3%

(b) ESMv1 ESMv1 30.7%

(c) CFSv2 CFSv2 24.4%

(d) HadISST

(e) ESMv1

(f) CFSv2
Seasonal cycle of precipitation and Nino 3 SST is captured in ESM & CFSv2.
Lagged correlation between ISMR and Nino3 SST in the preceding/following months are captured well in IITM ESM as compared to CFSv2.
Recent improvements in IITM ESM
Boreal summer monsoon (JJAS) precipitation and bias

(a) TRMM

(b) ESMv1 (T126)

(c) ESMv2 (T62)
Depletion of NH sea-ice during Jan-Mar

Weakening of AMOC

Sea-Ice concentration & AMOC
Black line is the preindustrial run. The red line shows the 20\textsuperscript{th} century simulation and the 21\textsuperscript{st} century portion of the SRES A1B simulation (stared from the end of the 20\textsuperscript{th} century simulation. The blue line shows the 22\textsuperscript{nd} and 23\textsuperscript{rd} century SRES A1B simulation.
Energy Balance of the Coupled System

NDSW – Net downward Short wave radiation
OLW- Outgoing Long wave radiation
DLW- Downward Long wave (depends on T of Atm)
ULW – Upward long wave (depends on T of Ocean)
SHF – Sensible heat flux
LHF – Latent heat flux

Surface Flux = NDSW – DLW + ULW + SHF + LHF

Net flux = TOA – Surface flux

Courtesy: Prajeesh
TOA Energy Balance

NDSW – Net downward Short wave flux at TOA

OLW – Outgoing Longwave flux (depends on layer temperature according to Stefan Boltzmann law)

NDSW

Internal Energy ($C_pT$)

Kinetic Energy (Winds)

Incr. Temp

Minimize atmospheric energy loss – Bretherton et al. 2012

TKE dissipation heating (Han)

$$\varepsilon = -K_h \frac{g}{\theta_v} \frac{d\theta_v}{dz} + K_m \left[ \frac{du}{dz} \right]^2$$

buoyancy production

shear production
Energy Balance in IITM ESM

Preindustrial TOA ($\text{Wm}^{-2}$)

Energy imbalance for CMIP5 Models (Forster et al., 2013)
Net Radiation (W m\(^{-2}\)) at TOA

Obs (CERES) vs IITM-ESMv2
## Energy Balance in IITM ESM

<table>
<thead>
<tr>
<th></th>
<th>Net flux TOA (W m(^{-2}))</th>
<th>Net Flux Surface (W m(^{-2}))</th>
<th>Difference (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ESMv1 (T126)</strong></td>
<td>6.6</td>
<td>1.2</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>ESMv2 (T62)</strong></td>
<td>0.80</td>
<td>0.81</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Sea-Ice concentration and AMOC in IITM ESMv2
Prescribed time-varying aerosol distributions in IITM ESM from CMIP

Aerosol TOA forcing (total sky) = -0.9

Courtesy: Ayantika, CCCR
Land use/land cover changes (Hurtt et al., 2015)

Pre industrial (1850)

Present day (2007)

Courtesy: Sandeep, CCCR
CMIP6 Concept:
A Distributed Organization under the oversight of the CMIP Panel

“DECK”:
Development
Evaluation
Characterisation of
Klima (German for ‘climate’)

Meehl et al., 2014: Climate Model Intercomparisons: Preparing for the Next Phase, Eos Trans. AGU, 95,77-84.
# CMIP6 Experiments

<table>
<thead>
<tr>
<th>Experiment Description</th>
<th>Forcing methods</th>
<th>Start Year</th>
<th>End Year</th>
<th>Minimum # Years</th>
<th>Major purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical AMIP</td>
<td>CO$_2$ concentration-driven</td>
<td>1979</td>
<td>2014</td>
<td>36</td>
<td>Evaluation</td>
</tr>
<tr>
<td>Pre-industrial control</td>
<td>CO$_2$ emission-or concentration-driven</td>
<td>1850</td>
<td>n/a</td>
<td>500</td>
<td>Evaluation, unforced variability</td>
</tr>
<tr>
<td>1 %/yr CO$_2$</td>
<td>CO$_2$ concentration-driven</td>
<td>n/a</td>
<td>n/a</td>
<td>140</td>
<td>Climate sensitivity, feedbacks</td>
</tr>
<tr>
<td>Quadruple CO$_2$ abruptly, then hold fixed</td>
<td>CO$_2$ concentration-driven</td>
<td>n/a</td>
<td>n/a</td>
<td>150</td>
<td>Climate sensitivity, feedbacks, fast responses</td>
</tr>
<tr>
<td>Past ~1.5 centuries</td>
<td>CO$_2$ emission-or concentration-driven</td>
<td>1850</td>
<td>2014</td>
<td>165</td>
<td>Evaluation</td>
</tr>
</tbody>
</table>
Summary

IITM ESMv1

• Significant reduction of cold bias of global mean SST by ~0.8°C
• ENSO & PDO are robust and spatially more coherent in IITM ESM
• ENSO and monsoon links are well-captured
• The IITM Earth System Model: Transformation of a Seasonal Prediction Model to a Long Term Climate Model. Swapna et al. (BAMS, 2015).

IITM ESMv2

- Reduced the TOA energy imbalance
- Improved the mean precipitation over Asian region
- Improved the sea ice distribution
- Included time-varying aerosol concentration
- Corrected the hydrology imbalance
- Improved representation of ocean BGC
• Development of High Resolution Global Model (~grid size 27 km) Atmospheric version of IITM-ESM for dynamical downscaling. Generation of high resolution global climate and monsoon projections.

• High-resolution IITM-ESM coupled model (atmosphere grid size: 27 km, ocean grid: 0.5 deg x 0.5 deg and 0.25 deg x 0.25 deg near equator) for long-term climate.

• Development of next-generation IITM-ESM coupled model, to include new components (eg., interactive aerosols, chemistry, carbon cycle).
Thank You