Towards Earth System Modelling for improving monsoon projections under changing climate

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Global Warming

Global Warming is the increase in the average temperature of the Earth’s near surface air and oceans since the mid-20th century and its projected continuation. (Wikipedia)

Global Temperature Change (°C)

- 0.76°C (1.4°F) since 1900
- 0.55°C (1.0°F) since 1979
An Elegant Science Question: Are increases in greenhouse gases responsible for increase in global mean temperature (global warming)?

Global Temperature & Carbon Dioxide 1860-2008

0.76°C (1.4°F) since 1900
0.55°C (1.0°F) since 1979
Degrees Celsius above or below 30-year average global temperature
Greenhouse gases increase due to human activities.

Global warming is due to increases in greenhouse gases.

Global warming is due to human activities.

**Alternative Hypothesis**

- Global warming is due to natural variations of climate.

How do you test such hypotheses?

Climate Models; IPCC
What is a Climate Model?

- Equations of motions and laws of thermodynamics to predict rate of change of:
  
  $T, P, V, q, \text{ etc.} \ (A, O, L, CO_2, \text{ etc.})$

- 10 Million Equations:
  100,000 Points $\times$ 100 Levels $\times$ 10 Variables

- With Time Steps of: $\sim$ 10 Minutes

- Use Supercomputers
Increase in Surface Temperature

- Observations
- Predictions with Anthropogenic/Natural forcings
- Predictions with Natural forcings

IPCC 2007
To build the capacity in the country for using a high resolution coupled ocean-atmosphere model or an Earth System Model to address issues on Attribution and Projection of regional Climate Change

To provide reliable input for Impact Assessment studies

Observational monitoring: Network with other Institutions
Questions : On Attribution?

- How much of the observed variability of the mean Indian Summer Monsoon rainfall due to Climate Change?
- How much of the observed increase in temperature over India been decreased by increasing presence of aerosols?

Questions : On Projections of Monsoon

- What will happen to the monsoon hydrological cycle 50-100 years from now under different scenarios? In particular, will the quantum of seasonal mean rainfall increase or decrease and if so by how much?
- What is the uncertainty in these projections? Can we quantify this uncertainty?
- How can we reduce this uncertainty?
To establish a High Altitude Cloud Physics Observatory for monitoring cloud-aerosol interactions – (Long-term)

To understand Past Changes in Monsoon Climate using Multiple Proxy Records. Reconstruction of an iconic monsoon index going back to a few thousand years – (Long-term)

To promote Outreach and Training for Capacity Building in Climate Change Research and Dissemination of Information – Long-term cont
Challenges in assessment of future changes in South Asian monsoon rainfall

• Wide variations and uncertainties among the IPCC AR4 models in capturing the mean monsoon rainfall over South Asia (eg., Kripalani et al. 2007, Annamalai et al. 2007).

• Systematic biases in simulating the spatial pattern of present-day mean monsoon rainfall (eg., Gadgil and Sajani, 1998; Kripalani et al. 2007)

• Realism of present-day climate simulation is an essential requirement for reliable assessment of future changes in monsoon
The 20c3m simulations attempt to replicate the overall climate variations during the period ~1850-present by imposing each modeling groups best estimates of natural (e.g., solar irradiance and volcanic aerosols) and anthropogenic (e.g. GHG, sulfate aerosols and ozone) during this period. Seven 20C3M models (GFDL CM2.0, GFDL-CM2.1, MPI-ECHAM5, MRI, MIROC3-HIRES, HadCM3, NCAR-PCM – Source: J. Shukla)
South Asia
(5-35N, 65-95E)

Source: Kripalani et al. 2010
High resolution dynamic downscaling of monsoon

- High-resolution dynamic downscaling of monsoon
  - WRF-ARW multi-year high-resolution simulations (50 km) using ERA-interim LBC completed
  - Completed 3 sets of ensemble perturbed physics runs – PRECIS (50 km) for uncertainty estimation
  - Initiated ultra-high resolution model simulations embedded in a high-resolution global model - LMDZ
Climatological mean summer monsoon (JJAS) rainfall
TRMM 3B42
Ultra high resolution monsoon simulations: Global model with zoom over monsoon domain

JJAS rainfall

Initial runs made at CCCR on PRITHVI, IITM
Roadmap towards 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 of the ESM
  - Aerosol and Chemistry Transport Module
  - Biogeochemistry Module (Terrestrial and Marine)
  - Sea-ice module
  - …
  - .
Basic framework for global climate modeling
Coupled Forecast System (CFS) T62L64

• The NCEP CFS Components -
  – T62/64-layer version of the CFS

• Atmospheric GFS (Global Forecast System) model
  – Model top 0.2 mb
  – Simplified Arakawa-Schubert convection (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)

• GFDL MOM-3 (Modular Ocean Model, version 3)
  – 40 levels
  – 1 degree resolution, 1/3 degree on equator
Climatological (JJAS) mean monsoon rainfall from CFS model – 100 year free run

Climatological (JJAS) mean SST from CFS model – 100 year free run
Taylor diagram of spatial pattern of climatological seasonal mean (JJAS) rainfall

CFS Model

High pattern correlation with observed rainfall over India (IMD gridded Dataset)

Source: Seasonal Prediction Group, IITM
Interannual variability of summer monsoon rainfall in the CFS model – 100 year free run
Domain: 70E-90E; 10N-30N

Time in years

CFS model
JJAS climatological mean rain rate = 5.80 mm / day (red line)
Standard Deviation of JJAS rain rate = 0.82 mm / day

Observed rainfall (IMD)
JJAS climatological mean rain rate = 7.5 mm / day
Standard Deviation = 0.85 mm / day
MONSOONAL DROUGHTS

Complex Interactive Mechanisms of Monsoon Droughts

Surface Boundary Conditions

Land Surface Process

SST

Eurasian Snow Cover

ENSO Cycle

Interactive Dynamics

Other Possible Causes

Low Frequency Intra-seasonal 30-50 day scale

Solar

Volcanic

Anthropogenic

Synoptic Scale <One Week

North Ward Moving Episodes

Stratospheric ?

East Ward Moving Episodes

S.H. mid Latitudes

Indian and West Pacific Ocean

N.H. mid Latitudes

Source: Sikka, 1999
Monsoon droughts in CFS model

- Atmosphere – Ocean coupling in the tropical Indo-Pacific sector
  - Tropical central-eastern Pacific (El Nino / Modoki)
  - Eastern equatorial Indian Ocean (Negative IOD)

- Monsoon and mid-latitude interactions
Monsoon drought composites in CFS model: Rainfall and wind (850 hPa) anomalies

Anomalous warming of the tropical Indo-Pacific: Atmosphere – Ocean Coupled Interaction

- Bjerknes-type feedback
- El Nino - Modoki
- Negative IOD

SST and wind (850 hPa) anomalies in the CFS model

Long-standing scientific question
Can the Indian Ocean dynamics influence the occurrence of long-lasting "breaks" in the monsoon rainfall over the Indian subcontinent?

Monsoon-midlatitude interactions during droughts over India

- Cold air advection from mid-latitude westerly troughs cools middle and upper troposphere
- Rossby response: Anomalous Troughs over West-Central Asia and Indo-Pak; a stagnant blocking ridge over East Asia
- Suppressed monsoon convection over sub-continent forces Rossby wave response extending over sub-tropics and mid-latitudes
- Decreases meridional temperature gradient; dry winds decrease convective instability, suppress convection and weaken monsoon
- Droughts emanate from prolonged monsoon-breaks

Rainfall and 850 hPa winds

Winds & temperature: 500 hPa

Wind anomalies: 200 hPa

Anomaly composites during monsoon droughts: CFS model

Krishnan et al. J. Atmos. Sci., 2009
Ongoing efforts towards development of Earth System Model (ESM) to address the Scientific Challenges of Global Climate Change and the Asian Monsoon System

- Plan to include ESM components in the CFS-2 coupled ocean-atmosphere model
- CFS-2 coupled ocean-atmosphere model simulations on HPC initiated
- Ocean Biogeochemistry Module coupled to MOM4. Runs are ongoing on HPC
- Aerosol Transport Module coupled to AGCM. Runs are ongoing on HPC
Summary

- A global atmosphere-ocean coupled model (CFS) is operational. A century long simulation and several seasonal runs have been performed.
- Aspects of the global and regional monsoon climate are realistically captured by CFS model.
- Realistic features of interannual variability of Indian monsoon rainfall:
  - Atmosphere-ocean coupling over tropical Indo-Pacific
  - Monsoon and mid-latitude interactions
- Need to reduce model systematic biases via realistic representation of ESM components.
- Ongoing efforts to include ESM components in the CFS model:
  - Aerosol Transport Module
  - Biogeochemistry Module (Terrestrial and Marine)
  - Sea-ice Module
Thank you