Systematic errors in monsoon simulation and process-based diagnostics

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Talk Outline

• Persistence of systematic errors over the Asian-Australian monsoon system

• Sources of systematic errors (limitations in these studies)
  
  (i) Misrepresentation of Orography
  (ii) Fast atmospheric processes (convection)
  (iii) Fast oceanic processes (Wyrtki Jet along EIO)

• Process-based diagnostics (Identify robust precursors)
“+ve errors along the climatological flow”

Errors in
(i) coupled processes and persist thru’ AC
(ii) MC - land-sea breeze
(iii) Land-atmosphere -

Uncertainties in future projections may not have reduced
Positive errors over MC persist thru A/C

Uncertainties persist in future projections - Perhaps due to persistence of systematic errors
1. Vertical Cloud distribution
2. Cloud-radiation interaction
3. Too much shallow?
4. Too little stratiform?

“moisture-convection” feedbacks (K/day)

(Cherchi, Annamalai et al. 2014)
• Many CMIP models exhibit cold SSTs in the northern Arabian Sea during winter and spring.

• These link a series of coupled biases in the Indian Ocean.

Sperber and Annamalai (2014) Climate Dynamics
Onset is further delayed in future projections (Sperber and Annamalai 2017)

Tropical precipitation annual cycle delay – SST amplitude and phase
(Tan et al. 2008; Biasutti and Sobel 2009; Biasutti 2013; Dwyler et al. 2014);
Australia - fractional

Onset is systematically early over Australia (No models capture the Asia-Australian monsoon)
Climatological rainfall: fractional accumulation (CMIP5: Various monsoon domains)

- **India, Gulf of Guinea, SAM:** most models **late annual cycle**
- **Sahel and NAM:** most models **early annual cycle**

Sperber and Annamalai (2014, Clim, Dyn)
Onset is further delayed in future projections (Sperber and Annamalai 2017)
SST amplitude and phase (Biasutti and Sobel 2009; Biasutti 2013; Dwyler et al. 2014)
Sources of systematic errors of mean monsoon

(i) Misrepresentation of **Orography** (advect low MSE air)

(ii) **Fast** atmospheric processes (convection)

(iii) Fast **oceanic** processes (Wyrtki Jet along EIO)
Modified topography recreates CMIP bias

Errors in surface $h$ (colors) and upper-tropospheric temperature (contours, negative dashed)
green and pink contours are 1.5 km surface altitude in control and perturbed model
(CESM5 0.9x1.25 coupled model, rcp8.5 scenario)

precip anomaly caused by truncating Hindu Kush to 1 km max height (mm/day)
1. Dry bias over continental India – not clear
2. Rainfall errors over Maritime Continent and tropical west Pacific - unclear

Ma et al. 2014, JC
“no SST errors”
Bush et al. 2015
Too much rainfall over BoB – less rainfall over equatorial eastern Indian Ocean

Local rainfall maxima over equatorial western Indian Ocean
JJAS Rainfall and SST Climatology

Rainfall maximum over BoB – realistic
EEIO experiences local rainfall maxima

CFES (JAMSTEC)

CFES – a laboratory tool

MIROC5
Uniqueness of the Equatorial Indian Ocean
Equatorial windstress climatologies (60°-90°E, 1°S-1°N)

Schott and McCreary (2001)
Equatorial Indian Ocean wind stress (CMIP5 models)

Nagura et al. (2013)

“errors in SST/precip → wind stress errors”
Equatorial eastward jets advect upper-layer warm waters from western to eastern EIO (Wyrtki 1971)
1. Near-equatorial surface **westerlies during Intermonsoons** (Apr-May; Oct-Nov)

2. **Ocean response**
   
   (i) Equatorial, eastward flowing currents termed Wyrtki Jets (WJs)
   
   (ii) Force oceanic Kelvin and Rossby waves (impact on thermocline)

3. **WJs are fast oceanic processes** and advect warm water from western to eastern EIO

   WJs are important in the EIO coupled process (**Bjerknens’ feedback**)

   “Unlike equatorial Pacific and Atlantic – no easterly wind”
Compared to climatology:

- In May, 40-45% weaker
- In November, 70% weaker

$\Delta \tau$ is a measure of Bjerkens’ feedback in the Equatorial Indian Ocean.
3°S-3°N – surface currents

Observations

1. Weak eastward WJs
2. Unrealistic westward currents
3. Pile-up of warm waters WEIO

CMIP5 MMM
1. Lack of upwelling-favorable winds off Sumatra
2. Center of action appears to be over WIO
3. WIO Precip anom – equatorial atmos KW
• Lack of upwelling-favorable winds off Sumatra - perhaps due to lack of organized –ve precip anom
• SST gradient exists along EIO
• Precip anomalies intensify over western EIO – force atmospheric Kelvin wave – easterly bias
• Thermocline deeper everywhere except EEIO (Jay’s talk tomorrow)
• BJ feedback exists during May-November
• Western EIO – “hot spot”
• North-south dynamical linkage stronger!
Idealized experiments with Coupled model for Earth Simulator (CFES)
Model biases exist – magnitudes are less compared to CMIP5 errors -

Precip and SST biases over western EIO are NOT collocated as in CMIP5 models

$\Delta \tau$ integrated along the EIO is near-zero
3°S-3°N – surface currents

Observations

CFES

3°S-3°N – surface currents

(cm/s)
$T_{\text{aux}}$ anomaly - imposed

1. Imposed throughout A/C
2. Imposed during spring and fall only

Could have perturbed ....

Precip or SST or Thermocline

dyn/cm$^2$
EXP2 SPRING_FALL $\Delta \tau$

$3^\circ$S-$3^\circ$N – surface currents

(cm/s)
EXP2 minus CTL

D20_JJAS

CMIP5 bias D20_JJAS
Cold SST bias over northern BoB – induced by coastal Kelvin wave (D20)
Could have contributed to monsoon weakening – later in the season (examining now)
EXP2 minus CTL

Precip / wind 850hPa

CMIP5 bias – Precip / wind stress

mm/day

mm/day
Misrepresentation of EIO coupled processes could lead systematic errors in the simulation of mean monsoon precipitation climatology.
Mean Monsoon and Intraseasonal Variability

Zonal Vertical Shear

Lau and Peng (1990)
Wang and Xie (1997)
Annamalai and Sperber (2005)
Initiation

Amplification

Poleward - India

Eastward – W. Pacific

Quadra-pole

Poleward – W. Pacific

Annamalai and Sperber (2005)

CsEOF
Typically, AGCMs poorly represent the BSISV tilted rainband (Waliser et al. 2003, *Clim. Dynam.*, 21, 423-446)
BSISV in Coupled Models: The Tilted Rainband (Day 10)

(Sperber and Annamalai 2007)
“except in CM_2.1 the phasing of the relationship is incorrect. However, the intensity of ENSO is too strong in GFDL_CM2.1”
CMIP5 20c3m Integrations

Lead/lag relationship between AIR and NINO3.4 SST

Spring barrier

[Graph showing the relationship between AIR and NINO3.4 SST]
CMIP5 20c3m Integrations

Lead/lag relationship between AIR and NINO3.4 SST

“correlations peak during late spring”
AIR-SST

El Nino

La Nina

MIROC – L500 Results

“systematic errors in regional SST”
-1σ for 7 days or more – extended break

+1σ for 7 days or more – extended active
Extended monsoon breaks over central India (1951-2009)

Individual year statistics – higher occurrences during El Nino
Space-time composites – MJO-like signal-
Extended breaks – nonlinear interaction between boundary forcing + internal dynamics

Prasanna and Annamalai (2012, JC)
Representation of interaction between cumulus convection and large-scale circulation

[Quasi-equilibrium concept of Arakawa and Shubert (1979)]

requires consideration of moisture and temperature, represented by MSE \( m \)

\[
m = C_p T + gz + Lq
\]

Vertically integrated MSE tendency is approximately given by

\[
\left\langle \frac{\partial m}{\partial t} \right\rangle = -\left\langle V \cdot \nabla m \right\rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + LH + SH + \left\langle LW \right\rangle + \left\langle SW \right\rangle
\]

“storage” “adiabatic terms” “diabatic terms”

diabatic and adiabatic terms feedbacks onto each other

1. Deep tropics – above PBL – no horizontal T variations (WTG)
2. Entropy forcing: LH, SH, LW, SW, moisture variations
3. Physical parameterizations (cloud-radiation, convection, surface fluxes etc)
MSE budget terms – Central India (18-27N; 71-87E)

- termination
- “weak active”
- “revival of Monsoon”

Initiation
maintenance

Dry adv → convection inhibition → LW cooling → descent/adiabatic warming
Horizontal advection of moisture initiates extended active and break episodes

Column radiative flux divergence maintains extended episodes

Prasanna and Annamalai (2012); Mohan and Annamalai (2016)
Dry air intrusion –

Convective inhibition layer

“deep convection sensitive to mid-troposphere moisture”

Bretherton et al. 2004;
Grabowski and Moncrieff (2004)

“moisture-convection feedback”

Useful predictive information

(2002/2009 Case studies)
Summary for Case II

**Extended monsoon episodes**

MSE budget analysis identifies

\[-\langle \bar{V} \cdot \nabla m \rangle\]  \text{initiation and termination}

\[-\langle \bar{V} \cdot \nabla T \rangle\]  \text{maintenance}

But.......large residuals – important moist and radiative processes missing

MSE is a useful diagnostic to identify leading moist and radiative processes deem responsible for rainfall anomalies over mean ascent regions

Applying this diagnostic to “all regional monsoon areas” within the

Asian-Australian monsoon domain (e.g., MC, Philippines, Sri Lanka, Burma etc)
MSE budget (composite)

CFSv2 – contributions from horizontal Temperature advection are stronger
MSE budget (false alarms)

Horizontal advection of "moisture" precedes break event!
SST anomalies lead “local” precip anomalies over BoB that subsequently leads Precipitation anomalies over central India

(Krishnamurti et al 1998; Sengupta et al 2002; Sengupta and Ravichandran 2001)
Mixed-layer heat budget equation

\[
\frac{\partial (T_{ml})}{\partial t} = \frac{Q_{net} - Q}{p_0 C_p h} - V \cdot \nabla T_{ml} - \frac{w_e (T_{ml} - T_d)}{h} + R
\]

- "storage"
- "net surface heat flux"
- horizontal advection
- entrainment

(adiabatic terms)

(diabatic term)

Sengupta and Ravichandran 2001; Sengupta et al. (2002); Santoso et al. 2010; Huang et al. 2010; Chi et al. 2014;
Mixed-layer heat budget equation (composite)

Net surface heat flux determines SST tendency consistent with observations
Mixed-layer heat budget equation (false alarms)

SST anomalies do not provide a “clean” precursor signal
Representation of interaction between cumulus convection and circulation requires consideration of moisture and temperature that is represented by MSE, $m$, given by

$$m = C_p T + gz + Lq$$

The vertically integrated MSE tendency is approximately given by

$$\left\langle \frac{\partial m}{\partial t} \right\rangle = -\left\langle \overline{V \cdot \nabla m} \right\rangle - \left\langle \omega \frac{\partial m}{\partial p} \right\rangle + LH + SH + \left\langle LW \right\rangle + \left\langle SW \right\rangle + \text{residuals}$$

WTG approximation – temperature advection is negligible

Charging/discharging

Horizontal advection

MSE export

Vertical adv

fluxes

Cloud-radiative interaction

Neelin and Held 1987
Raymond et al. 2009
Maloney 2009