Moist static energy budget diagnostics for monsoon research

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• Multiple regional rainfall maxima -
• EIO and SPCZ – still experience high precipitation (thermal equator at 20°N)
• Central India rainfall – dynamical effects; Rain-shadow regions
• absolute ascent over a large domain
Observed Boreal Summer ISV

Annamalai and Sperber (2005, JAS) Lau and Chan (1986, JAS)

"one-phase of the ISV"

"internal dynamics"

OLR anomalies W/m²
JJAS rainfall anomalies (2002/04/09) - TRMM

“Boundary forcing”
JJAS Precipitation response in CM_2.1

4xCO₂ minus 20c3m

Stowasser, Annamalai and Hafner (2009 J. Climate)
Overarching Hypothesis

Interaction between equatorial waves and moist physics needs to be understood for attributing the causes for precipitation anomalies over “mean ascent” regions
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

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

WTG approximation – temperature advection is negligible

Neelin and Held 1987
Raymond et al. 2009
Maloney 2009
MSE budget – Monsoon variability

• Case I – Extended monsoon breaks over South Asia

• Case II – Drying tendency over South Asia (long-term trend in observed rainfall)

• Case III – Severe weak/strong monsoons (> 15% of the seasonal normal)
  Developing phase of ENSO

“dryness at different time scales”
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)
MSE budget terms – Central India (18-27N; 71-87E)

Initiation

maintenance

termination

“weak active”

Dry adv → convection inhibition → LW cooling → descent/adiabatic warming
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 I

Extended monsoon breaks

MSE budget analysis identifies

\[-\langle \overline{V} \cdot \nabla m \rangle \quad \langle LW \rangle\]

initiation and termination \quad maintenance

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

On-going Work ......Monsoon Mission – CFSv2 –

physical processes representation – nudging reforecast experiments
“since 1994....in a given year monsoon rainfall over India has not exceeded 10% above normal” but such incidents have occurred in the past too -

2 La Nina years – below normal rainfall
Linear trend in monsoon rainfall

CRU product

“spatial coherency – amplitude differs”

Delaware product

PREC/Land (NOAA)

Black carbon aerosols – Ramanathan and Colleagues (Scripps/NCAR)
Sulphur aerosols – Ramasamy and Colleagues (GFDL)
CCSM4 – JJAS Rainfall trend (1951-2005) 7-member ens mean

“direct indirect”

CCSM4 – better representation of monsoon and its variability (Meehl et al. 2012)
Significant SST rise (above natural variability) since ~ 1950s
SST rise – shifts the monsoon circulation

more rainfall over tropical west Pacific

less rainfall over South Asia
Working Hypothesis

SST trend shifts the monsoon circulation – promotes more rainfall over the tropical western Pacific - subsequent descent through Rossby waves and dry air intrusion aid in the weakening of rainfall over South Asia

Annamalai et al. (2013, J. Climate)
Numerical experiments performed

Monthly observed SST trend (1949 – 2000) superimposed on clim. SST – 5 members

1. Tropical oceans (GFDL – AM2.1) – results are shown

1. Tropical Indo-Pacific warm pool (GFDL - AM2.1)

1. Tropical west Pacific only (GFDL – AM2.1)

2. Linear baroclinic model (steady-state solutions) – to identify Rossby wave dynamics
Linear trend simulated by AM2.1

Dry, cool air penetrates South Asia
Summary

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

• MSE budget residuals – observational constraints over Monsoon regions

• Model improvement – need 3-d moisture and radiation observations

• Scale interactions in causing dryness over India

(long term - interannual – extended breaks)

trends El Nino BF + ISV
Additional slides
Any precursors in moist and radiative processes?

- ERA-Interim (1989-2010) -

- For composite and individual cases, apply MSE budget

  Budget estimated over (i) central India

  (ii) Eastern equatorial IO

  (iii) Tropical western Pacific

Regional circulation anomalies forced by (ii) and (iii) are important
(a) SLP and 850 hPa winds

(b) Vertical velocity 400 hPa

Day 6

(c) SLP and 850 hPa winds

(d) Vertical velocity 400 hPa

Day 9

(e) Precipitation and 850 hPa winds

(f) Moisture advection

Day 20

Rossby wave interpretation
SST rise over climatological low rainfall regions – any changes in evaporation – obs??
monsoon trough over India weakens” SLP deepens over the tropical western Pacific – “Australian and Mascarene High – intensify – cross-equatorial flow over the western Pacific is strengthened - cyclonic vorticity (regional circulation changes)
“ Despite SST rise, atmosphere over the tropical Indian Ocean has not yet responded”
Rainfall linear trend (AM21 simulated)

SLP (shaded) and 850 hPa wind

“Australian high – not consistent with reanalysis products”
“Evaporation decrease along the cross-equatorial flow is due to wind anomalies despite SST rise is prescribed in the model experiment”
Severe weak monsoon years – associated with El Nino
May averaged CM2.1 composite of anomalous 850 hPa stream line and rainfall

Severe weak monsoons over south Asia co-occurred with developing phase of El Nino

NIO – anticyclonic vorticity – within 2-3 days of SST forcing – rainfall after about 20 days

Dry air advection from north is instrumental in initiating the dryness

Pillai and Annamalai (2012, J. Atmos. Sci.)
May rainfall and 850 hPa wind response to El Nino SST forcing
Summary – Case II

“dry advection leads rainfall anomalies – long lead time – useful for prediction”