Promises and Prospects for Predicting the South Asian Monsoon

Jim Kinter

COLA
George Mason University

Many Thanks To:
Rodrigo Bombardi, Paul Dirmeyer, Mike Fennessy, Bohua Huang, Subhadeep Halder, Larry Marx, Ed Schneider, J. Shukla, R. Shukla, Chul-Su Shin, Bohar Singh

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Principal Investigators Meeting
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South Asian Monsoon

– **One of largest variations of seasonal to interannual climate observed on Earth**

– **Affects lives, property and (largely agrarian) economies of countries inhabited by nearly 25% of human population …**

– **Current state of the science**
  - **Rudimentary understanding of monsoon dynamics**
  - **Extremely limited ability to predict monsoon variations**

… either by monsoon flood …

…or by monsoon drought

South Asian Monsoon

- One of largest variations seasonal to interannual climate observed on Earth

- Affects lives, property and (largely agrarian) economies of countries inhabited by nearly 25% of human population

- **Current state of the science**
  - **Rudimentary understanding of monsoon dynamics**
  - **Demonstrable predictability of monsoon seasonal rainfall**
  - **Limited ability to actually predict monsoon variations**

COLA Proposal to India's National Monsoon Mission to Improve Monsoon Prediction

Ocean-Land-Atmosphere Coupling and Initialization Strategies to Improve CFSv2 Monsoon Prediction

- Goal 1: Improve the coupled ocean-land-atmosphere model (CFSv2) performance.
- Goal 2: Improve initialization of ocean and land states in the pre-monsoon season to improve forecasts of onset, monsoon season precipitation.
- Goal 3: Improve representation of land-atmosphere feedback in monsoon-dominated regions
- Currently < halfway through project
- Many thanks to Ministry of Earth Sciences, India

NMM-COLA Research Team

- Co-Principal Investigators
  - Prof. Paul Dirmeyer (PhD, Maryland, 1992) - L-A Feedback
  - Prof. Bohua Huang (PhD, Maryland, 1992) - Ocean Dynamics
  - Prof. Jim Kinter (PhD, Princeton, 1984) - Project PI
  - Prof. Ed Schneider* (PhD, Harvard University, 1976) - Coupled Model
- Post-doctoral Research Scientists
  - (Aug'13) Dr. Rodrigo Bombardi (PhD, UC Santa Barbara, 2013) - Coupled Model
  - (Aug'13) Dr. Subhadeep Halder (PhD, Pune, 2013) - L-A Feedback
  - (Jun'13) Dr. Chul-Su Shin (PhD, Florida State, 2012) - Ocean Dynamics
  - (Jun'14) Dr. Ravi Shukla (PhD, Allahabad, 2011) - Characterizing Monsoon
- PhD Students
  - Andrew Badger - L-A Feedback
  - Guangyang Fang - Ocean Dynamics
  - Bohar Singh - Characterizing Monsoon

*** COLA is proud of its long history of working with India (NCMRWF, IITM, U. Allahabad, …)**

Climate Forecast System version 2 (CFSv2)

- **Global coupled model: Atmosphere, Ocean, Land Surface, Sea Ice**
- **Atmosphere:** based on the NCEP Global Forecast System (GFS) used for global numerical weather prediction
  - spectral discretization at T126 resolution (~100 km grid spacing)
  - 64 vertical levels
- **Ocean:** Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 4 (MOM4)
  - 1/2° horizontal grid spacing; 1/4° meridional grid spacing in the tropics
  - 40 vertical levels
- **Land Surface:** Noah (GFS grid)
- **Sea Ice:** a modified version of the GFDL Sea Ice Simulator (MOM4 grid)

Climate Forecast System version 2 (CFSv2)

- **Global coupled model: Atmosphere, Ocean, Land Surface, Sea Ice**
- **Atmosphere:** based on the NCEP Global Forecast System (GFS) used for global numerical weather prediction

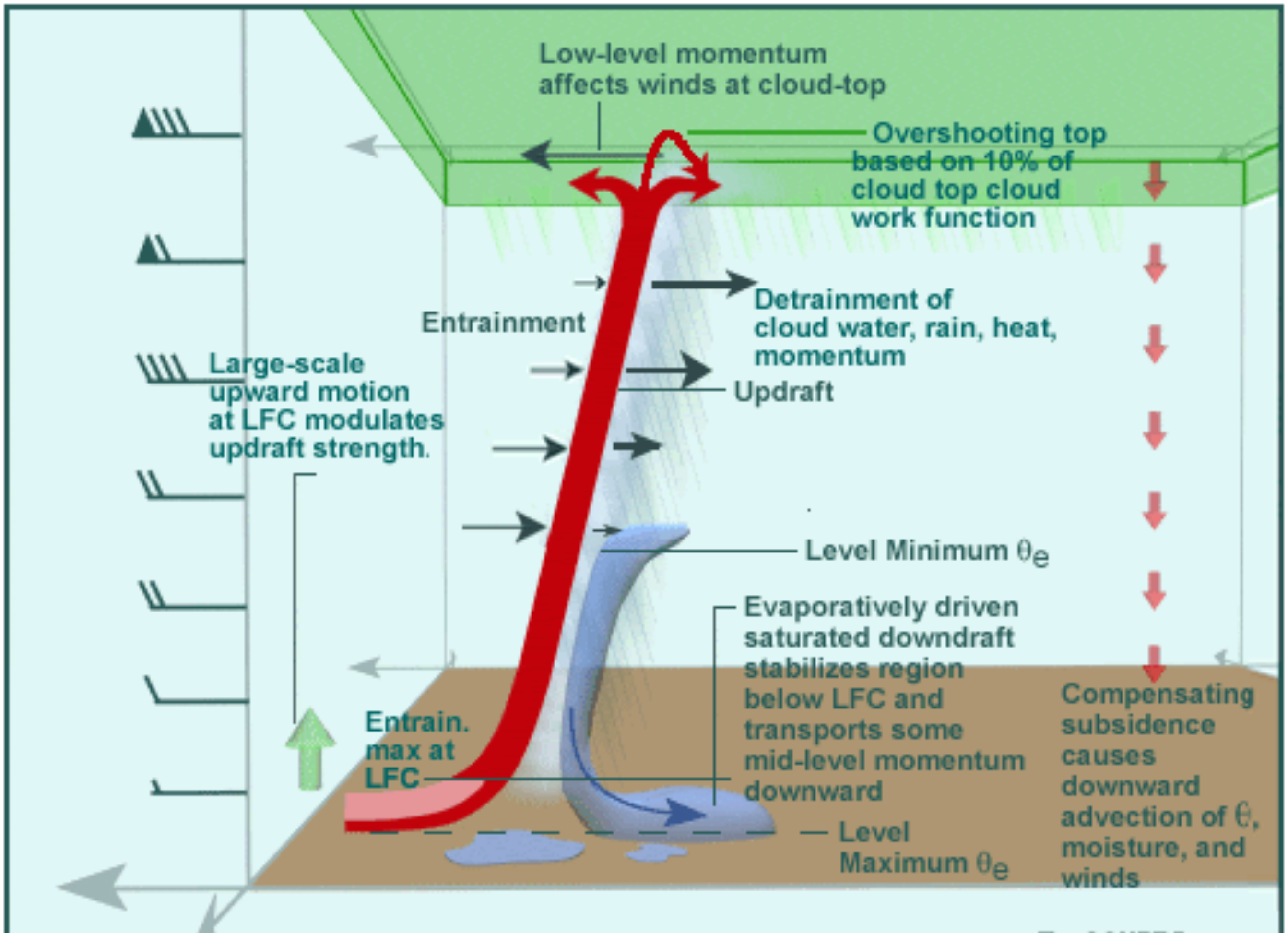
2011 Operational CFSv2 – plus COLA changes:

- **Corrected coding irregularity that produces mismatch in air-sea fluxes**
- **Corrected low value of sea ice albedo**
- **Testing various changes that can improve overall CGCM performance and especially monsoon prediction**

- **Land Surface:** Noah (GFS grid)
- **Sea Ice:** a modified version of the GFDL Sea Ice Simulator (MOM4 grid)

ROLE OF ATMOSPHERIC CONVECTION

Convective Cloud Parameterization: The Simplified Arakawa-Schubert (SAS) Scheme



Source: MetEd
http://www.meted.ucar.edu/nwp/pcu2/avncp1.htm

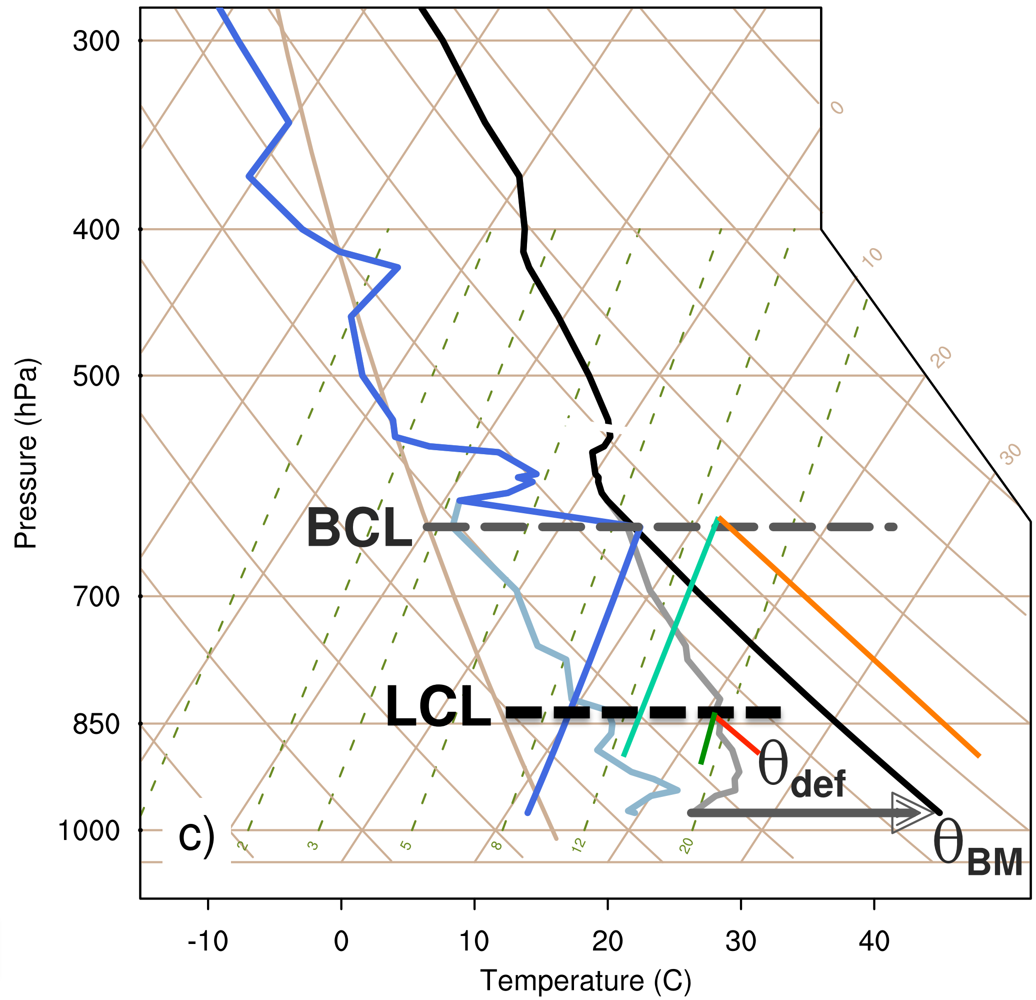
Deep Convection Trigger Mechanism:

Level of free convection (LFC) [for parcel with no sub-cloud level entrainment] being within 150-hPa of convection starting point
($\Delta P < 150$)

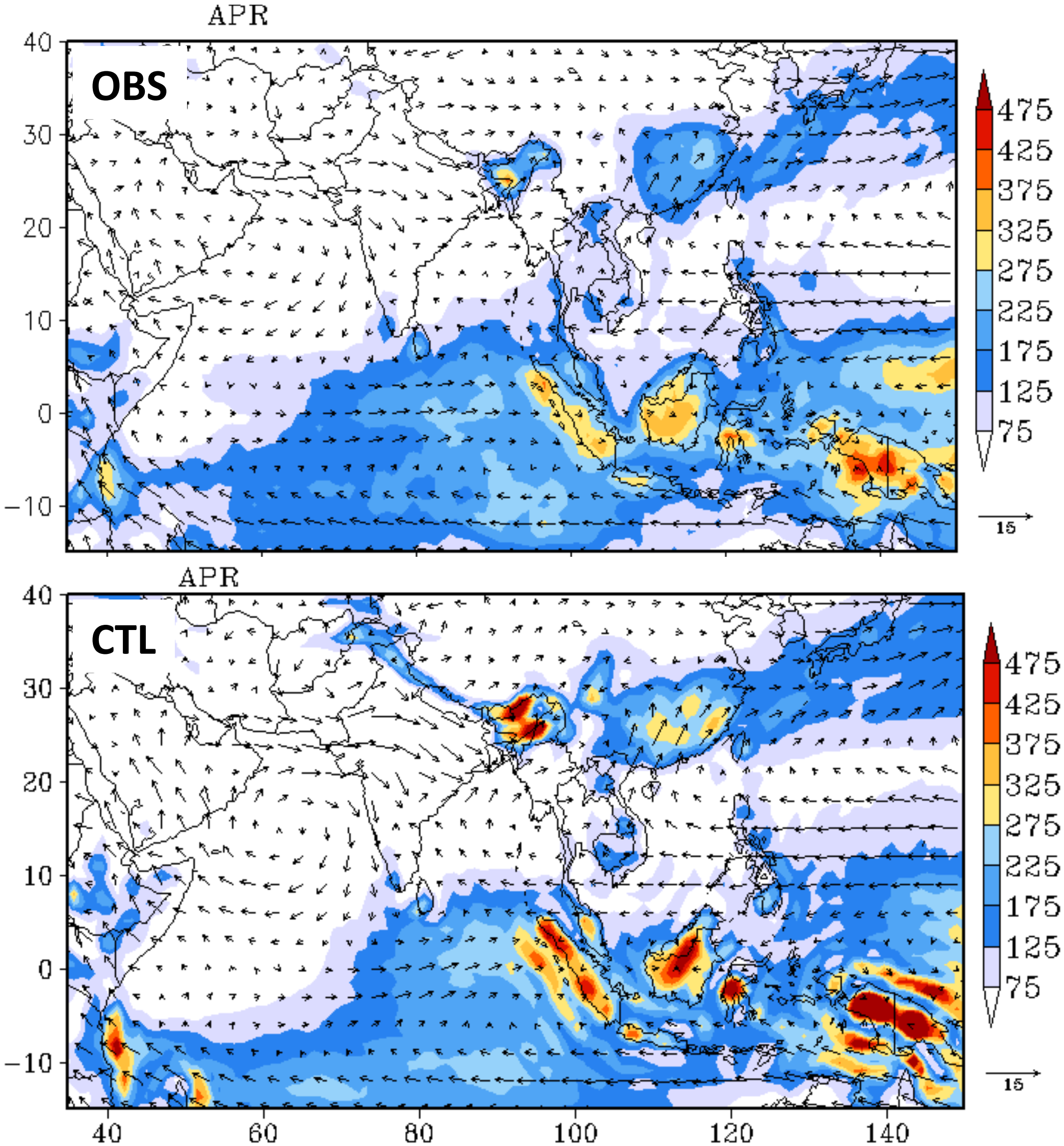
Hong & Pan (1996)

Does SAS (v1 or v2) Trigger Convection Adequately?

- Buoyant Condensation Layer (BCL): level where a heated and well-mixed boundary layer will reach saturation at the top.
- How much sensible heat flux will it take (θ_{def})?
- Can we reach saturation more quickly putting that energy into latent heat flux instead?



Tawfik & Dirmeyer, 2014: *Geophys. Res. Lett.*, 173-

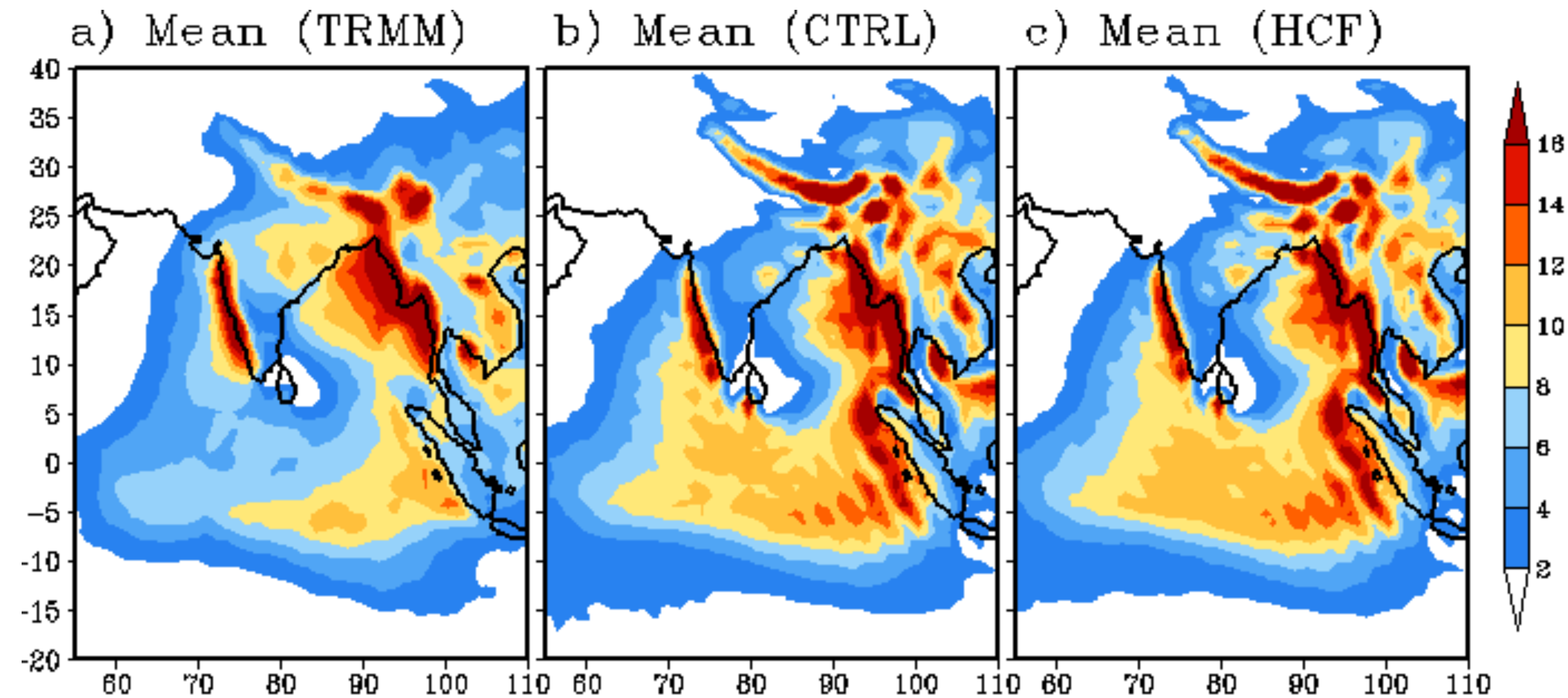


Monthly Accumulated Precip. (mm)

Experiments:

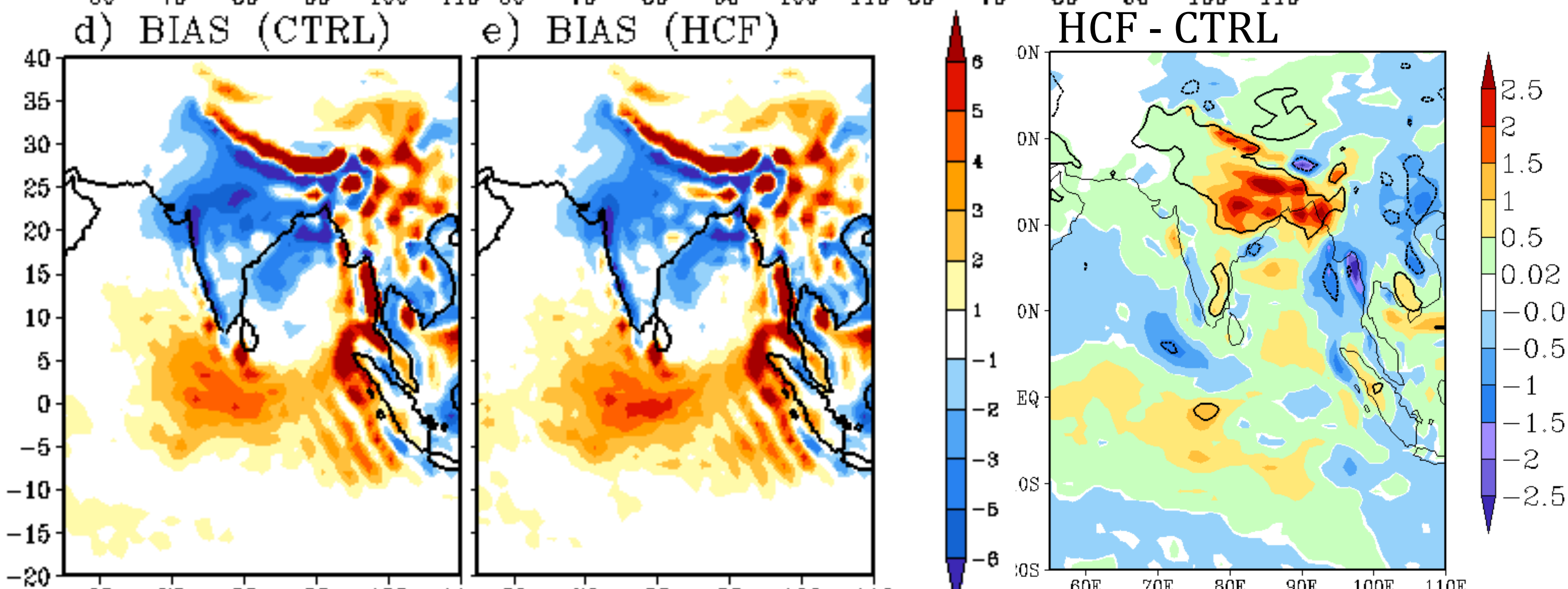
- Seasonal hindcasts
- Four members per year (1998 – 2010)
- From April to October starting on April 1,2,3, and 4
- With (HCF) and without (CTRL) the new trigger
- Additional subset tests with new SAS (Han and Pan 2011), shallow convection, and BCL cloud base criterion

Thanks to Rodrigo Bombardi



JJAS Precipitation

HCF Trigger:
Small but significant improvement of seasonal total

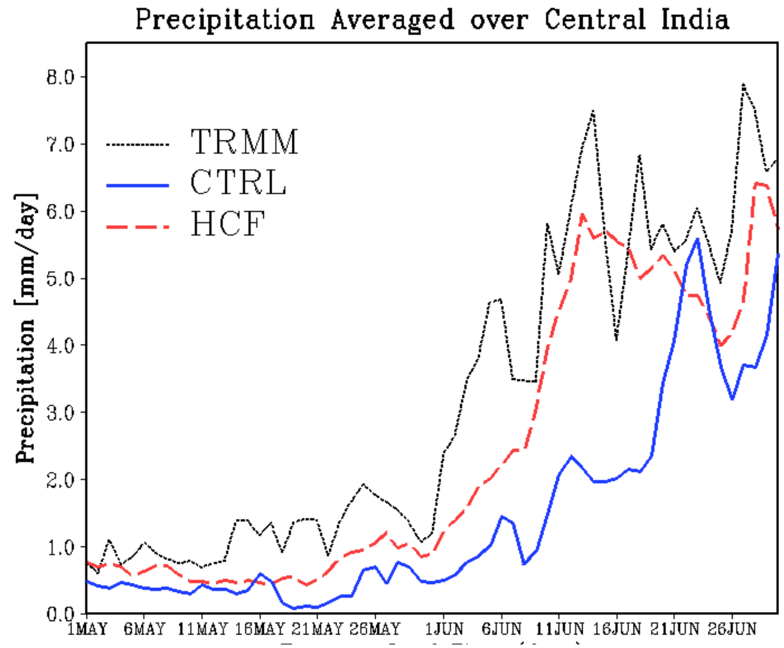


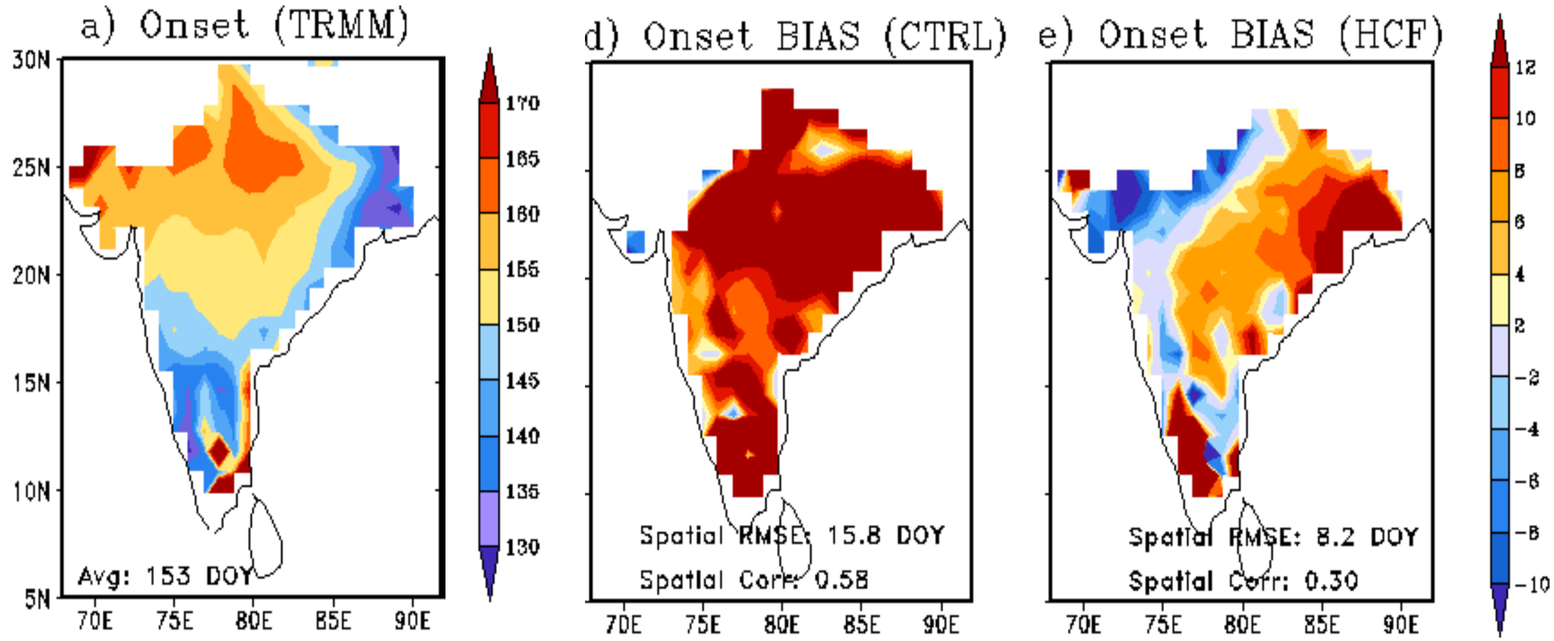
Thanks to Rodrigo Bombardi

Monsoon Onset

Improved seasonal cycle of precipitation

Improved rainy season onset dates.



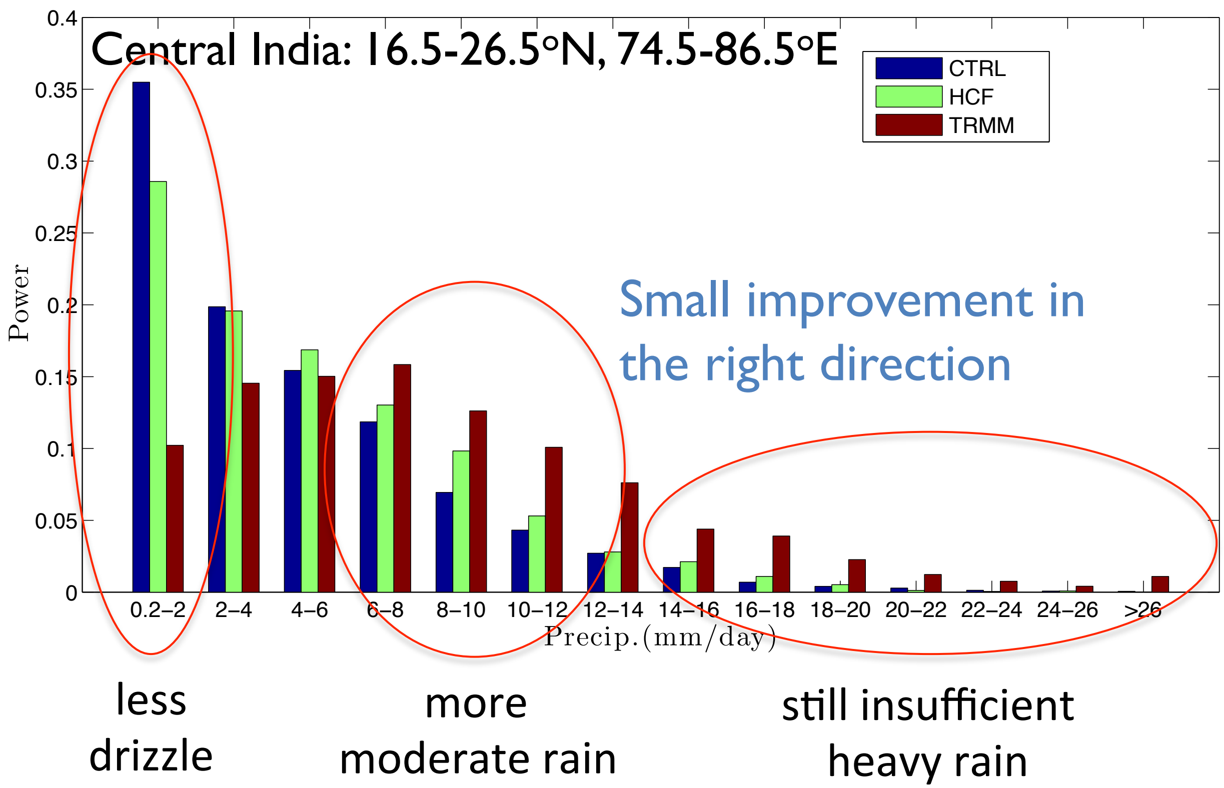


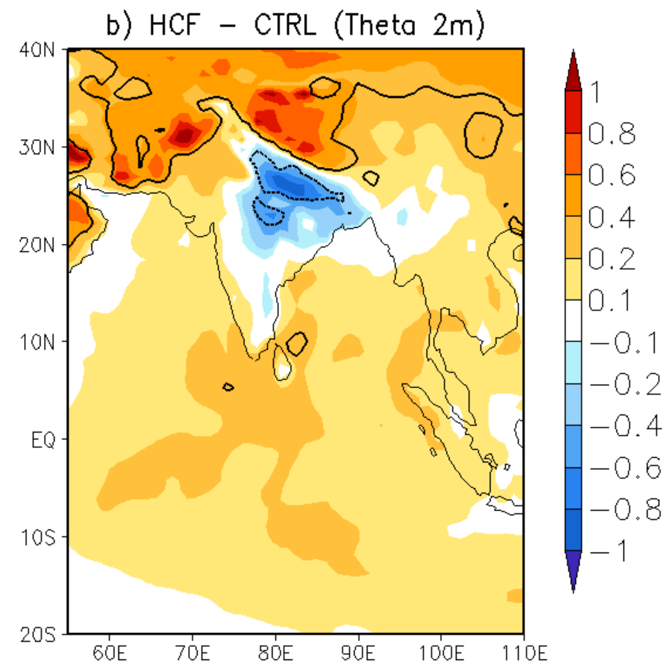
Thanks to Rodrigo Bombardi

Mechanisms

The new trigger is an alternative condition

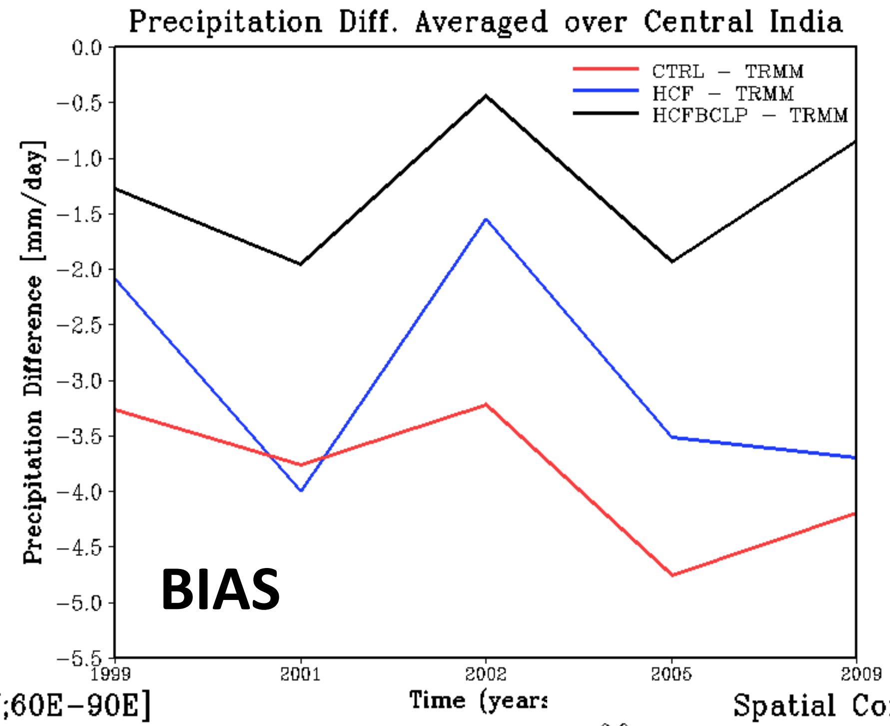
- Better representation of the background state of convection
- SAS triggers more frequently – produces more rainfall overall





Thanks to Rodrigo Bombardi

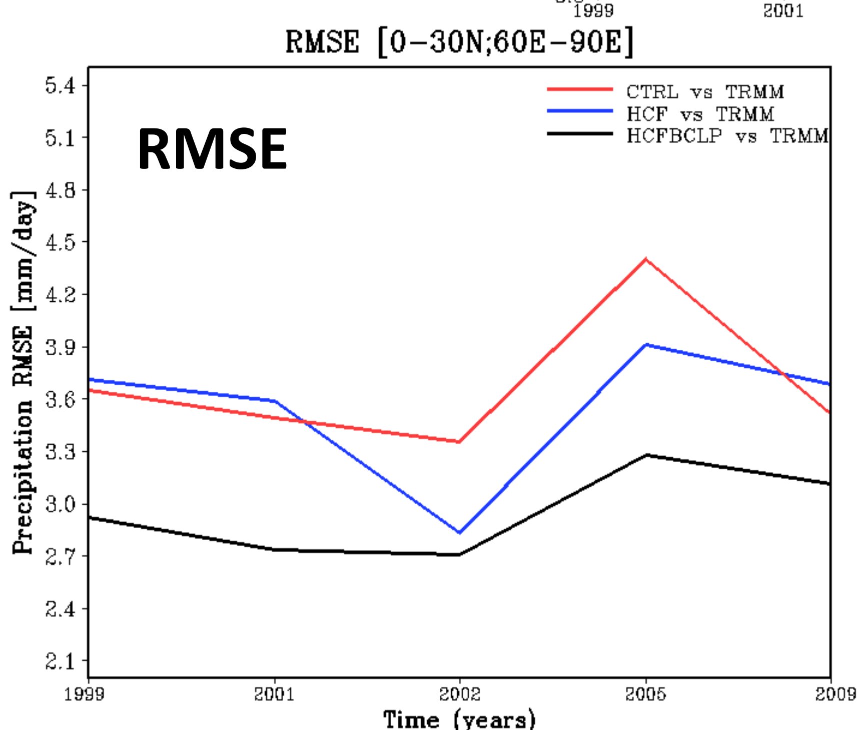
Central India
JJAS Precip

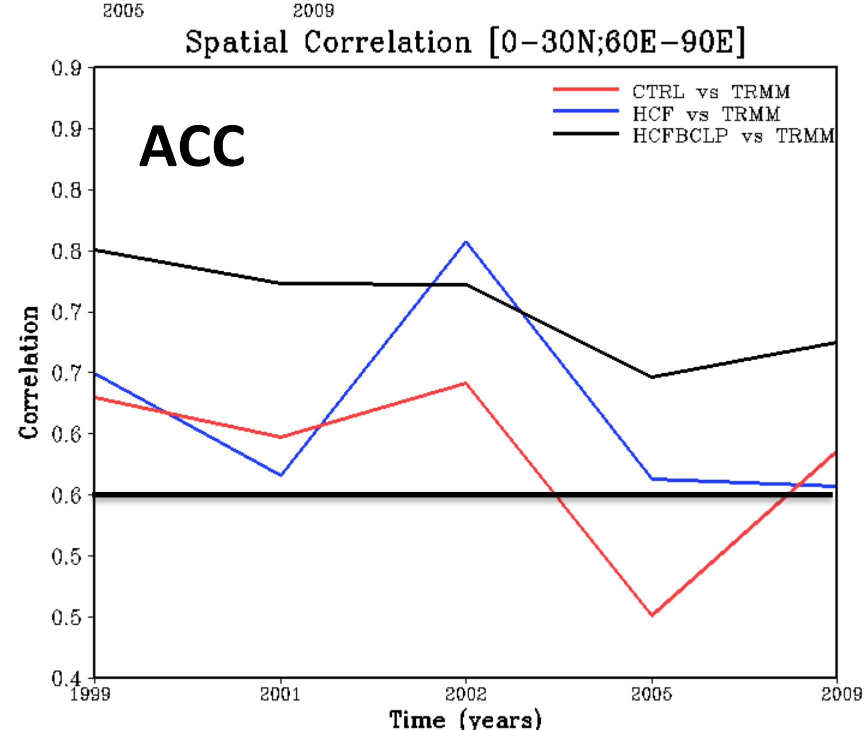


CTRL

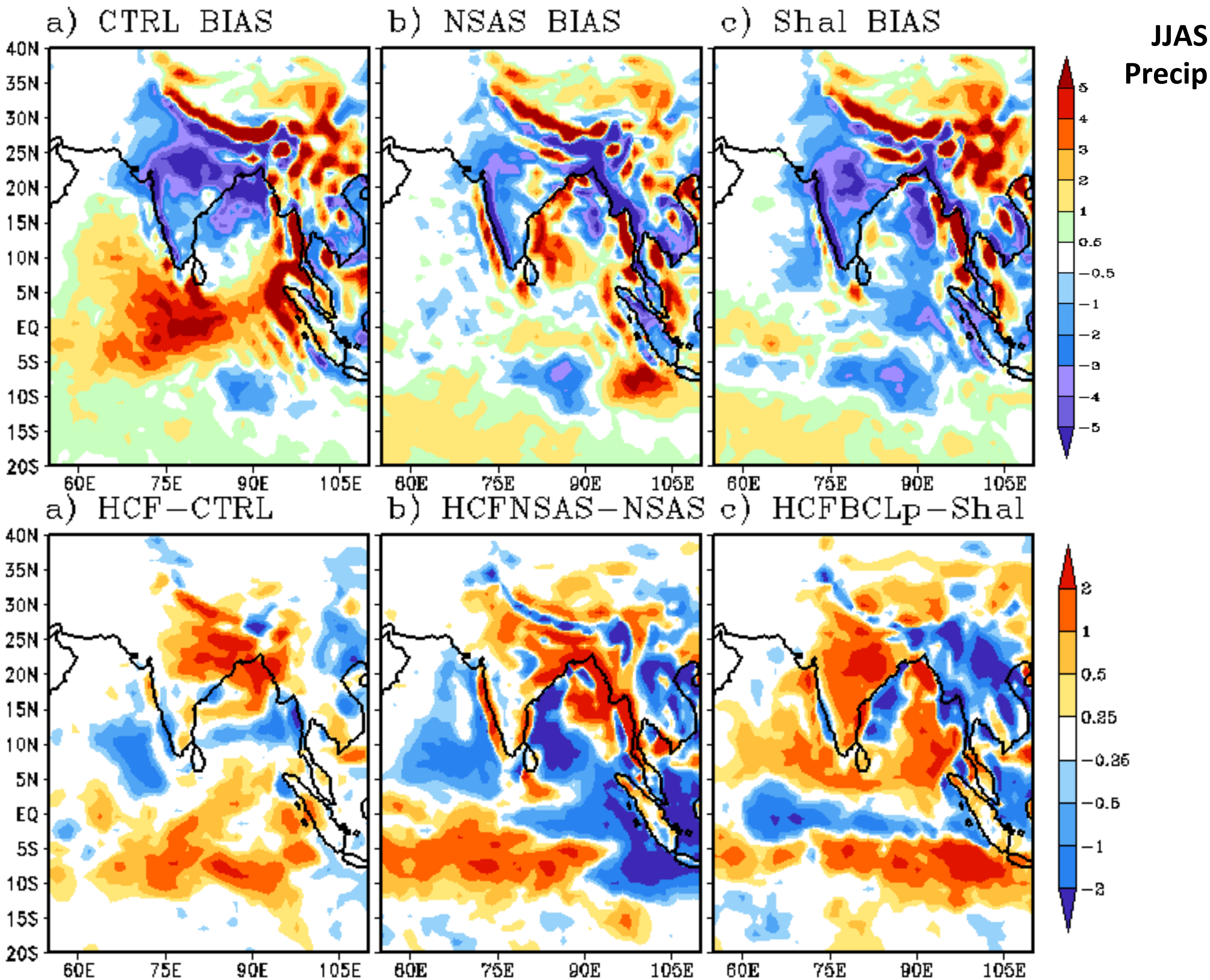
HCF

HCF/BCL

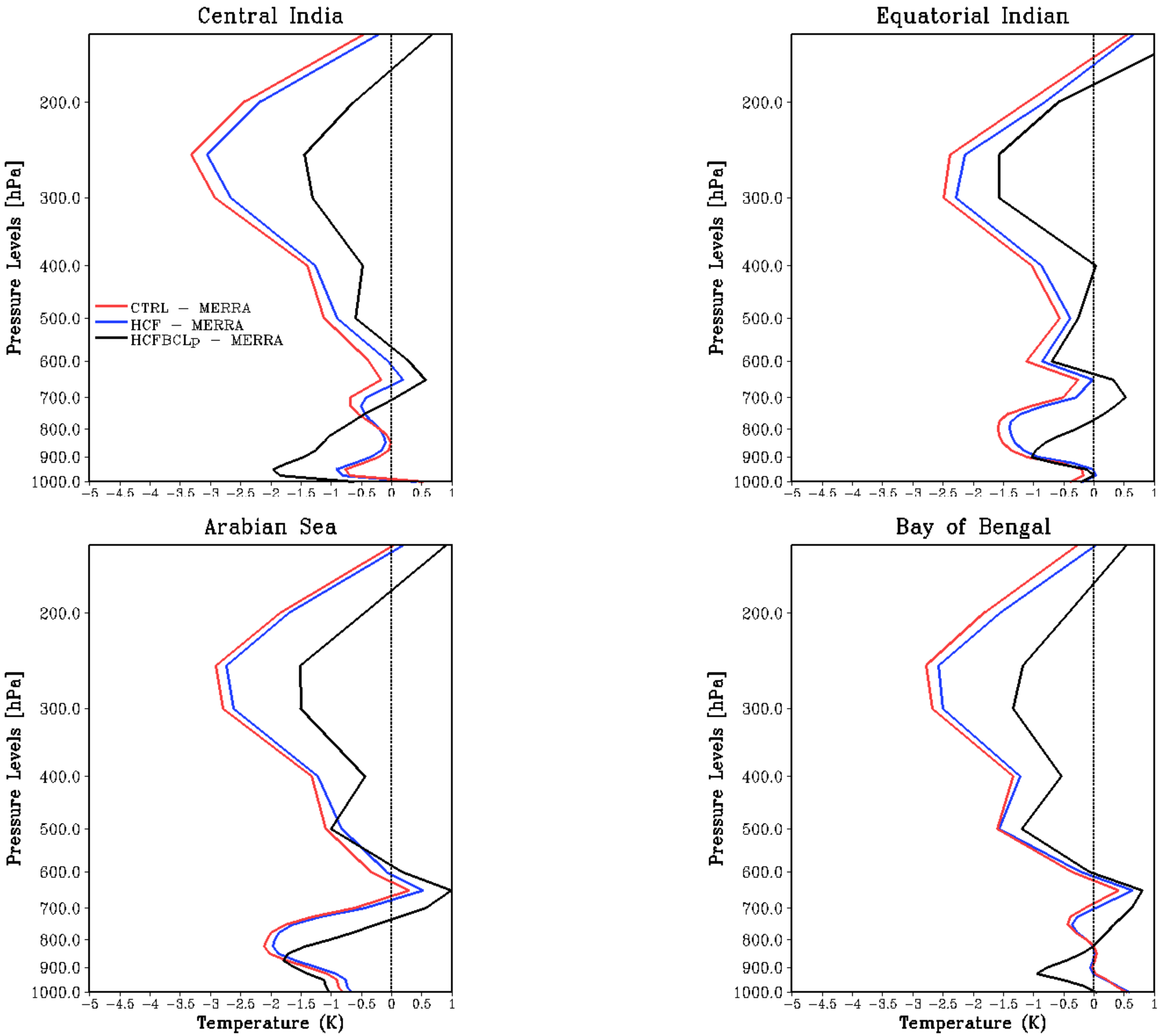




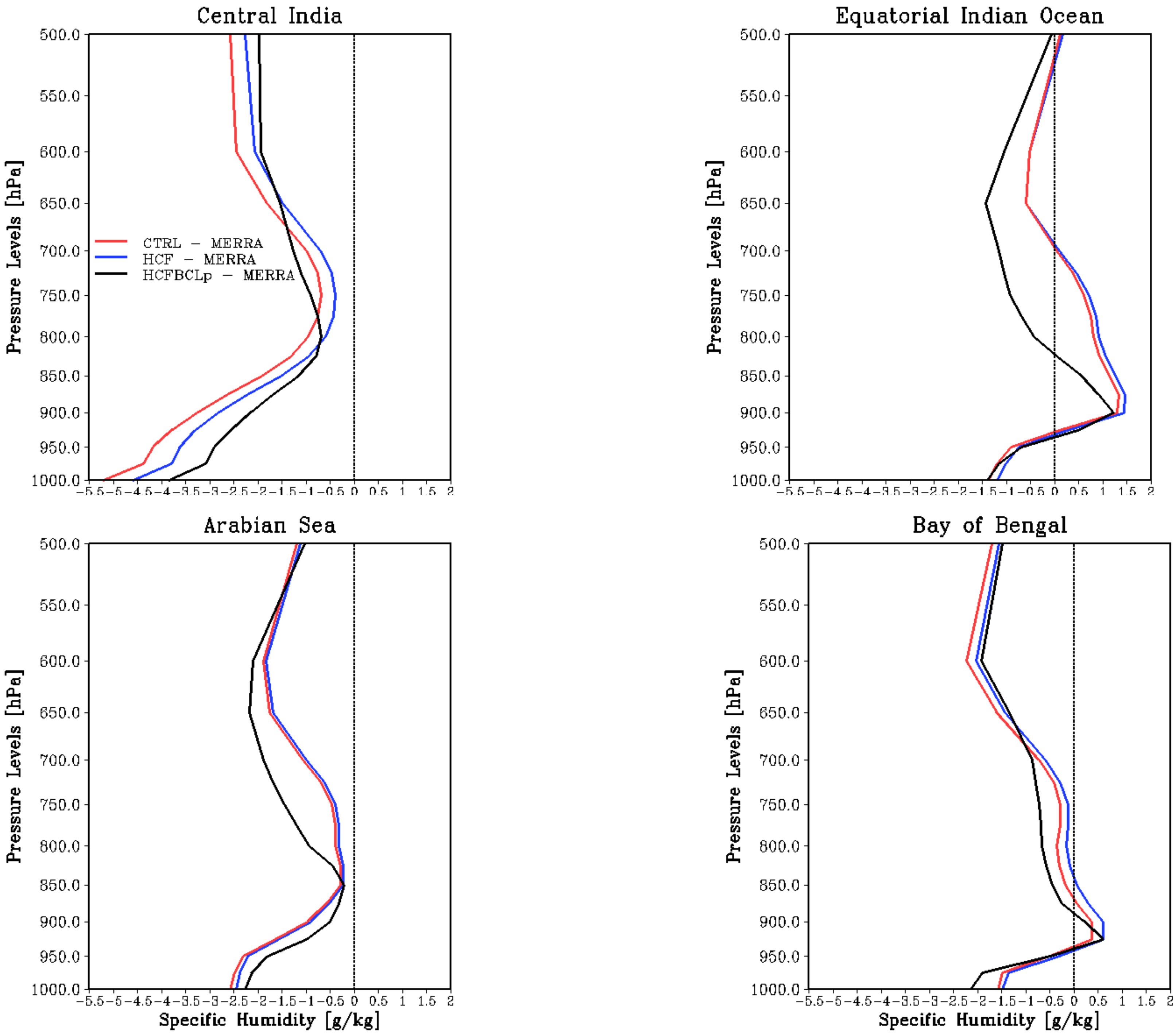
See Poster by Singh et al.



JJAS
Precip
a) CTRL BIAS
b) NSAS BIAS
c) Shal BIAS
a) HCF−CTRL
b) HCFNSAS−NSAS
c) HCFBCLp−Shal
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
60E
75E
90E
105E
5
4
3
2
1
0.5
−0.5
−1
−2
−3
−4
−5
2
1
0.5
0.25
−0.25
−0.5
−1
−2



Central India
Equatorial Indian
Arabian Sea
Bay of Bengal
CTRL – MERRA
HCF – MERRA
HCFBCLp – MERRA
Pressure Levels [hPa]
Temperature (K)
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
–5 –4.5 –4 –3.5 –3 –2.5 –2 –1.5 –1 –0.5 0 0.5 1


Central India
Equatorial Indian Ocean
Arabian Sea
Bay of Bengal
Pressure Levels [hPa]
Specific Humidity [g/kg]
CTRL – MERRA
HCF – MERRA
HCFBCLp – MERRA
500.0
550.0
600.0
650.0
700.0
750.0
800.0
850.0
900.0
950.0
1000.0
−5.5 −5 −4.5 −4 −3.5 −3 −2.5 −2 −1.5 −1 −0.5 0 0.5 1 1.5 2

LAND-ATMOSPHERE FEEDBACKS

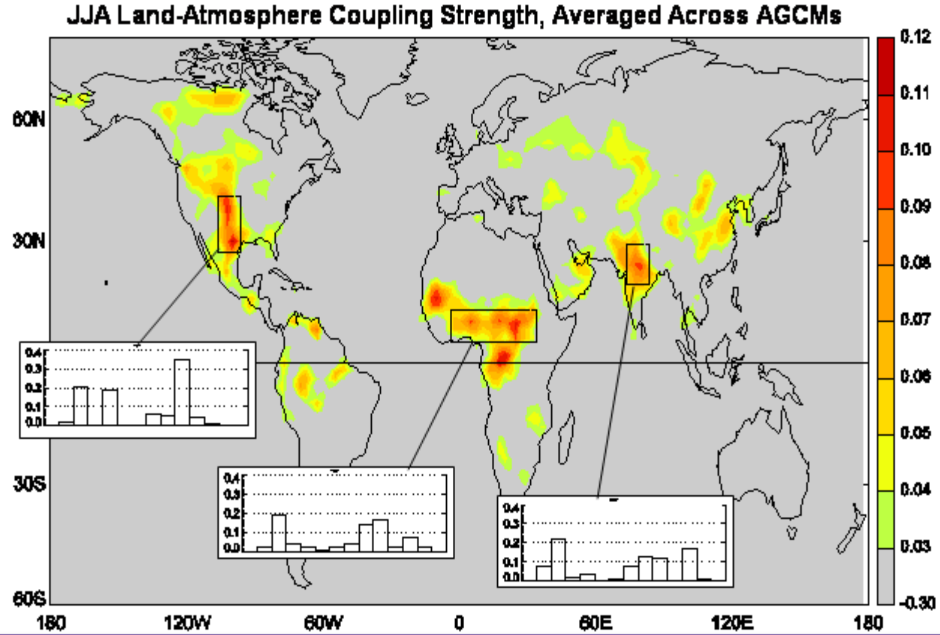
Ingredients for Coupled L-A Feedbacks

- Coupling
  - When/where is there active feedback from land surface to atmosphere?
  - Two-legged: *Terrestrial*: Land surface state → surface fluxes
    Atmospheric: Surface fluxes → atmospheric processes
- Variability
  - The forcing has to fluctuate sufficiently in time for a correlation to result in a significant impact (important to have good measurements of soil moisture and state of vegetation)
- Memory
  - The forcing anomaly has to persist, or else the impact will be minimal

We also need good models, and accurate initial conditions.

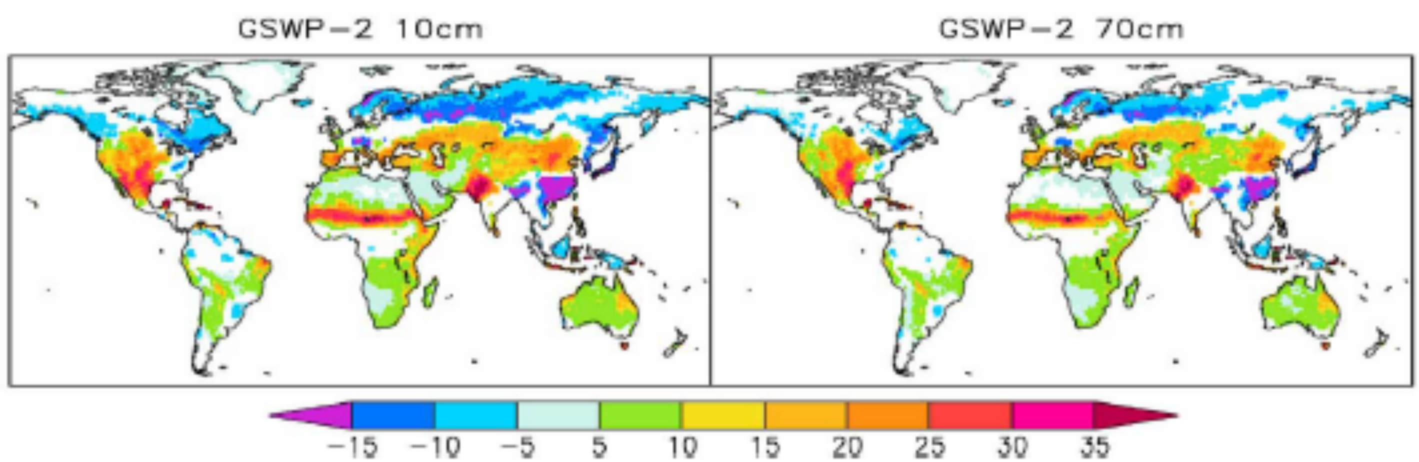
Hot Spots

The **Global Land-Atmosphere Coupling Experiment (GLACE)** : A joint GEWEX/CLIVAR modeling study



Koster, et al., 2004: *Science*. Dirmeyer, et al., 2006: *JHM*. Guo, et al., 2006: *JHM*. Koster, et al., 2006: *JHM*.

Multi-model results indicate that there are geographic "hot spots" where the atmosphere is responsive to the state of the land surface (soil moisture) = potential predictability.

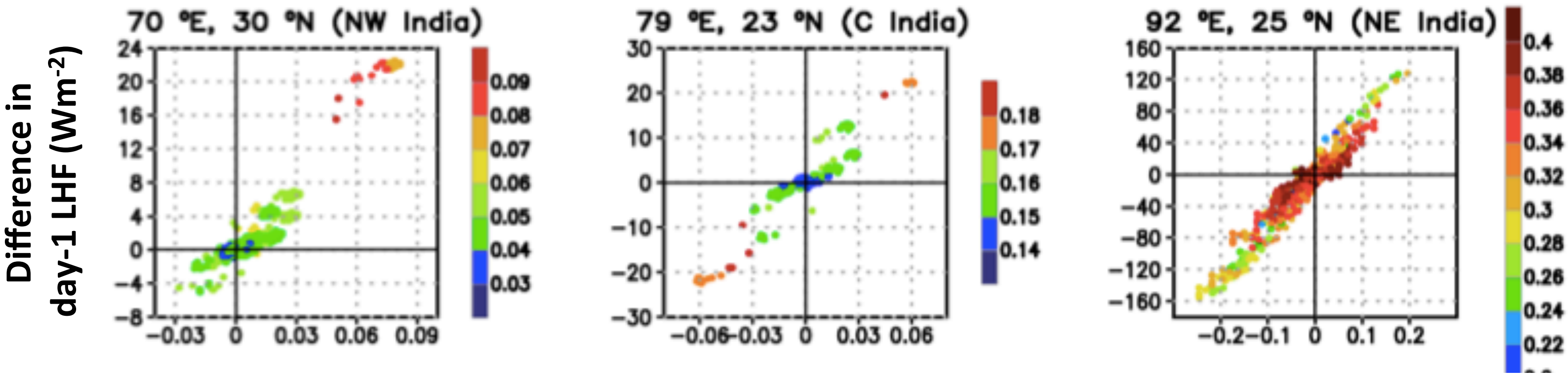


Terrestrial coupling index

Dirmeyer, P.A., 2011, GRL

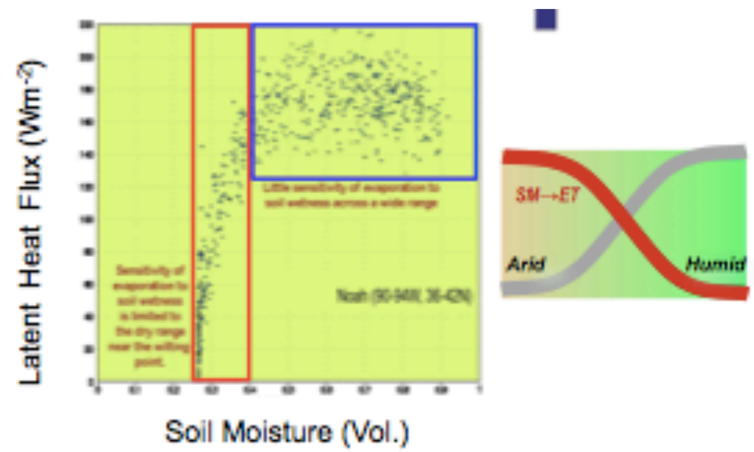
Thanks to Paul Dirmeyer

Spatial Variation of Sensitivity



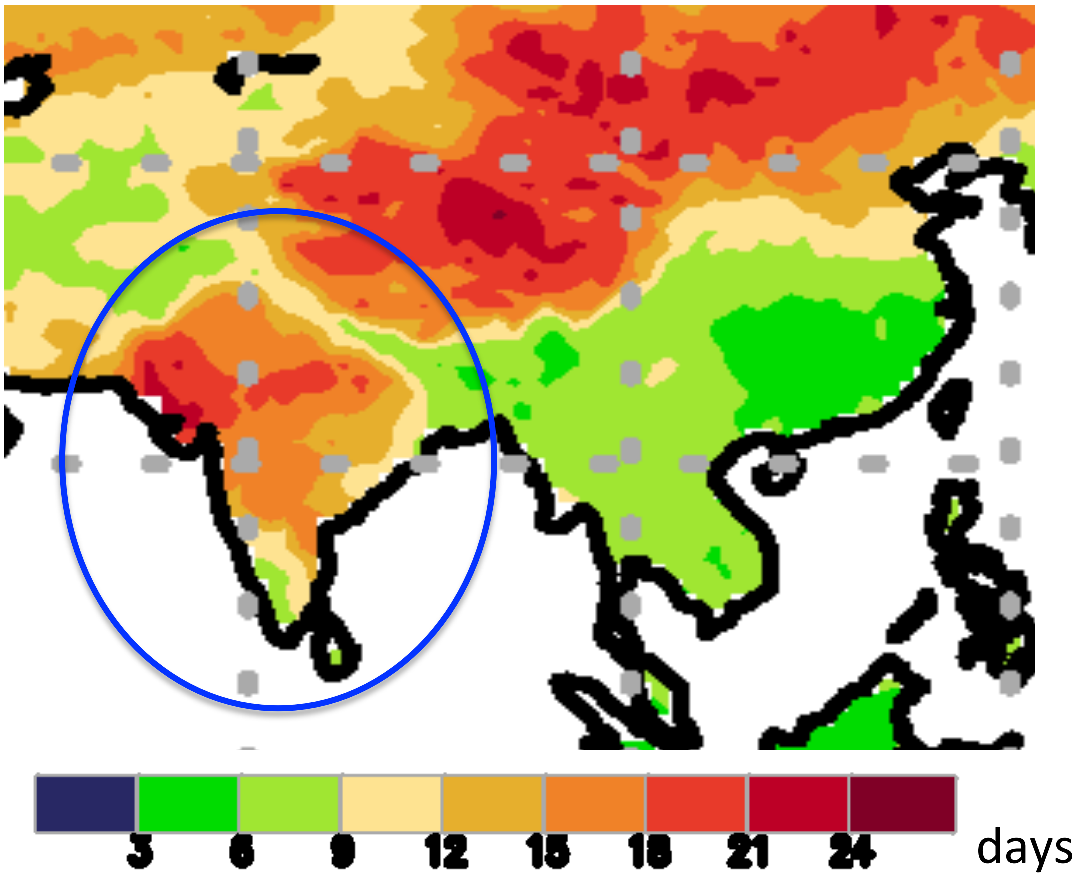
Difference in volumetric surface soil moisture initial state

Over the extreme north-west (dry), central (humid) and northeast (wet) India, correlation of LHF with SM is positive, but it strongly depends on the initial soil moisture condition and availability of radiation in June.



Thanks to Subhadeep Halder

Soil Moisture Memory (GLDAS-2)



Thanks to Subhadeep Halder

Design of experiments for studying impact of land surface initialization

ATM/ OCEAN INITIAL CONDITIONS \ LAND INITIAL CONDITIONS		0000Z 01APRIL							0000Z 01MAY							0000Z 01JUNE						
		1982	1983	1984	.....	2007	2008	2009	1982	1983	1984	....	2007	2008	2009	1982	1983	1984	....	2007	2008	2009
0000Z 01 APRIL	1982																					
	1983																					
	1984																					
	....																					
	2008																					
	2009																					
0000Z 01 MAY	1982																					
	1983																					
	1984																					
	....																					
	2008																					
	2009																					
0000Z 01 JUNE	1982																					
	1983																					
	1984																					
	....																					
	2008																					
	2009																					

All experiments continued till 0000Z 01 October of that year. In all, 784 simulations for each IC (total 1568 for May and June IC) are made, all 6-hrly data are averaged to daily values. Simulations with April IC are going on.

OCEAN INITIALIZATION

Multiple Ocean Initial Conditions (OICs) for CFSv2

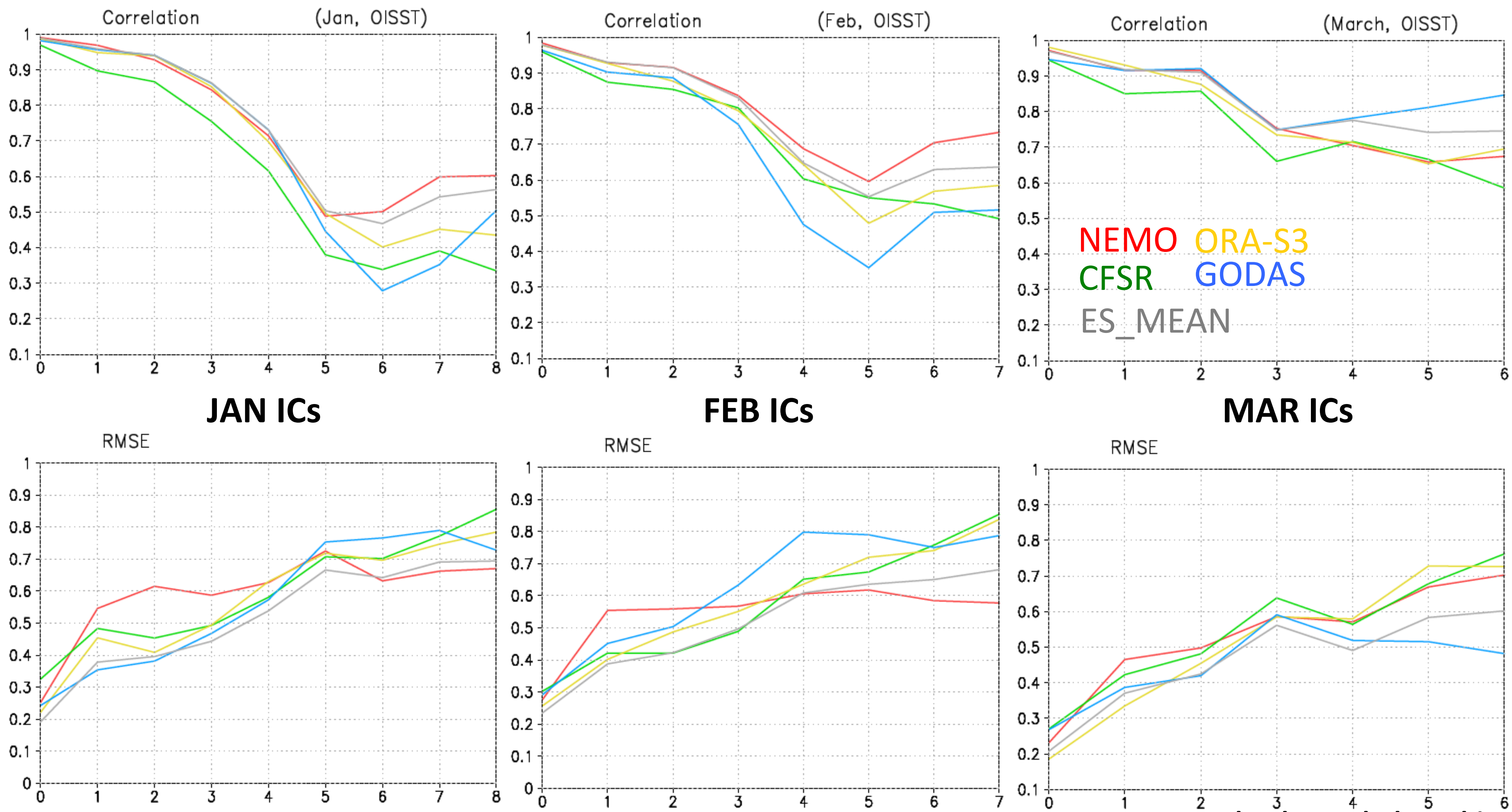
1. Four different ocean data sets
   - ECMWF **Combine-NV (NEMO)**
   - NCEP **CFSR** (Climate Forecast System Reanalysis)
   - ECMWF **ORA-S3** (Ocean Reanalysis System3; HOPE model)
   - NCEP **GODAS** (Global Ocean data Assimilation System)
2. Variables
   - Monthly mean **potential temperature**[°C], **salinity**[g/kg], **u**[m/s], **v**[m/s]
3. Pre-Processing
   - **Filling up (extrapolation) the land mass** to make up potential gaps due to different land-sea masks between each ocean analysis and MOM4 (Note that zonal mean of each variable is initially assigned to grids over the land as an initial guess.)
4. Period: 1979-2009 (Jan. – May)

CFSv2 Retrospective Forecasts with 4 OICs

OICs / Initial month	**NEMO** (4mem*30yrs)	**CFSR** (4mem*31yrs)	**ORA-S3** (4mem*31yrs)	**GODAS** (4mem*31yrs)
May (5-month lead)				
April (6-month lead)				
March (7-month lead)				
February (8-month lead)				
January (9-month lead)				
	600 runs completed	***620 runs completed***	***620 runs completed***	***620 runs completed***

** 4 members : 1st 4 days (00Z) of each month using the atmosphere/land surface conditions from CFSR*

CFSv2 Prediction Skill of NINO3.4 (1982-2008) vs. OISST



Thanks to Chul-Su Shin

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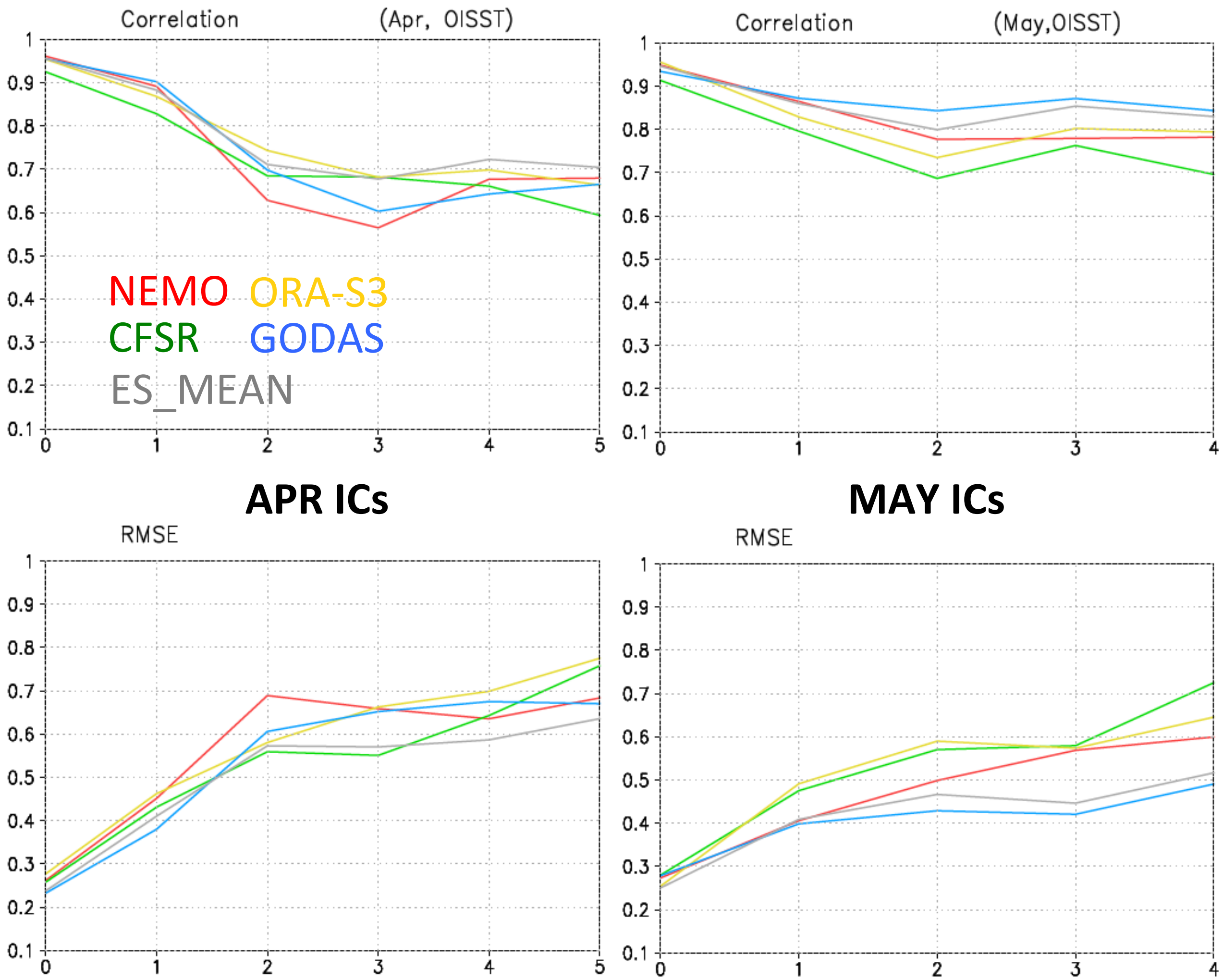

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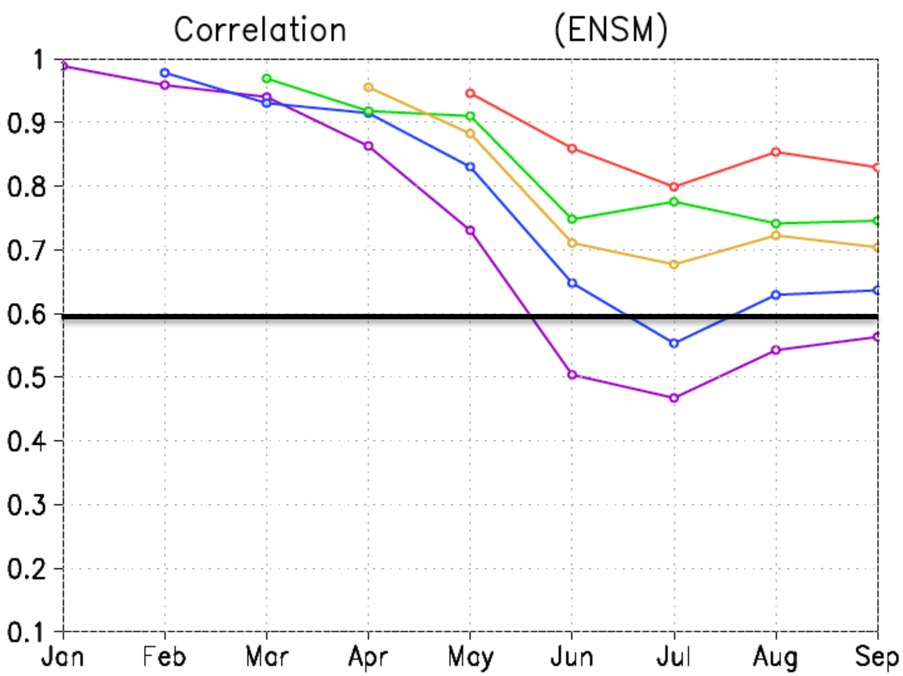
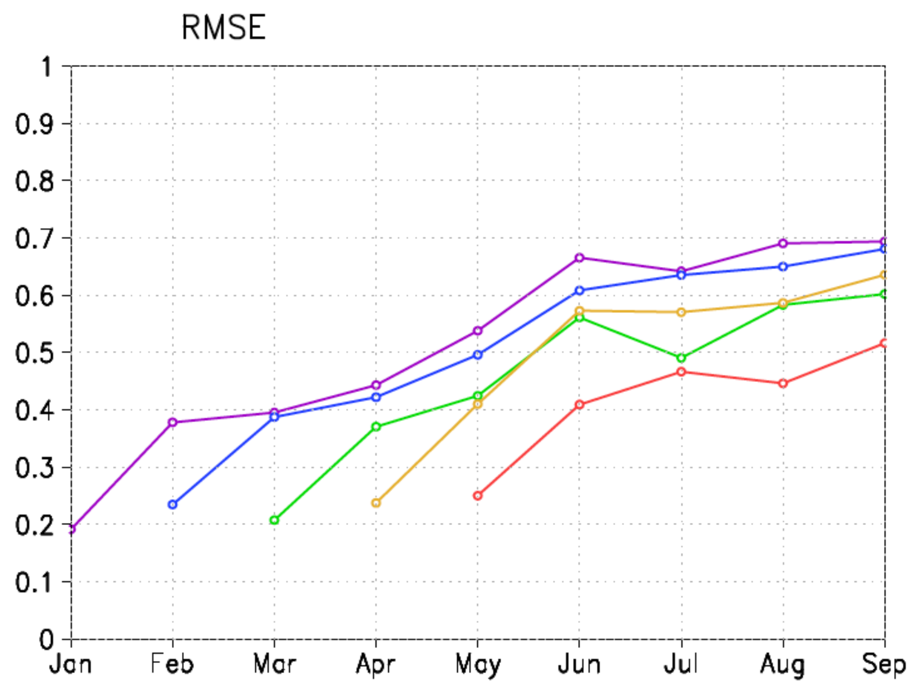


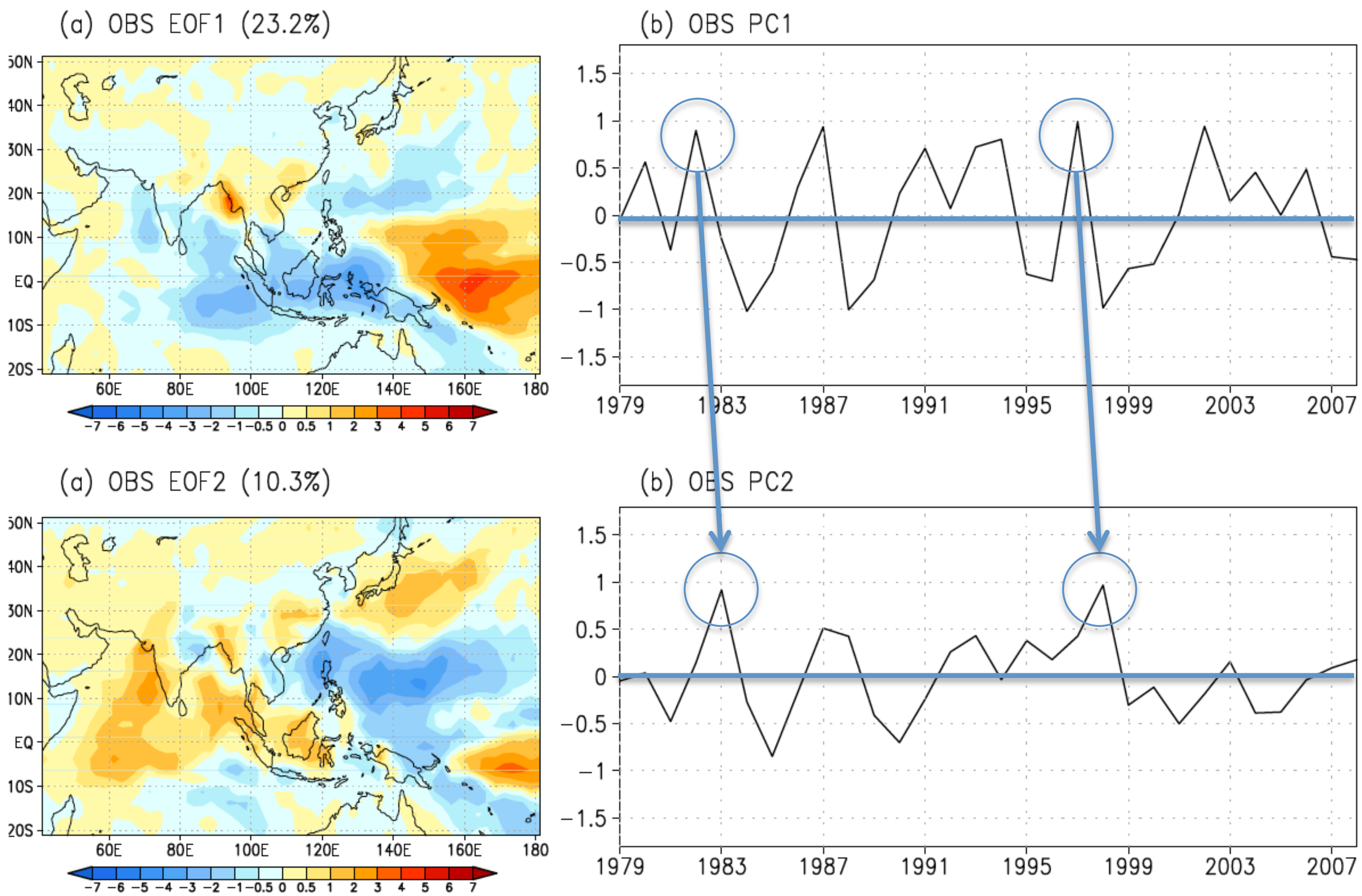


Multiple Ocean Analyses Ensemble Mean

Thanks to Chul-Su Shin

CHARACTERIZING MONSOON VARIABILITY W.R.T. ENSO (HINDCASTS)

2 Dominant Modes of JJAS Mean Precip



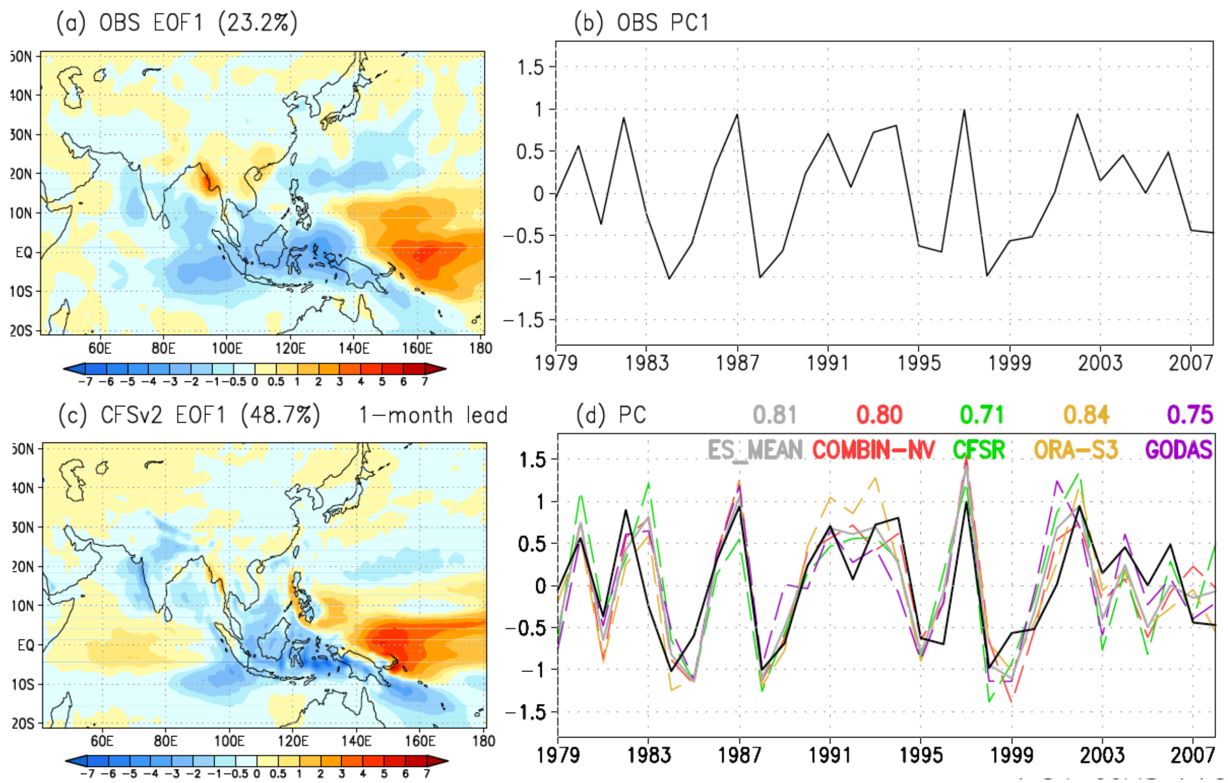
corresponds to ENSO *onset* years

corresponds to ENSO *decay* years

(1979 – 2008; linear trend removed)

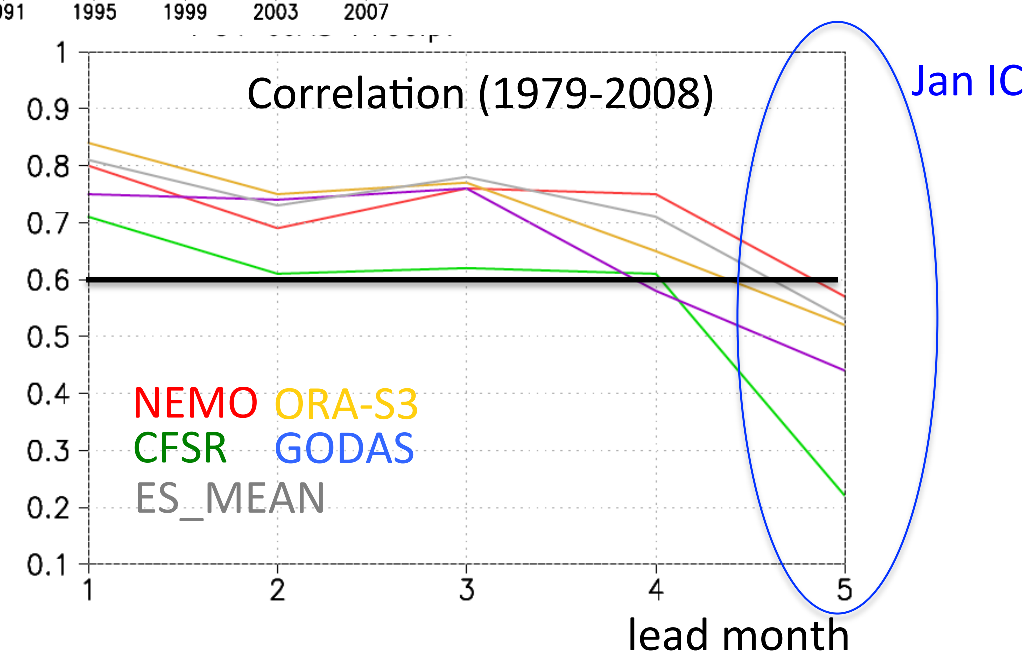
Thanks to Chul-Su Shin

1^{st} EOF Mode



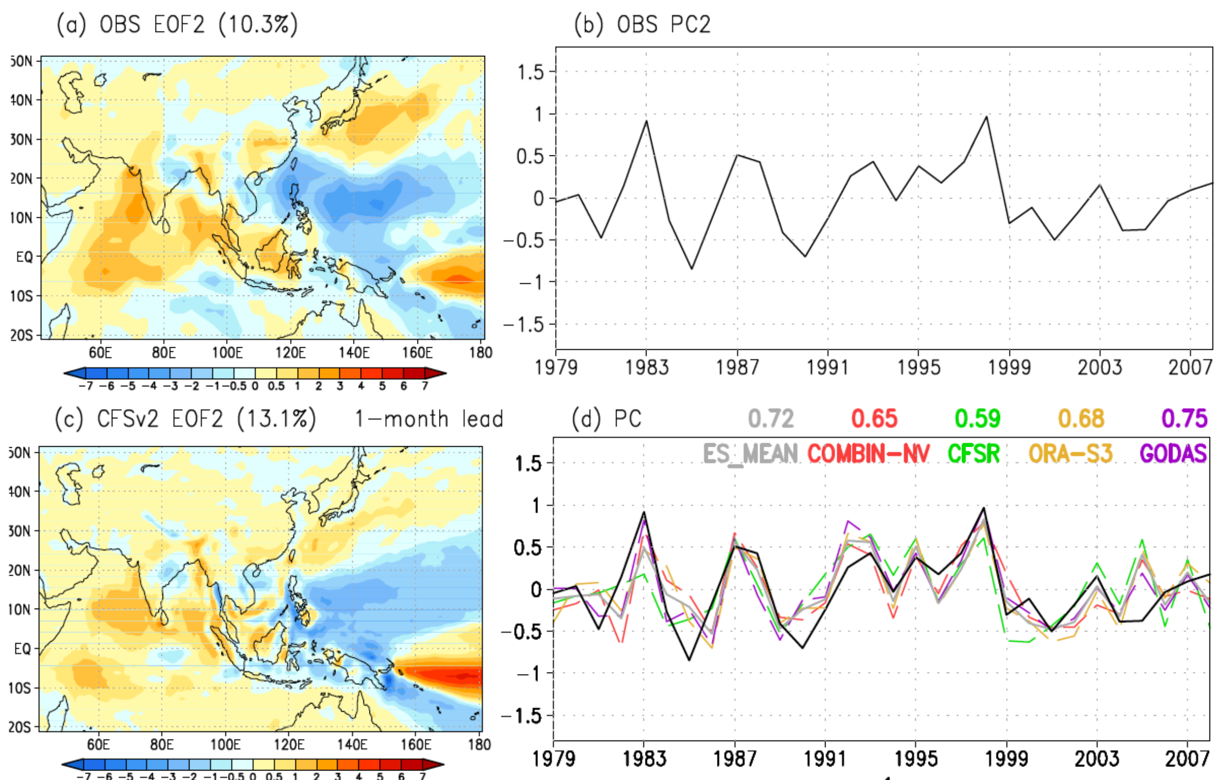
CMAP

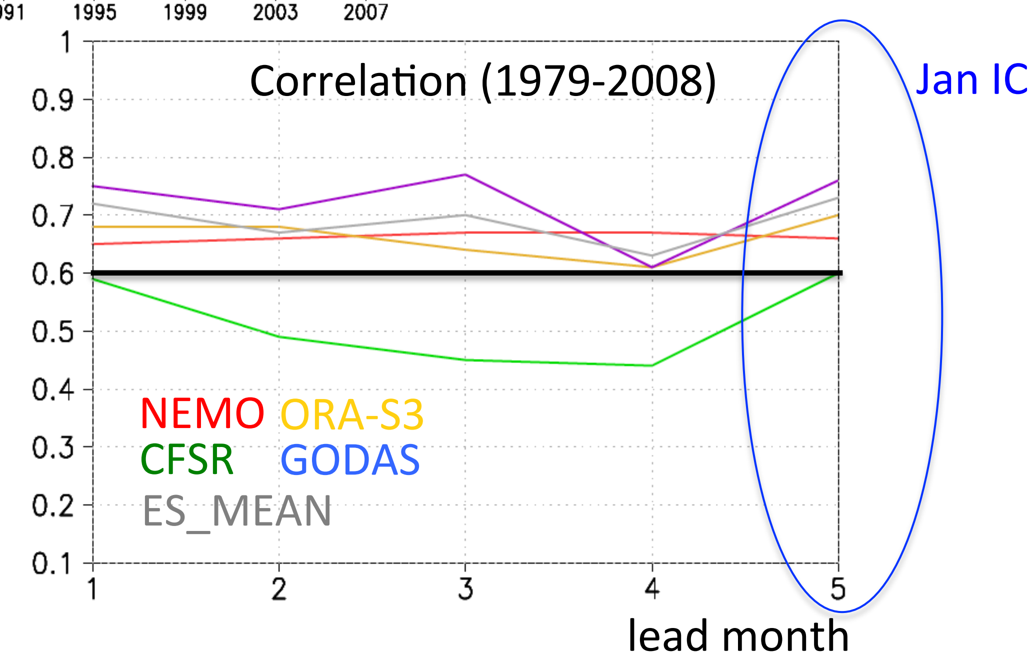
CFSv2



Thanks to Chul-Su Shin

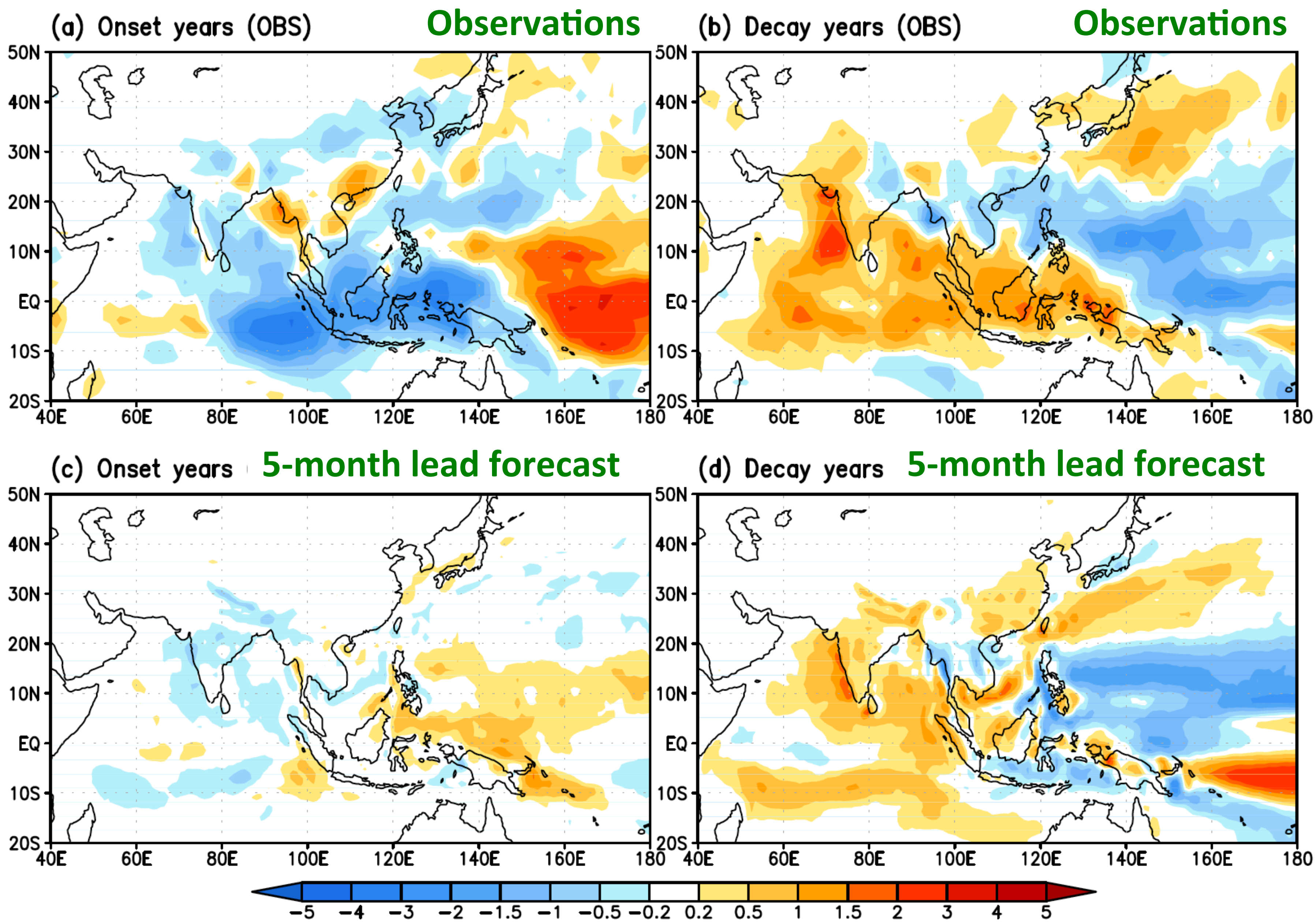
2nd EOF Mode





Thanks to Chul-Su Shin

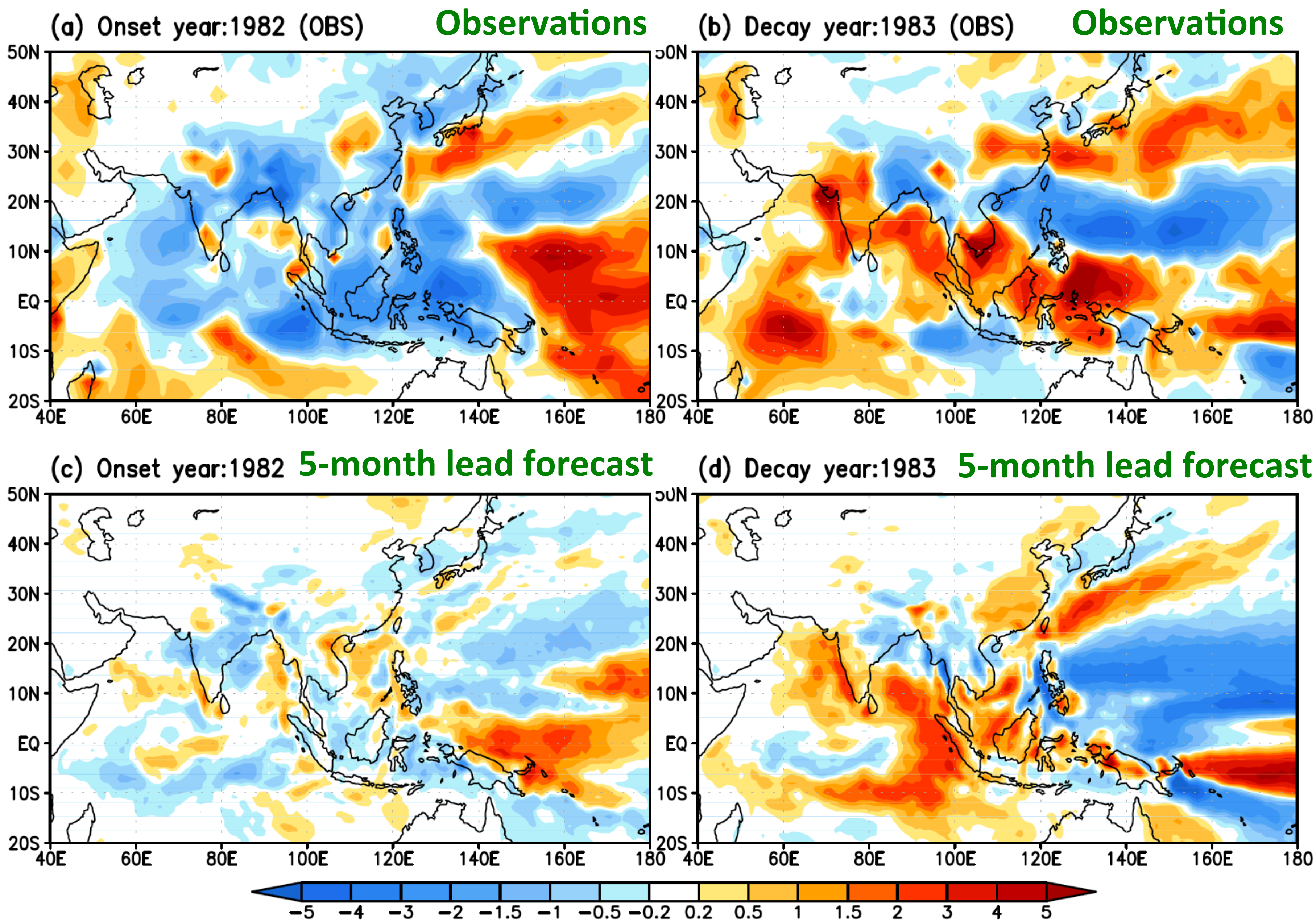
ENSO Warm Composite - JJAS Mean Rainfall Anomaly



Thanks to Chul-Su Shin

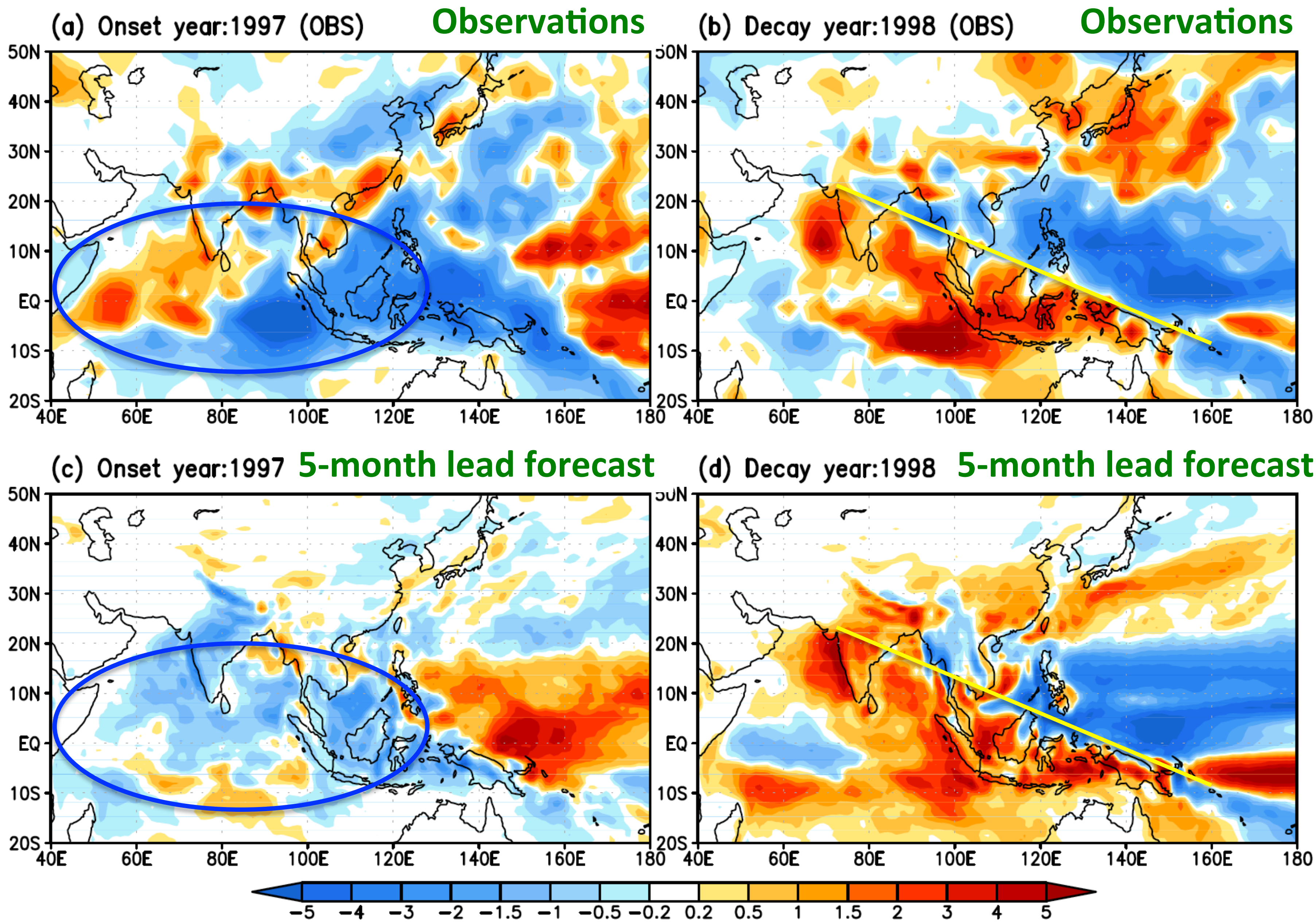
* Events: ’82-83, ’87-88, ’91-92, ’94-95, ’97-98, ’02-03, ’06-07

ENSO Warm Event ('82-'83) JJAS Mean Rainfall Anomaly



Thanks to Chul-Su Shin

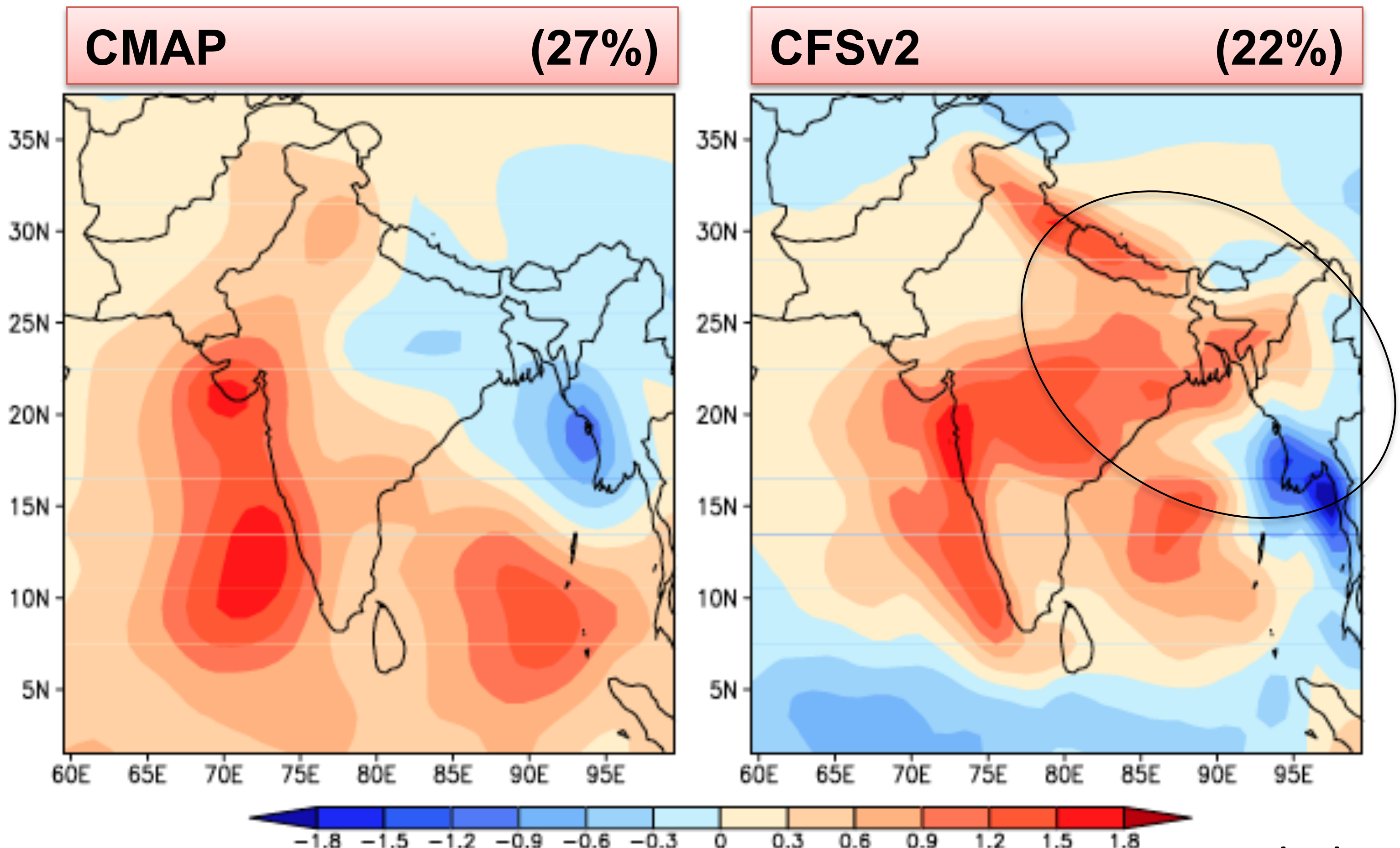
ENSO Warm Event ('97-'98) JJAS Mean Rainfall Anomaly



Thanks to Chul-Su Shin

CHARACTERIZING MONSOON VARIABILITY W.R.T. ENSO (LONG RUN)

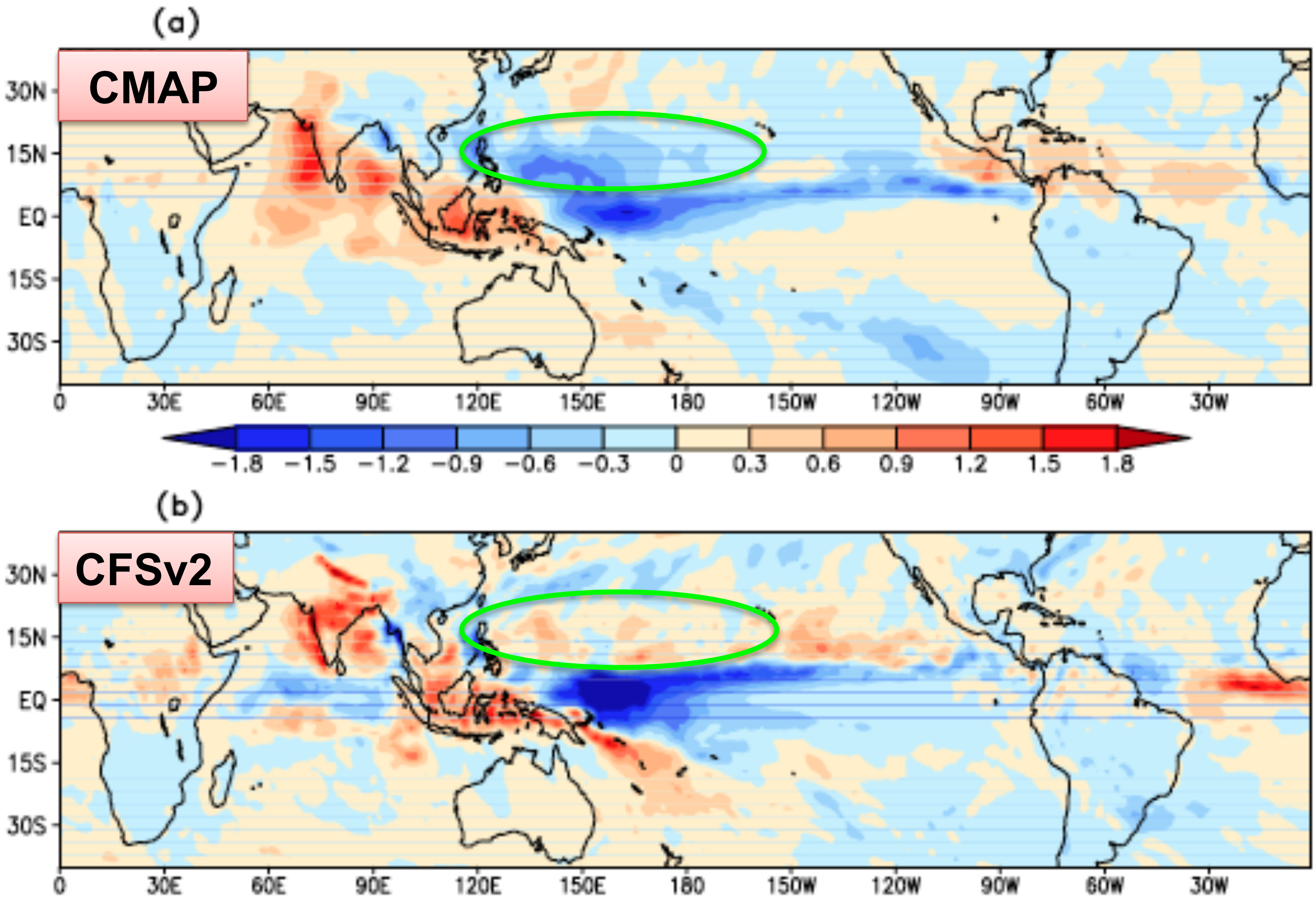
JJAS rainfall (regional) EOF-1



Thanks to Ravi Shukla

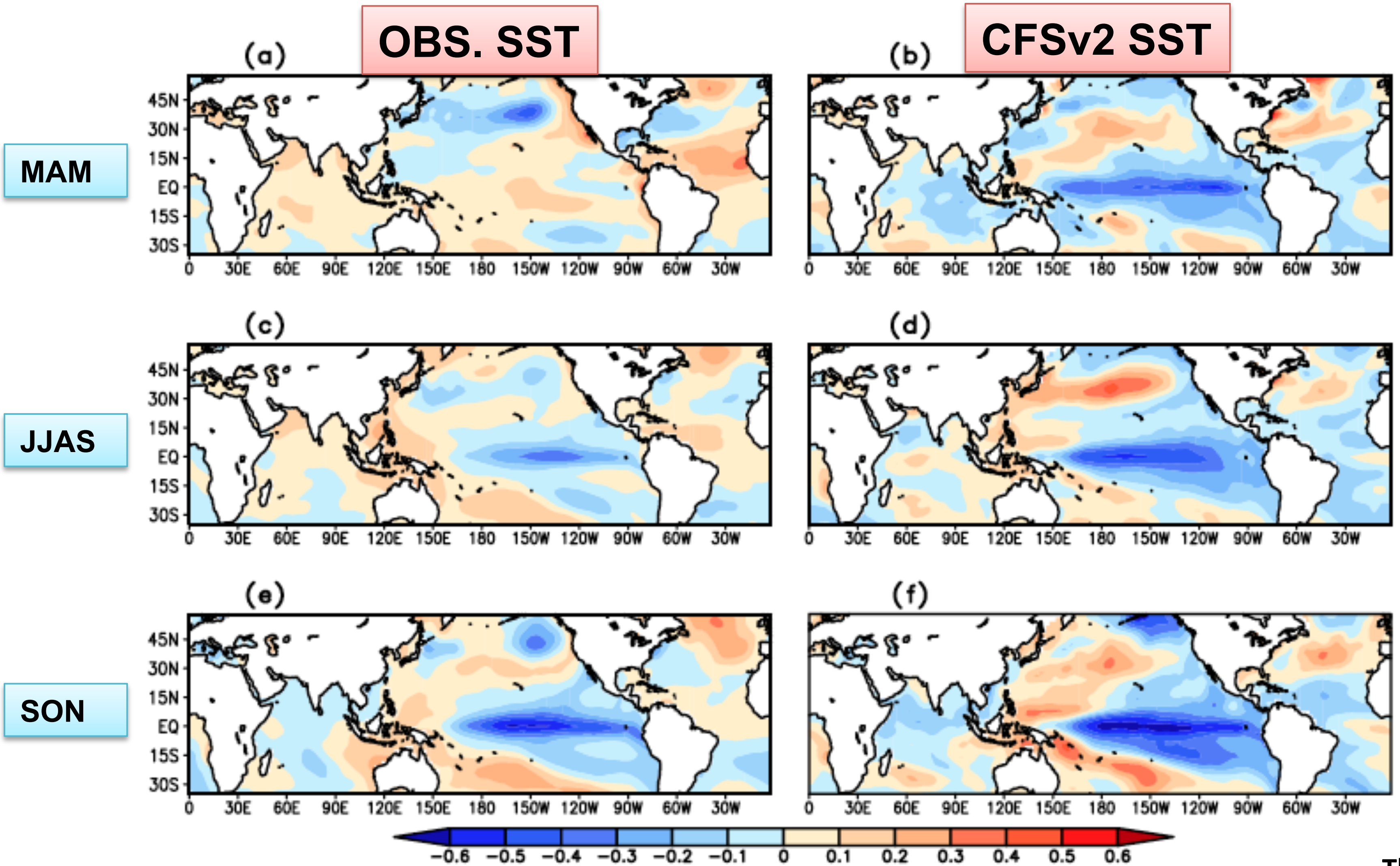
Shukla and Huang (2015) Physical processes associated with the interannual dominant mode of regional and global Asian summer monsoon rainfall in NCEP CFSv2, *Climate Dynamics* (in review)

Regression of Indo-Pacific JJAS rainfall against standardized PC1 of JJAS rainfall in extended Indian monsoon region (R)



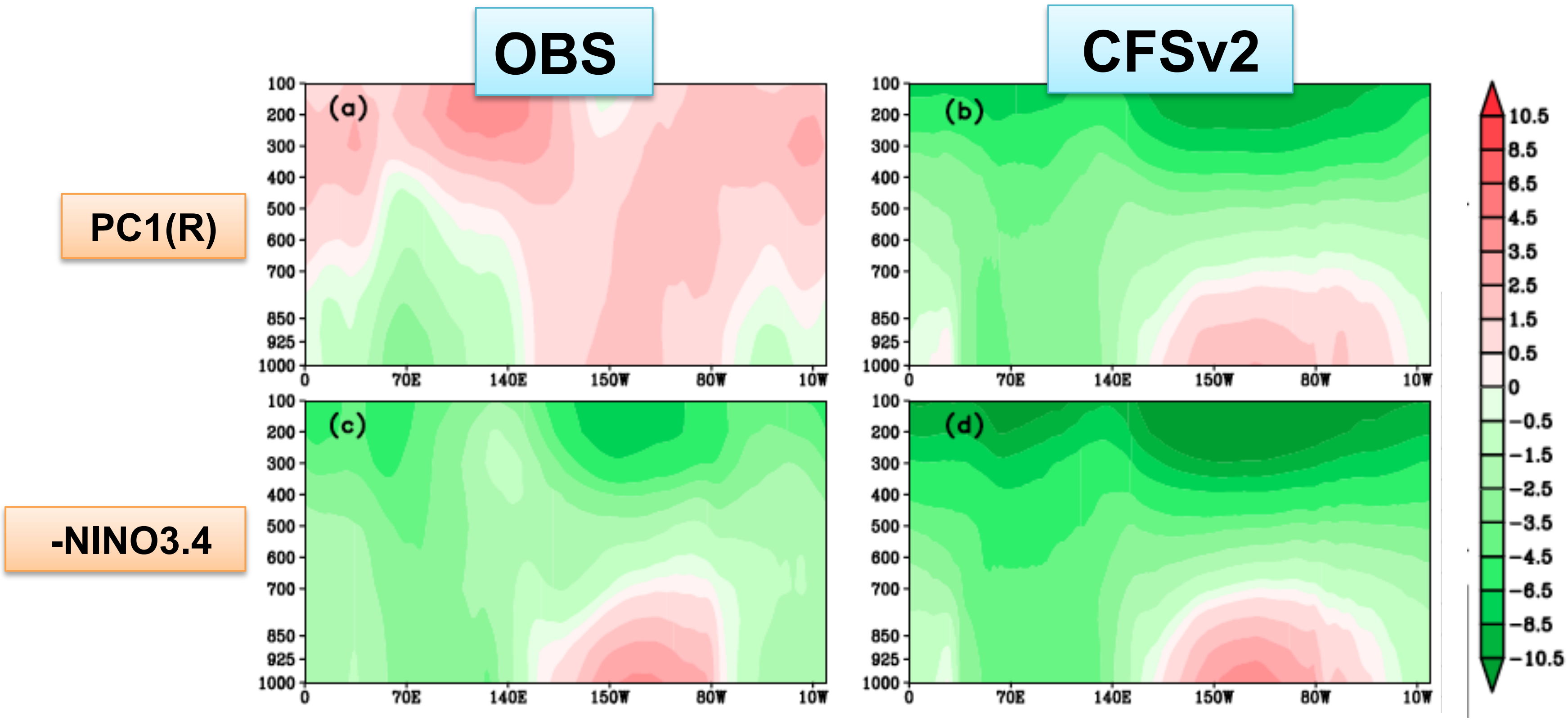
Thanks to Ravi Shukla

Regression of SST against standardized PC1(R) of JJAS rainfall



Thanks to Ravi Shukla

Regression of Z(p) against standardized PC1® and NINO3.4



Conclusions

- ROLE OF CONVECTION
  - HCF – alternative deep convection trigger condition and cloud base – implemented and tested with SAS, new-SAS, & shallow conv. in CFSv2
    - Better representation of convection: increased occurrence, total precip amount
    - Better daily and seasonal mean, seasonal cycle, onset dates
- LAND-ATMOSPHERE FEEDBACKS
  - Terrestrial leg of coupled L-A feedback pathway well represented in CFSv2.
  - Relatively weak sensitivity of PBL depth to surface flux variations over eastern part of central India: **atmospheric leg** not strong in CFSv2. Need better observations to validate.
- ROLE OF OCEAN ICs
  - Substantial dependence on ocean ICs of skill of monsoon rainfall forecasts
  - Multi-analysis initialization results in superior prediction, on average
- CHARACTERIZING MONSOON VARIABILITY
  - Considerable work remains to be done to beat down bias
  - Two main modes of monsoon variability, associated with onset and decay phases of ENSO, are well reproduced and predicted in CFSv2 with most ocean IC data sets
  - Fundamental ENSO-monsoon dynamics imperfect

Future Plans

- CFSv2 code improvements and re-forecast experiments:
  - Port to NCAR Yellowstone supercomputer for use by broader group of Monsoon Mission PIs
  - Ensemble hindcasts with additional initial condition dates
  - 10-day simulations with high frequency output (transpose AMIP) to diagnose and improve model biases in simulating the diurnal cycle of convection
- Land-atmosphere feedbacks:
  - Quantify L-A feedbacks in CFSv2 using coupling metrics (Dirmeyer 2011; Santanello et al. 2009, 2001; Findell and Eltahir 2003, Tawfik and Dirmeyer 2013)
  - Evaluate sensitivity of S2S IMR to Eurasian snow and 'hot-spot' soil moisture in spring
- Multiple ocean analysis initialization:
  - Additional multi-ocean analysis hindcasts with more recent ODA
  - Assess relative roles of Indian Ocean, and EP/CP ENSO in IMR predictability
- Improved representation of ocean-atmosphere relevant processes:
  - Test CFSv2 with new SAS, shallow conv., HCF and BCL cloud base in hindcasts
- Anticipated impacts:
  - Improve already skillful CFSv2 monsoon forecasts of seasonal IMR, onset date, and magnitude of intra-seasonal variability
  - Forecasts of opportunity based on antecedent state of ENSO and other tropical indicators

Publications

- Bombardi R. J., E. K. Schneider, L. Marx, S. Halder, B. Singh, A.B. Tawfik, P.A. Dirmeyer, J.L. Kinter III 2015: Improvements in the representation of the Indian Summer Monsoon in the NCEP Climate Forecast System version 2. *Climate Dyn*. DOI: 10.1007/s00382-015-2484-6
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- Tawfik, A. B., and P. A. Dirmeyer, 2014: A process-based framework for quantifying the atmospheric preconditioning of surface triggered convection. *Geophys. Res. Lett*., 41, 173-178, doi: 10.1002/2013GL057984.