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Monsoon Metrics: Skill and Process Assessment

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Why is it important to study monsoons?

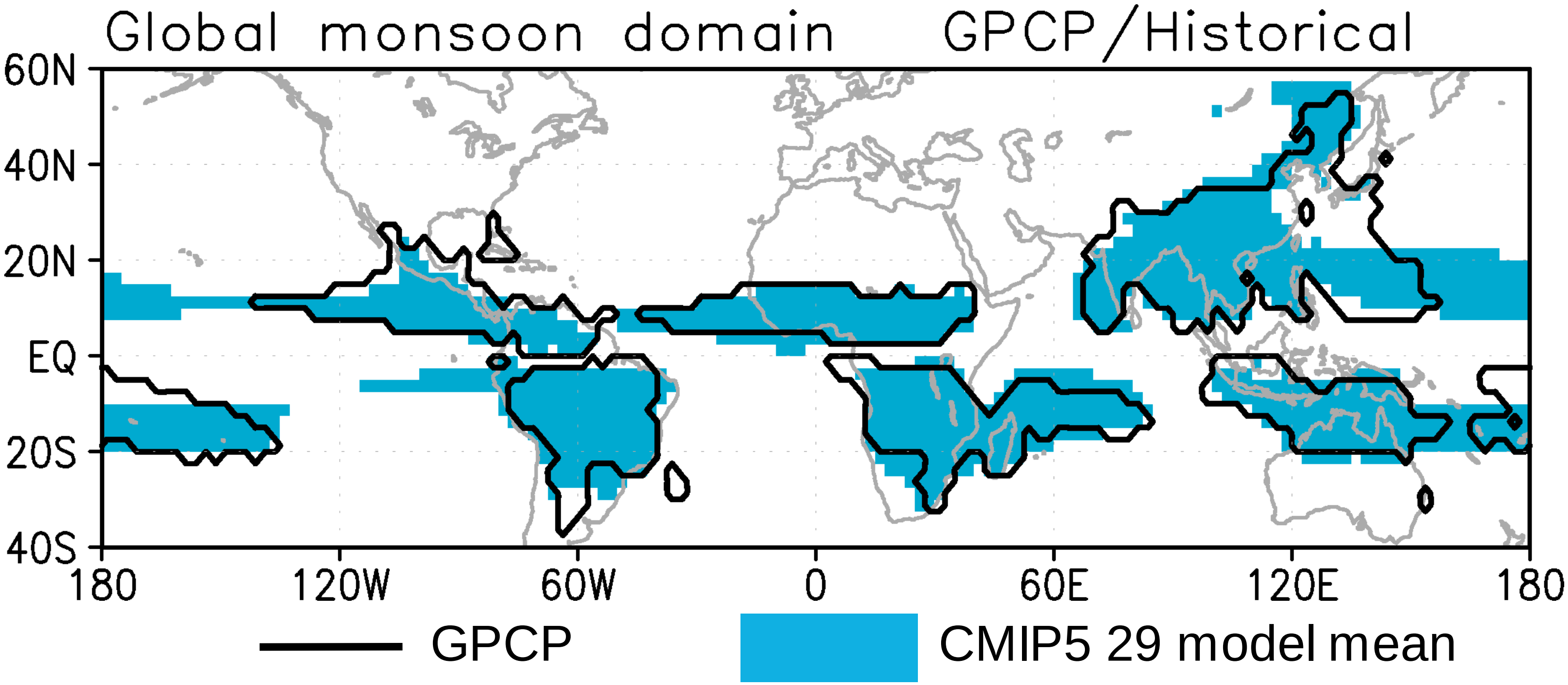
- Monsoon variability impacts the socio-economic well-being of nearly 3 billion people
  - Agriculture (crop selection and planting time)
  - Hydrometeorological Services (flood and drought mitigation)
- Monsoon forecasting has been a longstanding problem
  - Blanford (1884) monsoon vs. preseason snow-cover
  - Walker (1924) monsoon vs. pressure over the Pacific and Indian Oceans
- CLIVAR Asian-Australian Monsoon Panel
  - Assess climate variability and predictability of the A-A monsoon
    - Observations: monitoring (Indian Ocean moored array) and evaluation
    - AAMP sponsored numerical experimentation (e.g., MJO prediction and predictability, experimental real-time forecasting with MJOTF)
    - CMIP3, CMIP5 (standardized diagnostics for the broader climate community)
  - Improve understanding of mechanisms that modulate monsoon
    - MJO (e.g., CINDY/DYNAMO 2011), ENSO, Interdecadal variability
    - Workshops (MJO, Interdecadal variability)

Outline

- Monsoon precipitation: Annual cycle diagnostics and skill
  - Wang and Ding (2008)
    - Global monsoon (seasonal mean climatology)
  - Wang and LinHo (2002)
    - Asian summer monsoon (climatological pentad data)
  - Sperber and Annamalai (2014)
    - Regional monsoons (climatological and interannual pentads)
- Other processes and modes of variability
  - Diurnal cycle (Dirmeyer et al. 2013)
  - SST biases (Levine et al. 2013)
  - Moisture budget and air-sea interactions (Bollasina and Nigam 2009)
  - Impact of land surface parameterization (Li et al. 2015; Ma et al. 2013; Richter et al. 2012)
  - Impact of horizontal resolution (Sabin et al. 2013)
  - Impact of data assimilation (Raju et al. 2015)
  - MJO and moisture sensitivity (Kim et al. 2014)

Global monsoon domain (Wang and Ding 2008): present
Kitoh et al. (2013, JGR, 118, 3053–3065, doi:10.1002/jgrd.50258)

- Model mean generally reproduces the observed domain
- Some biases over eastern Asia and the tropical Pacific



Monsoon domain: Annual range ≥ 2.5 mm day^{-1}
Annual range: |MJJAS – NDJFM|

Previous work: CMIP5/CMIP3 model assessment

Sperber, K. R., H. Annamalai, I.-S. Kang, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou (2013) The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Clim. Dynam., 41, 2711-2744, doi: 10.1007/s00382-012-1607-6

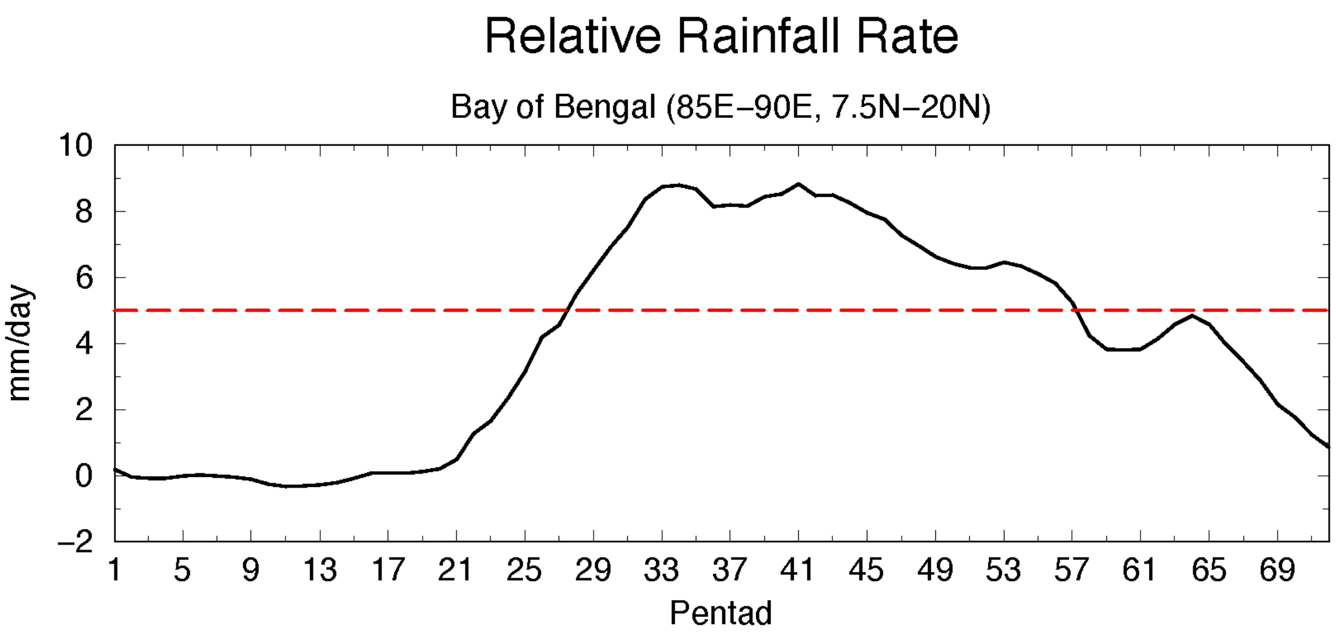
- Climatological Performance
  - Rainfall and 850hPa winds
- ***Climatological Annual Cycle***
  - Development of the oceanic and continental convergence zones (70°E-90°E)
  - *Monsoon Onset, Peak, Withdrawal, and Duration*
  - *Extent of the monsoon domain*
- ENSO-Monsoon Relationship
  - Correlation of all-India rainfall with NINO3.4 SSTA
  - NINO3.4 regressions with local rainfall (Do models get the pattern correct?)
- East Asian Summer Monsoon Interannual Variability
  - Relationship of precipitation and 850hPa wind to zonal wind shear index
- Boreal Summer Intraseasonal Variability (BSISV)
  - 20-100 day variance pattern and BSISV life-cycle
- Metrics of Skill Applied for each Diagnostic
  - Pattern correlation (2-D), space-time correlation (BSISV life-cycle), and hit-rate and threat score (Monsoon domain)

Resource for the modeling, diagnostics, and impact communities

- http://www-pcmdi.llnl.gov/projects/ken/cmip5_bsisv/Tables.html

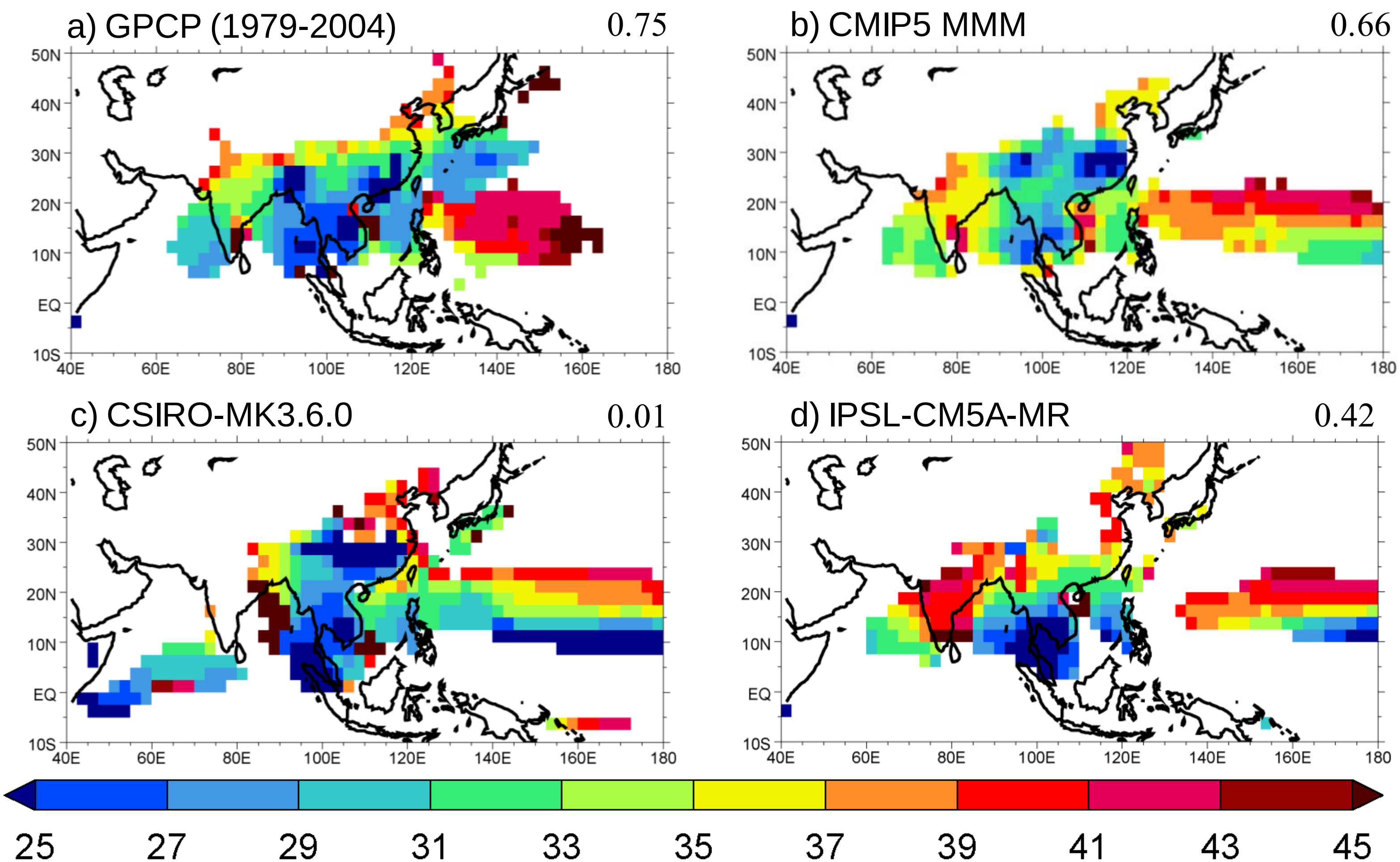
Climatological annual cycle of rainfall: monsoon onset, peak, withdrawal, and duration (pentad data)

- Sperber et al. (2013) used the approach of Wang and LinHo (2002, J. Clim., 15, 386-398) to evaluate Asian monsoon evolution in CMIP5 and CMIP3
  - Threshold-based: VERY STRINGENT TEST FOR A MODEL
  - Calculate pentad climatology of rainfall
  - Smooth the data, retaining intraseasonal time scales (5 pentad running mean)
  - Subtract the January mean from each pentad: Relative Rainfall Rate
  - Onset: Relative Rainfall Rate exceeds 5mm/day during May-September
  - Withdrawal: Relative Rainfall Rate drops below 5mm/day
  - Duration = Withdrawal – Onset pentads



CMIP5
Climatological monsoon onset (e.g., pentad 31 ~June 2)

- Individual models outperform the multi-model mean (not shown)
- Bias in the time of onset: too late over India (CMIP5 MMM and IPSL-CM5A-MR)
- ***Spatial extent of monsoon not defined over:*** India (e.g., CSIRO-Mk3.6.0) and China (e.g., IPSL-CM5A-MR) due to model dry biases



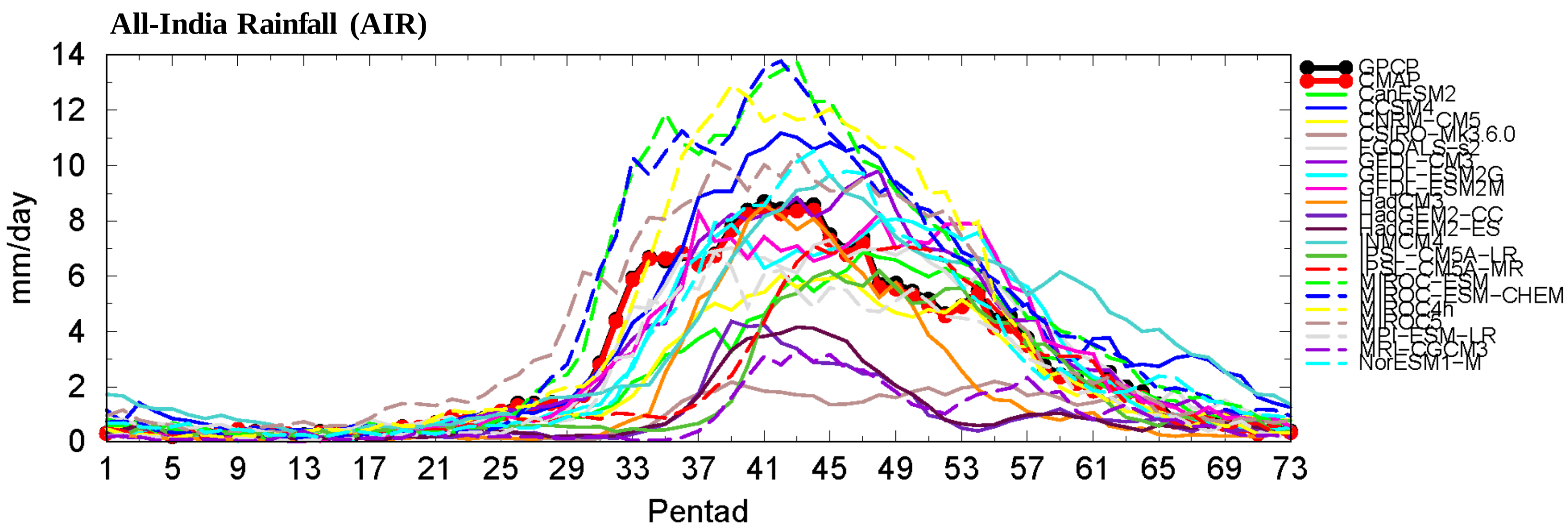
Climatological annual cycle of rainfall: An alternative approach using pentad data

Sperber and Annamalai (2014, The use of fractional accumulated precipitation for the evaluation of the annual cycle of monsoons. Clim. Dynam., 43, 3219-3244, doi: 10.1007/s00382-014-2099-3)

- Pentad precipitation: climatologies analyzed, with the exception of the interannual variability for which yearly pentads are used
  - Observations (1979-2004)
    - GPCP: SSM/I, TOVS, IR, OLR, and rain gauge data
    - CMAP: SSM/I, MSU, IR, OLR, rain gauge data, and NCEP/NCAR reanalysis
  - CMIP5 (21 models: historical runs, 1961-1999)
    - CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3.6.0, FGOALS-s2, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, HadCM3, HadGEM2-CC, HadGEM2-ES, INM CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC4h, MIROC5, MPI-ESM-LR, MRI-CGCM3, and NorESM1-M

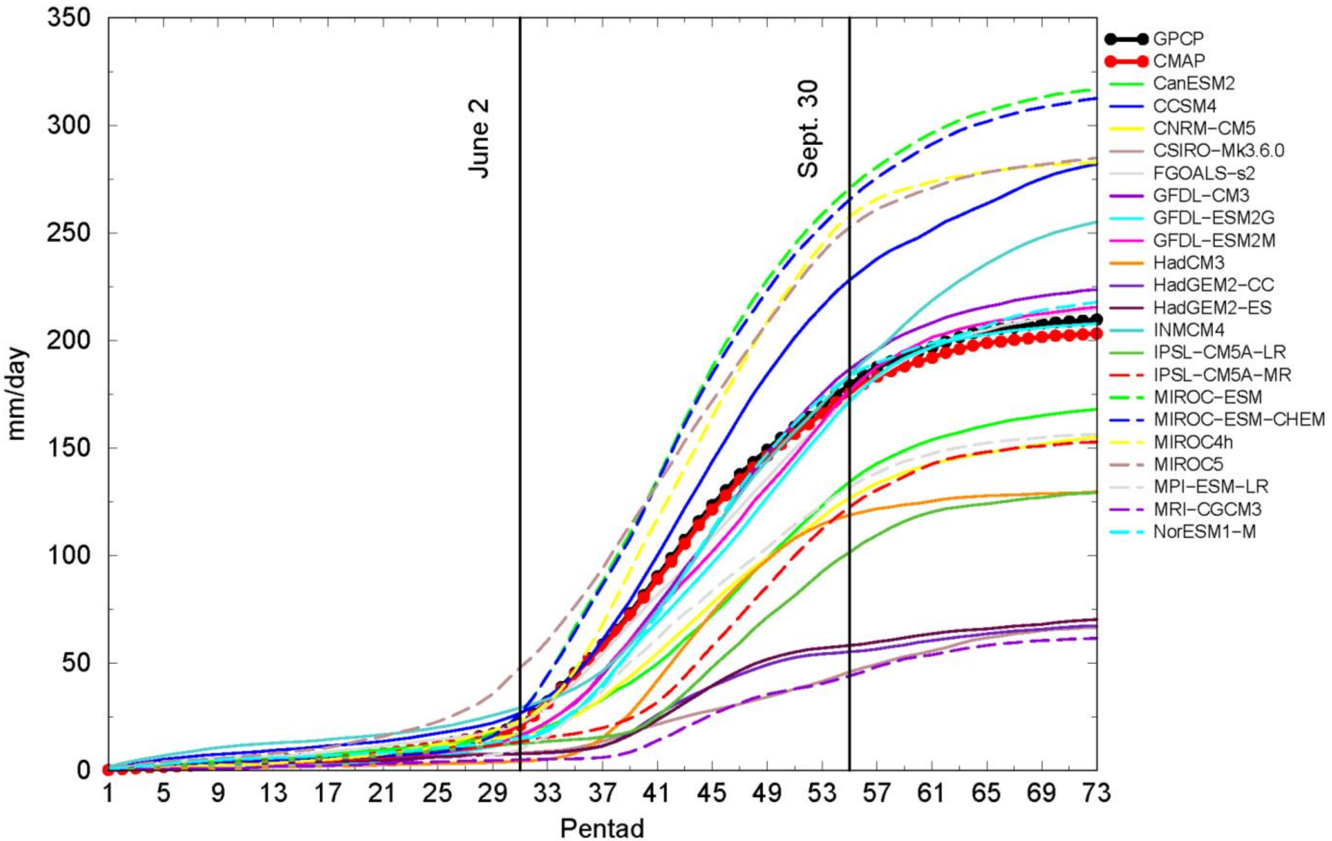
Climatological All-India Rainfall: illustration of the issue and goal

- All-India Rainfall (65°E-85°E, 7°N-25°N, land only), for example
  - The majority of models appear to have a dry bias
    - Issue: Is the late onset due to the simulated dry bias and/or poor simulation of the phase of the annual cycle?
  - The fidelity of an individual models' annual cycle is not apparent
- Goal: Develop an approach to analyze the annual cycle of rainfall in a uniform manner across all models, irrespective of mean-state bias



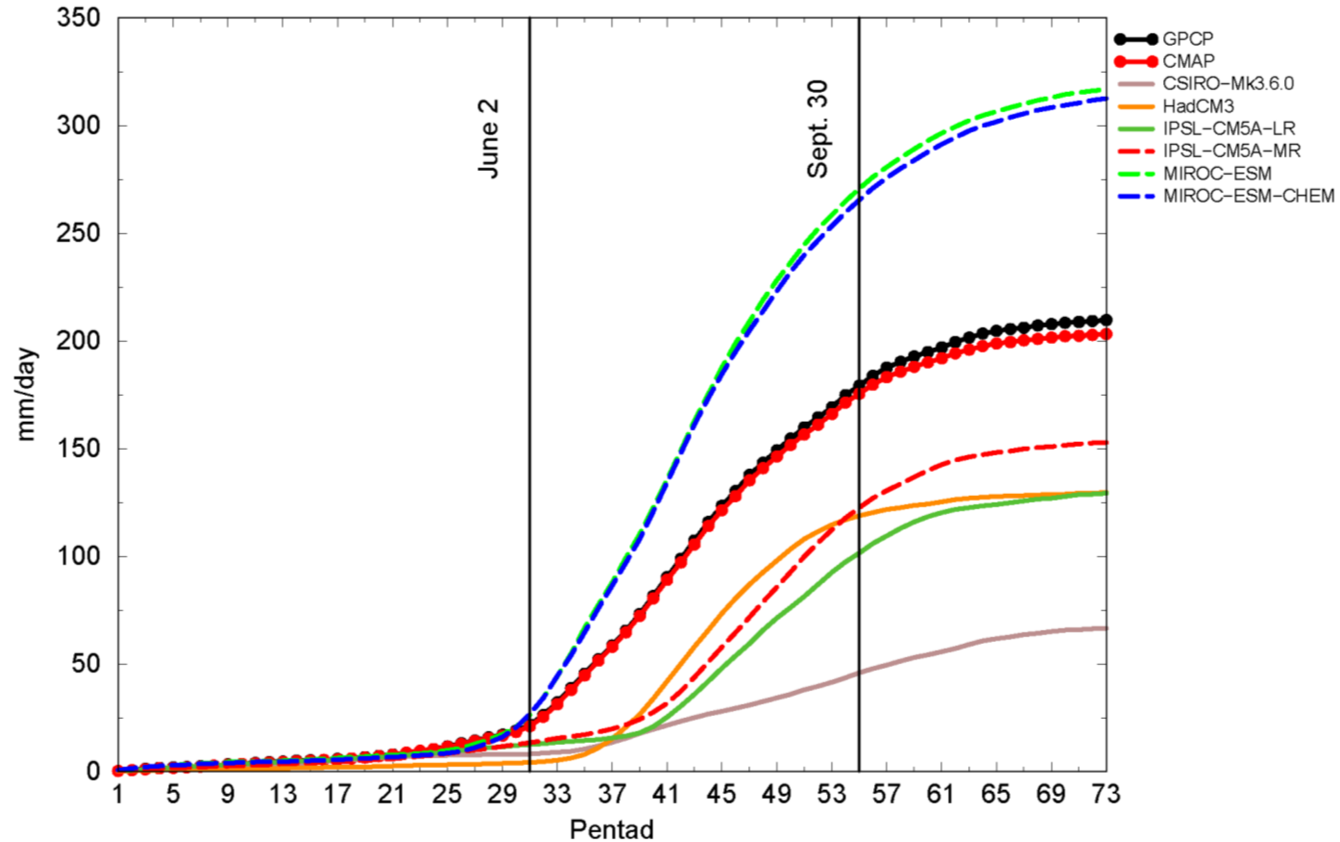
Climatological All-India Rainfall: cumulative (CMIP5)

- India (65^{o}E-85^{o}E, 7^{o}N-25^{o}N, land only)
  - Cumulative rainfall: large spread with a factor of ~6 spread in the total
  - Shows temporal evolution of rainfall accumulation and the bias development



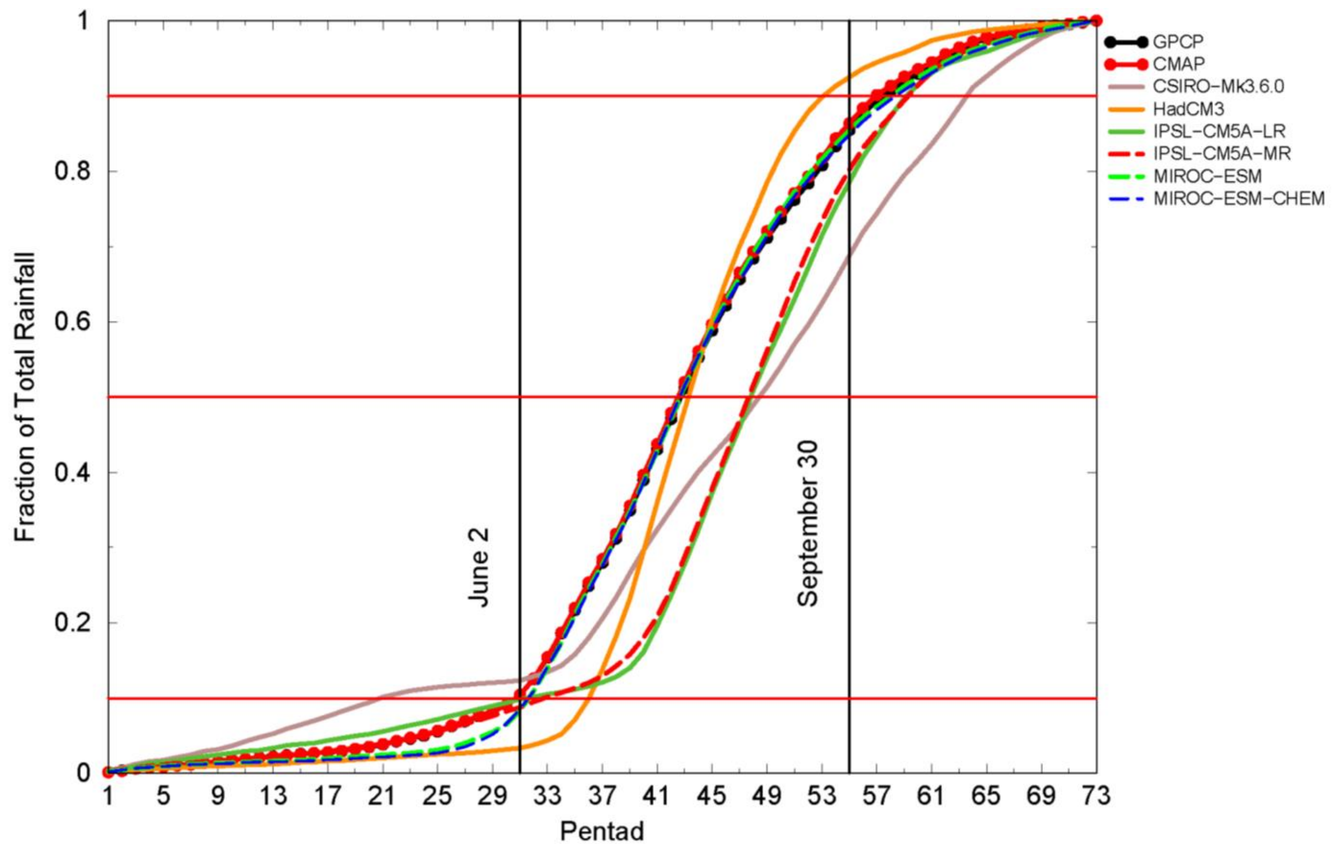
Climatological All-India Rainfall: cumulative (CMIP5, select models)

- India (65^{o}E-85^{o}E, 7^{o}N-25^{o}N, land only)
  - MIROC-ESM's: very large accumulation during boreal summer
  - Other models: dry bias, especially CSIRO-Mk3.6.0
  - IPSL-CM5A: medium-resolution has greater rainfall than the low-resolution version



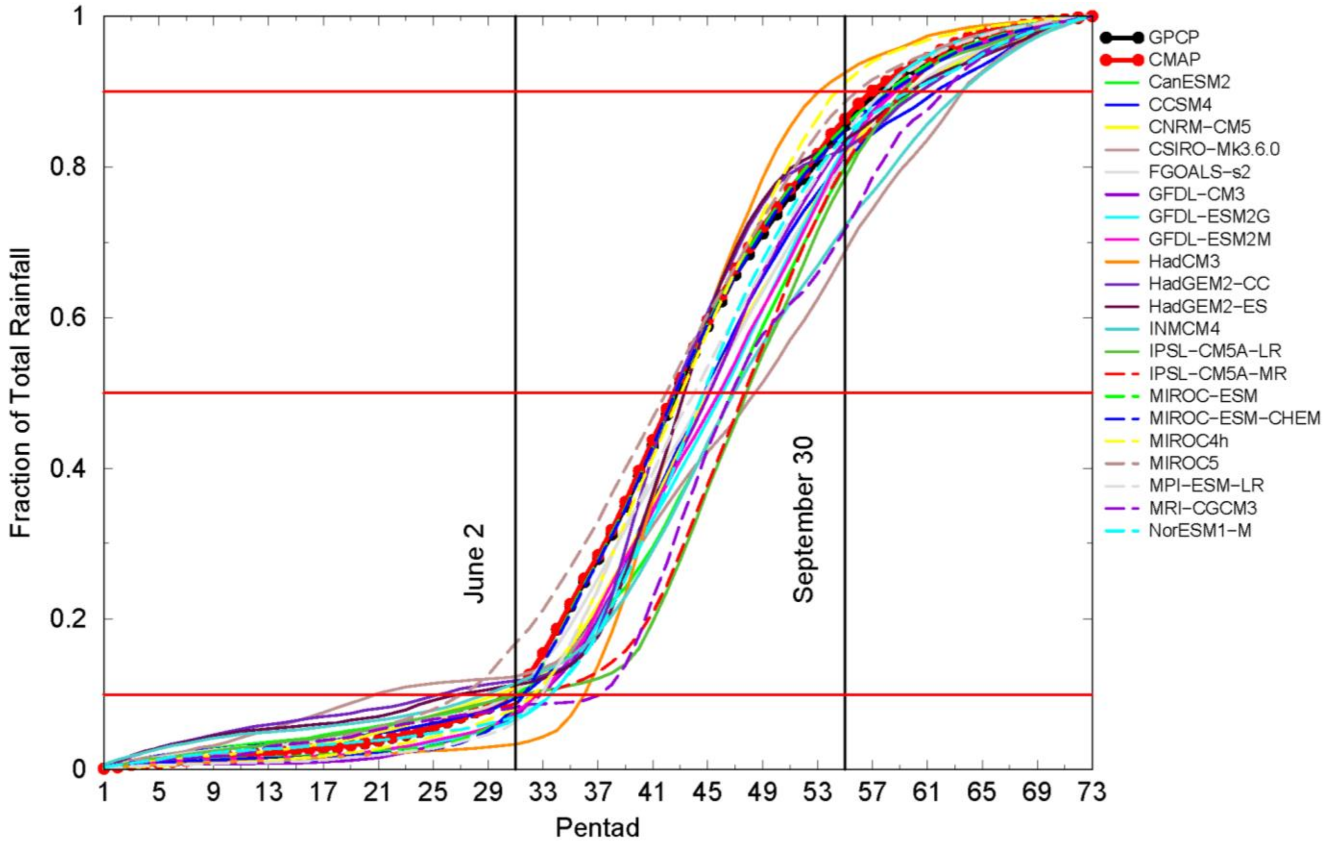
Climatological All-India Rainfall: fractional accumulation (CMIP5, select models)

- India (65°E-85°E, 7°N-25°N, land only)
  - Fractional accumulation of rainfall (accumulation to date/total accumulation)
  - CSIRO-Mk3.6.0: too much fractional accumulation pre-monsoon, and too little after
  - HadCM3: too little (much) fractional accumulation early (late) in boreal summer
  - IPSL-CM5A: low-res and medium-res fractional accumulation nearly identical
  - MIROC-ESM's: closely follow observed fractional accumulation



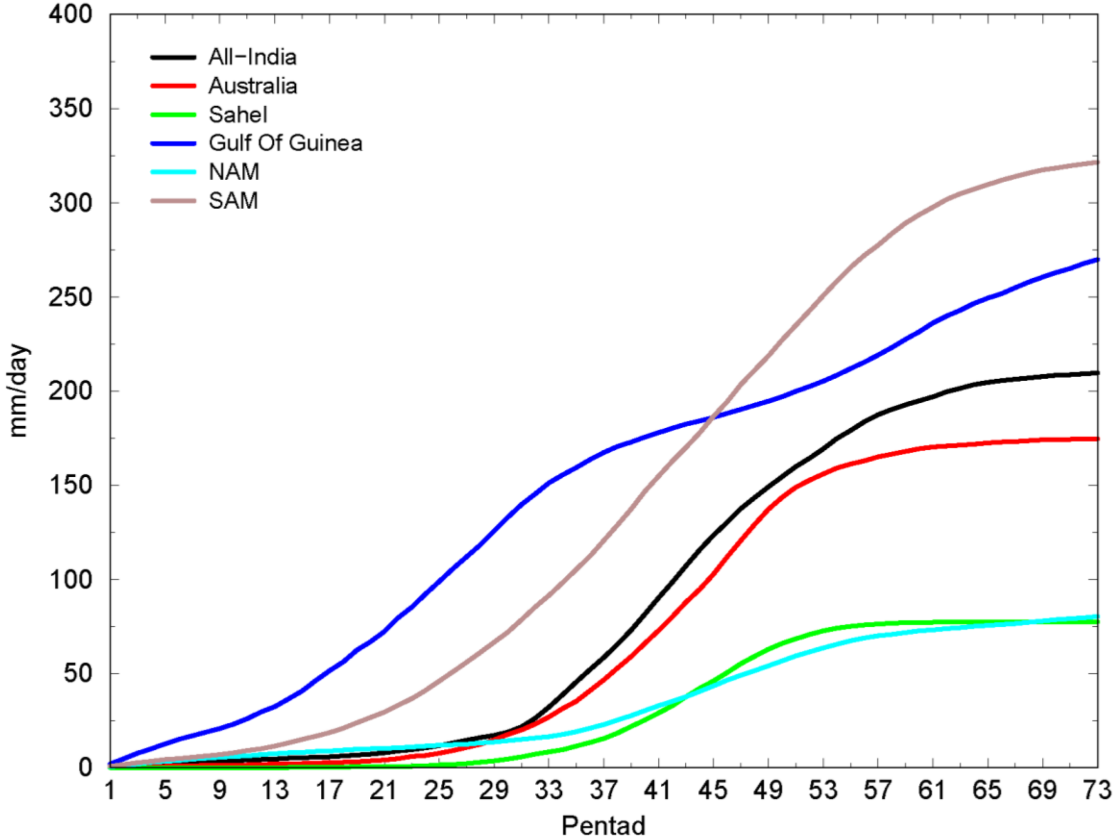
Climatological All-India Rainfall: fractional accumulation (CMIP5)

- India (65°E-85°E, 7°N-25°N, land only)
  - Virtually all models have a phase delay in the annual cycle
    - That is, it takes longer for the models to reach a given fractional accumulation compared to observations, especially during the summer monsoon season
  - In the subsequent analysis we will compare the simulated fractional accumulations and the pentads at which they occur against the observations



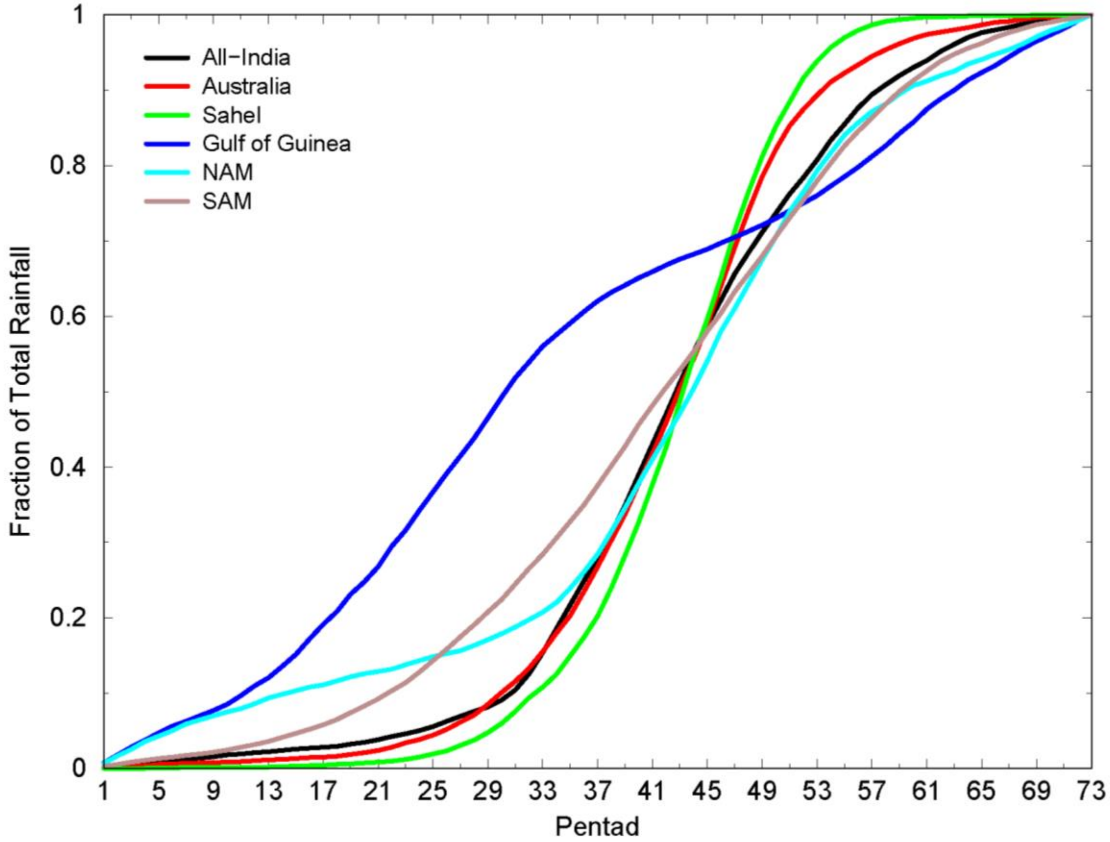
GPCP climatological rainfall: accumulation for various monsoon domains (S. Hemisphere domains: pentads reordered to July-June)

- India (65°E-85°E, 7°N-25°N, land only)
- Australia (120°E-150°E, 20°S-10°S, land only)
- Sahel (10°W-10°E, 13°N-18°N): Smallest rainfall accumulation
- Gulf of Guinea (10°W-10°E, 0°N-5°N)
- North America Monsoon (112°W-103°W, 20°N-37°N): 2nd smallest rainfall accumulation
- South America Monsoon (65°W-40°W, 20°S-2.5°S): Largest rainfall accumulation



GPCP climatological rainfall: fractional accumulation for various monsoon domains

- India (65ºE-85ºE, 7ºN-25ºN, land only)
- Australia (120ºE-150ºE, 20ºS-10ºS, land only)
- Sahel (10ºW-10ºE, 13ºN-18ºN): Fastest rapid fractional accumulation
- Gulf of Guinea (10ºW-10ºE, 0ºN-5ºN): Slowest rapid fractional accumulation
- North America Monsoon (112ºW-103ºW, 20ºN-37ºN)
- South America Monsoon (65ºW-40ºW, 20ºS-2.5ºS)
- ***Relationship is ~linear over the fractional accumulation range 0.2-0.8 (0.2-0.6 Gulf of Guinea)***



GPCP/CMAP climatological rainfall: Onset vs. rapid fractional accumulation (0.2-0.8; 0.2-0.6 GoG) (Method 1)

- ***Onset time (first pentad fractional accumulation ≥0.2) vs. slope of linear regression fit***
- India (65ºE-85ºE, 7ºN-25ºN, land only)
- Australia (120ºE-150ºE, 20ºS-10ºS, land only)
- Sahel (10ºW-10ºE, 13ºN-18ºN): Fastest rapid fractional accumulation
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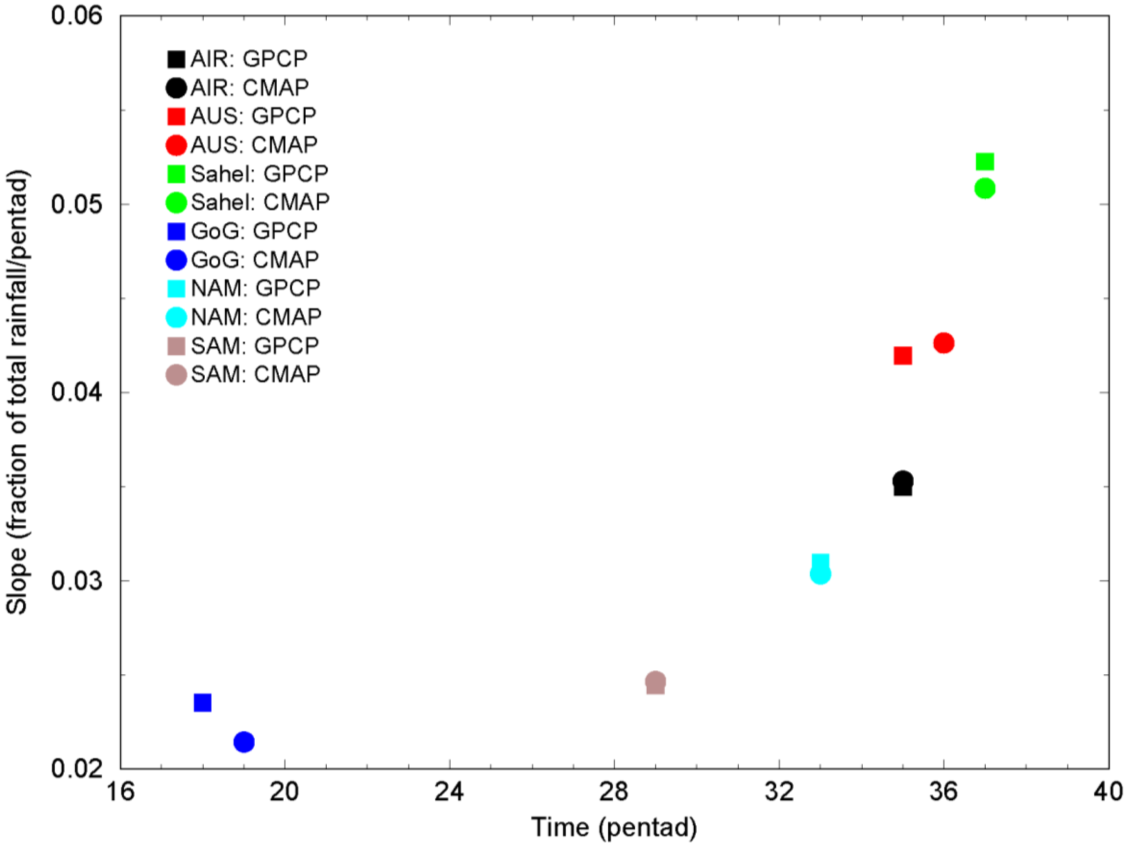
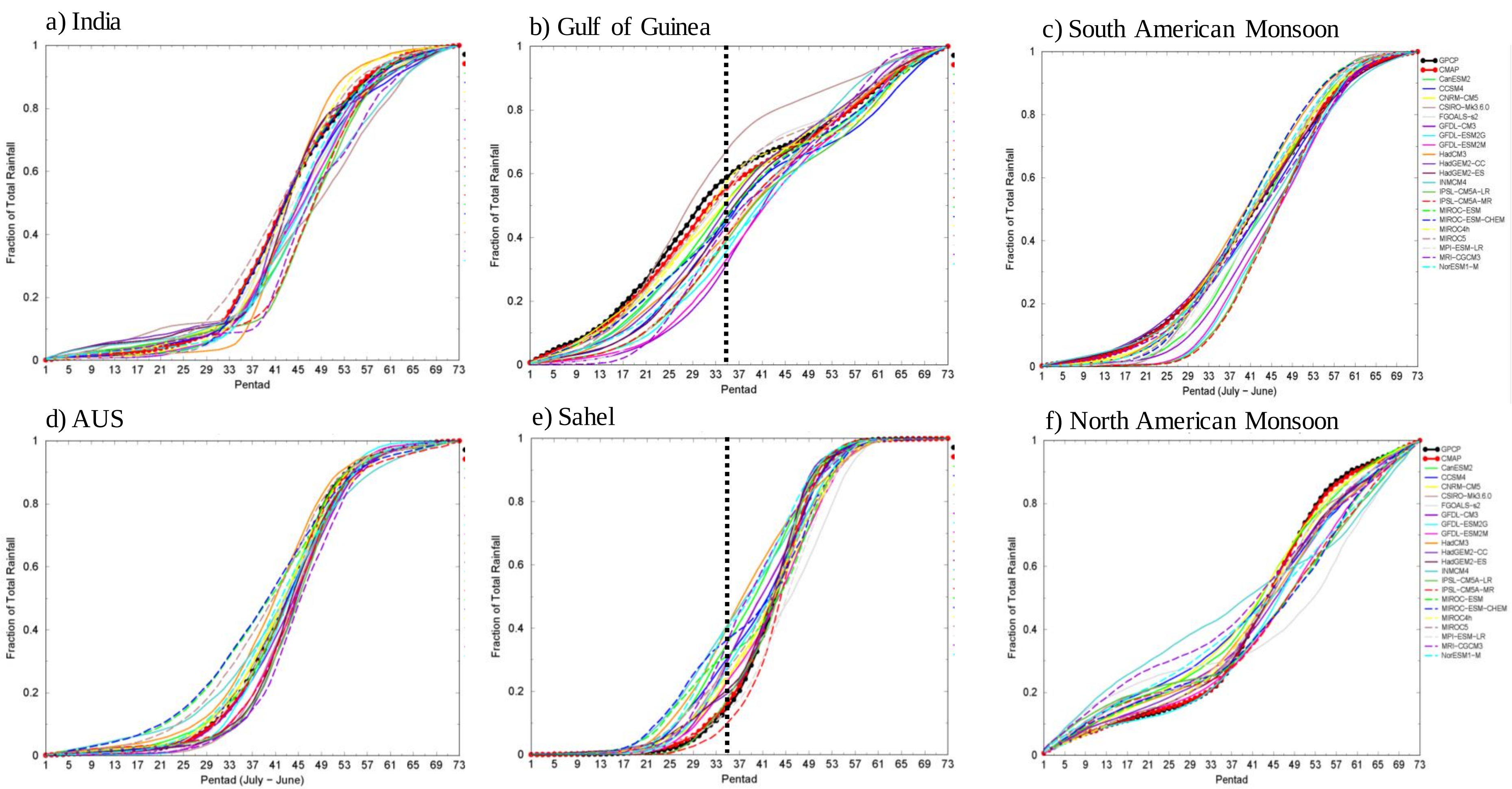


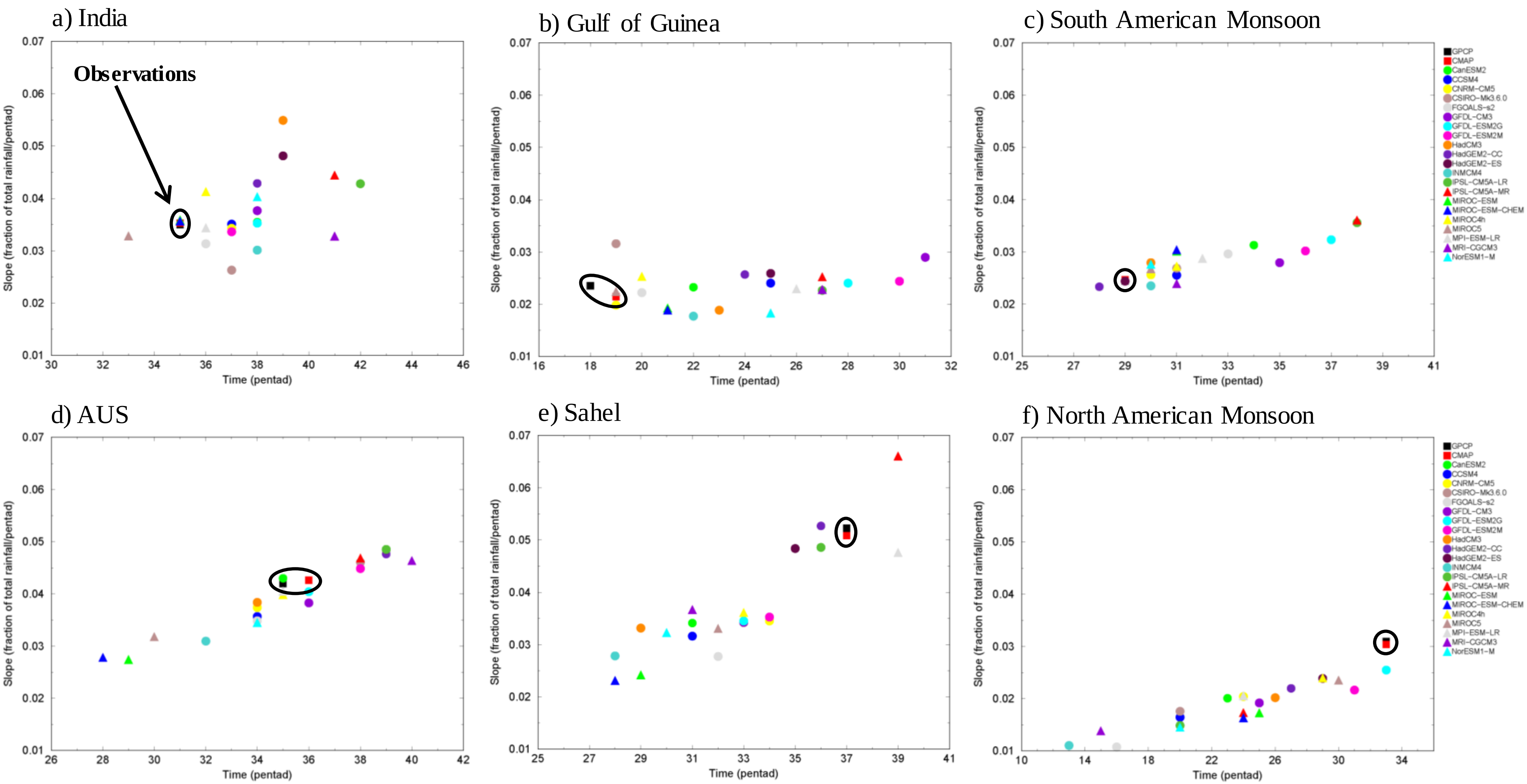
Climatological rainfall: fractional accumulation (CMIP5: Various monsoon domains)

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



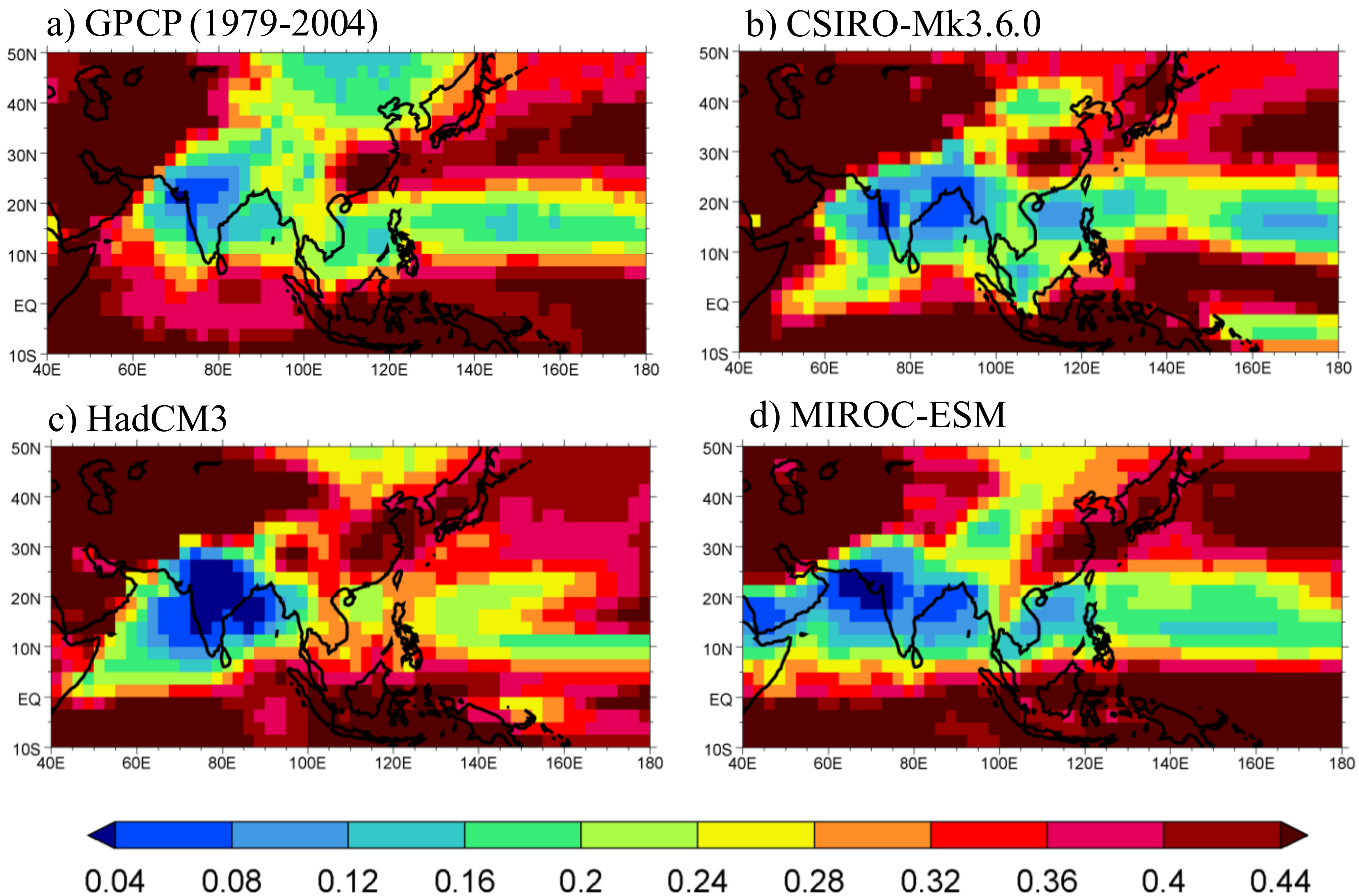
Climatological rainfall: onset vs. rapid fractional accumulation (CMIP5: Various monsoon domains)

- ***Time (first pentad fractional accumulation ≥0.2) vs. slope of linear regression fit***
- India, Gulf of Guinea, SAM: most models late annual cycle
- Sahel and NAM: most models early annual cycle, with weak slope (especially Sahel)



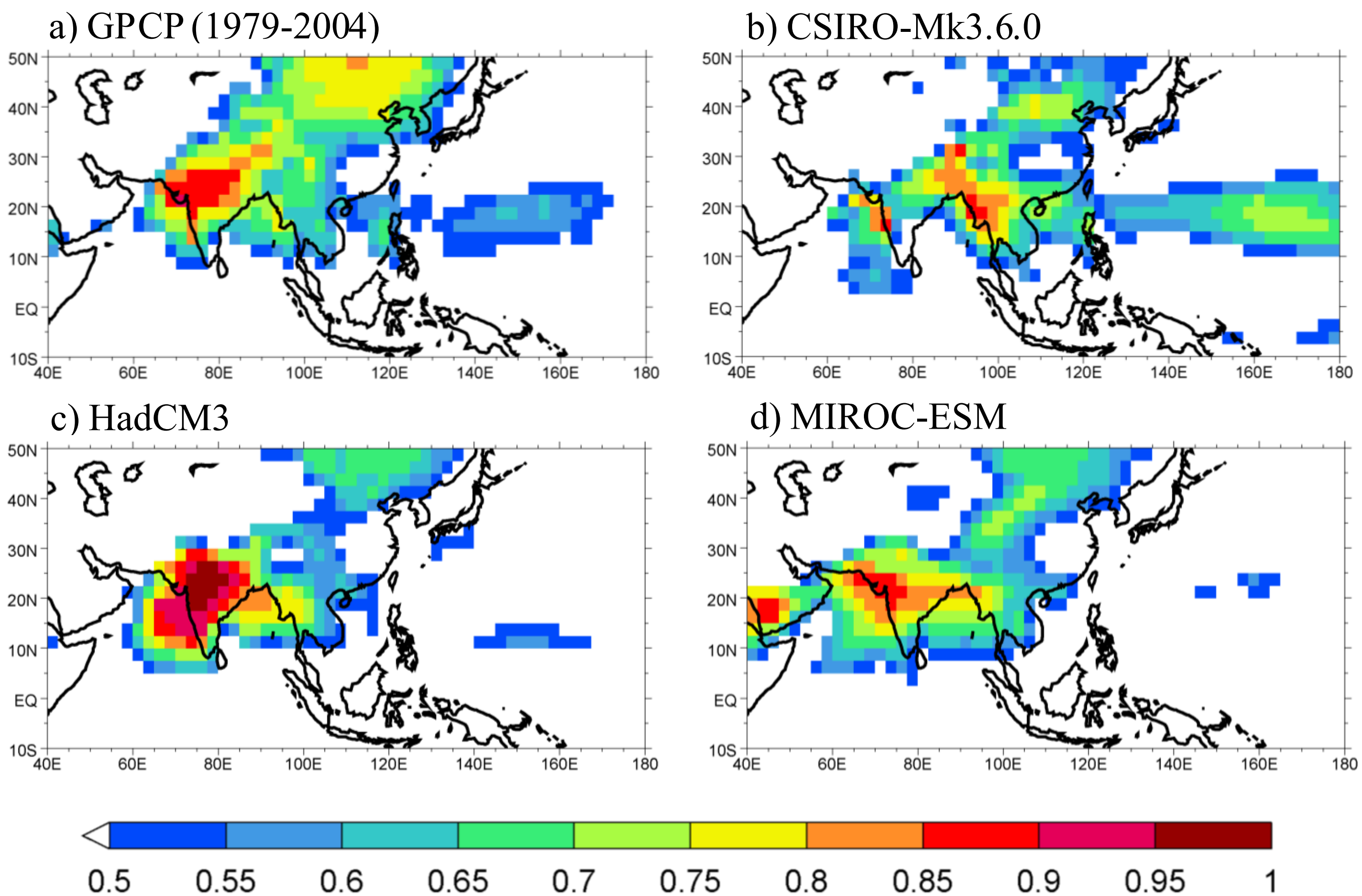
Climatological rainfall: fractional accumulation as of June 2 (pentad 31)

- Observations: the lowest fractional accumulation is over India, particularly the NW
  - CSIRO-Mk3.6.0 and MIROC-ESM represent this fairly well
  - HadCM3 underestimates the fractional accumulation over the Indian subcontinent
- China: conversely, the models overestimate the fractional accumulation
- ***Onset of the monsoon over southern India at a fractional accumulation of ~0.2***



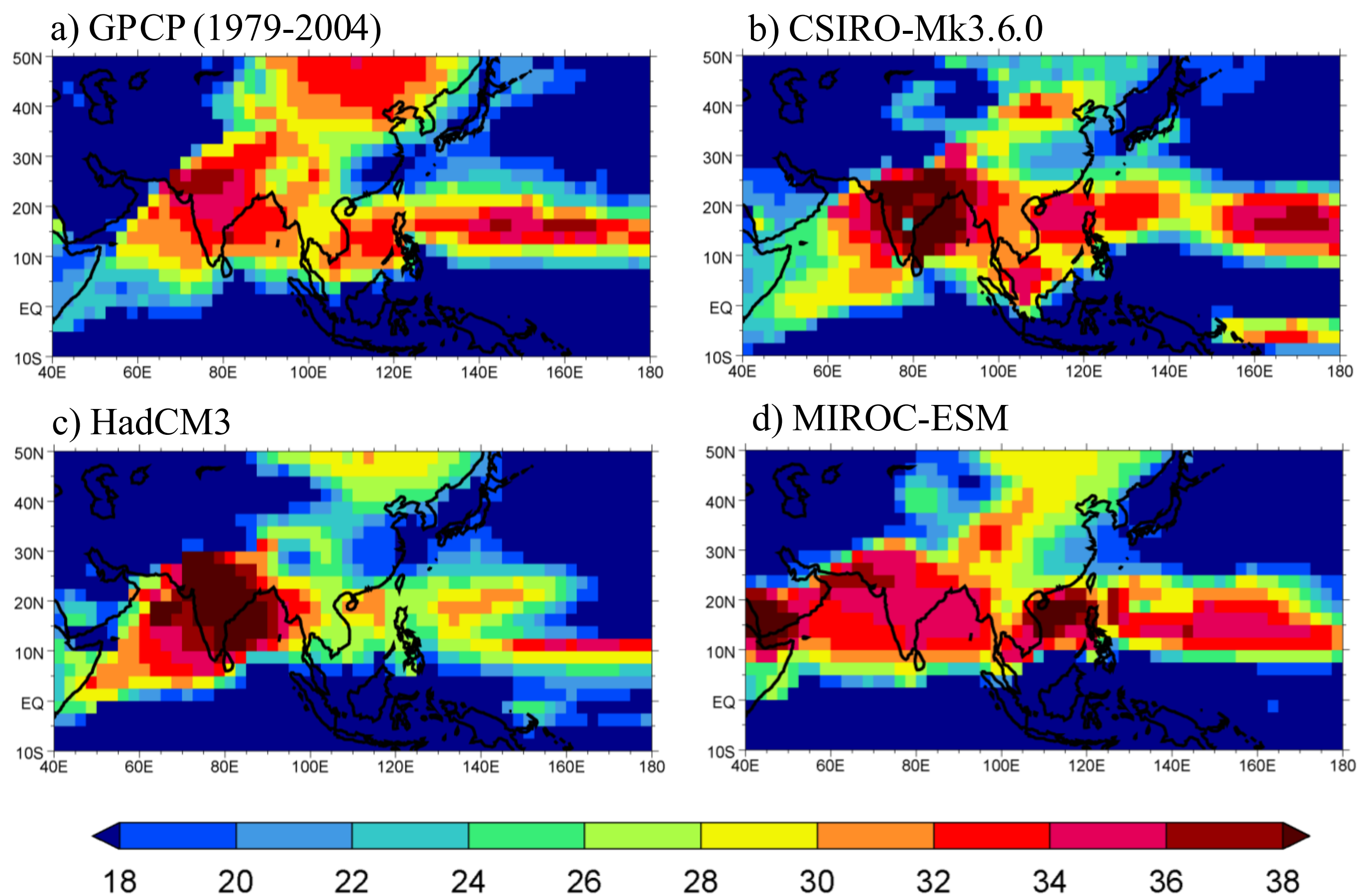
Climatological rainfall: fractional accumulation from June 2 - September 30 (pentads 31 - 55)

- Observations: the largest fractional accumulations occur from India to NE China
- India: MIROC-ESM is realistic, consistent with the AIR fractional accumulation
- India and China: Most models poorly represent the fractional accumulation
- Monsoon domain: ≥50% of the annual accumulation occurs during summer
  - *Compared to threshold-based approach, monsoon now defined over India for CSIRO-Mk3.6.0*



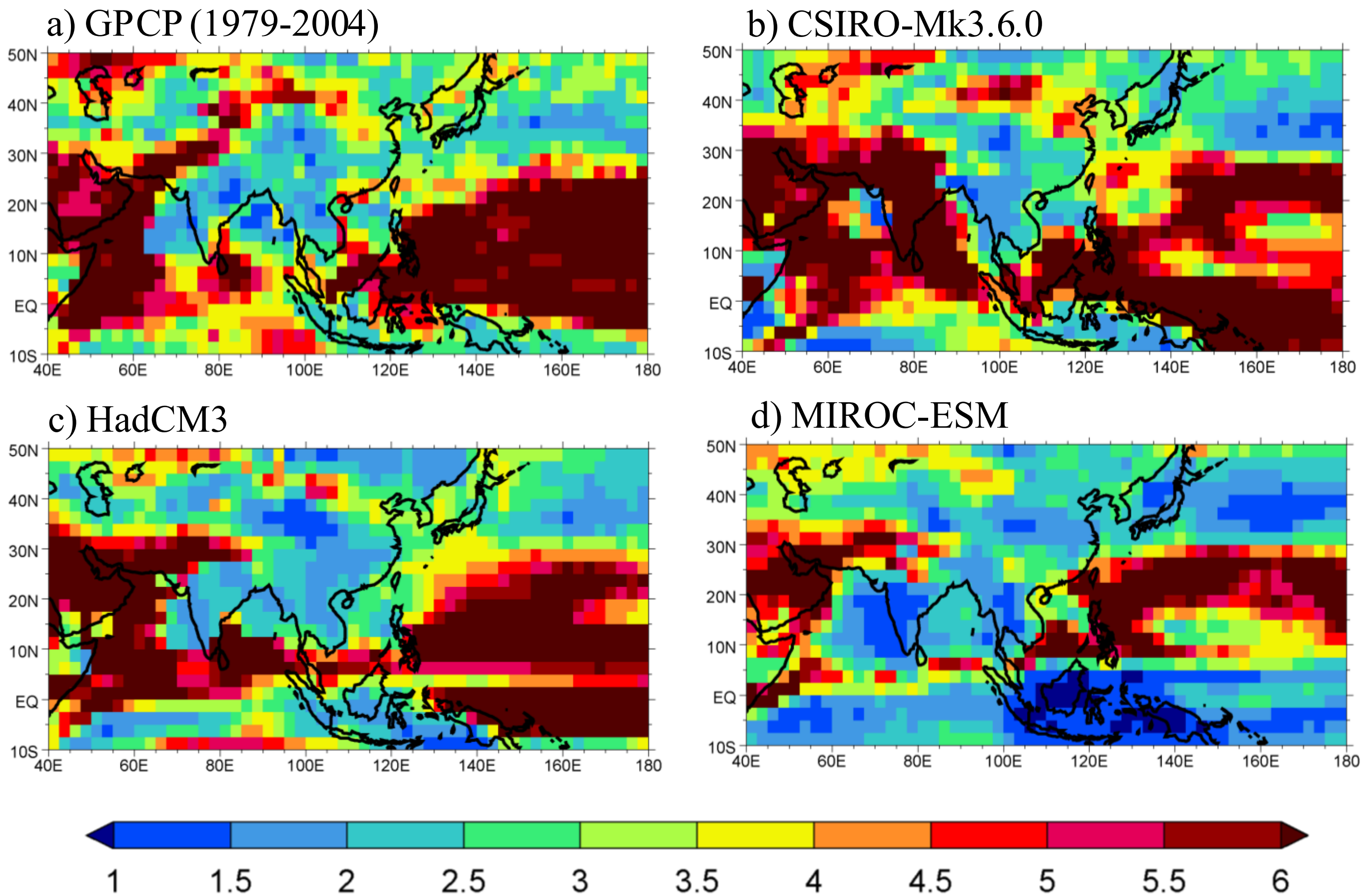
Climatological rainfall: monsoon onset: the pentad at which a fractional accumulation of 0.2 is reached

- Observations: onset first occurs over SE Asia, progressing to the north and west over India and China
- India: CSIRO-Mk3.6.0 and HadCM3 have late onset, with MIROC-ESM more realistic. These results are consistent with the AIR fractional accumulations
- North of 30^{o}N: the models are too early to varying degree



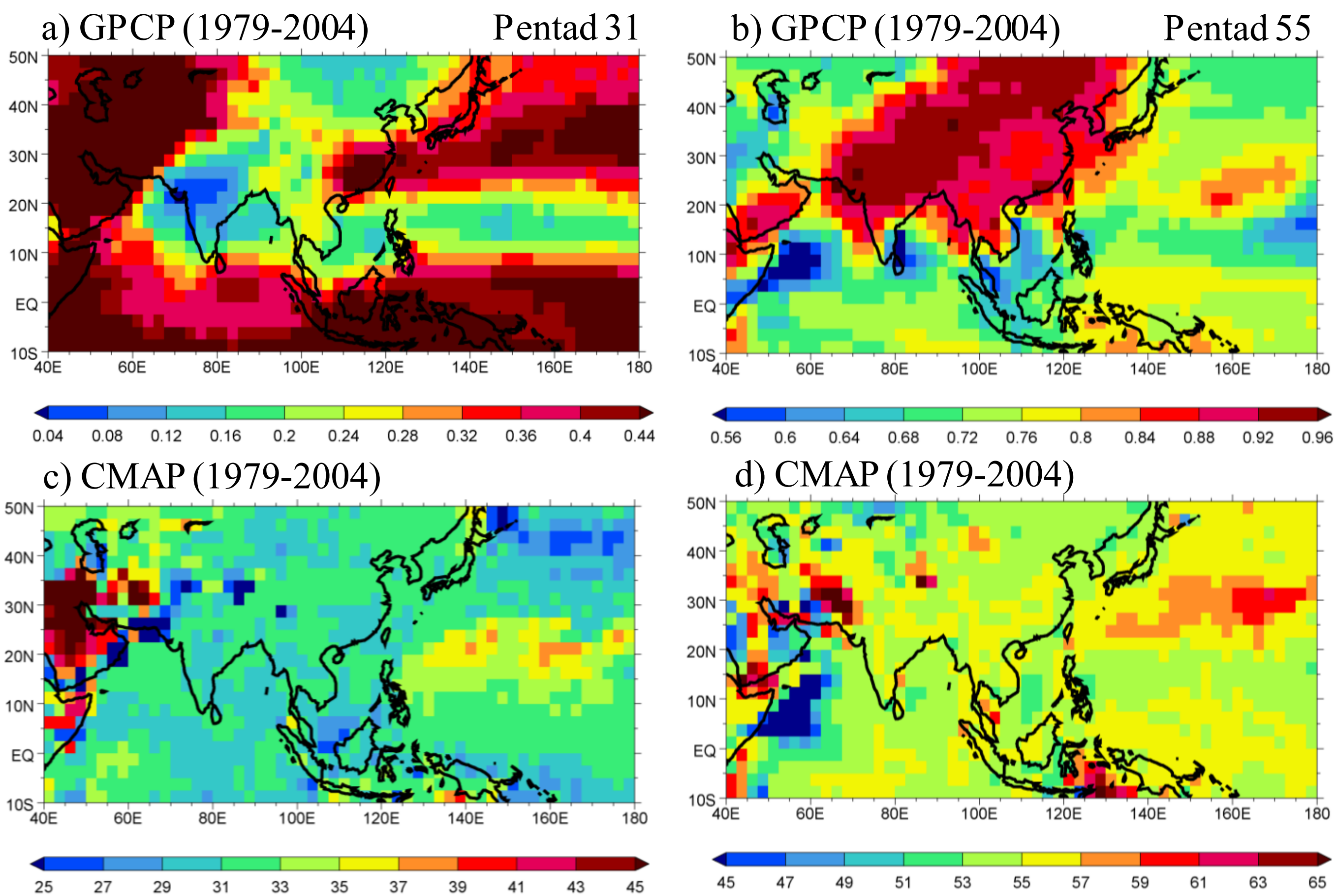
Monsoon Onset-Interannual variability of the pentad at which a fractional accumulation of 0.2 is reached

- The interannual variability is consistent with independent estimates (e.g., Kerala 8-9 days , ~1.5 pentads)
  - Most models are realistic in representing the interannual variability despite biases in annual cycle phase
  - CSIRO-Mk3.6.0 and 3 other models greatly overestimate the interannual variability over India. These are the models with the strongest dry biases over India



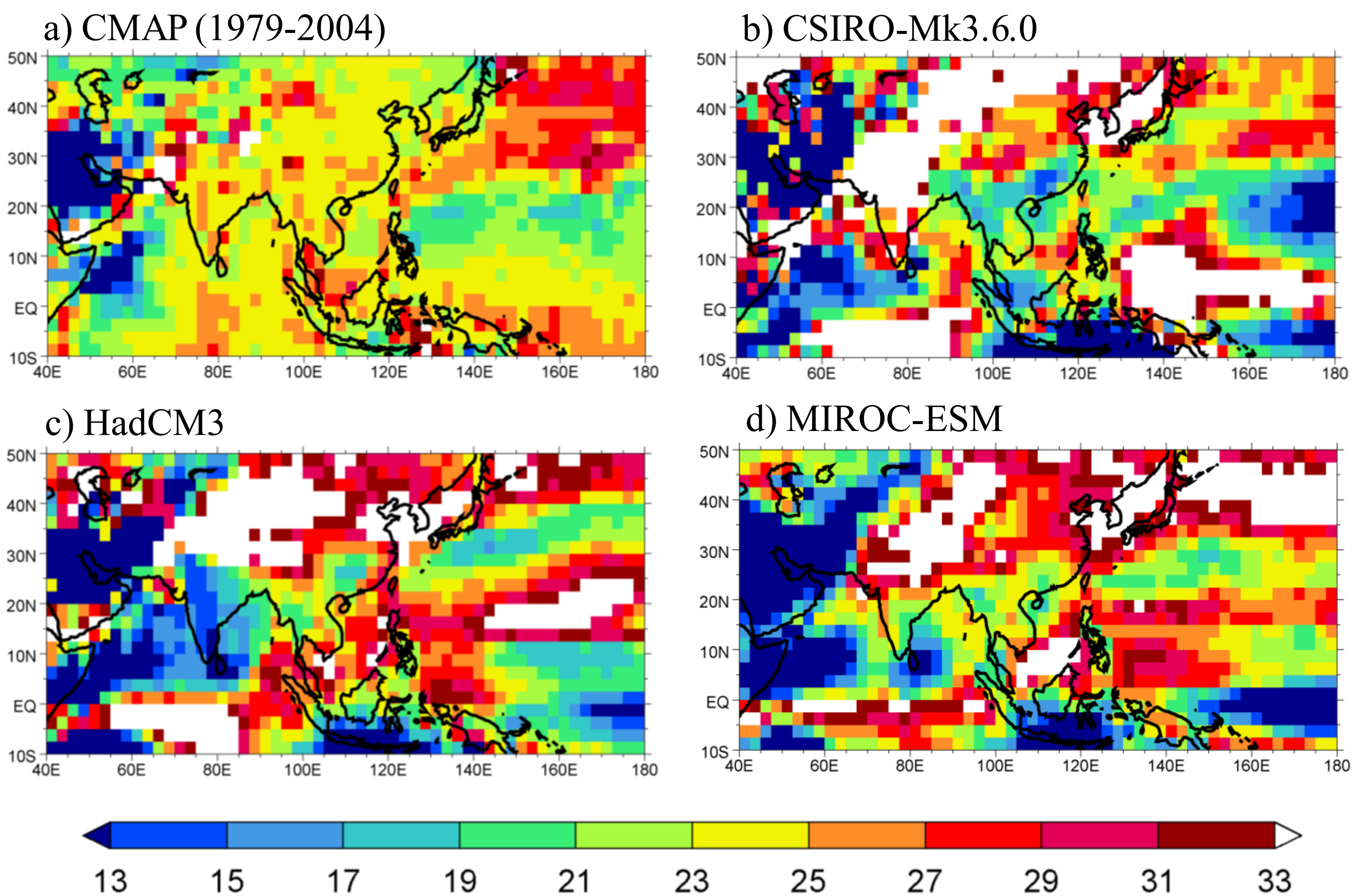
Climatological rainfall: Monsoon Duration calculation is based on models timing in attaining GPCP pentad 31 (June 2) and pentad 55 (September 30) fractional accumulations (Method 2)

- (a) and (b): GPCP fractional accumulations at pentads 31 and 55
- (c) and (d): Pentad at which CMAP reaches the GPCP fractional accumulations (should = 31 and 55, respectively, if perfect agreement)



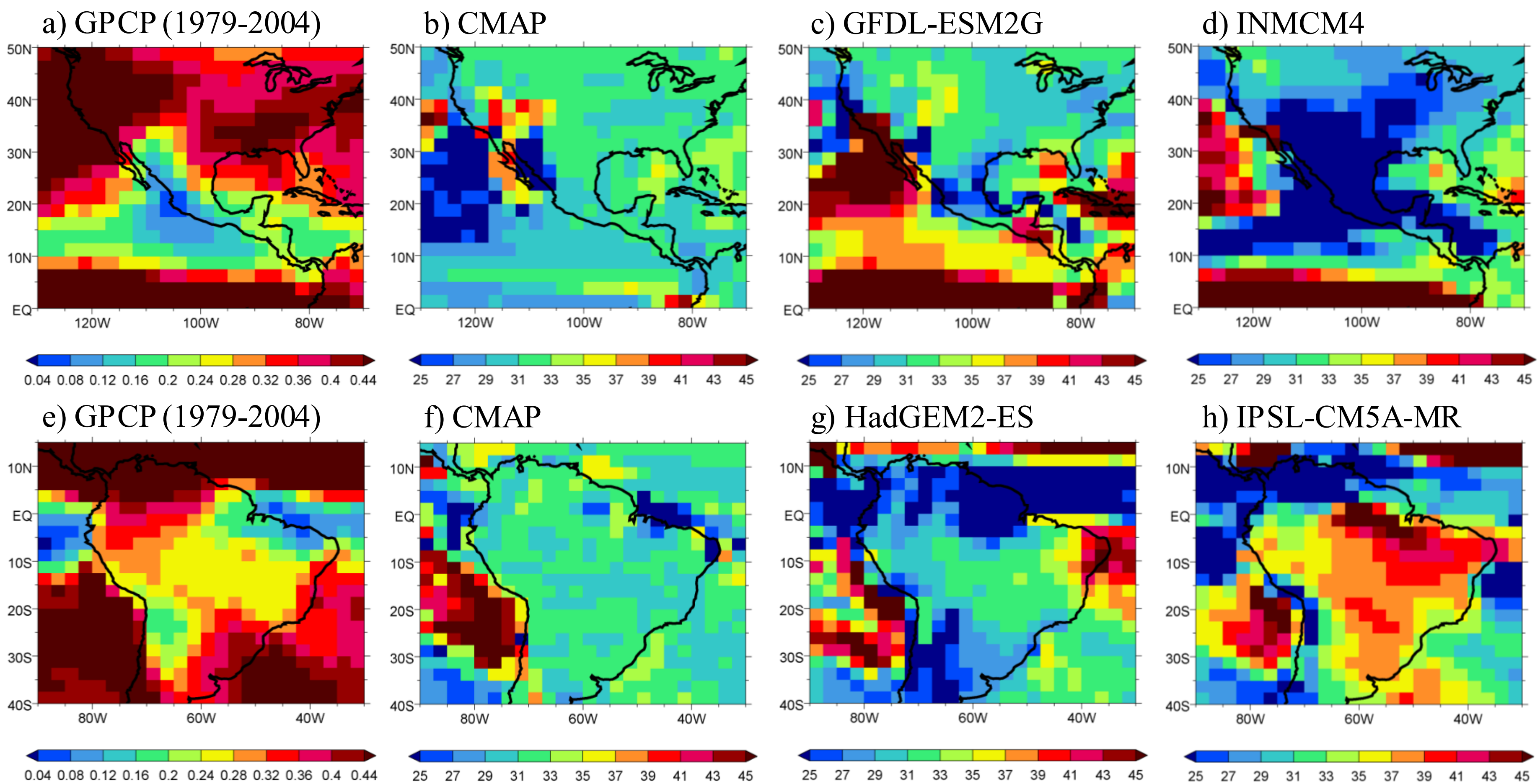
Climatological rainfall: Monsoon Duration based on models timing in attaining GPCP pentad 31 (June 2) and pentad 55 (September 30) fractional accumulations

- **1 + pentad the model reaches the GPCP fractional accumulation at pentad 55 – pentad the model reaches the GPCP fractional accumulation at pentad 31 (should = 25 for a perfect model)**
- India: CSIRO-Mk3.6.0 long duration; HadCM3 short duration; MIROC-ESM mixed signal
- North of 30^{o}N: the models have a longer than observed duration



GPCP rainfall: fractional accumulation at pentad 31; CMAP and models: pentad at which they reach GPCP fractional accumulation (should = 31 for a perfect model)

- <u>GPCP and CMAP:</u> Observational uncertainty, especially over NW Mexico and the SW U.S.
- <u>NAM:</u> GFDL-ESM2G had an excellent NAM index, but this is due to compensating error between ocean and land that is seen in many models (including over the Sahel and the Gulf of Guinea); INMCM4 is too early (like most models)
- <u>SAM:</u> HadGEM2-ES performs fairly well, IPSL-CM5A-MR is too late (like most models)



Summary

- The use of fractional accumulated rainfall is a powerful approach for evaluating the annual cycle
- The rapid fractional accumulation and the time at which it begins and ends are useful metrics for assessing how well models represent the development of monsoon rainfall
- In CMIP5, systematic errors are noted:
  - Annual cycle delayed: India, Gulf of Guinea, SAM
  - Annual cycle too early: Sahel, NAM
  - Most models have difficulty in representing the summer fractional accumulation
  - Land vs. Ocean behavior problematic
  - No single model performs well for all monsoon domains
- Except for models with the most extreme dry biases, the interannual variability of monsoon onset is well-represented
- Relative to the GPCP fractional accumulations at pentads 31 and 55 (Method 2), the monsoon duration is an integrated measure of the annual cycle phase error (non-linear behavior) and the rapid fractional accumulation growth rate (linear behavior)

Future work

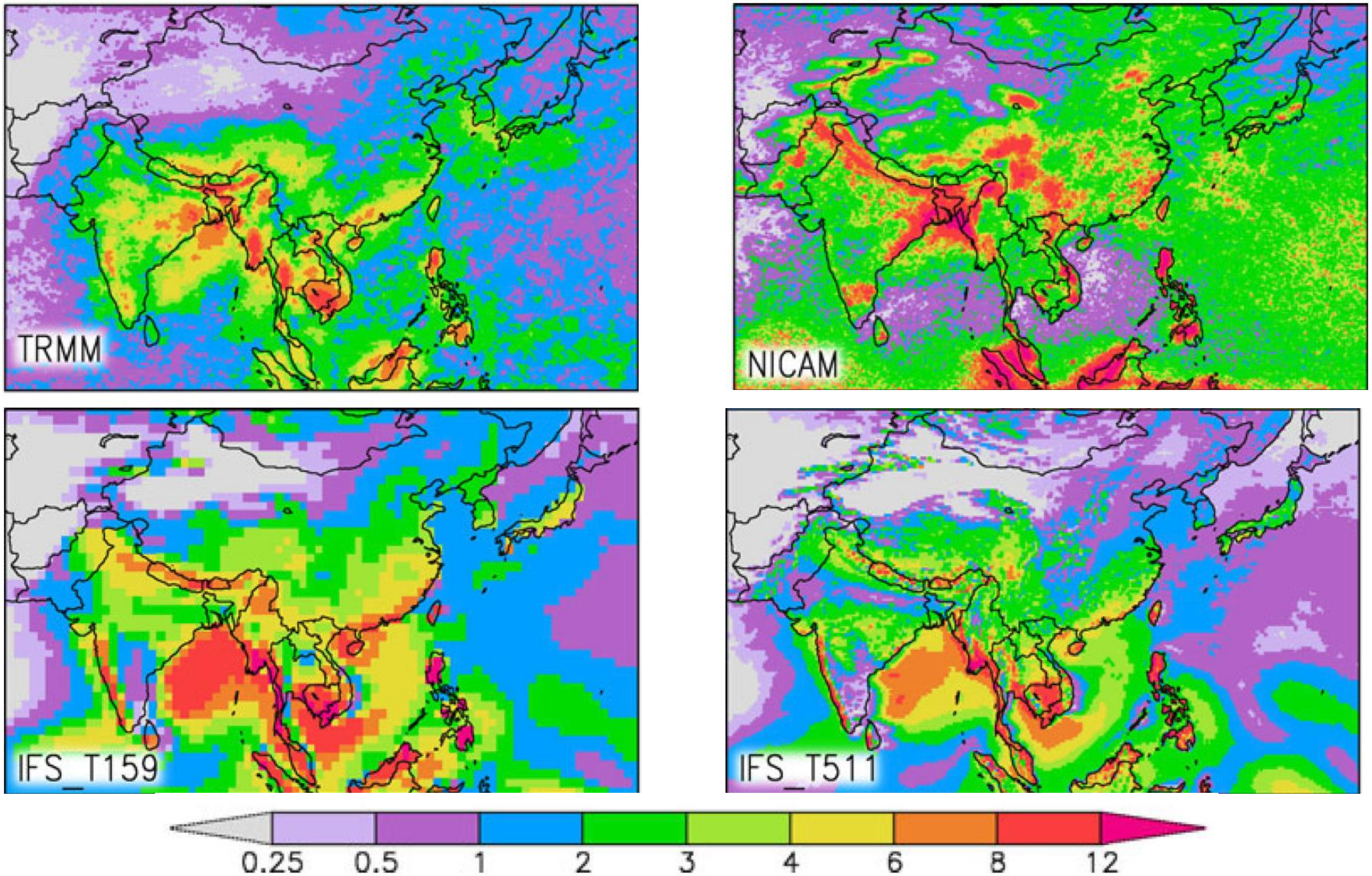
- Investigate the relationship between the rapid fractional accumulation and the spatio-temporal variability of rainfall?
  - For delayed onset and too rapid fractional accumulation: Is the rainfall too frequent and/or too intense?
- Evaluate the impact of anthropogenic forcing on the life-cycle of monsoon rainfall
  - Impact on the phase and duration of the monsoon season

Other processes and modes of variability

- Evaluating monsoons in isolation is a mistake
  - Local and remote processes can have an impact on regional monsoon simulation
    - Diurnal cycle (Dirmeyer et al. 2013)
    - SST biases (Levine et al. 2013)
    - Moisture budget and air-sea interactions (Bollasina and Nigam 2009)
    - Impact of land surface parameterization (Li et al. 2015; Ma et al. 2013; Richter et al. 2012)
    - Impact of horizontal resolution (Sabin et al. 2013)
    - Impact of data assimilation (Raju et al. 2015)
    - MJO and moisture sensitivity (Kim et al. 2014)

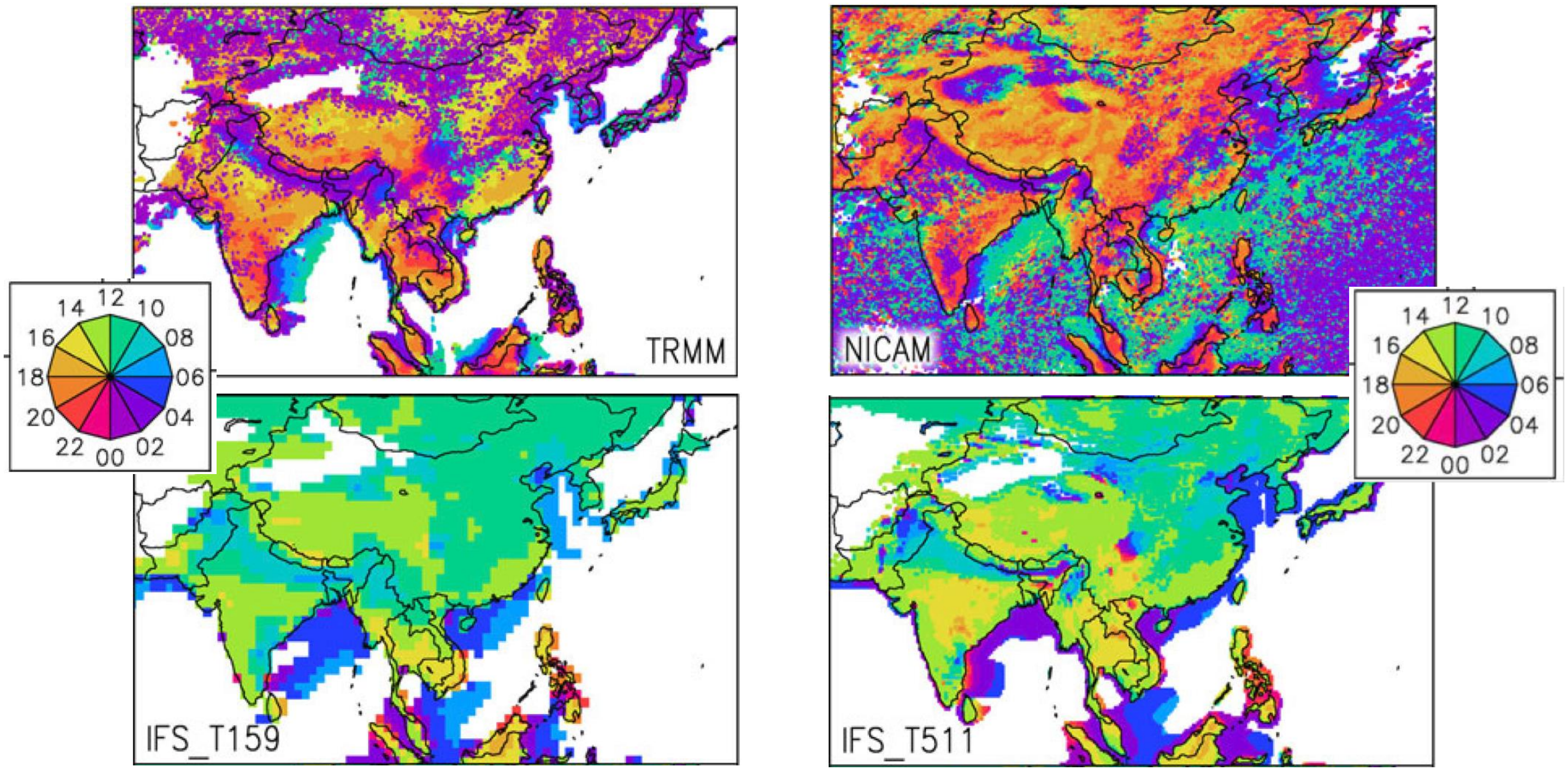
GCM: ASM rainfall diurnal cycle amplitude vs. resolution
Dirmeyer et al. (2013, Clim. Dynam., doi: 10.1007/s00382-011-1127-9)

- Athena simulations: NICAM and ECMWF IFS
  - NICAM diurnal cycle amplitude tends to be too high (low) over land (ocean)
  - ECMWF IFS, with parameterized convection, has a diurnal cycle amplitude that converges for resolutions ≥T511; best agreement w/obs for models analyzed



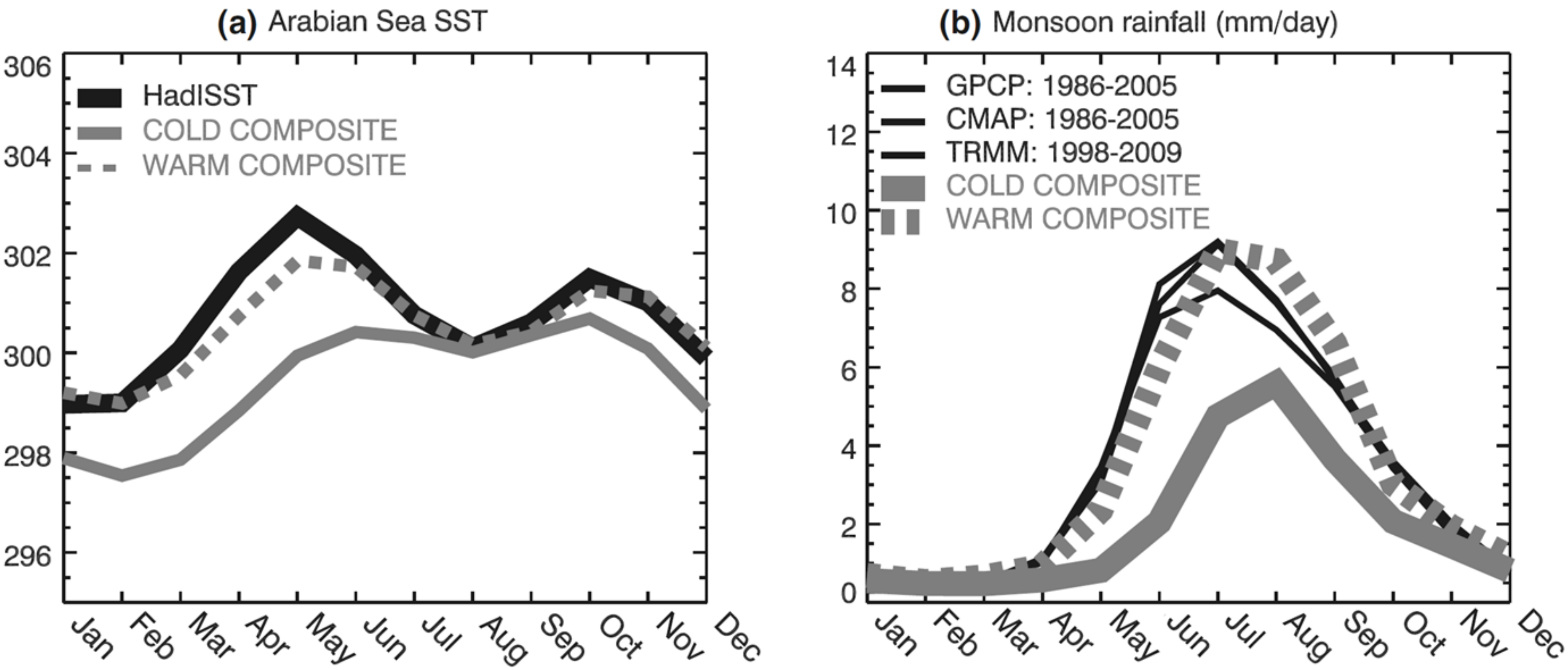
GCM: ASM rainfall diurnal cycle phase vs. resolution
Dirmeyer et al. (2013, Clim. Dynam., doi: 10.1007/s00382-011-1127-9)

- Athena simulations: NICAM and ECMWF IFS
  - NICAM captures well the late afternoon/evening diurnal cycle phase
  - ECMWF IFS, with parameterized convection, has diurnal cycle phase that converges for resolutions ≥T511; phase peaks too early, like most climate models



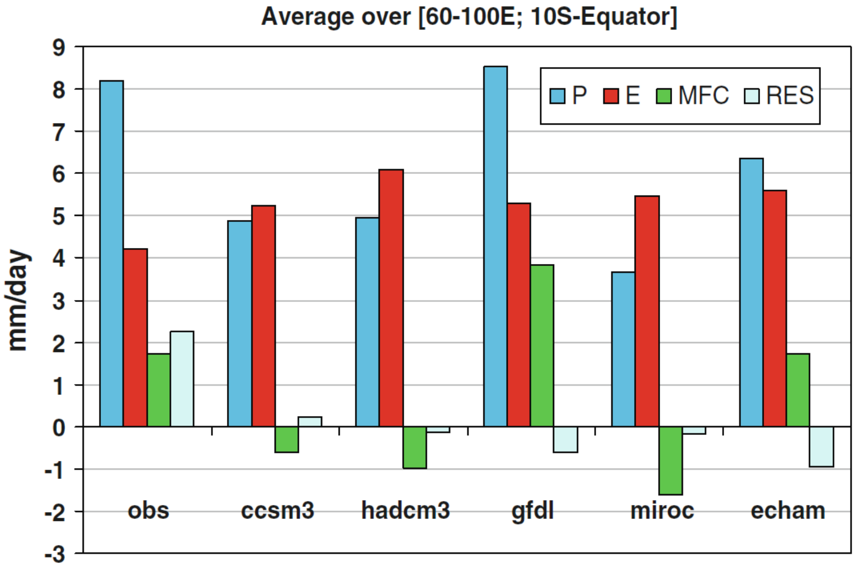
CMIP5: Indian monsoon rainfall biases vs. SST biases
Levine et al. (2013, Clim. Dynam., doi: 10.1007/s00382-012-1656-x)

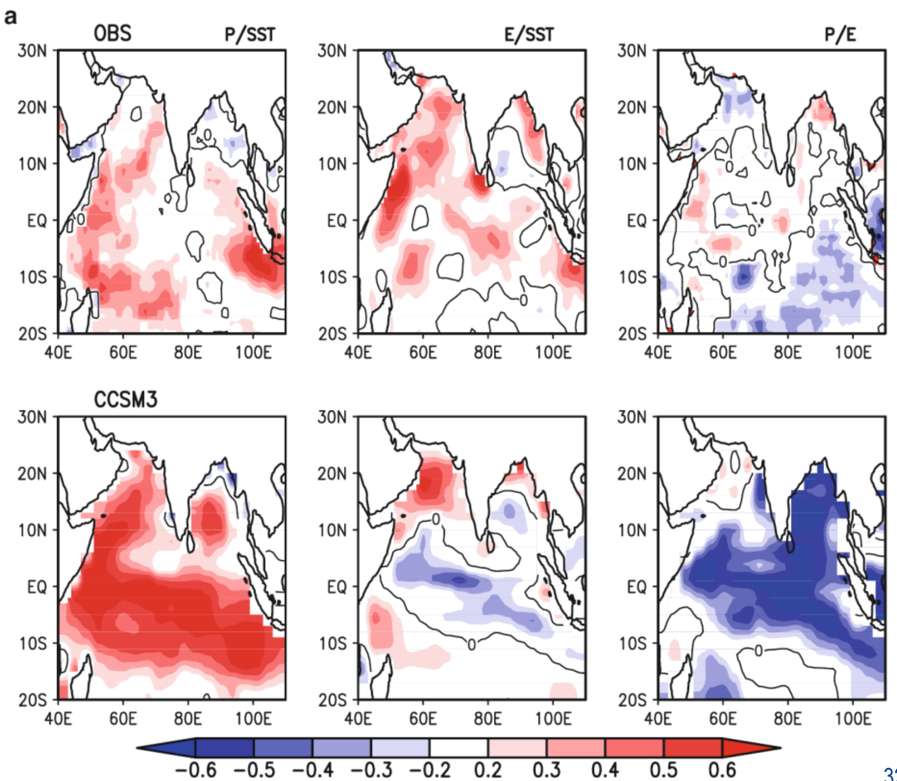
- 5 models with the warmest and coldest SST biases over the Arabian Sea
  - The warm (most realistic) models have a better representation of ISM rainfall
  - An overly strong winter monsoon circulation gives rise to the cold bias
    - Should not view the summer monsoon in isolation during process evaluation



CMIP3: Moisture budget and air-sea interaction
Bollasina and Nigam (2009, Clim. Dynam, doi: 10.1007/s00382-008-0477-4)

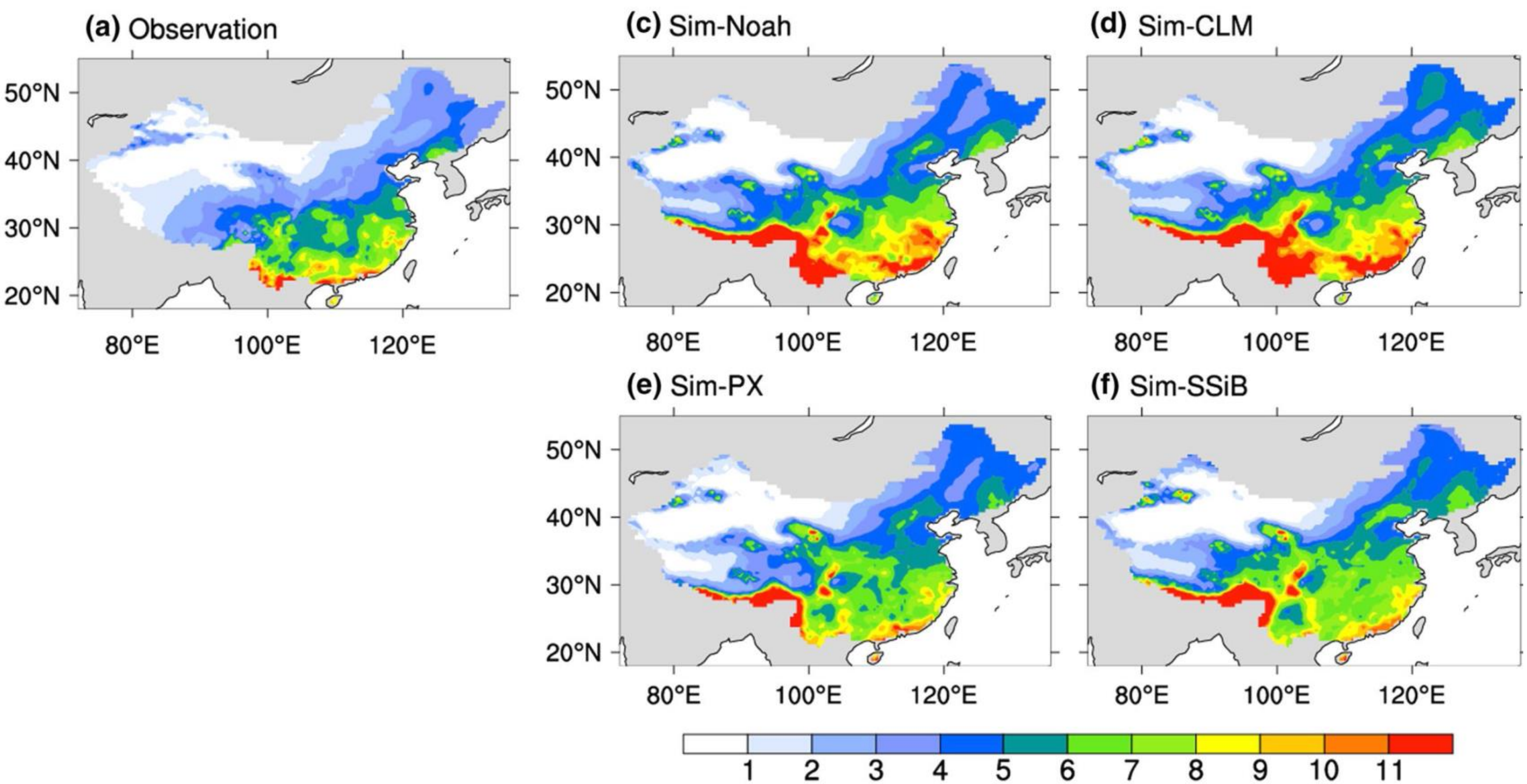
- Moisture budget (left)
  - Observations: Evaporation and the net import of moisture contribute to the accumulation of precipitation
  - Models: Factor of 2x in precipitation relative to observations, with tendency to incorrectly export moisture rather than import moisture
- Air-sea interaction (right)
  - The models tend to have too strong local coupling (correlation)





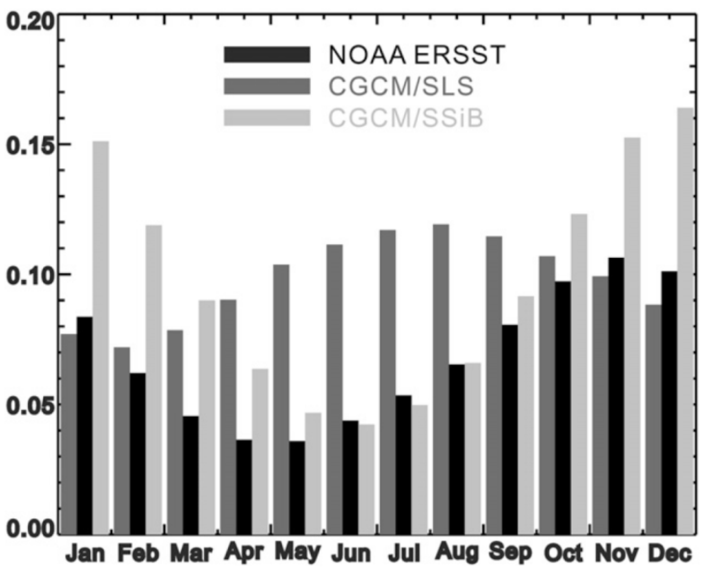
CMIP5: EASM rainfall and 2m T biases vs. land surface schemes
Li et al. (2015, Clim. Dynam., doi: 10.1007/s00382-015-2964-8)

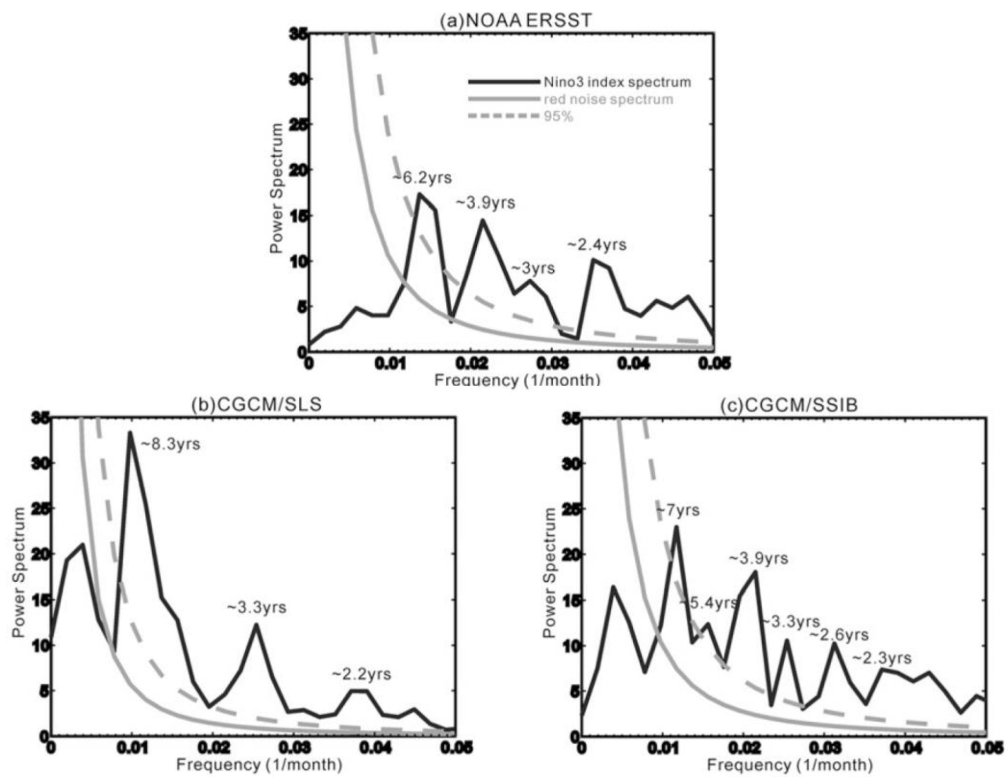
- Weather Research and Forecasting RGCM
  - EASM rainfall and 2m temperature better represented by Sim-PX and SIM-SSIB
  - In Sim-Noah and Sim-CLM
    - sensible heat flux is too strong over → overly strong land-sea thermal gradient → overly strong low-level winds → excessive precipitation



Nino-3 SST variance vs. land surface schemes
Ma et al. (2013, J. Clim., doi: 10.1175/JCLI-D-2-00142.1)

- UCLA AGCM coupled to the MIT OGCM
  - The seasonal cycle of SST (time-longitude; not shown) and Nino-3 SST variance and temporal variability are more realistic with SSiB (as are the annual means of the wind-drive currents, the zonal gradient of SST, and the thermocline structure)
  - Larger Bowen ratio over land → weaker convection over land → more realistic easterly trade winds over the tropical Pacific → stronger ocean-atmosphere feedbacks

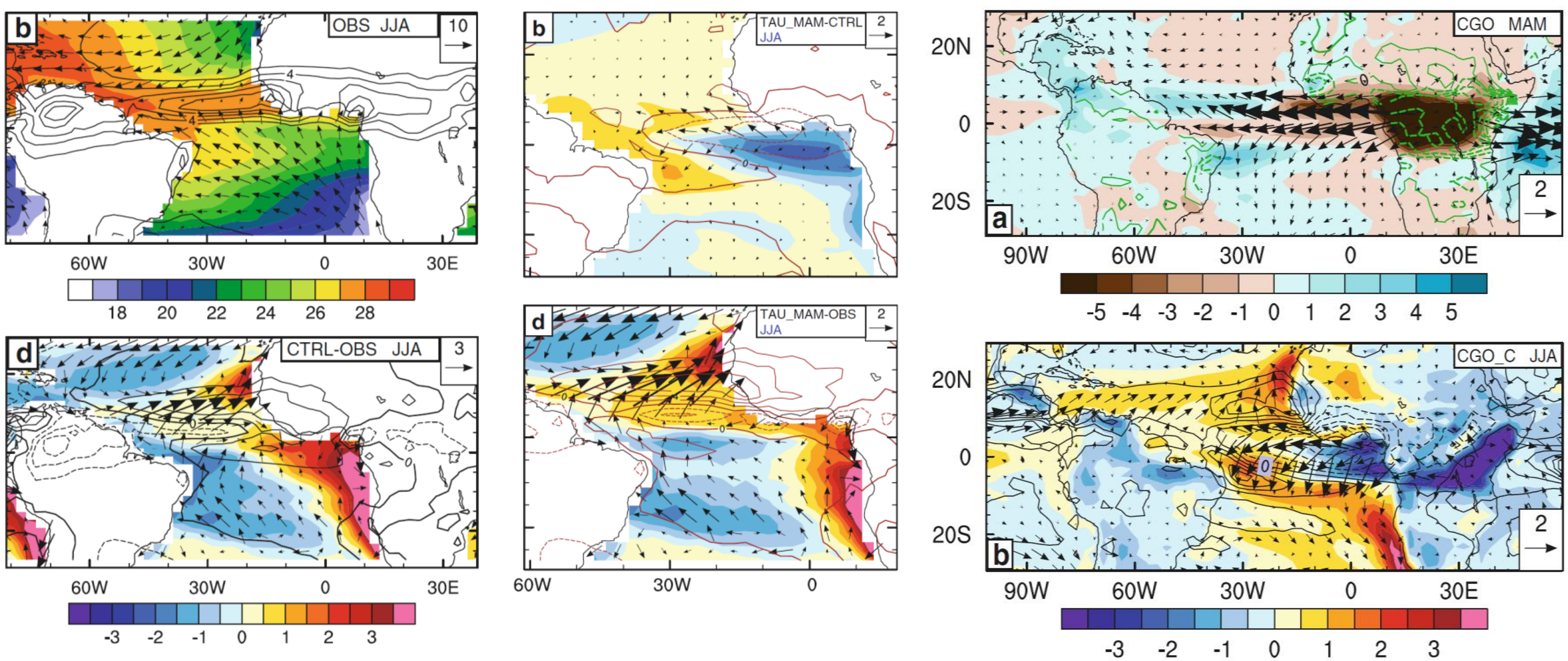




Atlantic tropical SST/pr vs. tau and land surface schemes
Richter et al. (2012, Clim. Dynam, doi: 10.1007/s00382-011-1038-9)

- GFDL CM2.1
  - Boreal spring and summer: the tropical Atlantic SST's are too warm, as is that adjacent to the west coast of Africa, due to too weak easterlies and along shore winds. The thermocline is too deep in the east and too shallow in the west (left)
  - Specifying observed equatorial Atlantic tau in MAM promotes upwelling in the east and downwelling in the west results with the temperature anomalies persisting into JJA (center)
  - By changing albedo and soil moisture over the Congo in MAM, tropical precipitation over Africa is weakened and equatorial easterlies are weakened, with reduced JJA equatorial SST and surface wind errors over the tropical Atlantic seen, although errors are worsened over the off-equatorial regions (right)

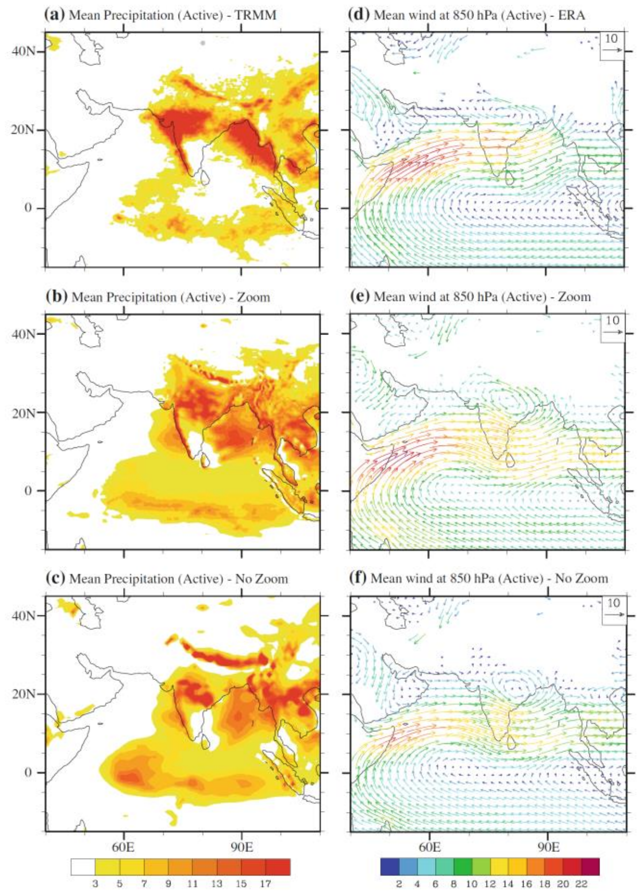
SST, surface wind, and Precipitation



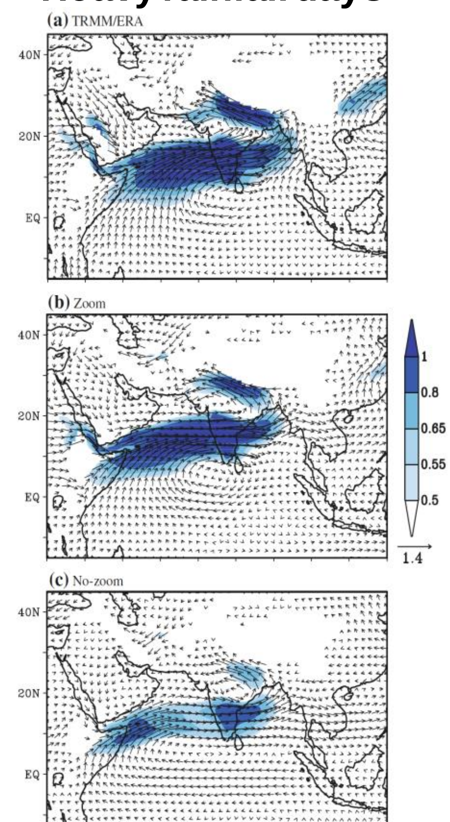
Climatology and subseasonal skill vs. horizontal resolution
Sabin et al. (2013, Clim. Dynam., doi: 10.1007/s00382/012-1658-8)

- LMDZ4 GCM: 360 x 180 gridpoints uniform (control) and 360 x 180 with ~35km resolution over South Asia (zoom version)
  - JJAS zoom has better mean state precipitation and 850hPa wind (left)
  - JJAS better representation of subseasonal variability of 850hPa wind (center), consistent with common mode of subseasonal and interannual variability from Sperber et al. (2000, QJRMS, 126, 2545-2574) (right)

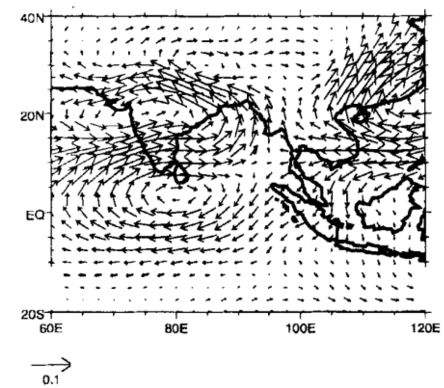
JJAS Climatology



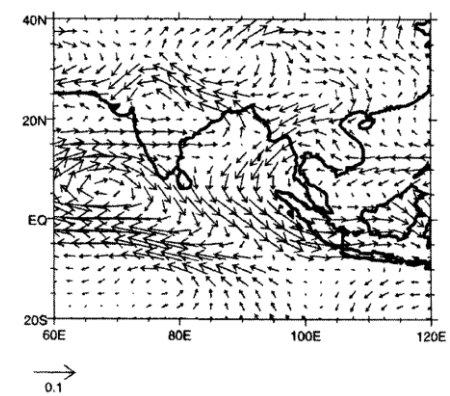
850hPa wind, Heavy rainfall days



NCEP 850hPa wind Subseasonal EOF-3

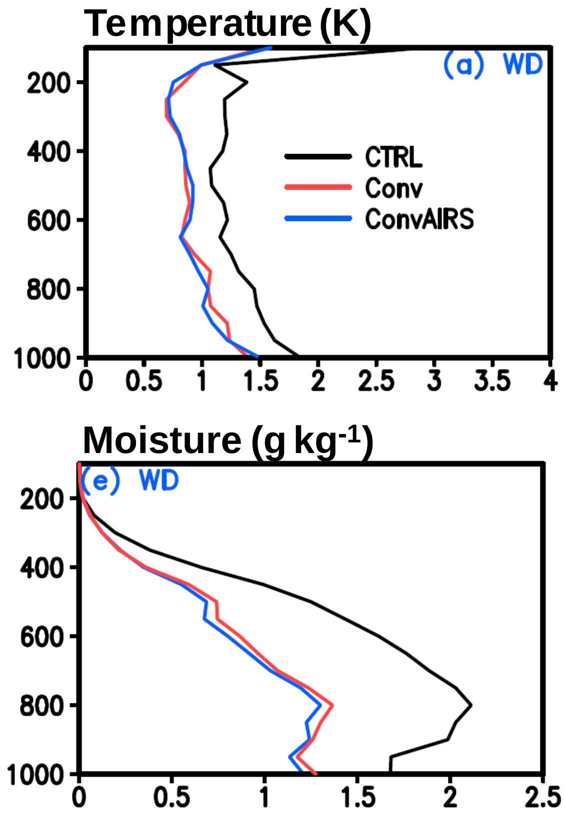


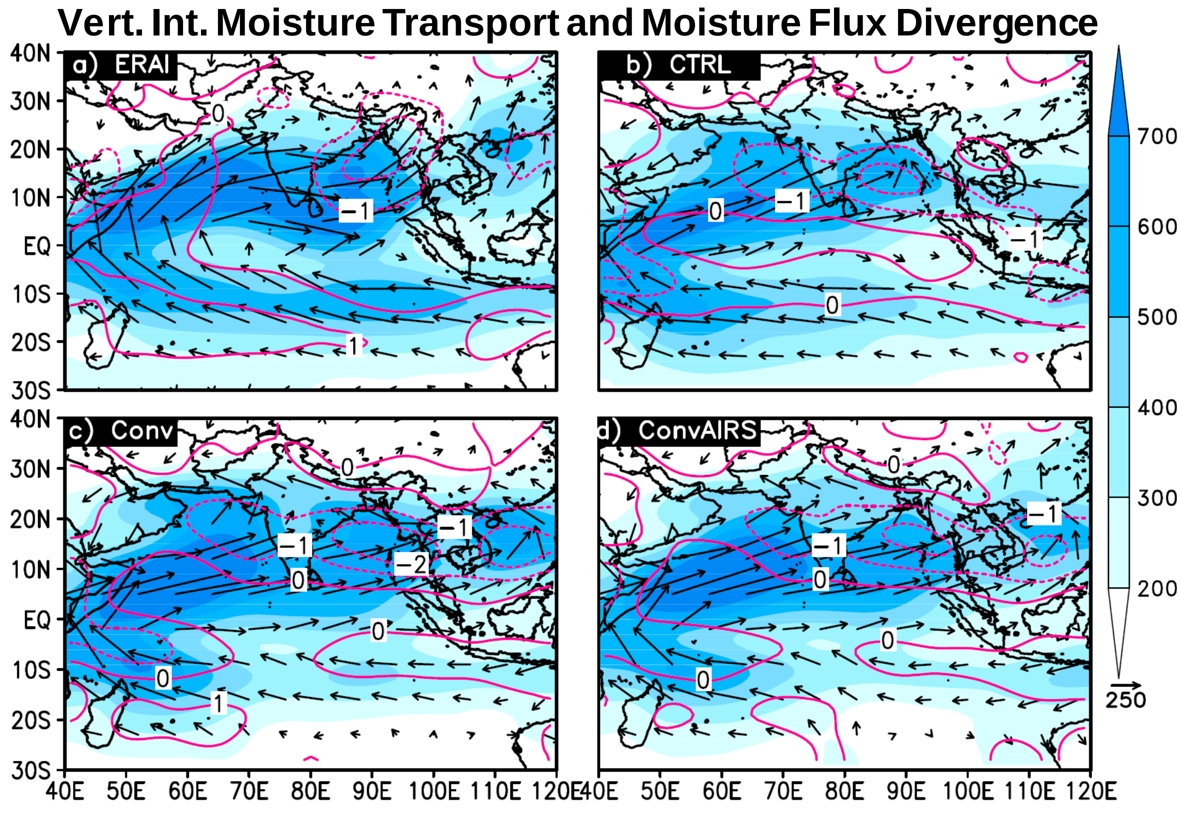
NCEP 850hPa wind Interannual EOF-4



ISM Hindcasts using WRF: Impact of data assimilation
Raju et al. (2015, J. Geophys. Res., doi: 10.1002/2014JD023024)

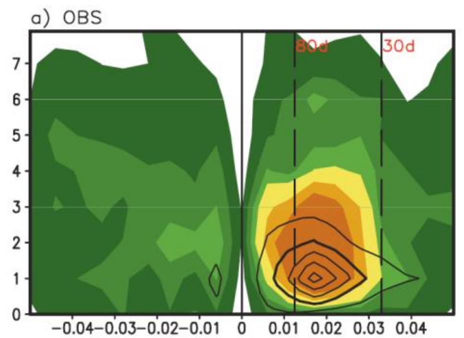
- Vertical profiles of temperature and moisture show pronounced changes due to assimilation (left)
- The vertically integrated moisture transport and moisture flux divergence show improvement relative to the control (right)
- Improvement in the representation of moisture convergence in boundary layer with an improved representation of the monsoon circulation due to improved thermal gradients

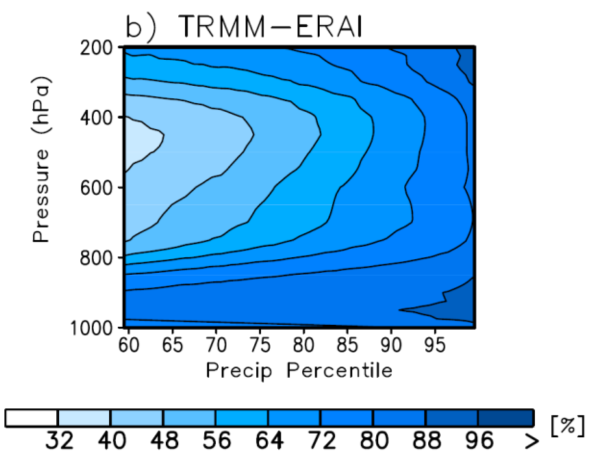


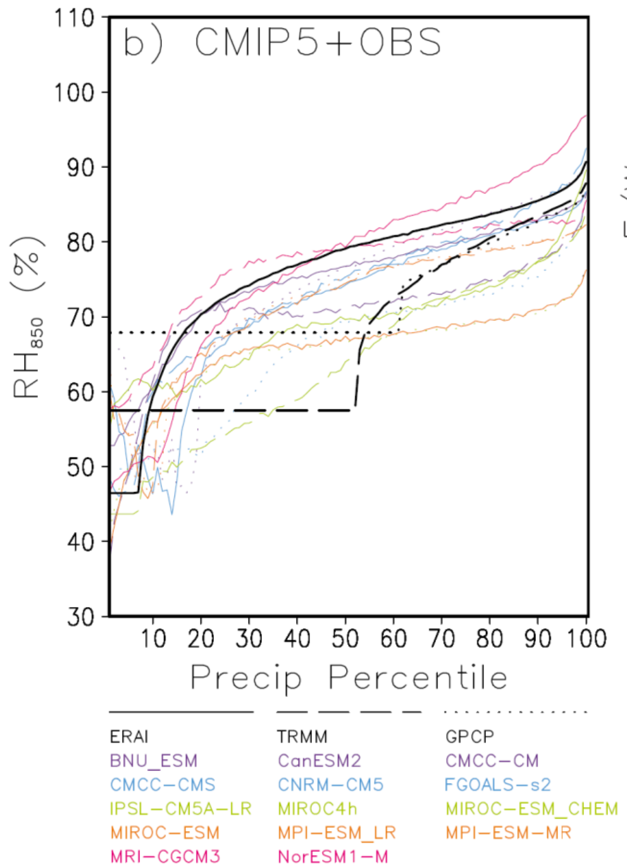


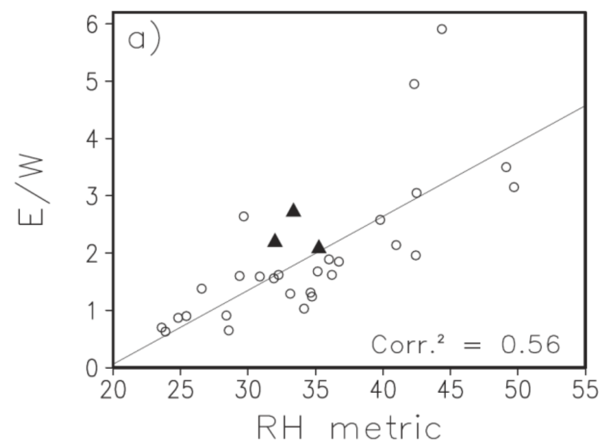
CMIP3 and CMIP5: MJO skill vs. moisture sensitivity
Kim et al. (2014, J. Clim., doi: 10.1175-JCLI-D-13-00497.1)

- MJO skill assessed by evaluation of the E/W power ratio for intraseasonal periods and wavenumbers using precipitation
- Physical Insight: Relative Humidity as a function of precipitation (60ºE-90ºE, 10ºS-10ºN)
  - RH Metric (850hPa) = RH(90-100%) – RH(0-10%)
  - The strength of the MJO is directly related to the ability to represent the lower-tropospheric humidity increase necessary to transition from weak to strong rain regimes









Opportunities

- The evaluation scale interactions requires more in-depth analysis, for example
  - The rectification of the diurnal cycle onto longer term variability
  - The impact of intraseasonal variability on precipitation extremes
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