The Use of Fractional Accumulated Precipitation for the Evaluation of the Annual Cycle of Monsoons in CMIP5 Historical and RCP8.5 Simulations

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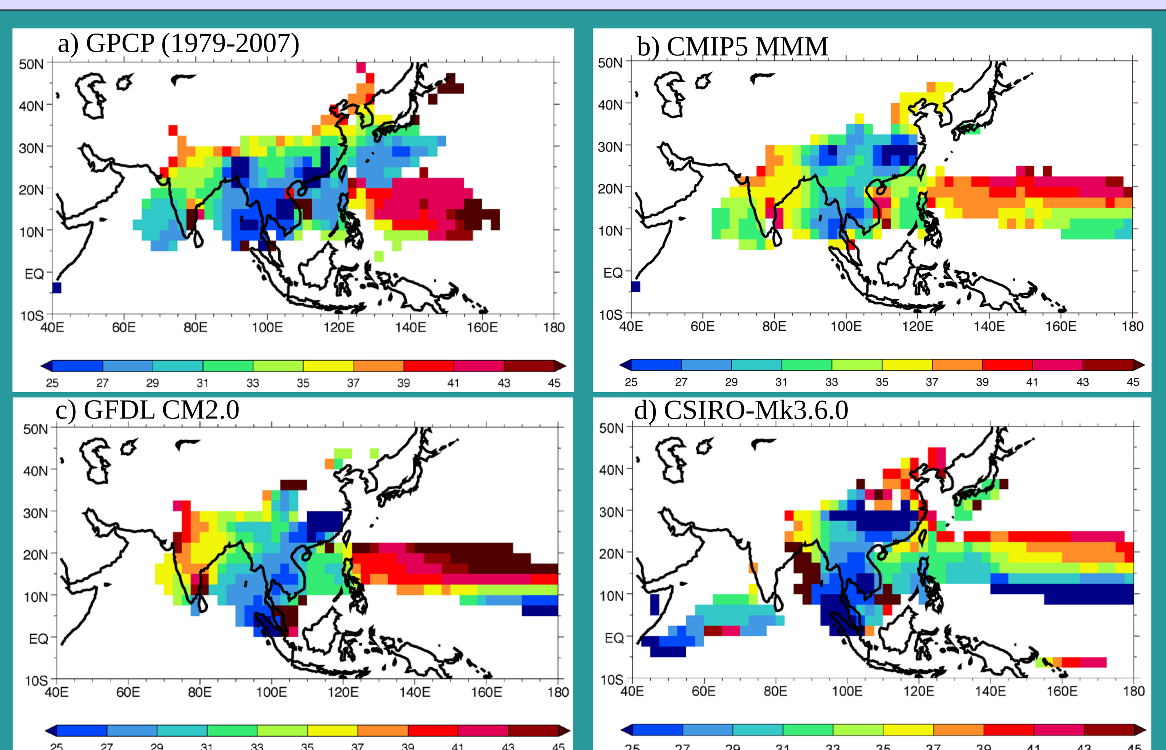
Goal: Develop an objective method and new metrics for analyzing the annual cycle of precipitation in climate models irrespective of mean-state biases

- Motivation and Issue
  - Previous approaches for analyzing the onset, peak, withdrawal, and duration of monsoon rainfall have been threshold-based (e.g., Wang and LinHo (2002, *J. Clim.*, **15**, 386-398)
  - As such, in some cases monsoon is not even “defined” in models that have dry biases (Sperber et al. 2013, *Clim. Dynam.*, **41**, 2711-2744, doi: 10.1007/soo382-012-1607-6)
  - Biases also affect the perception of the phase of annual cycle, such that models with dry (wet) biases may appear to have late (early) monsoon onset
- New Methodology
  - Use fractional accumulated rainfall to assess the fidelity of the annual cycle of monsoon, and evaluate the impact of anthropogenic climate change
- Outcomes
  - Systematic, but regionally dependent, biases in monsoon onset occur in CMIP5 Historical simulations
  - Significant changes in monsoon rainfall amount, timing, and duration occur in CMIP5 RCP8.5 simulations

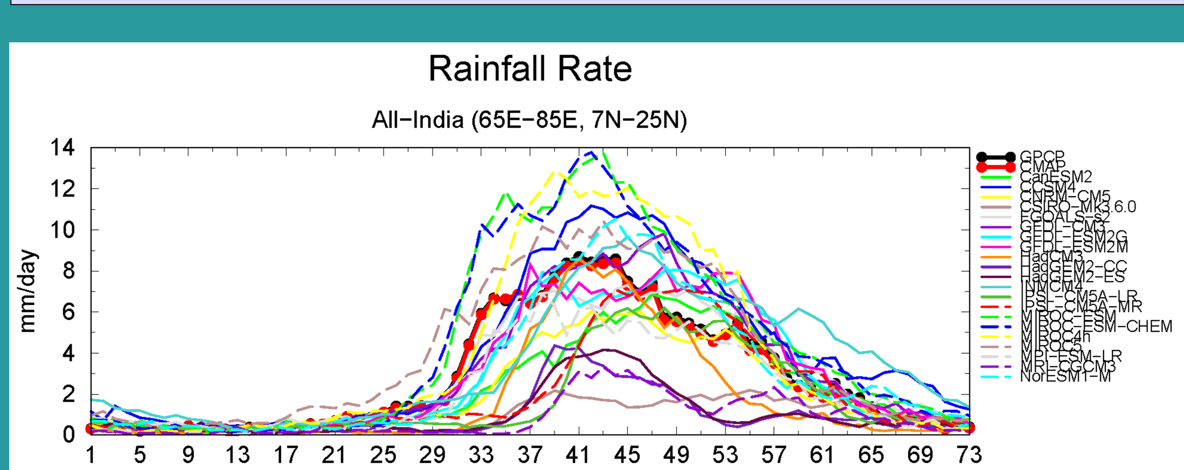
Motivation: Illustration of threshold-based evaluation of the monsoon precipitation

- Sperber et al. (2013) analyzed the annual cycle of Asian summer monsoon using the threshold based technique of Wang and LinHo (2002) using 21 CMIP5 Historical simulations and 22 CMIP3 Climate of the 20th Century simulations. **For monsoon onset**:
  - Individual models outperform the CMIP5 and CMIP3 multi-model means
  - The models have substantial biases in representing the time of onset
  - Relative to onset, peak, and withdrawal, the duration is more poorly represented (not shown)
  - In models with dry biases (e.g., CSIRO-Mk3.6.0), monsoon is not defined over regions where the threshold-based relative rainfall rate cutoff (5mm day^{-1}) is not reached



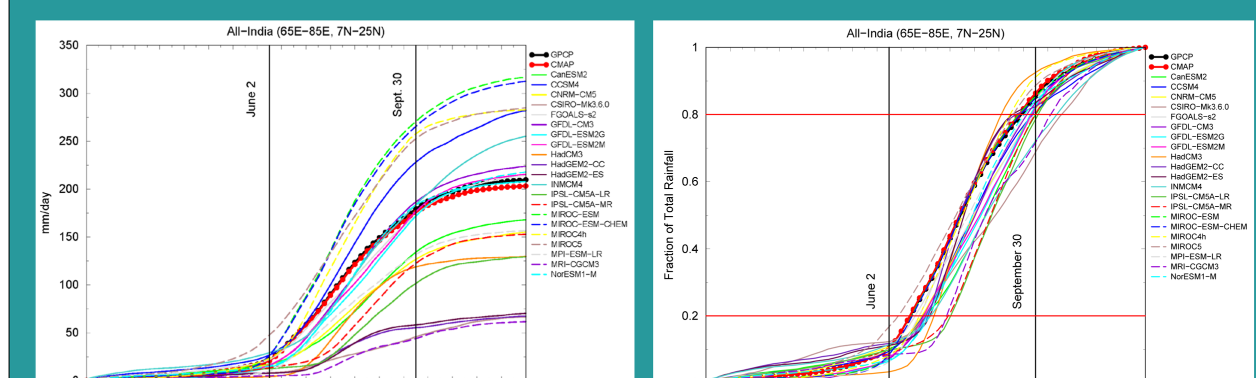
All-India Rainfall: Issues with model biases in analyzing the annual cycle

- In CMIP5 Historical simulations the majority of models have a dry bias
  - Is the late monsoon 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
  - How can we more clearly delineate the relative performance of the models?



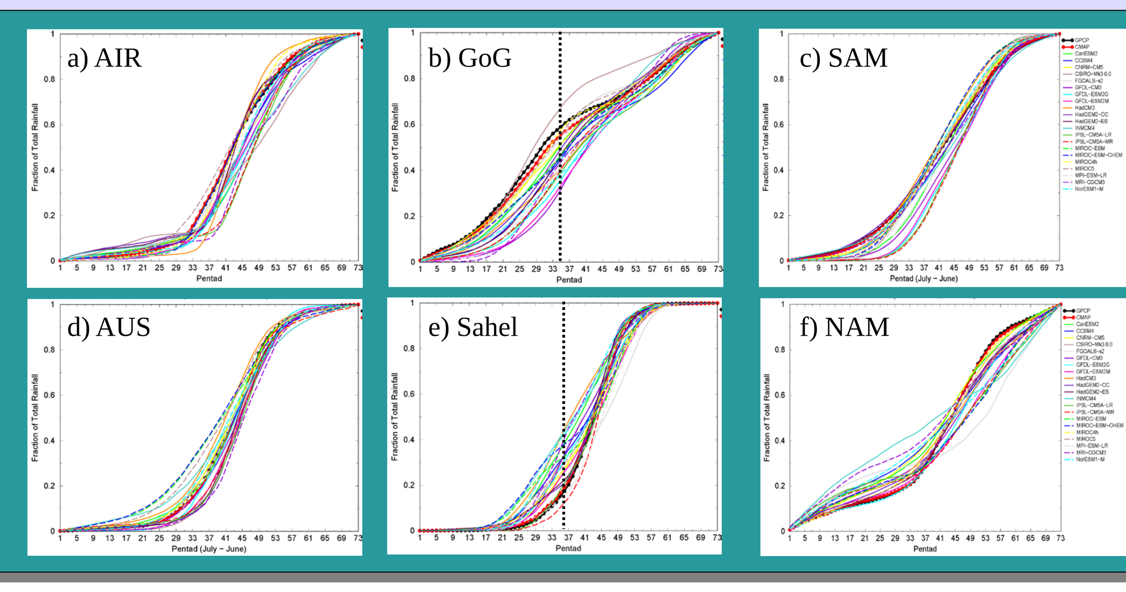
New Methodology: Accumulated rainfall and fractional accumulated rainfall

- The approach brings clarity to the simulation of the annual cycle of monsoon rainfall in disparate models
  - The accumulated rainfall clearly reveals model biases in absolute rainfall (left panel)
    - With higher horizontal resolution IPSL-CM5A-MR has > AIR than IPSL-CM5A-LR
    - MIROC-ESM and MIROC-ESM-CHEM are nearly identical, and have the largest wet biases
  - The fractional accumulation of AIR reveals that the majority of model have late onset (right panel)
    - The MIROC-ESM models closely follow the observed fractional accumulation despite their overestimate of absolute rainfall



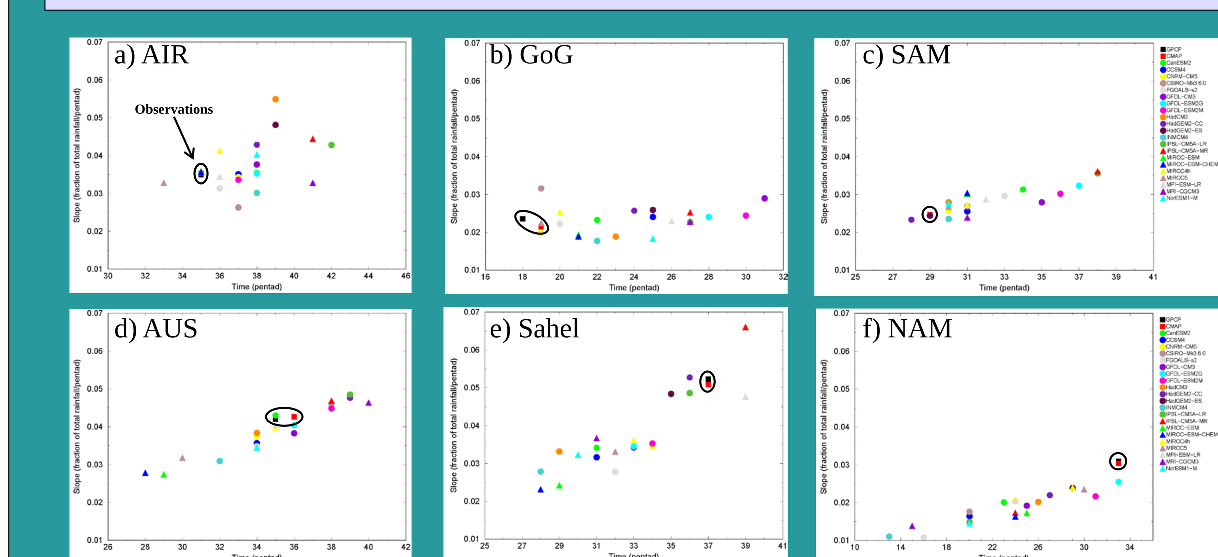
Various monsoon domains: GPCP and CMIP5 Historical fractional accumulated rainfall

- India (65ºE-85ºE, 7ºN-25ºN, land only)
- Australia (120ºE-150ºE, 20ºS-10ºS, land only)
- Sahel (10ºW-10ºE, 13ºN-18ºN): Smallest rainfall accumulation; fastest rapid fractional accumulation
- Gulf of Guinea (10ºW-10ºE, 0ºN-5ºN)
- North America Monsoon (112ºW-103ºW, 20ºN-37ºN): 2nd smallest rainfall accumulation
- South America Monsoon (65ºW-40ºW, 20ºS-2.5ºS): Largest rainfall accumulation
- Systematic biases in the time on monsoon onset are present
  - All-India Rainfall, Gulf of Guinea, and South America Monsoon: most models have late onset
  - Sahel and North American Monsoon: most models have early onset
  - Models fail to represent the cessation of rain over the GoG prior to the onset of Sahel rainfall
- ***The rapid fractional accumulation, occurring over the summer monsoon season, is ~linear over the range 0.2-0.8 (0.2-0.6 Gulf of Guinea)***



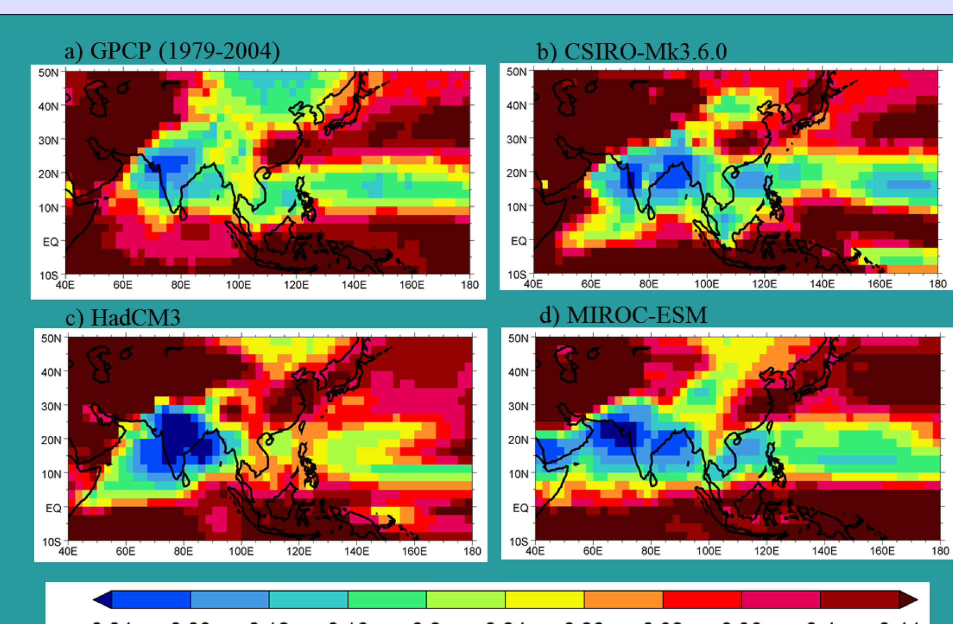
Various monsoon domains: Onset vs. slope of the rapid fractional accumulation

- Systematic biases in the onset time (pentad at which the fractional accumulation first becomes ≥0.2) and the rapid fractional accumulation (slope of the fractional accumulation over the range 0.2-0.8 (0.2-0.6 for Gulf of Guinea)
  - All-India Rainfall, Gulf of Guinea, and South America Monsoon: most models have late onset
  - Sahel and North American Monsoon: most models have early onset



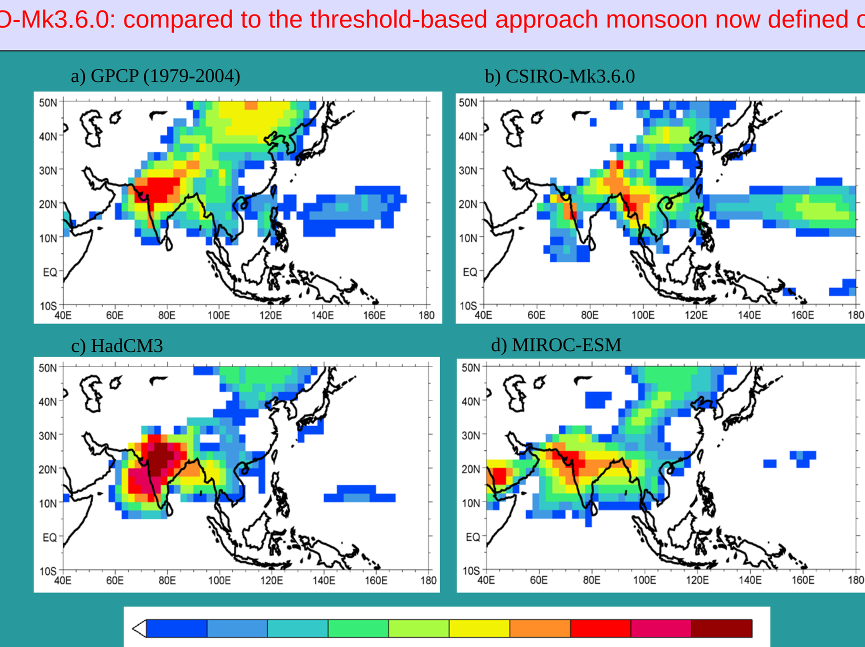
Fractional accumulation as of June 2 (pentad 31)

- In observations the lowest fractional accumulation is over India
  - CSIRO-Mk3.6.0 and MIROC-ESM represent this fairly well
  - HadCM3 strongly underestimates the fractional accumulation over India
- Over China, the models overestimate the fractional accumulation



Fractional accumulation from June 2 – Sept. 30

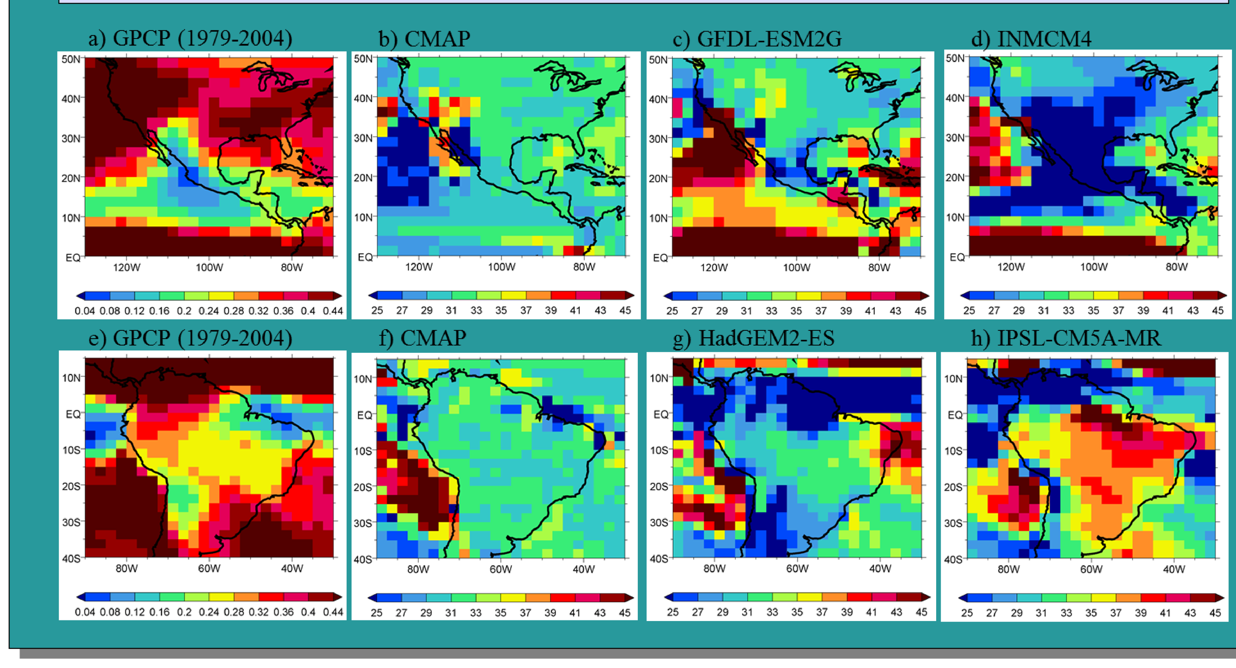
- In observations the largest fractional accumulation occurs from India to NE China
  - MIROC-ESM is realistic, especially over India (consistent with the AIR fractional accumulation)
  - India and China: Most models poorly represent the fractional accumulation
  - Monsoon Domain: defined where ≥50% of the annual accumulation occurs during summer
  - CSIRO-Mk3.6.0: compared to the threshold-based approach monsoon now defined over India



GPCP: fractional accumulation at pentad 31

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

- GPCP and CMAP: observational uncertainty, especially over NW Mexico and SW U.S.
- NAM: GFDL-ESM2G had an excellent NAM index, but this was due to compensating errors over ocean and land that is seen in many models (this also occurs over the Gulf of Guinea and the Sahel); INM-CM4 too early (like most models)
- SAM: HadGEM2-ES performs well, IPSL-CM5A-LR is too late (like most models)

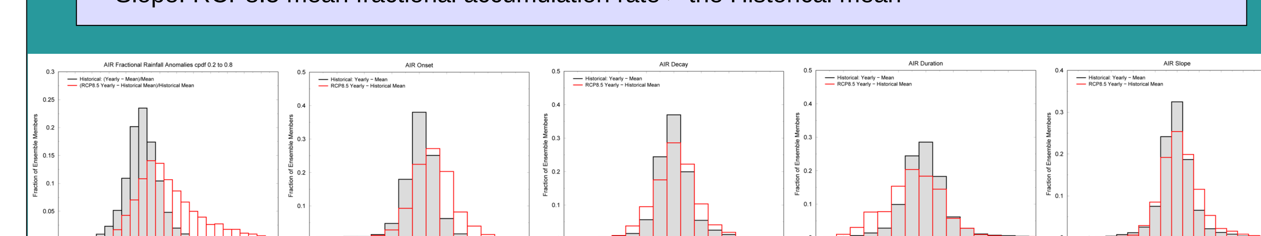


Monsoon Climate Change: CMIP5 Models

- Pentad precipitation: all available ensembles
  - CMIP5 (25 models: Historical, 1961-1999; RCP8.5, 2061-2100)
    - ACCESS1.0, ACCESS1.3, BCC-CSM1.1, BCC-CSM1.1m, BNU-ESM, CanESM2, CMCC-CESM, CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3.6.0, FGOALS-g2, HadGEM2-CC, HadGEM2-ES, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M
  - Historical: 2496 years of pentad precipitation analyzed
  - RCP8.5: 1917 years of pentad precipitation analyzed
- Analysis based on model dependent biases in onset (first pentad at which the fractional accumulation ≥0.2), decay (first pentad at which the fractional accumulation ≤0.8 [≤ 0.6 for GoG]), and the rapid fractional accumulation rate (slope of the fractional accumulation from 0.2-0.8 [0.2-0.6 for GoG])
  - Historical Simulations
    - ***For each model***, using all ensemble members, and for each year, build up a distribution of anomalies calculated relative to that models average
    - The Historical anomalies provide a reference distribution against which climate change perturbations can be assessed
  - RCP8.5 Simulations
    - ***For each model***, using all ensemble members, and for each year, subtract that models Historical average from the yearly value
    - The RCP8.5 anomalies provide a distribution that can be compared to the distribution of Historical anomalies to assess the impact of climate change
- Based on the ***rainfall accumulation*** that occurs for fractional accumulations of 0.2–0.8, evaluate perturbations to fractional changes in rainfall amount for AIR, AUS, Sahel, GoG (0.2-0.6), NAM, and SAM
  - Historical Simulations
    - ***For each model***, using all ensemble members, and for each year i, build up a distribution of fractional rainfall anomalies where:
      - $\overline{Hrain} = \frac{1}{n}\sum_{i=1}^{n} Hrain_i$ for fractional accumulations of 0.2-0.8 (0.2-0.6 for GoG)
      - $FHrain_i = \left(Hrain_i - \overline{Hrain}\right)/\overline{Hrain}$
    - The Historical anomalies provide a reference distribution against which climate change perturbations can be assessed
  - RCP8.5 Simulations
    - ***For each model***, using all ensemble members, and for each year i, calculate that models fractional rainfall anomalies relative to $\overline{Hrain}$:
      - $FRCPrain_i = (RCPrain_i - \overline{Hrain})/\overline{Hrain}$
    - The RCP8.5 anomalies provide a distribution that can be compared to the distribution of Historical anomalies to assess the impact of climate change
- t-test for changes in the means of the distribution
  - H_0: RCP8.5 mean = Historical mean
  - H_1: RCP8.5 mean ≠ Historical mean
  - 5% significance test
    - Degrees of freedom: 4411 = (2496 + 1917) - 2, assumes all years and all ensembles independent
    - Degrees of freedom: 1973 = (25 *39 + 25 *40) – 2, more conservative estimate based on the number of models and the number of years from a single ensemble member (but all members are used to generate the distributions)

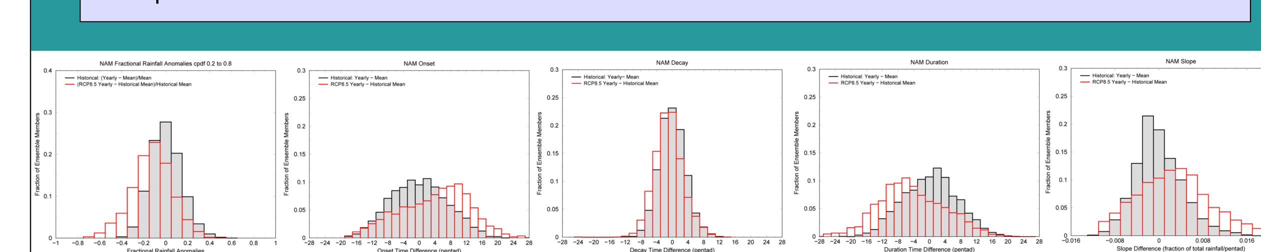
All-India Rainfall

- RCP8.5 fractional rainfall increase of 0.31 (31%) compared to Historical mean
- Onset RCP8.5 mean is 1.98 pentads later than the Historical mean
- Decay RCP8.5 mean is 0.33 pentads later than the Historical mean
- Duration RCP8.5 mean is 1.65 pentads shorter than the Historical mean
- Slope: RCP8.5 mean fractional accumulation rate > the Historical mean



North American Monsoon

- RCP8.5 fractional rainfall decrease of 0.12 (12%) compared to Historical mean
- Onset RCP8.5 mean is 3.75 pentads later than the Historical mean
- Decay RCP8.5 mean is 0.89 pentads earlier than the Historical mean
- Duration RCP8.5 mean 4.64 pentads shorter than the Historical mean
- Slope: RCP8.5 mean fractional accumulation rate > the Historical mean



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