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Seasonal Cycle of Precipitation in GCMs over Major Asian River Basins

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Outline

1. Background
2. Target Area
3. Data and Analysis
4. Results
5. Way Forward

Background

- **South and Southeast Asia face major challenges for water sector:** Population Growth, urbanization, industrialization, inefficient water use, ***all aggravated by climate change***
- **South and Southeast Asia is a hot spot of climate change;** changes in the hydrological cycle will be quite serious in this region.
- **Water management/hydrological risks** and climate change agenda.
- **GCMs are the state-of-the-art tools** used for climate variability change
- **GCMs' representation of monsoon is sub-optimal** (Boos and Hurley 2012)
  - **Seasonal** Modulation of the Hydrological cycle needs to be studies
- **CMIP3 models are widely employed** for downscaling purposes.
- **Self-consistency must be checked** Inconsistencies in water balance/in the energetics (Liepert and Previdi, 2012; Lucarini and Ragone, 2011).
- **Let's see the performance of CMIP5 GCMs**
- **Ideas discussed here can be reproduced for other regions/basins**

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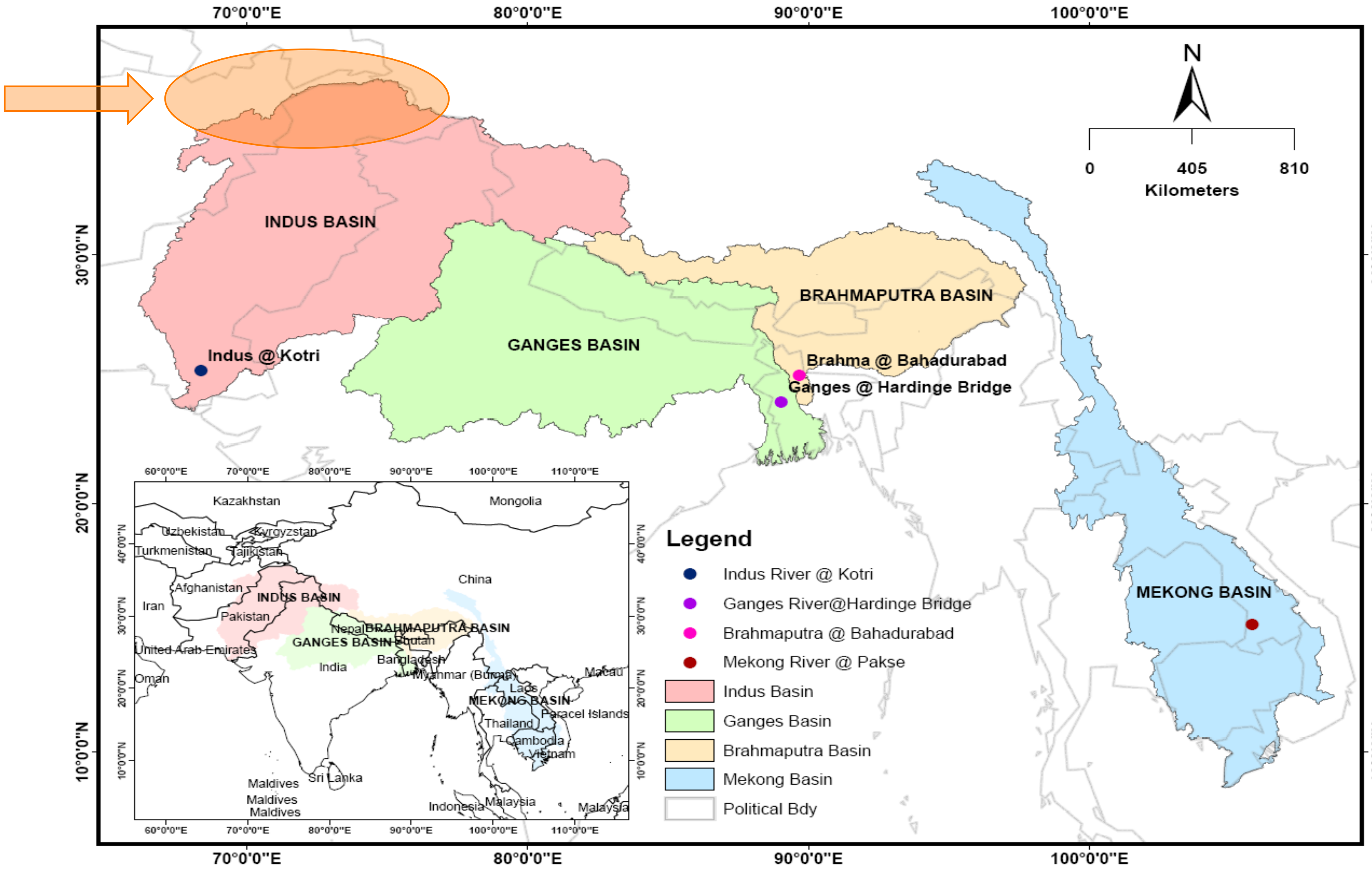
CAVEAT: Historical Climate change hard to represent in the UIB (T, P, Glaciers)

Specific Research Questions

1. How precisely do GCMs conserve water on basin scale?
    a. Indus, Gange, Brahmaputra, Mekong
2. How good is inter-model agreement? – ensembles?
3. Seasonal Cycle of Hydrological Properties?
4. How do GCMs project changes in the Hydrological Cycle?
5. Guidance for Downscaling/ Impact Assessment Communities…

Target Area



Large-scale circulation features: Monsoon plus Mid-latitude Disturbances

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General Features of the River Basins

Basin Characteristics	Indus	Ganges	Brahmaputra	Mekong
Basin Area (km^2)	1,230,000	1,000,000	530,000	840,000
River Length (km)	3,200	2,500	2,900	4,800
Near-to-Sea Gauge used in study	Kotri	Hardinge Bridge	Bahadurabad	Pakse
Annual Mean Discharge (m^3s^{-1}) / Runoff (mmy^{-1}) to Sea	1,250 / 32	11,000 / 345	20,000 / 1200	17,000 / 640
Discharge (m^3s^{-1}) equivalence to the 100mmy^{-1} Runoff	3,890	3,190	1,680	2,670
Peak Discharge Month	August	August	July	August
High Flow Season	April-September	July-October	April-November	June-November
No of Glaciers/ Area (km^2)	18,495 / 21,000	7,963 / 9,000	11,497 / 14,000	482 / 230
Snow Coverage (Annual Avg. %)	13.5	5	20	3
Snow & Glacier Melt Index	150	10	27	Negligible
Population Dependent (millions)	260	520	66	79
Major Consumption	**Agriculture**	Agriculture	Agriculture	Agriculture
Seasonal/annual Variability	High	High	High	High

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Data & Analysis

- We consider the GCMs output data distributed through the PCMDI/CMIP3 project, These include the data used for IPCC4AR and the GCMs routinely used **today** by local meteorological services for nesting RGCMs
- The monthly climatology of the hydrological quantities such as Total Runoff (R), Precipitation (P) and Evaporation (E) is considered for the analysis.
- Auditing and the verification of GCMs are performed over the historical simulations of XX century climate (1961-2000)
- Future changes have been ascertained for the corresponding climates of the XXI (2061-2100) and XXII (2161-2200) centuries under SRESA1B scenario.
- The surface upward latent heat flux is used to compute the evaporation from all models.
- We consider the monthly climatology of the historical river discharges (D) for the four rivers at their last available gauging stations near to sea **(Indus at Kotri, Ganges at Hardinge Birdge, Brahmaputra at Bahadurabad and Mekong at Pakse)**
- We then study CMIP5 model performances (consider RCP8.5 scenario)

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PCMDI/CMIP3 General Circulation Models

Name and Reference	Institution	Grid Resolution (Lat x Lon)
CNRMCM Salas-Me´lia et al., (2005)	Météo-France / Centre National de Recherches Météorologiques, France	T63
MRI-CGCM2.3.2 Yukimoto and Noda (2002)	Meteorological Research Institute, Japan Meteorological Agency, Japan	T42
CSIRO3.0 Gordon et al., (2002)	CSIRO Atmospheric Research, Australia	T63
ECHAM5 Jungclaus et al., (2006)	Max Planck Institute for Meteorology , Germany	T63
ECHOG Min et al., (2005)	MIUB, METRI, and M&D, Germany/Korea	T30
GFDL20 Delworth et al., (2005)	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA	2.5° x 2.0°
GISSAOM Lucarini and Russell (2002)	NASA / Goddard Institute for Space Studies, USA	4° x 3°
INMCM30 Volodin and Diansky (2004)	Institute for Numerical Mathematics, Russia	5° x 4°
IPSL-CM4 Marti et al., (2005)	Institute Pierre Simon Laplace, France	2.4° x 3.75°
MIROC (hires) K-1 Model Developers (2004)	CCSR/NIES/FRCGC, Japan	T106
PCM1MODEL Meehl et al., (2004)	National Centre for Atmospheric Research, USA	T42
UKMOHADCM3 Johns et al. (2003)	Hadley Centre for Climate Prediction and Research/Met Office, UK	2.75° x 3.75°
UKMOHADGEM3 Johns et al., (2006)	Hadley Centre for Climate Prediction and Research/Met Office, UK	1.25° x 1.875°

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Methodology

- **Coarse resolution** is relatively least important while looking for the basin-wide integrated quantities for the large river basins (Lucarini et. al., 2007 & 2008).
- **Voronoi or Thiessen tessellation** method is used (Okabe et al., 2000) for accurately computing the basin-wide monthly climatology of the hydrological quantities from the climate gridded datasets.
- **Inconsistencies** between GCMs' land-sea masks and extracted basin boundaries are adjusted.
- Annual means of relevant quantities (P, E, B=P-E and R) are computed carefully using the following:

$$\langle P\rangle_t - \langle E\rangle_t \approx \langle R\rangle_t \approx -\langle \overrightarrow{\nabla_H}.\vec{Q}\rangle_t \qquad \textbf{(1),}$$

Spatially integrating equation (1) over an area A of the river basin

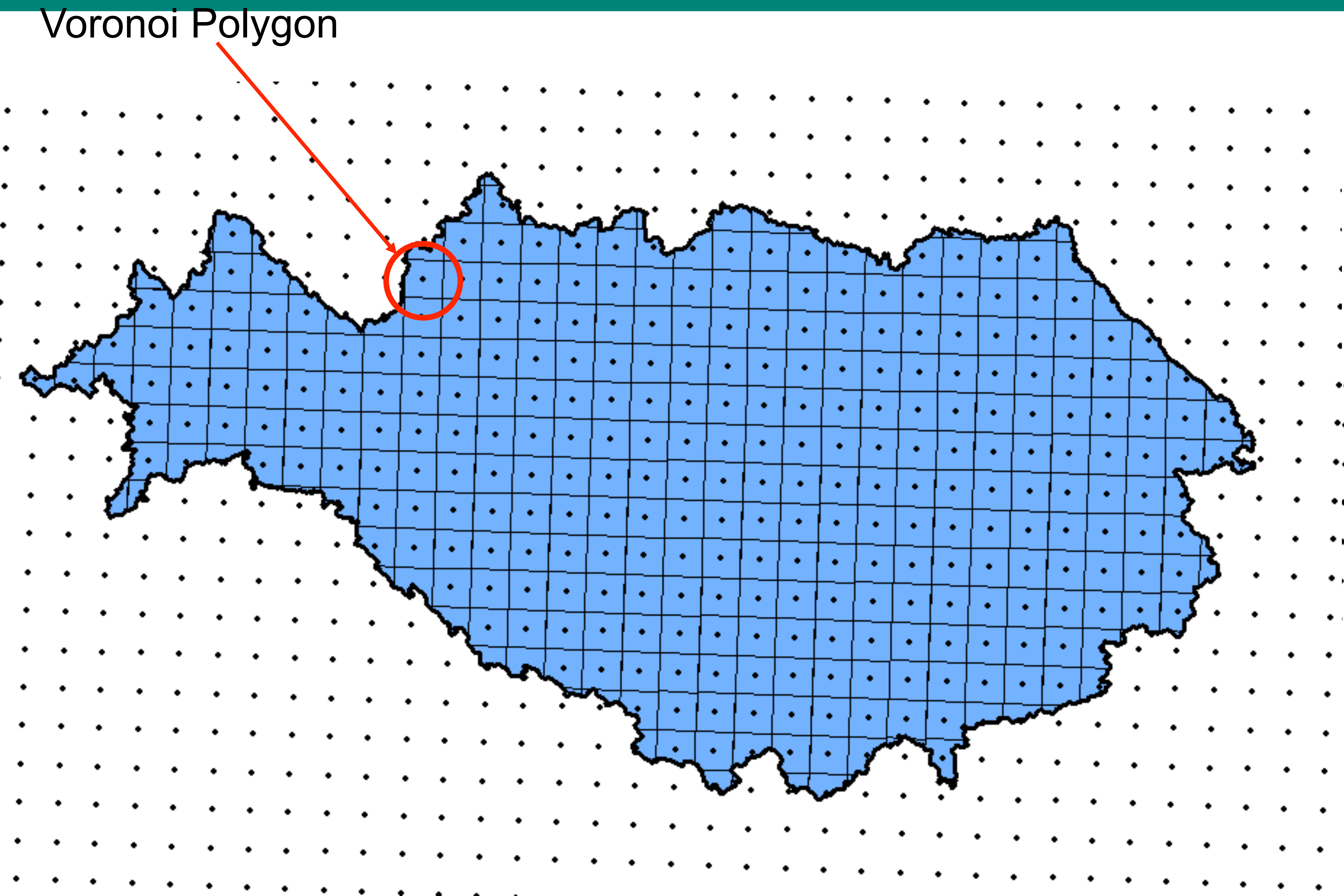
$$\int_A dxdy(\langle P\rangle_t - \langle E\rangle_t) = \int_A dxdy\langle B\rangle_t \approx -\int_A dxdy\langle \overrightarrow{\nabla_H}.\vec{Q}\rangle_t \approx \int_A dxdy\langle R\rangle_t \approx \langle D\rangle_t \qquad \textbf{(2),}$$

The equation (2) is satisfied if t ≥ 1year assuming inter-annual glaciers mass balance is negligible, or it gives minor corrections to the overall hydrological cycle. Assuming net glacier mass balance is either zero or negligible, in view of mixed response from Indus and small glacier melt contributions from other basins.

$$\overline{\beta}_i = \int_A dxdy\langle \beta\rangle_i \qquad \textbf{(3),}$$

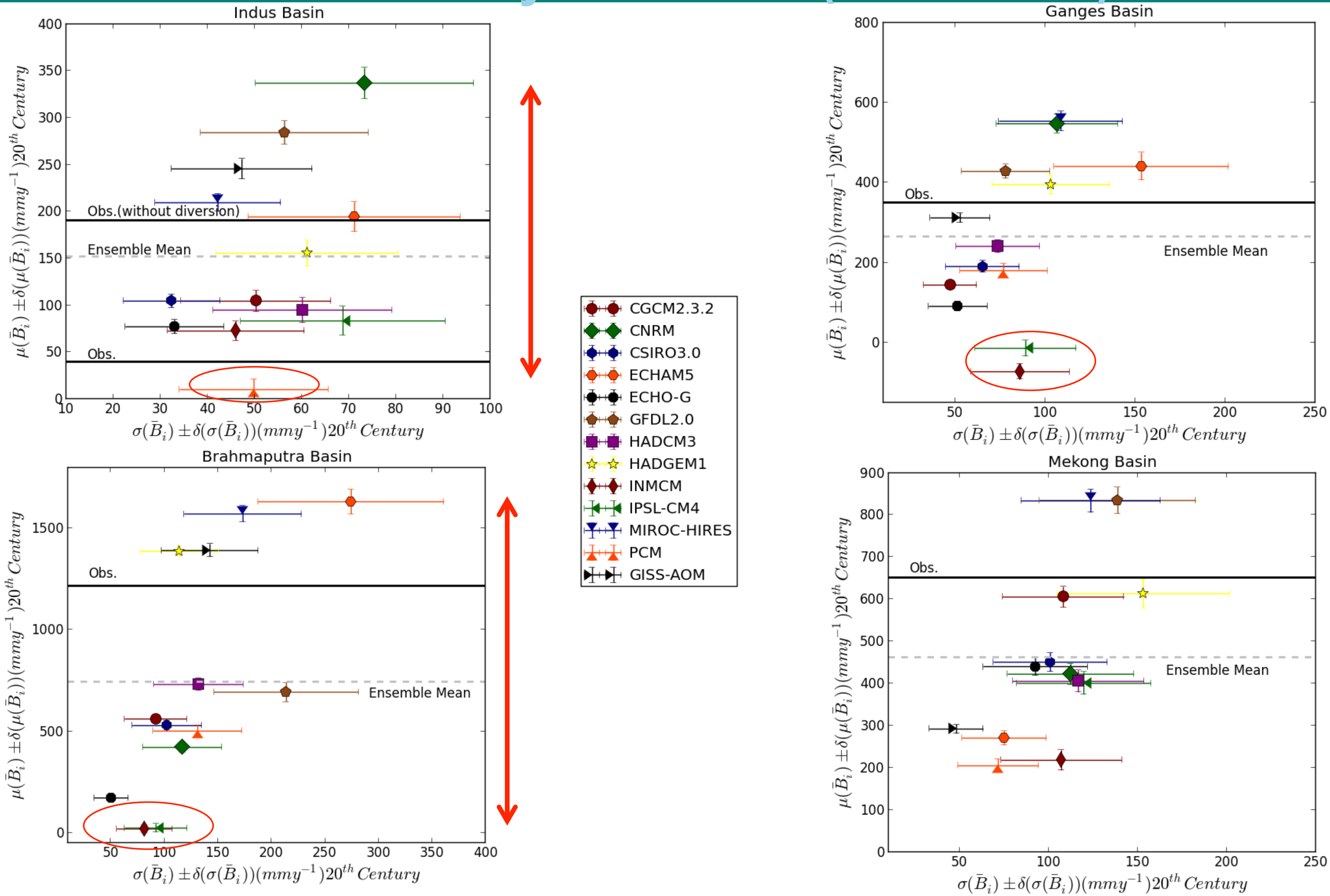
where
$\overline{\beta}_i,\ i = 1, \dots, 4$ corresponds to the mean monthly climatology of computed variable
A denotes the area of each considered river basin.

Data Gridding



Mean Balance (P-E) vs its Inter-annual Variability

Results - XX Century Climate – (1961-2000)



Range of GCMs‘ outputs larger than „ensemble mean“. No unimodal distribution.

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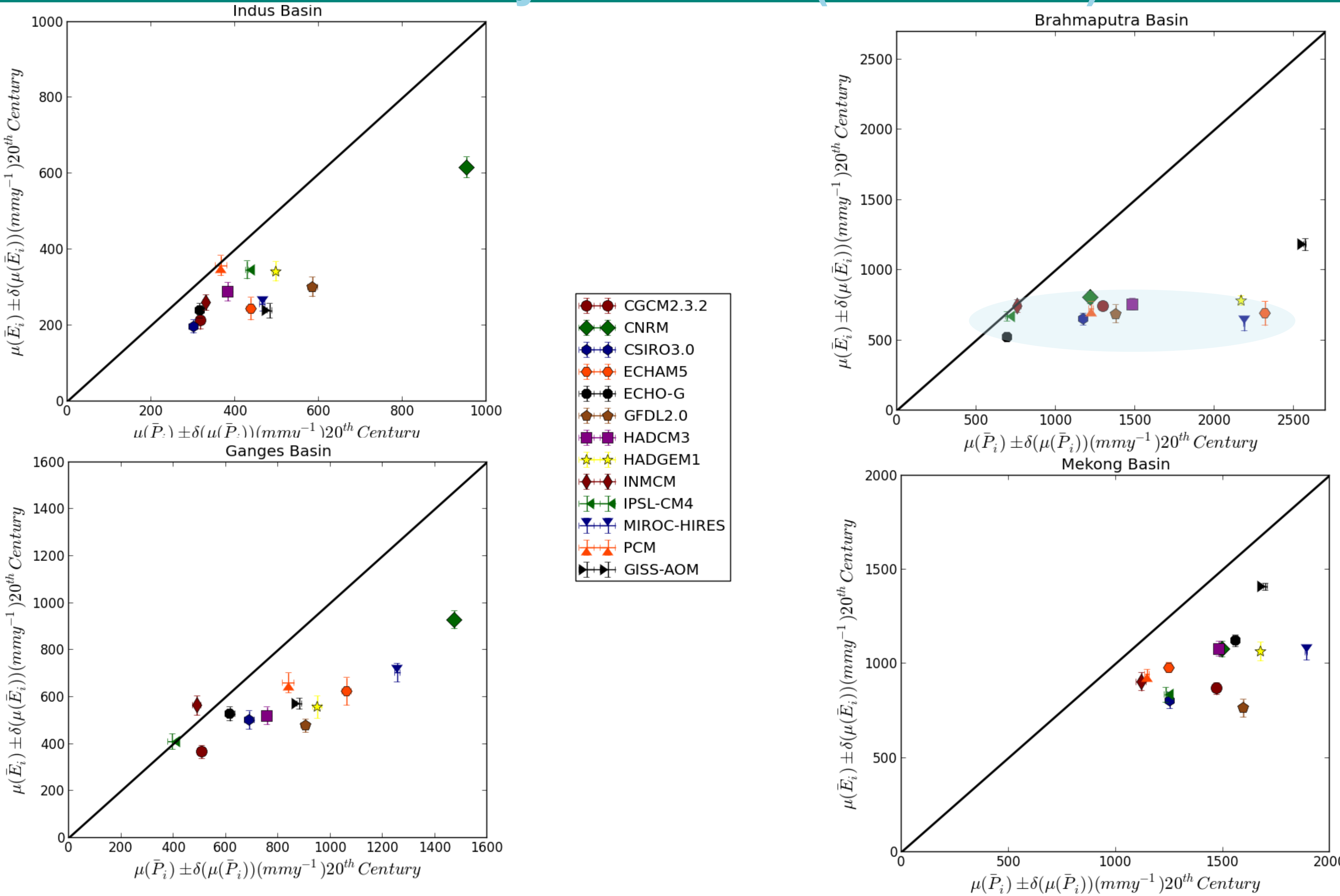
Mean Precipitation vs Mean Evaporation – (Annual)

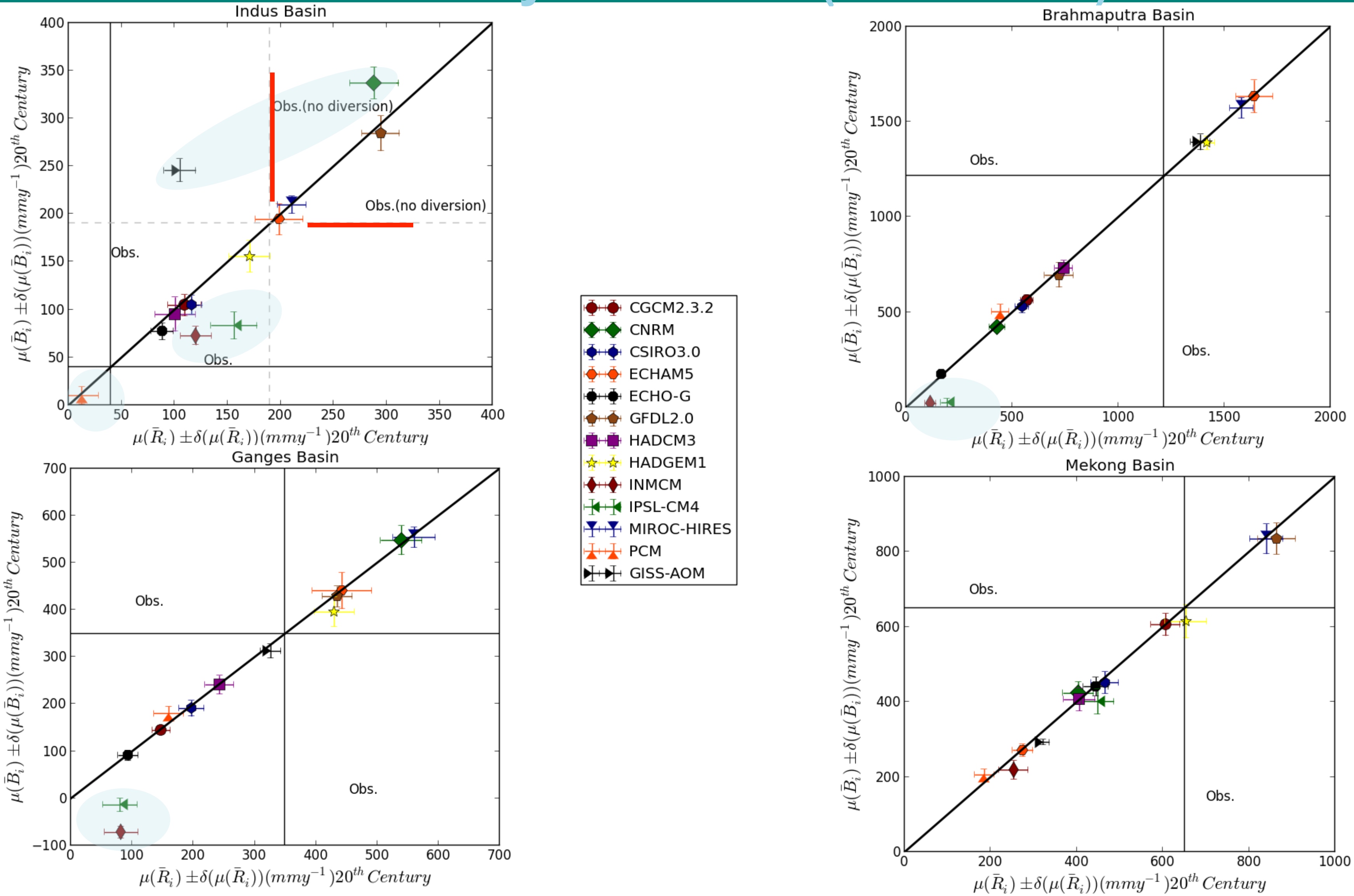
Results - XX Century Climate – (1961-2000)



Note: GCMs‘ discrepancies are more evident when considering P and E separately

Estimated B(P-E) vs Total Runoff

Results - XX Century Climate – (1961-2000)



Note: to account properly for Indus, we must consider the water diversion. Two models fail the „consistency check in three out of four basins (IPSL and INCM4)

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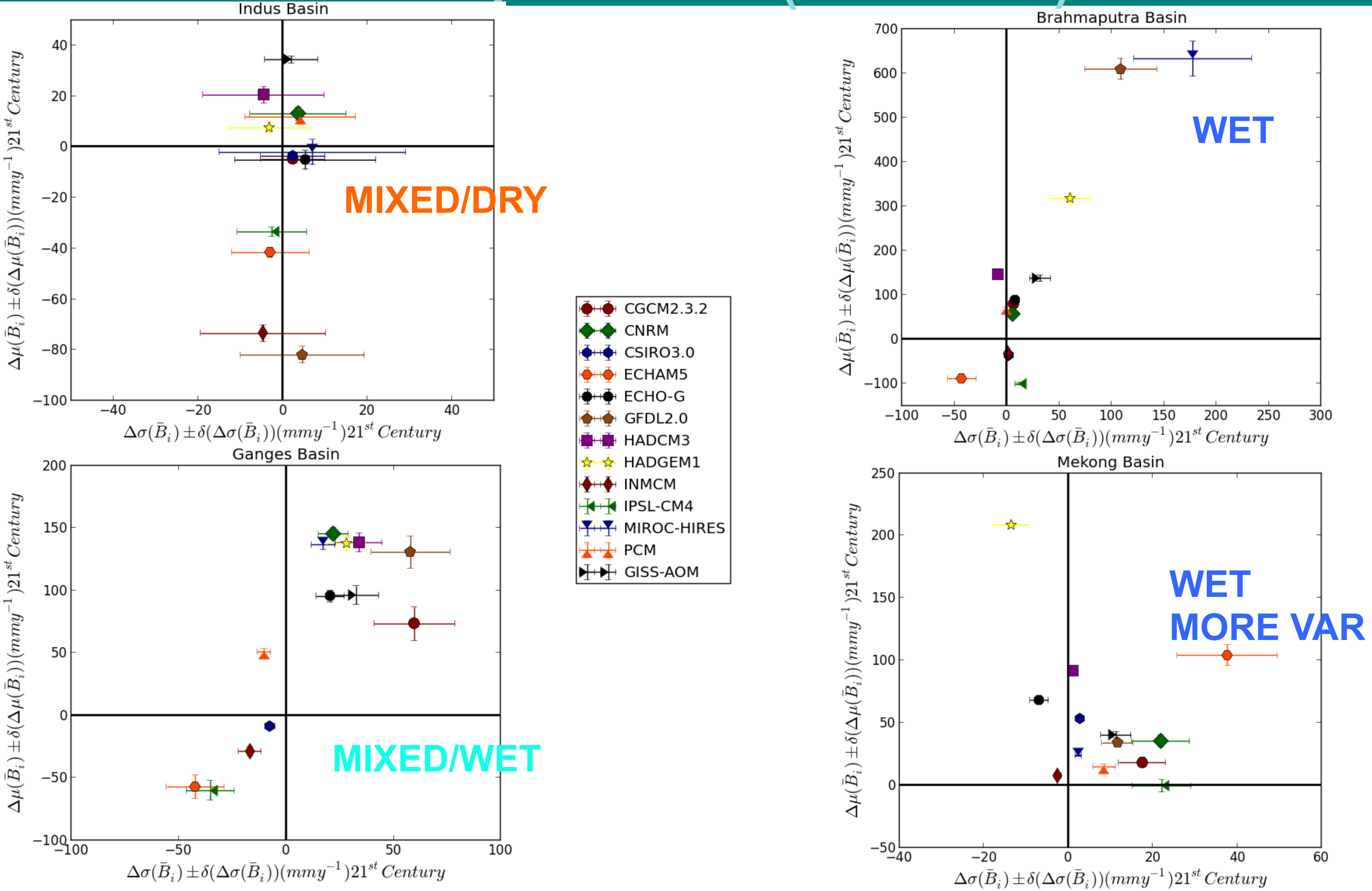
Change in Mean B=P-E vs Change in Variability

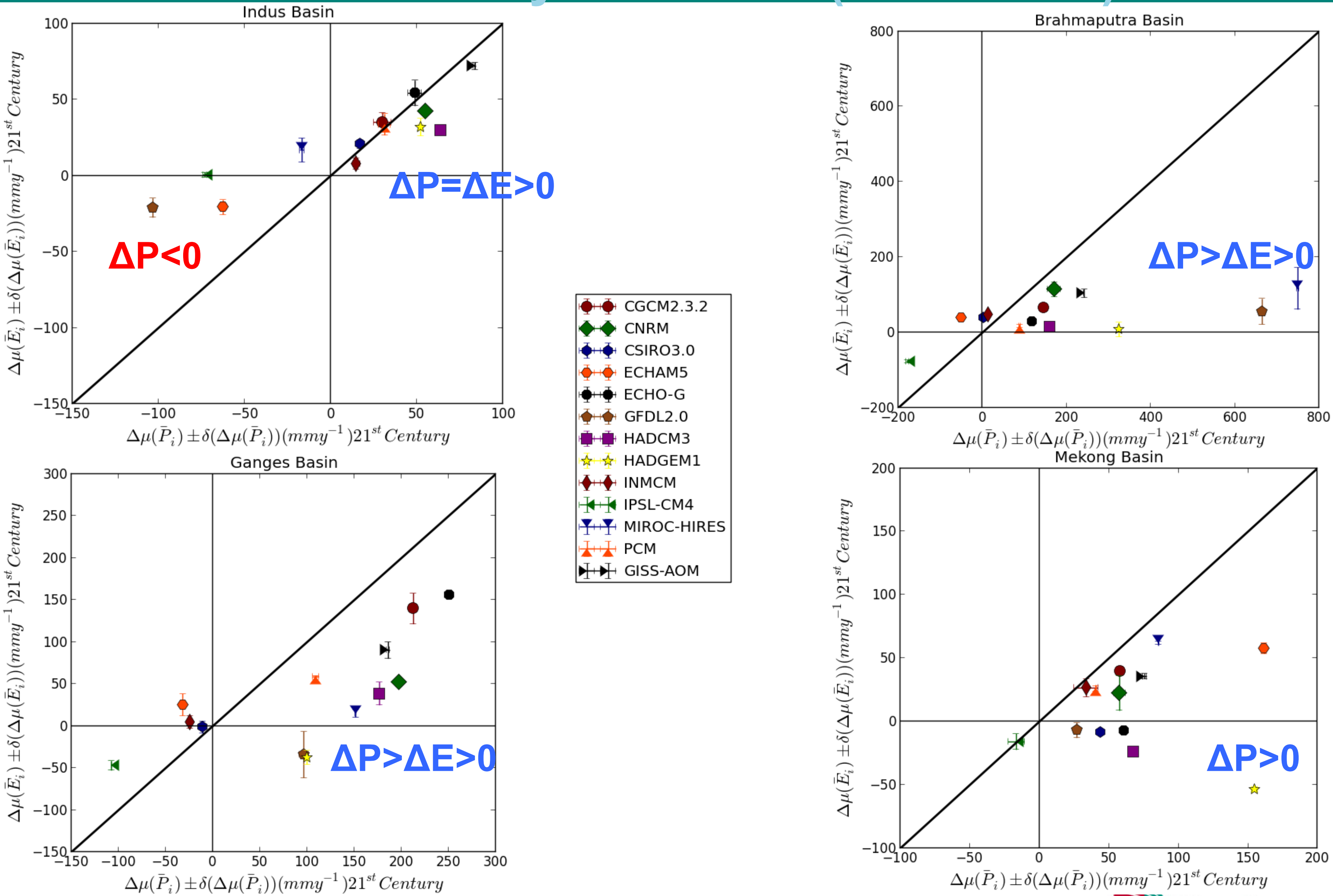
Results - XXI Century Climate – (2061-2100)



Note: Change is calculated with respect to XX Century Climate (1961-2000)

Change in Precipitation vs Change in Evaporation

Results - XXI Century Climate – (2061-2100)



Note: Change is calculated with respect to XX Century Climate (1961-2000)

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Monthly Climatology

- The hydrology of these river basins features strong seasonality
  - Monsoon (two monsoonal systems for Mekong)
  - Monsoon becomes weaker and shorter as we go west
  - Mid-latitude winter disturbances (Indus)
- We wish to test how the CMIP3 GCMs represent the seasonal cycle of P, E, P-E, and R
  - This is an additional piece of information crucial for downscaling studies (especially P-E – water convergence)
- Note: previous studies have emphasized the fact that CMIP3 and CMIP5 models have hard times in simulating the monsoon. Do we see the same here?

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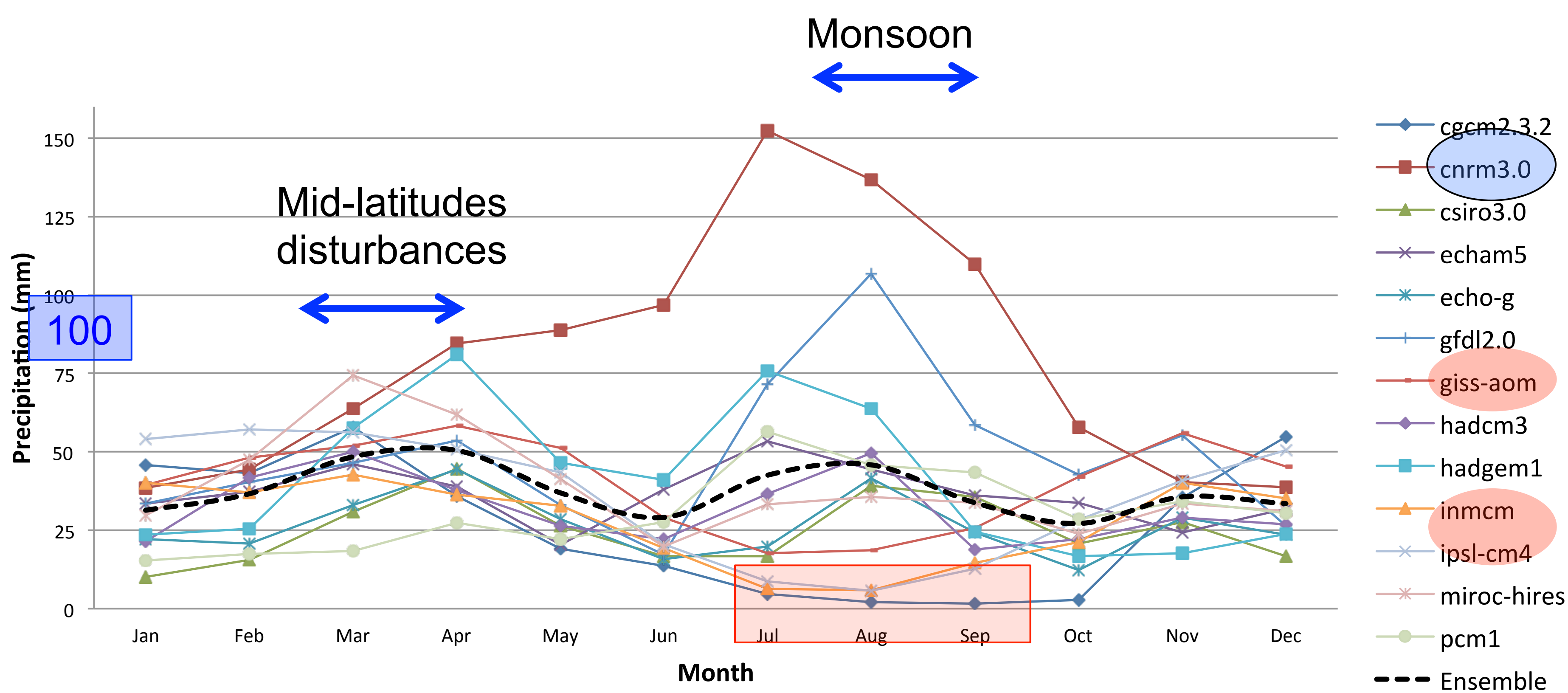
INDUS BASIN - Precipitation



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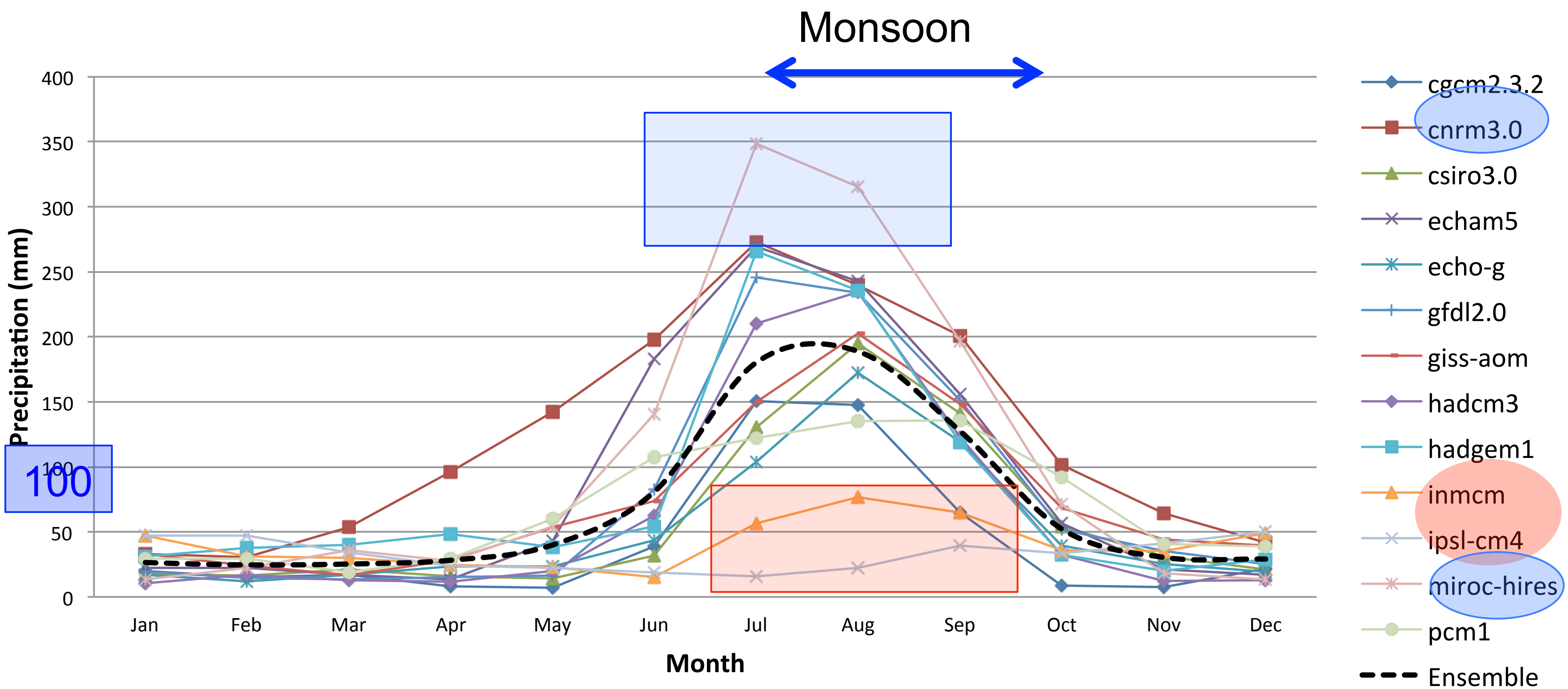
GANGES BASIN - Precipitation



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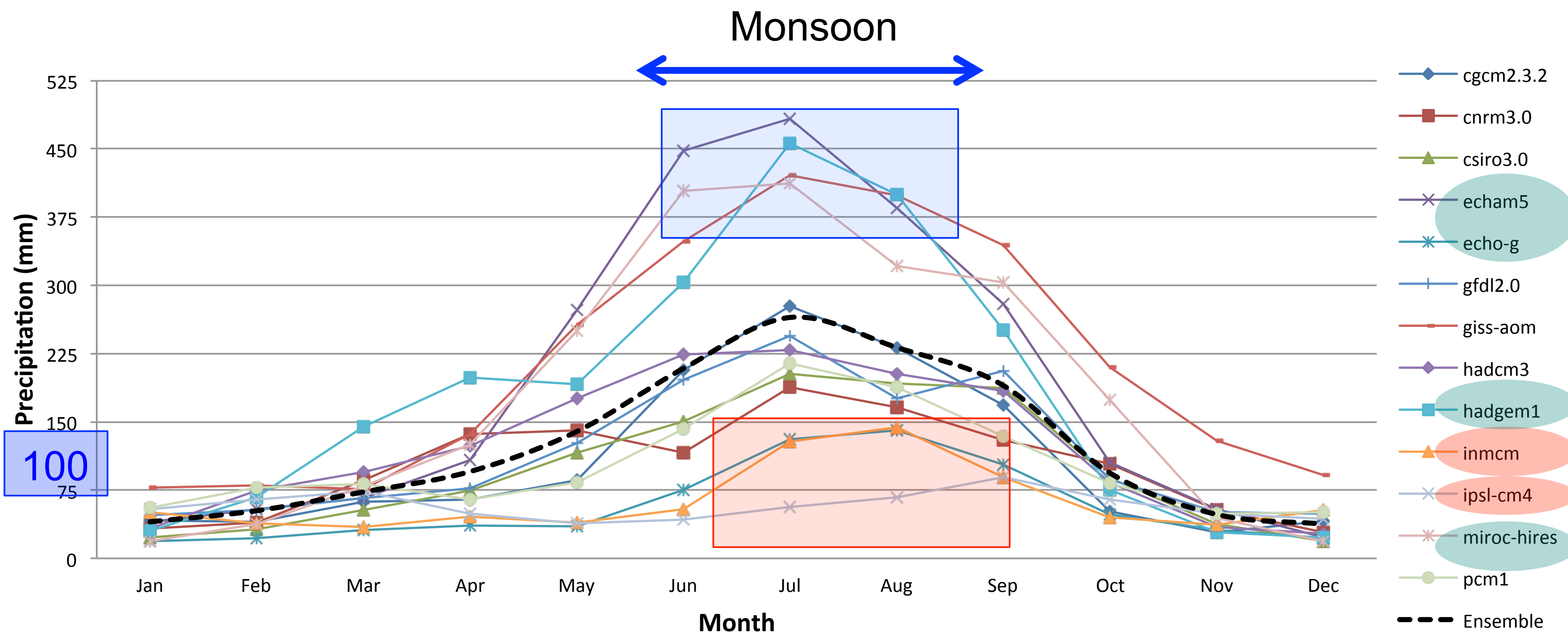
BRAHMAPUTRA BASIN - Precipitation



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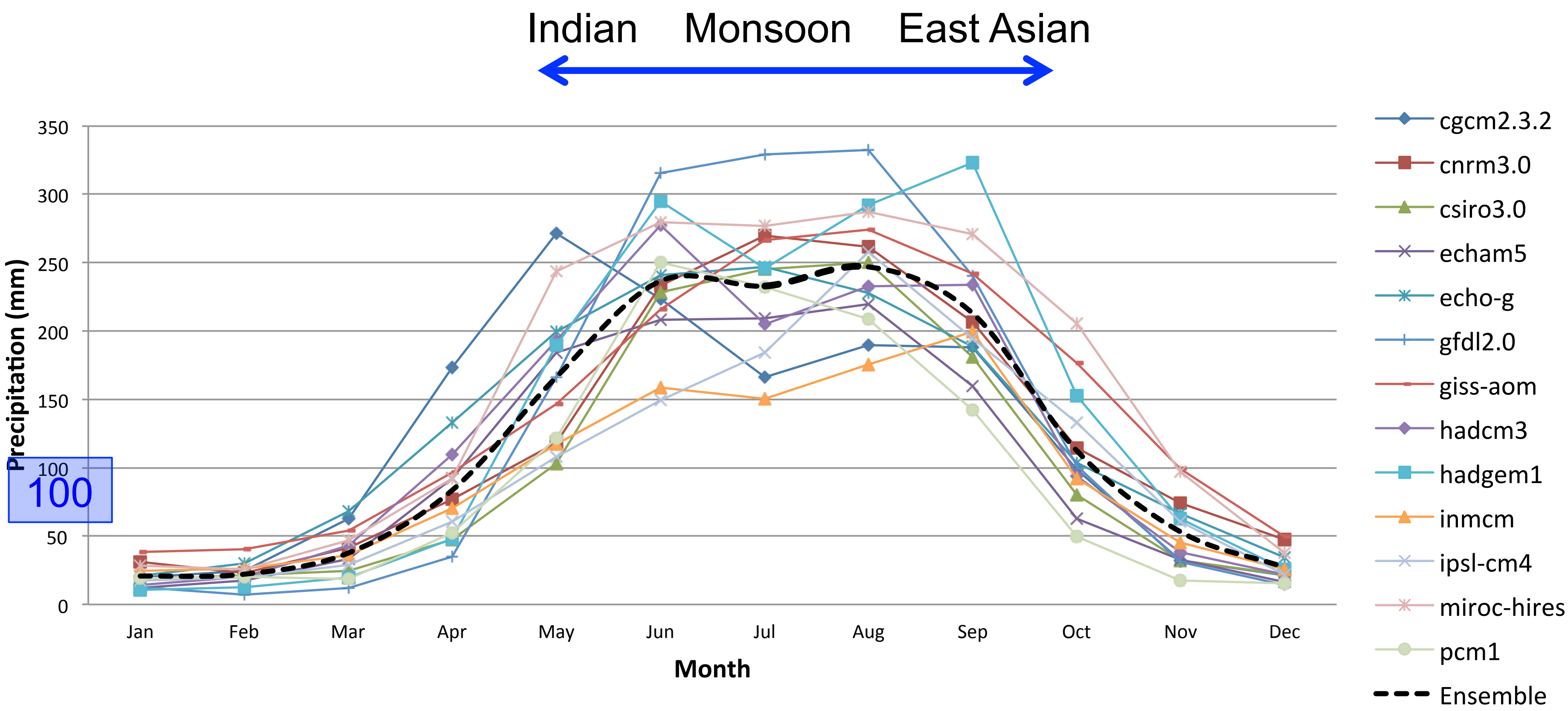
MEKONG BASIN - Precipitation



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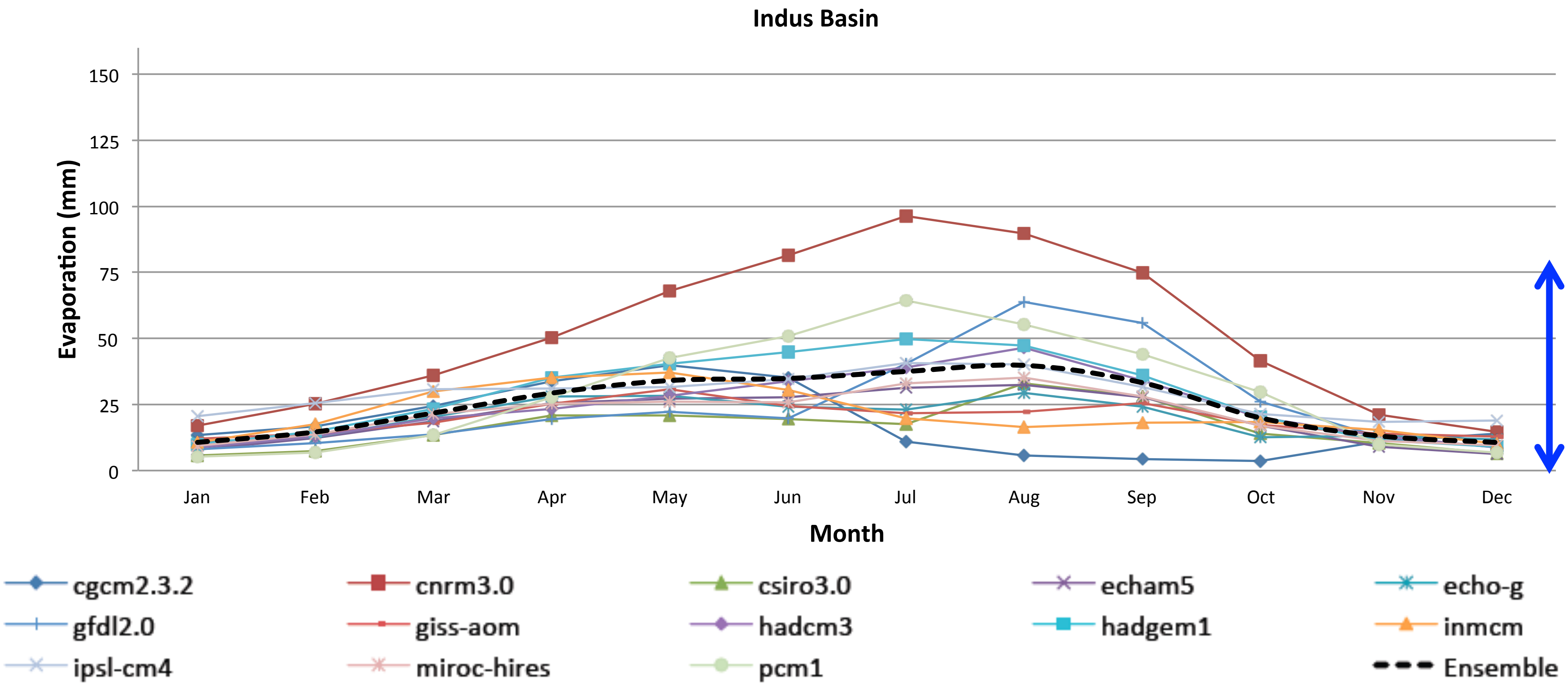
INDUS BASIN - Evaporation



- Mmmh agreement, probably effect of strongly water-limited evaporation, role of soil models?
- There is a good inter-model agreement of their simulated evaporation for other Basins

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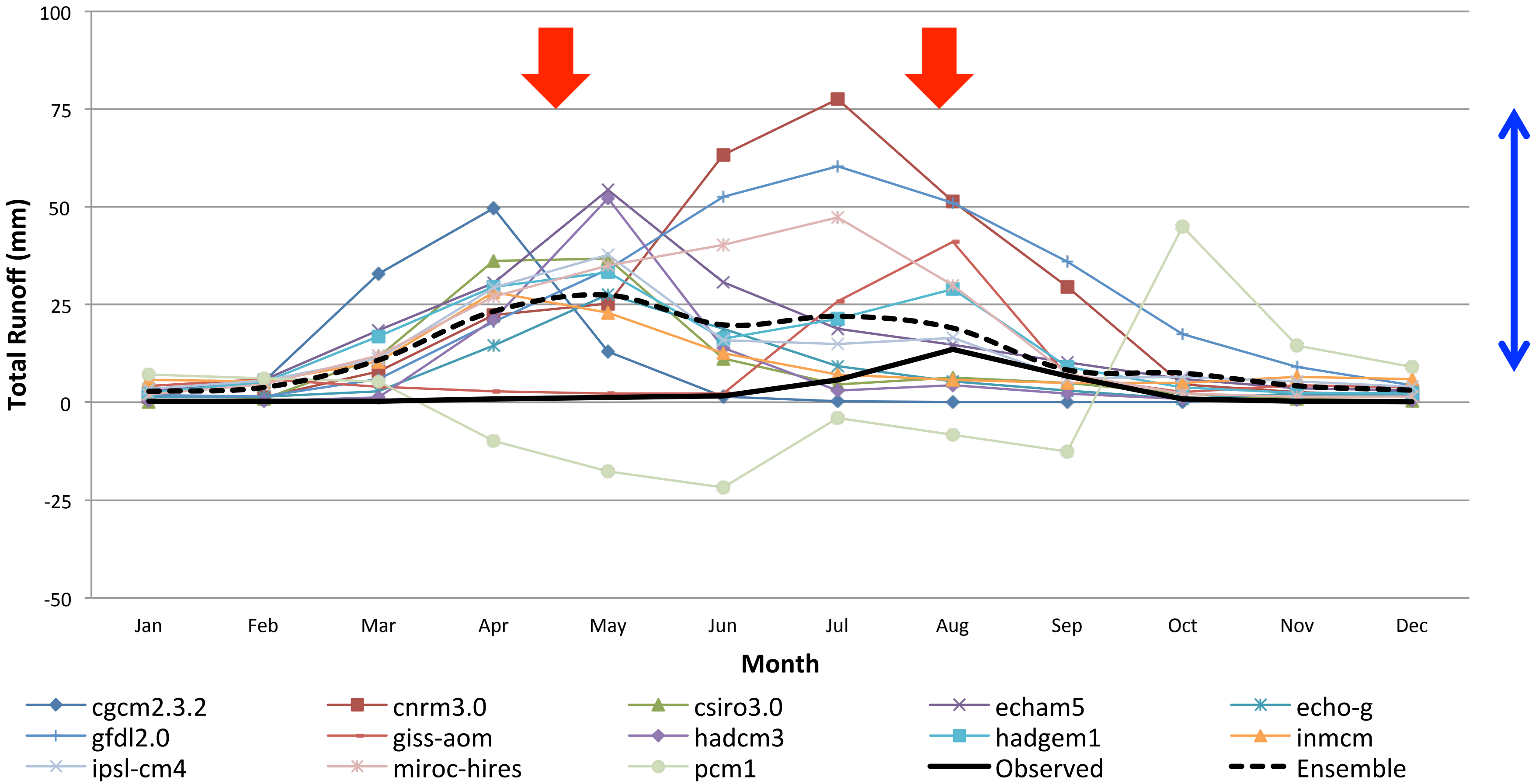
INDUS BASIN – Total Runoff



- PCM1 suggesting minimum annual total runoff for Indus Basin shows negative runoff from April to September
- Monsoon period runoff is biased

Note: Observed discharge is given for indicative purpose only

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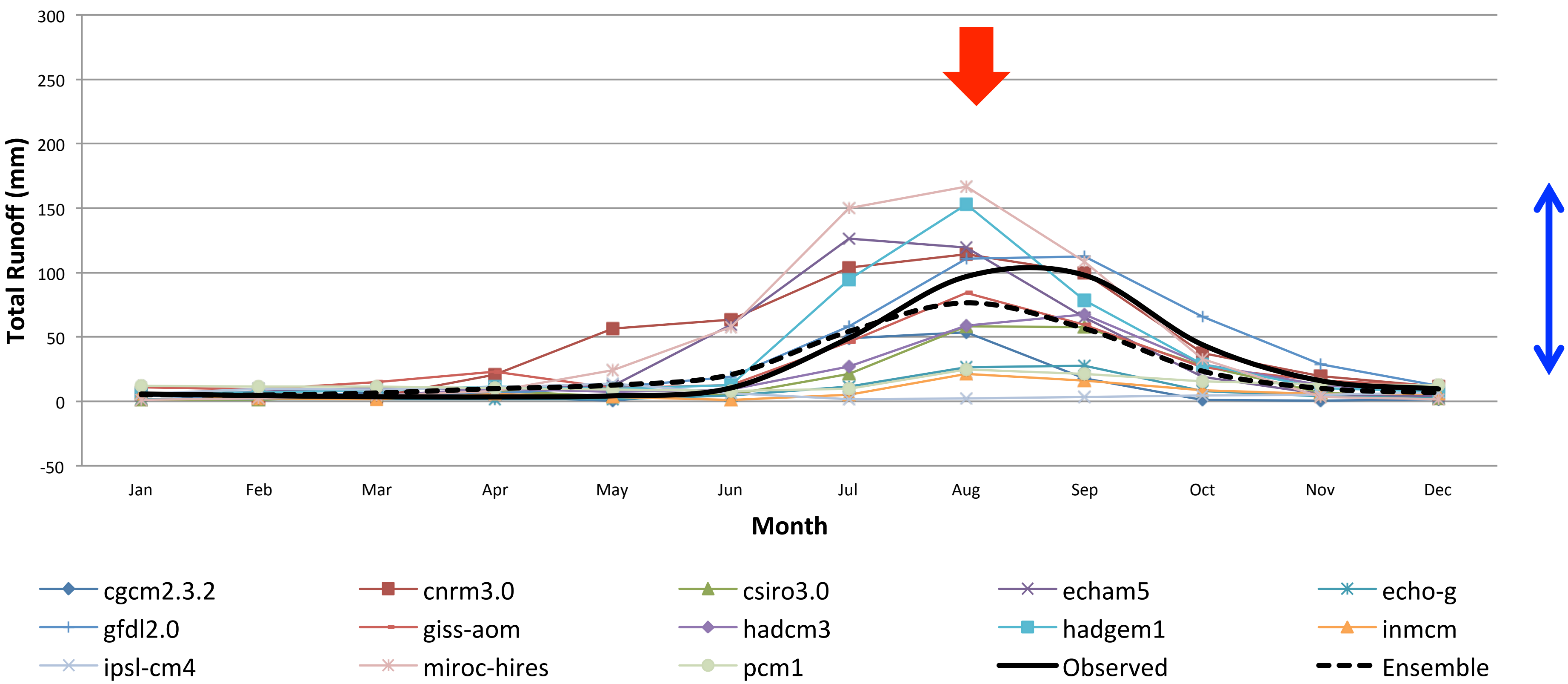
GANGES BASIN – Total Runoff



- IPSL-CM4 suggests no runoff at all
- Note: Observed discharge (in equivalent runoff unit) is given for indicative purpose only

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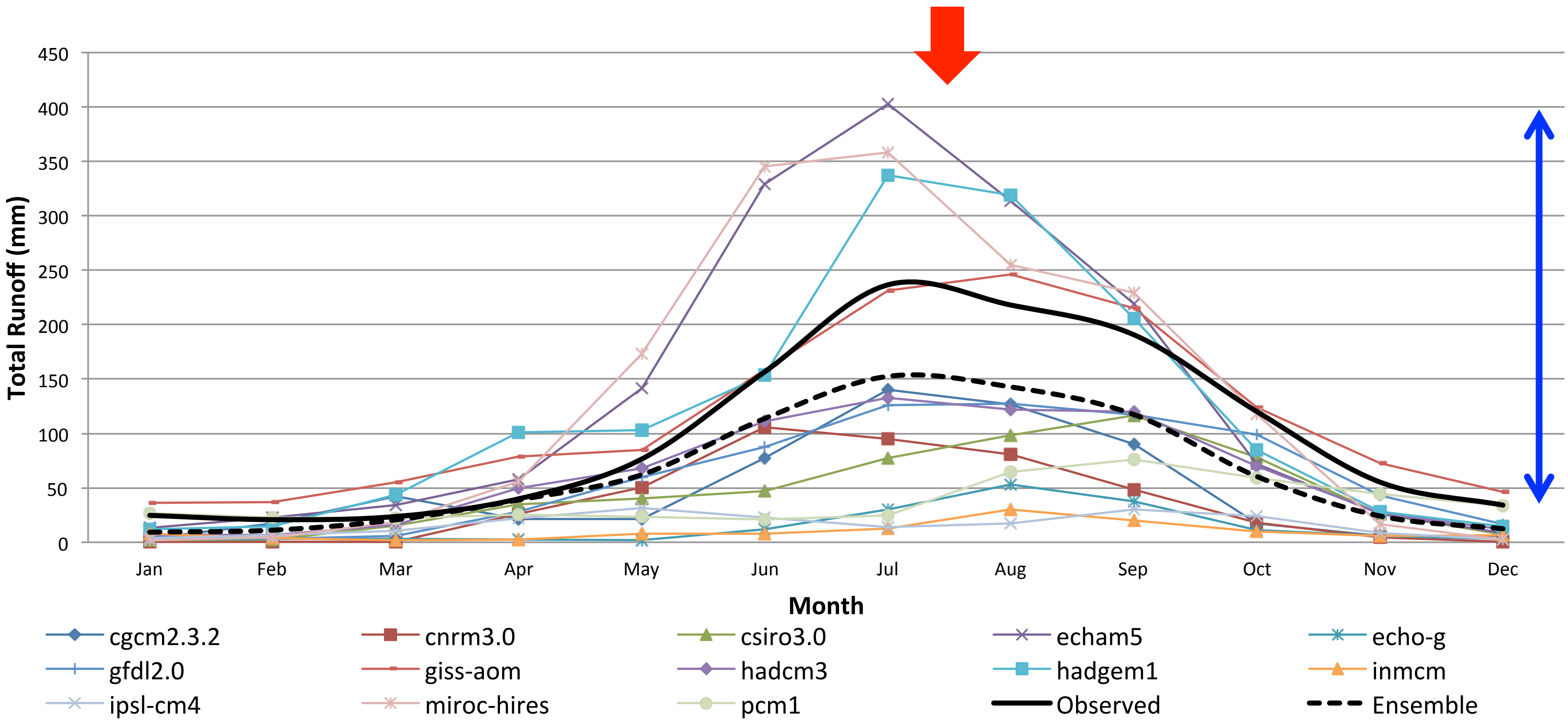
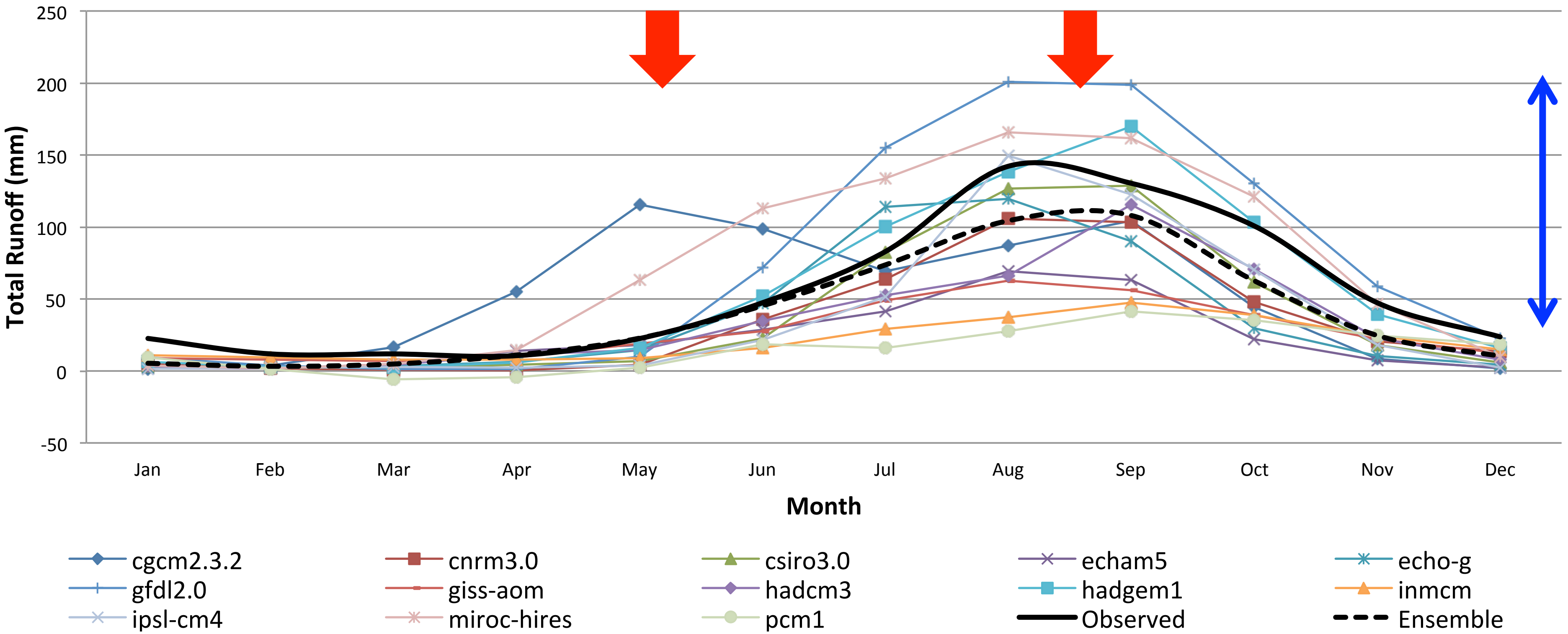
BRAHMAPUTRA BASIN – Total Runoff



- Note: Observed discharge (in equivalent runoff unit) is given for indicative purpose only

MEKONG BASIN – Total Runoff



- Note: Observed discharge (in equivalent runoff unit) is given for indicative purpose only

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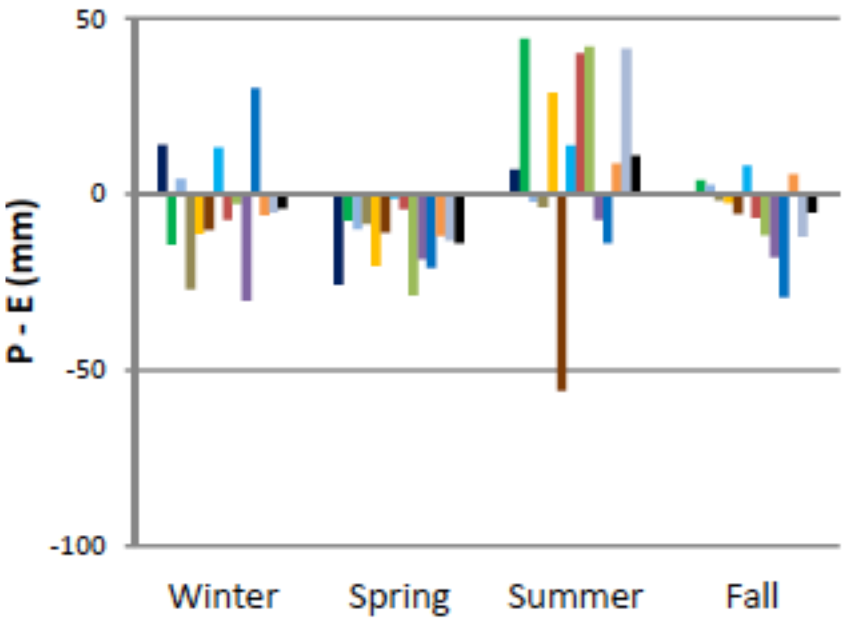
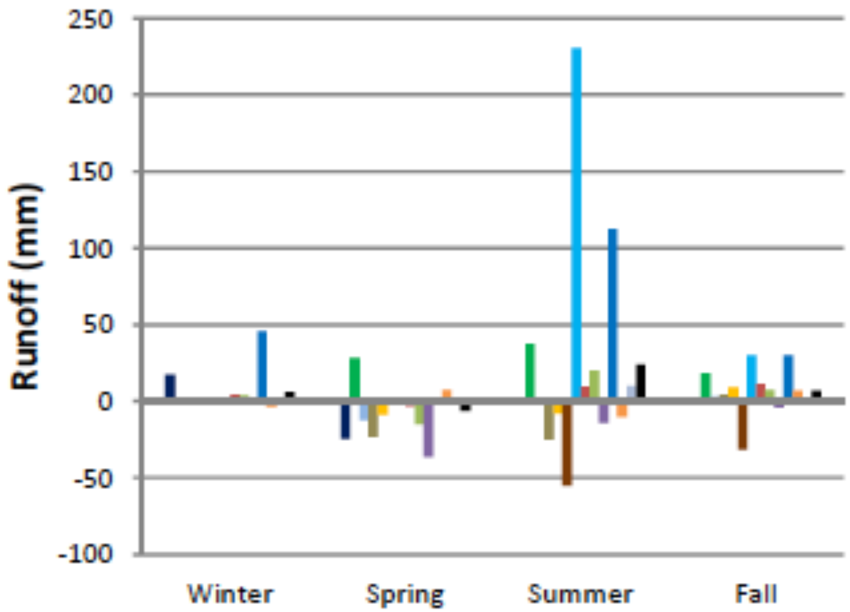
Seasonal Change in P-E and Runoff - Indus





- Drier Winter and Spring
- Solid ➔ liquid precipitation

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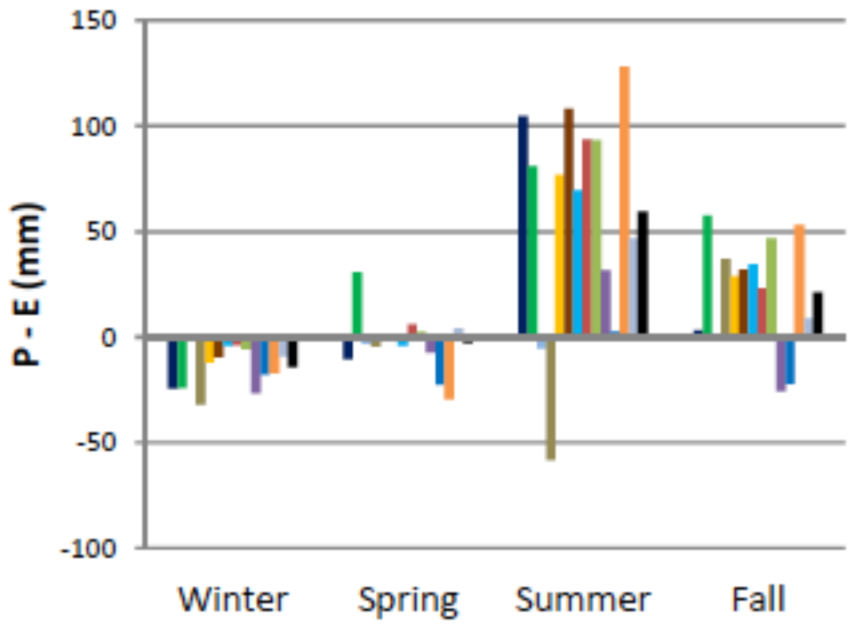
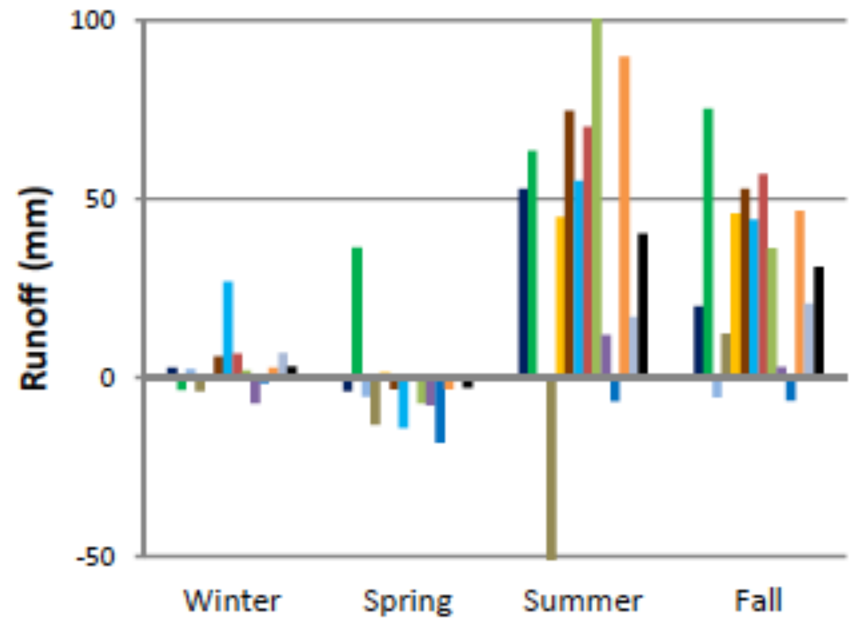
Seasonal Change in P-E and Runoff - Gange





- Wetter Summer and Autumn

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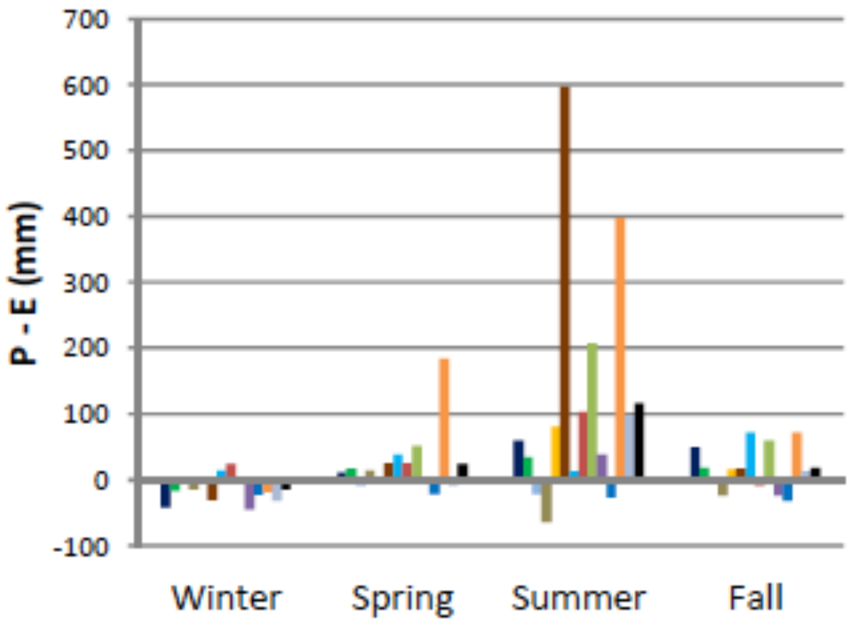
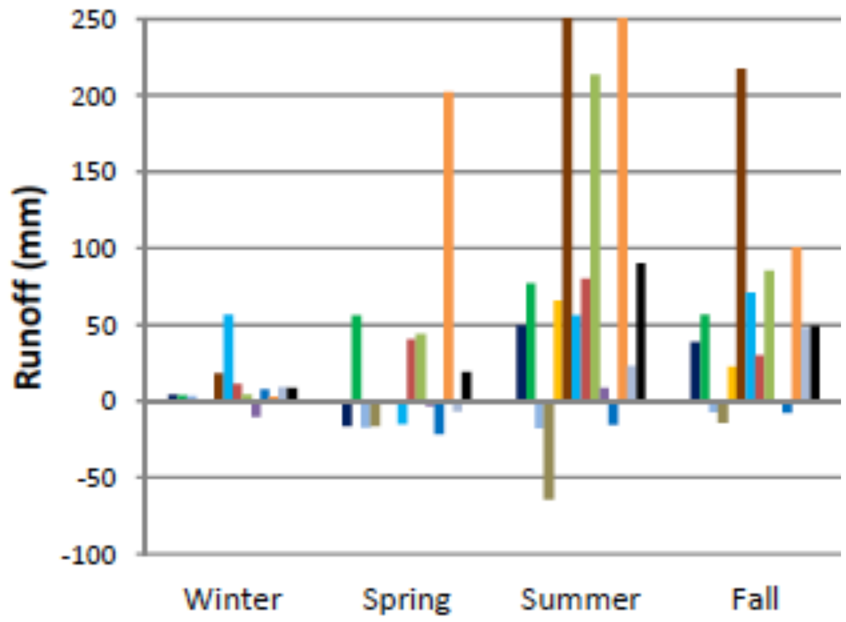
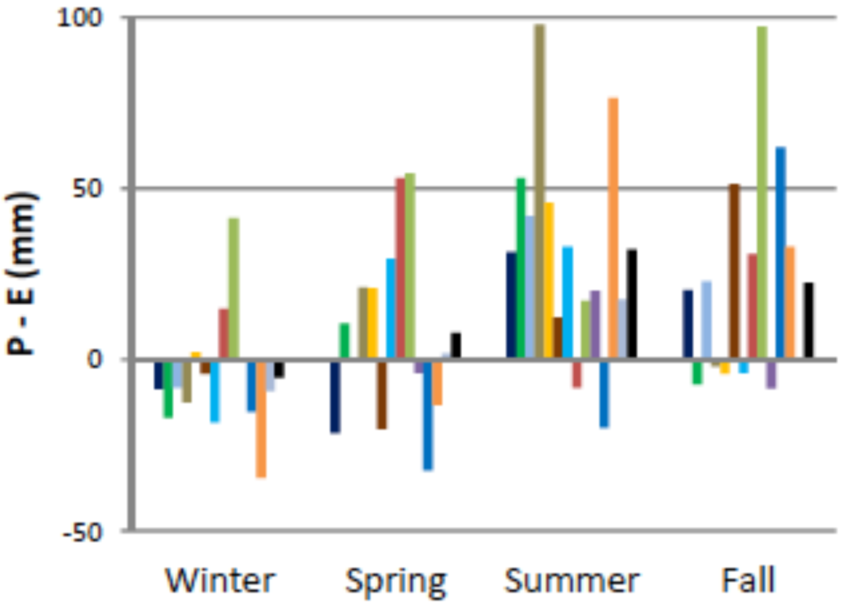
Seasonal Change in P-E and Runoff - Brahma

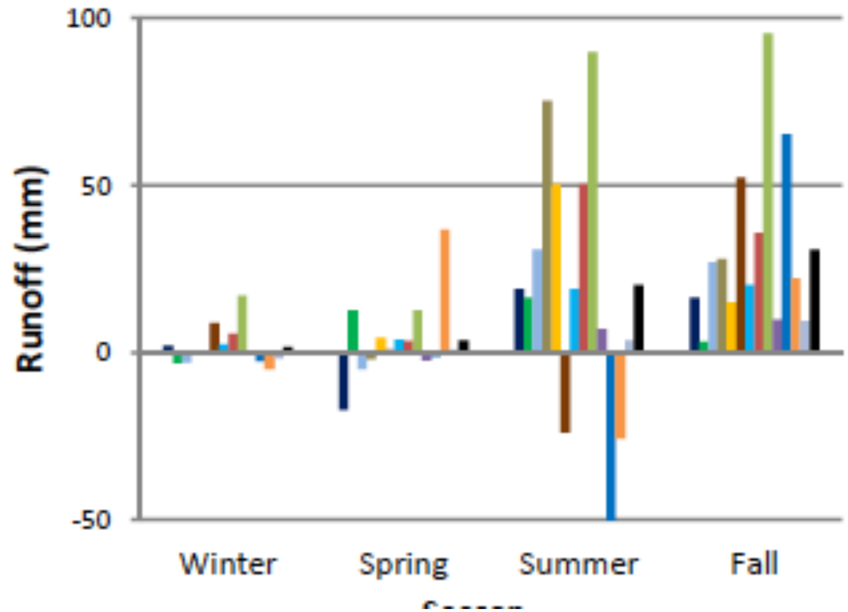




- Wetter Summer season

Seasonal Change in P-E and Runoff - Mekong





- The river basin becomes wetter, especially in Summer and Autumn

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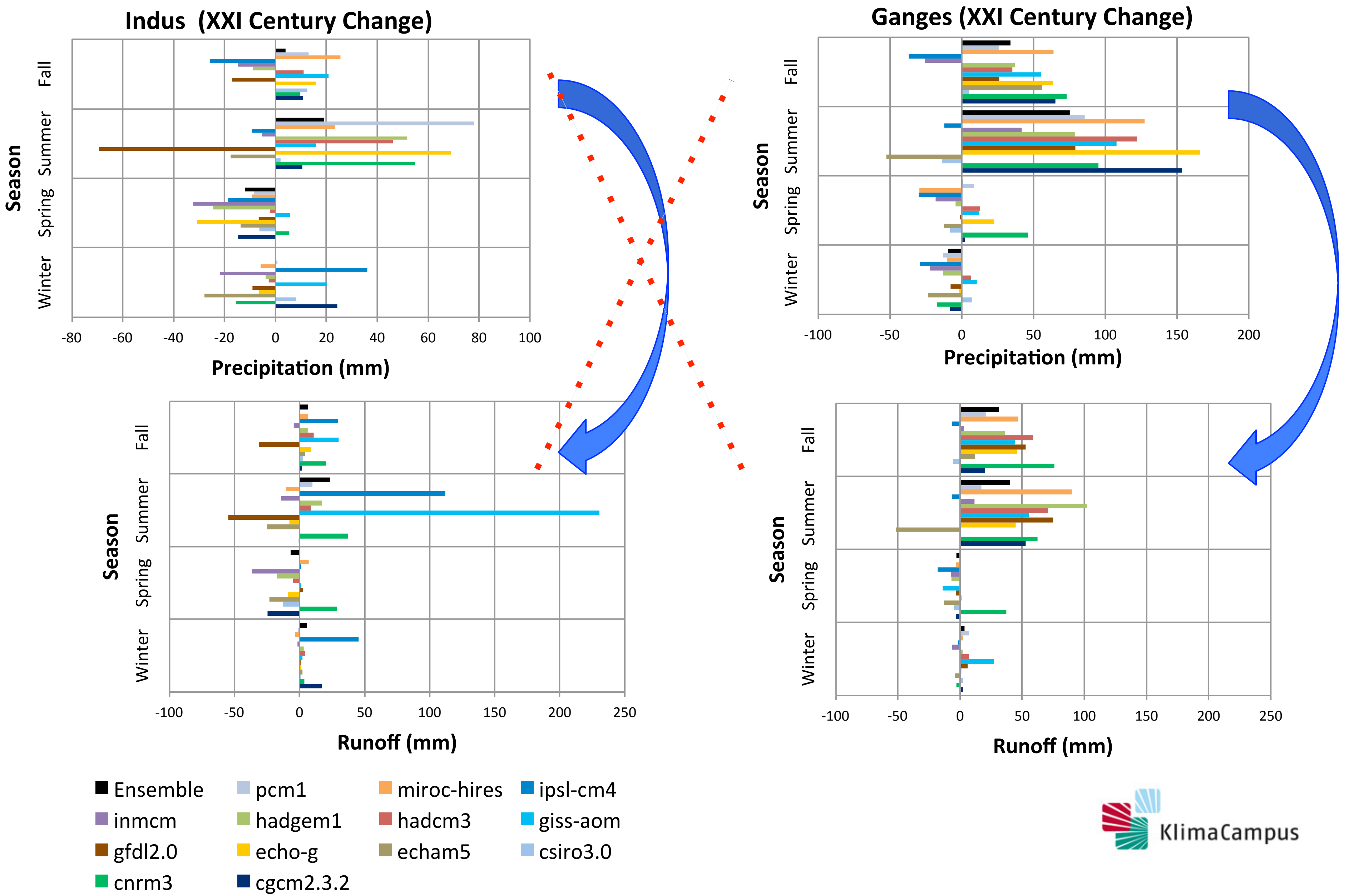
Seasonal Change in Precipitation and Runoff



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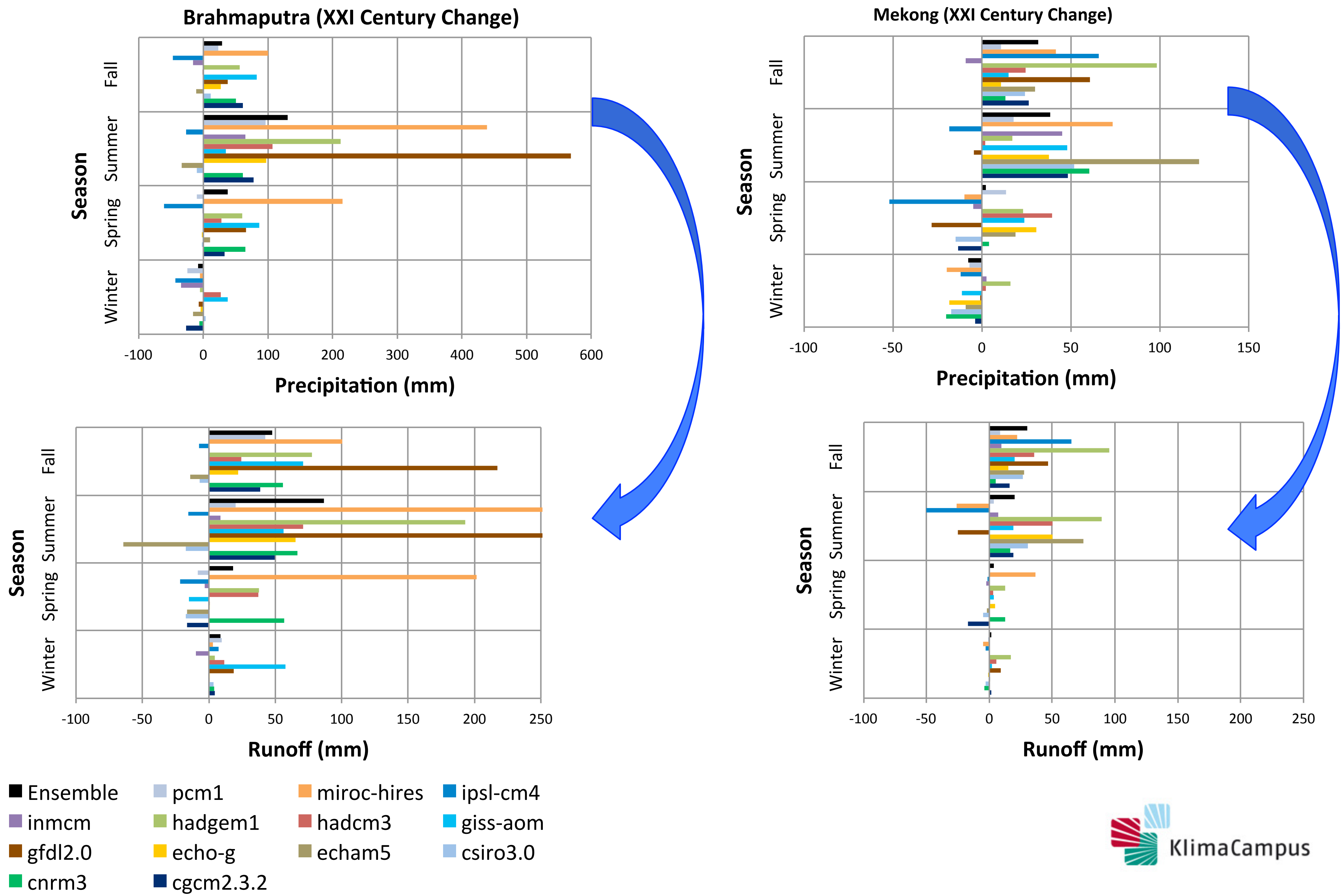
Seasonal Change in Precipitation and Runoff



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Performance of GCMs

Summary

XX Century

- Simulated ***P - E*** and total runoff (***R***) are neither consistent with the observed mean river discharges nor among the models themselves.
- The spread of GCMs' results is very large and distribution is not unimodal: ensemble mean has little relevance
- Most of the GCMs seem to conserve water at the river basin scale up to a good degree of approximation. Two models are consistently wrong
- Limited skill in simulating the monsoon precipitation regime for the Indus basin where few models completely failed to simulate it.
- Reasonable skill in simulating basic characteristics of monsoon precipitation regimes for the Ganges, Brahmaputra and Mekong basins and Mid-latitude disturbances for the Indus Basin
- Models also see difficulty in realistically reproducing some of the basic characteristics and the overall pattern of the runoff regimes for river basins

Performance of GCMs

Summary

XXI & XXII Century Projections

- Majority of GCMs foresee a negative change of *P-E* for Indus
- For Brahmaputra, Mekong and Ganges, most of the models project a positive change in both P and E, and a positive change in P-E
- Most models foresee an increase in the inter-annual variability of *P-E* for Ganges and Mekong basins which is consistent with the projected changes in the Monsoon precipitation.
- Evaporation feature overall positive sign of change through out a year and for both XXI and XXII centuries
- Winter precipitation decreases over all study basins, while spring precipitation decreases only over the Indus basin ➔Spring runoff drops for the Indus.
- Rise in the runoff during summer season & the projected increase in precipitation indicate intensification of the summer monsoon regime for all study basins

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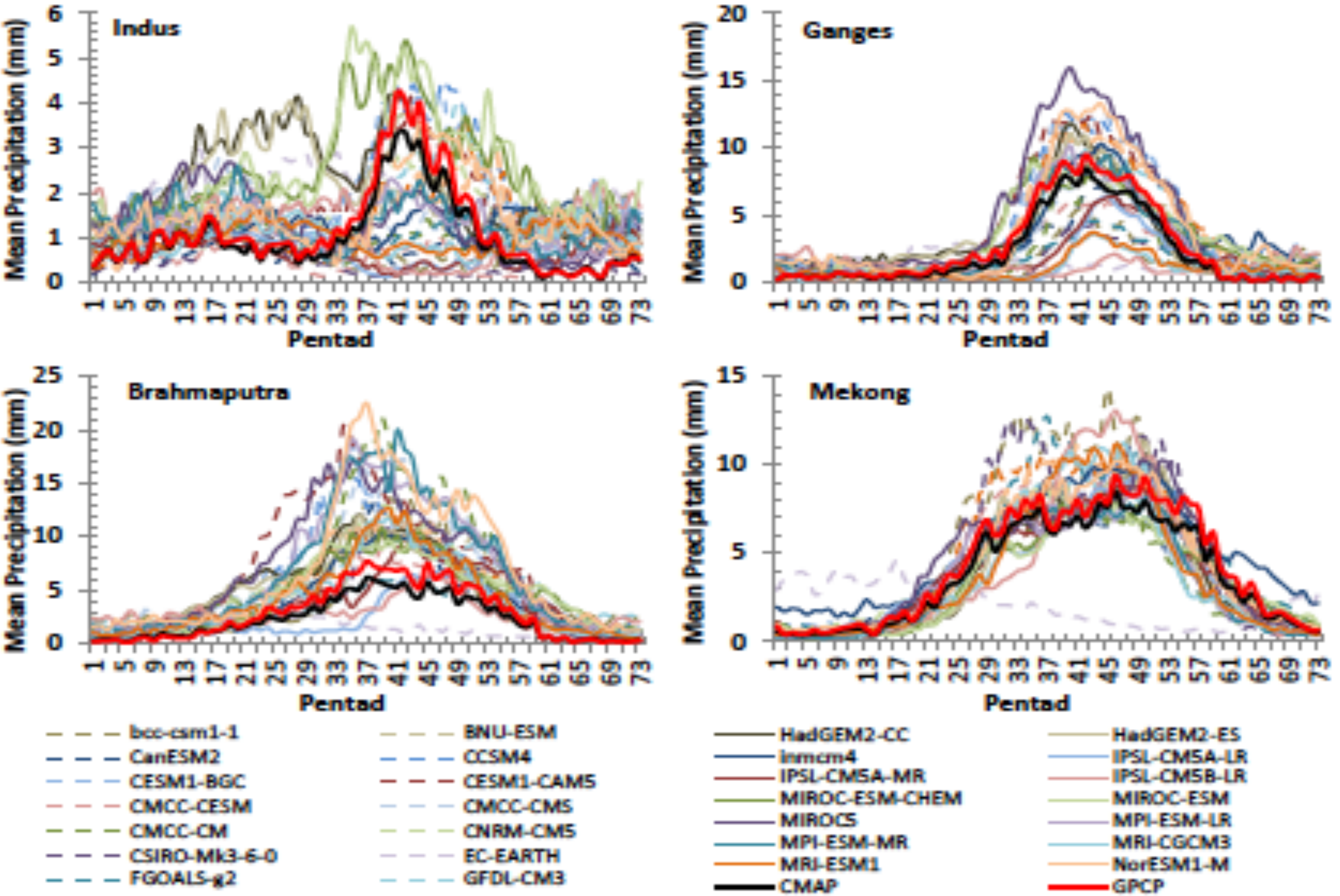
CMIP5 Analysis – Seasonal and Annual Precipitation

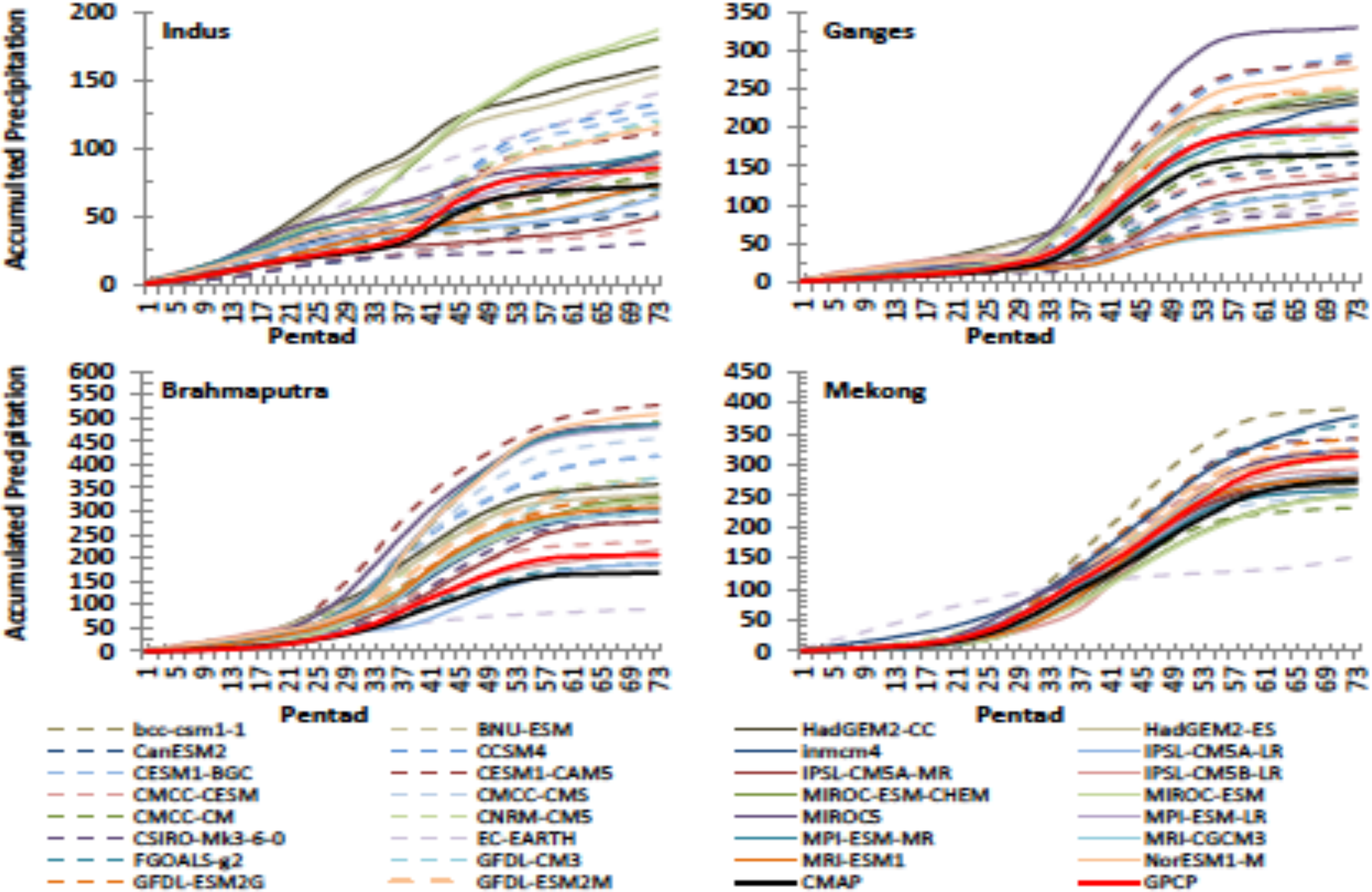
Table 1. List of CMIP5 models, their modelling groups and resolutions.

S. No.	Modeling Group	Model Name	Atm. Resolution (lonxlat)	Model Level
1	Beijing Climate Center, China Meteorological Administration(BCC)	BCC-CSM1-1	2.8 x 2.8	26
2	College of Global Change and Earth System Science, Beijing Normal University (GCESS)	BNU-ESM	2.8 x 2.8	32
3	Canadian Centre for Climate Modelling and Analysis (CCCMA)	CanESM2	2.8 x 2.8	35
4	NCAR Community Climate System Model, (CCSM)	CCSM4	1.25 x 0.94	27
5	Community Earth System Model Contributors (NSF-DOE-NCAR)	CESM1-BGC	1.25 x 0.94	27
6		CESM1-CAM5	1.25 x 0.94	27
7	Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC)	CMCC-CESM	3.75 x 3.75	39
8		CMCC-CMS	1.875 x 1.875	95
9		CMCC-CM	0.75 x 0.75	31
10	Centre National de Recherches Météorologiques Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	1.4 x 1.4	31
11	Commonwealth Scientific and Industrial Research Organization in collaboration with QCCCE (CSIRO-QCCCCE)	CSIRO-Mk3-6-0	1.875 x 1.875	18
12	EC-EARTH consortium (EC-EARTH)	EC-EARTH	1.125 x1.125	62
13	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University (LASG-CESS)	FGOALS-g2	2.8125 x 2.8125	26
14	NOAA Geophysical Fluid Dynamics Laboratory (NOAA-GFDL)	GFDL-CM3	2.5 x 2.0	48
15		GFDL-ESM2G	2.5 x 2.0	24
16		GFDL-ESM2M	2.5 x 2.0	24
17	Met Office Hadley Centre (MOHC)	HadGEM2-CC	1.875 x 1.24	60
18		HadGEM2-ES	1.875 x1.24	38
19	Institute for Numerical Mathematics (INM)	INMCM4	2 x1.5	21
20	Institut Pierre-Simon Laplace (IPSL)	IPSL-CM5A-LR	3.75 x1.89	39
21		IPSL-CM5A-MR	2.5 x1.25	39
22		IPSL-CM5B-LR	3.75 x1.9	39
23	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies (MIROC)	MIROC-ESM-CHEM	2.8 x2.8	80
24		MIROC-ESM	2.81 x 2.81	80
25		MIROC5	1.4 x 1.4	40
26	Max-Planck-Institut für Meteorologie (MPI-M)	MPI-ESM-LR	1.875 x1.875	47
27		MPI-ESM-MR	1.875 x1.875	95
28	Meteorological Research Institute (MRI)	MRI-CGCM3	1.125x1.125	48
29		MRI-ESM1	1.125 x 1.125	48
30	Norwegian Climate Centre (NCC)	NorESM1-M	2.5 x 1.9	26

CMIP5 Models: Average Precipitation – 1960-2000



CMIP5 Models: Average Cumulative Precipitation – 1960-2000



Model Bias is astounding

- Much work needed to reduce it
- What is a monsoon for these models? Is there a “monsoon”?
- Absolute thresholds cannot be used

Defining the Monsoon active phase

- Winter Season: **November to April (WPR)**
- Monsoon Season: **May to October (MPR)**
- For Monsoon season:
  - Relative P thresholds ➔ active Monsoon phase
  - Fractional Accumulation to reduce model bias
    - Ganges: 0.15 – 0.95 ➔ Active phase: 25 pen. RFA=0.036
    - Brahmaputra: 0.18 – 0.95➔ Active phase: 28 pen. RFA=0.030
    - Mekong: 0.11 – 0.95 ➔ Active phase: 36 pen. RFA=0.025
- **Problem:** *Indus features Winter precipitation*
  - Indus: 0.15 – 0.90 (of MPR) ➔Active phase: 16 pen. RFA=0.048
- Match IMD monsoon development criteria for center of the basins…

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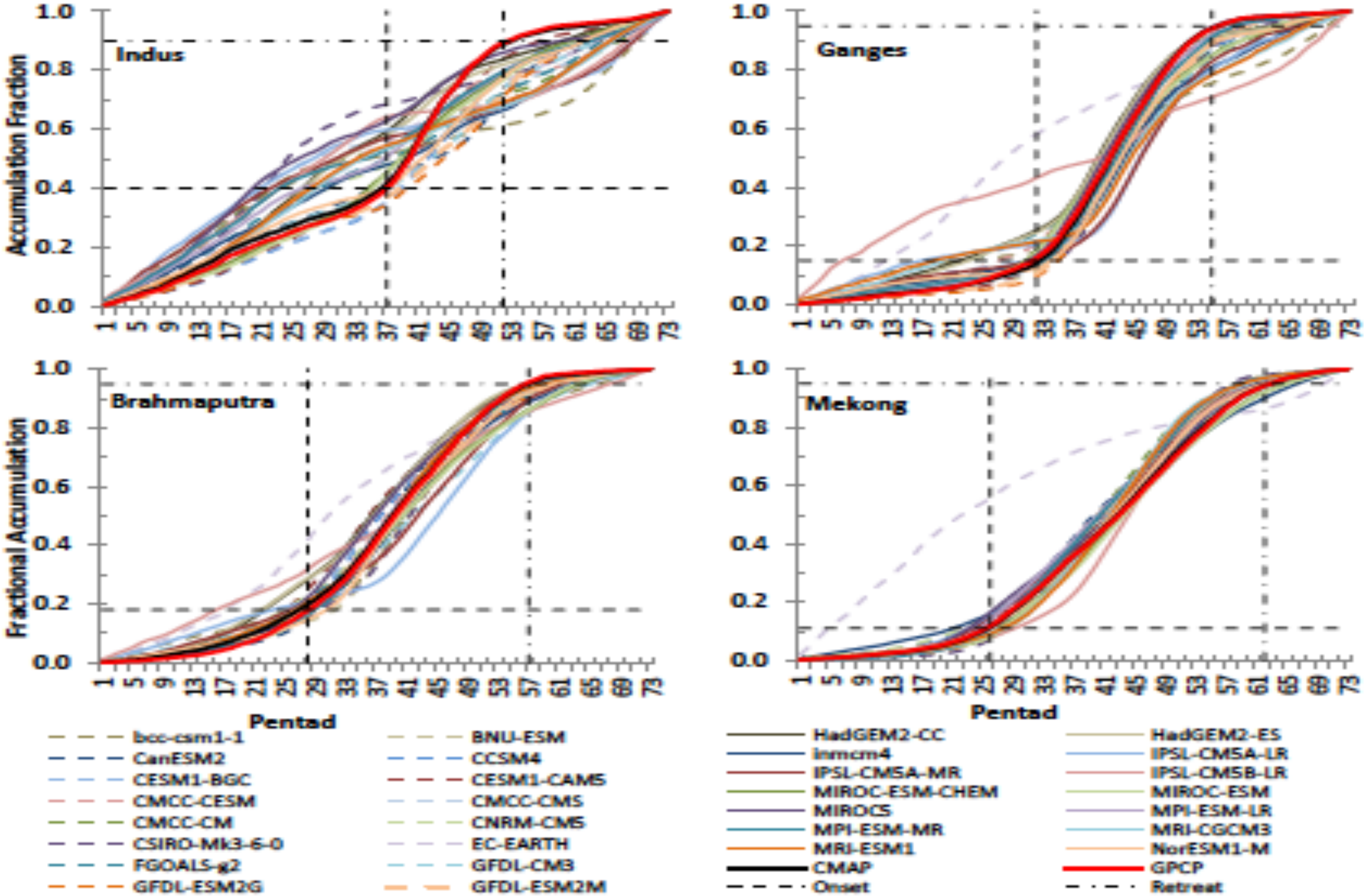
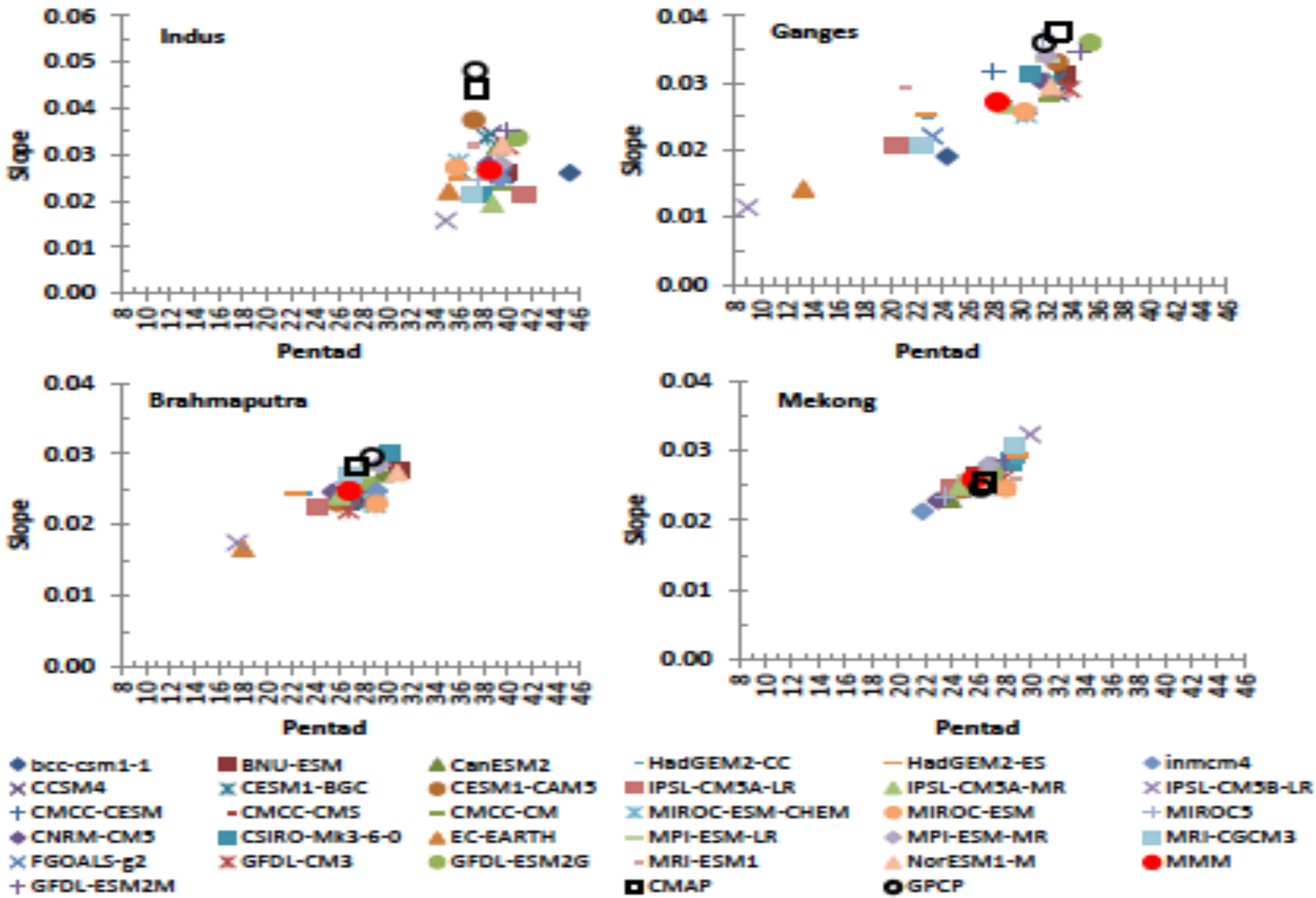
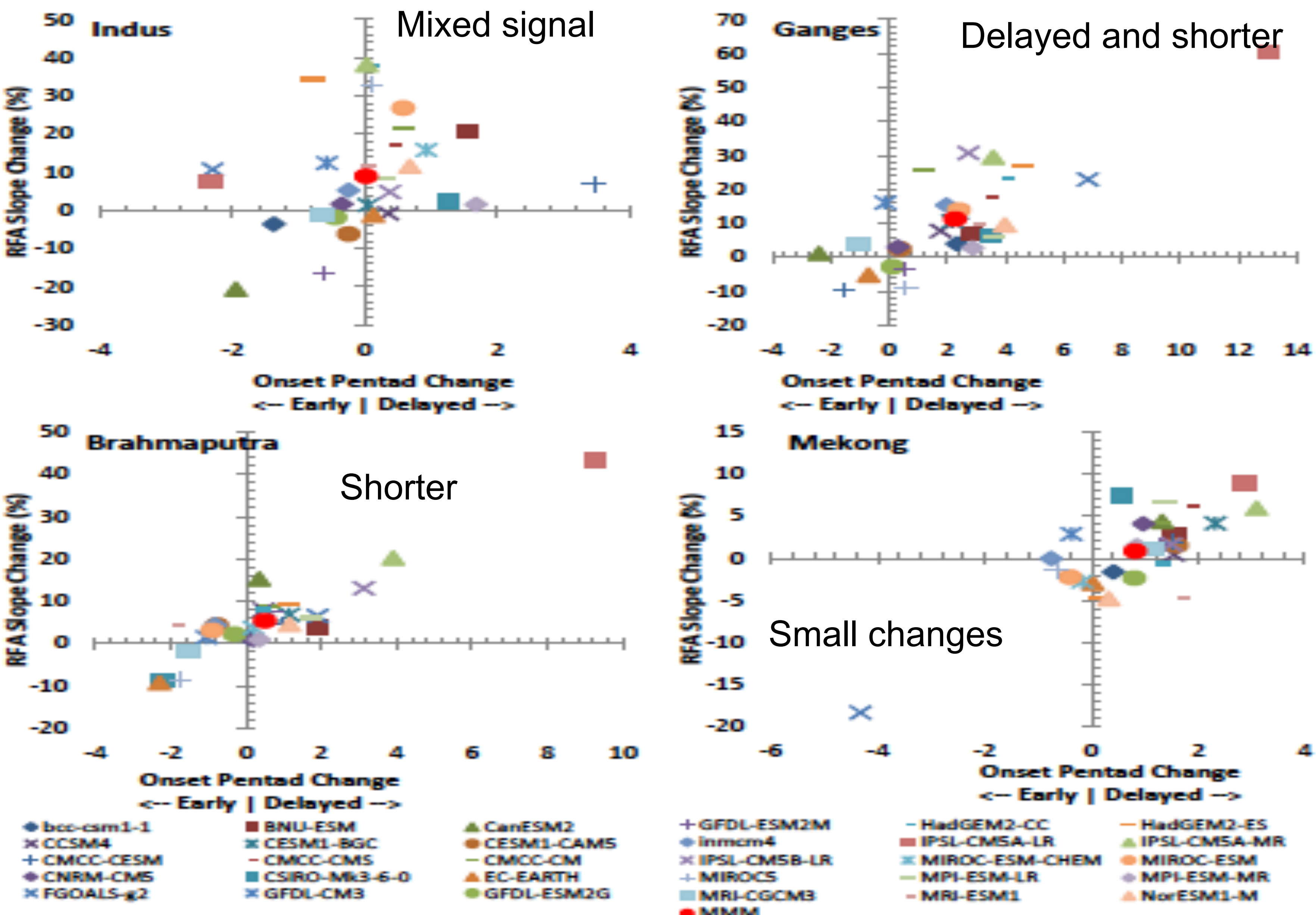
CMIP5: Fractional Cumulative Precipitation – 1960-2000



CMIP5 – Monsoon: RFA vs Onset – 1960-2000

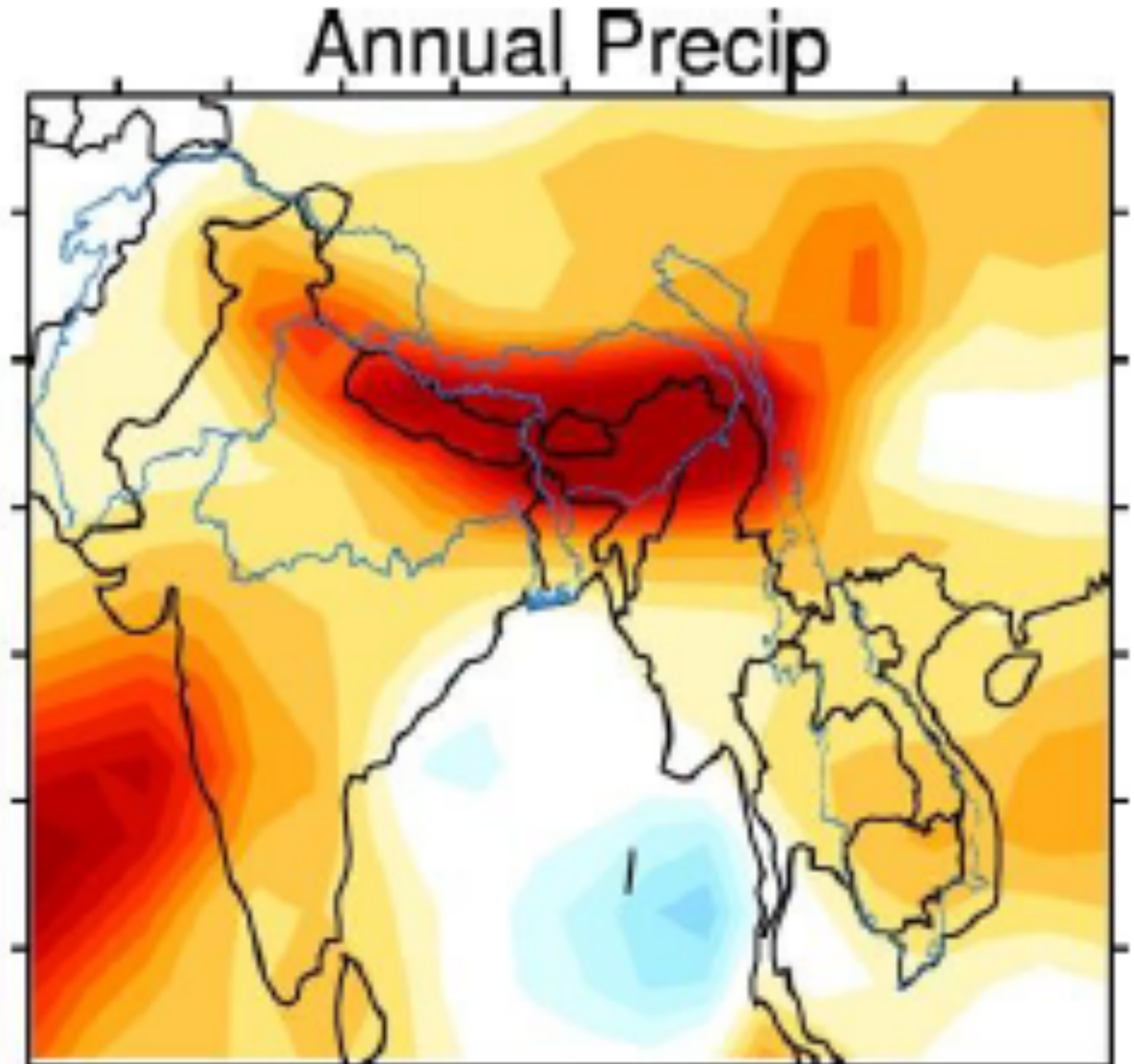


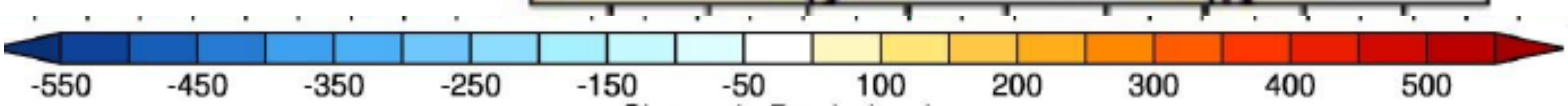
RCP8.5 (2061-2100) vs 1961-2000 Change in Monsoon



Change in annual precipitation– Ensemble mean

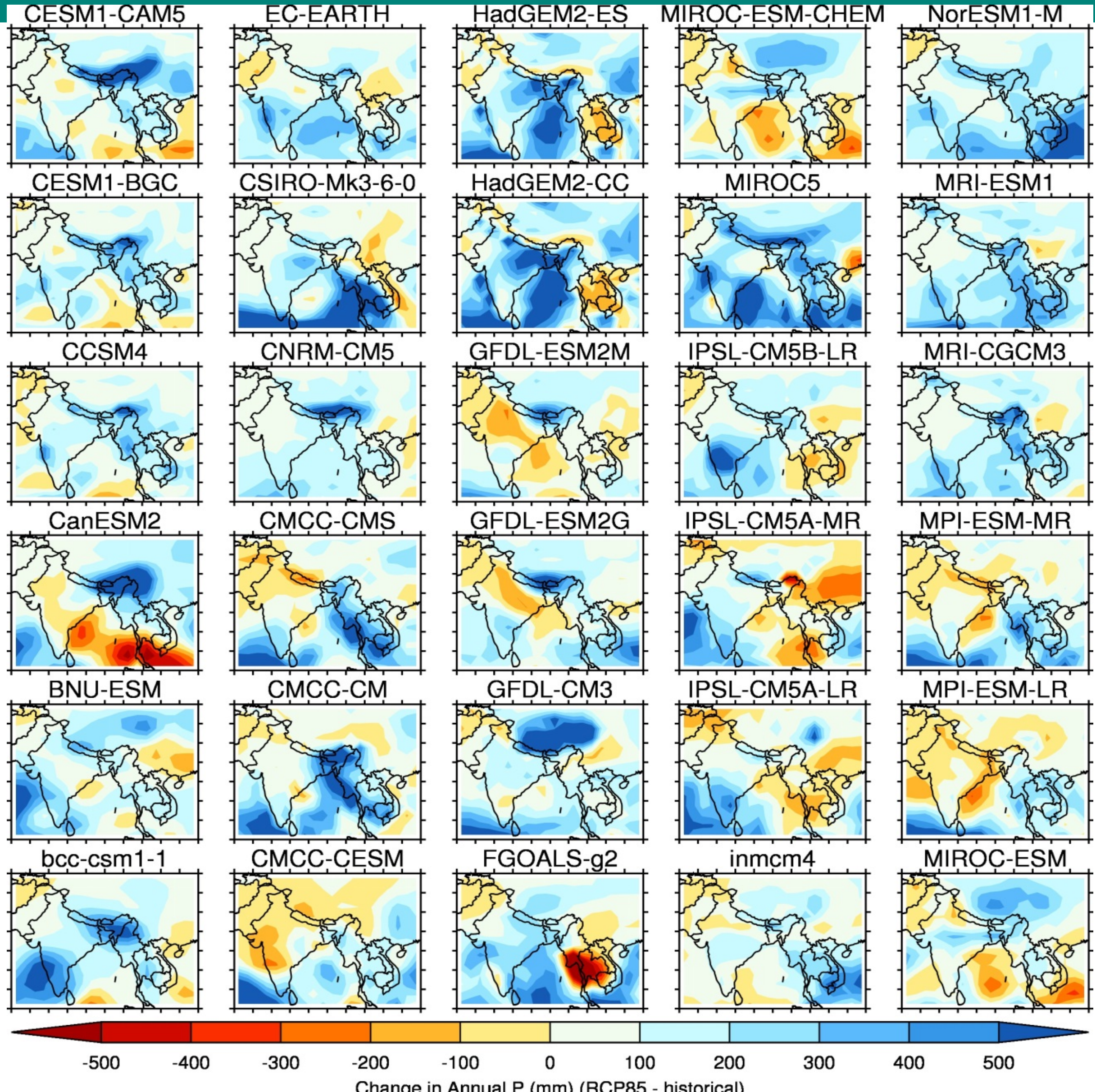
- Increase throughout (almost) the land domain





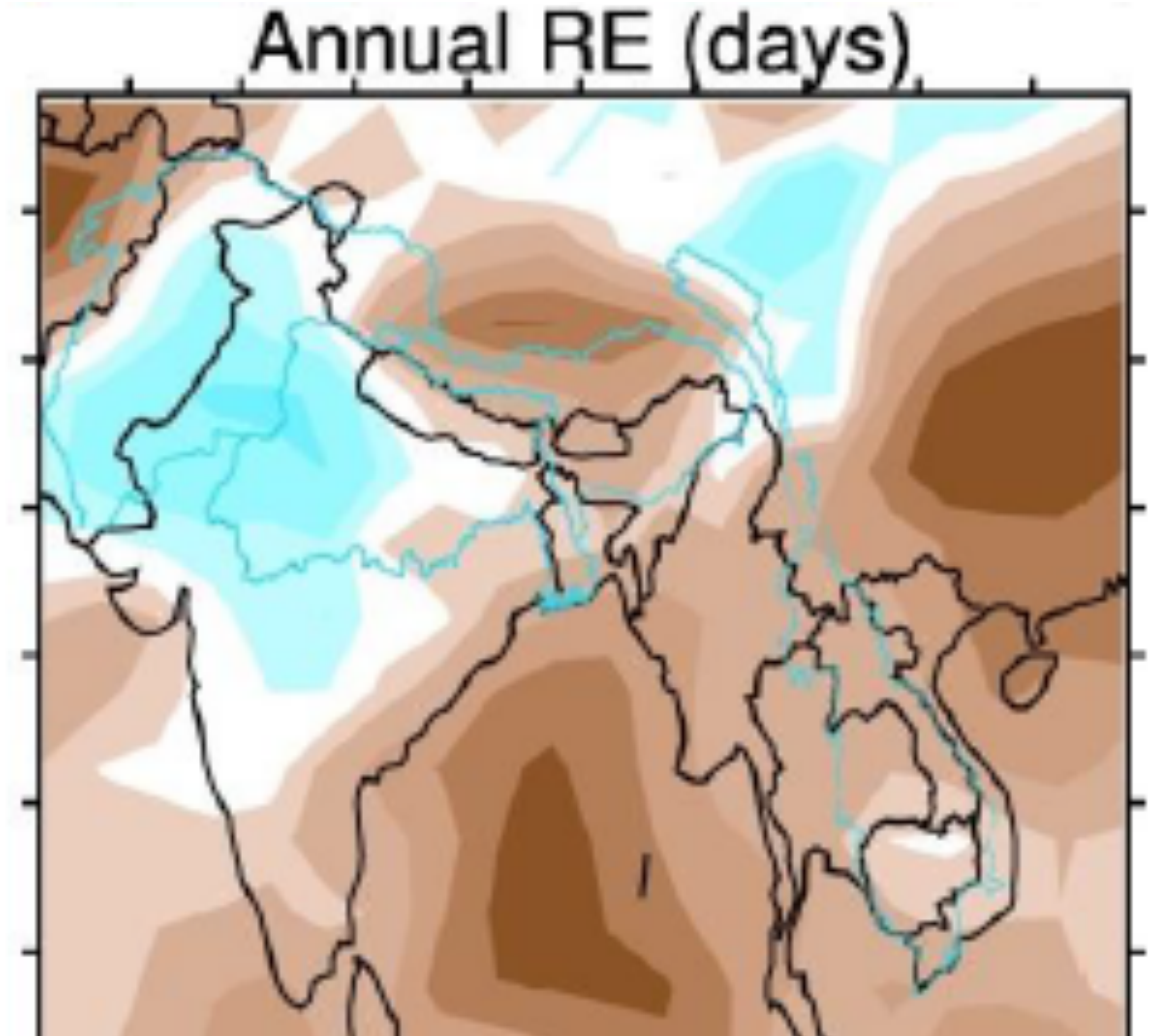
ANNUAL PRECIPITATION

- Large uncertainties
- Sorry, color code is inverted



Change in the number of dry days – Ensemble mean

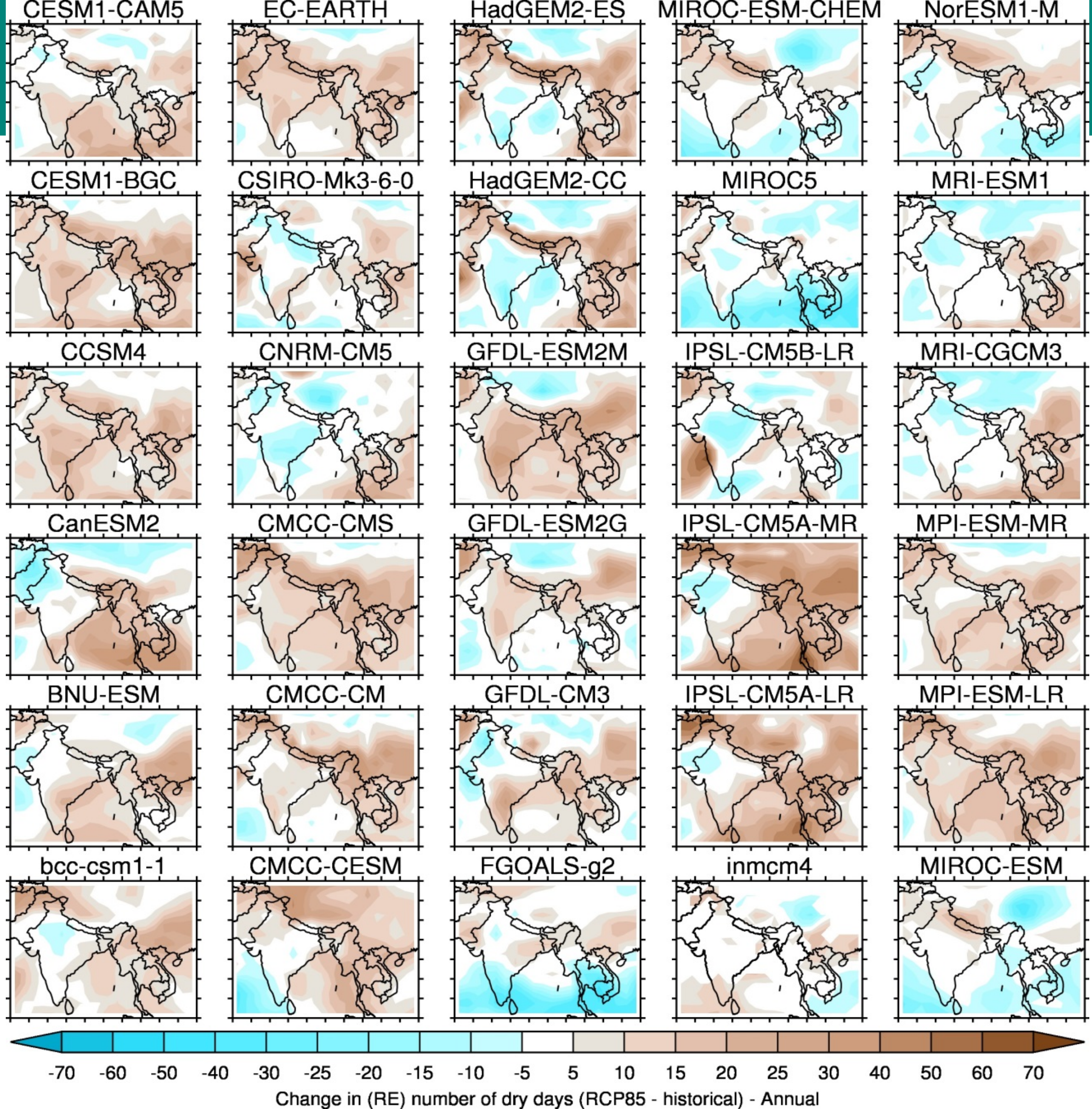
- Decrease in number of dry days in western subcontinents
- Increase in the eastern subcontinent



DRY DAYS

- Discrepancy of models in representing the change in the number of dry days

- Number of dry days seem to increase but large uncertainties exist



Way Forward

- There is a need to investigate the seasonal properties of the hydrological cycle - Monsoon and mid-latitude disturbances
- CMIP3 is relevant: GCMs are used for nesting in most South Asian institutes!
- Improvement in CMIP5? Model uncertainty?
- Long term wet and dry conditions and extreme events should be taken into consideration.
- Downscaling need input on the individual model performances

  „Science is not a beauty contest!“ (cit.) Yes, but we must inform users!
- Analysis of Cordex Data

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Relevant Literature

S. Hasson, V. Lucarini, and S. Pascale, Hydrological cycle over south and southeast Asian river basins as simulated by PCMDI/CMIP3 experiments, Earth Syst. Dynam., 4, 199-217, 2013

S. Hasson, V. Lucarini, and S. Pascale, Seasonality of the hydrological cycle in major Asian River Basins, **Earth Syst. Dynam. 5, 67-87 (2014)**

S. Hasson, S. Pascale, V. Lucarini, J. Böhner, Seasonal cycle of Precipitation over Major River Basins in South and Southeast Asia: A Review of the CMIP5 climate models data for present climate and future climate projections, Atmospheric Research, submitted (2015)

Lucarini V., R. Danihlik, I. Kriegerova, and A. Speranza: Does the Danube exist? Versions of reality given by various regional climate models and climatological datasets, J. Geophys. Res. **112**, D13103, doi: 10.1029/2006JD008360 (2007)

Lucarini V., R. Danihlik, I. Kriegerova, and A. Speranza: Hydrological Cycle in the Danube basin in present-day and XXII century simulations by IPCCAR4 global climate models, J. Geophys. Res. **113**, D09107, doi:10.1029/2007JD009167 (2008)

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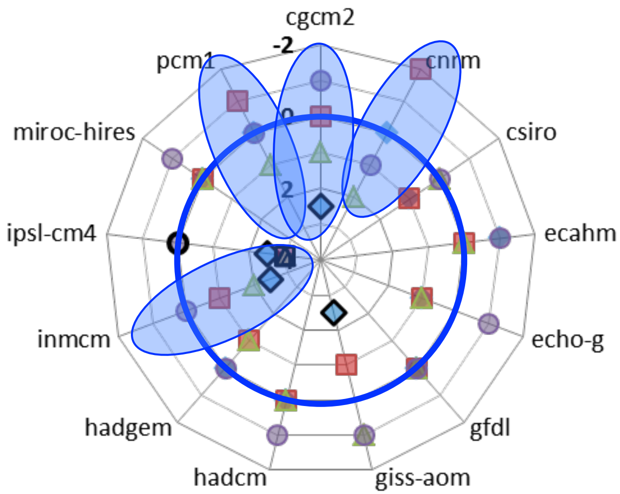
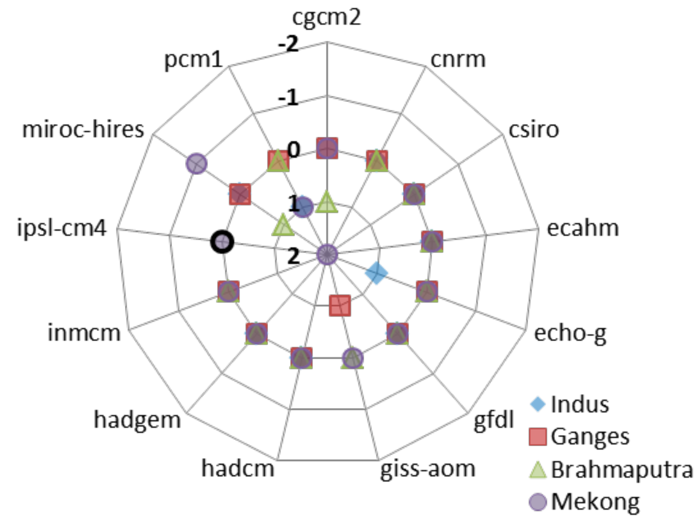
THANKS

MONSOON Onset-Month and its Change



(a) for XX Century climate (1961-2000) Relative to Observed



(b) for XXI Century Climate (2061-2100) relative to XX Century Climate

- Change in timings of onset-month, early (negative) and delayed (positive) duration in months;
- for XX Century climate (1961-2000) relative to the observed climatic onset-months for each basin (July for Indus, June for Ganges, Brahmaputra, Mekong)

  Indus: good if any; Others are OK within 1 month.
- for XXI Century Climate (2061-2100) relative to XX Century climate (1961-2000)

  Moderate variations

Note: GCMs which do not simulate Monsoon Precipitation Regime at all for the particular basin (markers with black border) are only shown for indicative purpose

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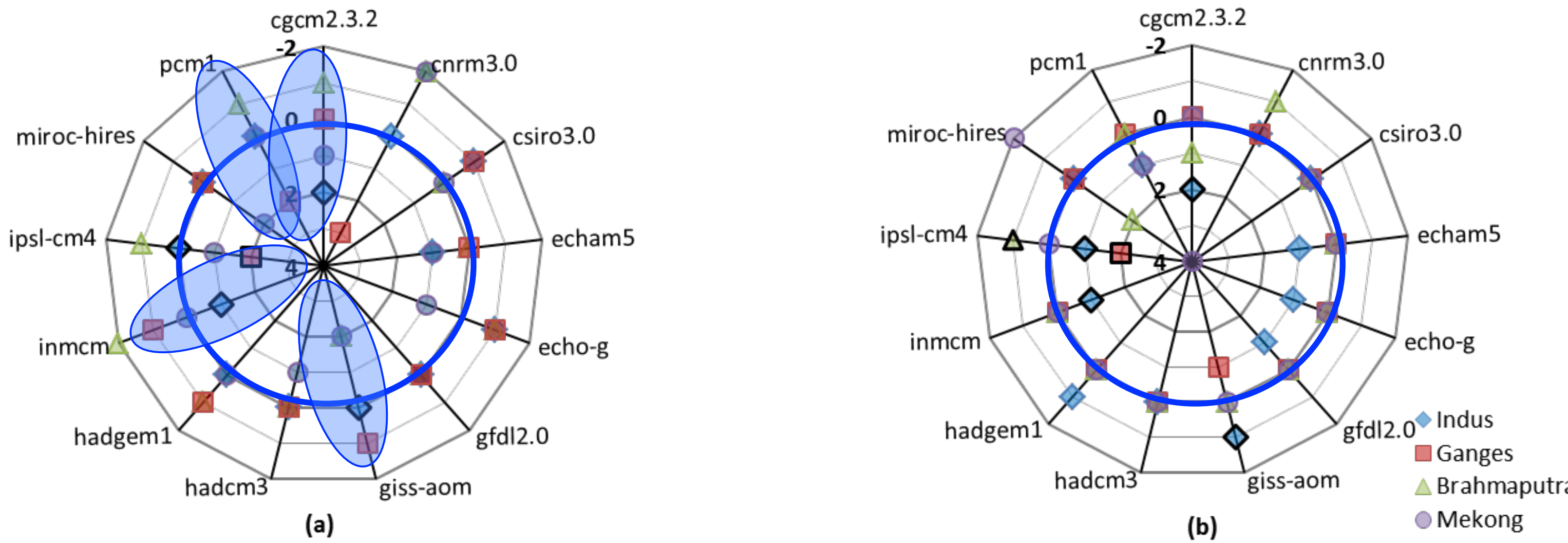
MONSOON Duration



- Difference of XX Century climate (1961-2000) relative to observations.

  Typical bias of 1-2 months, GFDL2.0 very good

- Change for XXI Century climate (2061-2100) relative to XX Century climate (1961-2000) (2 Months Indus, 3 Months Ganges, Brahmaputra, 4 Months Mekong)

  Durations is usually unchanged, some GCMs suggest shorter monsoonal rain on Indus

Note: GCMs which do not simulate Monsoon Precipitation Regime at all for the particular basins (markers with black border) are only shown for indicative purpose

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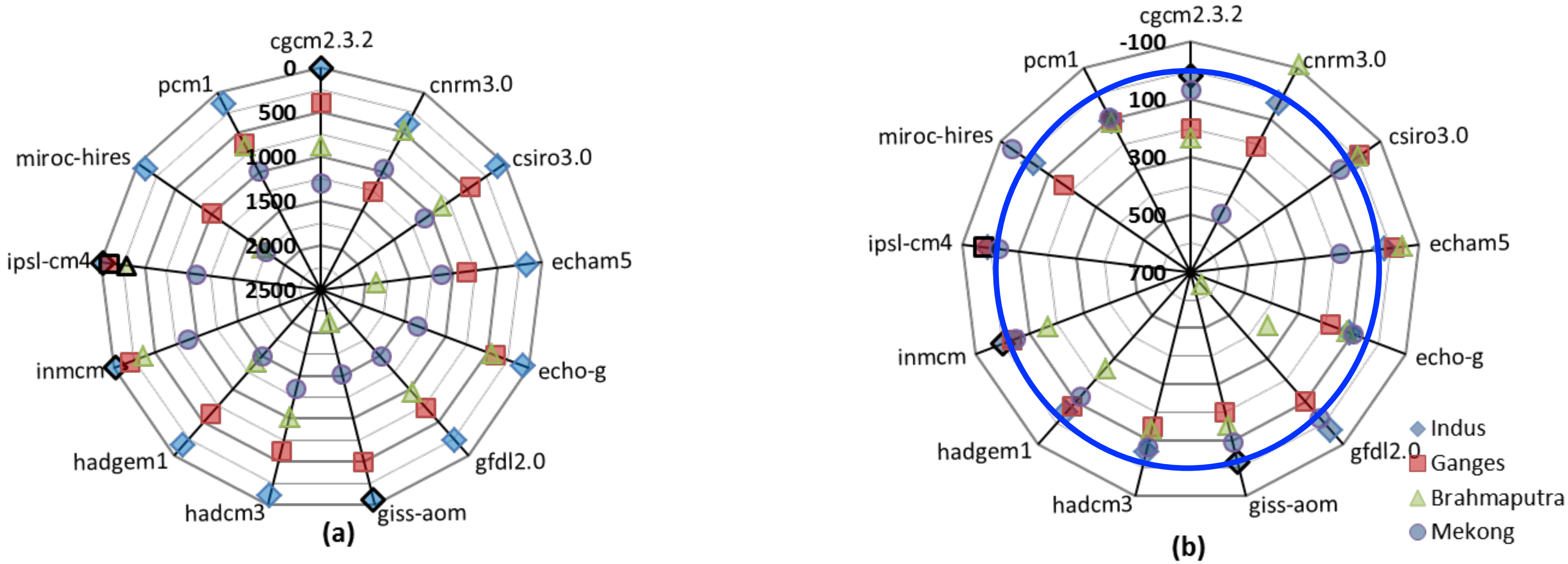
MONSOON Precipitation



- Monsoon Precipitation Magnitude (mm)
- XX Century climate (1961-2000)
  - Increase in intensity West ➔ East
- Change for XXI Century climate (2061-2100) relative to XX Century climate (1961-2000)
  - Increase in Precipitation in all Eastern Basins

Note: GCMs which do not simulate Monsoon Precipitation Regime at all for the particular basins (markers with black border) are only shown for indicative purpose

For (b) MIROC-HIRES suggests 1025mm for Brahmaputra Basin

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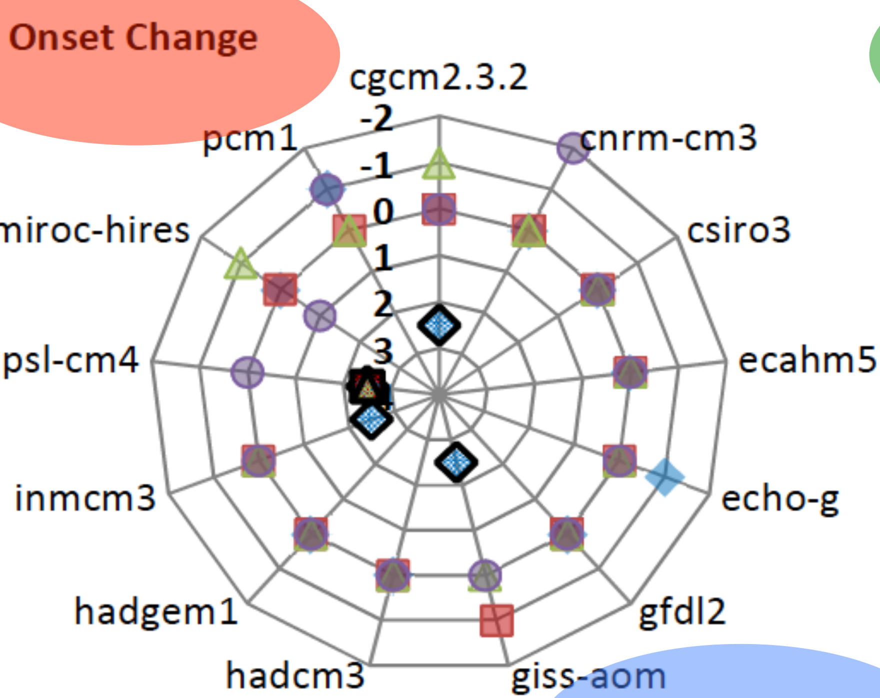

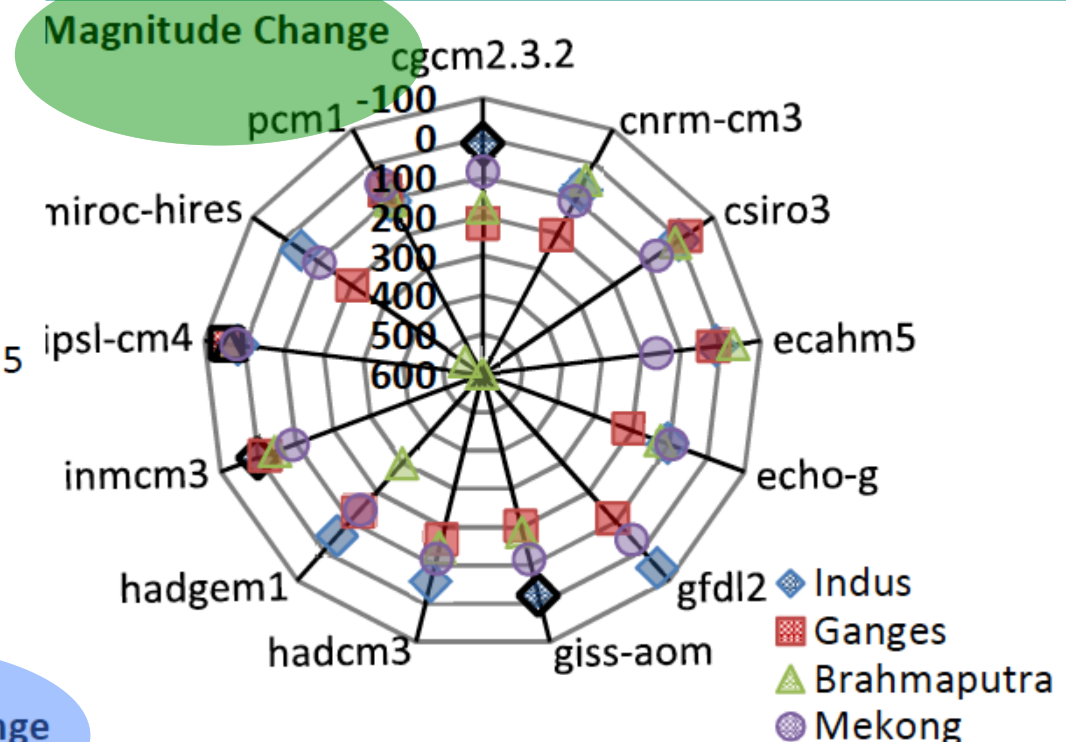

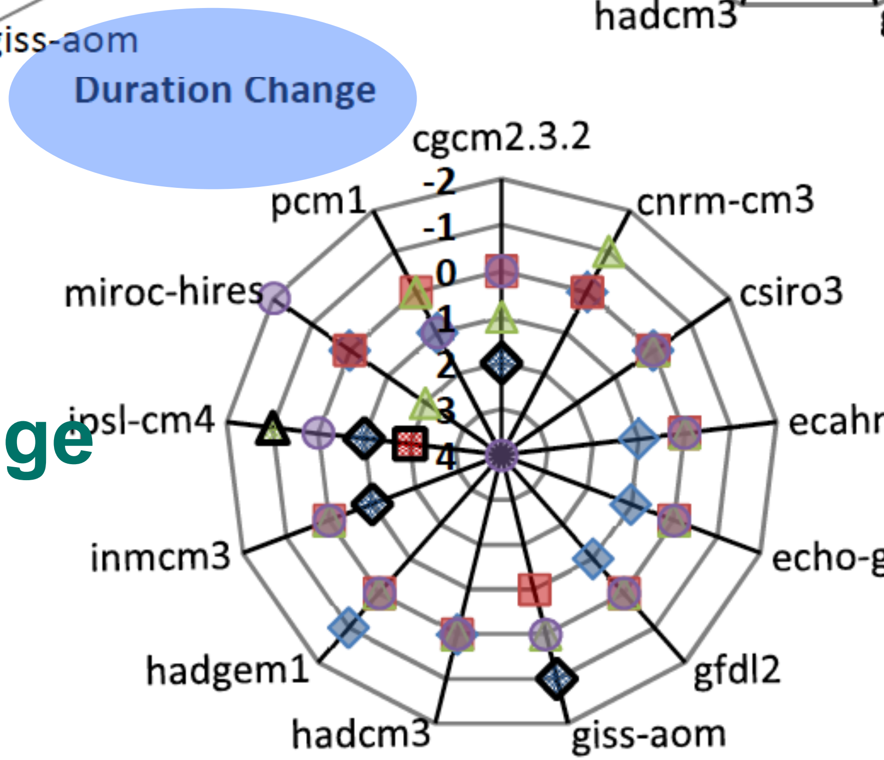

Climate Change Monsoon

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