South Asian Monsoon Precipitation in CMIP5: Linking Biases and Inter-model Spread to Model Representation of Tropical Convection

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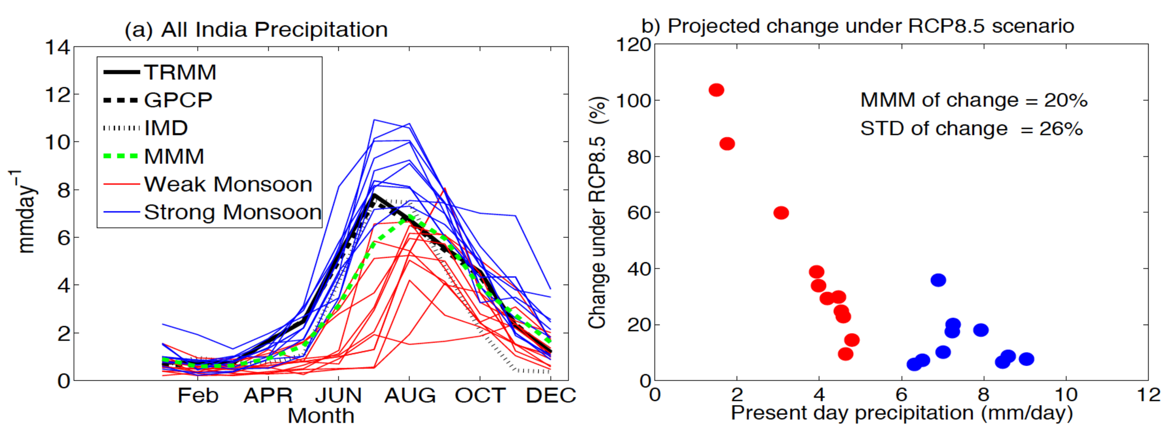
1. Large model biases and spread

- What are the sources of biases in the CMIP5 South Asian monsoon precipitation and inter-model spread in projected future changes?

Large biases in monsoon precipitation in present day simulations

Large spread in projected monsoon precipitation changes in the future

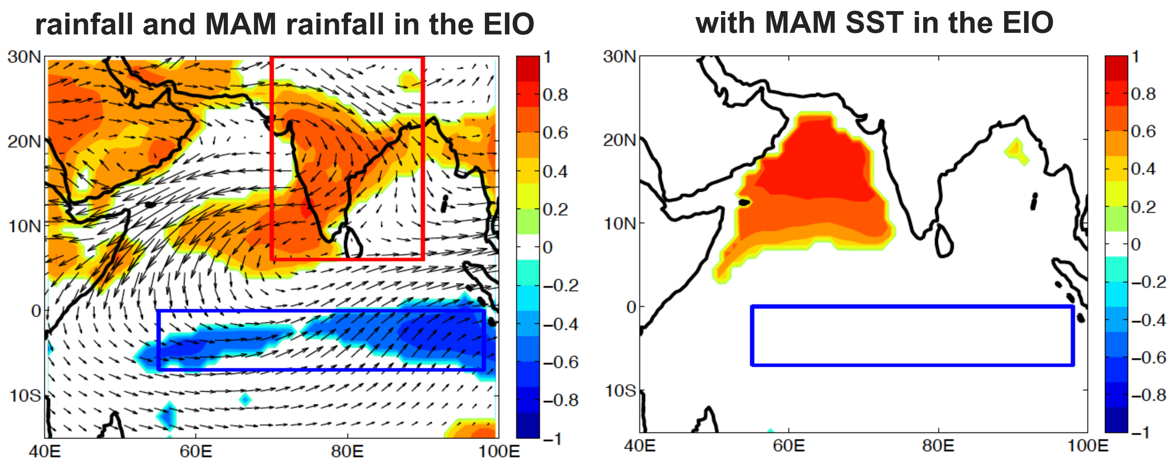


2. Convection over the Equatorial Indian Ocean may hold the key

- Tropospheric warming from excess precipitation in the Equatorial Indian Ocean (EIO) induces a northeasterly low level anomalous flow that counters the monsoon circulation and moisture transport
- Model biases are more of an atmosphere rather than coupled problem

Anti-correlation between JJAS Indian rainfall and MAM rainfall in the EIO

Monsoon rainfall has no correlation with MAM SST in the EIO



3. Divergence and precipitation in the tropics

From conservation of mass:

$$-\frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_d dp = \frac{1}{g}\int_{ps}^{pt} q\left(\frac{\partial\omega}{\partial p}\right)_d dp$$

From conservation of energy and the weak temperature gradient in the tropics:

$$\mathbf{v}\cdot\nabla T - S_p\omega = \frac{\mathbf{J}_d}{C_p}$$

Diabatic heating is dominated by latent heating in the tropics

$$\mathbf{J}_d \simeq P\hat{\mathbf{j}}_d(p)$$

Divergence and precipitation are strongly linked: (Moisture; Wind divergence)

$$-\frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_d dp \simeq \alpha_d P + \beta_d \qquad \alpha_d = -\frac{1}{C_p g}\int_{ps}^{pt} q\frac{\partial}{\partial p}\left(\frac{\hat{\mathbf{j}}_d(p)}{S_p}\right)dp$$

4. Precipitable water and precipitation

From conservation of moisture and partitioning the divergence into deep convection and subsidence:

$$P = E - \frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_s dp - \frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_d dp - \frac{1}{g}\int_{ps}^{pt}\mathbf{v}\cdot\nabla q dp$$

Using the linear relationship between moisture divergence and precipitation:

$$-\frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_d dp \simeq \alpha_d P + \beta_d \qquad -\frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_s dp \simeq \alpha_s P + \beta_s$$

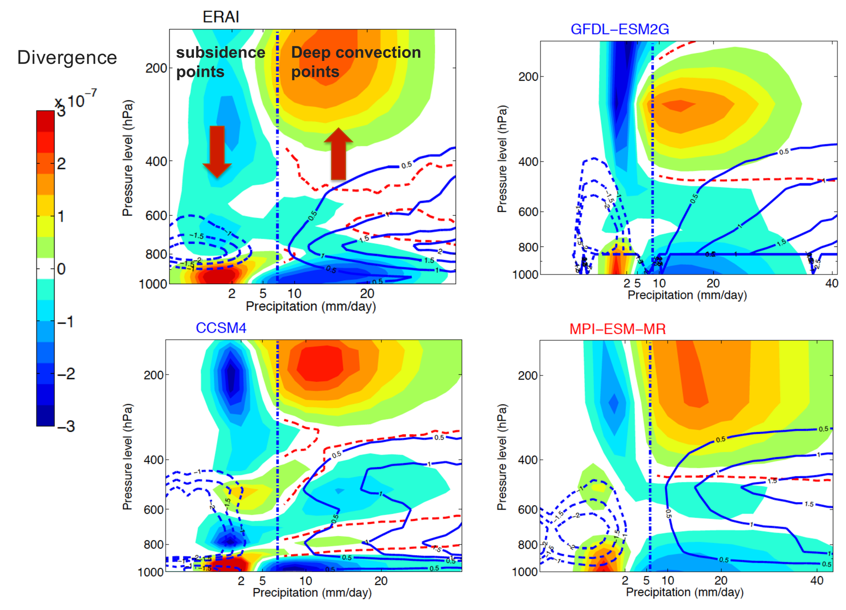
A normalized *pw* and *p* relationship analogous to the non-normalized *pw* and *p* relationship:

$$pr_N = \frac{1}{(1-pw_N)} \qquad pw_N = 1 - abs(1-(\alpha_d+\alpha_s))$$

$$pr_N = \frac{P}{(E - \frac{1}{g}\int_{ps}^{pt}\mathbf{v}\cdot\nabla q dp + \beta_s + \beta_d)}$$

5. Divergence and precipitation in the Equatorial Indian Ocean

$$\alpha_d = -\frac{1}{C_p g}\int_{ps}^{pt} q\frac{\partial}{\partial p}\left(\frac{\hat{\mathbf{j}}_d(p)}{S_p}\right)dp \qquad pw_N = 1 - abs(1-(\alpha_d+\alpha_s)) \qquad pr_N = \frac{1}{(1-pw_N)}$$



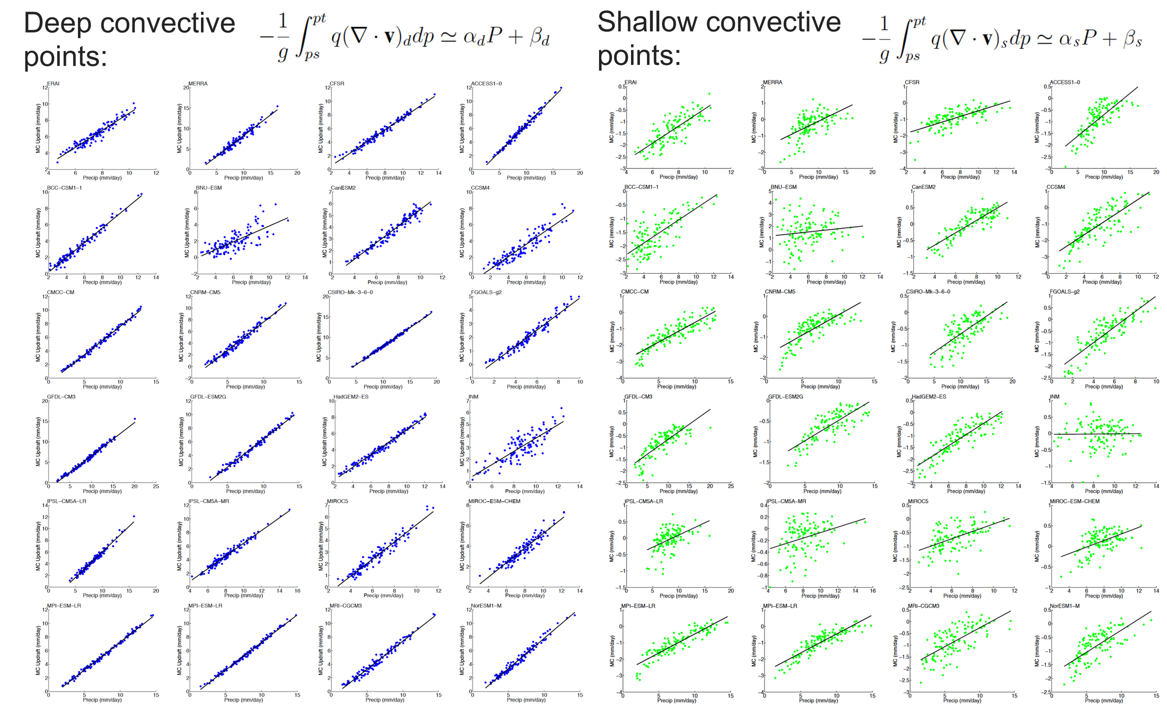
Strong monsoon: Shallow moist layer relative to the convergence layer
- pw_N and pr_N are small

Weak monsoon: Deep moist layer relative to the convergence layer
- pw_N and pr_N are large

6. Divergence and Precipitation in the equatorial Indian Ocean

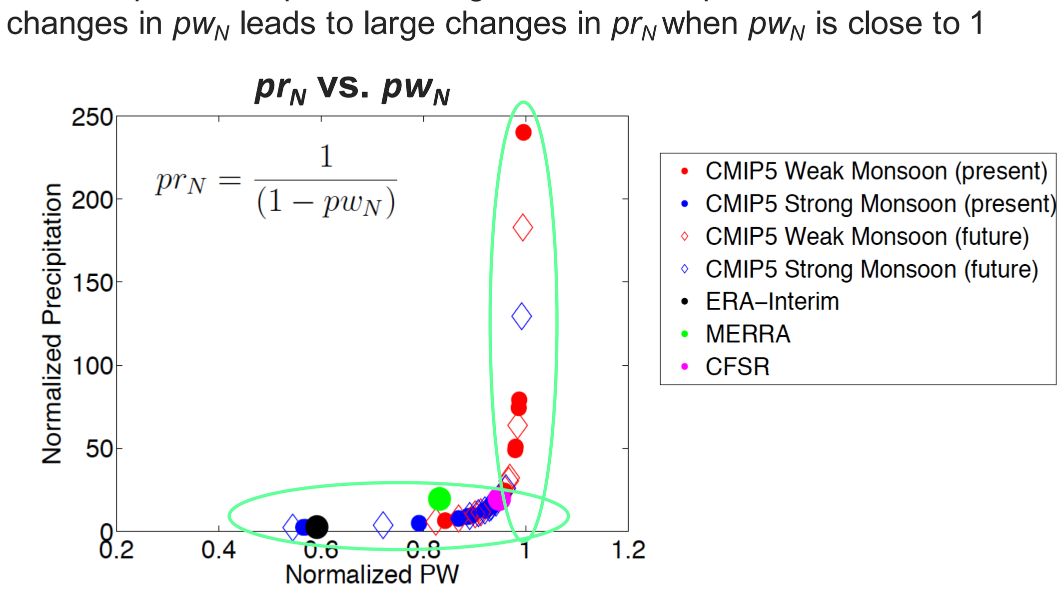
Deep convective points: $-\frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_d dp \simeq \alpha_d P + \beta_d$

Shallow convective points: $-\frac{1}{g}\int_{ps}^{pt} q(\nabla\cdot\mathbf{v})_s dp \simeq \alpha_s P + \beta_s$



7. A bimodal distribution of models

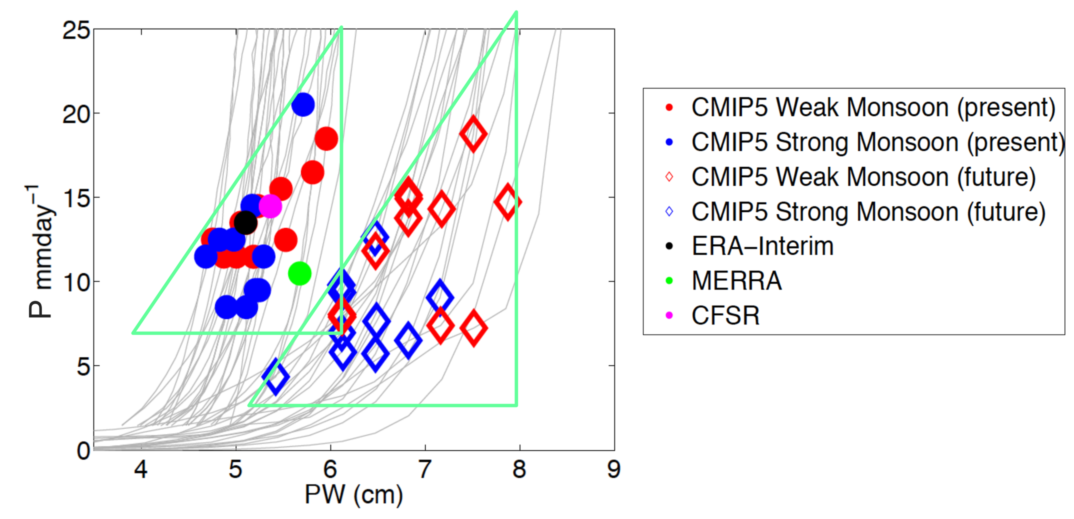
- Models that effectively utilize moisture from local convergence produce more precipitation in the EIO, hence weak monsoon, than models that rely on moisture supply from evaporation and advection
- The steep curve explains the large inter-model spread as small changes in pw_N leads to large changes in pr_N when pw_N is close to 1



8. A bimodal distribution of models

- As a consequence of the steep P vs. PW curve, the spread in the simulated precipitation over the EIO increases with the precipitable water
- In a warmer climate, the spread of PW increases, so the spread P also increases

Precipitation vs. precipitable water

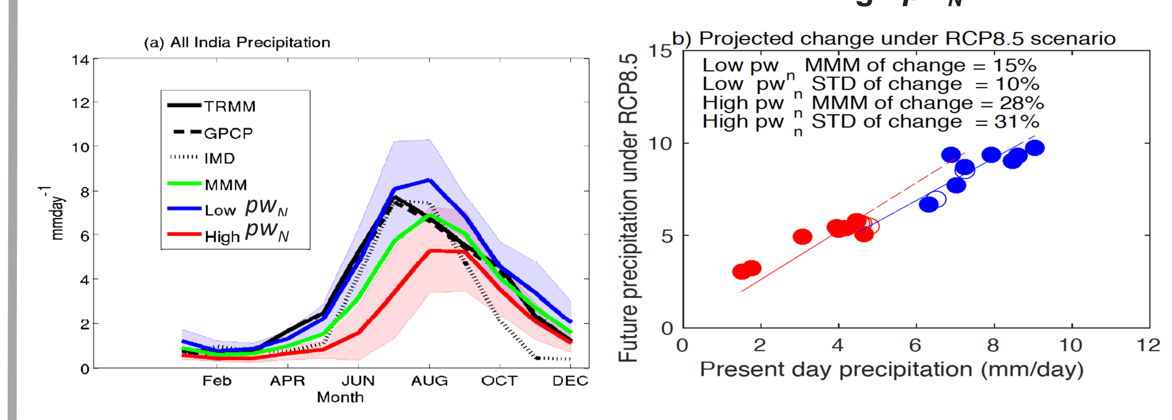


9. Predictive power of pw_N on model biases and inter-model spread

- Models with pw_N above the median value have weak monsoon (red) and vice versa (blue)
- Most of the spread in projected changes in monsoon rainfall is associated with models with weak monsoon and high pw_N

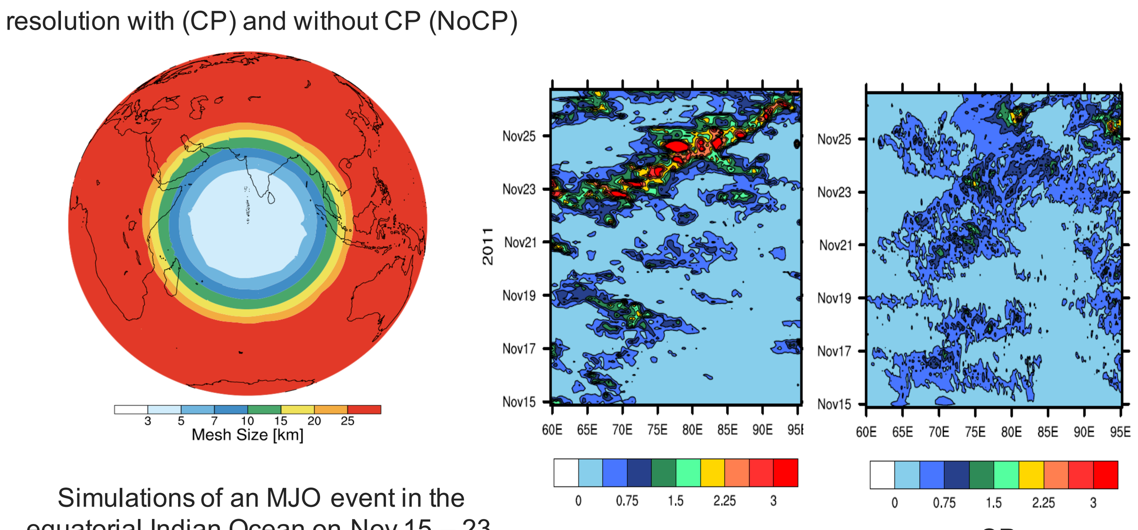
Dry bias in monsoon rainfall associated with high pw_N

Large spread in projected monsoon rainfall changes associated with high pw_N



10. Convection permitting modeling in a global variable resolution model

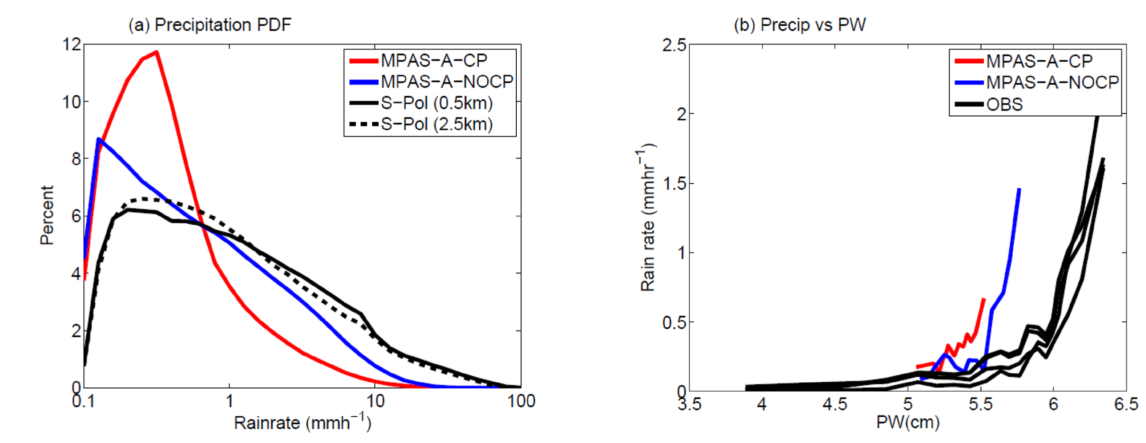
MPAS-CAM5 simulations at 4 km – 32 km resolution with (CP) and without CP (NoCP)



Simulations of an MJO event in the equatorial Indian Ocean on Nov 15 – 23, 2011 during AMIE/DYNAMO

11. Convection permitting modeling in a global variable resolution model

- Turning off CP leads to some improvements in simulating MJO, cloud characteristics, rain rates, and P vs PW
- But for climate simulations, scale-aware parameterizations are needed in global variable resolution models the spread also increases



Summary

- CMIP5 model biases in simulating South Asian monsoon rainfall are linked to convection in the equatorial Indian Ocean
- In the equatorial Indian Ocean, there is a bimodal distribution of models with high pw_N and high pr_N vs. low pw_N and low pr_N, as pw_N and pr_N are related by a non-linear relationship
- pw_N has predictive power for model simulated monsoon rainfall and inter-model spread
- pw_N is determined by the relative depths of divergence and moisture, which are associated with how convective parameterizations distribute moisture and latent heating vertically
- Convection permitting modeling may improve simulations of convection, but scale-aware parameterizations are needed in a global variable resolution modeling framework in which CPM is computationally feasible

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