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?

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

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

3. Divergence and precipitation in the tropics

From conservation of mass:

\[
\frac{1}{g} \int_a^b \nabla \cdot \mathbf{v} \, dp = \frac{1}{g} \int_a^b \frac{\partial}{\partial z} \left( \rho \mathbf{v} \cdot \nabla \mathbf{x} \right) \, dp
\]

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

\[
\frac{J}{g} \approx \frac{\partial}{\partial z} \left( \rho h c_p \right)
\]

Dissipative heating is dominated by latent heating in the tropics

\[
J \approx F_d(p)
\]

Divergence and precipitation are strongly linked:

\[
- \frac{1}{g} \int_a^b \nabla \cdot \mathbf{v} \, dp \approx \alpha_p P + \beta_p
\]

4. Precipitable water and precipitation

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

\[
P = E - \frac{1}{g} \int_a^b \nabla \cdot \mathbf{v} \, dp - \frac{1}{g} \int_a^b \nabla \cdot \mathbf{v} \, dp - \frac{1}{g} \int_a^b \nabla \cdot \mathbf{v} \, dp
\]

Using the linear relationship between moisture divergence and precipitation:

\[
- \frac{1}{g} \int_a^b \nabla \cdot \mathbf{v} \, dp \approx \alpha_p P + \beta_p
\]

A normalised p and r relationship analogous to the non-normalized \(p\) and \(r\) relationship:

\[
p = \frac{P - (1 - \nu_P)}{P}
\]

\[
\nu_P = 1 - \alpha_p \left( (\alpha_p + \beta_p) \right)
\]

5. Divergence and precipitation in the Equatorial Indian Ocean

\[
\nu_p = 1 - \alpha_p \left( (\alpha_p + \beta_p) \right)
\]

6. Divergence and Precipitation in the equatorial Indian Ocean

- Deep convective points:
  \[ \int_a^b c_X \int_a^b c_Y \, dp \]
- Shallow convective points:
  \[ \int_a^b c_X \int_a^b c_Y \, dp \]

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 \(\nu_P\) lead to large changes in \(P\) when \(\nu_P\) 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 of P also increases

9. Predictive power of \(p_c\) on model biases and inter-model spread

- Models with \(p_c\) 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 \(p_c\)

10. 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

11. Convection permitting modeling in a global variable resolution model

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