EGU24-15851
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Potsdam Institute for Climate Impact Research

PIK

Monsoon Planet

Studying Monsoon Dynamics in an Idealized Setup

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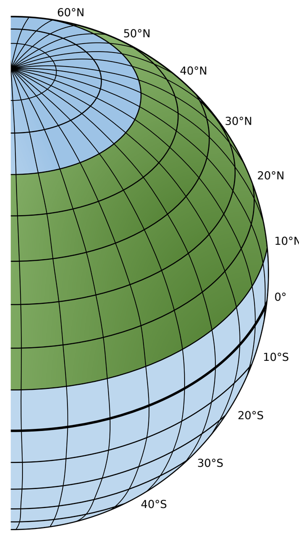
MOTIVATION & RESEARCH QUESTIONS

What controls the position, strength and variability of the tropical rainbelt?
One of four open challenges in climate science (Bony et al. 2015)

What role do meridional gradients play for the tropical rainbelt?

What is the origin of the atmospheric memory underlying the hysteresis?

STRATEGY: IDEALIZED SIMULATIONS



We use strongly idealized setups to focus on the meridional monsoon dynamics:

- **GFDL-AM2: Preindustrial atmosphere**
  No Aerosols, 280ppm CO2, 1364 W/m²
- **LaD: Idealized Land**
  Ring of land, grassland, surface albedo of 18.2 %
- **SLAB: Simplified slab ocean**
  Baseline configuration: slab depth of 50m

SIMULATIONS

In order to understand the role of different parameters and to test the robustness under varying conditions, we perform a sensitivity analysis:

Parameter	Range of variation
Land position	0-50, 2-52, ..., 16-66°
Slab ocean depth	1m, 5m, 50m, 200m, 500m
Solar constant	1000-1400W/m²
Carbon dioxide	70-1120 ppm
Sulfate aerosols (land)	0-10^{-4} kg/m²
Land surface albedo	10-34%

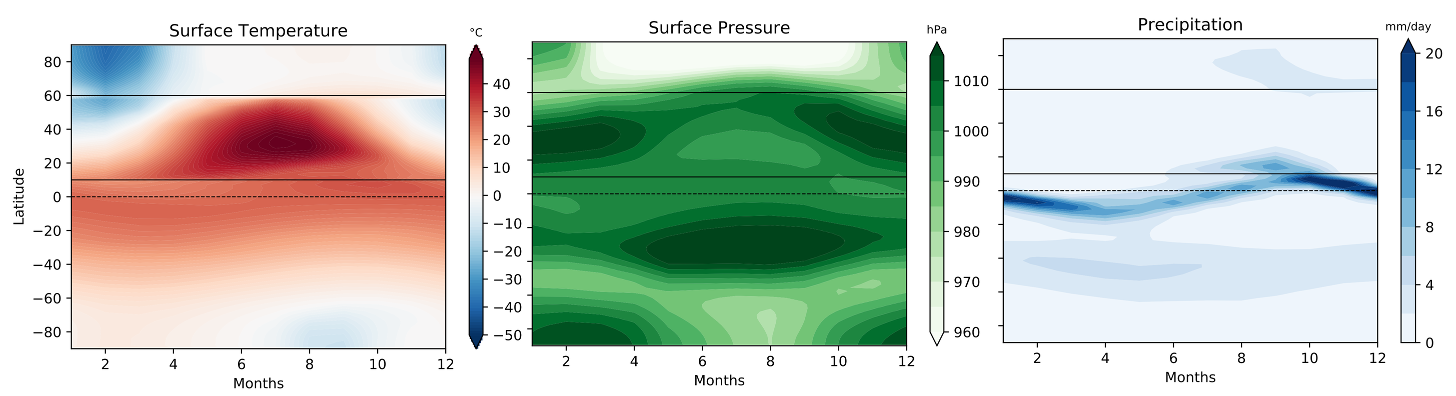


Fig. 1: Meridional distribution of surface temperature, pressure and precipitation (20-years average).

MONSOON HYSTERESIS REVEALS ATMOSPHERIC MEMORY

Katzenberger & Levermann: Under Review

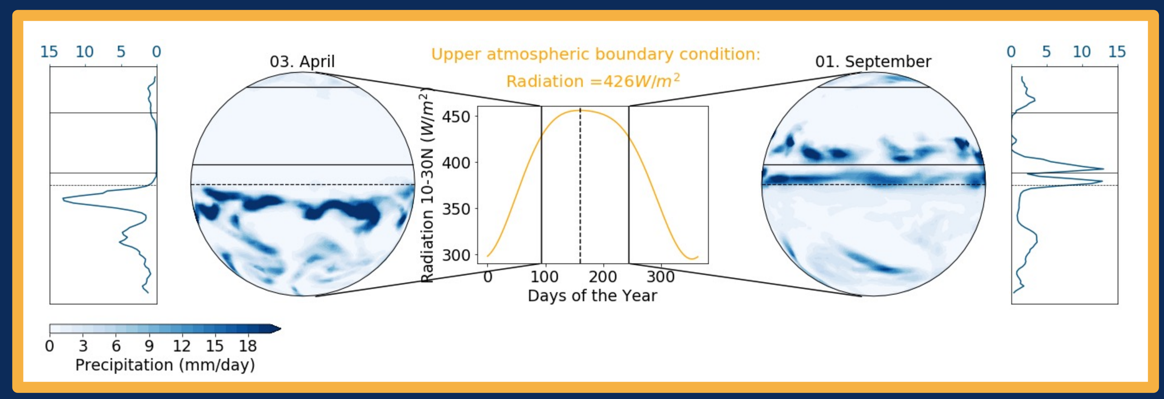


Fig. 2: Same boundary conditions (solar radiation = 426 W/m²) are associated with two different monsoon states indicating a memory effect.

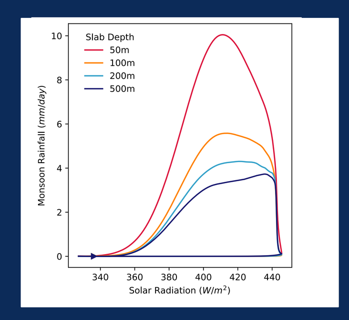


Fig. 3: Decreasing the slab ocean depth (and thus the ocean memory capacity) increases the hysteresis excluding the ocean as the origin of the hysteresis.

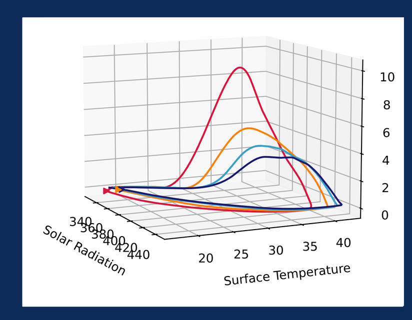


Fig. 4: The hysteresis remains also when taking to account the lower boundary conditions (surface temperature).

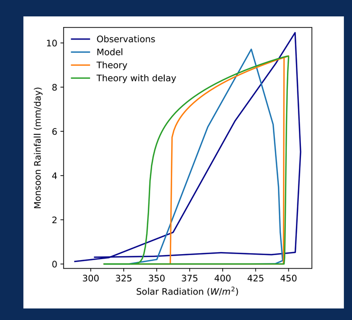


Fig. 5: The simulations are in line with monsoon observations and a simple conceptual theory focused on the role of latent heat.

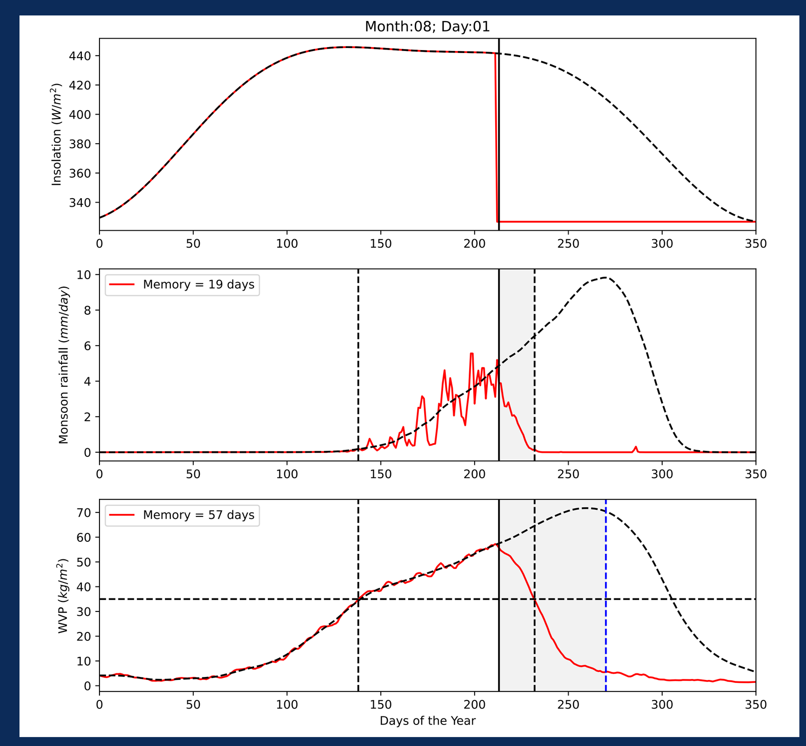


*Fig. 6: **Simulations to quantify the memory effect.** We interrupt the natural solar radiation at Augst 1st and set it to the regional minimum. Rainfall continues for approx. 19 days when the water vapor content falls below 35 kg/m². The water vapor storage needs 57 days from the intervention before it is fully emptied.*

PRESSURE BARRIER REGULATES MONSOON WINDS

Katzenberger, Petri, Feulner, Levermann (2024): Published in Journal of Climate

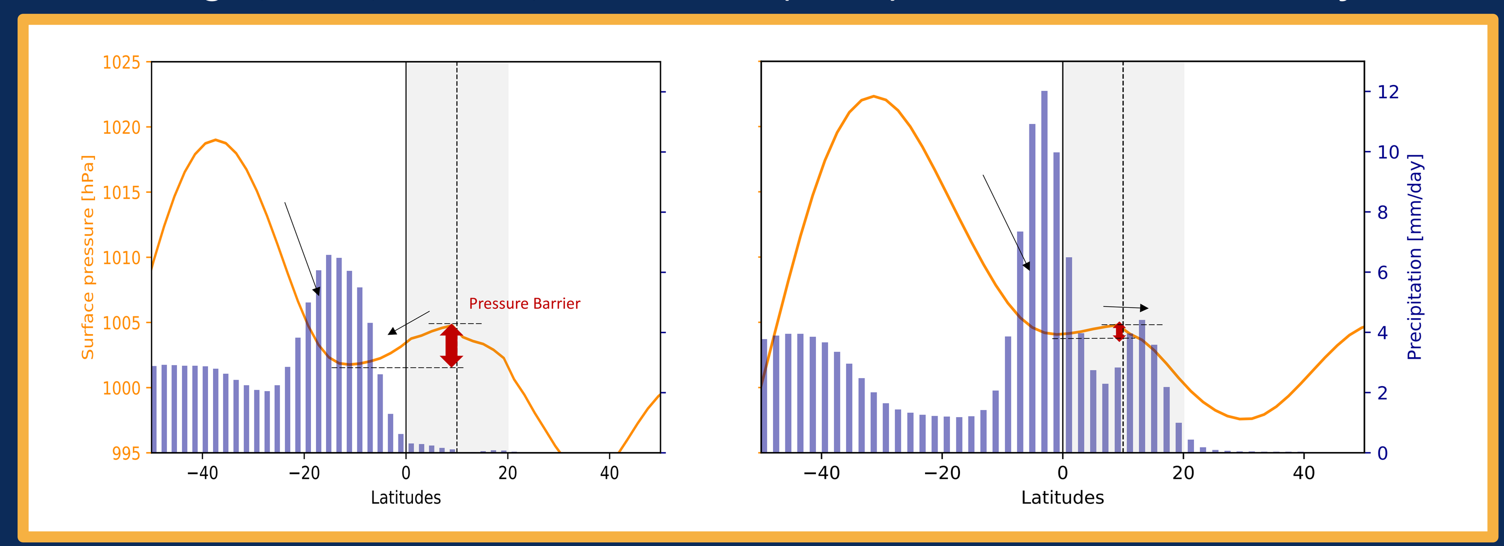


*Fig. 7 : **Pressure barrier mechanism.** Left: High pressure barrier before the monsoon season blocks landward moisture transport. Right: Reduced barrier allows northward moisture transport resulting in monsoon rainfall.*

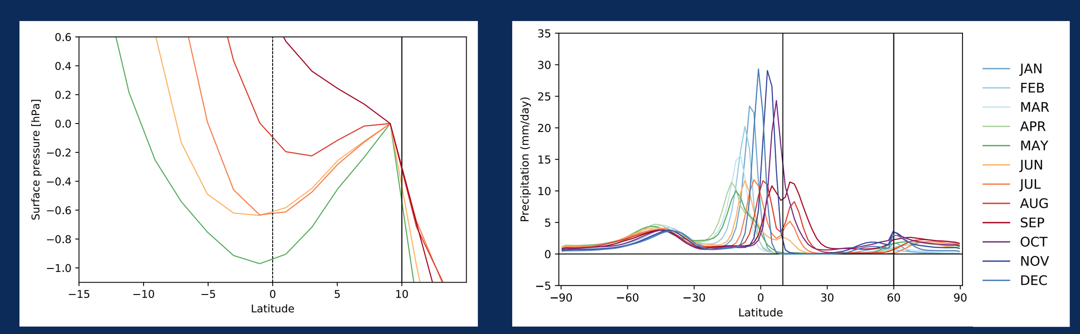


*Fig. 8: **Pressure barrier dynamics during the monsoon season.** As the solar radiation oscillates, the barrier reduces at the beginning of the season allowing moisture carrying winds to pass.*

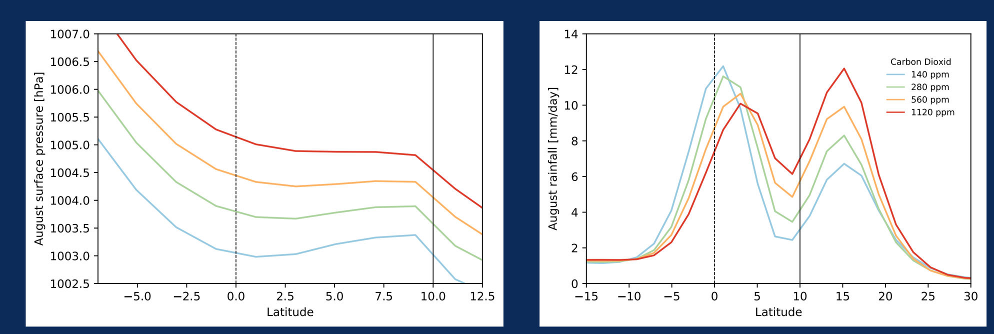


*Fig. 9: **Pressure barrier dynamics for varying CO_2 concentration.** High CO_2 concentration decreases the barrier resulting in intense monsoon rainfall.*

MONSOON DYNAMICS

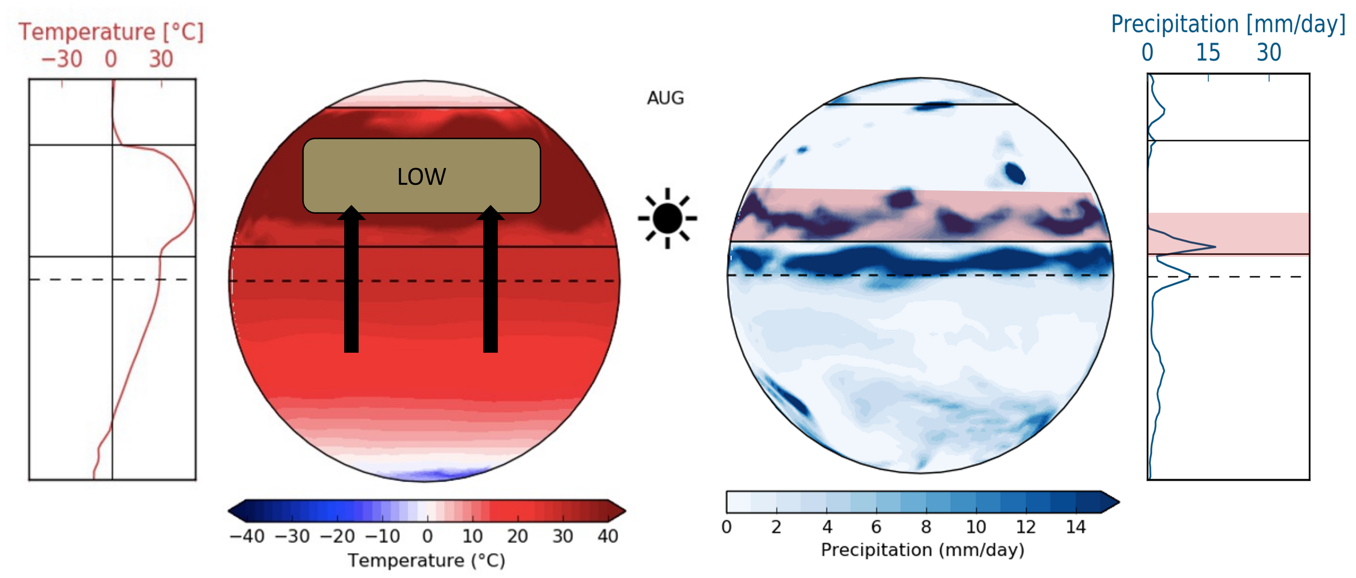


*Fig. 10: **Monsoon on the Monsoon Planet.** The real world monsoon dynamics are reproduced on the Monsoon Planet and are shown here for August.*

KEY POINTS

1. **The Monsoon Planet design provides a framework to study fundamental meridional monsoon dynamics.**

2. **Seasonal monsoon hysteresis indicates a memory effect.**

   Simulations with varying slab depths exclude the ocean as origin of this memory and reveal a memory capacity within the atmosphere itself.

   We find this hysteresis in observations, on the Monsoon Planet, and by a simple conceptual model.

   We quantify this memory effect to be of the order of weeks.

3. **A surface pressure maximum acts as a regulating barrier for monsoon winds determining the coastward moisture transport.**

   This barrier dynamic is present throughout the course of a year but also in a sensitivity analysis: Increased CO_2 reduces the barrier height and therefore leads to increased rainfall.

   The opposing effect is valid for sulfate aerosols.

ABSTRACT

Monsoon systems transport water and energy across the globe, making them a central component of the global circulation system. Each monsoon system has its own regional characteristics ranging from particular continental shapes to dynamic vegetation patterns and the influence of mountain ranges. This individuality makes it difficult to access the common core meridional monsoon dynamics by only using observations or realistic simulations. Idealized frameworks have proven to be useful approaches to study monsoon systems with regard to their commonalties. Here, we present the latest insight of our work on the Monsoon Planet – an aquaplanet setup with an idealized circumglobal land stripe.

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LITERATURE

Levermann et al. (2009): Basic mechanism for abrupt monsoon transition. *PNAS.*
Hui & Bordoni (2021): Response of monsoon rainfall to changes in the latitude of eq. coastline of zonally symmetric continent. *Journal of the Atmospheric Sciences.*
Zhou & Xie (2018): A hierarchy of idealized monsoons in an intermediate GCM. *JCL.*