A critical humidity threshold for monsoon transitions

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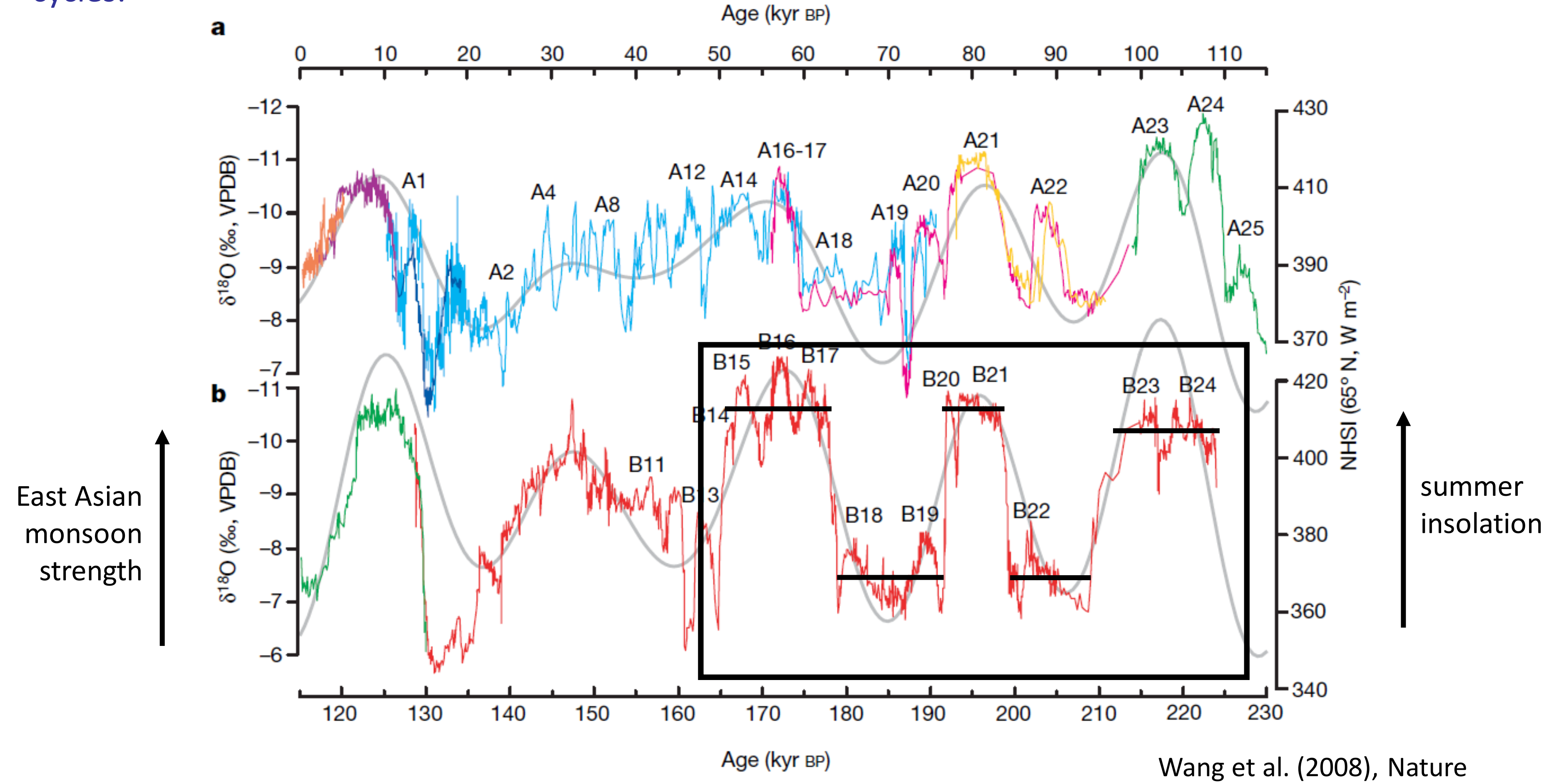
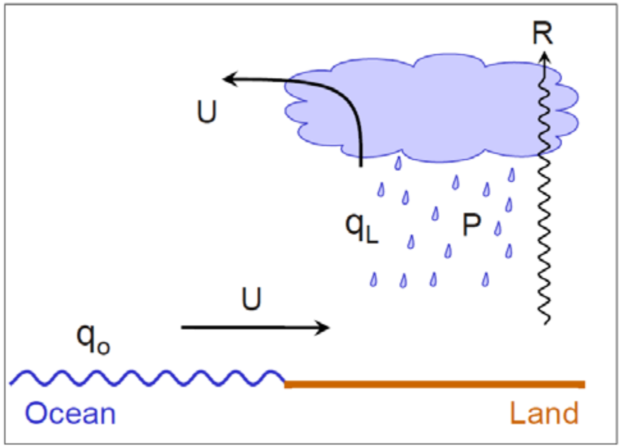
Abrupt monsoon transitions

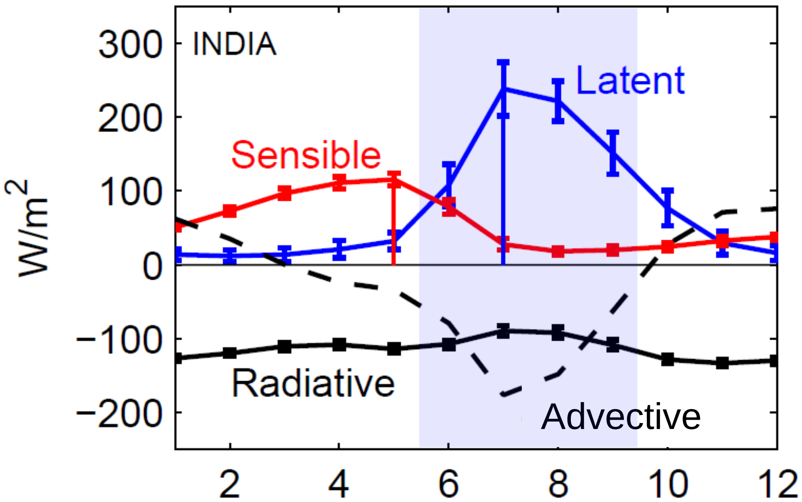
East Asian summer monsoon (EASM) proxy (speleothem) records spanning the last two glacial cycles:



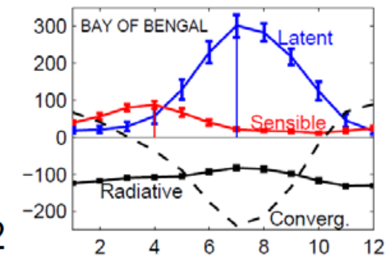
Wang et al. (2008), Nature

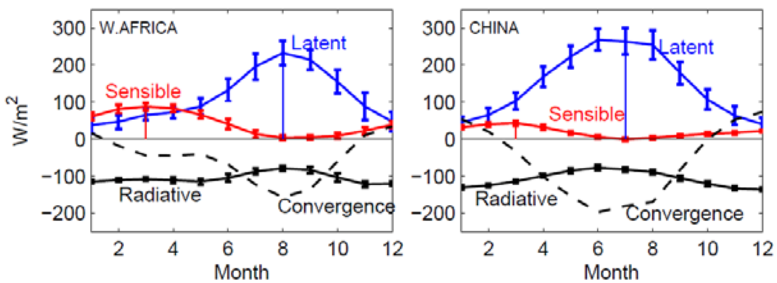
Minimal model of monsoon season





heat flux into atmospheric column over land (NCEP reanalysis)





Differential heating of land and ocean in spring triggers monsoon onset

But during the rainy season, latent heating is main energy source

→ First-order approximation for the rainy season:

$$\mathcal{L} \cdot P - \epsilon C_p U \cdot \Delta T + R = 0$$ Heat budget

$$\rho \epsilon U \cdot (q_o - q_L) - P = 0$$ Moisture budget

i.e. monsoon rainfall has to be balanced by moist inflow from the ocean (neglecting evaporation over land)

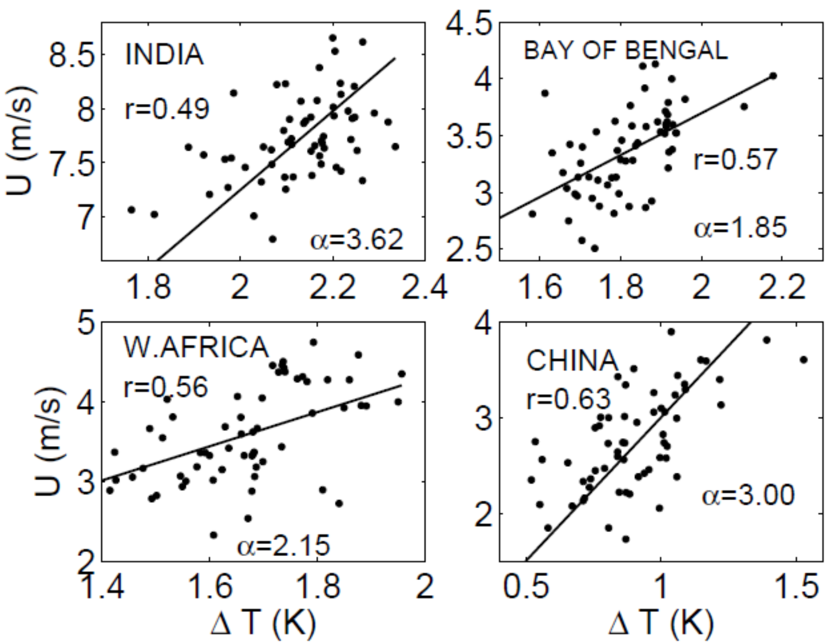
Levermann, Schewe, Petoukhov & Held (2009), PNAS

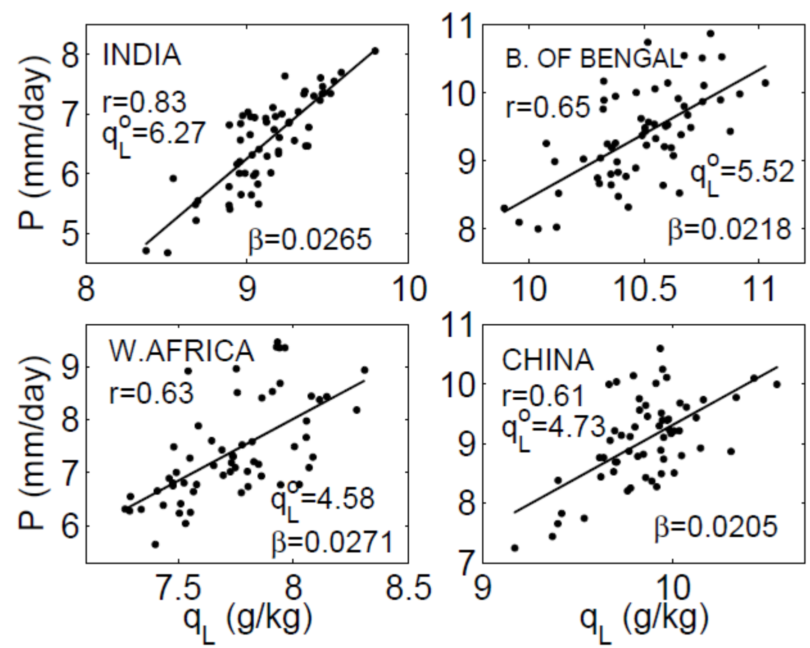
Schewe, Levermann & Cheng (2012), Clim. Past

Minimal model of monsoon season

$U = \alpha \cdot \Delta T$ Ageostrophic winds

$P = \beta q_{\mathrm{L}}$ Precipitation





NCEP reanalysis

Minimal model of monsoon season

$\mathcal{L} \cdot P - \epsilon C_p U \cdot \Delta T + R = 0$	Heat budget
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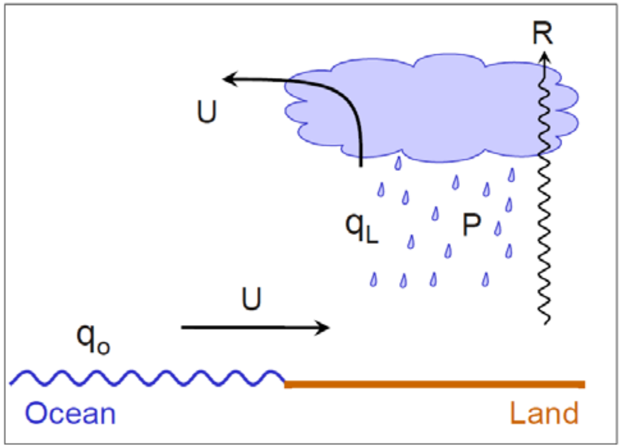
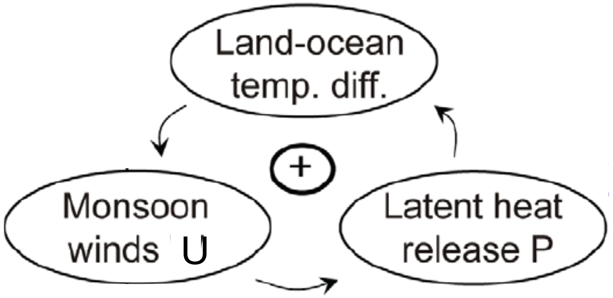


Minimal model of the monsoon season (stationary, highly aggregated, only includes most basic relations)



…incorporates self-amplifying 'moisture-advection feedback'

Minimal model of monsoon season

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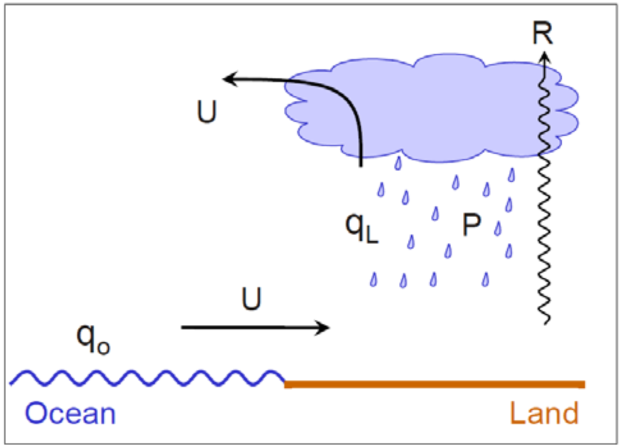

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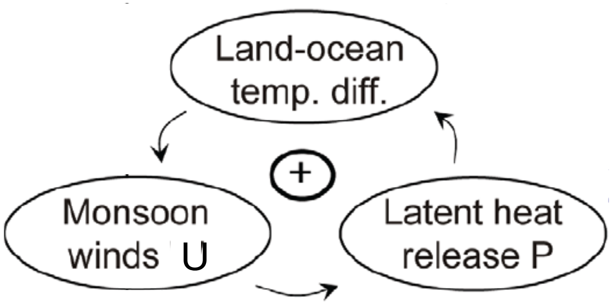


Substitute:

$$u \equiv U \epsilon \rho / \beta$$

$$r \equiv R \cdot \epsilon \alpha \rho / (C_p \beta^2)$$

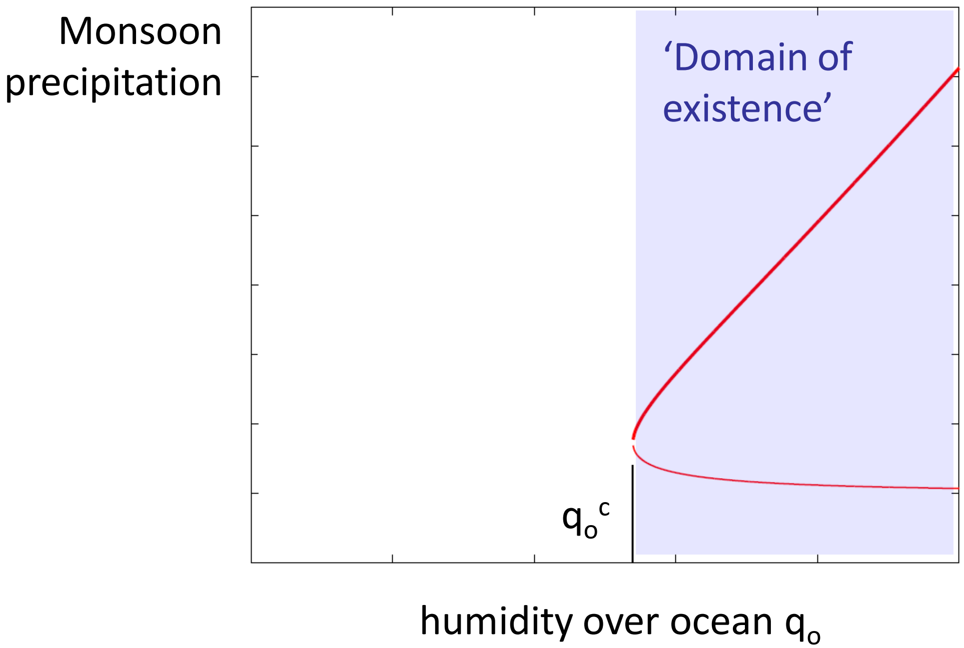
$$l \equiv (\epsilon \alpha \rho^2 \mathcal{L} q_o) / (C_p \beta)$$

Non-dimensional form:

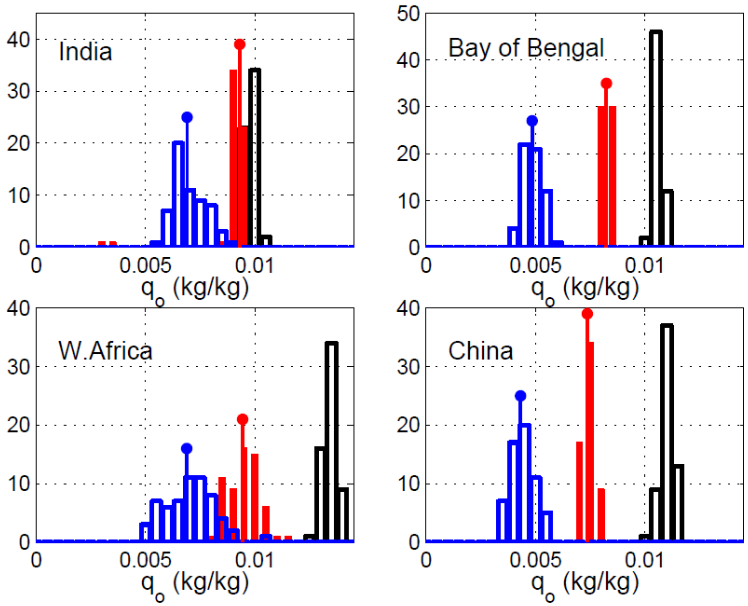
$$l = \left(1 + u^{-1}\right) \cdot u^2 - \left(1 + u^{-1}\right) \cdot r$$

Domain of existence for land monsoon rainfall

Due to positive feedback, model yields non-linear solution structure, including a threshold beyond which no solution exists.



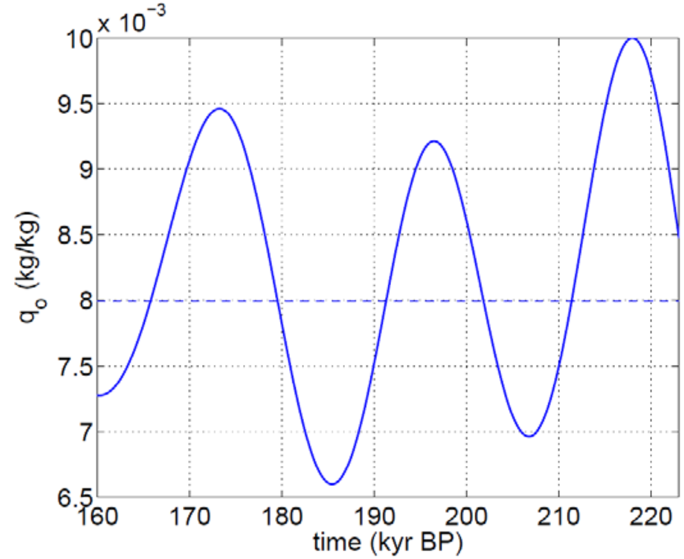
Estimate threshold q_o^c (based on present-day reanalysis data):

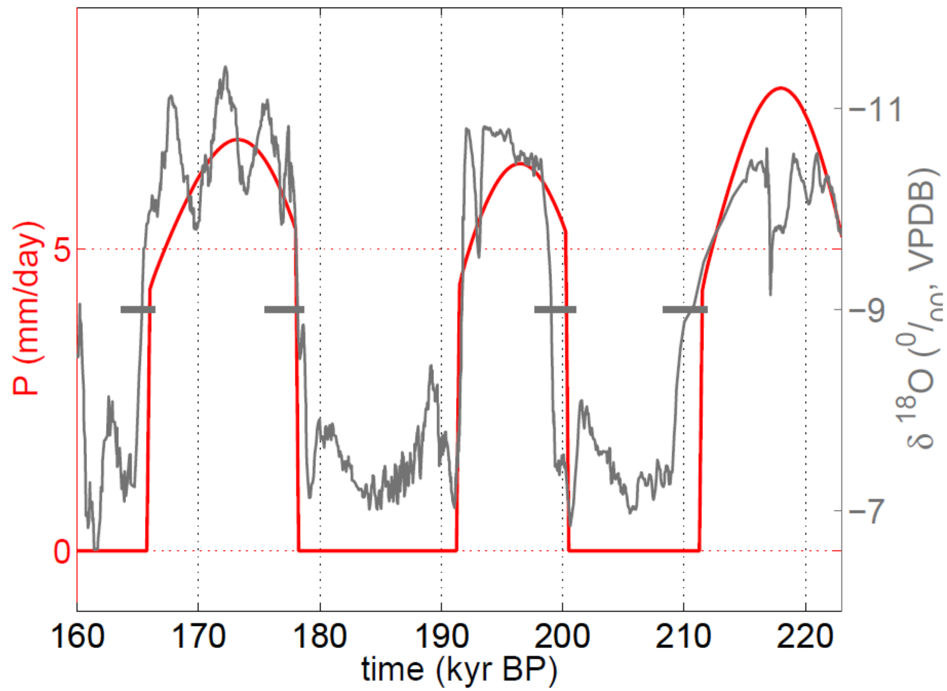


Below q_o^c, supply of moisture is not sufficient to balance radiative and advective heat losses

Reconstruct timing of abrupt transitions in East Asian summer monsoon

Scale q_o with Northern Hemisphere summer insolation (NHSI), such that q_o crosses the threshold q_o^c (Motivation: NHSI affects evaporation directly and/or indirectly, via surface temperature)





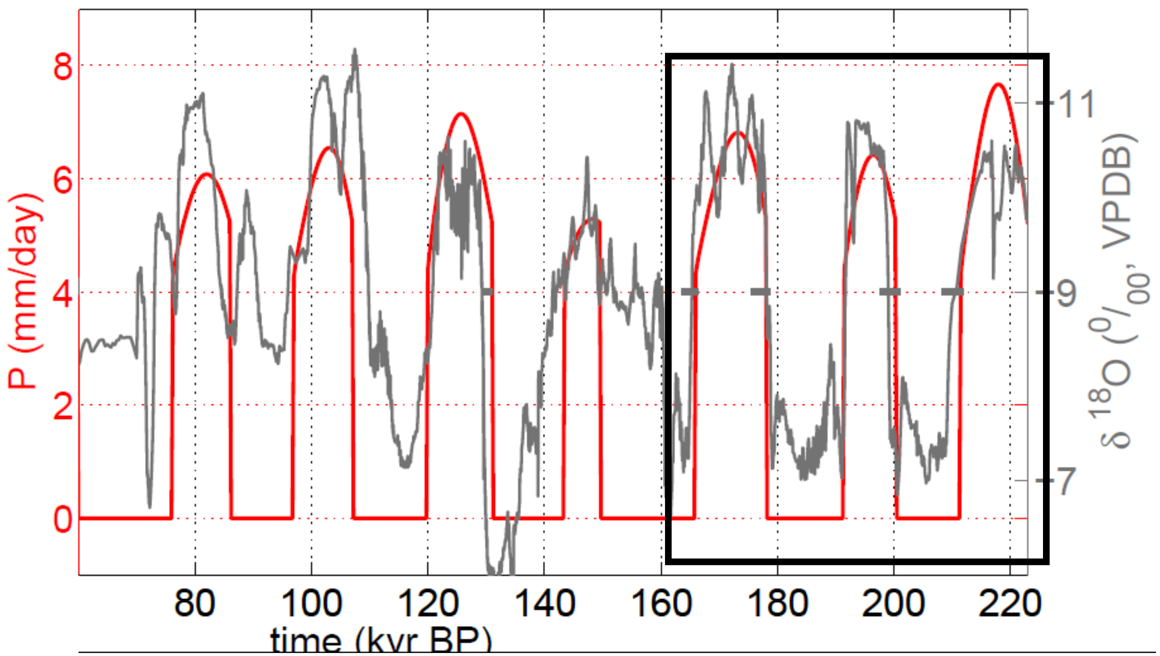
Assumptions:

- model parameters (e.g. α, β) remain unchanged throughout this period
- hysteresis behaviour when crossing threshold, e.g. due to ocean inertia (not fundamental, but improves timing)

Reconstruct timing of abrupt transitions in East Asian summer monsoon

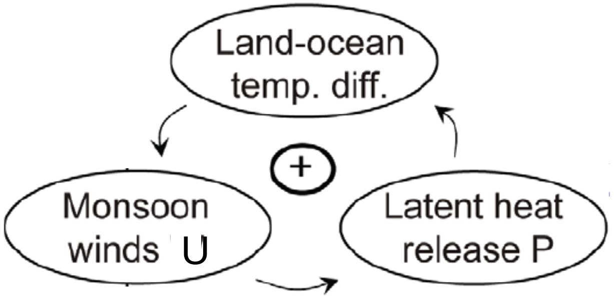
Timing of some later abrupt transition is also matched reasonably well, but generally, parameters may change on orbital timescales.

Refined and more informed estimation of model parameters for different periods could enhance applicability of the model



The seasonal timescale

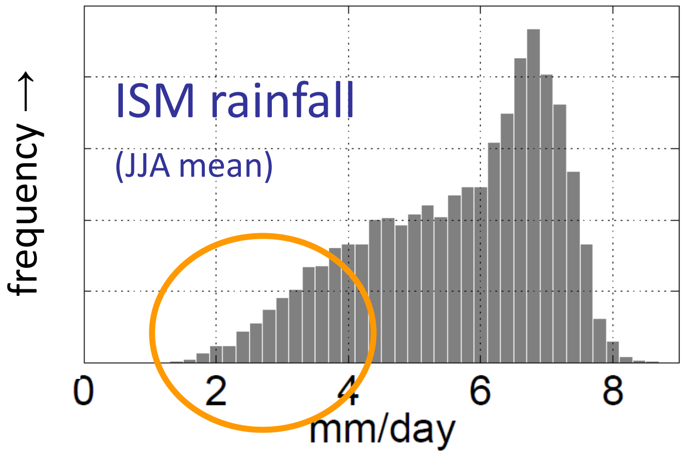
Moisture-advection feedback



On long timescales: Criterion of existence → Bistability

What about the seasonal timescale? Should the monsoon always be stable as long as the existence criterion is met?

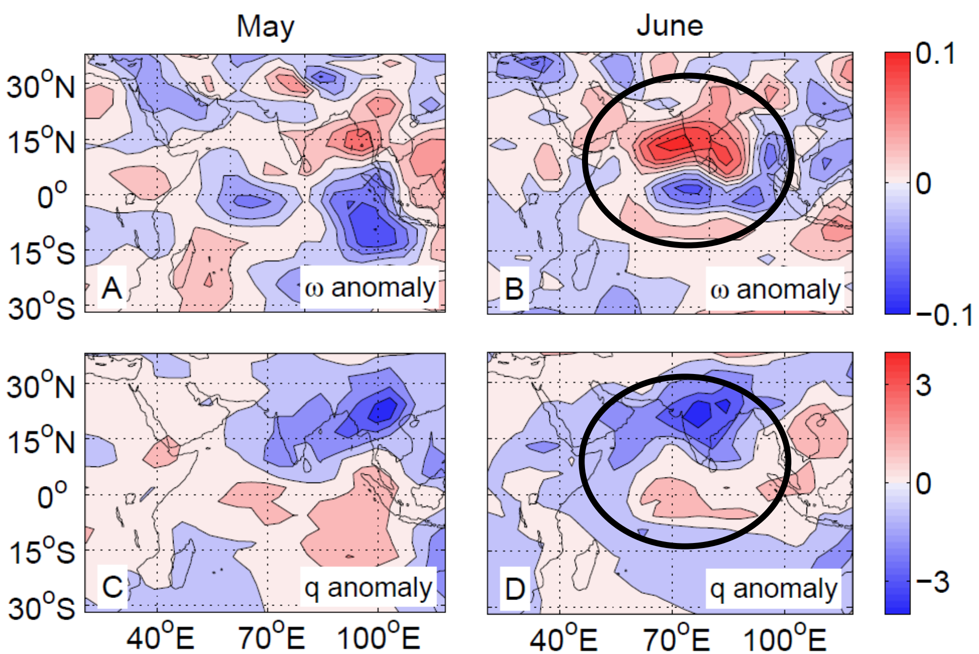
Indian summer monsoon in a millennial climate simulation (MPI-ESM): Includes very weak years even under stationary climate forcing



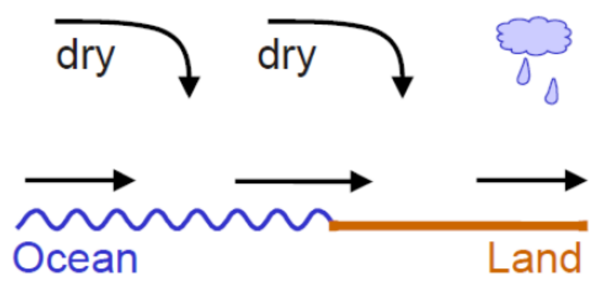
Schewe & Levermann (2012, subm.), ERL

The seasonal timescale

Typical weak year characterized by subsidence of upper-tropospheric air and associated moisture depletion of the monsoon winds



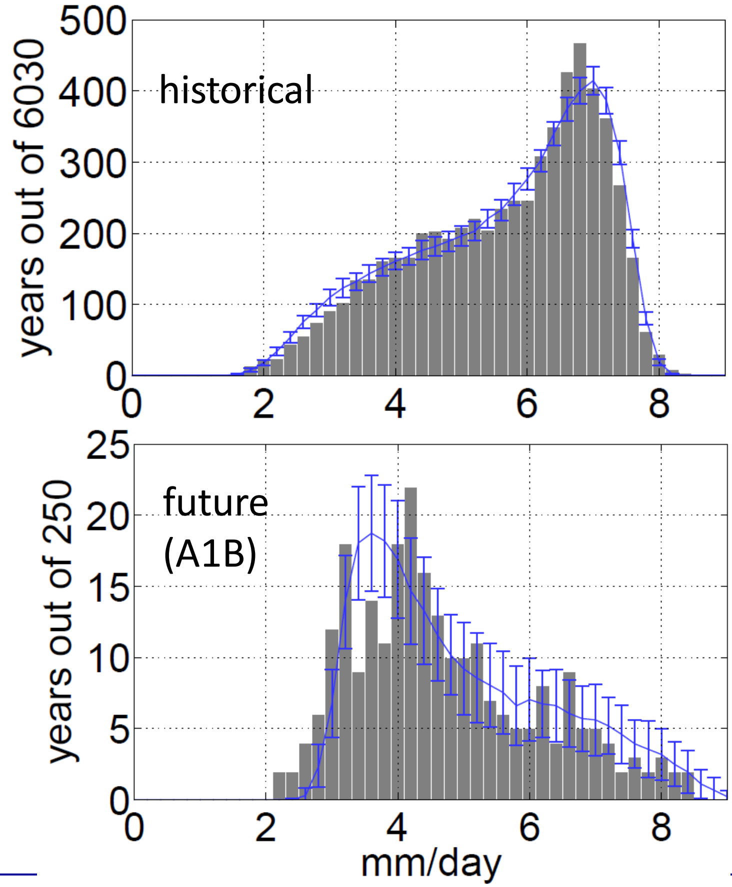
→ this dry state can also sustain itself



The seasonal timescale

Hypothesis: Monsoon season is governed by interplay between two opposing, self-amplifying feedback mechanisms.

Simple stochastic model built on this assumption can reproduce frequency distribution found in climate model.



Main parameter: Disposition at the onset time towards either the wet or the dry state – can depend on external influences (e.g. ENSO).

By varying this parameter, future distribution can be reproduced as well.

In this case, we use the mean state of the Walker circulation (weakens under global warming in the climate model) to determine the onset parameter; but other influences may enter, too, via this parameter.

Summary

- Central idea: Self-amplifying moisture-advection feedback is the fundamental driving mechanism of continental monsoon rainfall
- On long timescales, the resulting threshold defines domain of existence, offers explanation for abrupt transitions between different monsoon regimes
- Example: Timing of abrupt EASM transitions during penultimate glacial can be reproduced as response to slowly varying solar insolation

Reference:
J. Schewe, A. Levermann and H. Cheng, A critical humidity threshold for monsoon transitions, *Climate of the Past* 8 (2012), 535-544, DOI:10.5194/cp-8-535-2012.

- Within the season, internal variability (interplay between moisture-advection feedback and dry-subsidence feedback) largely determines seasonal average
- Simple stochastic model offers framework to connect, in a probabilistic way, ambient climate factors (Walker circulation, regional SSTs, Eurasian snow cover, …) to seasonal monsoon rainfall solely via their influence on the monsoon onset

Reference:
J. Schewe and A. Levermann, A statistically predictive model for future monsoon failure in India, *Env. Res. Lett.* (subm.)