

# Abrupt monsoon transitions as seen in paleorecords can be explained by moisture-advection feedback

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## Abrupt Monsoon Transitions Exist in Paleorecords and Pertinent Models

Paleoclimatic records show abrupt monsoon shifts at various different locations and historic periods (1–5). An important question is whether such transitions are possible in the future (6). To this end, we carved out the physical mechanism for such transitions in a purposefully simple conceptual model (7). Recently, Boos and Storelmo (8) claimed that introducing adiabatic cooling into our model (7) eliminates these abrupt transitions. This claim is not generally true. As can be seen from their figure 1, Boos and Storelmo (8) only eliminate abrupt transitions if most of the energy from the rain's latent heat release is consumed by adiabatic cooling. Although adiabatic cooling exists and is, as shown below, implicitly accounted for in ref. 7, it is not a valid assumption that most of the latent heat release is consumed by this process. By contrast, monsoon circulation is predominantly sustained by latent heat release, as shown in a number of studies (e.g., ref. 9) including figure 2 in ref. 7.

## Adiabatic Cooling Is Present in Our Model

Boos and Storelmo (8) used a very specific linearized representation of adiabatic cooling based on an approximation of the second horizontal derivative of temperature by a linear function of its first horizontal derivative, dividing velocity scale and length scale (their equations 1–3, S1, and S2). This approximation is crude. Here we show that our model (7) implicitly incorporates adiabatic cooling without eliminating the possibility of abrupt monsoon transitions as have been reported from paleorecords.

Our model (7) is based on the entropy equation

$$\rho \frac{ds}{dt} = \frac{Q_V}{T}, \quad [1]$$

with  $s = c_p \ln \vartheta$ ,  $c_p$ , and  $\vartheta$  being specific entropy, specific heat, and potential temperature of air, respectively.  $Q_V$  is the net heating rate per volume, and  $T$  is kinetic temperature. Vertical integration from Earth's surface to the tropopause,  $z_{tr}$ , and horizontally over the monsoon land region  $\Sigma$ , assuming quasi-stationarity,

continuity, and zero boundary conditions for vertical velocity at surface and tropopause, yields

$$c_p \int_{\Sigma} \left( \int_0^{z_{tr}} \nabla_H \cdot \rho \vartheta \vec{V}_H dz \right) d\sigma = \int_{\Sigma} \left( \int_0^{z_{tr}} \frac{\vartheta}{T} Q_{V,P} dz \right) d\sigma + \int_{\Sigma} \left( \int_0^{z_{tr}} \frac{\vartheta}{T} Q_{V,R} dz \right) d\sigma, \quad [2]$$

where  $H$  denotes the horizontal plane.  $Q_{V,P}$  and  $Q_{V,R}$  are the net heating rate per unit volume due to the condensation/precipitation and radiation, respectively. In our simple model, we neglected the sensible heat flux at the land surface. The precipitation heating is nonnegative and the radiation heating is nonpositive throughout the entire troposphere in the continental monsoon regions (10).

The deviation of the positive factor  $\vartheta/T$  from 1 quantifies the contribution of vertical motions to the atmospheric heat balance, i.e., in the adiabatic atmosphere ( $T = \vartheta$ ) vertical motions cannot contribute to the heat balance. Bringing  $\vartheta/T$  out of the integrals in Eq. 2, one obtains an equation with identical structure to equation 1 of ref. 7,

$$LPS_P - \varepsilon c_p W \Delta T + RS_R = 0, \quad [3]$$

where  $S_P$  and  $S_R$  are integral precipitation- and radiation-driven stability parameters. Using the same notation and definitions as in both models (7, 8), one then gets

$$W^3 + \frac{\beta}{\varepsilon p} W^2 - \frac{\alpha}{\varepsilon c_p} (LS_P \beta q_0 + RS_R) W - \frac{\alpha \beta}{\varepsilon^2 \rho c_p} RS_R = 0, \quad [4]$$

which has the same general structure as the governing equation 5 in ref. 7 showing the same abrupt transitions.

As a consequence, the threshold behavior is not eliminated by adiabatic cooling unless it consumes practically all of the energy of the latent heat release. However, the latter assumption is supported neither by record nor by theory.

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