Author response to interactive comment on
"A critical humidity threshold for monsoon transitions"
by J. Schewe, A. Levermann, H. Cheng

We thank the referee for the constructive and helpful comments. Please find below the referee's comments, quoted in *italic,* and our corresponding response.

Anonymous Referee #1

1) Even though the concepts discussed in the paper are interesting, the model is too simplistic to pretend to explain the monsoon transitions. First the simplistic model is only valid when the monsoon is developed and the assumption can be made that the latent heat release by condensation in the atmosphere is the major driver of the atmospheric circulation. In that case it sounds obvious that once the assumption is made that the only moisture source on the continent is moisture advection, critical moisture over the ocean is needed to provide enough moisture for condensation over the continent.

First, we would like to apologize that we have not sufficiently discussed the purpose and scope of the minimal model in the manuscript. It is not meant as a full representation of large-scale monsoon dynamics, capable of closely reproducing all observed trends in monsoon precipitation. In fact, it does not include any time-dependence. Rather, it defines a domain of existence for continental monsoon rainfall. If the moisture-advection feedback is indeed the dominant driver of conventional, seasonal-length monsoon conditions (which our analysis indicates), then such conditions can only occur if summer q_o lies within the domain described by the minimal model. The fact that the lower limit of this domain is associated with a nonzero precipitation level (i.e., that the transition between a state with conventional monsoon and one without is not smooth), is not trivial, especially as it is independent of whether an offset q_L^0 for the initiation of precipitation is considered in equation (4) or not. These facts are why the mechanism we suggest could be a candidate for explaining some of the abrupt monsoon variability seen in the paleo-record.

We will discuss this point more clearly in a revised version of the manuscript and also make clearer than in the present manuscript that we are not presenting a full-fledged, time-dependent model of the monsoon circulation, but rather provide energy and moisture balance considerations which evaluate the domains of existence of continental monsoon precipitation. The aim of the study is to identify the domains of existence with respect to a relevant external quantity (q_o) , and to demonstrate that this concept is applicable to the interpretation of monsoon paleo-records.

2) The interesting point in this paper is that the author quantified the moisture amount through a calibration on the NCEP/NCAR reanalysis. In the same way a minimum wind or temperature gradient could be estimated and discussed.

We are glad that the reviewer appreciates our estimates. Indeed, through the equations of the minimal model, the critical threshold in q_o is directly associated with a critical wind strength and a critical temperature difference. However, in the sense of the model, the latter two are

internal quantities that are ultimately determined by the amount of energy provided to the system by the external processes of latent heat advection (associated with q_o) and radiation (R): Wind strength simply follows the atmospheric temperature difference (eq. 2); and *within the monsoon season* (i.e. after the onset time that is characterized by significant sensible heating, cf. Fig. 2), the atmospheric temperature difference, in turn, is governed by latent heating and radiative cooling (eq. 2). When trying to assess possible external controls on monsoon existence, it is therefore more meaningful to estimate the critical values in R (see Levermann et al., 2009) or the more volatile q_o.

3) The values found are not fully discussed. In particular, the threshold humidity should be linked to evaporation over the ocean, considering the implication for temperature, wind, and atmospheric boundary layers over the tropical ocean and the fact that the relative humidity remains almost the same whatever the period? What are the conditions when the threshold is reached?

We regret that we have problems to understand the referee's remark here, but would be glad to provide the required information, if these could be specified a little further. Perhaps our reply to comment no. 10 below, related to evaporation and humidity, is already somewhat helpful.

4) The effect of a minimum humidity should be compared to other possible sources such as minimum wind of temperature gradient. Is the gradient (change in wind) or humidity more efficient in changing the amount of water vapour available for convection? Also this process should be put into perspective compared to the large scale gradients that trigger monsoon onset and decay.

From our point of view, the first question cannot be answered in a meaningful way within the framework of this study, because these quantities play fundamentally different roles. The humidity over ocean, q_o, is an external property which can be influenced e.g. by solar insolation over the ocean or by oceanic processes, i.e. processes that are not part of the core monsoon dynamics as represented in our analysis. On the other hand, wind W and temperature difference ΔT are internal properties that *adjust* to changes in q_o (and also R). Note that ΔT is the atmospheric temperature difference within the monsoon season; not the surface gradient that develops due to differential surface heating in spring and helps trigger the monsoon onset. Perhaps one could also imagine conditions in which the springtime surface gradient is not sufficient anymore to trigger the continental monsoon. Studying this would require a different theoretical setup in which the onset period is captured. Here, we take the development of a strong surface temperature gradient during springtime as a given, and focus on the conditions needed to sustain the resulting atmospheric temperature gradient throughout the monsoon season, even after sensible heating from the surface has become small (cf. Fig. 2). That means that outside of the domain of existence defined by our energy and moisture balance equations, the springtime surface temperature gradient could still trigger the onset of monsoon winds over the continent, but monsoon conditions could not be sustained throughout the summer due to the lack of moist inflow and latent heating.

We thank the reviewer for raising these questions, and we will take care to improve the discussion of these issues in the manuscript.

5) I am not convinced by some of the choices made for the model itself. In particular, the temperature gradient considered here is not the one that drives the large scale circulation and the monsoon advection.

We consider the regional-scale temperature differences between the land monsoon regions and the adjacent, upwind ocean regions. Since near to the equator winds are mainly ageostrophic, we find it sensible to align the temperature difference with the wind direction. As a measure of the continental-scale monsoon circulation, one might also be inclined to choose temperature differences across larger distances, e.g. in the case of India, between the centers of the Eurasian low and the Indian Ocean high pressure systems. However, we are primarily interested in the land regions that normally receive rainfall and in the portion of the monsoonal wind flow that actually delivers major amounts of moisture to those regions. We believe that this regional, ocean-to-land flow must adhere to the corresponding regional temperature gradient; and that the regional temperature gradient, in turn, is the one modified by changes e.g. in latent heating due to regional monsoon precipitation.

6) Further justification should be provided for the choices of the different boxes considered for the different monsoon systems. In particular, what motivated the choice of the boxes for Africa? The Gulf of Gulf of Guinea would be more appropriate.

We thank the reviewer for bringing this point to our attention. In fact, according to NCEP reanalysis data, the West African monsoon is supplied by moisture inflow of comparable magnitude both from the Gulf of Guinea (cross-equatorial, southerly winds), and from the central Atlantic ocean (westerly winds; for illustration, see attached Fig. S1). Therefore, our previous analysis which only takes into account the westerly inflow is somewhat incomplete.

Moreover, the lower, landward branch of the monsoon circulation is also shallower in Africa (approx. 900-1000hPa) than in the other major monsoon regions (approx. 500-1000hPa). Our previous analysis considered winds and q_o averaged over a larger vertical extent and therefore picked up part of the outflowing branch of the circulation.

We regret this inaccuracy, and have repeated the analysis taking into account the more complex situation in the African monsoon region as found in the NCEP reanalysis. We have combined the moisture inflow from the west and from the south into single, area-weighted averages of wind and q_o. This is possible because the westerlies that bring in moisture from the central Atlantic are an extension of the cross-equatorial monsoon flow and also scale with the same north-south (land-ocean) atmospheric temperature difference as the equatorial southerlies.

The refined analysis results in a better correlation between wind and ΔT (revised Fig. 3, attached). It also yields a lower slope α of the wind-ΔT-relation, which allows for a more realistic choice of ε in the computation of q_o^c (revised Table 1, attached). The resulting, new estimate of q_o^c is shown in revised Fig. 9 (attached).

7) Notation should also be revised since there is an ambiguity with the use of W for wind. In

most papers it is the vertical velocity.

We will revise the notation in a revised version of the manuscript, e.g. using "U" instead of "W", and "u" instead of "w" (as already done in the revised figure 3, attached).

8) Error bars should be provided for the estimates and used to provide an error bar (or envelop for P) in figure 10.

The uncertainty associated with the estimate of q_o^c, as represented by the spread in the distribution (fig. 9), is discussed in sections 4 and 6. The influence on the quantitative results of the radiative parameter *r* is shown in Fig. 11. We are aware that our quantitative estimates are subject to large uncertainties; besides the intentional simplicity of the model, this is e.g. due to the fact that model parameters are constrained by a relatively small set of reanalysis data, or hardly constrained at all (in the case of ε). Relating to our comments above, the main idea behind the study is not to validate our choice of parameters by reproducing the complete paleo-record; it is rather to show that our simple model setup, together with a realistic (albeit not unambiguous) set of parameters yields a series of abrupt transitions that is consistent with those found in the record, and that it therefore could help understanding how such transitions can occur.

We are therefore not entirely confident whether a more detailed propagation and representation of quantitative uncertainties (e.g. in the parameters α and β) would be of advantage to conveying the main points of the paper; but we are ready to add this if the referee and editor recommend that.

9) The application is a poor part in the paper. We do not understand why the example is only considered for one region and one record. The record is only shown between 160 and 220 kyr, because it seems to be the period during which the conceptual model has some skill. The results should be shown for the entire record. Otherwise there is absolutely no credibility in the results, and we have the feeling that the authors get something that fits the data only by chance. If it doesn't work for the other periods there is a need to discuss it, at the light of the hypotheses made.

Once again, we apologize for the insufficient explanation in the manuscript of the scope of the application. Our intention is not to reproduce the full timeseries of observed rainfall variation, but to propose a possible explanation for a feature of the record that is difficult to explain otherwise: Namely, the abruptness of the changes in rainfall amount at different points in the record. From the speleothem record (e.g. Fig. 1 in Wang et al., 2008) it is evident that the ups and downs in rainfall amount (as measured by delta18O data) largely follow the NHSI. However, the transitions between high and low rainfall occur much more rapidly than the NHSI variations. Our paper shows that the concept of a domain of existence for continental monsoon rainfall can explain this feature of the record – while it cannot account for many other characteristics of the record, like smaller-scale rainfall variations in between the transitions. Also, as the reviewer correctly points out, the conceptual model would obviously yield much worse results if applied to other parts of the record (e.g. within the last glacial cycle) *with the same set of parameters* that we used for the period 220-160 kyr BP. We do not expect these parameters to remain unchanged across two glacial cycles. However, we do not

have enough information to assess the parameter changes that might have occurred during this time. We therefore focus on a period where the variations in NHSI have an approximately constant amplitude and where the two monsoon regimes correspond to approximately constant rainfall amounts. This gives us some confidence that the parameters might not have changed too much during this period, and we estimate the parameters from present-day observations (NCEP reanalysis) and tune the model to best match the period 220-160 kyr BP with this parameter set. Certainly, in order to evaluate the conceptual model for the entire period of the record, a more thorough parameter estimation would be needed that takes into account changes in background climate across the last two glacial cycles that could have modified the parameters; moreover, there will still be other physical processes that are important in shaping the record apart from the simple first-order dynamics represented in our model. In the present paper, we merely aim to introduce the concept of a domain of existence for continental monsoon rainfall and show that it can be successfully applied to a real-world data set.

We will improve the related explanations in a revised version of the manuscript.

10) Also the assumption is made that humidity other the ocean varies linearly with insolation at 65°N. This is only valid if the 65°N insolation considered represents well an annual mean change in global forcing that can be linked to temperature and atmospheric moisture content. However, the insolation forcing has a negligible signature in annual mean, so that this assumption doesn't hold.

Latent heating of the continental atmosphere is required to maintain the atmospheric land-ocean temperature difference during the monsoon season, i.e. broadly during June-September. The atmospheric moisture that supplies the latent heat to the EASM region is collected mainly over the tropical Indian and Western Pacific oceans in the northern hemisphere. We therefore believe that it is sensible to use Northern Hemisphere Summer Insolation (NHSI) rather than a global, annual average. Wang et al. (2008) show that the 65°N insolation matches well the timing of the monsoon cycles; insolation changes at lower northern latitudes, i.e. closer to the EASM region, are very similar with regard to the timing of maxima and minima.

In our study, we do not employ a climate model, and do not aim to explore in detail the mechanisms that translate insolation changes into changes in atmospheric moisture content. However, we suggest that q_o changes on the relevant time scales are governed mainly by changes in ocean surface temperature (SST); rather than by changes in regional air temperatures, which would be expected to relate directly to regional insolation changes. q_o depends on the evaporation rate E from the ocean surface, which itself is

$$E \sim u \, (q_s - q_o)$$

where u is the wind speed, and q_s is the specific humidity at the sea surface. In equilibrium, q_s depends solely on the SST, not on the air temperature aloft.

SST can be affected on long timescales both directly by local/regional insolation changes and by changes in oceanic circulation, coastal upwelling etc., which in turn can be caused, in one way or the other, by the larger-scale redistribution of heat due to insolation changes. What we

offer in our study is, from this viewpoint, a possible mechanism to link regional SST changes to abrupt monsoon changes. We believe that using the insolation timeseries as a first-order proxy for SST is reasonable for demonstrating the applicability of this mechanism, as intended in this study. Of course, a more detailed analysis using regional SST reconstructions, if available, would be a very desirable next step.

We will discuss this in a revised version of the manuscript.

11) Simulation with general circulation in response to changes enhanced boreal summer insolation in the northern hemisphere show that the tropical ocean is colder, and evaporation is reduced over the ocean. Moisture increases over land because inland advection increases. The net result is a decreased humidity over the Tropical Ocean and increased humidity over land. It is not obvious to me to reconcile this result with the one proposed using the simple model described here.

Increased humidity over the land monsoon region in response to enhanced NHSI seems to be ultimately the same assumption that we make in our manuscript, so the contradiction would lie in the mechanism (evaporation and advection) by which this response is caused. However, since we do not know which study the referee is referring to here, we regret that we are unable to assess or discuss this alleged contradiction. We would be glad to discuss it if more context could be given.

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November 2011
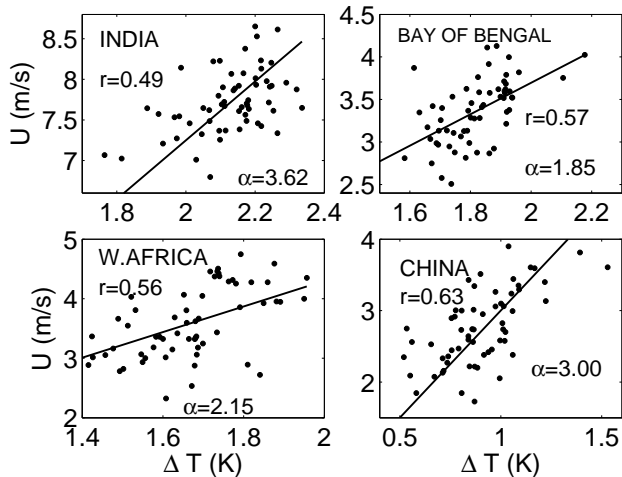
Fig. 3. Wind U versus temperature difference between land and ocean region, ΔT, from NCEP/NCAR reanalysis data, for the major monsoon regions of India, the Bay of Bengal, West Africa, and China (East Asia; see Table 1). The correlation coefficient r is indicated, as well as the slope α of a linear fit through the origin (black line).
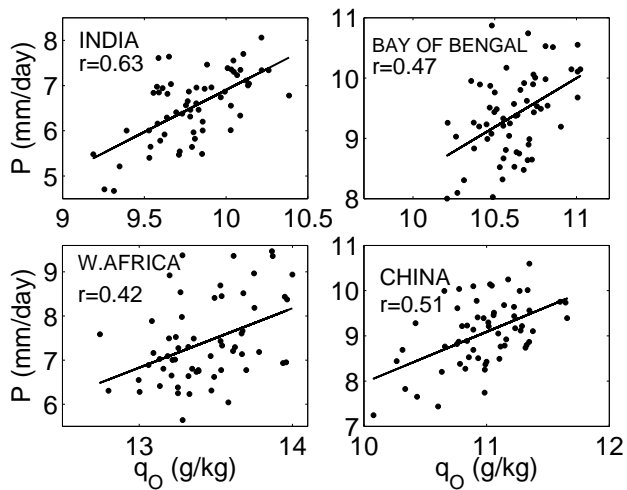
Fig. 8. Correlation between precipitation and specific humidity over the ocean from NCEP/NCAR reanalysis data. Black lines show the result of a linear regression, the correlation coefficients are indicated.
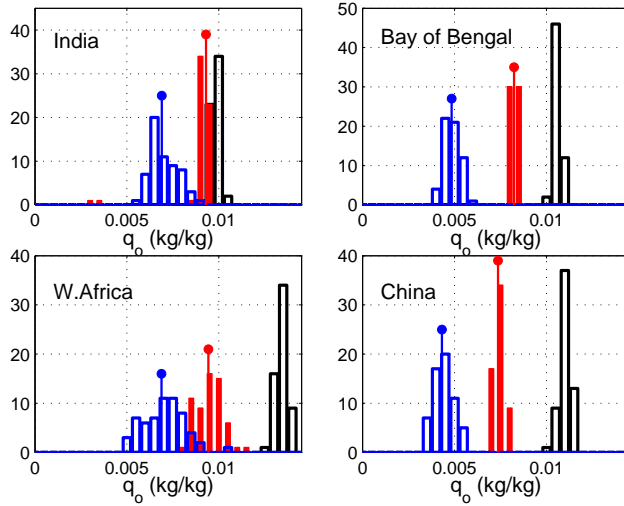
Fig. 9. Estimate of critical specific humidity value over the ocean, q_o^c, from NCEP/NCAR reanalysis data for the basic minimal model (blue) and including the effect of a minimum terrestrial humidity q_L^o required for the onset of precipitation (red). The black histogram shows the observed distribution of q_o. Pins mark the estimates obtained from time–mean parameter values.

Table 1. Regional definitions used for data analysis. Monthly–mean NCEP/NCAR reanalysis data has been averaged over the indicated regions and seasons; *Land* and *Ocean* indicate that only terrestrial or oceanic grid points have been considered, respectively; and $\Delta T = T_L - T_o$. The bottom row lists the values for the dimensionless parameter ϵ that have been used in the estimation of the critical threshold (see section 4).

| Quantity	INDIA	B. O. BENGAL	W.AFRICA	CHINA (EASM)
P, R, q_L (*Land*)	70-90°E	80-100°E	15°W-10°E	100-120°E
	5-30°N	15-30°N	2-14°N	20-32°N
q_o (*Ocean*)	65-78°E	80-100°E	20-15°W, 2-14°N;	105-115°E
	5-30°N	10-20°N	5°W-10°E, 2°S-7°N	15-25°N
T_L (*Land*)	70-90°E	80-100°E	10°W-10°E	100-120°E
	5-30°N	15-30°N	0-20°N	20-32°N
T_o (*Ocean*)	65-78°E	80-100°E	10°W-10°E	105-115°E
	5-30°N	10-20°N	10°S-5°N	15-25°N
U (westerly)	65-78°E	80-100°E	20-10°W	
	5-30°N	15-30°N	5-14°N	
U (southerly)			5°W-10°E	100-120°E
			2°S-5°N	20-32°N
Monsoon season	June–Aug.	June–Aug.	July–Sep.	June–Aug.
ϵ	$4.5 \cdot 10^{-3}$	$2.3 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	$6.7 \cdot 10^{-2}$
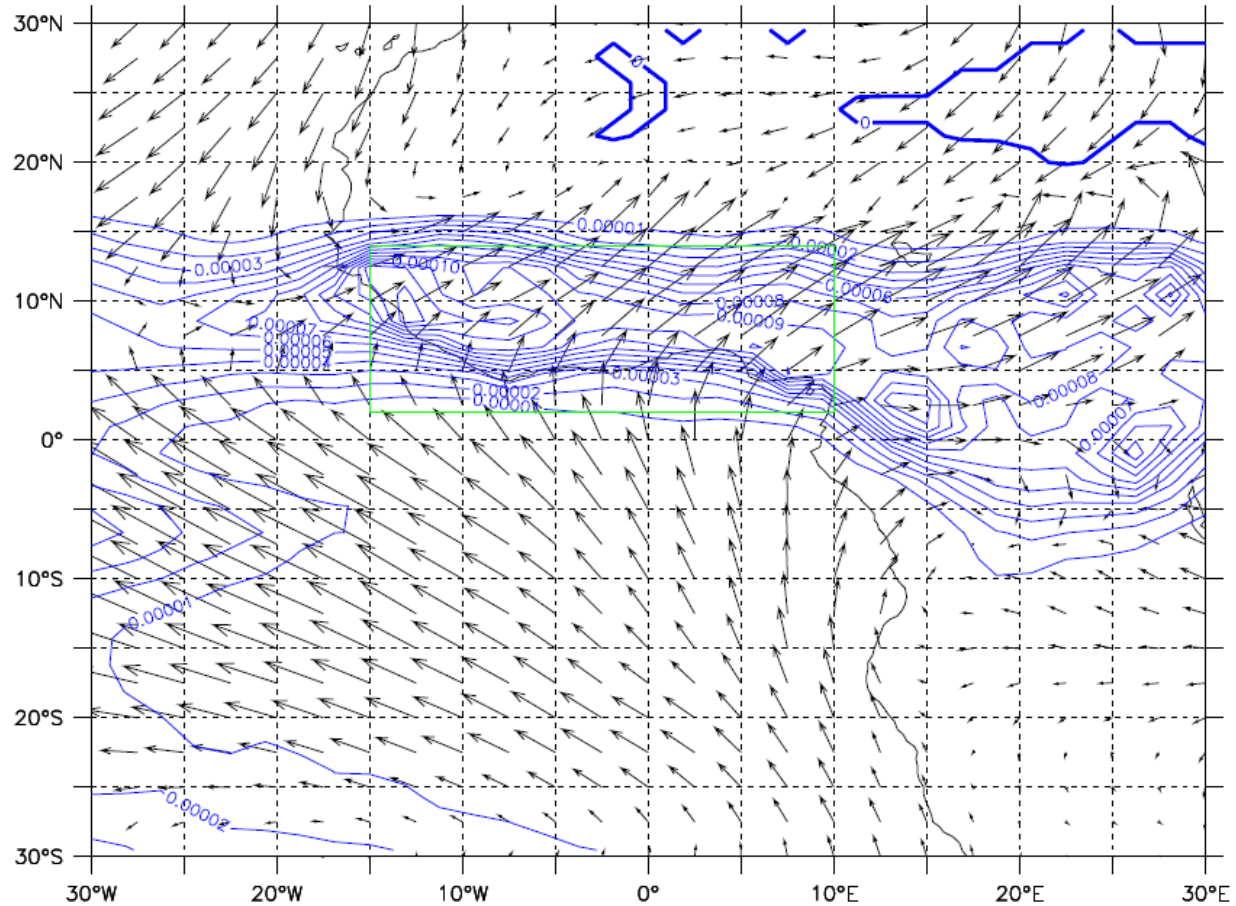
Figure S1 (for illustration only): Atmospheric moisture transport (900-1000hPa, vectors) and precipitation during summer (JJA), from NCEP reanalysis. The West African monsoon region defined in the manuscript is marked by the green box.