GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L15707, doi:10.1029/2005GL022771, 2005

Is the Indian summer monsoon stable against global change?

K. Zickfeld and B. Knopf

Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

V. Petoukhov

Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

Oboukhov Institute for Atmospheric Physics, Moscow, Russia

H. J. Schellnhuber

Tyndall Centre for Climate Change Research, Norwich, UK

Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

Received 23 February 2005; revised 6 June 2005; accepted 8 July 2005; published 9 August 2005.

[1] The stability of the Indian summer monsoon is investigated by means of a box model of the tropical atmosphere. At the heart of this model is the moisture-advection feedback which allows for the existence of two stable regimes: besides the "wet" summer monsoon, a stable state exists which is characterized by low precipitation. The model is employed for the identification of changes in the qualitative systems behavior in response to changes in boundary conditions. The most notable result is the occurrence of saddle-node bifurcations against changes in those quantities which govern the heat balance of the system, i.e., the planetary albedo, the insolation, and the CO_2 concentration. These findings are remarkable insofar as they indicate that anthropogenic perturbations of the planetary albedo, such as sulphur emissions and/or land-use changes, or natural variations in insolation and CO_2 concentration could trigger abrupt transitions between different monsoon regimes. **Citation:** Zickfeld, K., B. Knopf, V. Petoukhov, and H. J. Schellnhuber (2005), Is the Indian summer monsoon stable against global change?, *Geophys. Res. Lett.*, *32*, L15707, doi:10.1029/2005GL022771.

1. Introduction

[2] Palaeoclimatic records indicate that the Indian summer monsoon (ISM) has undergone a number of abrupt changes, both during the last glacial period [*Burns et al.*, 2003] and the Holocene [*Gupta et al.*, 2003]. Whether these events result from threshold crossing in response to smooth changes in forcing such as insolation, or are induced via teleconnections with other parts of the climate system, e.g. the North Atlantic, is still unresolved. The palaeoclimatic evidence also raises the question whether anthropogenic disturbances of the Earth System, such as emissions of greenhouse gases (GHGs) and aerosols or land-cover changes, could lead to abrupt transitions of the ISM in the future. This is of great interest as nonlinear monsoon changes induced on short time-scales (years to decades) would possibly transcend the adaptive capabilities of the people living in the rural areas of India. Studies with general circulation models (GCMs) investigating the response of the ISM to increased concentrations of GHGs and sulphate aerosols [*Meehl and Washington*, 1993; *Lal et al.*, 1995; *Hu et al.*, 2000; *May*, 2002] were so far not able to provide a clear answer.

[3] In this paper, we discuss a physical mechanism by which natural or anthropogenic perturbations of the Earth System (such as emissions of GHGs and scattering aerosols, insolation changes and land-cover transformation) could induce discontinuous responses of the ISM. At the heart of this mechanism is the moisture-advection feedback [*Webster et al.*, 1998] whereby the land-to-ocean pressure gradient, which drives the monsoon circulation, is reinforced by the moisture the monsoon itself carries from the adjacent Indian Ocean. As a consequence of this feedback, the ISM can operate in two stable states: one with strong and another one with weak precipitation over India. This suggests that any perturbation of the radiative budget over the sub-continent which tends to weaken the driving pressure gradient has the potential to destabilize the summer monsoon circulation.

[4] We capture this mechanism by means of a reduced-form model of the Indian monsoon which includes representations of the radiative and surface fluxes, the hydrological cycle and the surface hydrology (section 2). We employ this model in a way that is alternative to conventional scenario studies: Bifurcation analysis which allows us to systematically explore the potential for qualitative transitions in the system's dynamics against changes in parameters and boundary conditions (section 3). We show, in particular, that perturbations of the planetary albedo, such as sulphur emissions and/or land-use changes or changes in insolation and CO_2 concentrations, can spin down the summer monsoon circulation and trigger a transition to a state characterized by a much weaker hydrological cycle. These findings are relevant in the context of global environmental change as well as from a palaeoclimatic perspective (section 4).

2. Model Description

[5] The Indian monsoon is simulated through a one-dimensional model of the tropical atmosphere [*Zickfeld*, 2003]. This model reflects an idealized setting: a four-

0094-8276/05/2005GL022771$05.00

sided atmospheric box centered over India and delimited by the Indian Ocean at its boundaries. In the vertical, the atmosphere is represented by three layers: the planetary boundary layer (PBL) with the surface layer as its lowest stratum, the free troposphere, and the stratosphere. The underlying land compartment is represented by two soil layers. The state variables in the model are the near-surface air temperature and the specific humidity, denoted by T_a and q_a, respectively, and the soil moisture in two layers, w_1 and w_2. From these, all other variables (e.g., net longwave radiation, precipitation, evapotranspiration, surface wind) are diagnosed. Inside the box, the variables are described in terms of their spatial averages. The only meridional and zonal gradients are those between the box interior (i.e., the Indian sub-continent) and its boundaries, whose climatic conditions are externally prescribed. The associated temperature gradients drive the annual evolution of the local monsoon circulation. For the sake of simplicity, the large-scale circulation patterns such as the Hadley circulation and the zonal wind, which also influence the climate of India, are neglected. Experiments with a more comprehensive model version have shown that this simplification does not alter the qualitative systems dynamics which is the focus of the present study [cf. *Zickfeld*, 2003].

[6] The temporal evolution of the system is computed from the respective balance equations for heat, water vapor and soil water content. The heat balance equation for the combined surface-plus-atmosphere system reads:

$$\int_0^{H_a} c_p \, \rho \frac{\partial \theta}{\partial t} \, dz + h_s c_s \frac{\partial T_s}{\partial t} = F_{\downarrow}^{SL,TA}\left(1 - A_{sys}\right) + - F_{\uparrow}^{LW,TA} + A_T + \mathcal{L}(C - E), \qquad (1)$$

where θ is the potential temperature and T_s the surface temperature.

[7] The first term on the right hand side of (1) is the incident solar radiation at the top of the atmosphere, modified by the planetary albedo A_{sys}. This term is a function of the insolation I_0, the mean solar zenith angle ξ, the cloudiness and the albedo of the clouds and the surface. The term $F_{\uparrow}^{LW,TA}$, the net outgoing longwave radiation at the top of the atmosphere, is treated according to *Budyko* [1982] as a function of the surface air temperature, the cloudiness, and the CO_2 concentration in the atmosphere. The advective term in (1), A_T, is described in accordance with *Petoukhov et al.* [2000] as the vertical integral of the advective sensible heat flux due to the horizontal monsoon circulation velocity, the latter being calculated explicitly as a function of the land-sea pressure gradient. The condensation rate C is set equal to precipitation which is discussed below. The evapotranspiration E is described in the bulk transfer approach [*Hansen et al.*, 1986]. Further, H_a denotes the height of the atmosphere, $\rho = \rho(z)$ the air density, c_p the specific heat of air at constant pressure, h_s the depth of the upper soil layer and c_s the heat capacity per unit soil volume which increases along with the water content of the soil. $\mathcal{L}$ refers to the latent heat of evaporation.

[8] In order to reduce the dimensionality of the system, we shall assume $\partial T_s/\partial t \approx \partial T_a/\partial t$. This assumption has proven to influence the model behavior only marginally.

[9] The vertically integrated water balance equation is given by the expression:

$$\int_0^{H_a} \rho \frac{\partial q}{\partial t} \, dz = E - C + A_v, \qquad (2)$$

where $q = q(z)$ denotes the vertical profile of specific humidity and A_v the horizontal advection of moisture. The latter is computed similarly to A_T.

[10] The soil moisture, which determines evapotranspiration, is described explicitly according to a two-layer model [*Hansen et al.*, 1986]. The rates of change of moisture in the two soil layers are:

$$\frac{\partial w_1}{\partial t} = \frac{P - E - R}{f_1} - \frac{w_1 - w_2}{\tau}, \qquad (3)$$

$$\frac{\partial w_2}{\partial t} = \frac{f_1}{f_2} \frac{w_1 - w_2}{\tau}, \qquad (4)$$

where the wetness of the ith layer, w_i, is the ratio of available water to field capacity f_i. The precipitation P is described in accordance with *Petoukhov et al.* [2000] as a function of the vertically integrated specific humidity and cloudiness. The surface runoff R is assumed proportional to precipitation and water content of the upper soil layer [*Hansen et al.*, 1986]. τ denotes the time constant for diffusion of moisture between the two layers.

[11] The vertical profiles of temperature and humidity, $T(z)$ and $q(z)$, are parameterized in terms of the values at the surface, T_a and q_a, respectively. For T we assume a linear profile, while q is assumed to decrease exponentially with height (for a justification of this approach cf. *Petoukhov et al.* [2000]).

[12] The detailed model equations as well as the values of the model parameters are given by *Zickfeld* [2003]. Despite its high degree of idealization, the model satisfactorily captures relevant aspects of the observed monsoon dynamics, such as the annual course of precipitation averaged over India and the onset and withdrawal of the summer monsoon [cf. *Zickfeld*, 2003].

3. Bifurcation Analysis

[13] We employ the model described in the previous section for the exploration of bifurcations in the dynamics of the Indian monsoon against changes in parameters and boundary conditions. We devote particular attention to those quantities which (i) determine the radiative budget of the system and therefore play a crucial role in the destabilizing mechanism described in section 1, (ii) are influenced by human activities (e.g., emissions of GHGs and sulphur dioxide, land-cover changes) or subject to natural variability (e.g., insolation changes). These quantities therefore include the CO_2 concentration and the planetary albedo (i.e., the ratio of reflected to incoming solar radiation) at the top of the atmosphere. The latter is a function of the albedo of the land surface (and hence of vegetation type and fraction) and of the albedo of the cloudy and clear-sky atmosphere (and hence of the atmospheric opacity, the type and amount of clouds, and the optical cloud properties). The planetary

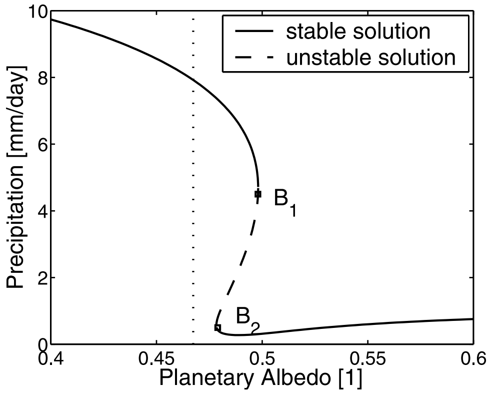

Figure 1. Bifurcation diagram of Indian summer precipitation against the planetary albedo. The B_1, B_2 mark the saddle-node bifurcations. The vertical dotted line indicates the present-day state.

albedo can be influenced by human activity through changes in the atmospheric load of sulphate aerosols (which are associated with the back-scattering of solar radiation and the alteration of optical cloud properties) and land-cover conversion. It should be noted that in the general formulation of the model the planetary albedo is a function of vegetation fraction and cloudiness. Given, however, that in the simplified version of the model used for this analysis these quantities are prescribed, the planetary albedo can be treated as a parameter.

[14] We focus our discussion on summer precipitation, as qualitative changes in this variable would most strongly affect India's agriculture and socio-economy. We wish to emphasize that because of the number of simplifying assumptions made in the model, our focus is on the qualitative aspects rather than on the quantitative values.

[15] The analysis is carried out with the bifurcation software AUTO [*Doedel*, 1981]. The steady-state solutions of the system and their linear stability are determined and tracked against the actual bifurcation parameter. Under present-day summer conditions two equilibrium solutions exist: one stable and the other unstable. The unstable solution is associated with negative values of soil moisture and humidity and is therefore unphysical.

[16] Figure 1 displays the physically meaningful steady-state solution against one of the bifurcation parameters, the planetary albedo A_{sys}. It shows that for increases in A_{sys} relative to the present-day value of 0.47, precipitation decreases. This decrease becomes very strong as the system approaches the point B_1. At this point, the system undergoes a so-called 'saddle-node bifurcation' which results in the destabilization of the stable summer monsoon regime. Because of the existence of a second stable state of the system in the parameter range $0.48 \leq A_{sys} \leq 0.50$ (a property referred to as 'bistability'), the system undergoes a transition to a state which is characterized by a much weaker hydrological cycle. Note that the existence of a bistable domain leads to hysteresis in the system: Let us assume, for instance, that the system settles in the dry monsoon regime: For the monsoon to recover to the present-day state, it is not sufficient to decrease the surface albedo below the bifurcation point B_1 – rather A_{sys} has to be decreased below B_2.

[17] Physically, the existence of two steady states is associated with the moisture-advection feedback which operates as follows: The summer monsoon transports moist air from the Indian Ocean towards India. Over the hot continent, this air rises and condensates, leading to the release of large amounts of heat to the middle and upper troposphere. This, in turn, strengthens the upper-level pressure gradient between India and the adjacent ocean, and hence the upper branch of the monsoon circulation. If the planetary albedo is increased, the atmosphere over land is cooled relative to that over the adjacent ocean. Once the albedo is large enough to force the driving pressure gradient below a critical value, the monsoon circulation cannot sustain itself and collapses.

[18] It is worth noting that the destabilization of the ISM occurs also at critical values of insolation (420 W/m^2 compared to the present-day value of 446 W/m^2). In fact, the relevant quantity is the amount of solar radiation which enters the atmosphere. This can be modified by changes either in the planetary albedo A_{sys} or in the insolation $F_{\uparrow}^{SL,TA}$ (cf. equation (1)).

[19] Another quantity which determines the heat balance of the system and can thus be expected to affect the stability of the ISM is the CO_2 concentration. Figure 2 displays the summer precipitation over India against this quantity. Figure 2 shows that the system responds nonlinearly to a decrease in the CO_2 concentration: at values of about 90 and 210 ppm, saddle-node bifurcations occur (cf. the circles denoted by P_1 and P_2 in Figure 2). The occurrence of these bifurcations can again be explained by the destabilizing mechanism suggested above: because of the lower heat capacity of the land relative to that of the ocean, lower CO_2 concentrations result in a decrease in the driving land-to-sea pressure contrast. As soon as the latter falls short of the critical value, the summer monsoon circulation loses its stability.

[20] So far, we considered perturbations of the planetary albedo and of the CO_2 concentration separately. In the past, however, these disturbances have taken effect simultaneously and it is likely that they will continue to do so in the future. We therefore tracked down the saddle-node bifurcations in the two parameter plane. The result is displayed in Figure 3. Figure 3 shows that the bifurcation

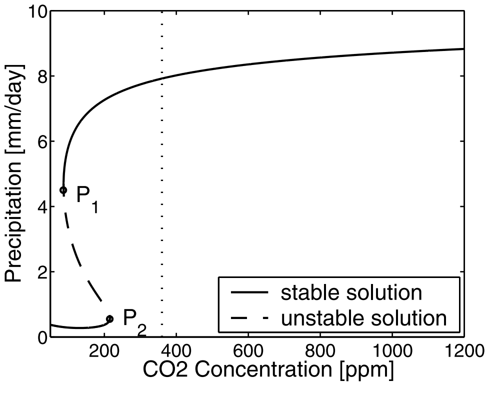

Figure 2. Bifurcation diagram of Indian summer precipitation against the CO_2 concentration. The P_1, P_2 mark the saddle-node bifurcations. The vertical dotted line indicates the present-day state.

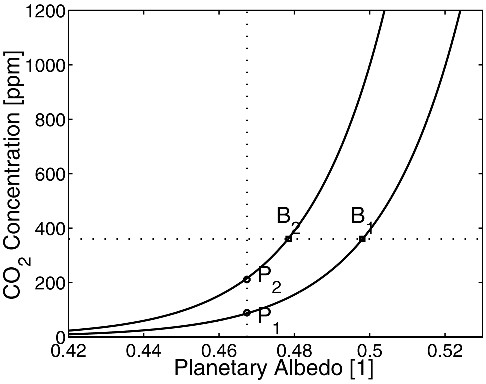

Figure 3. Continuation of the saddle-node bifurcations against the planetary albedo and the CO_2 concentration. The B_1, B_2 and P_1, P_2 mark the positions of the saddle-node bifurcations for present-day values of the CO_2 concentration and the planetary albedo, respectively.

points identified earlier are preserved throughout the depicted range of the CO_2 concentration (10–1200 ppm) and the planetary albedo (0.42–0.53). The bifurcation points B_1 and B_2 shift to higher (lower) values of the planetary albedo for increasing (decreasing) CO_2 concentrations. The width of the hysteresis, which is given by the horizontal distance between the two curves, changes only marginally with varying CO_2 concentrations. Similarly, increasing (decreasing) values of the planetary albedo A_{sys} lead to a shift of the bifurcation points P_1 and P_2 towards higher (lower) CO_2 concentration levels. The width of the hysteresis (now given by the vertical distance between the two curves) increases significantly with rising values of A_{sys}, however.

4. Conclusions and Outlook

[21] In summary, the most notable result of our study is the destabilization of the ISM under changes in those quantities which govern the heat balance of the system, i.e., the planetary albedo, the insolation and the CO_2 concentration. Physically, the destabilizing mechanism is associated with the moisture-advection feedback: once the driving land-to-sea pressure contrast falls short of a critical value, the amount of moisture advected towards the Indian subcontinent is no longer sufficient to fuel the heat engine which maintains the summer monsoon circulation.

[22] The findings presented in this paper may be of great relevance in the context of global environmental change as well as from a palaeoclimatic perspective. In fact, the existence of a critical value in the planetary albedo indicates that anthropogenic perturbations of this quantity, such as changes in the concentrations of scattering aerosols and land-cover conversion, could trigger a transition to a summer monsoon regime characterized by much lower precipitation than today's. This result acquires particular relevance in the light of observational evidence revealing that a large cloud of anthropogenic haze spreads over South and Southeast Asia [*Lelieveld et al.*, 2001].

[23] Therefore, the stage seems to be set for a man-made reduction of the ISM. On the other hand, we have shown that scattering aerosols and GHG emissions have opposite effects on the monsoon intensity (cf. Figures 1 and 2). As a consequence, a "roller coaster scenario" is not entirely unlikely: After a partial suppression of the ISM over the next decades, aerosol control policies (meant to mitigate intolerable impacts on human health, food production and ecosystems) take effect, while global economic growth pushes atmospheric CO_2 concentrations to record levels. The latter developments could re-establish the "wet monsoon" mode – at increased strength – within a few years only. Such a dynamics would seriously challenge the adaptive capabilities of India's rural society.

[24] Further, the existence of bifurcation points may provide an explanation for the abrupt climate changes over the sub-continent which are reflected in the palaeoclimatic records [*Burns et al.*, 2003; *Gupta et al.*, 2003]: natural variations in insolation, concentrations of GHGs and/or sulphate aerosols may have driven the system across some threshold. This would lend support to the hypothesis that the past abrupt changes in the Indian monsoon were induced by direct forcing rather than by teleconnections with other parts of the climate system (e.g., the North Atlantic), as was postulated by some authors [cf., e.g., *Gupta et al.*, 2003].

[25] In conclusion, our strategy to apply bifurcation analysis to a reduced-form model of the Indian monsoon allowed us to gain new qualitative insights into the systems dynamics. These, of course, will have to be corroborated by experiments with more complex models. In addition, there is the need for quantitative studies with complex 3D models that explore the location of the bifurcation points in relation to plausible changes in forcing, both for present-day and glacial conditions.

[26] **Acknowledgments.** We wish to thank H. Held and A. Levermann for fruitful discussions. We are grateful to E. Tziperman for useful comments on the manuscript. K.Z and B.K acknowledge support from BMBF (grants no. 01LD0016 and 01LG0002) and the Rosa Luxemburg Foundation.

References

Budyko, M. (1982), *The Earth's Climate*, *Int. Geophys. Ser.*, vol. 29, Elsevier, New York.

Burns, S., D. Fleitmann, A. Matter, J. Kramers, and A. Al-Subbary (2003), Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13, *Science*, *301*, 1365–1367.

Doedel, E. J. (1981), Auto: A program for the automatic bifurcation analysis of autonomous systems, paper presented at 10th Manitoba Conference on Numerical Mathematics and Computing, Univ. of Manit., Winnipeg, Manit., Canada.

Gupta, A., D. Anderson, and J. Overpeck (2003), Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, *Nature*, *421*, 354–357.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis (1986), Efficient three-dimensional global models for climate studies: Models I and II, *Mon. Weather Rev.*, *11*(4), 609–662.

Hu, Z.-Z., M. Latif, E. Roeckner, and L. Bengtsson (2000), Intensified Asian summer monsoon and its variability in a coupled model forced by increasing greenhouse gas concentrations, *Geophys. Res. Lett.*, *27*(17), 2681–2684.

Lal, M., U. Cubasch, R. Voss, and J. Waszkewitz (1995), Effect of transient increase in greenhouse gases and sulphate aerosols on monsoon climate, *Curr. Sci.*, *69*(9), 752–763.

Lelieveld, J., et al. (2001), The Indian Ocean experiment: Widespread air pollution from South and Southeast Asia, *Science*, *291*, 1031–1036.

May, W. (2002), Simulated changes of the Indian summer monsoon under enhanced greenhouse gas conditions, *Geophys. Res. Lett.*, *29*(7), 1118, doi:10.1029/2001GL013808.

Meehl, G., and W. Washington (1993), South Asian monsoon variability in a model with doubled atmospheric carbon dioxide concentration, *Science*, *260*, 1101–1104.

Petoukhov, V., A. Ganopolski, V. Brovkin, M. Claussen, A. Eliseev, C. Kubatzki, and S. Rahmstorf (2000), CLIMBER-2: A climate system model of intermediate complexity. Part I: Model description and performance for present climate, *Clim. Dyn.*, *16*, 1–17.

Webster, P., V. Magaña, T. Palmer, J. Shukla, R. Thomas, M. Yanai, and R. A. Thomas (1998), Monsoons: Processes, predictability and the prospects for prediction, *J. Geophys. Res.*, *103*(C7), 14,451–14,510.

Zickfeld, K. (2003), Modeling large-scale singular climate events for integrated assessment, Ph.D. thesis, Univ. of Potsdam, Potsdam, Germany. (Available at http://pub.uni-potsdam.de/volltexte/2005/153/)

B. Knopf, V. Petoukhov, and K. Zickfeld, Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, D-14412 Potsdam, Germany. (zickfeld@pik-potsdam.de)

H. J. Schellnhuber, Tyndall Centre Headquarters, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK.