Simulated changes in the Indian summer monsoon under enhanced greenhouse gas conditions in a global time-slice experiment

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Introduction

Our study is based on a so-called time-slice experiment that has been performed with the ECHAM AGCM at a high horizontal resolution of T106 corresponding to 160×320 grid points on a Gaussian grid. We have performed two simulations each covering a period of 30 years, one representing the present-day climate (1970-1999) and one representing the future climate after an effective doubling of the CO_2 concentration in the atmosphere (2060-2089). During these two time-slices the lower boundary forcing, i.e., monthly mean values of the sea surface temperatures (SSTs) and of the sea-ice extent and se-ice thickness, have been prescribed as obtained from a climate change simulation with the ECHAM4/OPYC coupled atmosphere-ocean model at a low horizontal resolution of T42 corresponding to 64×128 grid points (Roeckner et al., 1999). Further, the temporal evolution of the important greenhouse gases has been prescribed in the same way as in the respective climate change simulation, that is according to observations until 1990 and according to the IPCC scenario IS92a for the period after 1990. Further details on the experimental design of the time-slice experiment are given in May (1999), and a thorough discussion of the changes in the mean climate inferred from the two

time-slice can be found therein as well as in May and Roeckner (2001).

In the following we will describe the predicted changes in some important aspects of the Indian summer monsoon as obtained from the time-slice experiment. Hence, we will focus on the area covering southeastern Asia and the Indian Ocean and on the monsoon season including June, July, August and September.

Surface temperature

The anticipated increase in the atmospheric concentrations of the important greenhouse gases leads to a general warming of the surface temperatures in the area including southeastern Asia and the Indian Ocean. The warning is strongest on the land areas, in particular on the Arabian Peninsula and in Iran with changes of up to 5 °C and weakest for the Indian Ocean, where the warming is about 2 °C. As a consequence, the temperature difference between the Indian Ocean and the land areas to the north, which plays an important role in establishing the Indian summer monsoon, is enhanced in the future.

Large-scale circulation

The Indian summer monsoon circulation is characterized by a typical wind pattern in the lower troposphere, i.e., at 850 hPa, which is simulated realistically in the time-slice experiment. To the south of the equator the pattern reveals easterly winds, which change into westerly winds in the vicinity of the African continent, where they form the so-called Somali-jet. The westerly flow continues over the Indian sub-continent and extends into southeastern Asia. As for the future climate, we find only a slight intensification of this wind pattern, including a downstream extension of the Somali-jet.

In the upper troposphere, i.e., at 200 hPa, the Indian summer monsoon circulation is characterized by easterly winds over the tropical part of the Indian Ocean, i.e., between ca. 5° S and 25° N, leading to a vertical wind shear with westerly winds in the lower and easterly winds in the upper troposphere in this area. This vertical wind shear can actually be used as a dynamically based index in order to describe the strength of the Indian summer monsoon focusing on the large-scale aspects of this phenomenon (Webster and Yang, 1992). As for the future, the time-slice experiment simulates a reduction of the westerly winds in the aforemen-

tioned area, so that the vertical wind shear is decreased in the future.

Considering the whole area, the vertical wind shear is reduced from 20.22 m/s for the present-day climate to 17.56 m/s for the future climate (Table 1), indicating a weakening of the Indian summer monsoon in the future. The interannual variance is, on the other hand, enhanced by about a factor of 3. A look at the respective time series of the anomalies reveals the relatively strong variations of the vertical wind shear during individual years in the simulation of the future climate. These variations are possibly related to the rather strong variations of the SSTs in the tropical Pacific in association with the El Niño/Southern Oscillation (ENSO) phenomenon in the respective time-slice (May, 1999).

Hydrological cycle

The Indian summer monsoon is also characterized by a typical rainfall pattern, which is simulated reasonably well in the time-slice experiment. In addition to the maximum to the west of Indonesia, we find rather strong precipitation over the Bay of Bengal, in northeastern India and Bangladesh as well as over the foothills of the Himalayas. Moreover, the rainfall is relatively strong on the west coast of the Indian sub-continent due to the orographic forcing of the Western Ghats. In the future climate the amount of precipitation is increased in all those areas, where the rainfall generally is relatively strong, namely over the Bay of Bengal, in northeastern India and Bangladesh, over the foothills of the Himalayas as well as on the west coast of the Indian sub-continent, indicating an intensification of the Indian summer monsoon in the future climate.

As an alternative to the dynamically based index for the strength of the Indian summer monsoon, which we have presented above, one can use the all Indian rainfall as an indicative of the monsoon strength (e.g., Sontakke et al., 1993), which focuses more on the local aspects of the monsoon circulation. Different to the dynamical index, the rainfall index indicates a strengthening of the Indian summer monsoon in the future (Table 2), that is the area mean rainfall is increased by more than 10% in the future (6.65 vs 5.96 mm/d). Also the rainfall index reveals a stronger interannual variance in the simulation of the future climate, but the increase is only about 20% compared to the more than 200% for the dynamical index (see Table 1). This agrees with the observation that the correlation between ENSO and the dynamical index is considerably stronger than the correlation between ENSO and the rainfall index. This can

also be seen from the time series of the rainfall anomalies over India and Bangladesh, which reveal a considerable number of both strong and weak monsoons in both time-slices.

Even though the winds in the lower troposphere associated with the Indian summer monsoon are only slightly enhanced in the future (see above), is the transport of moisture accomplished by these winds considerably enhanced in the future. This is due to two different kinds of climatic changes in the future: Firstly, the specific humidity in the troposphere is enhanced due to the general warming in the future (May and Roeckner, 2001). Secondly, we find an increase in the source term of atmospheric moisture, i.e., the difference between evaporation and precipitation, over the southern and the western parts of the Indian Ocean.

As a consequence of the aforementioned changes in precipitation as well as of the changes in evaporation, we also find a change in the soil water content in the future. Apparently the soil water content is enhanced in those parts of India and Bangladesh, where precipitation is increased. Only in a latitudinal belt between ca. 15° and 20° N is the soil water content reduced.

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Table 1:

Period	Mean (m/s)	St.dev. (m/s)	Ratio
1970-1999	20.22	1.50	
2060-2089	17.56	2.66	
2060-2089 vs. 1970-1999			3.15

Difference of seasonal mean zonal wind component in 850 hPa and 200 hPa averaged over the area [EQ-20° N, 40-100° E] for June, July, August and September for the two time-slices, both the long-term means and the interannual standard deviations. Further, the ratio of the interannual variances within the two time-slices is given.

Table 2:

Period	Mean (mm/d)	St.dev. (mm/d)	Ratio
1970-1999	5.96	0.58	
2060-2089	6.65	0.64	
2060-2089 vs. 1970-1999			1.21

As Table 1, but for mean daily precipitation in India and Bagladesh.