Role of Asian and African orography in Indian summer monsoon

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[1] Role of Asian and African orography in the Indian summer monsoon has been investigated using a general circulation model. Orography of Asian region west of 80°E appears to have more impact on the Indian summer monsoon rainfall than the orography to the east of 80°E. It has been found that removal of the African orography increases the seasonal precipitation over the Indian subcontinent by 28%, whereas removal of orography over the entire globe reduces it by 25%. Moreover, there was a substantial delay in all-India monsoon onset in the experiment in which mountains were removed globally, mainly due to the intrusion of midlatitude dry air west of 80°E. The increase in precipitation in which orography over Africa was removed was due to the positive feedback between the wind over the East African coast/Arabian Sea and precipitation over Bay of Bengal, with the latter leading the former by about 2 days. *INDEX TERMS:* 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Chakraborty, A., R. S. Nanjundiah, and J. Srinivasan, Role of Asian and African orography in Indian summer monsoon, *Geophys. Res. Lett.*, *29*(20), 1989, doi:10.1029/2002GL015522, 2002.

1. Introduction

[2] Many studies have been conducted to examine the role of orography in the Indian summer monsoon. *Hahn and Manabe* [1975] first studied the impact of orography in the simulation of the Indian monsoon. They showed that monsoon substantially increases with inclusion of orography. The effect of Himalayan orography in the context of paleoclimate has been investigated by *Prell and Kutzbach* [1992, 1997]. However there are fewer studies about the impact of African orography in the Indian monsoon. African orography, especially the East African orography could have a large impact on the direction and strength of the cross-equatorial wind flow and hence on the Indian summer monsoon. *Sashegy and Geisler* [1987] using a simple linear model showed that the strength of the low-level jet as response to the monsoonal heat source increases substantially with the inclusion of a “wall-like” orography. *Mawson and Cullen* [1992] have also studied the low-level jet and the monsoons in the presence of African orography in idealized primitive equation and quasi-equilibrium models. In this paper we study the impact of global orography in general, and African orography in particular, on the strength of the Indian summer monsoon with a general circulation model (GCM). A GCM is better than simple models because the heating is not imposed but dynamically determined by the model itself.

2. Model Description

[3] The atmospheric GCM used in this study is a version of the NCMRWF (National Centre for Medium Range Weather Forecasting), which is a modified form of the research version of National Meteorological Centre (NMC, now NCEP) global spectral model [*Sela*, 1988] at T-80 resolution corresponding to a grid resolution of ~1.41° and 18 vertical levels. The model uses Simplified Arakawa-Schubert (SAS) scheme [*Grell*, 1993] for convection parameterization.

3. Experimental Details

[4] We have conducted seasonal ensemble integrations of the NCMRWF model for each experiment with five different initial conditions at 00:00 UTC from 1 to 5 March 1998 from NCEP/NCAR re-analysis [*Kalnay et al.*, 1996], and integrations were carried out till 30 September 1998. The monthly mean Reynolds Sea Surface Temperature (SST) was specified [*Reynolds and Smith*, 1994] as the surface boundary forcing over ocean. Ensemble mean values (average of the 5 members of each ensemble) are presented in this paper. In the control experiment mean orography from NCEP re-analysis dataset was used. Results from June to September is discussed in the present study. To examine the role of Asian and/or African orography in the Indian summer monsoon three experiments in addition to the control experiment were conducted by removing: *I*) orography all over the globe (will be termed as *noGlOrog* in this paper); *II*) orography between 80°E–120°E, 0–60°N (will be termed as *noTiOrog*); and *III*) all orography over the African continent (will be termed as *noAfOrog*).

4. Results

[5] Monthly mean precipitation values from observation and NCMRWF simulations over the Indian region (68.2°E–90.7°E, 8.4°N–28.0°N, land region only) are shown in Figure 1. The control experiment of the model could capture the mean precipitation over this region in all the four months when compared to the observation. Standard deviation (SD) of control ensemble members (not shown) was low in all months (SD of seasonal mean precipitation was 0.19 mm day^{-1}) except in June (0.80 mm day^{-1}). It was also noted that (not shown) differences in precipitation between Xie-Arkin [*Xie and Arkin*, 1997] and GPCP [*Huffman et al.*, 2001] datasets (both are observational datasets) was largest in June which is the onset month of summer monsoon in this region.

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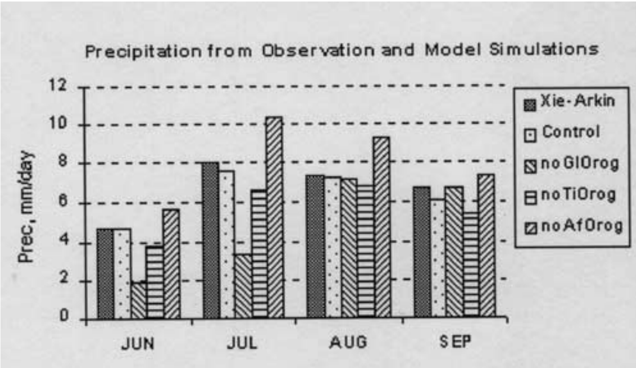

Figure 1. Precipitation in the Indian region from observation and NCMRWF simulations.

[6] Seasonal mean precipitation over the Indian region decreased by 25% when orography was removed over the entire globe (*noGlOrog* experiment). June and July precipitation from *noGlOrog* run was substantially lower than the control, which indicates a delay in monsoon onset. In Figure 2 time series of daily precipitation over the Indian region from *noGlOrog* simulation has shown along with the control, *noTiOrog* and *noAfOrog* simulations. If all-India monsoon onset date is defined as the first day of the monsoon season when precipitation exceeds 3.5 mm day^{-1} and remains above this value for at least 5 consecutive days, then the onset date for control experiment was 13 June whereas for *noGlOrog* experiment onset date was 18 July. After the onset of the monsoon in the *noGlOrog* simulation, the daily precipitation rate is comparable to that of the control value till the end of September. Monthly mean precipitation in September from *noGlOrog* run was 0.65 mm day^{-1} higher than that of the control. This result suggests that orography plays an important role in the onset of monsoon in this region. After monsoon onset orography appears to play a secondary role in modulating the rainfall over the Indian region.

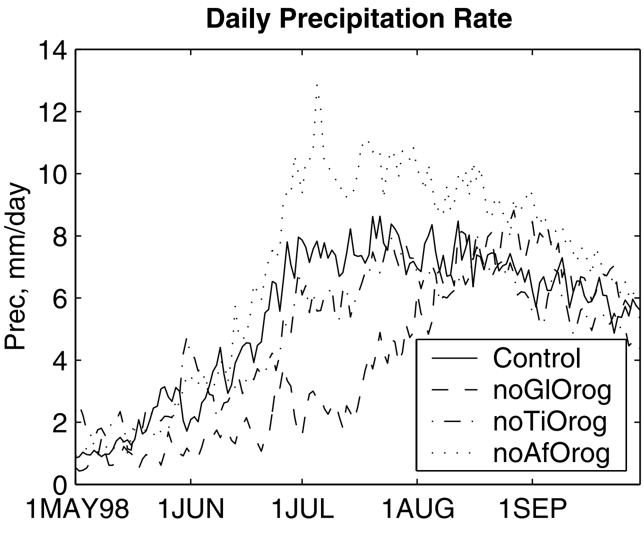

Figure 2. Time series of ensemble mean daily precipitation from control, *noGlOrog*, *noTiOrog* and *noAfOrog* runs.

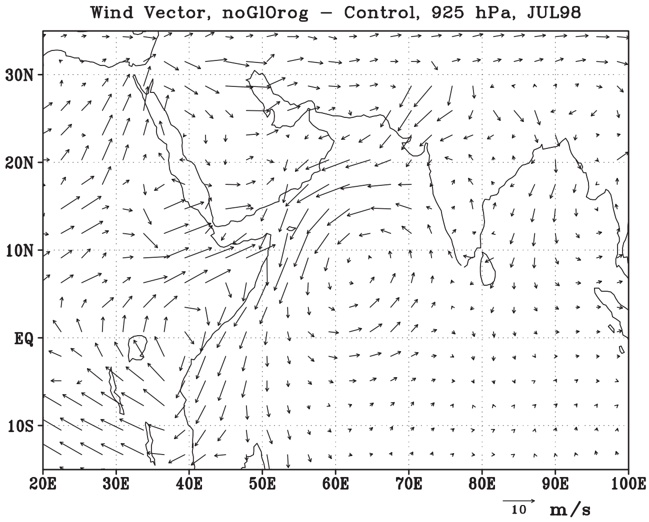

Figure 3. Difference in horizontal wind vector between *noGlOrog* run and control run in July 1998.

[7] Removal of Himalaya orography (in *noGlOrog* case) allows the midlatitude dry air to enter the Indian peninsula, which delays the monsoon onset and decreases its intensity. Difference in horizontal wind vector at 925 hPa between control and *noGlOrog* simulations for July 1998 is given in Figure 3. This figure reveals that south-westerly wind over Arabian Sea, which brings moisture into the land, has also decreased its intensity by about 7 m s^{-1} at the west coast of India. Also it can be noticed that jet at Somalia coast has been reduced by $\sim$10 m s^{-1} in *noGlOrog* case vis-a-vis the control simulation.

[8] The decrease in seasonal mean precipitation for the *noGlOrog* simulation qualitatively agrees with the results cited by previous studies [e. g., *Hahn and Manabe* [1975]; *Molnar et al.* [1993]]. It can be noted from Figure 3 that when orography from all over the globe was removed the main influence on precipitation over the Indian region was due to the absence of Himalaya orography, which allowed midlatitude dry air to come into the subcontinent and change the structure of the precipitation belt. Figure 3 also shows that the intrusion of midlatitude dry air into the Indian region was through the longitude belt 60°E–80°E. Hence we conducted another experiment removing orography in the region 80°E–120°E, 0–60°N which includes mainly the Tibetan orography. (this experiment is termed as *noTiOrog*).

[9] From Figure 1 it can be found that monthly mean precipitation values from *noTiOrog* simulation are greater than the *noGlOrog* simulation and closer to the control integration. Time series of daily precipitation for *noTiOrog* case (Figure 2) shows that onset of monsoon for this experiment was nearly simultaneous with the control onset, and intensity of daily precipitation rate was also comparable to the control till the end of September. These results are in agreement with *An et al.* [2001] whose simulations show that rainfall increases only with the westward development of the Tibetan plateau during the late Miocene period (their HT2 simulation with Tibetan plateau restricted to region east of 80°E). In this simulation the Indian monsoon rainfall was comparable to their HT1 simulation in which the Himalayan/Tibetan orography was very low and limited in

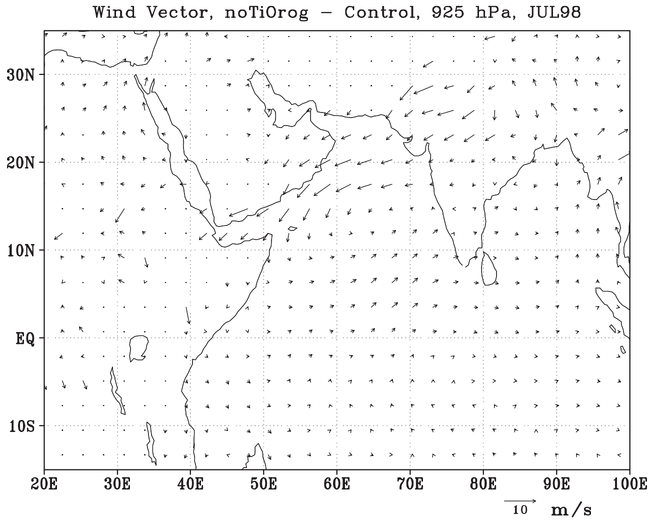

Figure 4. Difference in horizontal wind vector between *noTiOrog* run and control run in July 1998.

horizontal extent. The rainfall shows a significant increase in their HT3 simulation which has mountains west of 80°E.

[10] In Figure 4 we have shown the difference in horizontal wind vectors from *noTiOrog* and control simulations. Significant changes in wind (>5 m s^{-1}) can be noticed in the north-west part of India and over the north Arabian Sea. The west-Himalayan mountains (west of 80°E) do not allow midlatitude dry air to come into the Indian monsoon region resulting in a stronger monsoon. This clearly demonstrates that orography west of 80°E has greater impact (than orography east of 80°E) on the Indian summer monsoon.

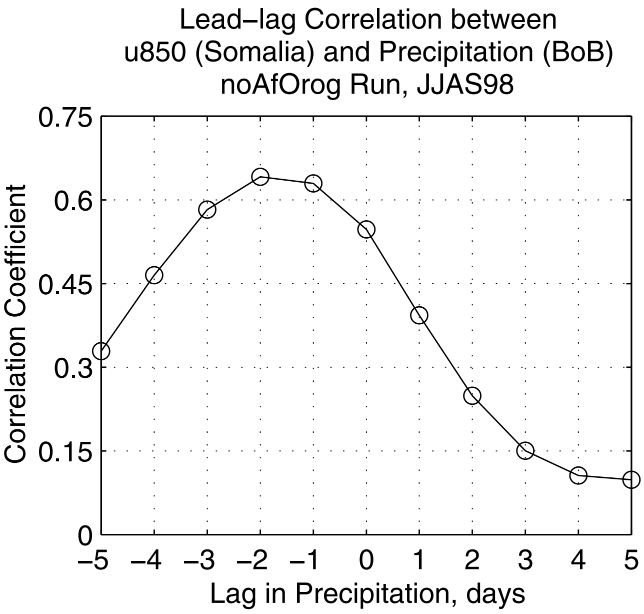

Figure 5. Lead_lag correlation between daily precipitation over Bay of Bengal (83.5°E–90.5°E, 11.5°N–18.0°N) and 850 hPa zonal wind over Somalia coast (50.0°E–57.0°E, 4.0°N–10.0°N) for *noAfOrog* run in June–September 1998. We can notice that 850 hPa zonal wind over Somalia cost lags precipitation over Bay of Bengal by about 2 days.

[11] In contrast to the *noGlOrog* seasonal mean precipitation over the Indian region increased by 28% when orography all over the African continent was removed in *noAfOrog* experiment. Time series of daily precipitation over the same region (Figure 2) reveals that although the onset of monsoon for *noAfOrog* was simultaneous with the control simulation onset, precipitation for *noAfOrog* was higher than that of the control from the second half of June and remains so till the end of September, with the major difference occurring in the month of July.

[12] This enhancement in Indian monsoon rainfall due to the removal of African orography was in contrast to the results obtained by *Sashegyi and Geisler* [1987] who used a linear model to show that the Somali Jet increases when a 'wall like' orography was included close to the East African coast. In the absence of east African orography, *Sashegyi and Geisler* [1987] found a weaker south-westerly wind flow over the Arabian Sea. A recent study by *Srinivasan and Nanjundiah* [2002] showed that there exists a high positive correlation between rainfall over Bay of Bengal (BoB) and 850 hPa kinetic energy over Arabian Sea, where BoB precipitation leads the Arabian Sea kinetic energy by about 3 days. *Li and Zeng* [2002] had also shown that rainfall anomalies over the Indian summer monsoon region are highly correlated with the wind anomalies west of 70°E (sector SASM1 of their study). In Figure 5 lead-lag correlation between precipitation over BoB and 850 hPa zonal wind over the Somalia coast has been plotted for the *noAfOrog* experiment. This figure again shows that precipitation over BoB leads by about 2 days to the wind over Somalia coast, similar to the results of *Srinivasan and Nanjundiah* [2002] and *Li and Zeng* [2002] indicating that there exists a positive feedback between precipitation over BoB and wind over Arabian Sea.

[13] In Figure 6 difference in horizontal wind vectors between *noAfOrog* and control runs at 850 hPa is shown for the month of June. A relative south-easterly wind is noticed in the longitude belt 60°E–80°E and north of 20°N. When compared to *noGlOrog* experiment, the increased south-easterlies prevent intrusion of dry air from the midlatitude

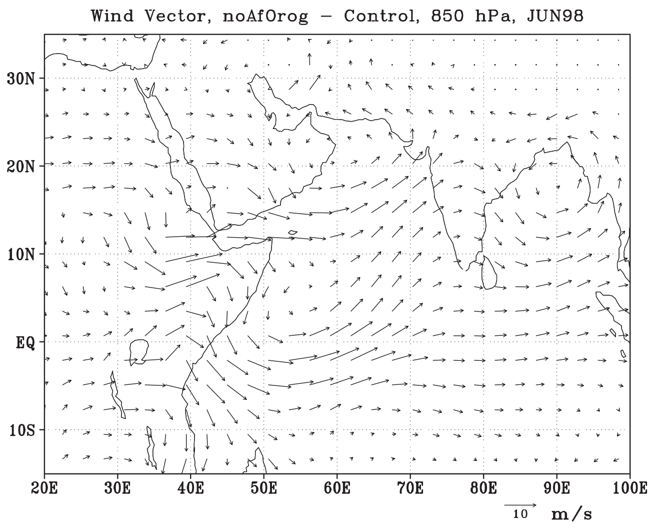

Figure 6. Difference in horizontal wind vector at 850 hPa between *noAfOrog* run and control run in June 1998.

into this region in *noAfOrog* case. Absence of African orography allows more mass flux towards the heating region centered at the Indian subcontinent. This increases precipitation over the Indian subcontinent during the early phase of summer monsoon season. An initial enhancement in precipitation over the BoB increased the strength of the low level jet over the Arabian Sea, and this enhanced the south-westerly flow (a flow that would have been otherwise hindered by the coastal mountains) and the cross equatorial jets at the Somalia coast bringing more moisture to the Indian subcontinent and increasing precipitation leading to a positive feedback between precipitation and strength of the jet.

[14] A moisture balance analysis for the Indian region shows that for *noGlOrog* simulation net zonal flux to this region was almost zero indicating a zonally symmetric nature of the atmosphere in this region in the absence of all orography over the globe. Net zonal moisture flux for *noAfOrog* simulation was about 7.5 mm day^{-1} to this region in the month of July 1998, which was the main factor for the increased precipitation in this experiment.

[15] Monthly mean precipitation values in the Indian region from observation and four model simulations discussed above (see Figure 1) show two different patterns, one in June-July and the other in August-September. While control was comparable to the observation in all four months, *noGlOrog* showed lowest rainfall and *noAfOrog* showed highest rainfall in June and July, *noTiOrog* being the member in between these two simulations. In August and September observation, control, *noGlOrog* and *noTiOrog* precipitation intensities were comparable, and *noAfOrog* showed more precipitation than the other simulations, which was consistent with the June and July precipitation values. Hence, we can say that orography, mainly the Himalayan orography is important in the onset phase of summer monsoon in this region. But after the onset the system is driven by its own thermodynamics, dynamics and the seasonal position of the Sun.

[16] In order to confirm that the results presented in this paper are not an artifact of interaction between the cumulus scheme and orography, we conducted the same simulations with the Kuo cumulus convection scheme [*Anthes*, 1977]. We found that the results were similar to those obtained with the SAS scheme.

5. Conclusion

[17] We find that African orography plays an important role in modulating the rainfall of the Indian summer monsoon. The strength of the Indian summer monsoon precipitation and the low-level jet increase in the absence of orography over Africa. However when mountains are removed over the entire globe, their strength reduces and the onset of monsoon is delayed by about a month. This delay in onset and decrease in precipitation was mainly due to the intrusion of midlatitude dry air through the 60°E–80°E longitude belt in the absence of Himalayan orography. The increase in strength of monsoon in *noAfOrog* simulation occurs due to an initial enhancement of precipitation in the Bay of Bengal which in turn increases moisture advection.

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References

An, Z. S., J. E. Kutzbach, W. L. Prell, and S. C. Porter, Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene Times, *Nature*, *411*, 62–66, 2001.

Anthes, R. A., A cumulus parameterization scheme utilizing a one-dimensional cloud model, *Mon. Weather Rev.*, *105*, 270–286, 1977.

Grell, G. A., Prognostic evaluation of assumptions used by cumulus parameterization, *Mon. Weather Rev.*, *121*, 764–787, 1993.

Hahn, D. G., and S. Manabe, The role of mountains in the south Asian monsoon circulation, *J. Atmos. Sci.*, *32*, 1515–1541, 1975.

Huffman, G. J., R. F. Adler, M. M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, Global precipitation at one-degree daily resolution from multisatellite observations, *Journal of Hydrometeorology*, *2*, 36–50, 2001.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Amer. Meteor. Soc.*, *77*, 437–471, 1996.

Li, J., and Q. Zeng, A unified monsoon index, *Geophys. Res. Lett.*, *29*, 10.1029/2001GL013874, 2002.

Mawson, M. H., and M. J. P. Cullen, An idealized simulation of the Indian monsoon using primitive-equation and quasi-equilibrium models, *Q. J. R. Meteorol. Soc*, *118*, 153–164, 1992.

Molnar, P., P. England, and J. Martinod, Mantle dynamics, uplift of the Tibetan plateau, and the Indian monsoon, *Rev. Geophys.*, *31*, 357–396, 1993.

Prell, W. L., and J. E. Kutzbach, Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution, *Nature*, *360*, 647–652, 1992.

Prell, W. L., and J. E. Kutzbach, The impact of Tibet-Himalayan elevation on the sensitivity of the monsoon climate system to changes in solar radiation, in *Tectonic Uplift and Climate Change*, edited by W. F. Ruddiman, pp. 171–201, Plenum Press, New York, 1997.

Reynolds, R. W., and T. M. Smith, Improved global sea surface temperature analyses using optimum interpolation, *J. Clim.*, *7*, 929–948, 1994.

Sashegyi, K. D., and J. E. Geisler, A linear model study of the cross-equatorial flow forced by summer monsoon heat sources, *J. Atmos. Sci.*, *44*, 1706–1722, 1987.

Sela, J. G., The new NMC operational spectral model, Eighth conference on numerical weather prediction, February 22–26, Baltimore, Maryland, 1988.

Srinivasan, J., and R. S. Nanjundiah, The evolution of Indian summer monsoon in 1997 and 1983, *Meteorology and Atmospheric Physics*, *79*, 243–257, 2002.

Xie, P., and P. A. Arkin, A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs, *Bull. Amer. Meteor. Soc.*, *78*, 2539–2558, 1997.

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