Proceedings of the First International Symposium in Cloud-prone & Rainy Areas Remote Sensing (CARRS), Chinese University of Hong Kong

Monsoon, Orography, and Human Influence on Asian Rainfall

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Abstract

Ocean's role in the seasonal monsoon rainfall over the Asian continent is revealed using recent high-resolution spacebased data. The balance of continental rainfall with moisture advected from the ocean is discussed. Temporal variation of rainfall in China and Indochina was found to be in phase and agree approximately in magnitude with moisture advection from the Indian Ocean but out of phase with those from the Pacific. During the onset of summer monsoon, moisture advected out of Indian into the Bay of Bengal occurs earlier than the moisture advected into the subcontinent from the Arabian Sea. Geographic distribution of rain is found to be governed by local orography, and narrow mountains anchor local rain and convection. Possible effect of orographic rain by urban pollution is suggested.

1 Introduction

Large-scale rainfall over the Asian continent is largely affected by monsoons, the seasonal change of winds caused by the reversal of land-ocean temperature gradient. The vagaries of monsoons have strong economic impact and may cause severe human suffering. Over land, the consequences of monsoon vagary are well observed, but the breeding ground over ocean has not been sufficiently monitored until recently by spacebased sensors. High-resolution satellite data used in this study is described in Section 2. Two examples of ocean's influence on continental-scale and seasonal changes of rainfall over land through monsoon are given in Section 3. While the temporal change of continental-scale monsoon has been well studied, the local distribution of monsoon rain has received little attention. Orographic induced convection may be one important factor, as discussed in Section 4. Possible anthropogenic modification of orographic rainfall trough urban pollution is suggested in Section 5.

2 Data

Rainfall data from the Tropical Rain Measuring Mission (TRMM) [Kummerow, et al., 2000] were obtained from the Goddard Earth Sciences (GES) Data and Information Services Center Distributed active Archive Center (DAAC). The TRMM data used to compute the rainfall over the India subcontinent and over East Asia is from TRMM 3B42, a gridded rainfall dataset, with 3-hour, 0.25° x 0.25° resolution. They are averaged to daily 1°x1° resolution in our analysis. In the analysis or orographic effect, the combined TRMM precipitation radar (PR)/ microwave imager (TMI) data are derived from TRMM product 2B31, provided with 4 km spatial resolution in a 220 km swath. The TMI data (G2A-12) are provided at 0.5°x0.5° grids on a 760 km swath. They were average to 0.5°x0.5° monthly maps.

Liu and Tang [2005] derived and validated a method to estimate the moisture transport integrated over the depth of the atmosphere (**Θ**) over ocean, using satellite data. The transport is the product of the precipitable water and an equivalent velocity ($\mathbf{u_e}$), which, by definition, is the depth-averaged wind velocity weighted by humidity. An artificial neutral network was employed to construct a relation between the surface wind velocity measured by the spaceborne scatterometer and coincident $\mathbf{u_e}$, derived using humidity and

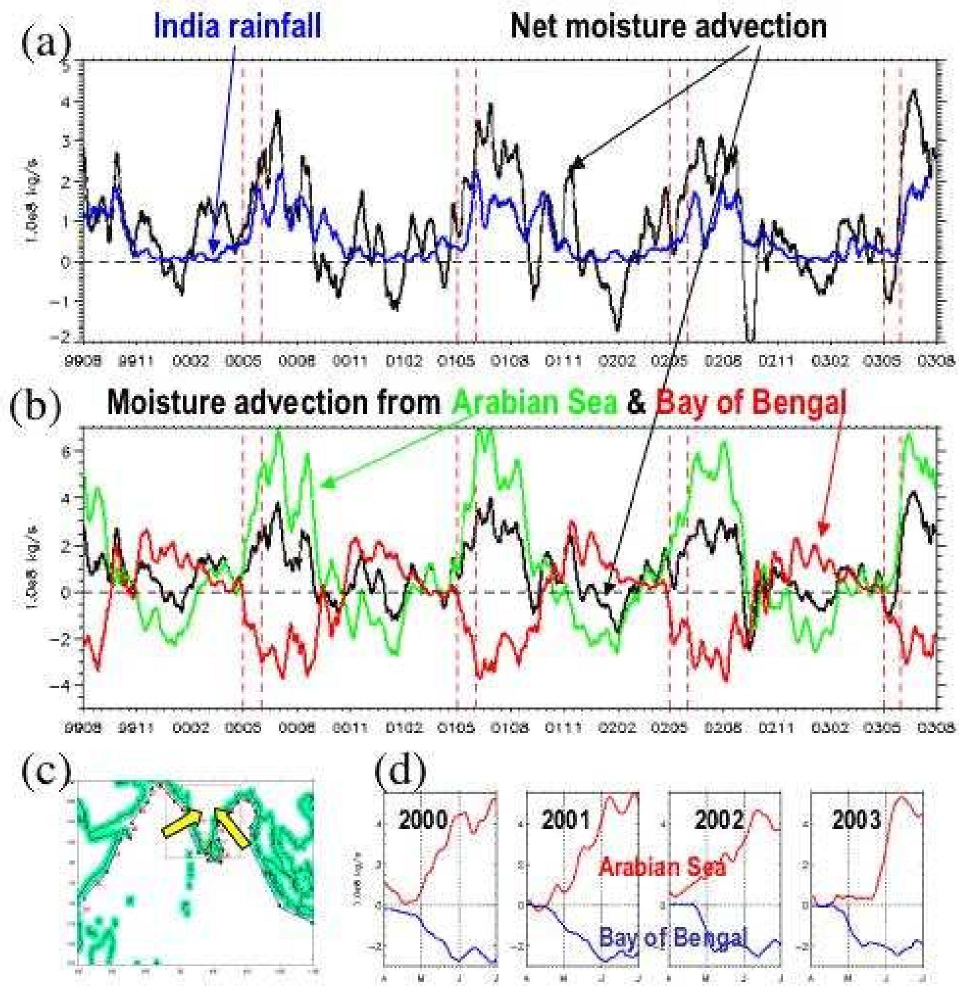

Fig. 1 (a) Time series of moisture transported into India from adjacent oceans (black) and TRMM measured precipitation integrated over India subcontinent (blue), from September 1999 to August 2003. (b) Moisture advection from Arabian Sea (green), from Bay of Bengal (red), and net moisture advection (black). (c) Map shows area and the boundaries for rain and moisture transport analysis shown in (a) and (b). (d) Moisture from Arabian Sea and Bay of Bengal during monsoon seasons from 2000 to 2003.

wind profiles measured by rawinsondes and produced by re-analysis of operational numerical weather prediction (NWP). Based on this relation, **Θ** fields are produced over global tropical and subtropical oceans (40°N-40°S) at 0.25° latitude-longitude and twice-daily resolutions, from August 1999 to December 2003, using surface wind vector from QuikSCAT [Liu, 2002]and precipitable water from TRMM.

3 Oceanic Influences

Figure 1 shows that during the summer monsoon, from May to November, moisture is transported into India from the Arabian Sea (green curve) and transported out to the Bay of Bengal (red curve). The transport is reversed for the rest of the year, with low activity in all segments between February and May, as expected. The total moisture advected from oceans (black) is in phase with the total rainfall integrated over land (blue). During the peaks of summer monsoon, the moisture from the ocean exceeds the precipitation, suggesting that moisture may move north over land.

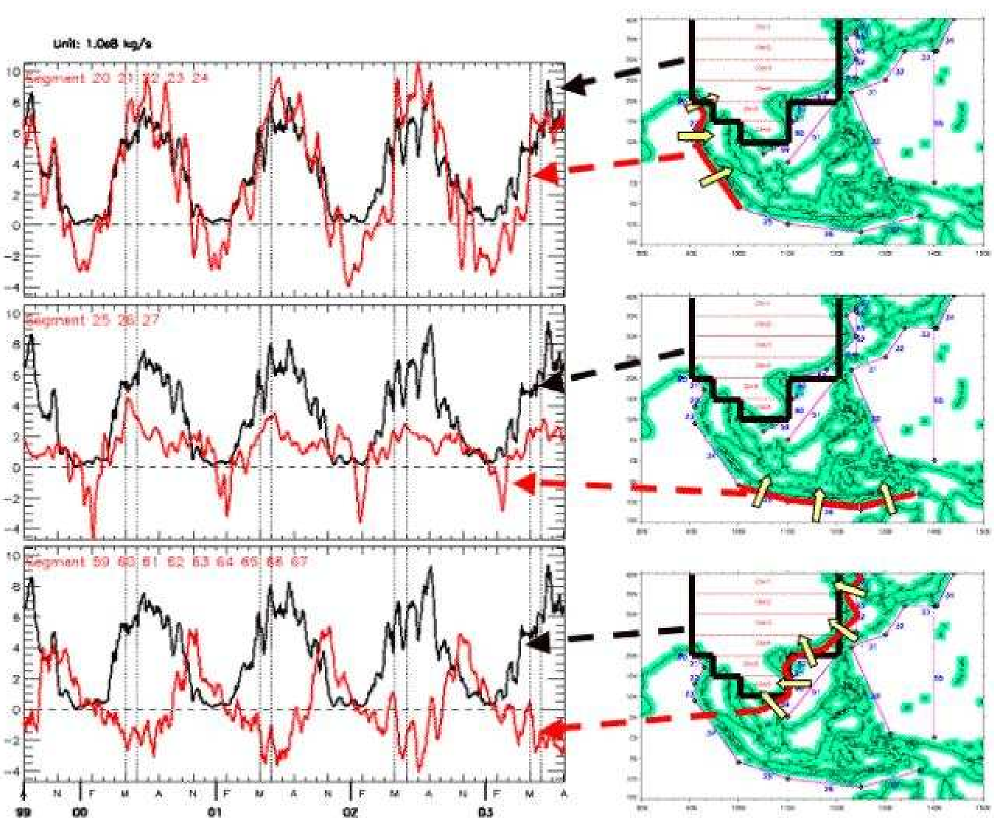

Fig. 2 Time series of precipitation (black curves) over land integrated in six parallel zonal segments in Indochina and China, as indicated by the black boundary lines in inserted map, measured by TRMM and other satellite product from August 1999 to August 2003. Moisture transport Θ (red curves) from Bay of Bengal (top), southern ocean (middle), and Pacific ocean (bottom), across the boundaries as indicated by yellow arrows.

The transport out of the eastern coastline, however, occurs earlier than the transport in from the western coastal line, as shown in the lower panels of Fig. 1. The delays are particularly sharp and long in 2002 and 2003. There were suggestions that the onset of summer monsoon occurs earlier in the Bay of Bengal than in the Arabian Sea, but these are the clearest and most direct observations. This delay may cause droughts in India just before the onset of the summer monsoon.

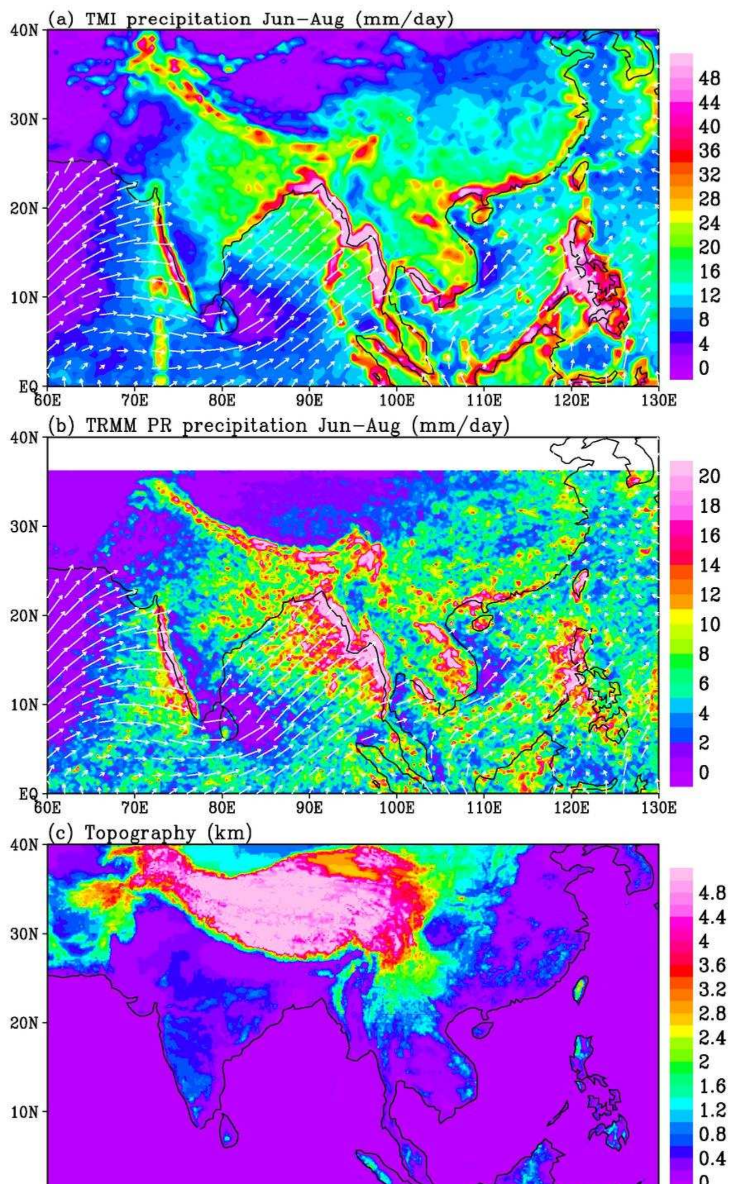

Fig. 3 Precipitation rate over Asia averaged during four boreal summers (June to August) from 2000 to 2003, derived from (a) TMI, and (b) PR. Topography is displayed in (c).

The temporal variations of the precipitation in 6 parallel zonal segments in Indochina and China (shown in the maps of Fig.2) measured by TRMM and other satellites rainfall product, are in phase, although the magnitude may be different. Continental rainfall integrated over the six areas and plotted as the black curve in Figure 32, agrees very well with the temporal variations of moisture advected from the Bay of Bengal. Precipitation increases sharply at the monsoon onset in May, and lasts until September. Part of the moisture passes over Indochina and moves back into land over the Chinese coast. However, over the major part of the Chinese coast, Figure 2 indicates that the sum of moisture influx from the Pacific Ocean occurs in fall, out of phase with the precipitation. during the rainy season in China (starting May).Part of the moisture may go out from the east coast of Indochina and northern China, but there should still be influx of moisture into southern China from the South and East China Sea.

4 Orographic Influences

While the contrast between the Asian continent (with dominating Tibetan Plateau) and the surrounding oceans drives the large-scale swing of the monsoon, the regional distribution of monsoon rain is governed, to a large part, by orography, as demonstrated in Fig. 3. During the summer monsoon season, both the active (Fig. 3a) and passive (Fig. 3b) sensors on TRMM show that rain centers are associated with local narrow mountain range, from the Western Ghat Plateau in the western India, to the Laccadive and Maldives atolls of the Indian ocean, from the Araka Yoma Mountains of Myanma to the Adaman Islands over the Bilauktaung Range that borders Thailand, the Cardamones of Cambodia, the Annam Cordillera of Vietnam, and the coastal hills of South China and Philippines. The anchors provided by these narrow mountains and low island in rain and convection have been overlooked in monsoon studies and modeling. The influence of these local orographic induced convection on the large-scale monsoon circulation is being studied and postulated by Xie et al. [2005].

5 Possible Human Influence

While orography enhances rain, such enhancement may be mitigated by human population through production of aerosols. We have observed gaps of Orographic rain enhancement downwind of urban centers in monsoon regions. Bombay is an example where such mitigation is consistently observed. Fig. 4 shows the enhancement of rain along the Western Ghat east of Bombay. A break is observed downwind of the city in the rainy season of each of the four years from 2000 and 2003. Our results spear to be consistent with the those of Givati and Rosenfeld [2004], who show decreasing trend of the ratio of the orographic rain on the hill to the rain in the coastal city upwind in the semi-arid regions of California and Israel. They postulated that urban aerosols produce large concentrations of small cloud droplets, making coalescence into rain more difficult, particularly in shallow warm clouds induced by orography. There may be other reasons

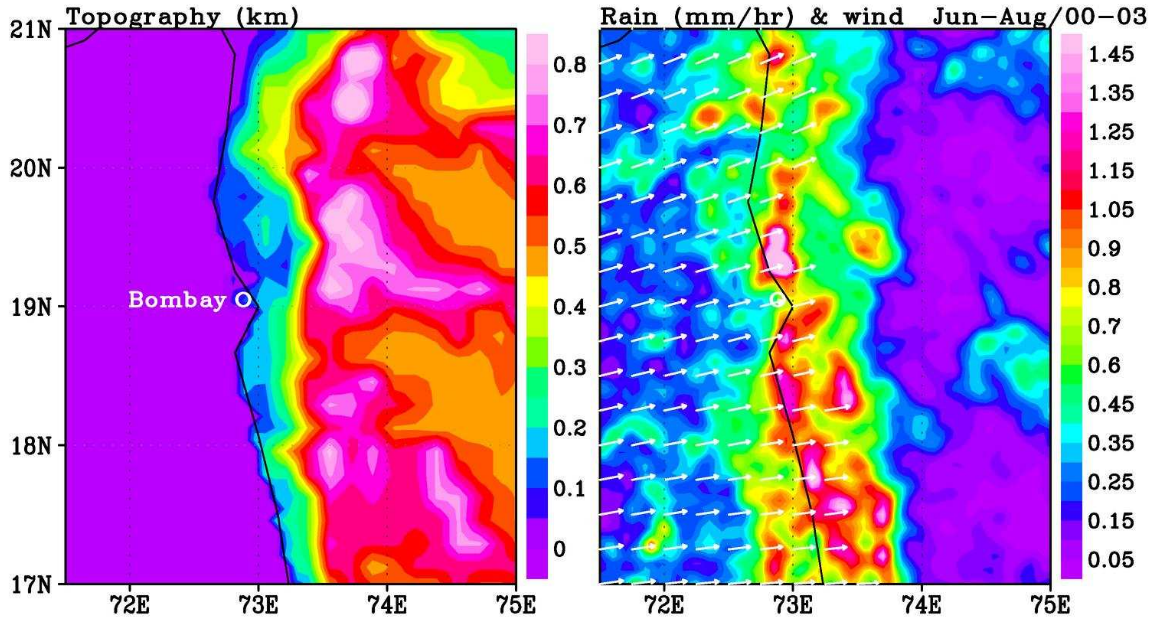

Fig. 4 (a) Topography, and (b) TRMM PR rain rate averaged from four boreal summers from 2000 to 2003, near Bombay, India.

that cause the rain gap in our observations, but the results seem to support such postulation.

6 Discussion

This study demonstrates the factors influencing Asian rainfall, from the large-scale seasonal monsoon driven by continent-ocean contrast, to regional modifications by orography, and possible human activities. It underscores the importance of continuous good-quality and high-resolution spacebased observations. The initiation of the NASA Energy and Water Cycle Study (NEWS), an end-to-end program from research to applications, is one significant step towards the characterization, understanding, and prediction of the global water cycle.

Acknowledgment

This study is conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract of the National Aeronautics and Space Administration (NASA). It was jointly supported by the Earth Observing Satellite, the Precipitation Missions, and the Ocean Vector Wind Programs of NASA. Discussions with Shang-Ping Xie and Ruby Leung have been useful.

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