NOTES AND CORRESPONDENCE

Role of Narrow Mountains in Large-Scale Organization of Asian Monsoon Convection*

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ABSTRACT

The Asian summer monsoon is organized into distinct convection centers, but the mechanism for this organization is not well understood. Analysis of new satellite observations reveals that narrow mountain ranges are an important organizing agent anchoring monsoon convection centers on the windward side. The Bay of Bengal convection, in particular, features the heaviest precipitation on its eastern coast because of orographic lifting as the southwest monsoon impinges on the coastal mountains of Myanmar (also known as Burma). This is in contrast to the widely held view that this convection is centered over the open ocean as implied by coarse-resolution datasets, a view that would require an entirely different explanation for its formation. Narrow in width and modest in height ($\leq$1 km), these mountains are hardly mentioned in conceptual depictions of the large-scale monsoon and poorly represented in global climate models. The numerical simulations of this study show that orographic rainbands are not a local phenomenon but exert far-reaching effects on the continental-scale monsoon. The realization that these overlooked geographical features are an important element of the Asian monsoon has important implications for studying the monsoon in the past, present, and future.

1. Introduction

Every summer, the southwest monsoon arrives in the Indian Ocean, South China Sea, and far western North Pacific, bringing much-needed rain to Asian countries that border these seas and supporting the livelihood of half the world's population. Monsoon rain is highly organized in space: in a 25-yr climatology based on a popular dataset that combines satellite and gauge observations (Xie and Arkin 1996), distinct centers are found in the eastern Arabian Sea, Bay of Bengal, west coast of Cambodia, and eastern South China Sea (Fig. 1a). Abnormal changes in these convective centers give rise to floods and droughts, causing hardship in society. While recent attention has focused on temporal variations (Webster et al. 1998; Saji et al. 1999; Wang et al. 2004), a fundamental question remains unanswered: What anchors these convection centers of Asian summer monsoon?

Rain, with condensational heat in its formation, is the driving force for the atmospheric circulation in the Tropics while the convergence of moisture-laden air in the lower atmosphere fuels convection. While the circulation response to convection is fairly well established (e.g., Rodwell and Hoskins 1996), the physical processes leading to convection are complicated and

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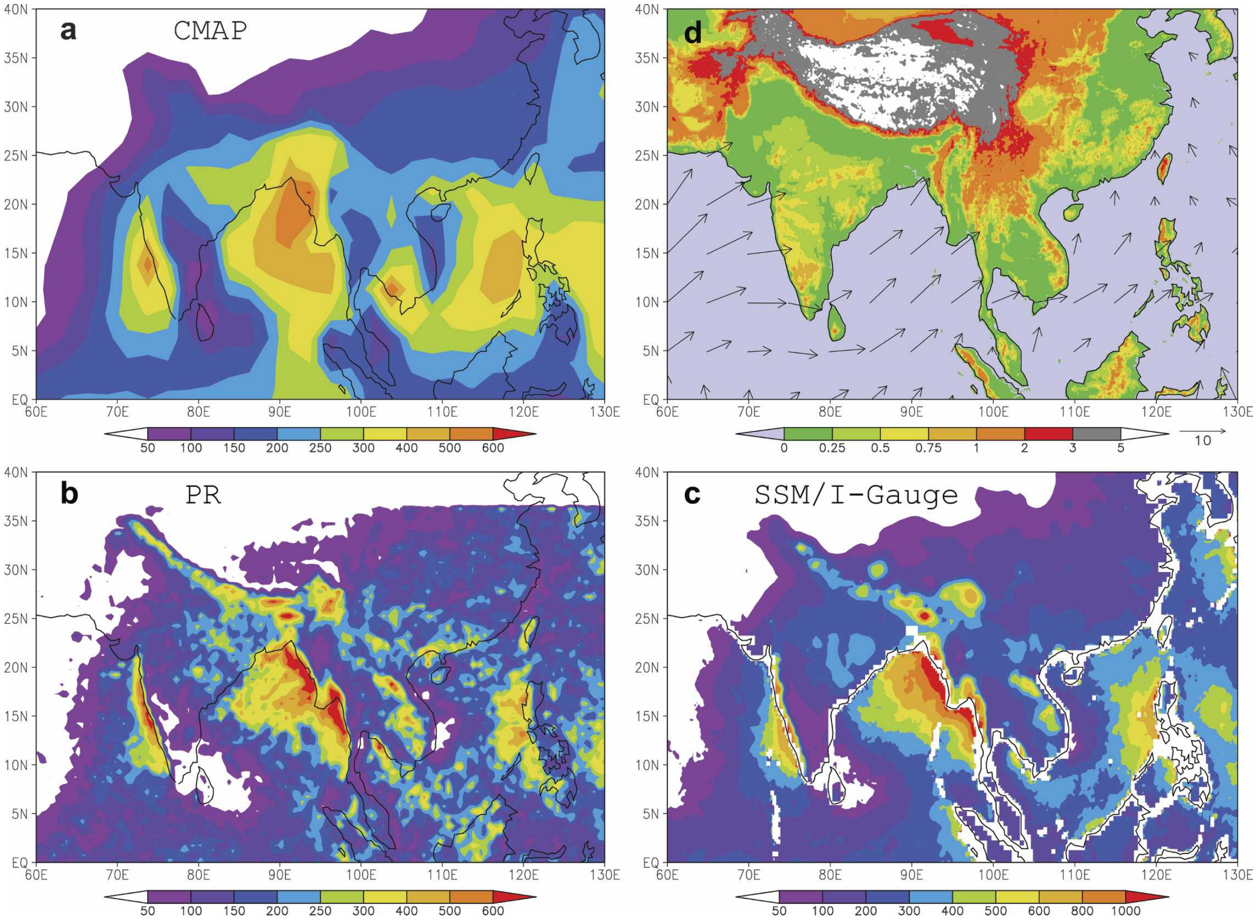

FIG. 1. Jun–Aug climatologies of surface precipitation (mm month^{-1}) based on (a) CMAP, (b) TRMM PR, and (c) SSM/I-gauge merged products. (d) Land orography (km) and QuikSCAT surface wind velocity (m s^{-1}).

poorly observed and modeled (Slingo et al. 1996). Sea surface temperature (SST) is an important mechanism for organizing atmospheric convection as attested by marked shifts in tropical convection during El Niño (Wallace et al. 1998). The SST bordering the monsoon Asia, however, is generally high with small gradients in space, rendering it ineffective in organizing convection over the ocean.

The Asian continent and its contrast with the ocean cause the planetary-scale summer monsoon. Over land, surface properties such as vegetation and soil moisture are considered to be important, but their interaction with precipitation and their role in determining rainfall distributions are complicated and not well understood. The Tibetan Plateau, absorbing intense solar radiation, serves as a massive elevated heat source for the atmosphere (e.g., Yanai and Li 1994), helping energize the summer monsoon (Hahn and Manabe 1975; Xie and Saiki 1999; An et al. 2001). In the Asian monsoon domain, there are many less remarkable mountain ranges (~1 km in height). Since they are narrow in width (500 km or less), we call them mesoscale mountains to distinguish them from the massive Tibetan Plateau. While the orographic lifting effects on rainfall are well known, the effect of mesoscale mountains on the continental-scale monsoon has rarely been discussed in the literature, because of inadequate observations. (In fact the Asian summer monsoon is almost always discussed as if these mountains do not exist.) Using a suite of new satellite observations, we show that the mesoscale mountains of Asia are an important agent for organizing monsoon convection through a strong interaction between convection and circulation.

2. Data

We use the following datasets: Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) surface rainfall product 3A25G2 (Kummerow et al. 2000; from December 1997 to September 2004 on a 0.5° grid); Special Sensor Microwave Imager (SSM/I) rainfall (Wentz 1997) from July 1987 to December 2003, and Quick Scatterometer (QuikSCAT) wind velocity (Xie et al. 2001; Chelton et al. 2001) from August 1999 to September 2004, both SSM/I and QuickSCAT datasets processed by Remote Sensing Systems on a 0.25° grid; terrestrial precipitation (Legates and Willmott 1990) from the University of Delaware Center for Climatic Research for 1950–99 at 0.5° resolution; and Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1996) from January 1979 to April 2004 on a 2.5° grid. The monthly climatology is constructed by averaging over the available period for each dataset. Multiple SSM/Is are simultaneously in orbit for the recent decade, and their observations are averaged in constructing climatology. Uncertainties remain in satellite estimates of precipitation (Wentz 1997; Kummerow et al. 2000); SSM/I rainfall is considerably larger than the TRMM PR product, but their spatial distributions closely resemble each other (section 3). For land orography we use the U.S. Geological Survey earth topography dataset on a 1/12° grid.

3. Orographic anchoring

Before the satellite era, rain gauges were the only tool for measuring global rainfall. Rain is sporadic in nature and poorly sampled over the ocean by sparse ships. Satellites make it possible to observe cloud regularly and globally. Most abundant are infrared observations of outgoing longwave radiation (OLR), from which rainfall estimates are made based on their correlation (e.g., Xie and Arkin 1996). This infrared method is rather indirect and subject to large errors since heavy rainfall tends to be confined in small convective regions while nonprecipitating cirrus clouds are much more extensive in area. Microwave remote sensing makes a more direct measurement of raindrop properties and offers better estimates of rainfall. But it is most useful over the ocean because of complicated land surface microwave emissions. The TRMM PR is the first rain radar flown in space and a significant improvement over all other remote sensing methods, making accurate observations of precipitation over both the ocean and land.

The TRMM PR's summer rainfall climatology agrees with CMAP on broad scales but differs significantly in details (Figs. 1a,b). It is these differences in detail that reveal the mechanism for aforementioned convection centers of the Asian monsoon. With no exception, each of these convection centers is anchored by a mesoscale mountain range (Fig. 1d). As the southwest monsoon impinges on the narrow mountains of South Asia, moisture-laden air is forced to rise, causing intense convection on the windward side. Specifically, from the west, a narrow rainband hugs the Indian coast west of the Western Ghats, a feature previously noted (Grossman and Durran 1984) and represented quite well in CMAP. The core of the Bay of Bengal convection lines up against its eastern coast as the southwest monsoon meets the narrow mountain ranges of Araka Yoma in the northern bay and Daiwna-Bilauktaung in the southern bay. (Figure 2 marks key geographical names and their locations.) The CMAP convection center on the Cambodian coast turns out to consist of two separate convection lines, one on the coast at the foothills of the Cardamom Hills, and one on the west slope of the Annam Cordillera range on the border between Laos and Vietnam. The South China Sea convection is anchored by the mountains of the Philippines. Each of these mesoscale mountain ranges entails a rain shadow on the leeside, another manifestation of their orographic effect. The Tibetan Plateau is of the continental scale but its steep south slope is a mesoscale feature that a narrow rainband hugs. On the south slope of the Himalayas that faces the Bay of Bengal, what in CMAP appears to be an inland extension of a broad convection center over the bay turns out to consist of three wet spots, each of them created by nearby mountains. In one of the wet spots lies Cherrapunji, India (25.2°N, 91.7°E), which is crowned the wettest place on earth with a whopping annual rainfall of 12 700 mm.

The TRMM PR's narrow swath limits its ability to sample adequately in time. We compare the PR climatology with that derived from two sets of independent observations, over the ocean by SSM/Is from space (Wentz 1997), and over land by rain gauges (Legates and Willmott 1990). We do not attempt to fill the data gaps on the coast. With a much larger swath and a longer record, SSM/Is offer one order of magnitude more observations for each gridbox average than PR. The merged SSM/I-gauge climatology is very similar to the noisier PR climatology in spatial distribution, reaffirming the orographic anchoring of monsoon convection on the west coasts of India, Indochina, and the Philippines, and on the foothills of the Himalayas and Annam Cordillera.

4. Bay of Bengal convection

The Bay of Bengal features intense convection in summer, recording the lowest OLR values of the Tropics. Rainfall increases eastward with a well-defined maximum on the eastern coast in both the PR and SSM/I-gauge merged observations. By contrast, the CMAP estimate places the center of the Bay of Bengal convection in the open ocean (Fig. 1a). This difference in the location of maximum precipitation between CAMP and

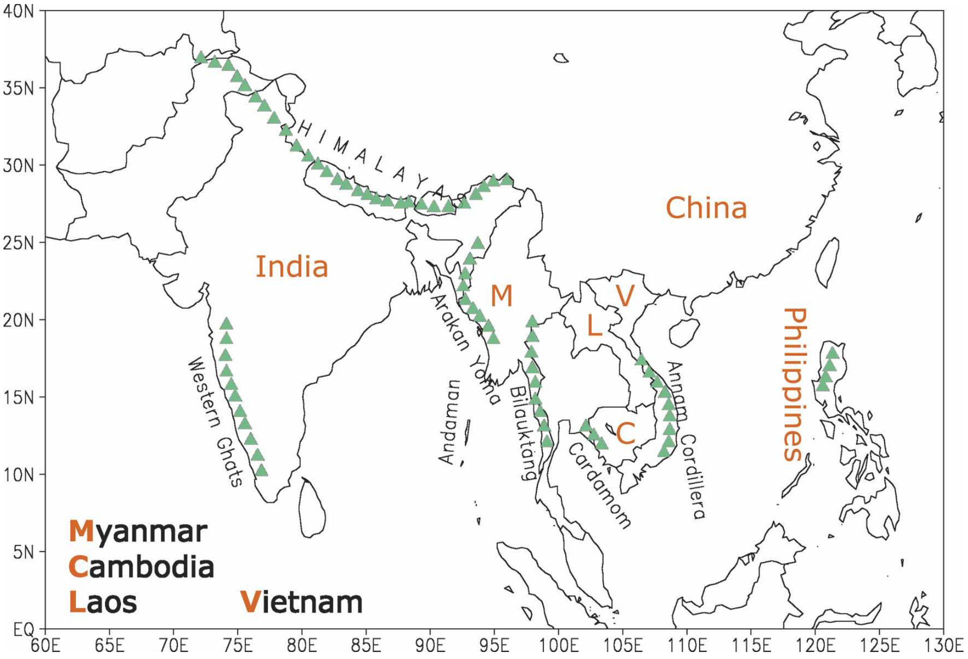

FIG. 2. Key geographical names used in the text.

PR is not just because of resolution; we have degraded the PR product onto the 2.5°CMAP grid, but the resultant rainfall distribution still features a clear maximum along the eastern coast of the bay (Fig. 3). The detailed and accurate rainfall observations by TRMM PR hold the key to isolating the mechanism for this important convection center: its climatology is indicative of orographic anchoring while a broad maximum in the open-ocean bay in CMAP would require a different physical mechanism for its formation.

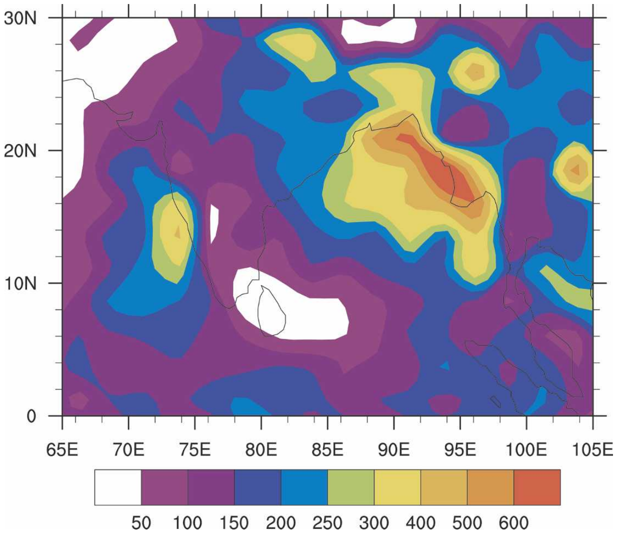

FIG. 3. The PR precipitation mapped onto the 2.5° CMAP grid, which still features a band of high rainfall on the eastern coast of the Bay of Bengal.

The distribution of PR rain frequency largely follows rain accumulation, with large values on the windward side of the aforementioned mesoscale mountain ranges (not shown). Rain is roughly equally divided between convective and stratiform types (Schumacher and Houze 2003). The mesoscale organization of convection varies across the bay: in the eastern basin cloud clusters are small in size and short lived, albeit with high frequency of occurrence, while they organize into larger sizes in the northwestern bay (Zuidema 2003), often in the form of monsoon depressions. These synoptic-scale depressions develop over the bay, travel northwestward, and bring rainfall to the Indian subcontinent (Lau and Lau 1992). These traveling disturbances help smooth the mean rainfall distribution over the Bay of Bengal.

Orographic lifting favors the windward to the leeward side of mountains for convection as is evident by comparing the eastern and western sides of the bay: south India facing the Bay of Bengal is dry savanna while the other side of the bay is dense forest on the Myanmar (also known as Burma) coast. A close examination of PR observations (Fig. 1b), however, indicates that the precipitation maximum is not located on the slope of coastal mountains of Myanmar but is instead displaced offshore by 50 km. This offshore displacement of maximum rainfall is observed also west of the

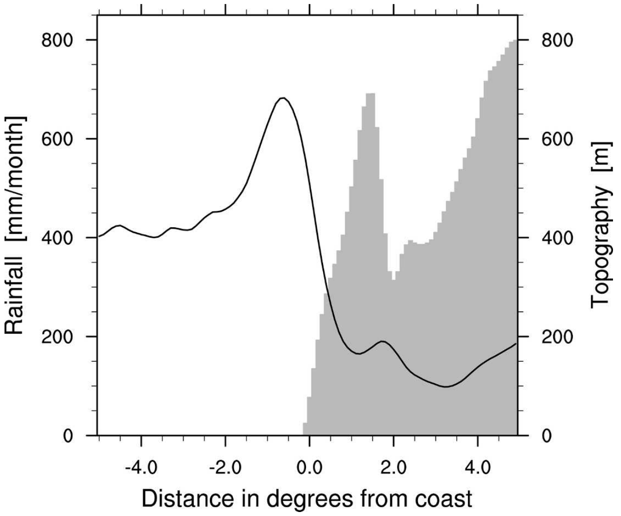

FIG. 4. Cross-shore distributions of precipitation (solid; mm month^{-1}) and orography (gray bars; m) averaged across the eastern coast of the northern Bay of Bengal.

Western Ghats and the Philippines. Figure 4 shows the cross-shore distributions of rainfall and orography across the eastern coast of the northern bay. The maximum rainfall is displaced windward of the maximum orography by as much as 200 km. This contrasts with the rainfall pattern one expects from a flow-over regime for short mountains: large rainfall on the windward slope with a maximum near the summit as is observed on Kaui Island of Hawaii (at the maximum elevation of 1598 m under an inversion of 2–3 km high; Ramage and Schroeder 1999). What causes this offshore displacement of rainfall maximum over the eastern bay is unclear at this time. Previous modeling studies based on short (~1 day) integrations indicate that the displacement of maximum rainfall away from the mountain summit is sensitive to vertical shear of the prevailing winds (Ogura and Yoshizaki 1988). Besides the orographic lifting effect as a dynamical barrier to the prevailing winds, coastal mountains affect convection also as a diurnal thermal forcing. Convection undergoes a strong diurnal cycle over the bay and surrounding land, in which mesoscale mountains seem to play an important role. Zuidema (2003) observes a band of high clouds off the eastern coast of the Bay of Bengal that reaches the maximum cloudiness in local morning (0900 LT) but disappears in the evening (2100 LT). The prevailing westerly winds at the low level may favor the land breeze over the sea breeze in intensity, helping displace the rainfall maximum offshore. Further observational and modeling studies are necessary to determine the detailed processes leading to this offshore displacement of rainfall maximum.

The rainfall maximum on the Bay of Bengal's eastern coast is consistent with detailed analyses of cloud observations. A subjective satellite analysis indicates that highly reflective cloud cover is much more frequently observed in the eastern than in the western bay (Grossman and Garcia 1990). Such cloud observations, however, do not identify raining convection well and are blurred by anvil clouds riding on the strong easterlies near the tropopause: highly reflective cloud cover in Grossman and Garcia (1990) spreads over much of the bay while PR and SSM/I show that rainfall maximum is tightly trapped on the coast.

It is unclear what causes the CMAP's differences from the PR product over the Bay of Bengal. Over the ocean, CMAP blends infrared and microwave observations from space. The Bay of Bengal is located near the edge of the disk sampled by geostationary satellites, the Geostationary Meteorological Satellite and Meteosat, which CMAP uses. This limb view may introduce an overestimation of precipitation as its infrared measurements are weighted more toward the higher altitudes. By methodology infrared retrieval of precipitation is less direct than either microwave or PR, and the resultant distribution is sensitive to the choice of threshold cloud-top temperature. Using a threshold cloud-top temperature of 235 K—which the CMAP adopts—Zuidema (2003) obtains a distribution of frequency of high-cloud occurrence similar to that of PR rainfall with a maximum on the eastern coast of the bay, from geostationary satellite observations by the Indian National Satellite System in 1988 and Meteosat in 1999. The high cloudiness resembles rather the CMAP distribution with a maximum at the northern head of the bay when a threshold cloud-top temperature of 205 K is used (Zuidema 2003). Thus, though lower in cloud-top height, orographically induced convection on the eastern coast is more intense in mean precipitation than convection over the northern head of the bay. Surface precipitation is a measure of latent heat release in the atmospheric column, which drives the circulation.

5. Seasonal and interannual variability

We now examine how monsoon convection evolves in time (Fig. 5). From the eastern Arabian Sea to the Philippines, most of rain takes place in the warm half of the year from May to October when both the warm Asian continent and high SST are conducive to convection. Monsoon convection is highly organized with persistent rainbands lining up against the windward slopes of mesoscale mountains. In May, these rainbands start to appear with the moderate southwest monsoon. At the height of the summer monsoon, both the southwest monsoon and the rainbands intensify, with the latter anchored by mesoscale mountains as discussed above.

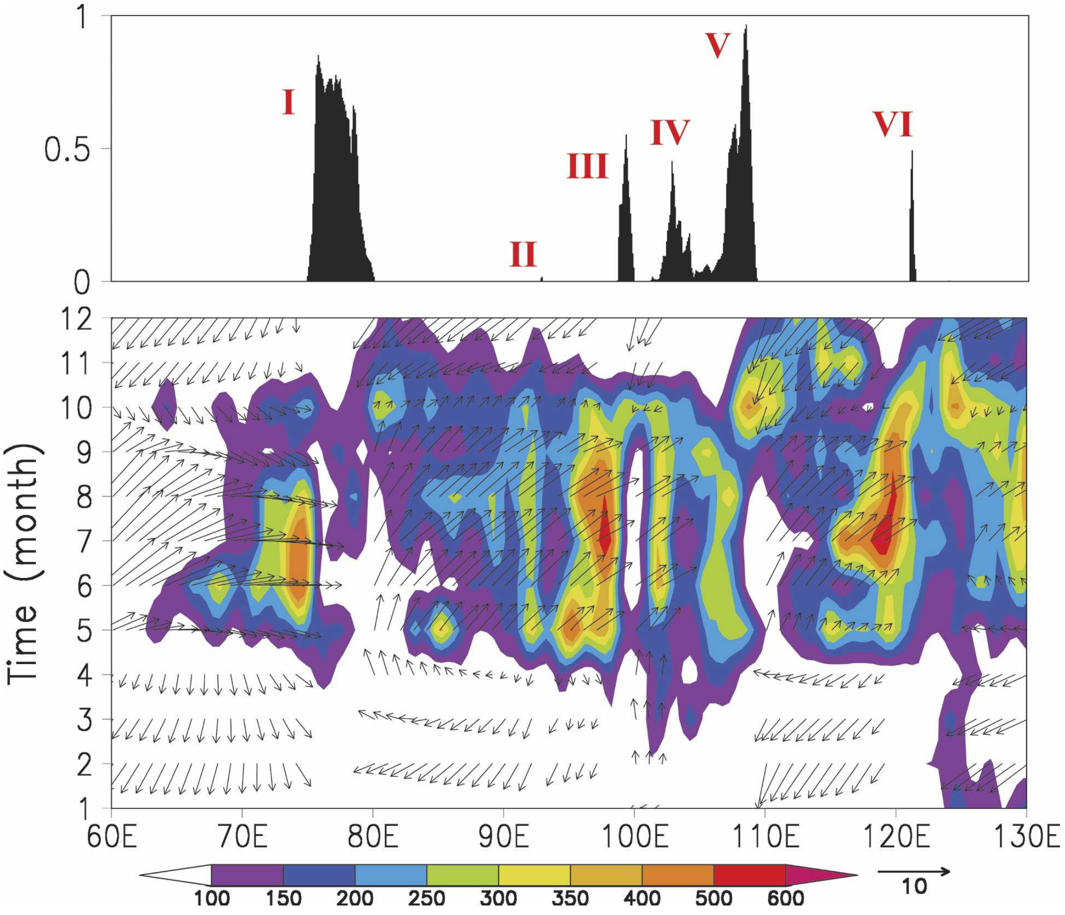

FIG. 5. The PR surface precipitation (shaded; mm month^{-1}) and QuikSCAT surface wind velocity ($\mathrm{m\,s}^{-1}$) at 12.5°N as a function of longitude and calendar month, along with land orography (top; km). Mountain ranges in the figure are: Western Ghats (I), Andaman Isle (II), Bilauktaung (III), Cardamom (IV), Annam Cordillera (V), and the Philippines (VI).

Peculiarly, the Bay of Bengal convection breaks into two separate centers at 12°N, one on the Myanmar coast and one centered at 93°E. The latter rainband forms west of the Andaman Islands. Though not tall with the highest peak at 738 m, this island chain leaves a distinctive signature in summer rainfall, with enhanced precipitation to its west and a rain shadow to the east, a feature clearly visible in both TRMM PR and SSM/I observations (Figs. 1b,c).

As the sun moves into the Southern Hemisphere, the first wind reversal takes place in October over the South China Sea and the western Pacific, where the rainbands shift from the west to the east side of Annam Cordillera and the Philippines (Fig. 5), facing the prevailing northeasterlies. The Vietnam coast rainband persists from October to December and weakens eventually because of the cooling of the South China Sea and advection of dry continental air by the northeast monsoon. The western Pacific rainband east of the Philippines lasts longer, persisting until the onset of the South China Sea summer monsoon the following May.

Both wind and precipitation in the Asian monsoon region display large interannual variability. Figure 6 shows the standard deviation of interannual rainfall anomalies based on the 25-yr CMAP observations. (TRMM is in orbit only for seven years while it is difficult to calibrate SSM/I sensors on different orbits.) All four major local maxima in variance are anchored by mesoscale mountains, off the west coasts of India, Indochina, Cambodia, and the Philippines. Most strikingly, over the Bay of Bengal, the variance maximum is more strongly trapped on the coastal mountains than the mean precipitation (cf. Fig. 1a). While all four convection centers of Asian monsoon are comparable in maximum rainfall in the seasonal mean, interannual variability is much higher along the coastal mountains of Myanmar and Cambodia for reasons not immediately clear. All these centers of action for convective

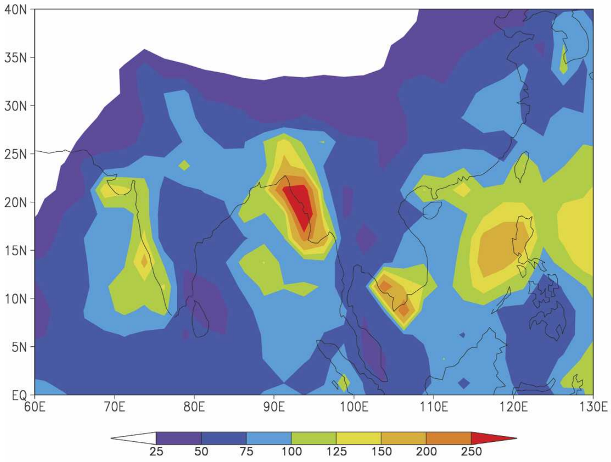

FIG. 6. Standard deviation of monthly CMAP precipitation (mm month^{-1}) averaged for Jun–Aug 1979–2003.

variability are associated with fluctuations in the southwesterly winds that impinge on the mountains (not shown), illustrating again the orographic organization of convection.

6. Large-scale implications

Orographic effects on rain are observed elsewhere, but they are often confined both in the horizontal and vertical: Kauai Island, Hawaii, holds the title of the second wettest spot on earth where the volcanic mountain forces the northeast trade winds to rise, but with little effect on large-scale circulation above the inversion. In the Asian monsoon region, by contrast, orographic-induced deep convection has large-scale effects because of its strong interaction with circulation. We use a full-physics regional atmospheric model (Wang et al. 2003) to investigate the effect of localized orographic rain on large-scale monsoon (see the appendix). The control run fails to capture orographic rain bands except off the Western Ghats. Imposing narrow bands of diabatic heating off the Myanmar and Philippine coasts and on the slope of Annam Cordillera between Laos and Vietnam leads to considerable improvements in the simulation of monsoon rain (Fig. A1). Besides a local increase in precipitation on the foothills of these mountains, the imposed narrow heating induces a basinwide intensification of convection over the northern Bay of Bengal (Fig. 7). Large remote response is also found in southern China and on the west slope of the Western Ghats where external heating is not prescribed. Overall, the inclusion of orographic rain intensifies the hydrological cycle of the summer monsoon, with precipitation increasing in 12°–22°N and decreasing both to the north and south. The precipitation increase west of the Western Ghats is associated with a gigantic cyclonic circulation in the lower atmosphere (Fig. 7), a Rossby wave response to the intensified hydrological cycle.

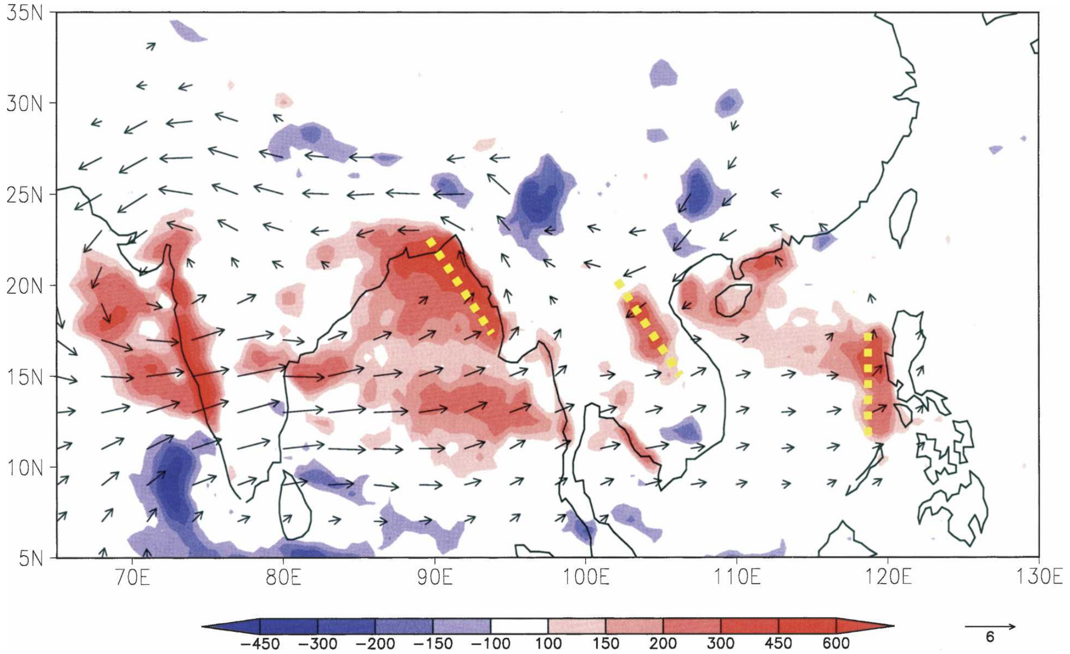

FIG. 7. Model response to narrow heating bands that mimic orographic effects of mesoscale mountain ranges: differences in precipitation (color; mm month^{-1}) and 850-hPa wind vectors (m s^{-1}) between the perturbed and control runs (see appendix for details).

While short of offering a solid solution to how to represent mesoscale mountains, the model results serve as a qualitative demonstration of their far-reaching effects on large-scale monsoon that result from the strong convection–circulation interaction in the region.

7. Summary

Over a vast region from the eastern Arabian Sea to the western Pacific, surface and atmospheric conditions are conducive to deep convection in summer. How monsoon convection organizes and where its centers form are important issues that have eluded a clear answer. New satellite observations reveal that small orographic features are an important agent for organizing monsoon convection—even the relatively flat island chain of the Andaman Islands leaves a pair of distinct rainband and shadow. Our results show that orographic rainbands are not just a localized phenomenon but form the cores of basin-scale convection over the Bay of Bengal and South China Sea. Thus, mesoscale orography is a key element of monsoon convection–circulation interaction, one that has been overlooked but is likely to simplify this long-standing difficult problem. This orographic organization appears to be important for both seasonal and interannual variability of monsoon rainfall, with centers of action anchored by coastal mountains.

Mesoscale orography needs to be included in our conceptual depiction and numerical models of the Asian summer monsoon. Consider a water-covered planet with a uniform SST of 28°C, a condition somewhat resembling the Indo-Pacific warm pool. Convection will be organized into transient modes such as the Madden–Julian oscillation through the complex interaction with circulation, a process that is poorly understood as illustrated by diverse behavior of aqua-planet model experiments (Numaguti and Hayashi 1991). Now if we add narrow mountain ranges in the system, they provide the seeds for convective organization, resulting in a reorganization of time-mean precipitation in space as seen in the Asian summer monsoon region. Most of the state-of-the-art climate models do not adequately resolve mesoscale mountains, which may explain their low skills in simulating monsoon rain and its variability (Lau et al. 1996). With several supercomputers now allowing integrations of global models at sufficient resolutions (Ohfuchi et al. 2004; Tomita et al. 2005; Shen et al. 2005), a critical test for these next-generation models is to reproduce the mesoscale orographic organization of convection described here. The offshore rainfall maximum, in particular, is a peculiar feature that requires further modeling studies to explain it.

On geological time scales, continents drift and mountains rise and fall in response to tectonic forces. Mountains east of the Bay of Bengal and the Himalayas are both part of a major mountain arc that results from active lithospheric plate motion between the Austral–Indian and Eurasian plates (Strahler and Strahler 1997). In light of the mountains' importance in organizing convection, paleoclimatic data need to be interpreted with care in relation to the evolving mountains—not just the Himalayas (An et al. 2001) but less mighty ones as well. As the current global warming proceeds, the hydrological cycle and the Asian monsoon in particular are likely to intensify (Cubasch et al. 2001). It is quite possible that this rainfall increase will be highly variable in space, more west of mesoscale mountains of Asia, while precipitation might even decrease in regions under the rain shadow, a hypothesis that needs to be tested.

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APPENDIX

Model Sensitivity to Orographic Rain

The regional atmospheric model solves primitive equations, including a land surface model and physical packages for radiation, cloud microphysics, subgrid-scale convection, and turbulence (Wang et al. 2003). The model domain extends from 55° to 135°E in longitude, and the equator to 40°N in latitude. The horizontal grid size is 0.5° and there are 28 sigma levels in the vertical. The initial and lateral boundary conditions are constructed based on the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (Kalnay et al. 1996). The lateral boundary conditions are updated four times daily. The surface boundary conditions are the weekly $1° \times 1°$ Reynolds et al. (2002) SST product. The model is initialized on 15 June 2000 and integrated for two and a half months. The July–August averages are analyzed.

The control run captures the rainband off the Western Ghats but not the intense convection in the northern Bay of Bengal and South China Sea (Fig. A1a), illustrating the difficulty in modeling monsoon convection (Lau et al. 1996). Possible reasons for these deficiencies include inadequate representation of narrow mountains that are often only 100 km wide, and inadequate physics and their interaction with circulation in the model.

In the perturbed run, we impose diabatic heating on

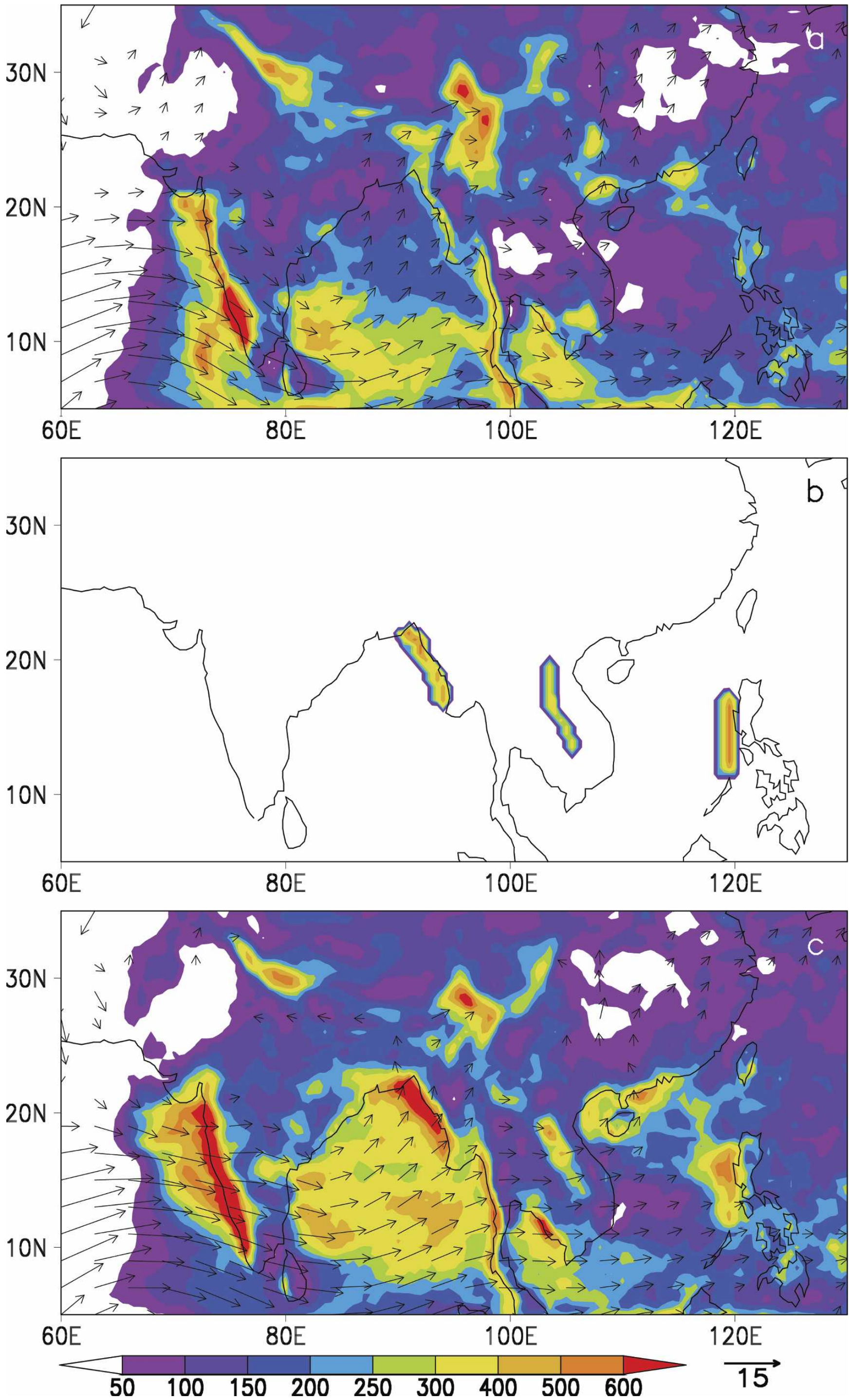

FIG. A1. Jul–Aug mean precipitation (mm month^{-1}) and 850-hPa wind velocity vectors simulated in (a) the control and (c) perturbed runs. (b) Orographic rainfall (mm month^{-1}) prescribed in the perturbed run.

the west coasts of Myanmar and the Philippines and on the slope of Annam Cordillera (Fig. A1b), where the control run severely underestimates orographic-induced rainfall. The heating profile in the vertical follows the observations of Yanai et al. (1973), peaking at 500–300 hPa and tapering off both up- and downward, with the maximum heating rate of 7.5 K day^{-1}. While further tuning would probably improve the control simulation to some extent, this model, though imperfect, appears appropriate for a qualitative demonstration of mesoscale orographic effect.

The precipitation distribution in the perturbed run (Fig. A1c) resembles observations (Fig. 1) more closely than in the control. Most notably, there is an active convection center, and the southwest monsoon intensifies by as much as 5 m s^{-1} at 850 hPa over the northern Bay of Bengal. Convection becomes more active also in the Arabian and South China Seas and off the Cambodian coast while little improvement is achieved at the foothills of the Himalayas. It is worth noting that the model's sensitivity to orographic rain is probably a lower limit since it is forced back to observed fields on its lateral boundaries.

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