On the Space-Time Patterns of Precipitation in the Himalayan Range: a Synthesis

Ana P. Barros
Pratt School of Engineering, Duke University, Box 90287, Durham NC 27708,
e-mail: barros@duke.edu

Abstract

Through diagnostic studies combining space-time scaling analysis of ground-based hydrometeorological observations, radiosonde profiles, METEOSAT and TRMM satellite data, as well as simulations using a Cloud Resolving Model, we were able to identify and characterize the dominant weather systems and associated precipitation processes in the Central Himalayas: a) monsoon depressions; b) wintertime storms; c) stationary orographic gravity waves; and d) ridge-locked convection. Our analysis shows that while the first two regimes are associated mainly with large-scale circulations, and exhibit strong inter-annual variability in frequency, intensity and spatial track; the second two regimes control the diurnal cycle during the monsoon and the spatial distribution of precipitation year round (Barros et al. 2004a-b, Lang and Barros 2004, Magagi and Barros 2004, Barros and Lang 2003, Lang and Barros 2002, Barros et al. 2000). Therefore, a synthesis of Himalayan hydrometeorology is proposed that relies on three principal modes of space-time variability: 1) an inter-seasonal mode linked to large-scale dynamics that explains infrequent events producing significant amounts of precipitation over one-three day periods (wintertime storms and monsoon depressions); 2) a regional mode linked to ocean-land-atmosphere interactions over Northern-India and the Bay of Bengal at time-scales of days to weeks consistent with the succession of rainy and dry episodes during the break and active phases of the monsoon; and 3) an orographic mode that explains the spatial variability of the diurnal cycle on the Himalayan range during the monsoon.

Keyword: Himalaya, Precipitation, Monsoon, Climate

1. Introduction

This manuscript consists of a review of recent publications that constitute the intellectual foundation of the synthesis proposed in the abstract.

2. Ground Observations

A hydrometeorological network was installed in the Marsyandi river basin in Central Nepal to obtain high-frequency (1/2 hourly) measurements of rainfall and snow accumulation, temperature, relative humidity, wind direction and speed along upwind ridges and adjacent valleys in central Nepal up to 5,500 m, and then into the rainshadow. The first phase of the hydrometeorological network was installed during the pre- and post-monsoon seasons in 1999 to augment the existing operational network operated by The Nepalese Department of Hydrology and Meteorology. This network has been enlarged by five stations and improved in the pre-monsoon season of 2000 with NSF funding. Currently the network consists of 20 operational stations, including six towers, distributed by three ridges, two valleys and the rainshadow plateau behind the Annapurna Range into the Tibetan Plateau (Barros et al. 2000). In the Spring of 2001, one of the network towers (Telbrung specifically, see diagram to the right) was equipped with radiation sensors (solar, longwave, PAR), soil temperature and soil moisture probes at three different depths, as well as relative humidity, surface pressure and air temperature and wind speed and direction sensors at two different levels.

The Marsyandi network provided new insights into the water cycle of the Himalayan region. For the first time, it was possible to document the widespread and long-lasting rainfall events associated with the monsoon onset in the region, showing that although precipitation mechanisms may differ, the monsoon onset is equally strong up to 5,000 m. Along altitudinal gradients in the Middle Himalayas, the annual precipitation total amounts to 4 m of water equivalent per unit area, and we do not detect substantial changes with elevation up to 5,000m. However, the timing and phase of precipitation does change for elevations above 3,000m with increasing snow component that reaches about 40% at 5,000m. The strong rainshadow effect in the monsoon season is not apparent during the winter. We find similar accumulations of snow from our highest station on the upwind slopes and up the valleys in the north-facing slopes of the Annapurnas into the Tibetan Plateau. This can be explained in part by the fact that snow is lighter than rain, and therefore can be transported and distributed over large distances.

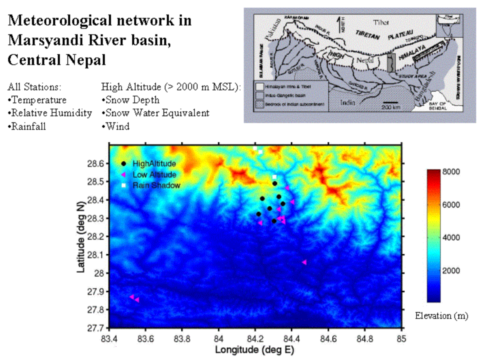

Fig. 1: Geographic location and layout of the network.

Analysis of METEOSAT data suggests however that the origin and pathways of storm systems during the winter season are very different from those during the monsoon and thus should be studied separately. Beside the aforementioned rainfall totals, both Barros et al. (2000) and Lang and Barros (2002a) noted significant spatial variability in precipitation (factor of ~4 over ~10 km distance), which did not show any specific dependence on elevation, particularly at the seasonal scale.

In addition, Barros et al. (2000) noted an interesting nocturnal peak in rainfall, just past midnight (See Fig.2 below).

This is unusual for mountainous regions, which often show an afternoon peak associated with diurnally forced upslope flow. While the afternoon peak is visible in the data (Barros et al. 2000), it is secondary, particularly at low elevations. One of the more interesting facets of the nocturnal rainfall peak is that it reaches a maximum during the summer monsoon, while during other times of the year the afternoon peak is predominant.

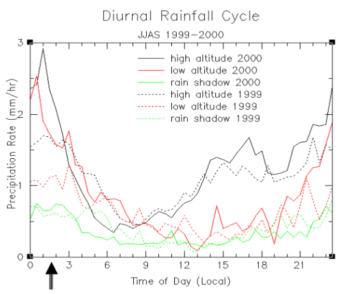

Fig.2: Average diurnal cycle of monsoon rainfall using stations marked in Fig.1 above.

3. Hydroclimatic Scenarios - Monsoon Onset

The local and large-scale aspects of the 1999, 2000 and 2001 monsoon onsets in this region have been described and explained through a variety of observations (Lang and Barros 2002, Barros and Lang 2003). The onsets manifested themselves in the form of heavy, multi-day rain events, which then heralded the arrival of subsequent daily/near-daily rainfall for the rest of the summer season. The rain events were synchronized with a regional wind shift to moist, conditionally unstable, southeasterly upslope flow. The rain systems consisted of broad areas of stratiform rain with embedded convection. The large variability in rain totals was the result of variability in convective activity; rain gauges with larger fractions of convective rainfall generally received the most rain, and vice-versa. Large-scale circulations likely set the stage for high precipitation accumulations. But small-scale and mesoscale circulations, affected by the local topography and unresolved by the ECMWF analyses used here, probably played key roles in actually realizing the heavy rains from convection, and determining which gauges received the most rain.

Through an examination of the large-scale conditions, it was determined that Bay of Bengal monsoon depressions were the proximate cause of the onsets in central Nepal. These depressions occurred very early in the season, as the Indian monsoon was strengthening and spreading northward. The most relevant features of these depressions were the enhanced winds on their northeastern flanks, in response to storm motion and blocking by the Himalayas. These winds provided moist upslope flow in central Nepal, and the convergence caused by their eventual deceleration led to the development of organized convection in this region. In summary, onset monsoon depressions tend to form over the easterly notch of the monsoon trough over the Bay of Bengal, and propagate westward on the northern flank of the westerly jet over the Indian subcontinent: the more southward the jet, the weaker the interaction with the easterly vertical shear along the Himalayas, keeping the depressions away from the Himalayan range, and favoring disorganized convection over northern India. For example, the 2001 onset depression moved mostly west from the Bay, and did not interact as strongly with the mountains as did the onset depressions from 1999 and 2000 (Lang and Barros 2002). Therefore, although the atmospheric structure exhibited definite changes, rainfall totals were not as high as in 1999 and 2000 because convection associated with the depression did not reach the mountains. That is, local processes facilitated by the synoptic SE monsoon flow were more important for rainfall during the 2001 onset.

4. MOHPREX – Monsoon Himalaya Precipitation Experiment

In June of 2001, with funding from the National Science Foundation, MOHPREX (Monsoon Himalaya Precipitation Experiment) took place. The experiment consisted of launching GPS radiosondes at 3-hour intervals from a location within the network region at the foothills of the Himalayan range during the 25 days at the beginning of the monsoon (Barros and Lang 2003). Although this experiment proper took place without NASA funds, several participants were supported by TRMM and the Marsyandi network provided the essential infrastructure. The comprehensive data sets obtained during MOHPREX are essential to evaluate the skill of our modeling efforts vis-à-vis the reproduction of the regional thermodynamic structure of the lower atmosphere during the monsoon, and to elucidate the role of surface hydrological processes on the diurnal cycle of rainfall which will be instrumental in establishing confidence to extrapolate our simulations of the space-time variability of rainfall from Central Nepal to the entire Himalayan range.

5. Modeling

A three-dimensional, anelastic, and non-hydrostatic cloud-resolving model (CSM) originally introduced by Clark (1977, 1979) and Clark and Hall (1991, 1996) was used in our modeling experiments. The focus of our initial modeling effort was to investigate the daily cycle of orographic effects on the spatial variability of winds and rainfall under monsoon conditions (deep moist flow) in the Himalayas (Barros and Lang 2003, Barros et al. 2004). The results indicate that orographic gravity waves forced by the underlying terrain may be responsible for much of the observed spatial variability. Vertical motion cells formed band-like structures that remained largely stationary in time, with updrafts on the slopes and downdrafts over ridges. Predominant wind direction was a critical factor in the spatial pattern of meteorological fields, reflecting the change in effective topography presented as an obstacle to flow. Upvalley flow in response to diurnal solar forcing was strongest in open valleys and weakest in enclosed ones. This flow weakened but did not reverse itself during the evening. The lack of a coupled land model to incorporate the diurnal cycle of surface fluxes as boundary conditions prevents the development of surface convergence zones along the Himalayan range, which may be critical to produce the observed nocturnal rainfall, a distinctive feature of the diurnal cycle of precipitation during the monsoon. For illustrative purposes, we discuss here a simulation of the 1999 monsoon onset. The model was initialized with ECMWF analysis data, with three nested grids at 24, 4, and 2 km resolution centered with a sub-domain that encompasses the central Nepalese Himalayas. Model simulations of the spatial distribution of cloud fields were compared to IR satellite imagery for the same times (see above). Note the rotational cloud structure at approximately 0600 UTC June 12, 1999, which is readily apparent in the IR imagery. The actual rain rates obtained from simulation results have a maximum near 70 mm/hr and their locations and spatial structure concur with the TRMM estimates of maximum values near 70 - 80 mm/hr.

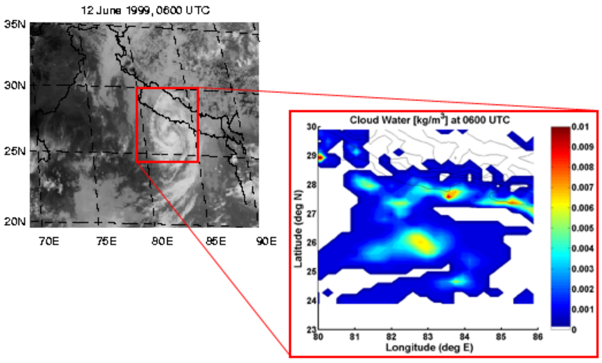

Fig. 3: Model simulations of onset depression in 1999.

6. Winter Hydrometeorology and Snow Storms

Snowfall contributes up to 25-35% of annual precipitation at high elevations in the central Himalayas. This percentage increases with altitude and tends to mitigate differences in annual precipitation between drier very high altitude stations (> 4000 m MSL) and wetter lower elevation ridge stations (3000-4000 m MSL). The snow contribution can be up to 100 cm or more, liquid water equivalent. However, these amounts are strongly modulated by inter-annual variability, which can exceed 20-30% of annual totals. Low-elevation stations (< 3000 m MSL) stay above 0 °C and receive little rain during the winter months. The bulk of winter precipitation in the central Himalayas is caused by so-called Western Disturbances, which are westerly waves trapped and intensified by the unique large-scale topographic features, most notably the notch formed by the Himalayas and Hindu-Kush mountains. The inter-annual variability of these systems is large, but difficult to predict based on popular climate indices (ENSO, AO, etc.). There is some evidence suggesting that the overall strength of the circumpolar westerly flow and the placement of the wave with respect to the Tibetan Plateau (north or south) are controlling factors in the frequency of snowstorms. Modeling simulations suggest that orographic forcing is the dominant factor in wintertime precipitation in the central Himalayas (Lang and Barros 2004, Barros et al. 2004). Significant precipitation in this region only occurs when the large-scale flow evolves to a favorable geometry with respect to the mountains. In addition, fast-moving precipitation features likely associated with along-boundary waves play an important role in bringing precipitation to lower elevations.

7. Energy and Moisture Fluxes - Latent Heating Retrieval

Based on a cumulus convection parameterization and the thermodynamic equilibrium equation, we developed a simple algorithm to extract the vertical profile of the latent heating from a combination of radiosondes and TRMM-PR data, mainly the radar reflectivity and the rain rate estimates. The methodology was evaluated through an application to the Himalayan region [70-95E, 15-32N]. As a first step we determine the spatial and temporal criteria that provided a convenient match between the TRMM-PR data and the radiosondes. Then, cloud parameters and the rain rates at the top of the moist layer were extracted from the TRMM-PR 2A25 products. For the months of June 1999, June 2000, and June 2001, average values of the maximum latent heating are 7.5 K hr^{-1}, 10 K hr^{-1}, and 9.50 K hr^{-1}, respectively, with a high variability probably related to the intrinsic variability of cloud and atmospheric parameters. Mean values of 4.06 km, 3.43 km, and 4.44 km were obtained, respectively, on June 1999, June 2000, and June 2001, for the height of the maximum latent heating. These results place the peak production of latent energy at the average height of the great Himalayan range, which is consistent with the observed distribution of rainfall in the region (Magagi and Barros, 2004).

8. Orographic Land-Atmosphere Interactions in the Himalayas During the Monsoon and Spatial Variability of Precipitation

The linkages between the space-time variability of observed clouds, rainfall, large-circulation patterns and topography in northern India and the Himalayas were investigated using remote sensing data. The research purpose was to investigate the hypothesis that cloudiness patterns are dynamic tracers of rainstorms, and therefore their temporal and spatial evolution can be used as a proxy of the spatial and temporal organization of precipitation and precipitation processes in the Himalayan range during the monsoon. The results suggest that the space-time distribution of precipitation, the spatial variability of the diurnal cycle of convective activity, and the terrain (landform and altitudinal gradients) are intertwined at spatial scales ranging from the order of a few kms (1-5 km) up to the continental-scale. Furthermore, this relationship is equally strong in the time domain with respect to the onset and intra-seasonal variability of the monsoon.

Infrared and microwave imagery of cloud fields were analyzed to characterize the spatial and temporal evolution of mesoscale convective weather systems and short-lived convection in Northern India, the Himalayan range, and in the Tibetan Plateau during three monsoon seasons (1999, 2000 and 2001). The life cycle of convective systems suggests landform and orographic controls consistent with a convergence zone constrained to the valley of the Ganges and the Himalayan range, bounded in the west by the Aravalli range and the Garhwal mountains and in the East by the Khasi Hills and the Bay of Bengal, which we call the Northern India Convergence Zone (NICZ). The NICZ exhibits strong night-time activity along the south-facing slopes of the Himalayan range, which is characterized by the development of short-lived convection (1-3 hours) aligned with protruding ridges between 1 and 3 AM. The intra-annual and inter-annual variability of convective activity in the NICZ were assessed with respect to large-scale synoptic conditions, monsoon activity in the Bay of Bengal, and the modulating role of orography. Scaling analysis of cloudiness suggests three different scaling regimes of orographic land-atmosphere interactions: 1) a synoptic-scale regime [70-80 km]; 2) an orographic meso- regime [30-70 km] associated with the succession of wide valleys and bulky terrain features; and 3) an orographic meso- regime [30 km] associated with the complex succession of protruding south-facing ridges and narrow valleys that characterize the Himalayan foothills between 3,000 and 5,000 m. In addition, empirical orthogonal function (EOF) and canonical correlation (CC) analysis suggest that joint modes of variability of monsoon weather and topography, which we call orographic land-atmosphere interactions, modulate the space-time variability of cloudiness in the region.

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