INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **24**: 1645–1659 (2004)

SPATIAL PATTERN IN THE PRECIPITATION REGIME OF NEPAL

SUNIL R. KANSAKAR,[a,b] DAVID M. HANNAH,[a,*] JOHN GERRARD[a] and GWYN REES[c]
[a] *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
[b] *Department of Hydrology and Meteorology, PO Box 406, Babar Mahal, Kathmandu, Nepal*
[c] *Centre for Ecology and Hydrology (CEH)-Wallingford, Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK*

Received 9 June 2003
Revised 4 August 2004
Accepted 4 August 2004

ABSTRACT

A large-scale perspective is provided upon the nature of precipitation regimes across Nepal by classifying long-term mean monthly precipitation data for 222 stations. The classification methodology is shown to be a useful tool for identifying underlying spatial structure in precipitation regime shape (seasonal variability) and magnitude (size) in an extreme physical environment where climatological patterns are complex and poorly known. Four precipitation regime shape classes are identified: (a) July–August peaks are typical of western regions; (b) marked July peaks are characteristic of the central region and eastern lowlands; (c) July peaks with gradual onset are mainly concentrated in eastern Middle Mountains; and (d) July–August peaks with winter precipitation are confined to western higher mountains, particularly the Trans-Himalayan region. Four precipitation regime magnitude classes are found: (a) low regimes clearly dominate western high-mountain areas but occur more widely across the High Mountains and High Himalaya; (b) intermediate regimes are distributed from east to west at low altitude, dominating the western Terai/Siwaliks; (c) moderately high regimes are widespread but most evident in the Terai (plains) to Middle Mountains of central and eastern parts and eastern high mountains; and (d) high precipitation zones are situated near Pokhara and northeast of the Kathmandu Valley around Langtang. A composite (shape and magnitude) regime classification indicates the key controls upon spatial patterns in Nepalese precipitation to be: length and timing of the summer monsoon (duration decreases east to west with later onset and earlier withdrawal in the west); successively higher altitude, east–west-trending mountain ranges causing rainfall to decline broadly south–north; topographic barriers that induce local rain shadows (lee) and precipitation hotspots (windward side); and westerly weather systems supplying winter precipitation to the northwest mountains. Although general patterns relating to zonal movement of the summer monsoon and physiographic (mountain ranges) controls upon precipitation may be identified, the role of mountainous relief in yielding localized precipitation patterns is significant. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: precipitation; monsoon; mountain climatology; regimes; regionalization; classification; Himalaya; Nepal

1. INTRODUCTION

The majority of precipitation studies of southern Asia have excluded the Himalayan belt due to the region's extreme, complex topography and lack of adequate rain-gauge data (Shrestha, 2000). Although numerous publications exist concerning Indian rainfall patterns (e.g. Kulkarni *et al*., 1992; Kumar *et al*., 1992; Subbaramayya and Naidu, 1992; Kripalani *et al*., 1996; Goswami *et al*., 1999), there has been very little examination of precipitation across Nepal, which represents the central Himalayan region. More specifically, research into regionalization of precipitation (i.e. determination of homogeneous areas) across Nepal has been extremely limited. It is important to understand spatial patterns in precipitation across Nepal from a climatological perspective and also for socioeconomic reasons. The major river systems of Asia are sourced from Himalayan headwaters and the subsistence agriculture practised by 90% of the economically active

---

[*] Correspondence to: David M. Hannah, School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK; e-mail: d.m.hannah@bham.ac.uk

population of Nepal is highly water dependent (Chalise, 2002). Landsliding and many other geohazards associated with the Himalayan environment are also precipitation driven (e.g. Gerrard and Gardner, 2000).

Nayava (1974) published the first overview of Nepalese rainfall in the open literature. Subsequently, Nayava (1980) described general features of the atmospheric circulation over Nepal and analyzed mean annual and summer monsoon precipitation for 168 stations (1956–75). This study indicated summer monsoon rainfall as a proportion of the annual total is broadly similar across the country (80–90%), except in the far west (55–70%). Shrestha *et al.* (2000) examined spatial and interannual variability in precipitation using data for 78 stations (1959–94). Composite precipitation records were derived for six regions across Nepal by averaging records for all stations. Such data pooling does not permit full analysis of rainfall patterns because regional averages smooth out finer scale spatial variability. An all-Nepal precipitation time-series was also developed. No distinct long-term trends were found in the regional or all-Nepal records over the 36 years. The all-Nepal time series compared poorly with the all-India precipitation record, highlighting the problems in generalizing about the South Asia monsoon and probable inaccuracy of extrapolating Indian research to the central Himalayan location of Nepal.

Shrestha (2000) used the percentage departure of Nepal monsoon rainfall (NMR: total June–September rainfall averaged for 60 stations) from its long-term mean (1957–88) to investigate interannual variation in summer monsoon precipitation in relation to the southern oscillation index (SOI). Negative (positive) values for the SOI were associated predominantly with lower (higher) NMR. A positive correlation was shown for months during and after the summer monsoon and SOI; but the relationship with SOI was poor for months prior to the summer monsoon. Shrestha (2000) also mapped annual and summer monsoon rainfall using isohyetals and concluded that the summer monsoon was most active in southern Nepal; however, on closer inspection, spatial patterns are much more complex.

At the smaller river basin-scale, precipitation during individual summer monsoons has been studied in the High Himalaya and central Nepal. Higuchi *et al.* (1982) found summer monsoon totals to be two to five times greater along ridge tops than in the main valley of the Dudh Kosi, High Himalaya. The daily timing of rainfall also varied between ridge tops (daytime maximum) and valley bottoms (nocturnal maximum) due to inferred convectional activity. Recent work has been conducted on summer monsoon dynamics in the Marsyandi basin, central Nepal, using a combination of rain-gauge networks, radiosondes, European Centre for Medium-Range Weather Forecasting analysis and remote sensing (Barros *et al.*, 2000; Lang and Barros 2002; Barros and Lang, 2003). For the 1999 monsoon, Barros *et al.* (2000) suggested TRMM satellite-derived rainfall estimates to be more accurate at low than at high elevations, although precipitation radar yielded estimates consistent with rain-gauges at elevations of 1000–2000 m above sea level (a.s.l.). Analysis of a 3-year data set from high-altitude gauges showed annual precipitation amounts of up to 5000 mm at elevations up to 4500 m a.s.l. (Barros *et al.*, 2000). Lang and Barros (2002) investigated monsoon onset in 1999 and 2000 with respect to large-scale circulation and noted up to an eightfold difference in rainfall amongst rain gauges due to the effect of small-scale terrain features. Barros and Lang (2003) identified a postmidnight peak in rainfall during June 2001 attributed to strong convection as a result of the interaction of ambient monsoon flows with the southerly slopes, modulated by diurnal variability in atmospheric state. Although these basin-scale studies provide useful insight into local variability and precipitation-generating processes, it is difficult to upscale from this research to generalize about wider spatial patterns, especially across mountainous relief.

There is a clear research gap in defining spatial variability in annual precipitation regimes across Nepal. The work reviewed above has largely dealt with the summer monsoon period and annual precipitation totals. Therefore, there is a need to consider the seasonal behavior of precipitation over the year (i.e. the form and magnitude of the precipitation regime). Large-scale patterns in precipitation timing are particularly poorly researched but very important, as knowledge about intra-annual variations is most critical for water resource planning (Chalise, 2002). Moreover, with respect to the spatial coverage and compositing of previously analyzed data sets, this has been somewhat inadequate to consider the detailed spatial structure of precipitation across Nepal, including the effects of extreme and complex topography.

This paper aims to characterize the nature of precipitation regimes across Nepal (using mean monthly data for 222 stations) and, thus, to elucidate the key controlling factors upon spatial patterns in seasonal precipitation behavior. This aim is achieved through the following specific objectives: (a) to test a classification scheme that identifies the ‘shape’ (seasonality) and ‘magnitude’ (size) of annual precipitation regimes; (b) to identify precipitation regime regions across Nepal; and (c) to interpret of the emergent precipitation regime regions.

2. STUDY AREA

Nepal extends 885 km east–west and 145–248 km north–south; and it is dominated by the northwest-to-southeast-trending Himalayan mountain range. Within this relatively small latitudinal extent, altitude rises from 60 m a.s.l. to the world’s highest peak (Mount Everest at 8848 m a.s.l.). The country can be divided into five physiographic regions. From south to north, and with increasing altitude, these are (Figure 1): (a) Terai, (b) Siwaliks, (c) Middle Mountains, (d) High Mountains and (e) High Himalaya. The Terai and Siwaliks are subtropical. The Middle Mountains are subtropical in valley bottoms but warm temperate on valley sides and cool temperate on higher ridges, which experience occasional snowfall. The High Mountains and High Himalaya are alpine with a nival climate above the snowline (3000–5000 m a.s.l.).

The timing and amount of precipitation and its distribution across Nepal are controlled fundamentally by the annual monsoon system. Four climatological seasons can be identified, for which Nayava (1980) details the associated synoptic weather patterns. The *pre-monsoon season* (March–May) is characterized by hot, dry weather with scattered rainfall with moderate to strong westerlies prevailing; toward the end of this period, it becomes more humid with thunder storms. The *summer monsoon season* (June–September) is governed by the southeasterly moisture-laden air-mass moving from the Bay of Bengal. The monsoon reaches eastern Nepal with a modal onset date of 10 June and advances westwards covering the whole country within a week. The *post-monsoon season* (October–November) has a modal onset date of 21 September. Rainfall activity is substantially reduced, with November typically the driest month. The *winter season* (December–February) is generally dry, although westerly weather systems may bring cold air and winter precipitation to northwestern areas (Shrestha, 2000).

There are three main river systems of Nepal that divide the country into approximately equal areas (Figure 1): (a) the Karnali in the west, (b) the Narayani in the central region, and (c) the Sapta Koshi in

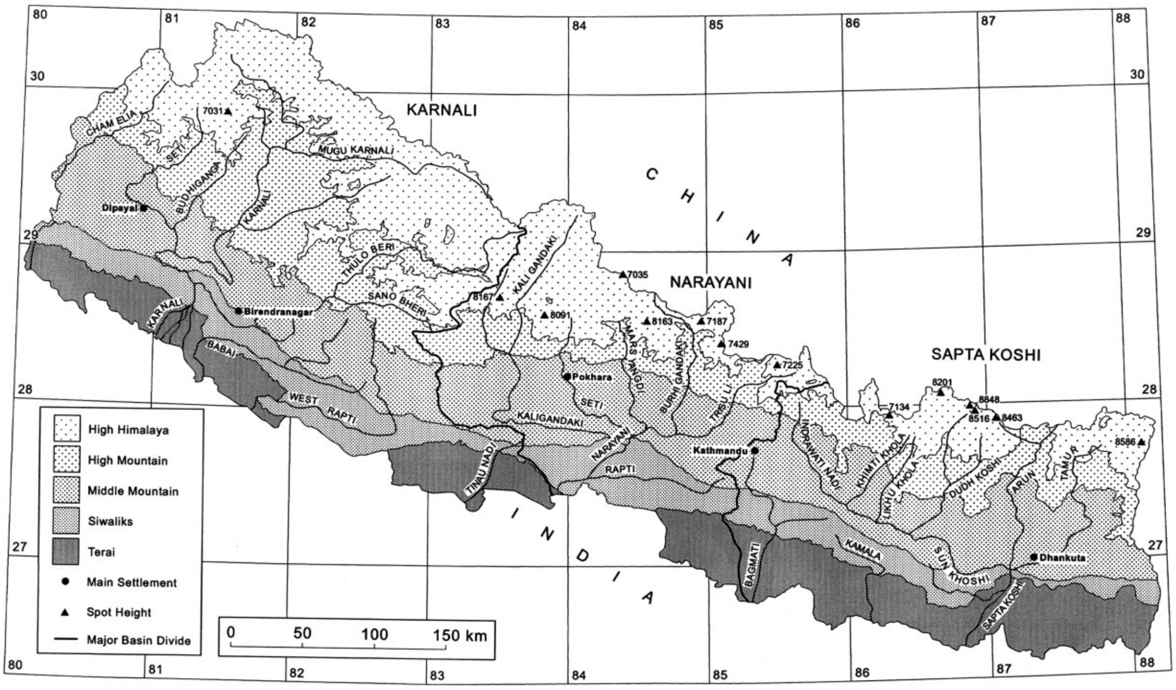

Figure 1. Physiographic regions and major drainage basins of Nepal

the east. This division is used (along with the physiographic regions) to structure data analyses, as it provides a convenient framework within which to examine regional precipitation variations.

3. DATA AND METHODOLOGY

3.1. Precipitation network and data

Nepal's precipitation network comprises 440 stations, of which 160 have only been established since 1998. The limited availability and variable quality of rain-gauge data remain a hindrance to research. Daily precipitation time-series were identified for 222 stations. These stations were selected because data are high quality and they provide optimum spatial coverage. Records vary in length from 12 to 31 years with an average length of 22 years and >95% of stations possessing >15 years; data span 1965 to 1995. Station elevations range from 80 to 3803 m a.s.l. Inspection of rain-gauge locations reveals most of the stations chosen follow main river valleys and the network to be particularly sparse in the northwest. It is acknowledged that Higuchi *et al.* (1982) and Barros *et al.* (2003) found marked differences in precipitation between valley bottoms and ridge tops at the basin-scale (see Section 1). However, although this paper's results may be biased due to the absence of high elevation rain gauges, it does employ considerably more points than other national-scale studies, cf. Shrestha *et al.* (2000) with 78 stations and Shrestha (2000) with 60 stations.

Prior to analyses, screening of daily data was conducted by visual comparison and double-mass curve analysis of neighboring gauges. Monthly totals (aggregated up from daily totals) were averaged across all available years to characterize long-term precipitation regimes (i.e. seasonal behavior over an annual cycle); hence differences in record lengths between stations should not influence results meaningfully. The selection of overlapping records only would have significantly reduced the spatial extent of observations. This research is part of a wider project to assess large-scale hydroclimatological and water resource patterns for Nepal; therefore, the hydrological year was taken as the time frame for analysis. Kansakar *et al.* (2002) and Hannah *et al.* (in press) identify Nepal's hydrological year to commence in March. This annual division is equally appropriate for precipitation, as the pre-monsoon season also starts then.

3.2. Regime classification methodology

Since it is important to assess the timing and size of annual precipitation regimes, a methodology is adopted that uses hierarchical, agglomerative cluster analysis to classify regimes separately according to their 'shape' and 'magnitude' (devised by Hannah *et al.* (2000), adapted by Harris *et al.* (2000), evaluated by Bower *et al.* (2004)). In summary, the 'shape' classification identifies stations with a similar form of annual regime, regardless of the absolute magnitude. In this application, the 'magnitude' classification is based upon five indices (i.e. the mean, minimum, maximum, standard deviation of mean monthly precipitation observations and summer monsoon season (June–September) total) for each station, regardless of their timing. This approach has the advantage that these two important regime attributes may be interpreted separately as well as jointly by simply combining shape and magnitude classes for each station to yield a 'composite' classification.

To classify precipitation regime shape independently of magnitude, the 12 monthly observations for each station were standardized separately using z-scores (mean of zero, unit standard deviation) prior to clustering. The five 'magnitude' indices were derived for the long-term regime for each station; it was necessary to standardize between indices (to control for differences in their relative values) by expressing each index as a z-score across the 222 stations.

For both shape and magnitude, classification was achieved by hierarchical, agglomerative cluster analysis using Ward's method. No single clustering algorithm is deemed universally 'best'; and different algorithms identify different groupings. Ward's method was selected because it typically outperforms other algorithms in terms of separation to give relatively dense clusters with small within-group variance (Yarnal, 1992; Griffith and Amrhein, 1997). Ward's method has been widely and successfully used in climatological studies (e.g. Stone, 1989). The structure of the cluster dendrogram and breaks of slope in the agglomeration schedule (scree) plot were used to determine the appropriate number of clusters (Griffith and Amrhein, 1997). Thus, each of the 222 stations was grouped by both regime shape and magnitude, which also permitted composite shape and magnitude classification. The spatial distribution of the shape, magnitude and composite classes allowed precipitation regime regions to be identified.

4. RESULTS AND DISCUSSION

4.1. *Precipitation regime shape*

Four precipitation regime shape classes were identified (Figure 2):

Class A,	a July–August peak with a relatively rapid onset and cessation of the summer monsoon (70 stations).
Class B,	a July peak with gradual onset and cessation of the summer monsoon (53 stations).
Class C,	a marked July peak with a rapid onset and gradual cessation of the summer monsoon (89 stations).
Class D,	a July–August peak with a secondary winter (January–March) peak (10 stations); the summer peak declines very markedly into a September–December dry spell.

For all classes, the wettest month is July; therefore, differences between groups are in terms of the length of the summer precipitation peak and the rate of rise to and decline from that peak. Class A represents a relatively short monsoon with a rapid onset and cessation, indicating little pre- and post-monsoon rainfall. Classes B and C characterize stations where the summer monsoon is intense at its July peak. However, for Class B the summer monsoon is extended (June–September) due to a gradual onset and cessation; whereas

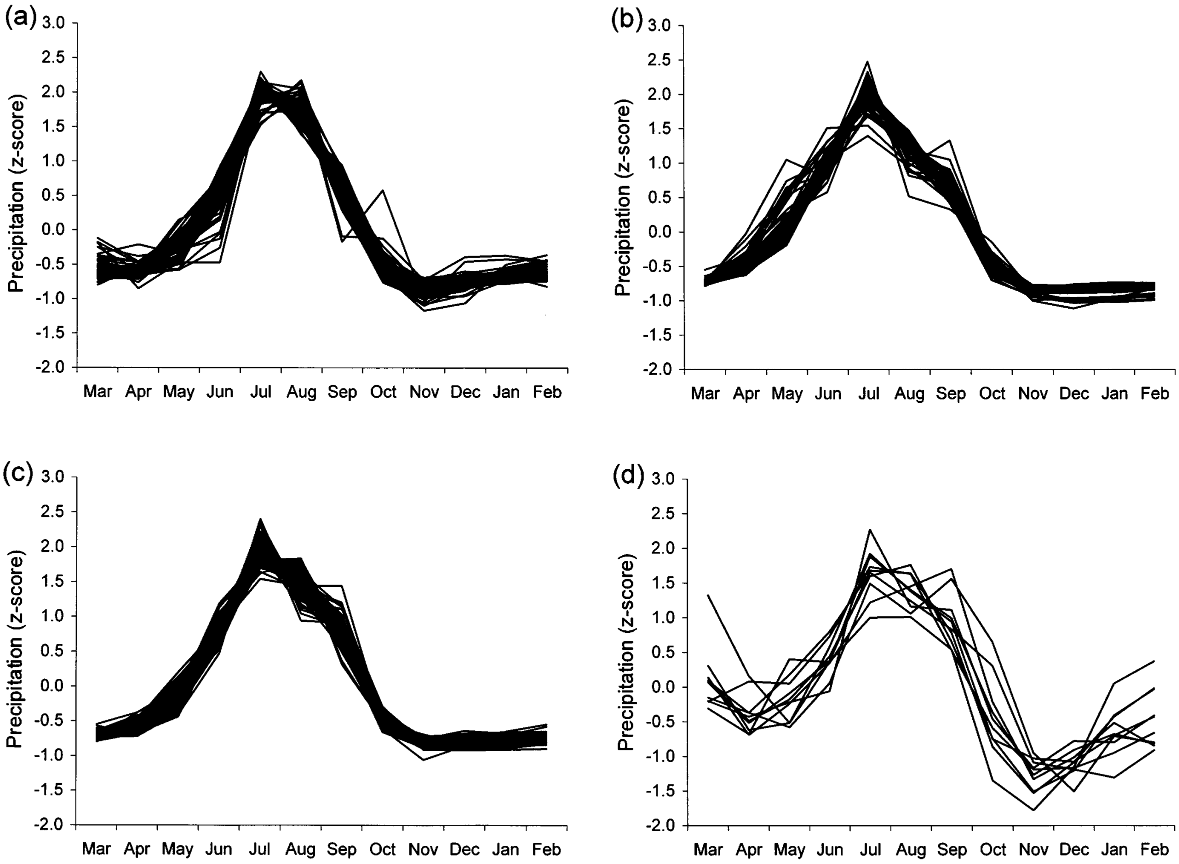

Figure 2. Standardized (z-scores) monthly values for all stations within the precipitation regime shape classes

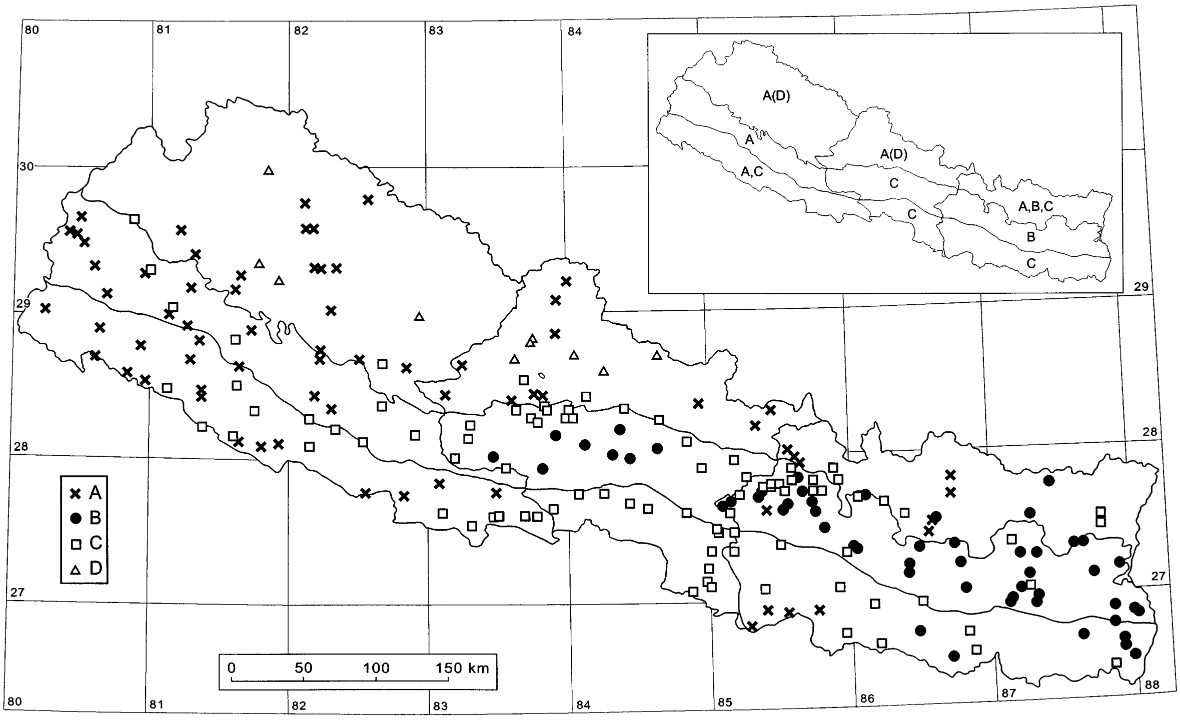

Figure 3. Spatial distribution of precipitation regime shape classes across Nepal with general summary pattern inset

Table I. Precipitation regime shape class frequencies in different drainage basins (percentages are rounded to the nearest whole number)

Class	Karnali basin	Narayani basin	Sapta Koshi basin
A	47 (64%)	11 (19%)	12 (13%)
B	—	8 (14%)	45 (51%)
C	23 (31%)	34 (58%)	32 (36%)
D	4 (5%)	6 (10%)	—

for Class C the onset is more rapid with the July peak prolonged by a gradual decline. Class D is distinct from the other regimes in possessing a secondary winter precipitation peak.

The spatial distribution of the stations within each precipitation regime shape class is illustrated in Figure 3. To examine patterns in a structured way, the physiographic regions (approximately parallel north–south) are subdivided east–west by the three main drainage basins (overlain upon Figure 3). To simplify analyses, the Terai and Siwaliks are combined, as are the High Mountains and the High Himalaya. The very distinctive Middle Mountains are kept as a single region. This subdivision differentiates nine regions of Nepal.

Summary statistics for the shape classes indicate differentiation between the three main drainage basins (Table I). The Karnali (west) is clearly dominated by Class A (64%), the Narayani (central) by Class C (58%), and the Sapta Koshi (east) by Class B (51%) but with a fair proportion of Class C stations (36%). The large number of Class C stations in all three basins suggests this regime is less influenced by any east–west-trending controls than other shape classes. These data indicate that the eastern and western basins can be fairly easily distinguished, with the central basin representing a transitional zone, as indicated by the occurrence of all four classes in the Narayani only. The dominance of Class A precipitation stations in the west is the result of a shorter and less intense summer monsoon. Class B stations, indicating a relatively

Table II. Precipitation regime shape class frequencies in the main physiographic regions (percentages are rounded to the nearest whole number)

Class	Terai/Siwaliks	Middle Mountains	High Mountains/High Himalaya
A	21 (31%)	16 (16%)	33 (57%)
B	6 (9%)	43 (44%)	4 (7%)
C	40 (60%)	39 (40%)	10 (18%)
D	—	—	10 (18%)

long monsoon, are dominant in the east. Class C possesses characteristics of both Classes A and B; thus the east-to-west differentiation in the spatial distribution is poorer. In some respects, Class C may be regarded as representing the 'typical' precipitation regime for Nepal (occurring at 40% of the stations). The number of Class D stations is comparatively small, with none occurring in the Sapta Koshi basin.

General physiography appears to influence spatial patterns in precipitation regime shape (Table II). The Terai/Siwaliks is clearly dominated by Class C (60%); the Middle Mountains region is more complex, however, with approximately equal frequencies of Classes B and C (44% and 40% respectively), as well as a number of Class A stations (16%). Class B accounts for only a small proportion of stations in the Terai/Siwaliks (9%) and the High Mountains/High Himalaya (7%). The High Mountains/High Himalaya is dominated by Class A (57%), followed equally by Classes C (18%) and D (18%). The greater occurrence of Class A at higher altitude and Classes B and C at lower elevations indicates that the east–west trending, successively higher mountains influence precipitation seasonality. The effect of mountains on precipitation has been an issue of long-standing debate (see Smith (1979) for a review). This paper does not seek to identify precipitation generating processes, which are better understood by a study of events over smaller spatial domains and using additional data to supplement rain-gauges (e.g. Barros and Lang, 2003); rather, it provides a large-scale perspective and infers key controls at the all-Nepal level in greater detail than previous work. Thus, it is not possible to explain results in terms of forced uplift, cyclonic convergence, the seeder–feeder mechanism and/or convection (see Johansson and Chen (2003) for an updated summary); however, the shape classes clearly illustrate relief to limit northwards penetration of precipitation and so reduce length and timing of the summer monsoon season.

All Class D stations are located in the High Mountains/High Himalaya, many north of the main physiographic divide in the Trans-Himalayan area. These stations are in the rain shadow of the Himalaya, receive reduced input from the summer southwest monsoon but experience precipitation (rain and snow) from air-masses moving from the west in the winter season (Nayava, 1980). The western disturbance is most active in the northwestern part on the leeward side of the High Mountains and High Himalaya (Shrestha, 2000).

The frequencies of precipitation shape regimes in the combined drainage basin and physiographic regions are shown in Table III. In the Sapta Koshi, the Terai/Siwaliks is dominated by Class C and the Middle Mountains by Class B. The High Mountains/High Himalaya of the Sapta Koshi exhibits a more complex pattern with Classes A, B and C almost equally represented. In the Narayani basin, the Terai/Siwaliks is clearly dominated by Class C, as is the Middle Mountains. Class A is most frequently represented for the High Mountains/High Himalaya of the Narayani but Class D is dominant in the High Himalaya. In the Karnali basin, the Terai/Siwaliks is dominated by Class A and, to a slightly lesser degree, Class C. Class A dominates both the Middle Mountains and High Mountains/High Himalaya of the Karnali with Class D occurring in the High Mountains/High Himalaya.

A summary of these patterns in precipitation regime shape is provided in the inset to Figure 3. The most predictable regions, in terms of dominant shape classes, are the Karnali (largely Class A, but with a significant proportion of Class C stations in the Terai/Siwaliks), the Terai/Siwaliks and Middle Mountains of the Narayani (Class C), and the Terai/Siwaliks (Class C) and Middle Mountains (Class B) of the Sapta Koshi. The High Mountains/High Himalaya of the Sapta Koshi is a more complex region, although Class A dominates the

Table III. Precipitation regime shape class frequencies in different river basins and in different physiographic regions (T/S: Terai/Siwaliks; MM: Middle Mountains; HM/HH: High Mountains/High Himalaya)

Class	Karnali basin			Narayani basin			Sapta Koshi basin		
	T/S	MM	HM/HH	T/S	MM	HM/HH	T/S	MM	HM/HH
A	17	15	15	—	—	11	4	1	7
B	—	—	—	—	8	—	6	35	4
C	15	7	1	14	16	4	11	16	5
D	—	—	4	—	—	6	—	—	—

Table IV. Average values of the precipitation indices for stations within the four regime magnitude classes (1: low; 2: intermediate; 3: moderately high; 4: high)

Precipitation magnitude index	Class average				Average (all stations)
	1	2	3	4	
Mean (mm month^{-1})	94.4	130.5	182.8	317.8	147.9
Maximum (mm month^{-1})	279.5	446.9	593.0	980.2	473.6
Minimum (mm month^{-1})	8.4	4.8	12.1	19.9	9.5
Standard deviation (mm month^{-1})	94.0	153.7	210.0	359.0	165.6
Monsoon total (mm)	833.2	1285.2	1782.1	3082.5	1414.6
No. of stations	75	55	79	13	222

High Mountains/High Himalaya of the Karnali and Narayani and Class D is common in the Trans-Himalayan region.

4.2. *Precipitation regime magnitude*

Four regime magnitude classes are clearly evident, which can be arranged with respect to the five precipitation indices in Table IV:

Class 1, low with the lowest values for four indices and second lowest value for minimum monthly precipitation (75 stations).
Class 2, intermediate with second lowest values for all indices and lowest minimum monthly precipitation (55 stations).
Class 3, moderately high, with the second highest values for all five indices (79 stations).
Class 4, high, with the highest values for all five indices; notably, total summer monsoon rainfall is over 1000 mm greater than Class 3 (13 stations).

The spatial distribution of precipitation magnitude regimes is shown in Figure 4. As for shape classes, patterns are analyzed with respect to the major drainage basin and physiographic regions. A brief, countrywide inspection of results shows low magnitude (Class 1) regimes clearly dominate the central and western High Mountains/High Himalaya region. The alignment of these mountains prevents large monsoon system inflows of moist air (Shrestha, 2000). Low precipitation areas in the eastern part are mostly the result of their location on the leeward side of the Middle Mountains range. Nayava (1980) states that rainfall increases with altitude on the windward side and sharply decreases on the leeward side in the Middle Mountains. More generally, low magnitude regimes occur over a large elevation range covering Terai to High Mountains regions (Figure 5), perhaps reflecting local topographic sheltering of some rain-gauges. Intermediate precipitation is distributed from east to west in the Terai/Siwaliks and foothills of Middle Mountains regions. It is clear that Class 2 mostly occurs at lower elevations (Figure 5). Moderately high-precipitation stations are mostly located in the

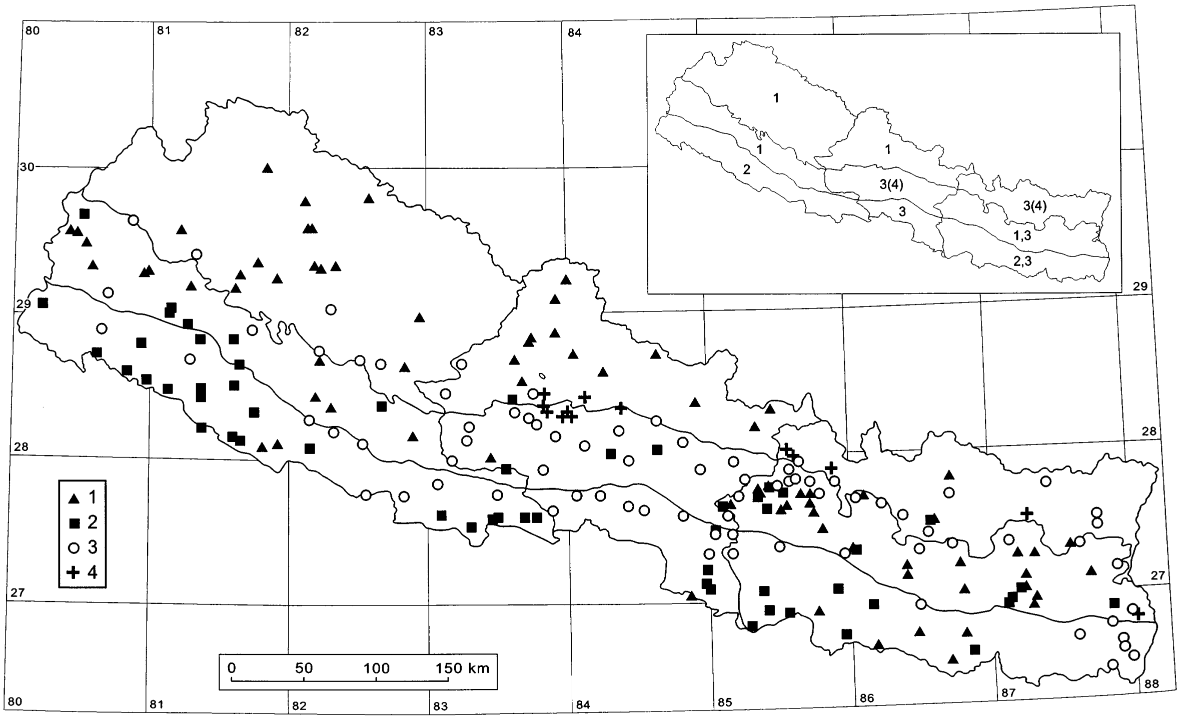

Figure 4. Spatial distribution of precipitation regime magnitude classes across Nepal with general summary pattern inset

foothills of the Siwaliks and Middle Mountains of the central and eastern regions. The Siwaliks (maximum elevation ~1500 m a.s.l.) and Middle Mountains (maximum elevation ~2400 m a.s.l.) are key topographic barriers that obstruct moist air advected from the southwest. Two clear pockets of high precipitation are located around Lumle (near Pokhara) and northeast of the Kathmandu Valley around Langtang. Many of these high magnitude precipitation stations are located on hilltops in the Middle Mountains and in the foothills of the High Mountains (Figure 5; cf. Barros *et al.*, 2000).

Summary statistics (Table V) for the Karnali clearly show low and intermediate magnitude classes to be dominant (77%), reflecting the much weaker summer monsoon in western parts. The Narayani (central) is dominated by moderately high magnitude precipitation stations (49%). Stations in the Sapta Koshi (east) are almost equally represented by low (36%) and moderately high (37%) classes, which may be accounted for by local or regional effects of highly complex basin relief (below).

In terms of broad physiography, the Terai/Siwaliks is dominated by intermediate (49%) and moderately high magnitude (39%) precipitation regimes (Table VI). The Middle Mountains have a fairly even spread of low, intermediate and moderately high magnitude classes. Two classes dominate the High Mountains/High Himalaya (low: 54%; moderately high: 30%), which may be due to these major topographic barriers inducing rainfall on the windward side and creating a rain shadow on the lee side. However, it is not only altitude that determines the precipitation patterns, but also the spatial configuration of topographic gradients and winds (Johansson and Chen, 2003).

In the Sapta Koshi, the Terai/Siwaliks is dominated equally by intermediate and moderately high precipitation regimes with a lesser amount of low magnitude stations (Table VII). The Middle Mountains region is dominated by low magnitude regimes closely followed by the moderately high class. A detailed analysis of the Sapta Koshi in the Middle Mountains shows that an extensive 'lowland' has been created by expansion of the drainage network in an east-to-west direction following structural weaknesses in the underlying geology. An area of lower precipitation matches this lowland very closely. The surrounding 'highlands' are characterized by greater precipitation. The High Mountains/High Himalaya region of the

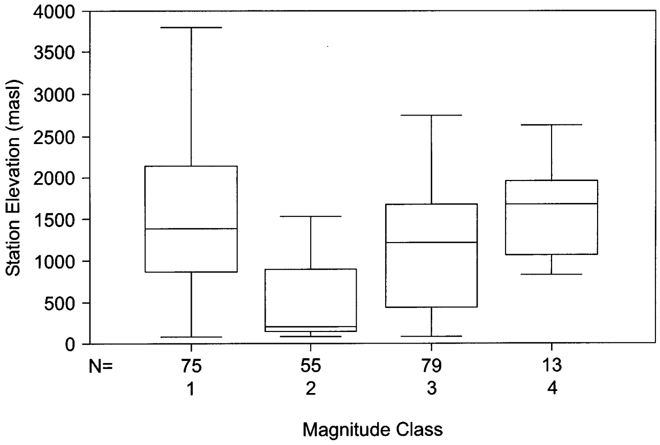

Figure 5. Box and Whiskers plots of station elevation for each precipitation regime magnitude class

Table V. Precipitation regime magnitude class frequencies in the different drainage basins (percentages are rounded to the nearest whole number)

Class	Karnali basin	Narayani basin	Sapta Koshi basin
1	28 (38%)	15 (25%)	32 (36%)
2	29 (39%)	7 (12%)	19 (21%)
3	17 (23%)	29 (49%)	33 (37%)
4	—	8 (14%)	5 (6%)

Table VI. Precipitation regime magnitude class frequencies in the different physiographic regions (percentages are rounded to the nearest whole number)

Class	Terai/Siwaliks	Middle Mountains	High Mountains/High Himalaya
1	8 (12%)	37 (37%)	31 (54%)
2	33 (49%)	20 (20%)	2 (4%)
3	26 (39%)	36 (36%)	17 (30%)
4	—	6 (6%)	7 (12%)

Sapta Koshi is dominated by moderately high regimes with four high magnitude stations. The Terai/Siwaliks of the Narayani is dominated by moderately high magnitude regimes. The Middle Mountains region is also dominated by moderately high regimes, but there are also five high magnitude stations. Low magnitude classes dominate the High Mountains/High Himalaya, but there are three high magnitude stations. In the Karnali, intermediate magnitude is clearly the main regime in the Terai/Siwaliks, whereas the Middle Mountains region is largely dominated by low magnitude with a subsidiary number of intermediate regimes. The High Mountains/High Himalaya region of the Karnali is dominated by low magnitude regimes. A summary of these patterns is illustrated in the inset to Figure 4.

4.3. Composite (shape and magnitude) precipitation regimes

A composite precipitation classification may be achieved by combining shape and magnitude; this permits standardized seasonal responses to be scaled by precipitation amount. Figure 6 illustrates the frequencies of composite classes. Of the 16 possible, 13 composite classes are observed across 222 basins. The missing composite regimes all involve Class D (July–August peak with secondary winter peak). There is only one composite regime for this shape class with low magnitude (Class 1D). As Class D is confined to western

Table VII. Precipitation regime magnitude class frequencies in different river basins and in different physiographic regions

Class	Karnali basin			Narayani basin			Sapta Koshi basin		
	T/S	MM	HM/HH	T/S	MM	HM/HH	T/S	MM	HM/HH
1	2	11	15	1	1	13	5	24	3
2	21	8	—	4	2	1	8	10	1
3	9	3	5	9	16	4	8	17	8
4	—	—	—	—	5	3	—	1	4

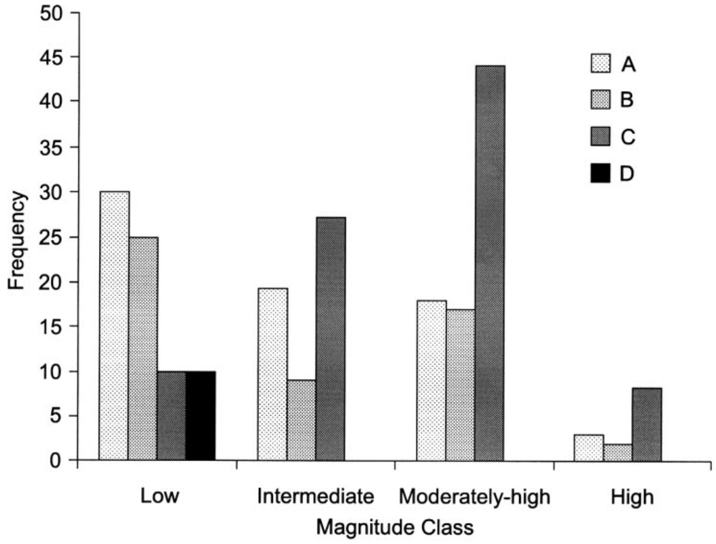

Figure 6. Frequency distribution of composite (shape and magnitude) precipitation regime classes

Nepal, often beyond the High Himalayan watershed, it may be expected that combinations are limited to low magnitude. The most common composite regime by far is Class 3C (moderately high, marked July peak; 44 stations). Classes 1A, 1B and 2C are the next most frequent regimes, occurring at 30, 25 and 27 stations respectively. Hence, the most common low magnitude regimes occur with Classes A (July–August peak) and B (July peak with gradual onset), with a much-reduced number of stations combining with Class C (marked July peak; 10 stations). In addition to Class C, intermediate magnitude regimes combine with Class A (19 stations) and, to a considerably lesser extent, Class B (nine stations). Although overall Class 3C is the dominant composite regime, moderately high magnitude joins relatively frequently, and in almost equal occurrence, with Classes A (18 stations) and B (17 stations). High magnitude regimes are the least common and combine with Classes C (eight stations), A (three stations) and B (two stations) in decreasing numbers. The general lack of exclusive shape–magnitude combinations has implications for climatological understanding and techniques. Because there is no clear evidence that the timing or length of the summer monsoon yields particular magnitudes (i.e. regime size is not dependent upon precipitation seasonality, nor *vice versa*), it is necessary to adopt analytical methods, such as those herein, that assess both these key precipitation regime characteristics.

The composite precipitation regimes are categorized according to the main drainage basins and physiographic regions of Nepal in Table VIII and mapped in Figure 7. It is possible to discern underlying spatial patterns in composite precipitation regimes, as shown in the inset to Figure 7. In the Sapta Koshi, the Terai/Siwaliks exhibits a complex pattern, but Class C dominates, particularly combined with intermediate and moderately high magnitude. The Middle Mountains region of the Sapta Koshi is more clearly dominated

Table VIII. Precipitation regime composite (shape and magnitude) class frequencies in different river basins and in different physiographic regions

Class	Karnali basin			Narayani basin			Sapta Koshi basin		
	T/S	MM	HM/HH	T/S	MM	HM/HH	T/S	MM	HM/HH
1A	2	9	11	—	—	6	1	—	1
2A	9	4	—	—	—	1	3	1	1
3A	6	2	4	—	—	3	—	—	3
4A	—	—	—	—	—	1	—	—	2
1B	—	—	—	—	1	—	2	20	2
2B	—	—	—	—	2	—	—	7	—
3B	—	—	—	—	5	—	4	7	1
4B	—	—	—	—	—	—	—	1	1
1C	—	2	—	1	—	1	2	4	—
2C	12	4	—	4	—	—	5	2	—
3C	3	1	1	9	11	1	4	10	4
4C	—	—	—	—	5	2	—	—	1
1D	—	—	4	—	—	6	—	—	—

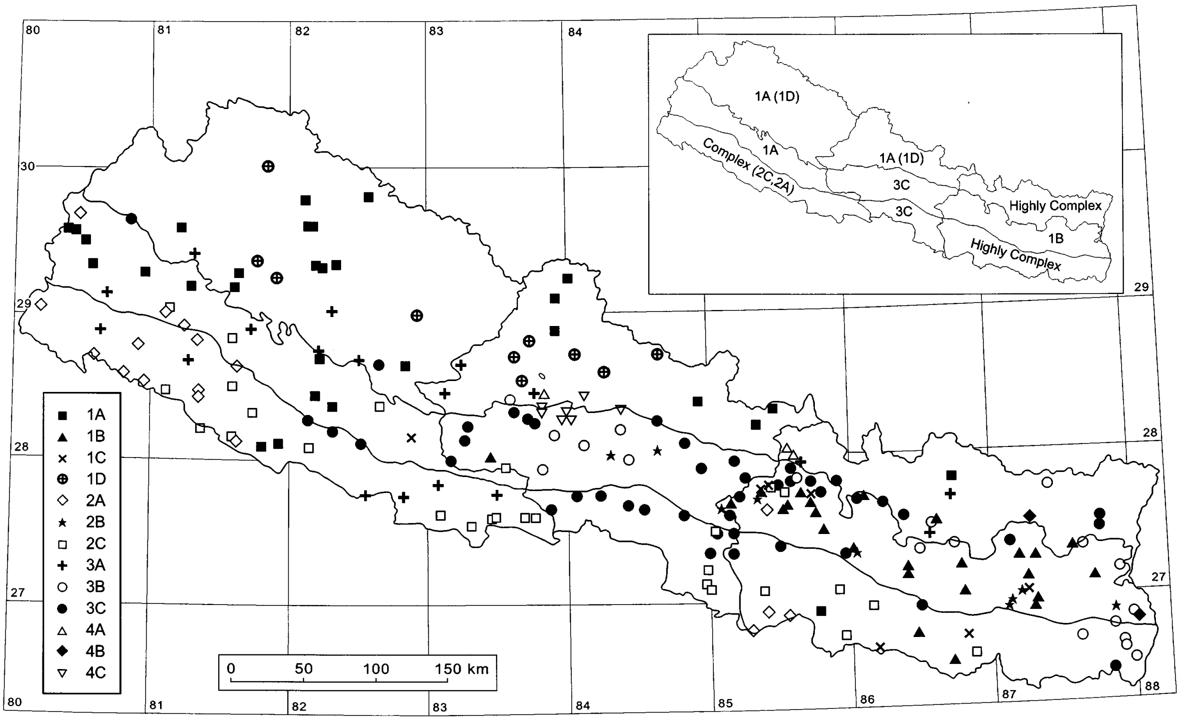

Figure 7. Spatial distribution of composite (shape and magnitude) precipitation regime classes across Nepal with general summary pattern inset

by Class 1B. No dominant pattern in composite regime classes is found for the eastern High Mountains/High Himalaya. However, closer examination of the spatial distribution within this high mountainous region of the Sapta Koshi indicates clustering of similar composite classes, which may reflect local topographic controls. In the Narayani, Class C occurs exclusively in the Terai/Siwaliks with Class 3C being most common. Similarly, the central Middle Mountains region is dominated by Class 3C. The High Mountains/High Himalaya region of the Narayani is dominated by Classes 1A and 1D. In the Karnali, Classes 2A and 2C are the main composite classes in the Terai/Siwaliks. The western Middle Mountains and High Mountains/High Himalaya are both dominated by Class 1A. Thus, there would appear to be three relatively 'simple' regions with respect to composite precipitation regime occurrence: (a) High Mountains/High Himalaya of the Karnali and Narayani basins and the Middle Mountains of the Karnali (Class 1A); (b) the Terai/Siwaliks and Middle Mountains of the Narayani (Class 3C); and (c) the Middle Mountains of the Sapta Koshi (Class 1B). This leaves three 'complex' areas: (a) the Terai/Siwaliks of the Karnali; (b) the Terai/Siwaliks of the Sapta Koshi; and (c) the High Mountains/High Himalaya of the Sapta Koshi. Overall, the Sapta Koshi emerges with the most complex patterns and the Narayani with the simplest. Since interpretation of spatial patterns in constituent shape and magnitude classes is covered in Sections 4.1 and 4.2, the inferred controlling factors are not restated here but are synthesized in Section 5.

5. CONCLUSIONS

This paper provides a large-scale perspective upon the nature of precipitation regimes across Nepal. The classification methodology employed is shown to be a useful tool for identifying the underlying spatial structure in annual precipitation regime shape (form) and magnitude (size) in an extreme physical environment where regional climatological patterns are complex and, to date, poorly known. The resultant patterns are interpretable, which gives confidence in the analytical techniques, and allow inference of the key factors controlling the spatiality of intra-annual precipitation behavior across the country.

In terms of precipitation seasonality (i.e. regime shape), July–August peaks (Class A) are most typical of western regions, but a number of Class C stations occur at low altitude (Terai/Siwaliks). Marked July peaks (Class C) are characteristic of the central region and eastern lowlands. July peaks with gradual onset (Class B) are mainly concentrated in the Middle Mountains of the east. July–August peaks with winter precipitation (Class D) are confined to western higher mountains, particularly the Trans-Himalayan region.

With respect to precipitation regime size, low, intermediate, moderately high and high magnitude classes (1, 2, 3 and 4 respectively) are identified. This classification represents structure within the data set analyzed, as by global standards the Nepalese precipitation amounts are very high. Low magnitude classes clearly dominate western high mountain regions, but they also occur more widely across the High Mountains/High Himalaya. Intermediate regimes are distributed from east to west at low altitude, dominating the western Terai/Siwaliks. Moderately high regimes are widespread, but they are most evident in the Terai to Middle Mountains of the central and eastern parts and eastern High Mountains/High Himalaya. High precipitation zones are found near Pokhara and northeast of the Kathmandu Valley around Langtang.

Composite regime classes scale standardized seasonal precipitation response (shape) by size (magnitude). It is necessary to analyze the two regime attributes both separately and in combination to provide a more climatologically informative classification, since there is no consistent association between shape and magnitude classes. Three relatively 'simple' regions with respect to composite precipitation regimes (i.e. areas dominated by a particular class) are evident: (a) the Terai to Middle Mountains of central Nepal (Class 3C; moderately high, marked July peak); (b) western Middle Mountains and central to western High Mountains (Class 1A; low, July–August peak); and (c) eastern Middle Mountains (Class 1B; low, July peaks with gradual onset). 'Complex' regions in terms of composite precipitation classes (i.e. no single regime is clearly dominant) are found: (a) the Terai/Siwaliks in both eastern and western Nepal and (b) the eastern High Mountains/High Himalaya.

These annual regime classifications indicate the key controls upon spatial patterns in Nepalese precipitation as: length and timing of the summer monsoon (duration decreases from east to west, with later onset and earlier withdrawal in the west); successively higher altitude, east–west trending mountain ranges causing rainfall to decline broadly south–north; topographic barriers that induce localized rain shadows (lee) and precipitation hotspots (windward side); and westerly weather systems supplying winter precipitation to the northwest mountains. The east–west progression of the summer monsoon and physiography (mountain ranges) explain the 'simple' patterns in precipitation: short peak, low magnitude regime in the higher mountains of western and central parts, and the (low) extended summer monsoon in the east and moderately high, marked July regime in central Nepal. The westerly disturbance accounts for the low July–August peak regimes with winter precipitation in the High Mountains/High Himalaya of western and central Nepal. Local relief effects upon precipitation may explain the complex regions; most notably, the extreme topography of the eastern higher mountain ranges yield very intricate precipitation patterns. The western Terai/Siwaliks is also complex, but there is evidence of subregional structure. The Siwaliks extend over the border with India in the area of the West Rapti basin, splitting the Terai into far-western and mid-western parts. These two Terai subregions are dominated by Classes 2A (far-western) and 2C (mid-western), reflecting a shorter summer monsoon on the leeward, far-west side of the Siwaliks. Hence, although broad patterns relating to zonal movement of the summer monsoon and physiographic controls upon precipitation may be identified, the role of mountainous relief in yielding localized precipitation patterns is significant.

These findings are not only of climatological interest, they also have practical implications for the assessment and prediction of water resources across Nepal. Previous regionalization work has largely focused upon annual or summer monsoon precipitation totals (see Section 1); it has not fully considered seasonality. Since this paper shows precipitation regime shape and magnitude to be independent, predicting precipitation timing across Nepal needs further scientific attention, particularly because intra-annual precipitation behavior has the most significant impact upon potential water resource utilization (see Section 1).

This paper focused upon the spatiality of long-term average precipitation regimes, but, given present concerns about climate change, it is important to understand the year-to-year variability to assess current and potential future water resource stress. Research is in progress to identify interannual precipitation regime variability and links to river flows. Our initial findings tentatively suggest precipitation regime shape may be more temporally stable than magnitude, which implies less interannual variability in summer monsoon timing but more interannual variability in precipitation amount (Hannah *et al*., 2004). However, further research is required to investigate and understand spatiotemporal precipitation regime patterns across Nepal more fully.

ACKNOWLEDGEMENTS

The Department of Hydrology and Meteorology (DHM), Kathmandu, provided all data sets. S.R. Kansakar is supported by a UK Department for International Development research studentship (project number AG2206 held by CEH-Wallingford). The Royal Society and University of Birmingham funded research visits to Nepal by D.M. Hannah and J. Gerrard respectively. A. Ankorn and K. Burkhill (University of Birmingham) redrew the figures. We are grateful for constructive comments provided by an anonymous reviewer.

REFERENCES

Barros AP, Lang TJ. 2003. Monitoring the monsoon in the Himalayas: observations in central Nepal, June 2001. *Monthly Weather Review* **131**: 1408–1427.

Barros AP, Joshi M, Putkonen J, Burbank DW. 2000. A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations. *Geophysical Research Letters* **27**: 3683–3686.

Bower D, Hannah DM, McGregor GR. 2004. Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrological Processes* **18**: 2515–2543. DOI:10.1002/hyp.1479.

Chalise SR. 2002. Management of water resources for poverty alleviation in the Hindu-Kush Himalayas. In *FRIEND2002-Regional Hydrology*, van Lanen HAJ, Demuth S (eds). International Association of Hydrological Sciences Publication, No. 274. IAHS Press: Wallingford; 27–34.

Gerrard AJ, Gardner RAM. 2000. Relationships between rainfall and landsliding in the Middle Hills, Nepal. *Norsk Geografisk Tidsskrift* **54**: 74–81.

Goswami BN, Krishanmurthy V, Annmalai H. 1999. A broad-scale circulation index for the interannual variability of the Indian summer monsoon. *Quarterly Journal of the Royal Meteorological Society* **125**: 611–633.

Griffith DA, Amrhein CG. 1997. *Multivariate Statistics for Geographers*. Prentice-Hall: New Jersey.

Hannah DM, Smith BPG, Gurnell AM, McGregor GR. 2000. An approach to hydrograph classification. *Hydrological Processes* **14**: 317–338.

Hannah DM, Kansakar SR, Gerrard AJ, Rees G. 2004. Linking river flow and precipitation regimes for Himalayan basins of Nepal: assessing hydroclimatological variability and implications of climate change. *Hydrology: Science and Practice for the 21st Century — Proceedings of the British Hydrological Society International Symposium, London*, vol. I: 38–45.

Hannah DM, Kansakar SR, Gerrard AJW, Rees G. In press. Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. *Journal of Hydrology*.

Harris NM, Gurnell AM, Hannah DM, Petts GE. 2000. Classification of river regimes: a context for hydroecology. *Hydrological Processes* **14**: 2831–2848.

Higuchi K, Ageta Y, Yasunari T, Inoue J. 1982. Characteristics of precipitation during the monsoon season in High-Mountain areas of the Nepal Himalaya. *Hydrological Sciences Journal* **27**: 251.

Johansson B, Chen D. 2003. The influence of wind and topography on precipitation distribution in Sweden: statistical analysis and modelling. *International Journal of Climatology* **23**: 1523–1535.

Kansakar SR, Hannah DM, Gerrard AJW, Rees G. 2002. Flow regime characteristics of Himalayan river basins in Nepal. In *FRIEND2002-Regional Hydrology*, van Lanen HAJ, Demuth S (eds). International Association of Hydrological Sciences Publication, No. 274. IAHS Press: Wallingford; 425–432.

Kripalani RH, Inamdar S, Sontakke NA. 1996. Rainfall variability over Bangladesh and Nepal: comparison and connections with features over India. *International Journal of Climatology* **16**: 689–703.

Kulkarni A, Kripalani RH, Singh SV. 1992. Classification of summer monsoon rainfall patterns over India. *International Journal of Climatology* **12**: 269–280.

Kumar KR, Pant GB, Parthasarathy B, Sontakke NA. 1992. Spatial and subseasonal patterns of the long-term trends on Indian summer monsoon rainfall. *International Journal of Climatology* **12**: 257–268.

Lang TJ, Barros AP. 2002. An investigation of the onsets of the 1999 and 2000 monsoons in central Nepal. *Monthly Weather Review* **130**: 1299–1316.

Nayava JL. 1974. Heavy monsoon rainfall in Nepal. *Weather* **29**(12): 443–450.

Nayava JL. 1980. Rainfall in Nepal. *The Himalayan Review: Nepal Geographical Society* **12**: 1–18.

Shrestha ML. 2000. Interannual variation of summer monsoon rainfall over Nepal and its relation to southern oscillation index. *Meteorology and Atmospheric Physics* **75**: 21–28.

Shrestha AB, Wake CP, Dibb JE, Mayyewski PA. 2000. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large-scale climatology parameters. *International Journal of Climatology* **20**: 317–327.

Smith RB. 1979. The influence of mountains on the atmosphere. *Advances in Geophysics* **21**: 87–229.

Stone RC. 1989. Weather types at Brisbane, Queensland: an example of the use of principal components and cluster analysis. *International Journal of Climatology* **9**: 3–32.

Subbaramayya I, Naidu CV. 1992. Spatial variations and trends in the Indian monsoon rainfall. *International Journal of Climatology* **12**: 597–609.

Yarnal B. 1992. *Synoptic Climatology in Environmental Analysis: A Primer*. Belhaven Press: London.