Article

Meteorological observations at high altitude in the Khumbu Valley, Nepal Himalayas, 1994-1999

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Abstract

The main meteorological features of the area surrounding Mt. Everest (Khumbu Valley, Nepal Himalayas) were investigated by means of the dataset collected at the Pyramid Meteorological Station (5050 m a.s.l.) from 1994 to 1999. Particular attention was given to the characteristics of the summer monsoon season, whose mean onset and decay dates (12 June and 5 October, respectively) were identified. The predominant type of summer monsoon precipitation was drizzle, with sporadic more intense events from the late afternoon through the night. Active/break periods of the summer monsoon were identified and their large-scale characteristics were highlighted by means of daily global gridded data. Two different daily profiles were found within the Pyramid precipitation and wind direction records, depending on the level of activity of the summer monsoon circulation. Spectral analysis revealed the existence of a 5-day and a 10-day periodicity in the daily precipitation records associated to similar oscillations of the Tibetan High.

1. Introduction

The Himalayas and the Tibetan Plateau play an important role in the monsoon circulation system, both as an elevated heat and moisture source/sink in the upper troposphere (due to the strong warming/cooling of the ground and the release of large quantities of condensation heat) and as an orographic barrier to wind flows (Murakami, 1987; Yanai *et al.*, 1992). The Indian monsoon flow is strongly correlated to the snow cover in these areas as demonstrated in several studies on the topic (e.g., Dickson, 1984; Vernekar *et al.*, 1995; Ose, 1996; Sankar-Rao *et al.*, 1996; Bamzai and Shukla, 1998). Meteorological conditions affect the mass balance of glaciers and, as a consequence, the availability of water in the plains. A long-term time series of meteorological observations thus proves fundamental in the study of glacier fluctuations as a response to global climate change.

Over the past decades, some meteorological observations have been collected at high altitudes in the Himalayan Range for limited periods of time, mostly during the summer monsoon season. Only in the 1990s were a few permanent stations set up under the management of various countries, such as Nepal (Shrestha *et al.*, 1998; 2000), Japan (Ueno *et al.*, 1996), China (Liu and Chen, 2000) and Italy (Stravisi *et al.*, 1998).

In 1990 an Automatic Weather Station (AWS) was installed by the Italian National Research Council Institute of Water Research (IRSA/CNR) in the Nepal Himalayas near Mount Everest, at 5050 m a.s.l. This AWS is named "Pyramid" given its location a few dozen meters from the Italian and Nepalese pyramidal-shaped scientific Laboratory/Observatory above Lobuche village. The AWS is, like the Laboratory itself, part of the Interdisciplinary Ev-K^2-CNR High Altitude Scientific and Technological Research Project. Project objectives include development of high altitude and remote area studies in various fields, such as medical-physiological sciences, earth sciences, technology, environmental sciences and meteorology. Meteorological observations at the Pyramid AWS are conducted in order to provide permanent monitoring of the monsoon at high altitude.

The purpose of this paper is to describe high altitude (above 5000 m) climate characteristics in an area where only few and incomplete observations have been carried out so far, and to outline the interaction between local features and large-scale monsoon circulation. The former are studied by means of the Pyramid AWS dataset collected continuously from 1994 to 1999, while synoptic scale patterns are highlighted by means of daily data available from

NCEP/NCAR Reanalysis on a global 2.5° × 2.5° grid (Kalnay *et al.*, 1996). Particular attention is placed on the summer features, as well as on the intraseasonal variability of the monsoon, with a detailed discussion of wind circulation and precipitation characteristics. A comparison with data recorded at Syangboche AWS is also made.

2. Data and methods

The Pyramid Laboratory/Observatory is located at 5010 m a.s.l. in a secondary valley oriented NNW-SSE off of the main Khumbu Valley, which forms the confluence of the Lobuche and Khumbu Glaciers (Fig. 1). The AWS, one of the highest operating meteorological stations in the Himalayan Range, is located on the northern ridge of this secondary valley (geographical coordinates: 27°58′ N, 86°48′ E) and it is well exposed to the Khumbu Valley wind.

Since December 1993, the AWS has run continuously year round, recording air temperature, precipitation, wind speed, wind direction, global solar irradiance, relative humidity and atmospheric pressure every two hours. Air temperature, humidity, and pressure are instantaneous values; precipitation is cumulated over the two preceding hours; solar irradiance, wind speed and wind direction are averaged over the previous 20 minutes. In particular, the bi-hourly wind direction data are calculated by the processing unit using an algorithm based on an arithmetic average of the instantaneous values recorded every two seconds, and accounting for abrupt changes in successive direction values (MTX Co., user's manual). The bi-hourly wind speed data are arithmetic averages of instantaneous values recorded every two seconds. The data are stored in solid-state memory and are retrieved twice a year by an Italian expedition. Measured variables for each sensor are listed in Table 1. Data processing and quality check are performed in Italy.

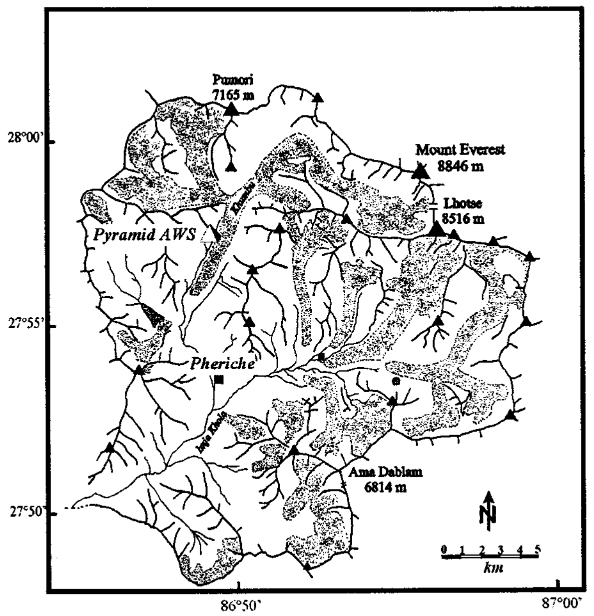

Fig. 1. Geographic location of the Pyramid Meteorological Station in the Khumbu Valley, Nepal Himalayas.

For our analysis, we defined winter, pre-monsoon, summer and post-monsoon seasons, as per usual definitions, the months of December to February, March to May, June to September and October to November, respectively. Monthly mean values were calculated when more than 20 daily data items were available (each one calculated as average of the 12 bi-hourly data).

Over the six-year period, errors were found in two sensors. The global solar irradiance sensor showed a slow, constant distortion in daily data starting in 1994; all radiation values have consequently been rejected and a new sensor was installed in October 1999. The wind direction sensor seemed to work well until April 1996 and to loose precision from May 1996 onwards. At the end of September 1998 the sensor was replaced, but unfortunately the data recorded by the new instrument proved to be incoherent with the 1994-1995 data. Only the latest scientific expedition organized in September 2000 - the first with a solely meteorological aim - allowed researchers to verify accurate functioning of the new sensor and validate the data. Records from January 1994 to September 1998 have thus been rejected. To make up for this lack of data, at least in part, the analysis of wind direction in this paper was extended to the bi-hourly records collected during January and February 2000, allowing for consideration of two complete winter seasons. Furthermore, temperature values were missing from the end of July 1994 to the first days of November 1994, and during July-September 1995. The percentage of missing daily values for each sensor is shown in Table 2.

Table 1. List of sensors, with measurement height and accuracy. All sensors were manufactured by MTX Co., Italy.

Parameter	Sensor	Accuracy
AIR TEMPERATURE	*Precision linear thermistor (2 m)*	0.1 °C
PRECIPITATION	*Tipping bucket (1.5 m)*	0.2 mm
RELATIVE HUMIDITY	*Solid state hygrometer (2 m)*	3 %
ATMOSPHERIC PRESSURE	*Aneroid capsule (2 m)*	0.5 hPa
WIND SPEED	*3 cups rotor (5 m)*	2 %
WIND DIRECTION	*Direction vane (5 m)*	3 °
GLOBAL SOLAR IRRADIANCE	*Pyranometer with 72 thermocouples (2 m)*	0.1 cal/cm^{2}h

Table 2. Yearly percentage of missing daily values.

Parameter	1994	1995	1996	1997	1998	1999
AIR TEMPERATURE	27	25	3	0	0	4
PRECIPITATION	0	0	3	11	0	4
RELATIVE HUMIDITY	0	0	3	0	0	4
ATMOSPHERIC PRESSURE	0	0	3	0	1	4
WIND SPEED	0	2	6	0	1	4
WIND DIRECTION	100	100	100	100	75	15
GLOBAL SOLAR IRRADIANCE	100	100	100	100	100	76

The wind and precipitation instruments are not heated; however, data correction for freezing of the sensors and wind-induced loss of snowfall (Ueno and Ohata, 1996) was not calculated. Thus, wind speed and precipitation records could prove to be underestimated, especially in winter. Moreover, solid precipitation may be recorded with some delay due to the deferred melting of snow; however, this delay is limited to few hours, at least for the greater part of the year. Indeed, accurate on site observations combined with analysis of the diurnal variations in air temperature, precipitation and recent solar radiation values (recorded from October 1999) have demonstrated that from the pre-monsoon to the post-monsoon season snow fallen in the evening melted rapidly between 08:00 and 10:00 of the following morning (even on the coldest days) due to the prevailing fair weather, the strong radiation heating the instrument and above-zero temperature conditions. Strong solar radiation values were recorded in winter, too. Moreover, it appears that air temperature can fluctuate widely during winter and several "warm events" (characterized by a daily mean temperature of around −2°C and above-zero temperatures between 10:00 and 14:00) were recognizable from the end of December to the middle of February (clearly evident in Fig. 4). It is therefore reasonable to assume that snow accumulated during the rare and short winter precipitation events (also identifiable by the relative humidity) melted a few days later.

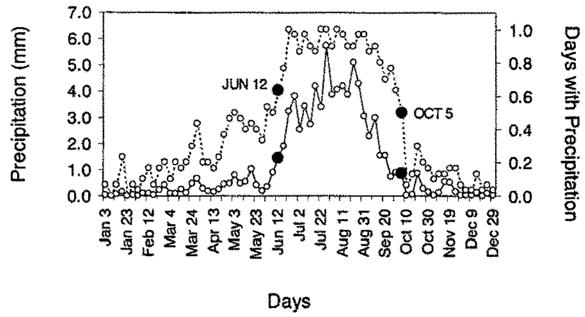

Fig. 2. Annual variation of the 5-day centred means of daily total precipitation (continuous line; values on the left axis) and of the number of days with precipitation (dotted line; values on the right axis) averaged over 1994-1999. The full black circles indicate the onset/decay dates of the summer monsoon (centres of the pentads).

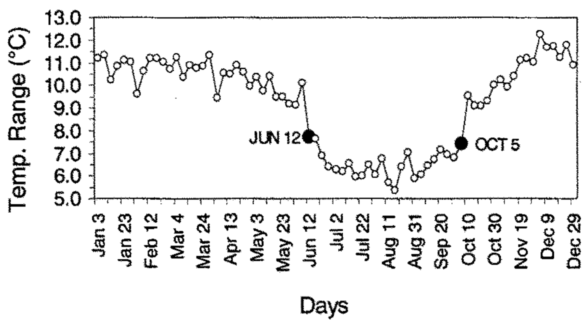

Fig. 3. Annual variation of the 5-day centred mean of daily temperature range averaged over 1994-1999. The full black circles indicate the onset/decay dates of the summer monsoon.

3. Results

3.1. *Onset and decay of the summer monsoon*

To temporally define the monsoon period at the Pyramid Station, the average annual variation of total daily precipitation and the number of days with precipitation (daily total precipitation equal or greater than 0.2 mm) over the six year period were calculated. The 5-day average non-overlapping centered means (pentads) are represented in Fig. 2. A rapid increase around the second half of June and a similar decrease at the beginning of October are evident. These abrupt changes can be considered the average (center of the pentads) onset and decay dates of the monsoon: respectively, June 12 and October 5. The 5-day centered means of the diurnal range of temperature also demonstrate an abrupt decrease and increase on the same days, as Fig. 3 clearly highlights. During the monsoon period, the diurnal range of the temperature was low (rarely higher than 10°C on the average) as clouds prevented substantial heating (cooling) during the day (night) (for a similar application see Tangborn *et al.*, 1980). On the contrary, the generally clear sky in winter caused the range to be high (some days even above 20 °C, with maximum values in December). The onset and decay dates of the summer monsoon are also clearly revealed by the annual variations of the 5-day centered means of relative humidity and atmospheric pressure. Mean relative humidity exceeded 90% during the monsoon period while, during the dry winter (December and January), it showed the minimum values (mean of 33%). During the pre-monsoon (post-monsoon) season relative humidity increased (decreased). Atmospheric pressure had a similar variation, with the highest values during the monsoon period (mean of 555.6 hPa), and the lowest in winter (mean of 550.1 hPa). For both these parameters, abrupt changes were noted in correspondence to the cited dates. These results perfectly fit the climatological onset and decay dates over Northern India reported by Rao (1981).

3.2. *Diurnal variation of precipitation*

The annual precipitation recorded at the Pyramid Meteorological Station was low mainly due to the high altitude of its location in the inner Himalayas. For the six years examined, the averaged annual precipitation was 465 mm. Nearly 90% of it was recorded between June and September (Table 3), while in the summer monsoon period (12 June - 5 October) average precipitation was 400 mm. From June to September, precipitation occurred on more than 85% of the days, with the highest frequency in August.

Table 3. Total monsoon precipitation (mm) and number of days with precipitation for each summer monsoon season (June -September).

	1994	1995	1996	1997	1998	1999
total (mm)	419	373	418	382	401	442
days with precipation	92	106	101	90	88	93

Annual variations of minimum, mean and maximum temperature averaged over the six-year period are represented in Fig. 4. Air temperature drops below freezing during the non-monsoonal seasons with few minimum temperatures above 0°C. During winter, days with temperatures above freezing occurred with an average frequency of 68%, with the highest frequency of 78% in February, the coldest month. During the pre-monsoon and post-monsoon seasons, days with freezing prevailed (an average of 71%). Over the course of a year, only around a quarter of the days showed a minimum temperature above 0°C. The warmest month was July, when 94% of the days had a minimum temperature above 0°C. Moreover, during summer, the maximum temperature was constantly above 0°C. These results are summarized in Fig. 5.

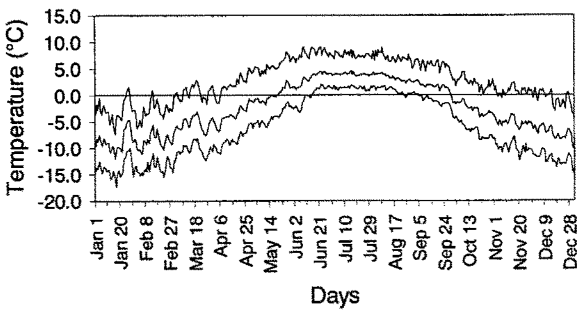

Fig. 4. Annual variation of daily maximum, mean and minimum temperature averaged over 1994-1999.

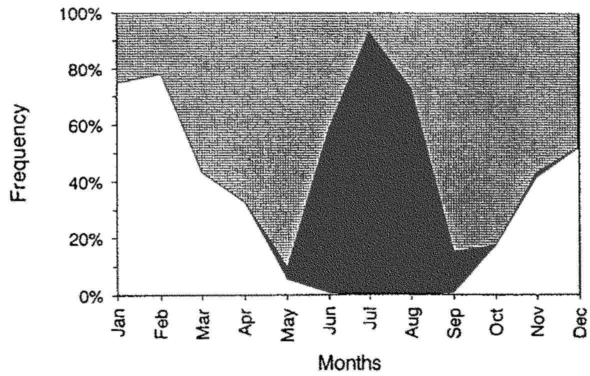

Fig. 5. Frequency of occurrence of days with freezing (minimum temperature = 0°C, maximum temperature > 0°C; grey area), without thaw (maximum temperature = 0°C; white area) and without freezing (minimum temperature > 0°C; black area). Data averaged over 1994-1999.

Based on the above considerations, it can be concluded that nearly all the precipitation in July is rain, with no delay in data recording (as discussed in Section 2). Consequently, the daily variation of monsoon precipitation can be well described by analyzing data recorded during this representative month. In particular, it is possible to point out that rain occurred mainly from the afternoon through the night (Fig. 6), both in terms of frequency of occurrence and intensity. Further examination revealed that drizzle type precipitation (< 1 mm in two hours) was predominant throughout the day (over 75% of the events) and that, on average, 95% of the precipitation events were below 3 mm in two hours. However, between 04:00 to 12:00 the frequency of drizzle was highest (about 82%), while during the rest of the day more intense precipitation occurs with greater frequency. This is especially true between 14:00 and 18:00, when the frequency of drizzle dropped to 70% while the frequency of events with a bi-hourly total between 1 and 3 mm increased to 26%. This is due to convective activity. Furthermore, sporadic heavy events (between 3 and 8 mm in two hours) occurred, with the highest frequency (average of 8.5%) between 18:00 and 24:00.

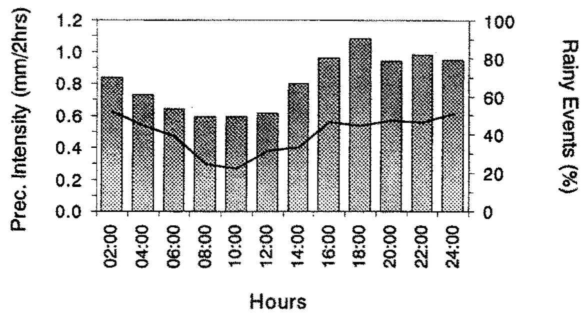

Fig. 6. Diurnal mean variation of precipitation intensity (histogram; values on the left axis) and percentage of rainy events (line; values on the right axis) during July in the period 1994-1999. Bi-hourly totals of precipitation were averaged only on precipitation events.

3.3. Characteristics of local circulation

The mountain/valley breeze circulation system clearly dominated at the Pyramid Station. Wind direction and wind speed are represented on separate figures due to the different period covered by the data. Fig. 7a shows the diurnal variation of the wind direction (wind speed arbitrarily fixed) during each season. As can be seen, a strong valley wind, coming from south-southwest, prevailed in the daytime reaching its maximum speed between 12:00 to 14:00 throughout the year (Fig. 7b). Except for the monsoon season, this up-valley wind began blowing after sunrise and stopped in the evening. During the monsoon season, a weaker valley wind prevailed also at night, even if the mountain wind (coming from NW-NE) occasionally appeared at 06:00. The mountain wind was more evident during non-monsoon seasons. It was especially prevalent between 20:00 and 08:00 in the post-monsoon season, from midnight to 08:00 during winter and from 02:00 to 06:00 in the pre-monsoon season. The occurrence of the mountain wind was highest in November and December, when this wind blew continuously from 18:00 to 08:00. It was also noted that, during winter, the mountain wind tended to blow from NW (probably affected by the general circulation), while during the other seasons it came from NE. The frequency distribution of the bi-hourly wind direction values clearly showed the prevalence of the valley wind, nearly 80% during summer, from 30% to 45% during the other seasons, with a decreasing trend from the post-monsoon to the pre-monsoon. Also, the occurrence of the mountain wind decreased significantly between the non-monsoon seasons (30-38%) and summer (about 11%).

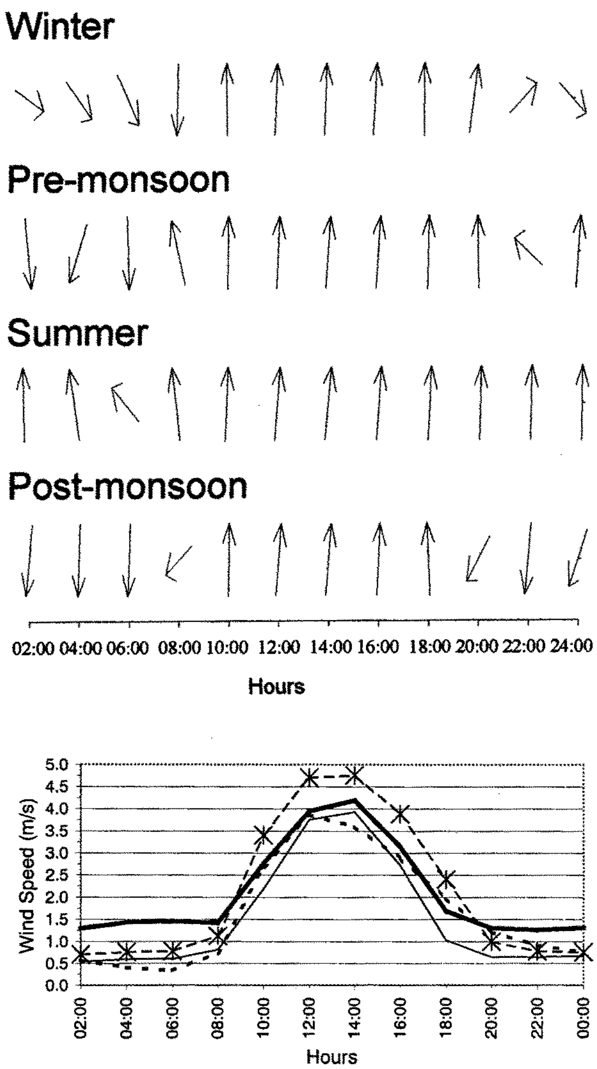

Fig. 7. Diurnal variation of the wind direction (a) and wind speed (b) for each season. For wind direction (data from October 1998 to February 2000), the length of the arrow is arbitrarily fixed and data are presented from winter (upper) to the post-monsoon season (lower). For wind speed (data for the six-year period), the thick, crossed, dashed and thin lines correspond to winter, pre-monsoon, summer and post-monsoon season, respectively.

The diurnal variation of the wind speed (bi-hourly averaged value) for each season is represented in Fig. 7b. The three profiles for the non-monsoon seasons are similar, with an increasing of the wind speed at around 08:00 (when the valley breeze started), a maximum past noon, then a slow decrease until about 20:00, while from 20:00 to 06:00 the values are relatively constant. The highest values were recorded during the pre-monsoon season (about 4.8 m/s), due to the strong driving force caused by the heating of the ground. During summer, the valley wind started at about 06:00, was at its maximum value at 12:00 (which was, however, lower than the maximum values recorded during other seasons), then slowly decreased until the minimum at about 06:00 (when the mountain wind was observed in some cases). On site observations showed that, in summer, humidity was driven from the bottom of the valley by the wind and that convective clouds began to form above the mountains at approximately 08:00, with the sky being completely covered by midday. The resulting outcome was a reduction of the amount of solar radiation and a weakening of the wind. The maximum wind speed was thus recorded just prior to the moment when clouds obscured the sun. Significant heating led to maintenance of the valley wind even in the afternoon, while the persistence of this wind until early morning could be explained by latent heat release by convective clouds (Ohata *et al.*, 1981). By grouping together wind speed profiles from the non-monsoon seasons, it can be seen that the wind was generally weaker during summer than in other seasons, with the exception of the 18:00-22:00 period, when the valley breeze was still blowing. The highest daily-averaged values were recorded during winter (2.1 m/s) when the large-scale flow was characterized by strong eastward winds associated with the Subtropical Jet Stream, while the summer monsoon winds were the weakest (a daily average of 1.5 m/s).

3.4. Comparison with other observations

Accounting for differences in the analysis, some results obtained by means of Pyramid data can be compared with meteorological observations conducted at another weather station located about 18 km SW far from the Pyramid AWS. Syangboche AWS was established in 1994 at 3833 m a.s.l. in the framework of the Glaciological Expedition in Nepal (GEN) (Ueno *et al.*, 1996; Ueno *et al.*, 2001). As expected, the main difference is found in the precipitation: at Pyramid the summer total was about 55% of that recorded at Syangboche. However, the mean onset and decay dates of the monsoon were nearly the same, even if they were calculated with different methods. Moreover, the comparison of data permits to conclude that precipitation at higher altitude was weaker and with few heavy events.

The temperature range during summer was higher at Pyramid than at Syangboche (6.9 °C and 4.5 °C, respectively), due to the more intense cooling in the early morning. In fact, in situ observations reported that high in the Khumbu Valley the sky was often only partially cloudy at the sunset. This is also confirmed by the annual variation of relative humidity: Syangboche monthly mean values were always higher than at Pyramid (a difference of +17% in the yearly averages), and reduced only during summer (+4%).

At Pyramid the mountain/valley breeze system was more developed: in particular, the mountain wind was clearly evident in all the non-monsoon seasons, while at Syangboche it prevailed at night only during winter. Moreover, a weak valley wind in summer prevailed all night long at Pyramid; at Syangboche it ceased at midnight.

3.5. Intraseasonal variability of the summer monsoon
3.5.1 Active/break phases of the monsoon

It is well known that the Asian summer monsoon shows a strong intraseasonal variability, in that the monsoon exhibits a succession of active spells and break periods (e.g., Gadgil and Asha, 1992; Fennessy and Shukla, 1994; Krishnamurthy and Shukla, 1999). Although many authors referred to the All India Monsoon Rainfall (Parthasarathy *et al.*, 1995) in order to demonstrate the monsoon periodicity, it is essential to highlight the fact that such criterion is not easily applicable on a large scale (not limited to the Indian area), because precipitation is a difficult quantity to measure and may be affected by numerous small scale processes. It is therefore important to define an index of monsoon strength based on large-scale circulation variables, as pointed out for example by Webster and Yang (1996).

Magaña and Webster (1996) defined three conditions to be satisfied by 850 hPa winds and outgoing longwave radiation in order to classify a day as belonging to an active or a break period. Lau *et al.* (2000) recently proposed two regional circulation indices to characterize the variability of the Asian summer monsoon, based on the vertical shear of the meridional component of the wind between 850 hPa and 200 hPa, averaged over two different regions (10°N-30°N, 70°E-100°E; 40°N-50°N, 100°E-150°E), demonstrating that they proved to be valid measurements of local sub-components of the monsoon, respectively the South-Asian monsoon and the East-Southeast Asian monsoon. These indices were then successfully applied in the study of seasonal and interannual monsoon variability. A similar approach had previously been followed also by Goswami *et al.* (1997). Furthermore, it is generally accepted (Fennessy and Shukla, 1994; Annamalai *et al.*, 1999) that a seasonally strong monsoon is characterized by prolonged and intense active periods, while the reverse occurs for a weak monsoon.

Bearing in mind these considerations, a circulation index (CI) was defined as:

$$CI = v^*_{850hPa} - v^*_{200hPa}$$

where v^*_{850hPa} and v^*_{200hPa} are, respectively, the deviations from the seasonal means of the meridional component of the wind at 850 hPa and 200 hPa averaged over the region 10°N-30°N, 70°E-100°E. This index was chosen to represent the daily strength of the monsoon, and time series were thus calculated using NCEP/NCAR Reanalysis daily data (from June to September) for all the years 1994-1999. It should be pointed out that CI is nearly identical to the RM1 monthly index proposed by Lau *et al.* (2000).

A common feature in the time series of CI is the increase of the index value around mid-June and the gradual shift towards negative values from the middle of September on, corresponding respectively to the beginning and the progressive weakening of the summer monsoon on a large scale. Extremely positive and negative peaks which fall between the end of June and the first days of September, with a very large and high peak around the middle of July in all the years, are also particularly evident on each series. Attributing positive (negative) peaks to active (break) days in order to form composites, active monsoon periods were defined as continuous periods of 5 days or longer in which the index equalled or remained constantly above the value of 1, while monsoon break periods were defined as intervals of at least 2 days with the index equal or below the value of −1. In this way, isolated peaks and short period oscillations of the index were filtered out and only significant active/break cycles were considered. Based on this definition, NCEP/NCAR Reanalysis daily data of geopotential height at 500 hPa and 200 hPa and of wind at 850 hPa were used to produce composite maps. The results are presented in Figs. 8, 9 and 10. Each active map is the composite of 173 days, while

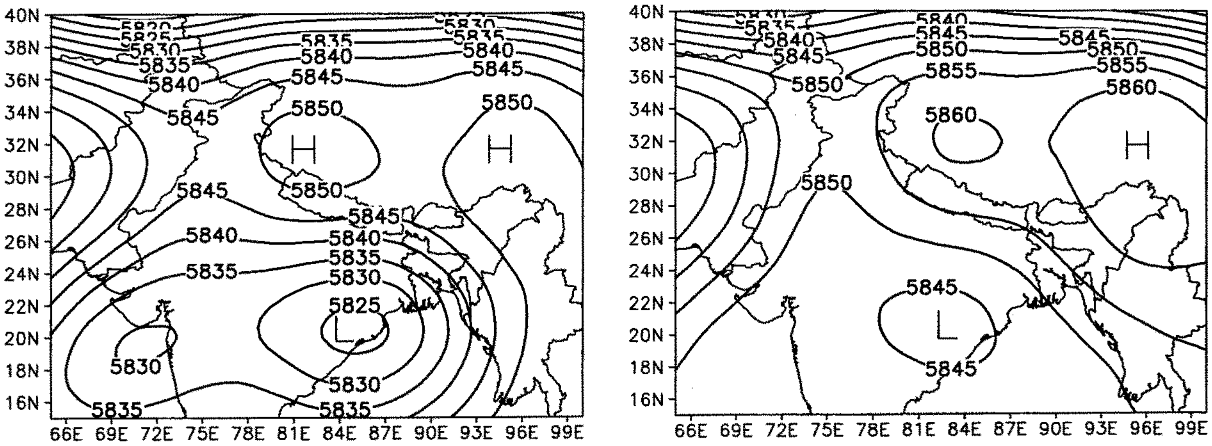

Fig. 8. Composite of 500 hPa geopotential height for active (a) and break (b) phase days of the summer monsoon in the period 1994-1999.

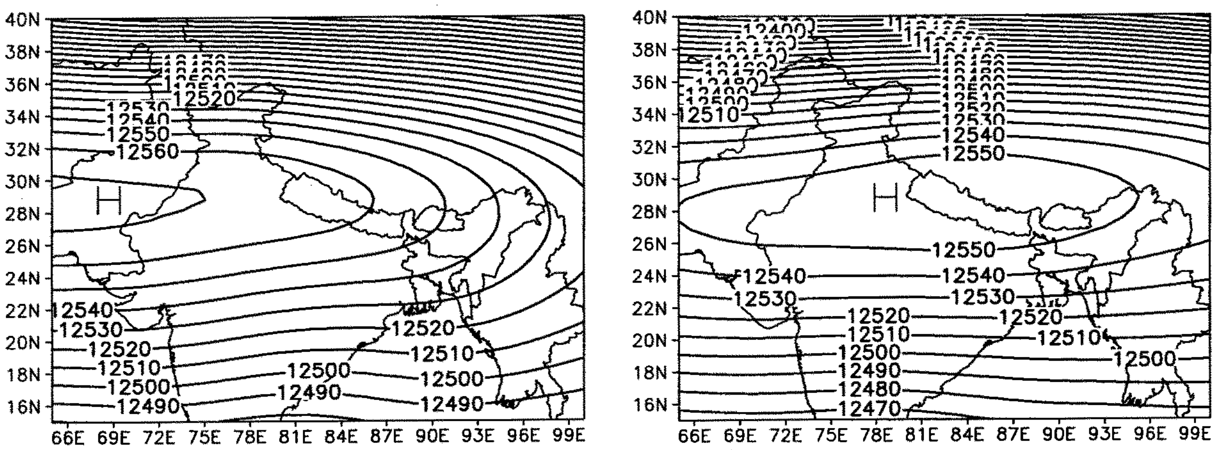

Fig. 9. Composite of 200 hPa geopotential height for active (a) and break (b) phase days of the summer monsoon in the period 1994-1999.

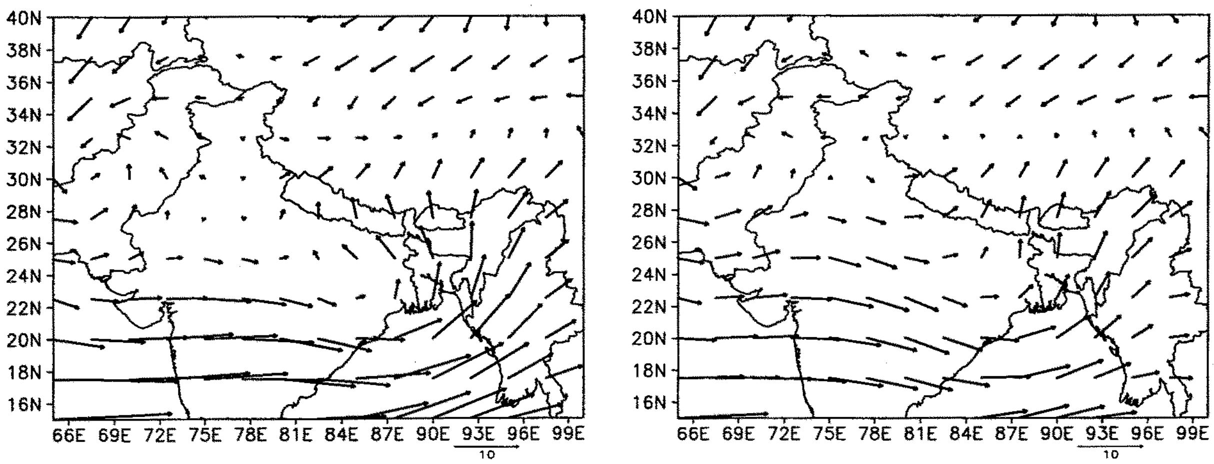

Fig. 10. Composite of 850 hPa wind for active (a) and break (b) phase days of the summer monsoon in the period 1994-1999.

each break map is the composite of 105 days. During the active phase, a deep monsoon trough is recognizable at 500 hPa east of India, with the high core of the Tibetan High at 200 hPa west of the Himalayas and enhanced westerlies over India (with associated easterlies at the foothills of the Himalayas) at 850 hPa. On the contrary, on a break day, the trough at 500 hPa is reduced, the Tibetan High at 200 hPa is weakened and moves eastwards (as found, for example, also by Krishnan and Fennessy, 1997), while the westerly circulation over India at 850 hPa is weaker (and the easterlies are practically absent). These patterns agree well with the known features of active/break periods, described for example by Gadgil and Asha (1992). It is thus possible to conclude that both NCEP/NCAR Reanalysis daily data and the CI index defined above provided to be suitable in highlighting various large-scale circulation characteristics of active/break cycles of the monsoon.

The same analysis was also carried out for comparison with the index of Magaña and Webster (1996), but the results were not satisfactory.

3.5.2 Intraseasonal variability at Pyramid

Having identified active and break days for each summer and described their common characteristics by means of gridded data over the Indian Sub-Continent, precipitation and wind records at the Pyramid AWS were examined looking for a relationship with large-scale circulation features. Yasunari (1976b) well described the seasonal evolution of weather in the Khumbu Himalayas, highlighting the relationship between local weather and the periodic oscillation of the Tibetan High (whose strength was indicated by the extension of the 5820 m contour on the 500 hPa geopotential map). Fig. 11 represents the composite profiles of precipitation intensity at the Pyramid corresponding to active and break phases of the summer monsoon (composite map of 61 days and 33 days, respectively); as discussed in section 2, to ensure a better generalization of the results, only records from

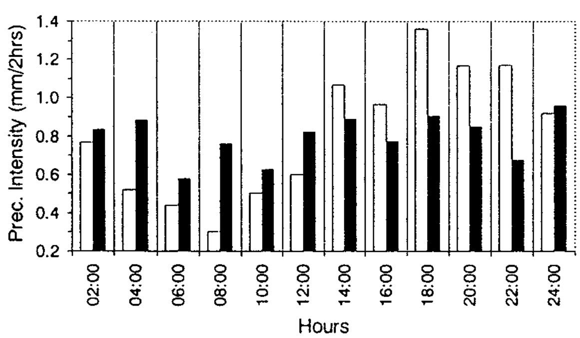

Fig. 11. Composite of the diurnal profile of precipitation at Pyramid for active (black rectangles) and break (white rectangles) phase days of the monsoon during July 1994-1999. Bi-hourly totals were averaged only on precipitation events.

July were used to compute the profiles of Fig. 11. The same features were however also recognizable on the profiles computed with all the data used in drawing Figs. 8, 9 and 10. On an active day, precipitation usually occurred nearly all day, with a predominant enhancement during nighttime. On the other hand, on a break day, almost all precipitation occurred between 14:00 to 24:00, with a significant peak at 18:00. The strong increase of precipitation in the afternoon of a break day can be attributed to convective precipitation from cumulus clouds which started to form late in the morning. On an active day, humid air (cumulus clouds) coming from the plain (related to the deep trough at 500 hPa) was brought up along the valley throughout the day by a persistent valley breeze, causing continuous precipitation (Ageta, 1976). On a break day, in relation to a weaker synoptic-scale monsoon circulation, the valley breeze was again predominant, even if a weak mountain breeze limited to the early morning (04:00 - 06:00) was observed as well.

Finally, the profile of precipitation resulting from the sum of the active and break period profiles is obviously practically identical to that reproduced in Fig. 6. Its most relevant characteristic is a net decrease between 18:00 and 22:00, which can be seen also in Fig. 6 at 20:00. The same feature can be recognized during the summer monsoon season in the hourly course at the nearby Syangboche AWS (Ueno *et al.*, 1996), located about 18 km southwest of the Pyramid, and at high altitude stations in Langtang Valley, west of Khumbu Valley (Ueno and Yamada, 1990; Ueno *et al.*, 1993). At Pyramid AWS this feature has been seen to depend on the superimposition of the two different diurnal profiles of precipitation described, with opposite trends exactly from 18:00 to 22:00.

The occurrence of periodic oscillations in the Pyramid dataset was investigated for the six summer seasons also by means of spectral analysis on normalised daily values, as suggested by Yasunari (1976a). Yasunari (1976a) reported the existence of two periodicity in the monsoon precipitation series of stations located in the Nepal Himalayas: a main periodicity of approximately 10 days and a secondary periodicity of about 5 days. The method used is described in Jenkins and Watts (1968). The time interval of 1 day and a maximum lag of 30 days were chosen in the calculation, and power spectra with a period longer than 15 days were not considered. The spectra obtained for each of the six years under investigation are quite similar, showing a predominant peak with a period of 8 to 10 days, and another lower peak of about 5 days. Fig. 12a shows the results of this analysis for the 1995 Pyramid data, those which best presented these features.

A similar periodicity (a main peak of about 8 days and a secondary peak of about 5 days) was found on

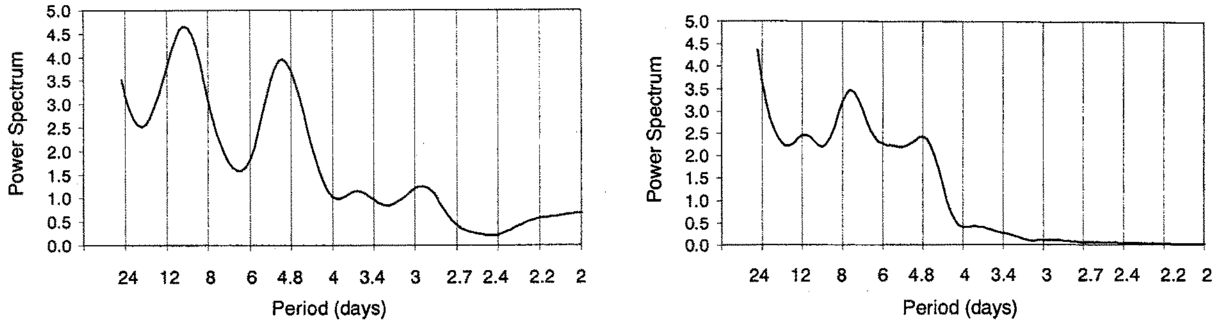

Fig. 12. Power spectrum of normalized precipitation data at Pyramid (a) and of geopotential height at 500 hPa averaged over the grid mesh (28-35°N; 80-100°E) (b) for the period 1 June 1995 -30 September 1995.

daily mean values of 500 hPa geopotential height over an area enclosing the Eastern Himalayas and the Tibetan Plateau (28-35°N, 80-100°E) using the NCEP/NCAR Reanalysis data (Fig. 12b).

From the results described above, in view of the outlined relation between local phenomena and synoptic-scale circulation, it is reasonable to assume that both the peaks found in the spectral Pyramid precipitation series are related to oscillations of the Tibetan High and, as a consequence, to the break and active phases of the monsoon. During the break phase of the monsoon, the Tibetan High weakened, convective activity was greatly enhanced and precipitation at the Pyramid occurred mainly in the late afternoon. In the active phase of the monsoon, the Tibetan High got stronger, convective activity was reduced and monsoon precipitation at the AWS occurred almost all day long.

4. Conclusions

The analysis of the bi-hourly dataset recorded at the Pyramid Meteorological Station, 5050 m a.s.l., Nepal Himalayas, from January 1994 to December 1999 was presented and discussed in this paper. Where possible, a comparison with Syangboche AWS (3833 m a.s.l.) was made. The main results are summarized as follows:

1) The onset (decay) of the summer monsoon period at the foot of Mt. Everest was identified: it was characterized by an abrupt increase (decrease) in the time sequence of daily precipitation, relative humidity and atmospheric pressure records, and by an abrupt decrease (increase) in the diurnal temperature range. In the six-year period investigated, the mean onset and decay dates (as centers of pentad means) were 12 June and 5 October, respectively. These dates confirm the findings at Syangboche and agree with the climatological onset/decay dates provided by the Indian Meteorological Department.
2) The summer monsoon precipitation was usually light and in the form of drizzle (< 1 mm in two hours). In the late afternoon and in the evening, more intense precipitation (between 1 and 3 mm in two hours) also occurred with higher frequency. At lower altitude the precipitation increased, with more frequent strong events.
3) The mountain/valley wind system dominated, with a strong valley wind from south-southwest in the daytime and a weaker mountain wind in the nighttime. In the summer season the valley wind prevailed all day long, and brought monsoon clouds and precipitation from the bottom of the valley to higher altitudes. The mountain wind was particularly strong from the end of the post monsoon season to the beginning of winter. These features were not so enhanced at Syangboche, probably due to its altitude and location.
4) Active/break cycles of the summer monsoon were identified by means of a large-scale circulation index based on the vertical shear of meridian wind. The main characteristics of synoptic circulation were recognized: during the active phase, the monsoon trough at 500 hPa was evident over the Bay of Bengal and at 200 hPa the Tibetan High was strong and centered west of the Himalayas. On the other hand, during the break phase, the monsoon trough almost disappeared, the Tibetan High weakened and shifted its core east of the Himalayas.
5) Different daily profiles of precipitation and wind circulation were recognized at the Pyramid in relation to the active/break phases of the monsoon. During the active phase, precipitation occurred for the greater part of the day and the valley breeze was observed all day long; during the break phase, precipitation occurred mainly in the late afternoon and a weak mountain breeze was observed in the early morning (04:00 · 06:00). These features were explained in term of lower (stronger) convective activity during an active (break) day in response to different large-scale circulation patterns.

6) Spectral analysis on daily totals of monsoon precipitation revealed the presence of two main periodicity, 5 days and 8-10 days. Large-scale analysis made it possible to ascertain that these peaks were related to oscillations of the Tibetan High.

The Pyramid Meteorological Station has proved to be an important point of observation of the Indian monsoon characteristics at high altitude. The dataset collected since 1994 also allowed for the outlining of clear signals of a well-known large-scale biennial periodicity called Tropospheric Biennial Oscillation (Bertolani *et al.*, 2000). In order to provide continuity of data for as long as possible, a new AWS with one hour recording time step was installed in September 2000 near the old station and it will eventually become the new Pyramid Weather Station, assuring recording of better quantitative and qualitative data. Moreover, in recognition of the importance of this area as a climate change observatory, during 2001 a network of AWSs will be installed along the Khumbu Valley. In this way it will be possible to monitor the monsoon with more precision during its progression in the Himalayas. Modeling studies of the monsoon will soon begin using a high-resolution numerical atmospheric circulation model. The results will be also applied to the study of transport and deposition of pollutants on Himalayan snow cover. Collaboration with Nepalese researchers of the Department of Hydrology and Meteorology of Kathmandu and of Japanese researchers belonging to GEN-AWS group will be strongly promoted.

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