Stepwise Onset of Monsoon Weather Observed in the Nepal Himalaya

K. UENO AND K. TOYOTSU*

Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan

L. BERTOLANI

Epson Meteo Centre, Research and Development Division, Cinisello Balsamo, Milan, Italy

G. TARTARI

Ev-K2-CNR Committee, Bergamo, and Water Research Institute, National Research Council, Brugherio, Milan, Italy

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ABSTRACT

Mountain weather changes in the Nepal Himalaya were intensively examined during the 2003 monsoon onset using in situ datasets, observed by multiple automatic weather stations (AWS) distributed across the Coordinated Enhanced Observing Period (CEOP) Himalaya reference site at locations with significant differences in altitude. Onset of monsoon rainfall characterized as nighttime precipitation was initiated simultaneously at all stations with the occurrence and migration of a monsoon depression in the north of the Bay of Bengal. Satellite infrared images detected evident suppression of diurnal cloud development after the onset. About two weeks prior to the onset, the mountain weather abruptly changed such that the daytime valley wind at lower elevations weakened associated with morning clouds and the nighttime southerly wind began at upper elevations. The timing corresponded with the weakening of the westerly wind over the Himalaya due to the northward shift of the upper subtropical jet stream. The time lag between the precipitation onset and the change in the mountain weather was confirmed by 9 yr of in situ AWS data. The mechanism of nighttime southerly winds at high elevations is also discussed in relation to large-scale monsoon flow and local circulation.

1. Introduction

The Nepal Himalaya constitute the southern periphery of the Tibetan Plateau (TP). The complex topography includes 8000-m-high mountains and deep valleys, with more than 1000–2000-m altitude differences between the two. Annual meteorological observation of the Himalaya was first done in the upper Khumbu area with manual observations in the 1970s by a Japanese scientific expedition known as the Glaciological Expedition of Nepal (GEN). There researchers found a prevalence of daytime precipitation on ridges and nighttime precipitation in valley bottoms, which they explained was due to the simple diurnal development of clouds caused by the local circulation associated with orographic convection (Ageta 1976). Higuchi (1977) stressed that the diurnal weather change is important to evaluating the mass balance of glaciers, which acts as a key buffer between precipitation and runoff in Nepal. The actual precipitation pattern was quite heterogeneous depending on the direction steep mountain slopes faced in regard to the monsoon flow (Yasunari and Inoue 1978). Ohata et al. (1981) found that valley winds continued during the night in the monsoon season and speculated that the cause was the latent heat release of cloud formation and precipitation. Subsequently, the systematic diurnal changes of mountain weather were determined to be common characteristics of other parts of the Himalaya. Egger et al. (2000) ob-

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* Current affiliation: Showa Shell Sekiyu K.K., Minato-ku, Tokyo, Japan.

Corresponding author address: K. Ueno, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tennodai 1-1-1, Tsukuba, Ibaraki, 305-8577, Japan.
E-mail: kenueno@sakura.cc.tsukuba.ac.jp

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served the daytime valley wind at a depth of 1000–2000 m in the Kali Gandaki Valley of western Nepal. Kurosaki and Kimura (2002) clarified via geostational satellite data that daytime cloud development over the Himalaya was associated with a relatively lower cloud top compared to that over the TP during the monsoon season, which suggests that monsoon clouds over the Himalaya are primarily due to orographic ascent along the slope. For nocturnal precipitation, Tropical Rainfall Measuring Mission (TRMM) satellite data clearly show the 1000-km-scale zonal distribution along the southern periphery of the Himalaya (e.g., Bhatt and Nakamura 2005). Barros and Lang (2003) proposed that the mechanism of nighttime precipitation may be explained by a weakening of nocturnal valley winds that block the large-scale monsoon flow toward the TP at the bottom of the Himalaya. As a result, diurnal changes in the precipitation system during the monsoon season in the Himalaya are caused by the coupling of local circulations with large-scale monsoon flows. However, it is still not clear how systematic changes in mountain weather relate to the establishment of the subcontinental-scale monsoon circulation.

There are several definitions of “continental-scale monsoon onset” based on diagnosing the atmospheric flows or convection. The simplest definition of “regional monsoon onset” is “the beginning of continuous rainfall.” Generally, the Indian monsoon progresses through two regions: from the western peninsula of India to the northeast, and from the Bay of Bengal (BOB) to the northwest (Indian Meteorological Department 1943). Orographic effects on the moist low-level jet cause the major rainbelts over the land. Monsoon depressions (strong cyclonic vortices), formed over the southeast Arabian Sea or northern BOB under a monsoon trough, produce heavy rain events. In Nepal, the onset climatologically occurs in the middle of June. Monsoon precipitation generally accounts for 80% of annual precipitation, but this varies annually. For instance, Shrestha (2000) found that year-to-year variability of monsoon precipitation is strongly related to the Southern Oscillation index. Prediction of the onset date is of primary interest to local people for agriculture activity and water-resource management. The Department of Hydrology and Meteorology (DHM) in Nepal maintains more than 300 rain gauge stations; however, they are mainly distributed below 3000 m and most stations record daily data. Monitoring other meteorological elements such as wind, humidity, or radiation is still rare in the Himalaya. Therefore, characteristics of the diurnal changes in the mountain weather have not been grasped by multiple meteorological elements. And the linkage of the unique diurnal weather change in the Himalaya and synoptic-scale monsoon onset has not been fully investigated.

Some important relationships between Himalayan weather and large-scale circulation were found during the GEN’s two full years of observation in 1973–74. For instance, Yasunari (1976) pointed out that a monsoon burst was more strongly related to the development of a low pressure area at 500 hPa in the northern Indian region than the cloud-amount changes observed around the in situ observatories. Inoue (1976) attributed the difference between the monsoon rainfall amounts in 1973 and 1974 to the frequency of relatively heavy rainfall events that were not caused by the local cloud development. In 1999–2000, Lang and Barros (2002) conducted intensive precipitation observations in the central Nepal Himalaya and confirmed that the monsoon onsets for the two-year cases were associated with the development of monsoon depressions north of Bangladesh. Establishment of the monsoon trough adjacent to the Himalaya, which is due to surface heating surrounding the TP and convergence of subcontinental-scale monsoon flows, provides favorable conditions for activation of the monsoon depression (Bollasina and Benedict 2004). Recently Sato and Kimura (2007) examined the thermal and dynamical effect of the TP on the establishment of the Indian monsoon using a simplified regional climate model; they proposed that a descending flow in the middle troposphere over northern India could be a suppressor of precipitation onset. To confirm the actual status of the monsoon onset at the periphery of the TP, precise monitoring of seasonal changes of mountain weather and their relation to the convective activity by the mesoscale observation network is expected.

Basin-scale observation of mountain weather in the Khumbu area was initiated after the installation of multiple automatic weather stations (AWS) began in 1994 (Ueno et al. 1996; Tartari et al. 1998). Pyramid station is the highest observatory located at 5035 m above mean sea level (MSL), where biannual oscillating signals in the midtroposphere were discovered (e.g., Bertolani et al. 2000). Active and break cycles of the monsoon were strictly linked with a large-scale circulation index based on the vertical wind shear of the meridional wind (Bollasina et al. 2002). At Syangboche station, 3833 m MSL, Ueno and Pokhrel (2002) found an abrupt increase of surface air temperature in snow-free periods during winter with a prevailing synoptic-scale high pressure system.

In 2002–04, the Khumbu area was categorized as one of the reference sites of the Coordinated Enhanced Ob-

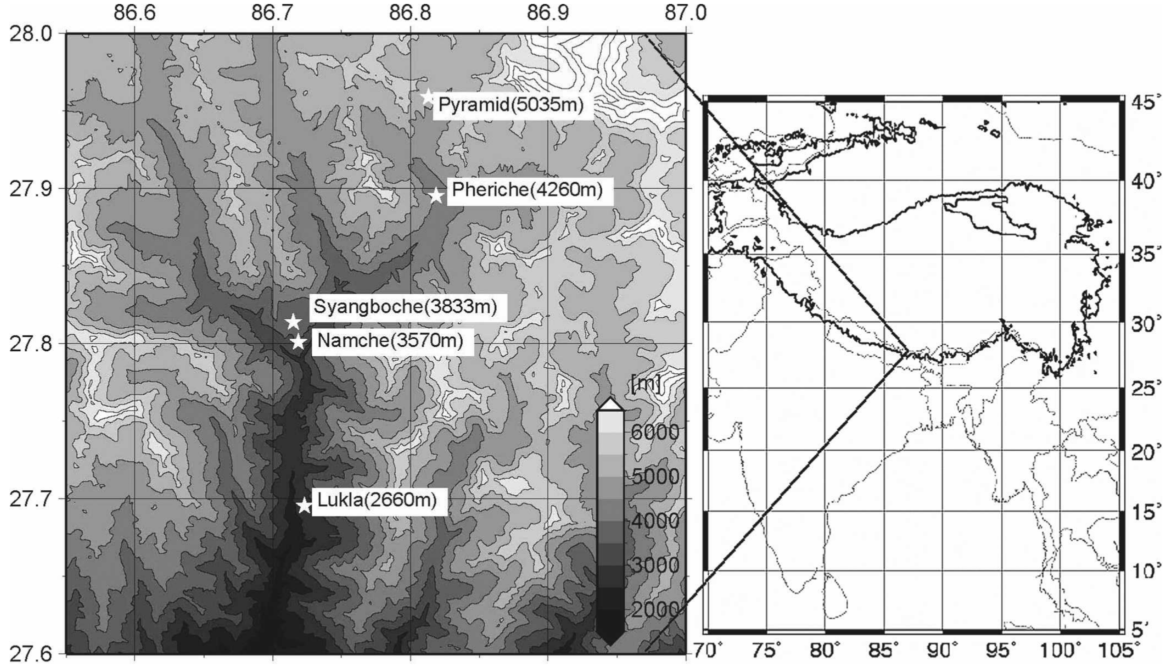

FIG. 1. Location of the (right) CEOP Himalaya reference site and (left) AWS distribution. A thick counter in (right) corresponds to 3000 m MSL, and the topography in (left) was countered based on digitized elevation data with 2 arc s interval from the Nepal government survey department 1:50000 maps.

serving Period (CEOP) Project (Koike 2004): it became the CEOP1 Himalaya reference site (Fig. 1). Data from five AWS were merged with a unified format by Epson Meteo Centre, Italy, and were accumulated at the CEOP data center. The Himalaya comprehensive dataset is beneficial for many applications such as understanding systematic weather changes in complex terrains, verifying satellite estimates, and checking a model's performance in simulating and predicting local weather parameters. For instance, when the Epson Meteo Centre compared rainfall data recorded in July 2004 with its operational global circulation model (GCM) output and satellite-derived precipitation estimates, they found out that most models tend to overpredict both the amount and the frequency of rainfall (Bertolani et al. 2007). Meinke et al. (2007) compared simulated precipitation by the regional spectral model with CEOP observations during the nonmonsoon season and noted out that positive bias was related to stratiform precipitation over the Himalaya.

In this paper, multiple-station data of the CEOP Himalaya reference site from April through September 2003 were analyzed to reveal the relationship between local mountain weather changes and the monsoon onset of the alpine Himalaya. To confirm the relationship, year-to-year variability was examined using 9-yr data accumulated at one of the AWS sites.

2. Observation site and data

Figure 1 shows the location of the CEOP Himalaya reference site with AWS distribution. The site is in the eastern Nepal Himalaya, Solo Khumbu district; Mt. Everest is at the northeast edge of the basin. Forests exist only in the limited valley-slope areas below the 4000-m level and the landscape around the AWS is mostly rocky or bare land with sparse small shrubbery. Because of steep slopes surrounding deep valleys, only two AWS are located in a widely distributed flat field: Pheriche is at the bottom of a U-shaped valley with a flat fetch of about 1 km from west to east and 3 km in a north–south direction, and Syangboche is on a yak farm field with 100–300-m-scale flat fetch. GEN's key meteorological observatory in 1970 was located at Lhajung (27°53′N, 86°50′E; 4420 m), which is on a hill about 500 m east of Pheriche AWS. Namche and Pyramid AWS are located at small hilly places on the ridges, and Lukla AWS is on the river terrace of a V-shaped valley.

The analysis period from April through September 2003 was when most of the surface meteorological measurements were completed in the CEOP phase-1 database. Hourly base precipitation, shortwave radiation, wind, relative humidity, and temperature data at five AWS sites were intensively analyzed. Precipitation was measured by a tipping-bucket rain gauge without a heating system. Temperature and humidity were measured with a radiation shield under natural ventilation conditions. All data were automatically saved in the data-logging system. Some problems with automated measurements in alpine regions were due to snowfall on the tipping-bucket rain gauge and the freezing of the anemometer and the wind vane. To compensate for the snowfall, we evaluated the possibility of missing data by comparing precipitation signals with the surface air temperature as described in the next section. Nine years of data from 1996 to 2004 accumulated at Syangboche were also used to analyze year-to-year variability. The activity of synoptic-scale circulation and cloud development around the Nepal Himalaya were examined using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) and Meteorological Satellite (*Meteosat*)-*5* geostationary satellite data provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

3. Mountain weather changes in the 2003 premonsoon season

The onset of precipitation with its diurnal variations in 2003 was examined at different altitudes, as shown in Fig. 2. Unfortunately, precipitation data at Lukla were missing, so the lowermost data were at Namche (3850 m MSL). Nepal standard time (NST) is 5 h and 45 min ahead of Greenwich mean time. The AWS were operated under the coordinated universal time (UTC) system to fit with other CEOP reference sites' time stamps. To avoid the confusion of a 15-min difference between NST and so-called local time in the world standard time coordination, we used UTC time stamps to describe the diurnal variations in the figures.

To check the effects of snowfall on the precipitation data, 0°C contour line of the surface air temperature was overlapped, as shown in Fig. 2. At Pyramid and Pheriche, nighttime temperatures were below 0°C during April and May 2003 when no precipitation records were found, but some precipitation was recorded in the morning (around 0200–0400 UTC) after surface air temperature exceeded 0°C. This evidence indicates that nighttime snowfall that had accumulated on the gauge was melted by the insolation. Besides, temperature data at Syangboche and Namche were mostly above 0°C throughout the period, and signs of the morning snowmelt were not observed. We therefore concluded that precipitation data after June were not affected by snowfall at any stations.

Tendencies of monsoon precipitation by means of absolute amount and its altitudinal differences in 2003 were compared with those in the 1970s. According to Yasunari and Inoue (1978), daily average precipitation from 1 June through 30 September in 1976 was 2.6 mm day^{-1} at Lhajung (4420 m). At Pheriche station (4260 m), the nearest station to Lhajung, it was 1.9 mm day^{-1} in the same months of 2003. Both values are nearly the same order. In the same period, accumulated precipitation was 6.5 mm day^{-1} at Namche (3570 m) and 2.9 mm day^{-1} at Pyramid (5035 m), corresponding to 2.5 and 1.1 times that of Pheriche, respectively. Similar rates, such as 1.9 and 1.1 times, were observed by Ageta (1976) during the 1974 monsoon, showing that precipitation largely decreases with increasing elevation around 3500–4500 m MSL. Thus, the precipitation amount and its altitude dependency in the 2003 monsoon were almost the same as the studies done in the 1970s.

Figure 2 showed a sudden increase of precipitation at all stations after 19 June. According to the diurnal precipitation changes averaged after from June to September (Fig. 3), Namche recorded most of its precipitation at nighttime (after 1400 UTC). The total precipitation amount decreased with increasing elevation, such as at Pyramid AWS, and daytime precipitation exceeded the nighttime precipitation. This altitudinal tendency of diurnal precipitation changes agreed with the characteristics of monsoon precipitation observed in the Himalaya by previous studies (e.g., Ageta 1976; Ueno and Yamada 1990). Namely, the rainy season in the Khumbu started simultaneously at all altitudes in the middle of June (around 19 June).

Local weather changes such as the occurrence of clouds and mountain–valley circulations were examined using downward shortwave radiation and surface wind data. Figure 4 shows the seasonal change in radiation in the morning and afternoon averaged for the four stations in which the Lukla data were used instead of the Syangboche data. A large amount of morning radiation during April and May indicated that morning weather was fair at all altitudes. Further, afternoon radiation frequently decreased in April, indicating that diurnal cloud development had already started along the valley by early spring. An increase of afternoon radiation in early May and near the end of May indicates the prevalence of fair weather on a typical day in May. This evidence is consistent with the analysis by Fujinami and Yasunari (2001), which clarified the period with evident diurnal convective activities in the early spring season from the satellite data over the TP. After 3 June, morning radiation suddenly started to decrease. This feature was clearer at Namche and Lukla, stations at lower elevations. At the same time,

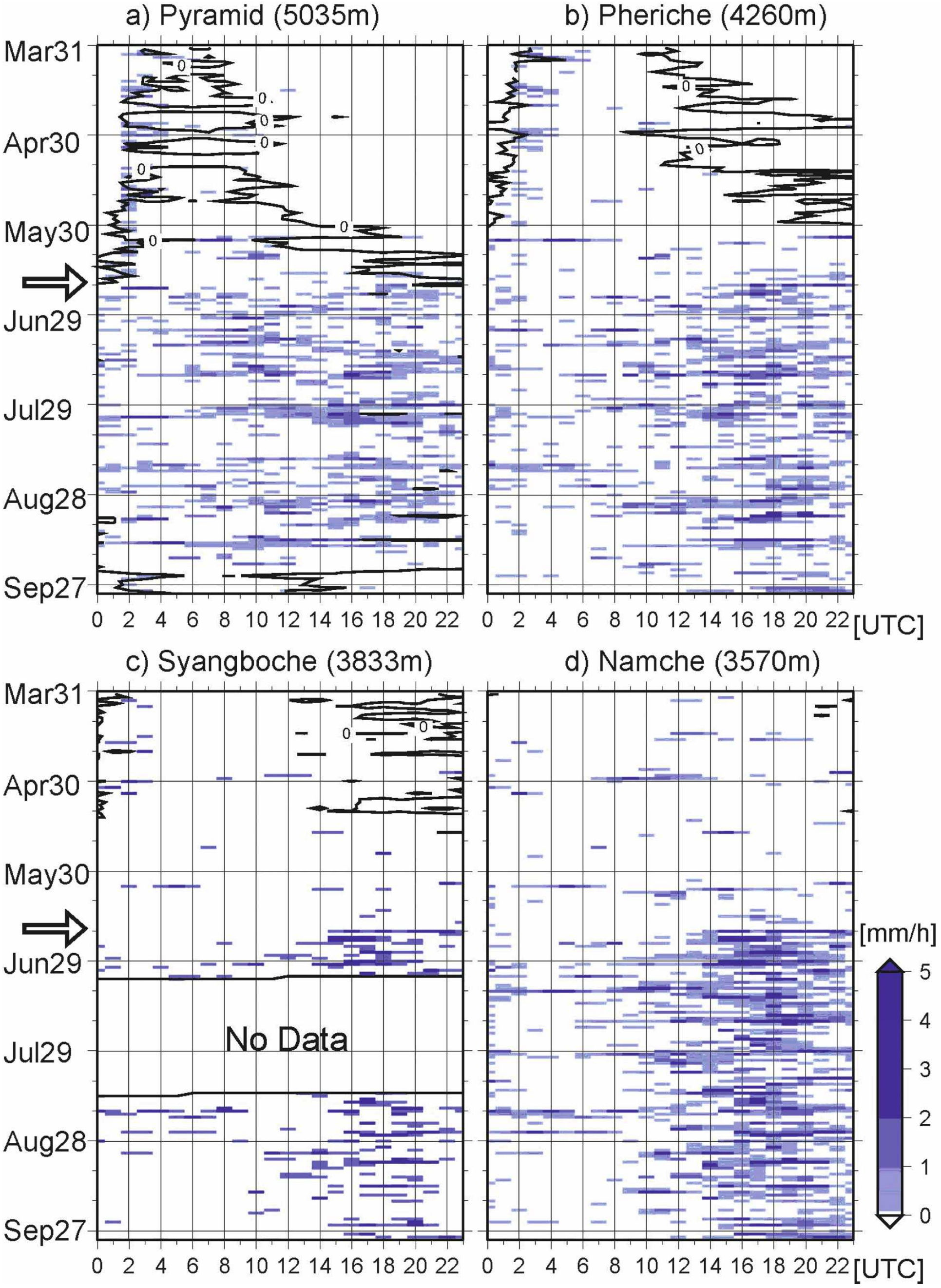

FIG. 2. Day versus UTC cross section of hourly precipitation from 31 Mar to 27 Sep 2003. Nepal standard time is 5 h 45 min advancing to UTC. Date of precipitation onset (19 Jun) was marked by arrows on the left axis.

morning relative humidity began to reach high values, especially at Namche with more than 90% (figure omitted). This evidence indicates that the near-slope atmosphere began to saturate and cloud occurrence began in the early stage of daytime after 3 June.

Diurnal changes of wind fields from April to August at four different altitudes, and its annual variations at two representative AWS are examined in Figs. 5 and 6. As the Khumbu Valley faces south (Fig. 1, left), the southerly wind corresponds to the valley wind, and the northerly wind corresponds to the mountain wind by means of local circulation. Figure 5 shows a clear diurnal change of the wind system occurring during April and May: strong valley winds (warm colors) started

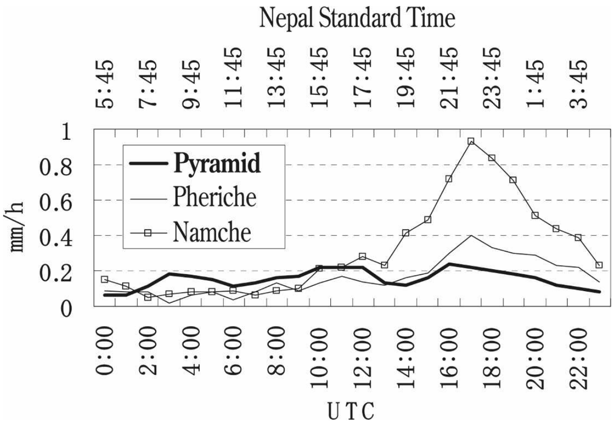

FIG. 3. Diurnal variation of hourly precipitation at three stations averaged for June–September.

around 0300 UTC, and weak mountain winds (cool colors) replaced them after around 1500 UTC. At Pyramid AWS, daytime winds were relatively weaker compared to other stations even though it is at the highest elevation. This is because the AWS location was not exposed to the Khumbu Valley (see section 2) but lay behind the side-moraine of the Lobuche glacier, which disturbed the anabatic circulation along the main valley. Weakening of valley winds near the mountain ridge is another reason.

In general, a valley wind is induced by the heating of the atmosphere over the slope of a mountain, which causes a horizontal gradient of potential temperature with a generating horizontal pressure gradient. As the Himalaya are composed of very steep slopes with more than 3000-m differences between the Indo-Gangetic Plain and the TP, there must be at least two different scales when considering the mechanism of anabatic flows there. One is the large-scale thermal circulation supposed to cover the northern Indo-Gangetic Plain and the southern TP, such as examined by the Flohn (1968) or Egger (1987). Pressure gradient around the TP due to the daytime elevated heat source is the principal factor. Therefore the circulation is plausible when the upper westerly wind flow is weakened, such as in the monsoon season. Actual monsoon flows over the Himalaya include the southerly winds by dynamic forced ascent from the BOB and are enhanced by the cloud development with latent heat release over the TP. Therefore purely induced anabatic circulation between the lower plain and the elevated plateau is difficult to detect by observation. At least the strong daytime valley winds prevailing prior to May were not this type of flow because of strong westerlies over the Himalaya (shown later). Evidence of the large-scale monsoon flows in the in situ data will be discussed again later in this section.

The other scale is the mesoscale circulations mostly within the deep valley initiated by upslope winds, which are generally controlled by energy exchanges between the free atmosphere and the atmosphere near the mountain slope and establish valley-scale flows. The upvalley wind prevails in almost all seasons during the daytime in the Khumbu Valley (Ohata et al. 1981; Bollasina et al. 2002). The daytime southerly wind shown in Fig. 5 is also part of this mesoscale circulation. Zängl et al. (2001) simulated the upvalley winds of the Kali Gandaki Valley in the central Nepal Himalaya, and explained the strong upvalley winds observed more than 15 m s^{-1} as supercritical flows established in the widening part of the valley. Though we did not observe such strong winds in the Khumbu Valley, stronger winds at Pheriche AWS (located in the bottom of a

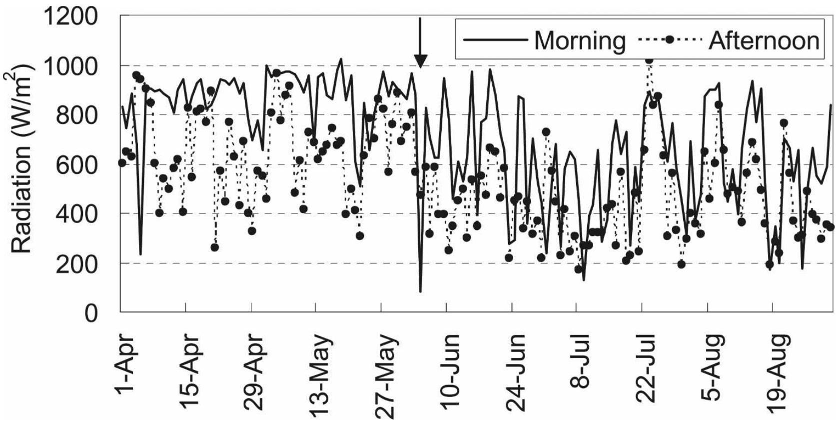

FIG. 4. Time variation of radiation averaged at four stations in the morning (0300–0500 UTC; solid line) and afternoon (0007–0900 UTC; dashed line), respectively; 3 Jun was marked by an arrow.

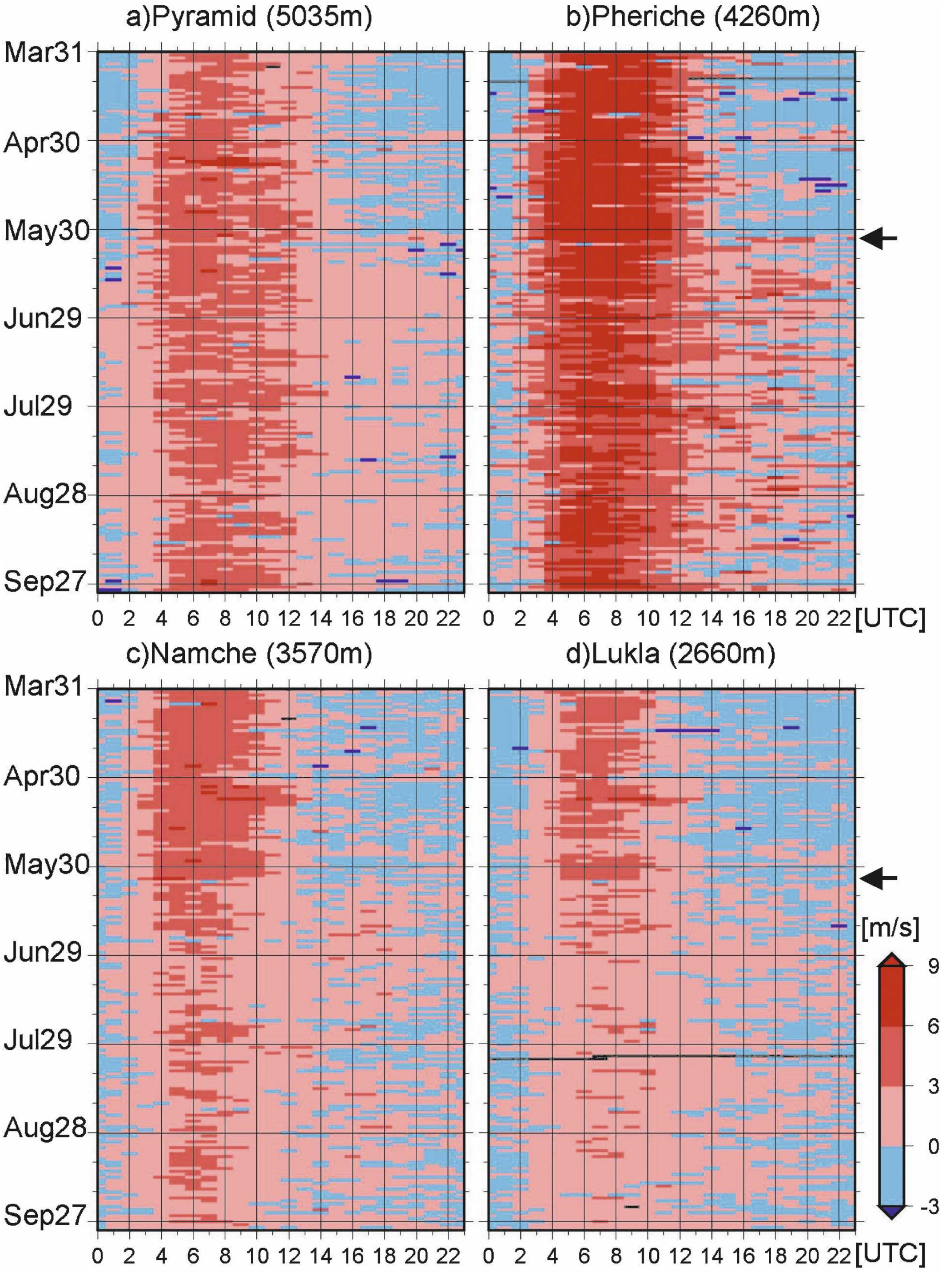

FIG. 5. Same as Fig. 2, but for meridional component (along valley) of surface wind. Warm color corresponds to southerly wind, and blue color corresponds to northerly wind. Date of wind transition (3 Jun) was marked by an arrow.

U-shape valley) indicate that there may be some dynamical mechanism that accelerates the southerly flow due to the change of valley shape in the upper basin.

Nighttime mountain winds can be explained as katabatic flows with downslope movement of cold air due to nocturnal radiative cooling at the slope surface. They prefer to flow along the bottom of a valley, which is where most AWS were located and thus could detect

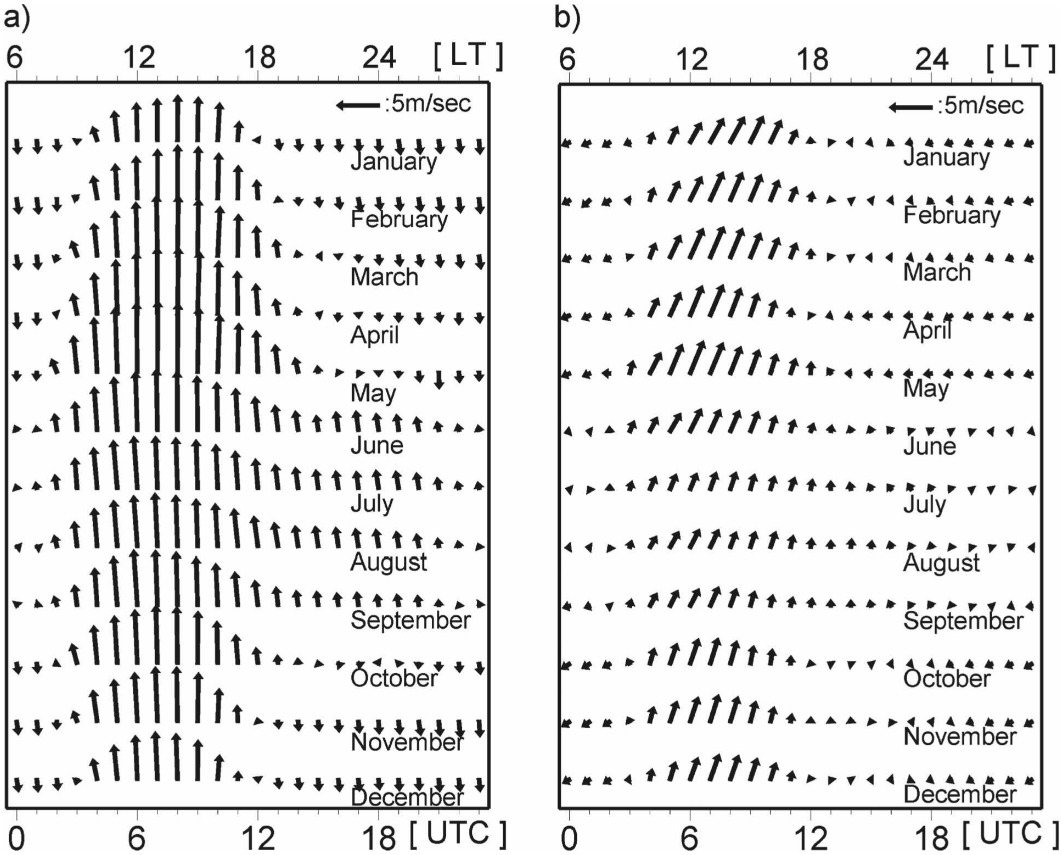

FIG. 6. Diurnal variation of the monthly surface wind vectors at (left) Pheriche and (right) Lukla in 2003.

the flow. During April and May, the timing of the change from a valley wind to a mountain wind was 1–2 h earlier in the lower stations (e.g., Lukla, at 1300 UTC) than in the upper elevations (e.g., Pyramid, at 1500 UTC); the nighttime mountain wind was stronger at Pheriche (Fig. 5). We speculated that observed characteristics may reflect the effect of earlier sunset at the bottom of a deep V-shaped valley in a lower basin and glacier flows initiated at the Khumbu Glacier located at the head of the valley. As the upper reaches of the Khumbu Valley feature a variety of glaciated valleys (e.g., Mueller 1958), the detail passes of the downslope winds may be more dependent on each drainage area.

After the beginning of June, there were evident changes in the surface wind system (marked by arrows at the right sides of Fig. 5). The first change was that the daytime valley wind speed became weaker (indicated by the color change from red to pink). This feature was apparent at lower elevations, such as at Namche and Lukla. Reduction of net radiation at the surface and vertical convection associated with neutral or unstable conditions sometimes prevent the development of anabatic flow along the slope (e.g., Orville 1964). As the timing of a reduction of in situ insolation (Fig. 4) coincided with the weakening of valley winds, we presumed that mesoscale upslope circulation was weakened by the development of cloud cells in the morning.

The other changes were that nighttime mountain winds were frequently replaced by southerly (upvalley) winds. The same phenomenon had been observed at Lhajung (4420 m) in the 1970s by Ohata et al. (1981). However, the present study found that this characteristic is more apparent at higher elevations, such as at Pyramid and Pheriche. Comparison of monthly mean wind vectors at different altitudes indicate that the southerly winds at Pheriche continued until 0300 LT, not throughout the day, from June to September (Fig. 6). The nighttime (2200–0300 LT) average southerly wind speed at Pheriche was stronger in June (at the beginning of the monsoon season) and weaker in August, which corresponded to the large-scale monsoon flow activity. At lower elevations such as at Namche and Lukla, northerly winds were sporadically observed after June (Fig. 5). Cold katabatic gravity currents prefer to flow along the bottom of local concave topography, then the northerly winds were attributed as downslope drainage flows. In the Kali Gandaki Valley, the depth of the nighttime weak drainage flow was around 1000 m at around 3000 m MSL in late September 1998 (Egger et al. 2000). We speculated that the nighttime southerly wind observed in the upper Khumbu Valley would be part of a larger-scale flow migrating from the Indo-Gangetic Plain into the TP throughout the day, which flowed passing above the shallow stable katabatic currents in the deep valley and was captured at the head of basin. Weakening of upper westerlies (explained in the next section) creates favorable conditions to enhance such meridional flows crossing the Himalaya. This hypothesis is based on the idea of the existence of large-scale inflows toward the TP trough in a typical day. It partially supports the results of Barros and Lang (2003), who proposed that a mechanism of nighttime precipitation below the 3000-m level along the foot of the Himalaya was due to convergence between a large-scale ambient monsoon flow throughout a day and a weakening of upvalley winds near the surface in the night.

However, we were more interested in how the start of nighttime southerly winds related to the nighttime precipitation onset. In the next section, we compare local mountain weather changes with seasonal progress of large-scale circulations and discuss the transition mechanisms of daytime convections associated with clouds and the start of rains in relation to subcontinental-scale monsoon progress.

4. Stepwise onset of monsoons in the Nepal Himalaya

There is one important feature in the timeline of mountain weather changes shown in the figures of the previous section: precipitation onset and modulation of local circulation did not occur simultaneously. Weakening of daytime valley wind associated with cloud development and the starting of continuous nighttime southerly wind began around 3 June. This date was about two weeks before the beginning of the rainy season around 19 June.

Figure 7 shows the seasonal march of geopotential height with wind fields and moisture flux throughout May and June of 2003. The Khumbu area is located at around 27.5°N (indicated by arrows on the right side of Fig. 7). In the beginning of May, a subtropical jet stream at 200 hPa is located at 25°–30°N with a large longitudinal pressure gradient (Fig. 7a). The southern border of the pressure gradients, that is, the northern edge of the subtropical anticyclone, gradually shifted northward during May and rose above the Himalayan range (27.5°N) by the beginning of June. At 500 hPa, a strong westerly jet stream prevailed in 20°–27.5°N for April and May (Fig. 7b). In the north part of this jet stream, wind speed is weak because of the near surface of the TP. The strong westerlies over the Himalaya became weak at the beginning of June because of a

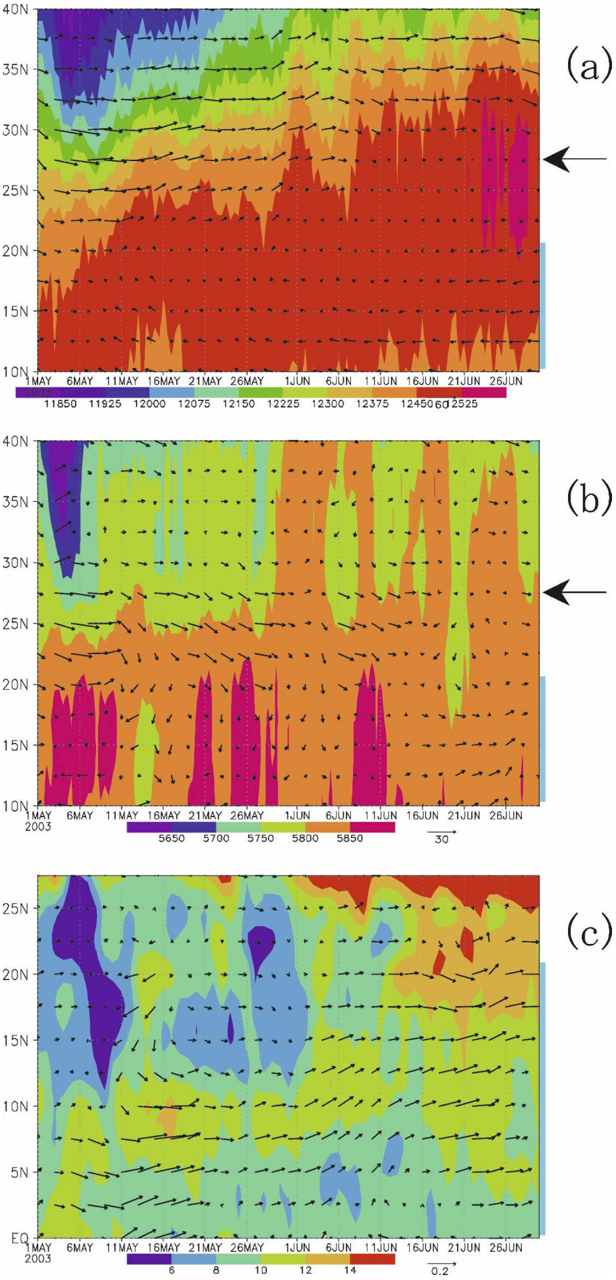

FIG. 7. Day–latitude cross section of NCEP–NCAR (a) 200- and (b) 500-hPa geopotential height with wind vectors, and (c) 850-hPa specific humidity distribution with $q\mathbf{V}$ vectors along 85°E, from 1 May to 30 Jun 2003. Arrows beside (a) and (b) indicate the latitude of Khumbu area, and vertical blue bars indicate the latitudes over the BOB. In (c), areas north of 27.5°N were omitted because of the topography of the TP.

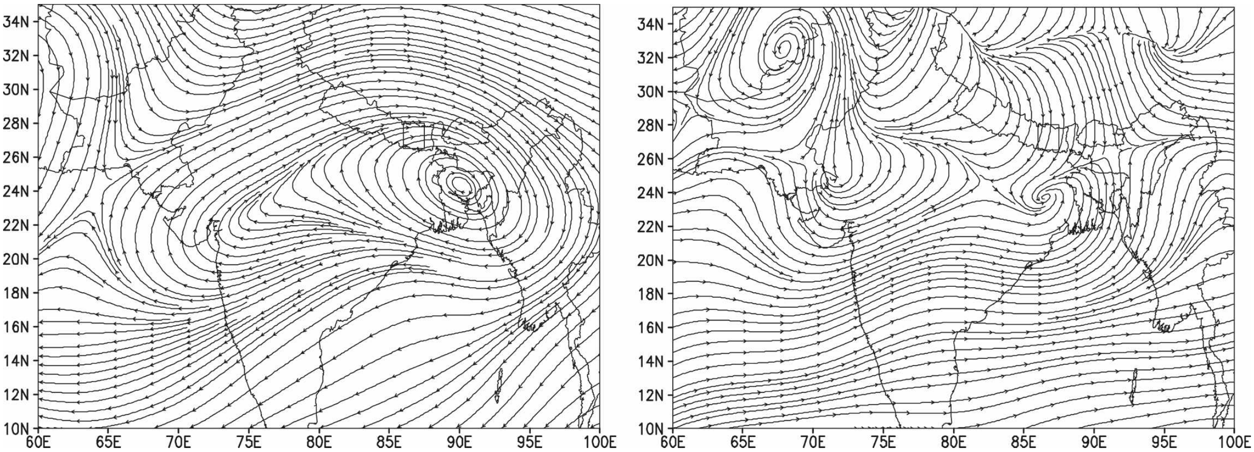

FIG. 8. Distribution of stream lines at (left) 200 and (right) 850 hPa on 0000 UTC 19 Jun 2003. Khumbu area is shown as a square box in the eastern Nepal.

northward shift of the main subtropical jet stream in the upper troposphere, which corresponded to the timing of local circulation changes in the Khumbu area around 3 June. The subtropical jet stream is caused by angular momentum transport from the deep tropics accomplished through the local Hadley circulation, which differs from the midlatitude eddy-driven jet stream by baroclinic instability (Lee and Kim 2003). Therefore, the sudden change of local circulation was caused by the seasonal evolution of general circulation of the atmosphere in the tropics. At that moment, the main monsoon flow, indicated as a moisture conveyer belt at 850 hPa (Fig. 7c, greenish-yellow zones), was still located over the BOB, at 5°–10°N, far south of the Himalayan ranges. The monsoon flow moved into the middle of the BOB around 6 June. An isolated high humid zone appeared in the north of the BOB (around 20°N) 13 June, and then the precipitation onset occurred at the Khumbu area. Therefore the development of morning clouds in the beginning of June was not caused by the intrusion of moisture flow from the main monsoon channel but by weakening of general flows over the Himalaya.

Following this discovery, we examined what started the continuous rains associated with the synoptic-scale increase of low-level moisture around the Himalaya in the middle of June. Figure 8 shows distributions of the streamfunction at 200 and 850 hPa on 19 June. A monsoon depression, a cyclonic flow in the lower troposphere with an anticyclonic center in the upper troposphere was found in the north of the BOB (24°N, 90°E). This is the area where the maximum number of low pressure systems are analyzed during the monsoon season (Mooley and Shukla 1989). It is also the area where the first evident monsoon depression occurred in 2003 according to the time sequence of vorticity at 850 hPa (shown in Fig. 10). The occurrence of the depression was also recognized on the NCEP–NCAR 850-hPa moisture field as a cyclonic flow pattern appeared with moistened area around 20°N (Fig. 7c). Meteosat geostationary satellite images showed two distinctive cloud covers associated with the depression: one is a massive core area over the cyclonic center and the other is a frontal cloud band formed at the northwestern edge of the cyclone extending from the Indian peninsula toward the central TP. The latter cloud band initiated the rain onset in the Khumbu Valley. The depression center was divided into east and west cores on the map of streamfunction, and a west core reached to the Nepal Himalaya on 21 June. Namely, the monsoon onset of the Khumbu area was instigated by the occurrence of the monsoon depression that accompanied the cloud system and moisture intrusion from the main monsoon channel into the Himalayan range. This evidence agreed with an analysis by Lang and Barros (2002) which also revealed that monsoon onsets in 1999 and 2000 were associated with monsoon depressions from the BOB causing upslope flows on their eastern flank over the Himalaya. Figure 9 shows a time sequence of blackbody temperature (Tbb) above the Khumbu Valley observed by *Meteosat-5* infrared (IR) channel. Because of missing data covering several days at the end of May, differences of Tbb variability before and after 3 June could not be examined well. Besides, there is a clear gap in the Tbb changes after the precipitation onset (19 June), such that the large diurnal variation was depressed and daytime Tbb started to remain below 250 K, indicating the lowering of daytime cloud height. Kurosaki and Kimura (2002) examined the daytime cloud activity by using geostational meteorological

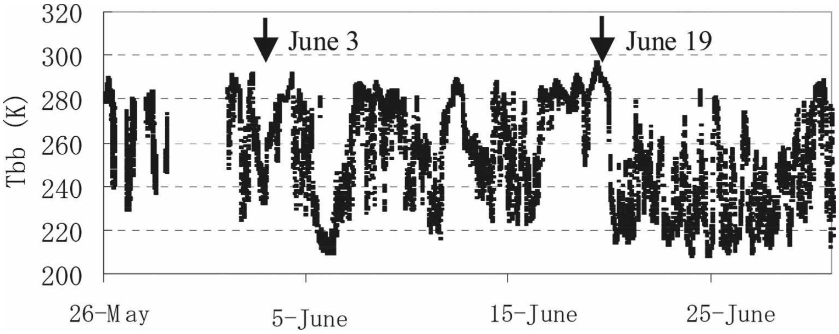

FIG. 9. Time sequence of *Meteosat-5* IR Tbb from 26 May to 30 Jun in 30-min intervals over the Khumbu area. Data are missing for 29–31 May.

satellite visible and IR data: they showed that low-level cloud cover prevailed over the southern slope of the Himalaya during the monsoon season. Lang and Barros (2002) showed that a vertical cross section of a TRMM satellite image indicated shallow stratiform rain after the monsoon onset. Therefore, the transition of Tbb behavior after 19 June indicates that convective-type clouds associated with diurnal circulations changed to more-stratiform-type clouds associated with orographic ascending affected by the moisture intrusion from the tropical disturbance.

In 2003, a stepwise alternation of premonsoon weather changes observed in the Nepal Himalaya was explained by the disappearance of the strong westerly jet at first and then the migration of the first onset of a monsoon depression in the northern BOB. To confirm this mechanism and order, nine years of data accumulated since 1996 at Syangpoche AWS were analyzed. At first, in situ daily precipitation data were compared with 850-hPa daily vorticity over the northern BOB (20°–25°N, 85°–90°E) in Fig. 10. It is clear that most of the increases of vorticity after May corresponded with heavy precipitation events within a time lag of several days. This confirms that the occurrence of the monsoon depression in the northern BOB frequently caused the precipitation onset in the eastern Nepal Himalaya. In the figure, we can also see year-to-year variability of the precipitation tendency and relations to the vorticity variability, especially in May. The years 1997, 1998, and 2003 showed little precipitations in May with a very clear monsoon onset in June. In 1999, an increase of the vorticity at the end of May was associated with a major precipitation event, but a similar increase did not accompany the significant precipitation increase in 2000. In 2002, amplitude of the vorticity was small, and frequent small amounts of precipitation prevailed throughout April and May.

Here, we want to propose two important factors to explain the year-to-year variability. One is the precipitation event initiated by a synoptic disturbance migrating from the west that develops or stagnates along the southern flank of the TP; this particularly causes early spring precipitation in the southern TP and the Himalaya (e.g., Ueno 2005). Vorticity over the BOB could be a good indicator for identifying the "monsoon onset" by a tropical-orientated disturbance. Another factor is the variability of storm tracks after landing over the Indo-Gangetic Plain, as discussed in Lang and Barros (2002). Both factors would be affected by subcontinental-scale circulation variability in the spring season.

Next, the relation between the activity of the subtropical jet and cloud development was analyzed by comparing the daily averaged NCEP–NCAR 200-hPa wind speed at 27.5°N, 85°E (a nearest grid point of the Khumbu area) with in situ downward radiation in the morning (Fig. 11). In most of the years, upper wind speed started to decrease after April. The decreasing trend was not always linear but went up and down weekly depending on the years; this indicated that the so-called northward jump of the subtropical jet is not a single event. A seasonal change in the lowering of radiation corresponded well to the decrease in wind speed, indicating that weakening of the westerly jet over the Himalaya due to the northward shift of the subtropical jet provided favorable conditions for initiating local convective clouds. Besides, a decrease in wind speed is not always accompanied by a decrease in radiation. For instance, the relation was clear in 2003 and 2004, but ambiguous in 1998 and 2000. Although the upper winds are calm, other factors, such as large-scale subsidence or local stability within a valley, will suppress the morning cloud development.

Dating the start of convection and precipitation based on observations is necessary to quantify the duration of time lag between them, and could be utilized by the Nepalis to follow the monsoon progress. In

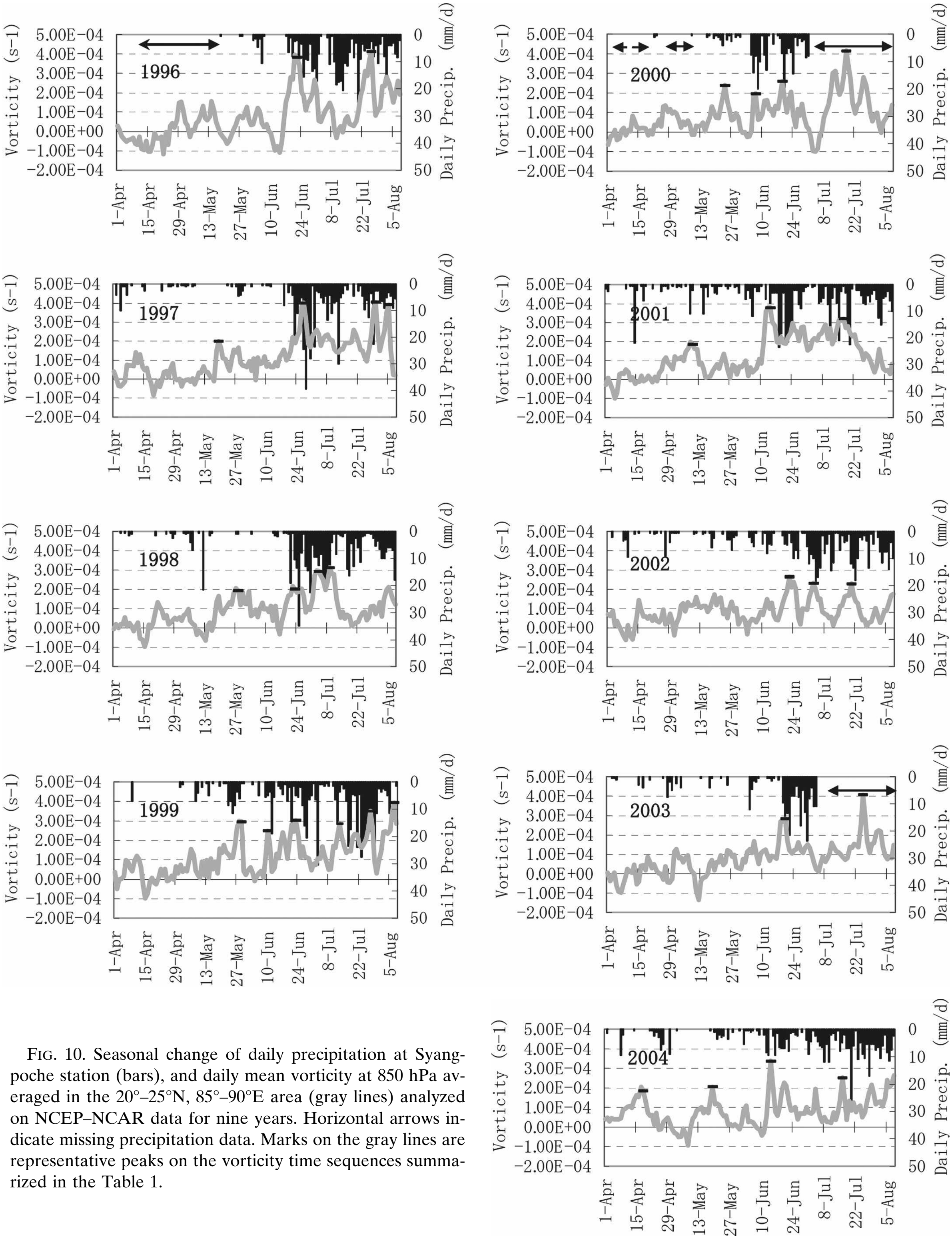

FIG. 10. Seasonal change of daily precipitation at Syangpoche station (bars), and daily mean vorticity at 850 hPa averaged in the 20°–25°N, 85°–90°E area (gray lines) analyzed on NCEP–NCAR data for nine years. Horizontal arrows indicate missing precipitation data. Marks on the gray lines are representative peaks on the vorticity time sequences summarized in the Table 1.

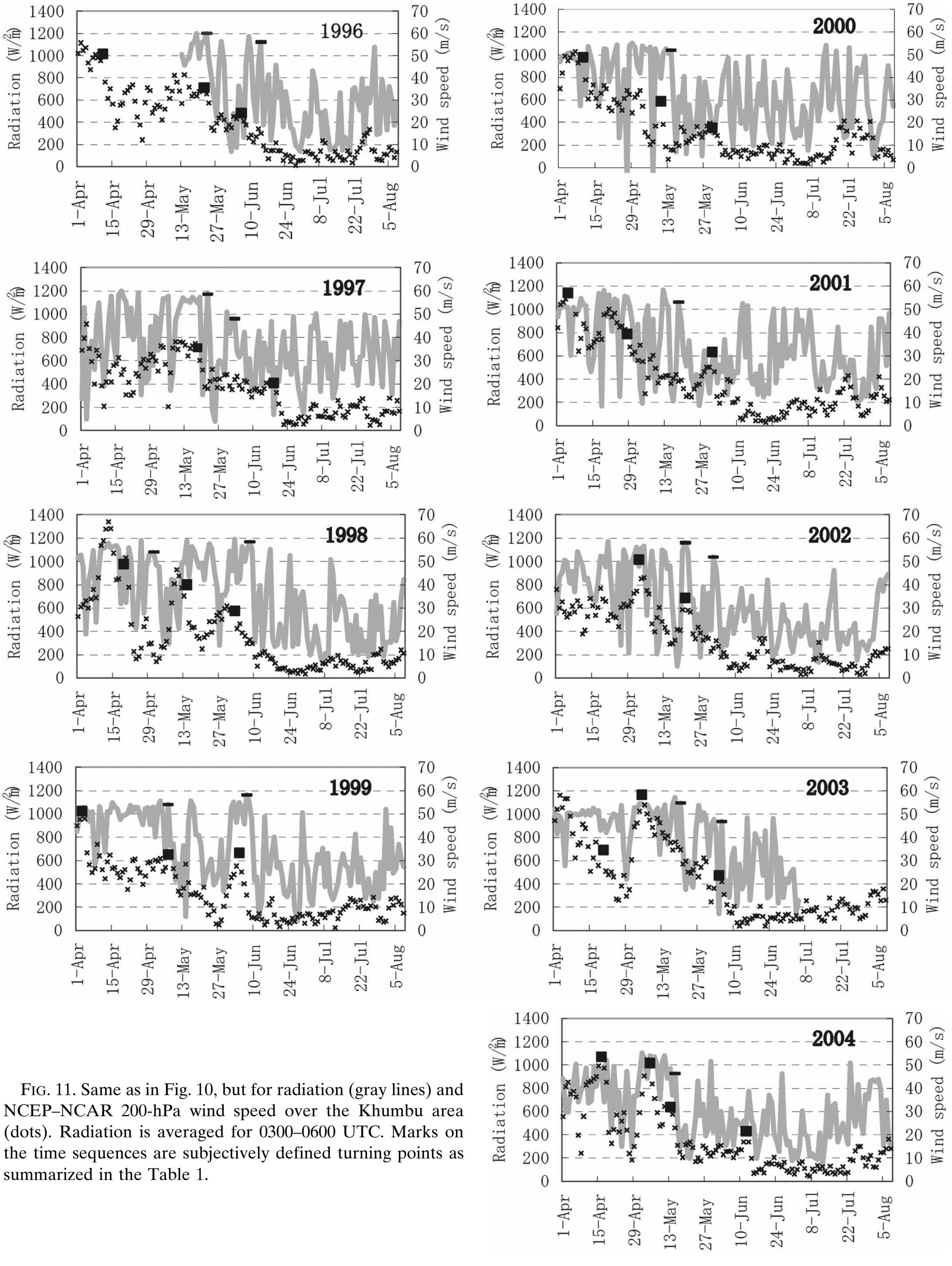

FIG. 11. Same as in Fig. 10, but for radiation (gray lines) and NCEP–NCAR 200-hPa wind speed over the Khumbu area (dots). Radiation is averaged for 0300–0600 UTC. Marks on the time sequences are subjectively defined turning points as summarized in the Table 1.

TABLE 1. Dates of mountain weather change and continuous rain with averaged duration between them defined in the Figs. 10 and 11. Letters are the initials of months: A = April, M = May, J = June, JL = July, and AU = August; and the number corresponds to the day, e.g., M23 = 23 May. All the dates are converted to the DOY, and the averaged DOY is again converted to the calendar date (avg date) at the bottom of the table.

	Mountain weather change		Rain onset	
Yr	Radiation	200-hPa wind	BOB vorticity	Precipitation
1996	M23, J14	A11, M22, J6	J20, JL26	J18
1997	M22, J2	M18, J18	M19, J27, J30, AU5	J23
1998	M1, J8	A19, M14, J2	M28, J23, JL4, JL9	J21
1999	M7, J7	A3, M7, A4	M29, J10, J23, JL13, JL27, AU7	M23
2000	M14	A10, M10, M30	M24, J7, J19, JL18	J5
2001	M18	A5, A28, M31	M10, J14, JL17	J14
2002	M21, J21	M5, M21	J22, JL3, JL20	J21
2003	M20, J5	A20, M5, J4	J20, JL25	J19
2004	M15	A16, M5, M13, J12	A18, M19, J14, JL16	J12
Avg DOY	147	131	177	165
Avg date	27 May	11 May	26 Jun	16 Jun

Figs. 10 and 11, the dates of the abrupt changes were subjectively marked on the time sequences and summarized in Table 1. The beginning of sudden stepwise decreases of radiation (200-hPa wind speed) above 600 W m^{-2} (40 m s^{-1}) were the criteria. To determine an occurrence of depression, single peaks above the vorticity of 2.00×10^{-4} s^{-1} were subjectively extracted. The earliest day with an occurrence of precipitation over 5 mm day^{-1} with subsequent continuous rain days, associated with an increase of evident vorticity, was defined as precipitation onset, and listed in a column labeled "precipitation" in Table 1. According to this table, we can reconfirm that neither the modulation of mountain weather nor the occurrence of the monsoon depression was a single event during the monsoon progress. The dates of the weakening of the upper wind were earlier than the start of cloudy days in most cases, which confirmed the previous discussions that the activity of the subtropical jet primarily controls the local cloud development. The occurrence of the vorticity over the BOB began sometime in April, but it did not always cause heavy precipitation in the Nepal Himalaya. If the beginning of successive rains associated with a vorticity increase at BOB were dated as the monsoon precipitation onset, it mostly occurred in the middle of June in the Khumbu Valley and agreed well with the results of Bollasina et al. (2002). Dates were averaged in each element by means of the day of the year (DOY), and compared at the bottom of the Table 1. The method is not always objective because the sampling period was limited to 1 April–5 August, and the timing is geographically dependent. But, at least, we could identify that mountain weather changed two to three weeks prior to monsoon precipitation onset at the Khumbu area.

5. Summary and discussion

This study intensively analyzed the CEOP Himalaya reference site data on the 2003 premonsoon season. The mechanism of nonuniform changes in mountain weather was explained based on the linkage of synoptic conditions and local circulations. Nine years of long-term AWS data were utilized to verify the accuracy of the mechanism. Results are summarized as follows:

1) In 2003, precipitation onset in the Khumbu Himalaya was clearly identified as 19 June. The onset was caused by the development of a monsoon low in the northern BOB, which indirectly caused orographic precipitation and migrated toward the Himalaya.
2) About two weeks prior to the precipitation onset, modulation of local circulation was found in the radiation, wind and humidity data. After 3 June, development of morning clouds began and daytime valley wind weakened, especially at lower elevation stations. Also, a continuous southerly wind prevailed during the night at higher elevation stations. This timing was due to the weakening of westerlies over the Himalaya with a northward shift of the upper subtropical jet stream.
3) Nine years of onsite data from Syangboche AWS confirmed a time lag between the modulation in mountain weather as described in the previous paragraph (paragraph 2) and the beginning of the rainy season as described in paragraph 1 above for several weeks. Therefore, we propose a mechanism of stepwise onset of monsoon weather in the Nepal Himalaya; for example, at first there is a weakening of mountain–valley circulation due to a weakening of westerlies with a northward shift of the subtropical jet. Secondly, there is precipitation onset due to the

development and intrusion of a monsoon depression from the BOB.

4) Nighttime southerly winds prevailed at higher elevations, such as above 4500 m MSL in the Khumbu Valley after the weakening of the subtropical jet. We speculated that this wind evidences large-scale monsoon flow into the TP, which passes over stable katabatic winds in the deep valley.

Activity of the subtropical jet is controlled by the atmospheric dynamics of general circulation in the tropics. Also, energy propagations between subtropical and midlatitude eddy-driven jet streams exist (Lee and Kim 2003). A monsoon depression is a synoptic-scale cyclonic disturbance formed under the conditions of a monsoon trough (Sikka 1977). A mesoscale surface observation network clarified that activity of those two systems with different scales and mechanisms, such as the subtropical jet stream and a monsoon depression, provide stepwise transitional periods. Important points are that heating of the upper troposphere over the southern periphery of the TP is expected during the period because of the activation of daytime cumulus convection over the individual mountains, and this period is prior to so-called monsoon onset defined by the beginning of continuous precipitation. On the other hand, Ueda et al. (2003) mentioned the importance of troposphere heating by moistening processes over the western TP prior to the Indian monsoon onset. According to a detailed examination of their figures, areas of the "western Tibetan Plateau" largely cover the periphery of the plateau, such as the western Himalaya, where the heating periods were May to early June. This leads to the likelihood that a large-scale heat source (Q1) analyzed by Ueda et al. (2003) occurred over the Himalaya, not over the flat plateau areas, during the transitional period identified by this study. If so, the fact that the heating process in the Himalaya occurs before the start of the rainy season plays an important role in establishing Indian monsoon circulations through the change of the meridional temperature gradient over the southern slope of TP with the maturing of the monsoon trough. Once the precipitation onset has been triggered by a monsoon depression, orographic precipitation by the forced ascending of the Himalaya starts and the mountains would not so much act as a sensible heat source for the atmosphere.

Recently, the Pyramid observatory started monitoring concentrations of atmospheric gases and aerosols in the framework of the United Nations Environment Programme (UNEP) Asian Brown Cloud project. If the nighttime southerly flow observed at high altitudes during the transition period is part of large-scale circulations crossing over the Himalaya, it will contain aerosol or atmospheric pollutants transported for long distances, particularly when it is at the end of a dry season and prior to the washout (heavy rain) season in the India. In this event, the Pyramid observatory is at a suitable altitude to assure long-distance transportation of atmospheric pollutants.

The present observation network in the Khumbu area lacks its lowermost stations below 2000 m MSL, where the nighttime precipitation is apparent from the TRMM observation. The indigenous population in the Nepal is mostly concentrated at lower elevations where they engage in agriculture. Prediction of precipitation onset and occurrence of heavy rain events are crucial to their lives. We expect that real-time monitoring of mountain weather by multiple AWS in the reference basin will contribute to improved operational forecasts or nowcasts.

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