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Seasonal transition characteristics of the westerly jet: Study based on field observations at an altitude of 6900 m on the Mt. Xixiabangma Dasuopu glacier

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To better understand ultra-high-altitude climate characteristics and their changes, an automatic weather station was installed on August 4, 2005 on the Mt. Xixiabangma Dasuopu glacier (28°23.04′N, 85°43.72′E, 6900 m a.s.l.) in the middle of the Himalayas. Mountain weather conditions were observed continuously and automatically. This paper is the first to publish meteorological data for a whole year for a high-elevation region, and analyze wind direction, wind speed, air temperature, air pressure and humidity. Analysis of the observation data reveals that this region was strongly influenced by the westerly jet from October 10, 2005 to April 21, 2006 and by the Indian monsoon from May to September. The seasonal transitions of the westerly jet were characterized by changes in meteorological elements. In winter, influenced by the westerly jet, the wind speed in the study region was very high and fluctuated violently, gale days were frequent, temperature and air pressure fluctuated dramatically, the diurnal range of temperature decreased and the diurnal range of air pressure increased, relative humidity and specific humidity declined sharply, and air was dry. In summer, influenced by the Indian monsoon, the relative humidity and specific humidity were high. In addition, we analyzed reanalysis data for the location of the automatic weather station. The results confirmed that this region was strongly affected by the westerly jet from October 10, 2005 to April 21, 2006 and the observations that the seasonal transitions of the westerly jet were characterized by changes in meteorological elements.

Mt. Xixiabangma, Dasuopu glacier, meteorological observation, westerly jet, ERA-Interim

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The Himalaya constitutes the southern periphery of the Tibetan Plateau. Because of its unique geographical location and topography, the Himalaya is an ideal field for studying the westerly jet, monsoon circulation, mountain climate and climatic change. In terms of general circulation, the Himalayan region is controlled by the westerly jet in winters and by the Indian monsoon in summers. Because of the influence of the two different types of atmospheric circulation, many meteorologists have investigated the characteristics of climate in this region, especially at ultra-high altitudes.

The mean onset and decay dates of the Indian monsoon have been identified respectively as June 12 and October 5, with precipitation periodicity being 5 days or 8–10 days according to observations at the Pyramid Laboratory/Observation site (5079 m a.s.l.) [1]. In Nepal, precipitation mainly falls during the monsoon period, and the variation in this precipitation is closely related to the Southern Oscillation Index [2]. Recent studies show that the monsoon onset is related to the occurrence and migration of a monsoon low

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in the north of the Bay of Bengal [3]. The onset of monsoon rainfall characterized as nighttime precipitation has been observed to initiate simultaneously at all stations, and about two weeks prior to the onset, mountain weather abruptly changes [4]. Yeh first discovered that the westerly jet was split into two branches by the barrier of the Tibetan Plateau, one flowing around the southern edge of the plateau and the other around the northern edge. He also noticed the abrupt nature of seasonal variations in the East Asian atmospheric circulation [5]. Recent studies have shown that a northward jump of the westerly jet over East Asia in early May typically precedes the onset of the summer monsoon over the South China Sea [6,7]. The median dates for such jumps in spring and autumn fall respectively on April 28 and October 12 [8]. However, because of poor accessibility, rugged terrain and harsh weather conditions, field monitoring at ultra-high altitudes (>6000 m) and in remote areas remains difficult. As a result, there are limited field observational data, and even conventional meteorological observations are scarce. Although existing research has enhanced our understanding of high-altitude climatic characteristics in this region, most studies extend only over timescales of days, weeks, months or the ablation season rather than the entire annual cycle [9–15]. Therefore, the Indian monsoon, westerly jet evolution and details of climate characteristics in such ultra-high altitude regions as the central Himalaya are still poorly understood.

In this paper, we use continuous meteorological data acquired during the first annual cycle of operation of an automatic weather station (AWS) set up on the Mt. Xixiabangma Dasuopu glacier on 4 August 2005 to study the characteristics of seasonal transitions of the westerly jet in the central Himalaya.

1 Observation site

The Mt. Xixiabangma Dasuopu glacier is located on a northern slope of the central Himalaya. It is an ENE (pass)–NE (valley) valley glacier with extensional faulting, total area of 21.67 km^2 and length of 10.50 km. The glacier extends from 7200 to 5600 m a.s.l., with the snowline being higher than 6000 m a.s.l. The highest platform for snow and ice accumulation is higher than 6900 m a.s.l. and is 3 km in length and 1.5 km in width [16,17], and we installed our AWS on this flat platform (Figure 1).

2 Data

In August 2005, our expedition to Mt. Xixiabangma Dasuopu glacier established an AWS at the pass of the glacier. It is one of the highest-elevated AWSs in the world. The AWS was produced by Campbell Scientific Inc. and incorporates a CR10X measurement and control system. The specifications of sensors in the AWS are given in Table 1. The AWS recorded meteorological data continuously every 30 minutes (taking 30-min averages) and every 24 hours (taking daily absolute maxima and minima) from August 4, 2005 to August 20, 2006. The AWS operated under Beijing standard time. The heights of the actinometer/anemometer and dog-vane, hygrothermograph and barometer were 3.20, 3.15 and 2.30 m, respectively, when the AWS was installed on August 4, 2005. Because of underlying snow, the heights of the sensors varied with snow accumulation and ablation. When we collected data on August 20, 2006, the heights of all probes were 1.05 m less than stated above. This paper analyzes the characteristics of the

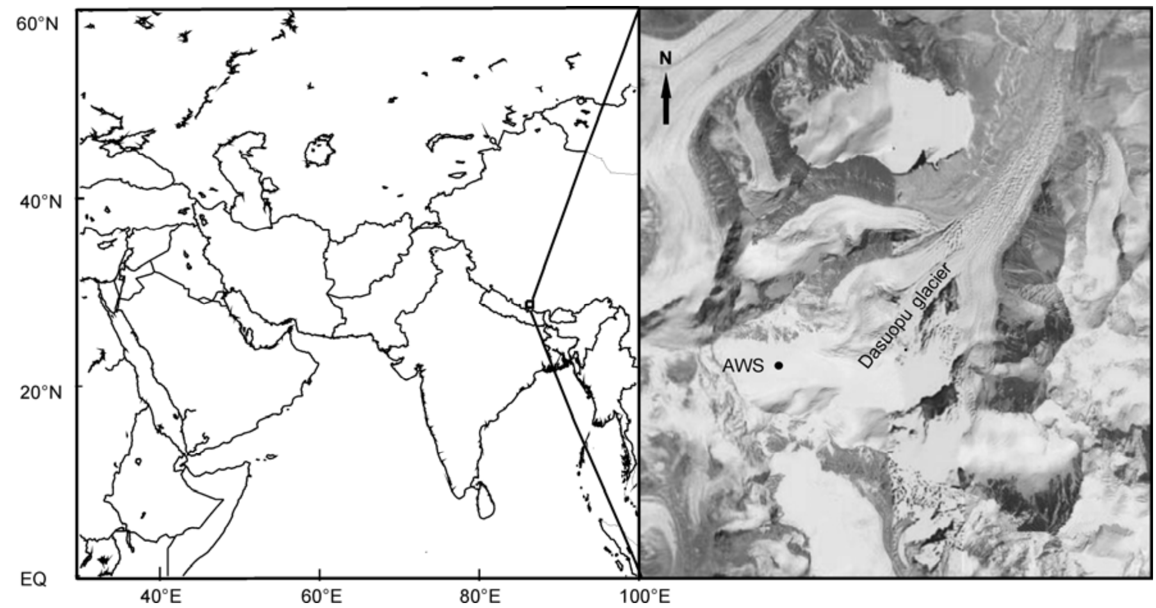

Figure 1 Location map for the AWS on the Dasuopu glacier. The black dot shows the AWS location.

Table 1 Specifications of the sensors installed at the AWS on the Dasuopu glacier

Sensor type	parameter	Accuracy	Range
PTB210	air pressure	±0.5 hPa	50–1300 hPa
LI200X	radiation	±3%	400–1100 nm
HMP45C	air temperature	<0.5°C	–40–60°C
	relative humidity	±2%	0–100%
15103	wind direction	±3°C	0°–355° (5° open)
	wind speed	±0.3 m/s	0–60 m/s (Max is 60 m/s)

seasonal variation in the westerly jet in this region using data of the wind direction, wind speed, temperature, relative humidity and specific humidity recorded from August 4, 2005 to August 19, 2006.

3 Results and discussion

3.1 Seasonal transition characteristics of the westerly jet recorded by the high-altitude AWS on the Dasuopu glacier

(i) Wind regime. Influenced by the narrow mountains on both sides of the pass and valley, the main prevailing wind direction changed little between summer and winter. The prevailing wind directions in summer and winter were WSW and SW, respectively; i.e. parallel to the direction crossing the pass or the direction of the valley. Nonetheless, there were two slight but obvious changes in wind direction throughout the year (Figure 2a). The first occurred on October 10, 2005, after which the prevailing wind direction changed from WSW to SW. The second occurred on April 21, 2006, after which the WSW wind again prevailed. Thus, the prevailing wind direction was SW from October 10, 2005 to April 21, 2006, while the WSW wind prevailed at other times.

The monthly mean wind speed was low in summer and high in winter, with the minimum in July (3.83 m/s) and the maximum in December (12.18 m/s); i.e. the monthly mean varied by 8.35 m/s. The annual mean wind speed was 7.63 m/s. The maximum instantaneous wind speed was 37.85 m/s, observed on January 12, 2006. The monthly mean daily maximum wind speed was also in January (24.55 m/s). The number of gale days (i.e. days on which gale-force winds were recorded) also had obvious seasonal variation. Gale days were mainly in fall, winter and spring, but especially in winter. In total, there were 149 gale days throughout the year. The number of gale days per month reached a maximum in December (28 days). It is noteworthy that a change in wind speed corresponded to an abrupt change in the prevailing wind direction (Figure 2b). For instance, with the change in wind direction on October 10, 2005, the daily wind speed averaged over 10 days abruptly increased from 5.01 to 10.59 m/s, the daily maximum wind speed averaged over 10 days jumped from 10.62 to 16.63 m/s, and the frequency of gale occurrence increased from 0 d per 10 days to 3 d per 10 days. With the change in wind direction on April 21, 2006, the wind speed again changed; the daily wind speed averaged over 10 days decreased from 10.61 to 4.52 m/s, the daily maximum wind speed averaged over 10 d decreased from 20.04 to 11.51 m/s, and the frequency of gale occurrence dropped from 10 d per 10 days to 0 d per 10 days.

During winter and summer, the westerly jet is located to the south and north of the Tibetan Plateau respectively. During spring and autumn, there are jet transitions from south to north and vice versa. Generally, there is a northward jump of the westerly jet over East Asia in early May, which is typically preceded by the onset of the summer monsoon over the South China Sea [6,7]. Recent research identified the median dates for these transitions as April 28 and October 12 [8]. We therefore deduce that during our observation from October 10, 2005 to April 21, 2006, the AWS site was mainly affected by the westerly jet, witnessing high wind speeds with large fluctuations and many gale days. In particular, the average wind speed and mean daily maximum wind speed reached 10.12 and 20.74 m/s, respectively. In addition, the probability of gale occurrence was as high as 75%.

From the frequency of the wind direction in summer and winter (Figure 3a and b), we see that there were no obvious diurnal changes in wind direction in winter and summer. Under the influence of the westerly jet, the wind direction in winter was SW; i.e. parallel to the valley. In summer, the wind direction was WSW; i.e. parallel to a line crossing the pass. From the average diurnal variations in wind speed in summer and winter (Figure 3c), we see that wind speed in winter was very high and there was no obvious diurnal variation, whereas in summer, wind speed was low and the diurnal variation in wind speed was obvious. The average wind speeds in winter and summer were 10.65 and 4.78 m/s. The average wind speed in winter was 2.23 times that in summer. In summer, the diurnal variation in wind speed was characterized by one peak with asymmetry during day and night. Wind speed increased abruptly after noon (13:00), and reached a maximum in the early evening (18:00), then decreased and changed little during the night and the following morning until the next noon.

(ii) Air temperature regime. Owing to the low latitude and high elevation, there was a distinct change in air temperature on Mt. Xixiabangma throughout the year (Figure 2c). The temperature variation followed the annual cycle of solar radiation, with the monthly means ranging from –3.88°C (July) to –22.01°C (December); i.e. the monthly mean varied 18.13°C. There were the same seasonal changes for the monthly mean daily maximum temperature, monthly mean daily minimum temperature and monthly mean temperature. The maximum warming rate was for April to May, while the highest cooling rate was for September to October. The cooling rate was slightly higher than the warming rate.

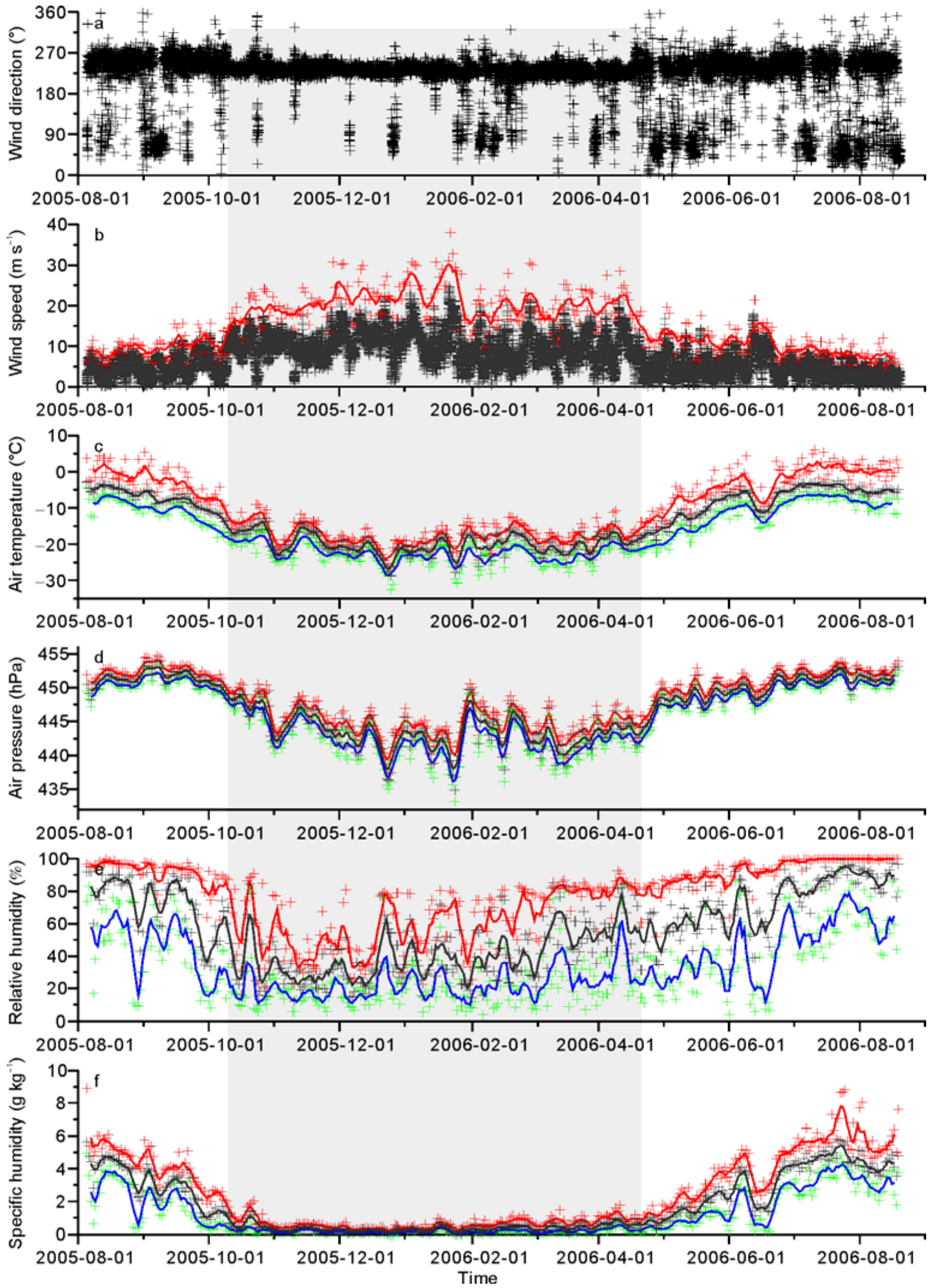

Figure 2 Seasonal variation in each meteorological element. a, Wind direction; b, wind speed (red +: daily maximum wind speed, black +: wind speed averaged over half an hour); c, air temperature; d, air pressure; e, relative humidity; f, specific humidity; red +: daily maximum; black +: daily mean; green +: daily minimum; red, blue and black solid lines are the 7-day moving averages of the daily maximum, minimum and mean, respectively.

The annual mean daily minimum temperature was –17.03°C, whereas the annual mean daily maximum temperature was –10.86°C. The corresponding annual mean temperature was –14.19°C. The monthly mean temperature was higher than the annual mean value from May to September, and the October mean was the most similar to the annual mean temperature. The monthly average of the daily lowest temperature varied from –6.76°C to –24.02°C, spanning 17.26°C, while that of the daily highest temperature varied from 1.22°C to –20.06°C, spanning 21.29°C, thus revealing large seasonality in the monthly mean maximum temperature. The diurnal range for air temperature, generally large in summer and small in winter, showed marked seasonality, and had an annual mean of 8.08°C (Figure 4a). The monthly mean diurnal range of air temperature was greater from May to September than the annual mean value, and the

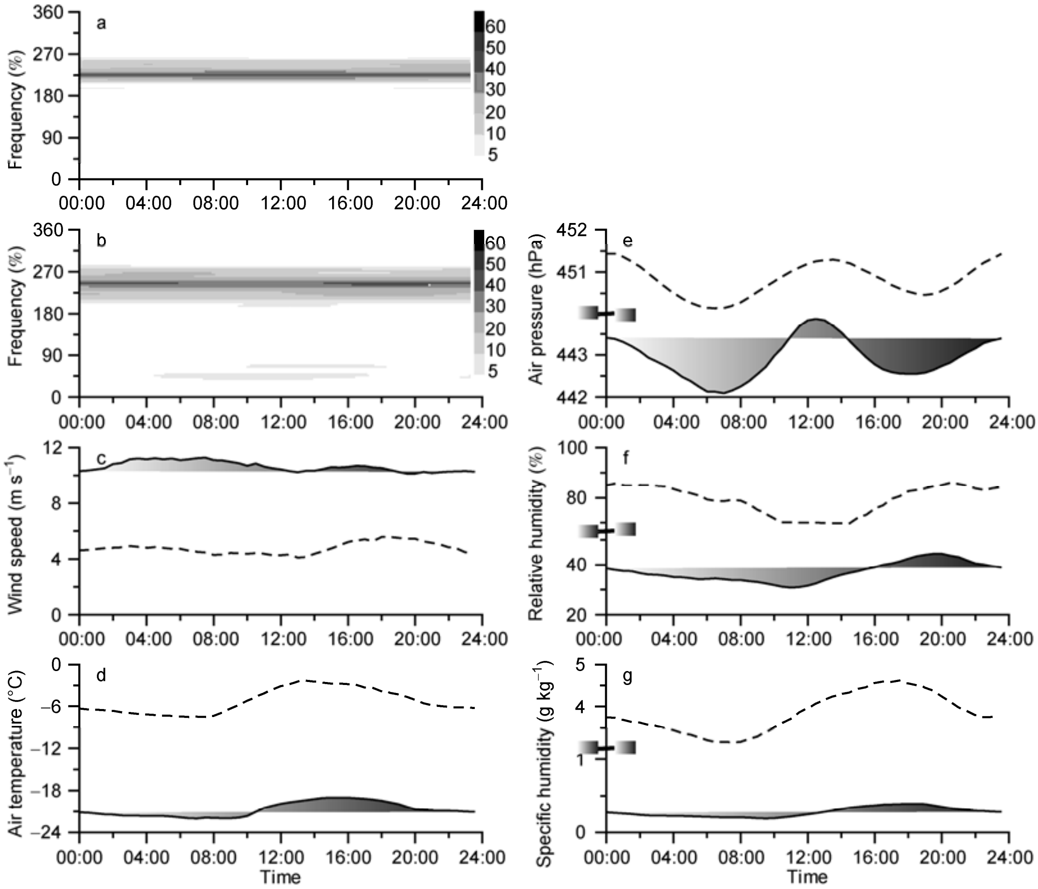

Figure 3 Average diurnal variation of meteorological elements in winter (June to August) and summer (December to February). a, Frequency of winter wind direction; b, frequency of summer wind direction; c, wind speed; d, temperature; e, air pressure; f, relative humidity; g, specific humidity; black dashed line and solid line represent the average diurnal variations in the meteorological elements in summer and winter, respectively.

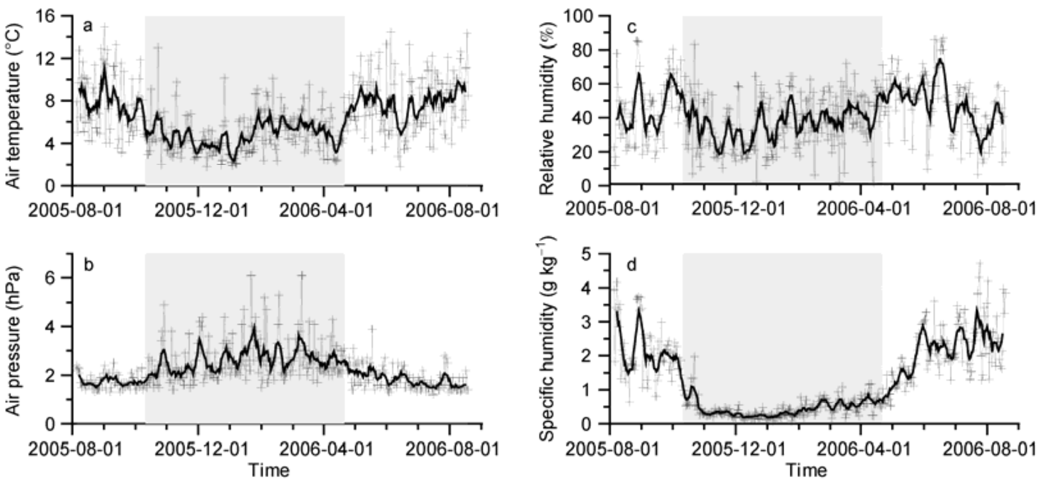

Figure 4 Seasonal variation in the diurnal range of each meteorological element. a, Temperature; b, air pressure; c, relative humidity; d, specific humidity; solid line represents the 7-day moving average.

October mean was most similar to the annual mean value. Although the temperature in the 30-min record exceeded 0°C on 45 days during the observation year, the daily mean temperature remained below 0°C. The highest absolute maximum temperature within the aspirated radiation shield was recorded on July 15, 2006. On that day, the temperature reached 5.80°C. The lowest absolute minimum temperature was –32.18°C on December 25, 2005.

With the abrupt changes in wind directions and wind speed, air temperature also changed obviously on October

10 and April 21. From October 10 onward, the 10-day-averaged daily maximum, minimum temperature and diurnal range of temperature reduced 5.97°C, 3.53°C and 2.44°C, respectively, while from April 21 onward, the 10-day-averaged daily maximum, minimum temperature and diurnal range of temperature increased 4.45°C, 1.08°C and 3.57°C, respectively. Note also that the variation in daily maximum temperature tended to be more dramatic than that in the daily minimum temperature, suggesting the inhibitory effect of high wind speed of the westerly jet on temperature. For this reason, the diurnal range of temperature at the Dasuopu glacier was high in summer and low in winter, and thus, the diurnal range of temperature at the Dasuopu glacier had seasonality, as opposed to what has been observed at relatively low altitudes of Himalayan glaciers [12]. When influenced by the westerly jet, from October 10, 2005 to April 21, 2006, the temperature fluctuated dramatically, and the diurnal range of the temperature decreased.

Figure 3d shows that the diurnal variation in air temperature is characterized by one peak and one valley. Air temperature in summer and that in winter had the same trend, but these processes were not synchronized. The warming rate was higher than the cooling rate. The minimum and maximum temperatures in summer were at about 08:00 and 13:00, respectively, about two hour earlier than those in winter. The average diurnal air temperature ranges in summer and winter were 7.68 and 4.68°C, respectively; the average diurnal air temperature range in summer was 1.64 times that in winter.

(iii) Air pressure regime. Air pressure was low in winter and high in summer (Figure 2d). Annual mean air pressure was 446.78 hPa. The minimum air pressure was in December (442.00 hPa), while the maximum was in September (452.03 hPa). Over the course of the year, there was a significant difference in monthly mean air pressure, as large as 10.03 hPa. The diurnal range of air pressure also had obvious seasonal variation (Figure 4b), being small in summer and large in winter. In addition, on October 10 and April 21, there were marked sudden changes in the diurnal range of pressure. Taking October 10, 2005 (April 21, 2006) as the borderline, the 10-day averaged diurnal range of air pressure increased (dropped) by 0.30 hPa (0.46 hPa). From October 10, 2005 to April 21, 2006, because of the influence of the westerly jet, the air pressure fluctuated dramatically and the diurnal range of air pressure increased.

Figure 3e shows that the average diurnal variation in air pressure had twin peaks and twin valleys. The twin peaks occurred at midnight (00:00) and noon (12:30–13:30). The minimum valley appeared before sunrise (06:00–07:00) and the sub-minimum valley occurred during sunset (18:00–19:00). Comparing the diurnal variation in air pressure for winter and summer, there was no change in the order of the two valleys, while there was a change in the order of the two peaks; in summer, the maximum peak was at midnight, while it was at noon in winter. The diurnal amplitudes of air pressure in winter and summer were 2.77 and 1.73 hPa, respectively; i.e. the diurnal amplitude of air pressure in winter was 1.60 times that in summer.

(iv) Humidity regime. The annual mean daily minimum relative humidity was 28.65%, in contrast to the annual mean daily maximum relative humidity of 86.44%. The annual mean relative humidity was computed as 55.11%. The monthly mean from April to September was higher than the annual mean value, with April having the closest mean relative humidity to the annual value. With the abrupt changes in wind directions and wind speed, relative humidity also changed obviously on October 10 and April 21 (Figures 2e and 4c). From October 10 onward, the 10-day-averaged daily maximum, minimum relative humidity and diurnal amplitude of relative humidity reduced 15.05%, 1.48% and 16.54%, respectively, while from April 21 onward, because of the influence of pre-monsoon precipitation (here taking rainfall data recorded at Nyalam as a reference), relative humidity changed abnormally. The 10-day-averaged daily mean relative humidity did not increase but decreased by 11.60%. The maximum and minimum relative humidity also decreased by 4.63% and 14.14% respectively. However, the diurnal amplitude of relative humidity increased 9.44%. The annual mean specific humidity was computed to be 1.58 g/kg. The humidity was highest in July (4.68 g/k) and lowest in December (0.19 g/kg). The monthly mean from May to September was higher than the annual mean value, with May having specific humidity most similar to the annual value. During the observation period, specific humidity also changed suddenly. For example, from October 10 onward, the 10-day-averaged specific humidity, daily maximum and minimum specific humidity and diurnal amplitude of specific humidity reduced 0.70, 1.16, 0.17 and 0.99 g/kg, respectively, while from April 21 onward, the 10-day-averaged humidity, maximum and minimum humidity and diurnal amplitude increased 0.12, 0.24, 0.05 and 0.20 g/kg, respectively. During the period from October 10, 2005 to April 21, 2006, influenced by the westerly jet, relative humidity and specific humidity were very low. The average relative humidity and specific humidity were 40.37% and 0.36 g/kg, and thus, air was dry.

Maximum humidity was always associated with high air temperature and heavy rainfall, and the opposite was true for minimum humidity. In late May, with the arrival of water vapor brought by the Indian monsoon, the relative humidity and specific humidity abruptly increased and remained high [13]. Subsequently, frequent monsoon precipitation substantially enhanced the maximum relative humidity, which almost reached saturation, together with the daily mean relative humidity, which thereupon seldom dropped below 70%. Specific humidity in the interim also rarely dropped below the annual mean. This situation continued till early October. After October, the study region was dominated by westerly circulation and influenced by airflow from arid and semiarid regions. Therefore, the relative humidity and specific humidity abruptly dropped and remained low until the following March. The humidity then increased with large fluctuation because of the influence of pre-monsoon precipitation (here taking precipitation data recorded at Nyalam as a reference).

Figure 3f shows that the average diurnal variation of relative humidity had an obvious feature of one peak and one valley. Relative humidity in summer and in winter had the same trend of change, but these processes were not synchronized. Relative humidity began increasing abruptly after noon (13:00 in summer and 11:00 in winter), reached a maximum about 20:00, and then decreased slowly, reaching a minimum at the following noon. Relative humidity was high in summer and low in winter. The average relative humidity was 78.58% in summer and 36.99% in winter. The average relative humidity in summer was 2.12 times that in winter. The average diurnal amplitudes of relative humidity in winter and summer were similar (i.e. 36.45% and 45.32%, respectively). Figure 3g shows that the average diurnal variation in specific humidity also had a feature of one peak and one valley, and specific humidity had the same trend of change in summer and winter, but these processes were not synchronized. After sunset (08:00 in summer and 10:00 in winter), specific humidity increased gradually, and reached a maximum at about 18:00 before decreasing gradually. It reached a minimum at sunrise the next day. Specific humidity was 3.85 g/kg in summer and 0.28 g/kg in winter; i.e. specific humidity in summer was 13.85 times that in winter. The diurnal amplitudes of specific humidity were 2.43 and 0.34 g/kg respectively; i.e. the diurnal amplitude of specific humidity in summer was 7.25 times that in winter.

(v) Numerical test of the seasonal transition characteristics. The above analysis indicates sudden changes in meteorological elements during seasonal transitions in summer and fall. We now ask whether these changes are real. Three methods, the Mann-Kendall test, sliding *t*-test and Yamamoto test are employed to determine sudden changes in wind speed that can best embody the seasonal transition characteristics [18]. The test results are consistent with observations, revealing that there were sudden-change features for meteorological elements during the seasonal transitions. Figure 5 shows the Mann-Kendall test results for average wind speed.

3.2 Seasonal transition characteristics of the westerly jet recorded by reanalysis data

Reanalysis data have been generally used to analyze weather or climate events and climate change. In particular, model reanalysis data provided by the European Centre for Medium Range Weather Forecasting (ECMWF) and the National Centers for Environmental Prediction/The National Center for Atmospheric Research (NCEP/NCAR) have been the most widely used. A previous study showed that reanalysis data from ECMWF are more suitable for the Tibetan Plateau [19]. Thus, we investigated whether the seasonal transitions found in the present study are observed in ERA-Interim reanalysis data for the location of the AWS [20].

When there was no influence by the westerly jet, the average wind speed was only 4.40 m/s and the half-hour average wind speed was rarely higher than 10.00 m/s. However, when the region was influenced by the westerly jet, the average wind speed reached 10.12 m/s. Therefore, we applied eq. (1) to determining whether the location where the AWS was located was affected by the westerly jet.

$$|V| \geqslant 10 \text{ m s}^{-1}, \quad u \geqslant 0 \text{ m s}^{-1}. \qquad (1)$$

From a 450 hPa (which is close to the observed annual average pressure of 446.78 hPa) wind field map (Figure 6a), we see that the westerly jet jumped to the AWS location on October 10, 2005. After April 21, the westerly jet move southward and the influence of the westerly jet on the AWS weakened or disappeared. At the grid point (28.5°N, 85.5°E) very close to our observation site (Figure 6b), we see that wind direction and wind speed at a pressure level of 450 hPa also changed obviously on October 10, 2005 and April 21, 2006. Taking October 10 as the borderline, and daily wind speed averaged over 10 days at a pressure level of 450 hPa increased from 5.15 to 12.43 m/s. Meanwhile, the daily maximum wind speed averaged over 10 days increased from 6.73 to 13.39 m/s. On the other hand, from April 21, 2006 onward, the daily mean and maximum wind speed averaged over 10 days decreased abruptly from 14.34 to 5.95 m/s and from 16.51 to 8.25 m/s, respectively. After April 21, 2006, because of the southward movement and rising of the westerly jet (Figure 6a and b), the influence on

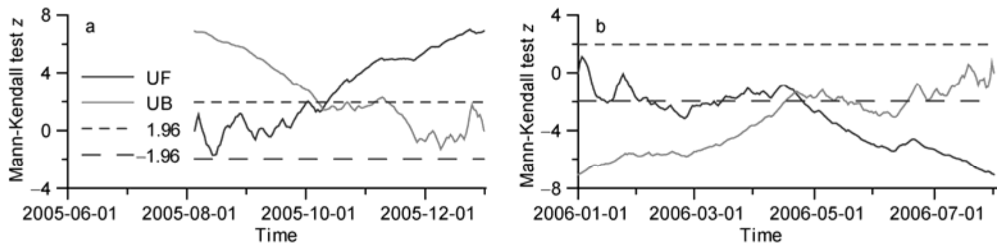

Figure 5 Mann-Kendall test for average wind speed.

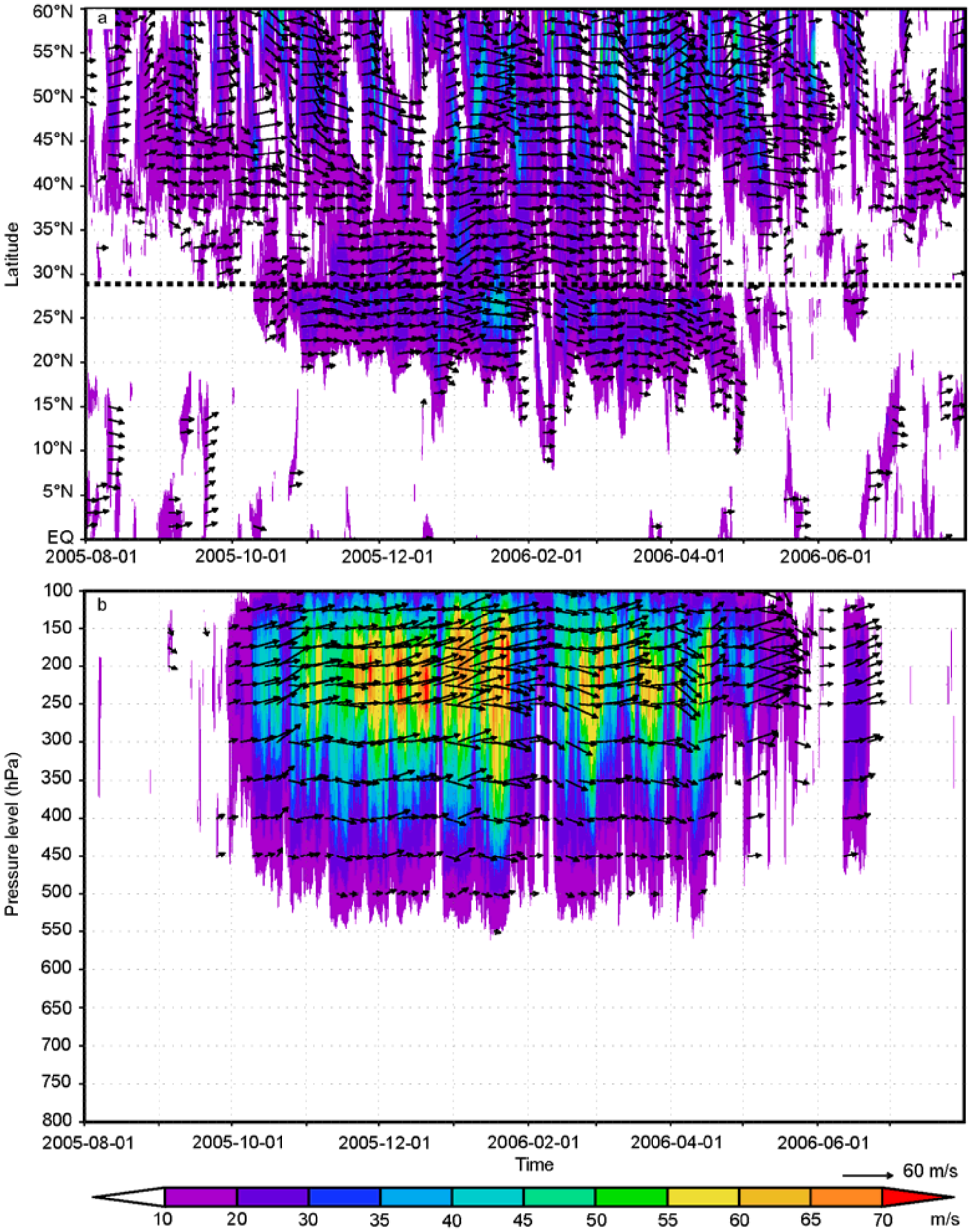

Figure 6 a, Wind speed (color map), wind speed and wind direction vector map at 450 hPa along a longitude of 85.5°E from 0° to 60°N; b, wind speed (color map), wind speed and wind direction vector map at grid point (28.5°N, 85.5°E) from 800 to100 hPa; the black dotted line indicates the location of the AWS.

the AWS weakened and disappeared. Reanalysis data confirmed our inference that during the observation period, the latitude and height of the AWS was influenced by the westerly jet and the seasonal transitions of the westerly jet are characterized by changes in meteorological elements.

4 Conclusions

For the first time, *in situ* observations of mountain weather conditions for an entire year at an altitude of nearly 7000 m were studied, and the primary seasonal transitions characteristics of the westerly jet in the study region revealed. During the observation period, the study region was strongly affected by a westerly jet from October 10, 2005 to April 21, 2006, while this region gradually became controlled by the Indian monsoon after May. The transitions from Indian monsoon to westerly jet were characterized by changes in meteorological elements. Numerical test results for wind speed, which can best reflect the seasonal transition, indicate that the meteorological elements do have change characteristics during the seasonal transitions.

We also analyzed reanalysis data for the location where the AWS was located. The results confirmed that the study region was strongly affected by the westerly jet from October 10, 2005 to April 21, 2006. When the study region was controlled by the westerly jet, the wind speed was very high, the wind speed fluctuated wildly, and gale days were frequent. When the region was controlled by the westerly jet, the air temperature and air pressure also fluctuated violently, the diurnal range of air temperature decreased and the diurnal amplitude of air pressure increased. At the same time, relative humidity and specific humidity decreased sharply, and air was very dry. After the transition from the westerly jet to monsoon, the weather characteristics were found to be completely opposite.

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