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Observational Study of Surface Wind Regime on the North Slope of Mount Qomolangma (Mount Everest)

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Abstract

From May 2007 to September 2008, six automatic weather stations (AWS) were installed along the traditional mountaineering line on the north slope of Mount Qomolangma. The elevations of the stations ranged between 5207 and 6560 m above sea level (a.s.l.). Some sounding data were also measured at Base Camp (5207 m a.s.l.) in late April and early May of 2007 and 2008. The spatial arrangement of the stations and temporal duration of the measurements, as well as the sounding data, generated a data set enabling the analysis of the wind regime in this region. The wind directions and speeds show change at different elevations because of the complicated terrain, the glacier-moraine-rock transition underlying surface, and the synoptic-scale wind. The katabatic wind dominates at low-elevation areas in the Rongbuk Valley, and the depth and frequency of it are about 800 m and 59% during the observational period. The up-valley wind always erodes the katabatic wind, and causes the lowest directional constancy in summer. With the elevation ascending, the katabatic wind weakens due to the smaller fetch and temperature contrast, as well as the relatively open landscape of the valley and smaller glacier area. At site 3 (5792 m a.s.l.), the frequency of the katabatic wind is only 25%, whereas the frequency of the up-valley wind is 47%, and especially in winter, the up-valley wind (82%) predominates all day. Moreover, the synoptic-scale wind also plays an important role in the surface wind regime on the north slope of Mount Qomolangma. From November to March, the active westerly troughs always intrude into the bottom of the Rongbuk Valley and could maintain the strong katabatic wind, and the maximum wind speed reaches 43.1 m s^{-1} at site 1 (5207 m a.s.l.). At high-elevation areas, the westerlies can penetrates more easily, and dominate the wind regime. The wind speed can reach as high as 57.1 m s^{-1} at site 3 in winter.

Introduction

Mount Qomolangma (27°59'N, 86°55'E, 8844.43 m a.s.l.), the world's highest peak, is located in the central Himalaya on the south margin of the Tibetan Plateau. Because of its unique natural ecology and extreme sensitivity to climate and environmental change, it has received great attention from the scientific community (Somervell and Whipple, 1926; Xie, 1975; Bertolani and Bollasina, 2000; Kang et al., 2002; Moore, 2004; Ming et al., 2007; Barry, 2008). As early as the 1920s, Somervell and Whipple (1926) conducted some measurements of air temperatures, wind directions and speeds, and related weather conditions at different elevations on the north slope of Mount Qomolangma, and the lapse rate of temperature was also calculated. Since the late 1950s, three major comprehensive scientific experiments were conducted in the same region during the periods 1959–1960, 1966–1968, and 1975, focusing on hydrology, meteorology, glacier, and so on (Xie, 1975). Moore (2004) studied the cause of a snow plume blowing from the summit of Mount Qomolangma, and also analyzed the impact on snow cover and glacier mass balance. Katabatic winds were observed in the Rongbuk Valley of the north slope of Mount Qomolangma in 1959–1960 (Ye and Gao, 1979). Although in situ observations were conducted in spring and winter, the site was at relatively lower elevations (4950–5120 m a.s.l.). Observations at higher elevation mainly focused on spring months and were discontinuous, and they showed a distinct diurnal wind cycle, as well as the air exchange, in the downstream of the Rongbuk Valley in spring (Gao, 1980). However, insufficient measurements prevented further understanding of the wind regime, especially the seasonal variations at different elevations in this remote area. Later, numerical simulation showed that the temperature gradient along the Rongbuk Valley played a very important role for driving the katabatic wind from noon to midnight in summer (Cai et al., 2007; Song et al., 2007). There were no data to validate these simulated results. The katabatic wind also could be "pumping down" ozone-rich (70–80 ppb) and dry air from the upper troposphere to the surface of the Rongbuk Valley (Zhu et al., 2006).

To better understand weather regimes and meteorological conditions on the north slope of Mount Qomolangma, six automatic weather stations (AWSs) were established in May 2007 and continuous measurements were conducted until September 2008 (Yang et al., 2011). This study attempts to analyze the surface wind regime in this region using measurements from six in situ sites (Fig. 1), as well as sounding data measured by radiosonde at Base Camp (5207 m a.s.l.) from late April through early May in 2007 and 2008.

Study Region and Measurements

The terrain on Mount Qomolangma is very steep, and the elevation difference between the crest and Rongbuk Valley is nearly 4000 m. The Rongbuk Valley is oriented from south-southeast to north-northwest, with a floor width of 1.0–1.5 km and length of about 16 km. Four main glaciers, namely the West, Middle, East, and Far East Rongbuk Glacier, are located on the
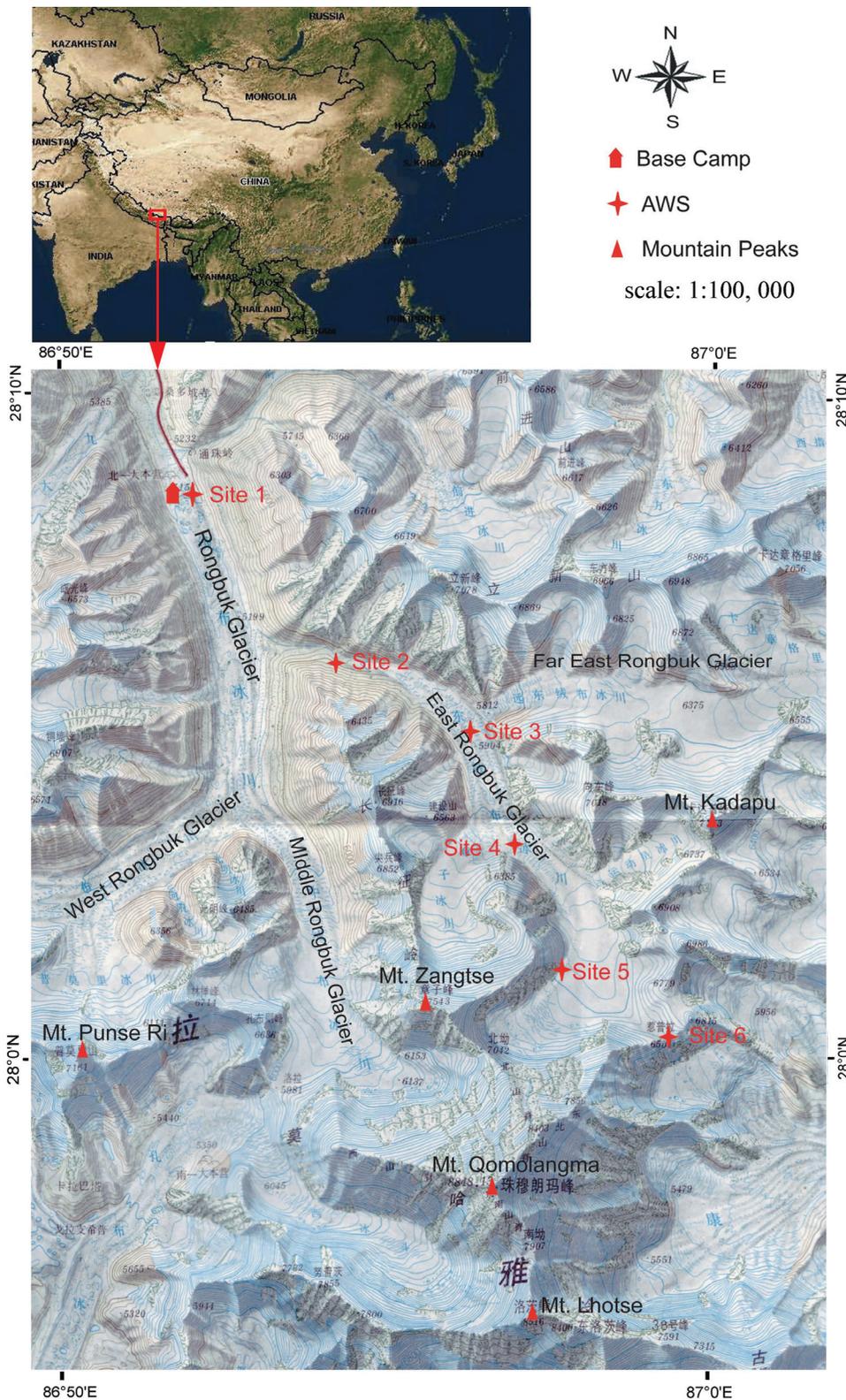
FIGURE 1. Geographical location of the Mount Qomolangma region in southwestern China (up left corner) with major mountain peaks. Automatic weather stations are located along the traditional mountaineering route on the north slope of Mount Qomolangma.

north slope of Mount Qomolangma region. The total glacial surface area is about 148 km². Two tributary glaciers, the West and Middle Rongbuk Glacier, converge to form the Rongbuk Glacier extending into the Rongbuk Valley. The East and Far East Rongbuk Glaciers are oriented from southeast to northwest and east to west, respectively (Qin, 1999). The remaining Rongbuk

Valley surface is generally covered by moraines in this semi-arid climate region.

Six AWSs were installed along the mountaineering line on the north slope of Mount Qomolangma, one in the middle of the Rongbuk Valley (site 1), four in the East Rongbuk Valley (sites 2, 3, 4, and 5), and one on the Ruopula Pass (site 6) (Fig. 1). The land

TABLE 1

Location and meteorological variables at each site on the north slope of Mount Qomolangma from May 2007 to August 2008.

		Site No.[a]					
		1[b]	2	3	4[d]	5	6
Site location	Latitude (N)	28°8′	28°6′	28°5′	28°4′	28°2′	28°1
	Longitude (E)	86°51′	86°53′	86°55′	86°55′	86°56′	86°57′
	Elevation (m a.s.l.)	5207	5550	5792	5955	6300	6560
Site description		rock debris flat surface	rock debris flat surface	moraine 4°incline	moraine 6° incline	rock debris 10° incline	snow/firn flat surface
Observational period		5 May 2007 to 31 August 2008	5 May 2007 to 30 May 2008	5 May 2007 to 31 August 2008	5 May 2007 to 31 July 2008	20 April to 8 May 2008	2 October 2007 to 19 January 2008
Wind speed (m s⁻¹)	Average	5.0	4.3	5.0	1.6	3.7	10.9
	Maximum	43.1	11.7	57.1	30.0	16.6	34.9
Prevailing wind direction		SE, SSE	E, ESE	NW, WNW	N, NNW	—	NW, NNW
Directional constancy		0.62	0.62	0.63	0.24	0.20	0.93
Air temperature (°C)	Average	0.2	–1.9	–4.4	–5.4	–8.3	–15.4
	Maximum	16.4	6.7	9.1	18.6	0.2	0.8
	Minimum	–24.2	–8.8	–28.8	–29.3	–16.1	–27.5

[a]Average, maximum, and minimum values are calculated based only on available data.

[b]Sounding observation was carried out two times (5:00 and 17:00 LT) every day from 10 April to 8 May 2007 and 13 April to 8 May 2008 with the exception of 6–9 May 2007; and 22 and 23 April, and 6–8 May 2008, when it was operated at a frequency of 6 to 12 times a day.

[c]Data absent from 1 November 2007 to 25 April 2008, and temperature (T) and humidity (H) only were available on May 2008.

[d]Data absent from 1 to 30 June 2007, and wind speed and direction were not available from 1 January to 30 July 2008.

surfaces are covered by rock debris around sites 1, 2, and 5, and by moraines around sites 3 and 4, and by snow and firn around site 6, respectively (Table 1).

Air temperature, relative humidity, wind speed, and direction were measured at 2 m, with a humidity and temperature probe (HMP45D) and a Young anemometer (05103). Atmospheric pressure was measured with a pressure sensor (PTB210) in the data logger box at 0.5 m height. All measurements, including mean, maximum, and minimum values, were recorded every hour. Before activation, all sensors were calibrated in the laboratory. There were some missing values for sites 2, 4, 5, and 6 due to power shortage and AWS malfunction during the period of measurements. And rawinsonde observations were performed at approximately 5:00 and 17:00 Local Time (LT) every day from 10 April through 8 May in 2007, and 13 April through 8 May in 2008, with the exception of a few intensive observation days of 6, 7, and 8 May. More details for each site and technical details about the sensors can be found in our earlier work (Yang et al., 2011). We mainly focus on data from sites 1 and 3, and the available data from sites 2, 4, 5, and 6 are also used for comparison.

Results

WIND DIRECTION

Figure 2 shows daily cycles of the wind direction averaged from 1 May 2007 through 31 August 2008 in the middle of the Rongbuk Valley at site 1, and on the lateral moraine of the East Rongbuk Glacier at site 3. At site 1 (Fig. 2, part a), the wind regime is dominated by the katabatic flow (SE or SSE), especially from noon to midnight. The up-valley wind occurs only around 10:00 LT. The mean frequency of wind blowing from southeast is about 59% over the period of measurements. By the frequency of wind direction, we mean the percentage of the number of a given wind direction's occurrences over the total number of all wind direction occurrences during the period of the in situ measurements. On the contrary, the prevailing wind is the up-valley flow (NW or NNW) and maintains from morning to midnight at site 3 (Fig. 2, part b). The katabatic flow only appears in the later night and the mean frequency is only 25%. The directional constancy is defined as the ratio of the magnitude of the time-averaged wind vector over the time-averaged wind speed (Van den Broeke et al., 1994). A value of directional
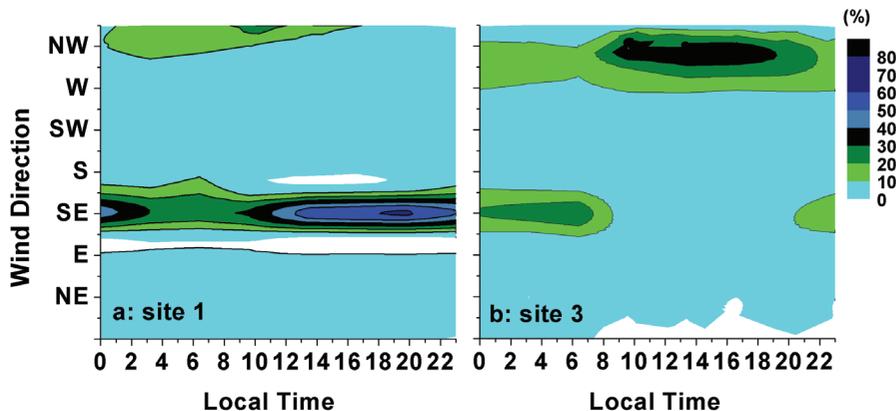
FIGURE 2. Mean diurnal distributions of the wind direction frequency at (a) site 1 and (b) site 3. The frequency was calculated at the same times every day based on hourly measurements from May 2007 to August 2008. Note that frequencies add up to 100% at each given time.

constancy 1 indicates that the wind blows from one direction, whereas a value of 0 means that the wind blows from a random direction. The directional constancy is almost identical at sites 1 and 3 (Table 1).

Seasonally, katabatic winds (SE or SSE) are observed with the mean frequency of approximately 63% of the measurements in spring (March to May), autumn (September to November), and winter (December to February) at site 1, whereas the mean frequency is about 50% during summer (June to August). Up-valley winds always occur before 12:00 LT with a mean frequency of about 31% (Fig. 3, part b). The directional constancy is the highest in spring (0.75) and lowest in summer (0.43). In the East Rongbuk Valley at site 2, about 1500 m from the glacier terminus, katabatic winds (E or ESE) are

observed with the mean frequency of approximately 50% from May through October 2007, about 10% lower than that at site 1 during the same period. The similar results were also observed at different sites along the downstream of the Rongbuk Valley in spring and early summer (Cai et al., 2007; Song et al., 2007; Zou et al., 2008).

At site 3, the up-valley wind dominates the whole day with the mean frequency of about 82% in winter (Fig. 4, part d). The up-valley wind is also observed with the mean frequency of approximately 46% in spring to about 37% in autumn, while the katabatic wind occurs in the late night with the mean frequencies ranging from 16% to 27% from spring through autumn (Fig. 4, parts a, b, and c). The directional constancy is the highest in winter (0.90) and lowest in summer (0.32). The same distribution of wind

FIGURE 3. Mean diurnal distribution of the wind direction frequency at site 1 in different seasons. The frequency was calculated with the same method as that in Figure 2. Note that frequencies add up to 100% at each given time. (a) Spring (March–May), (b) summer (June–August), (c) autumn (September–November), and (d) winter (December–February).

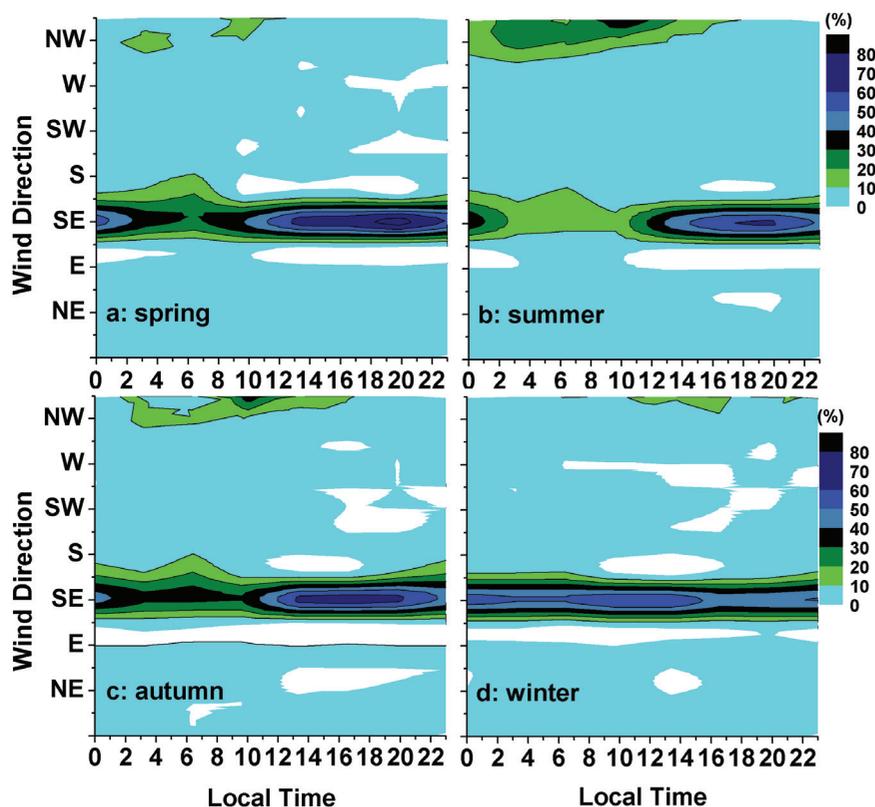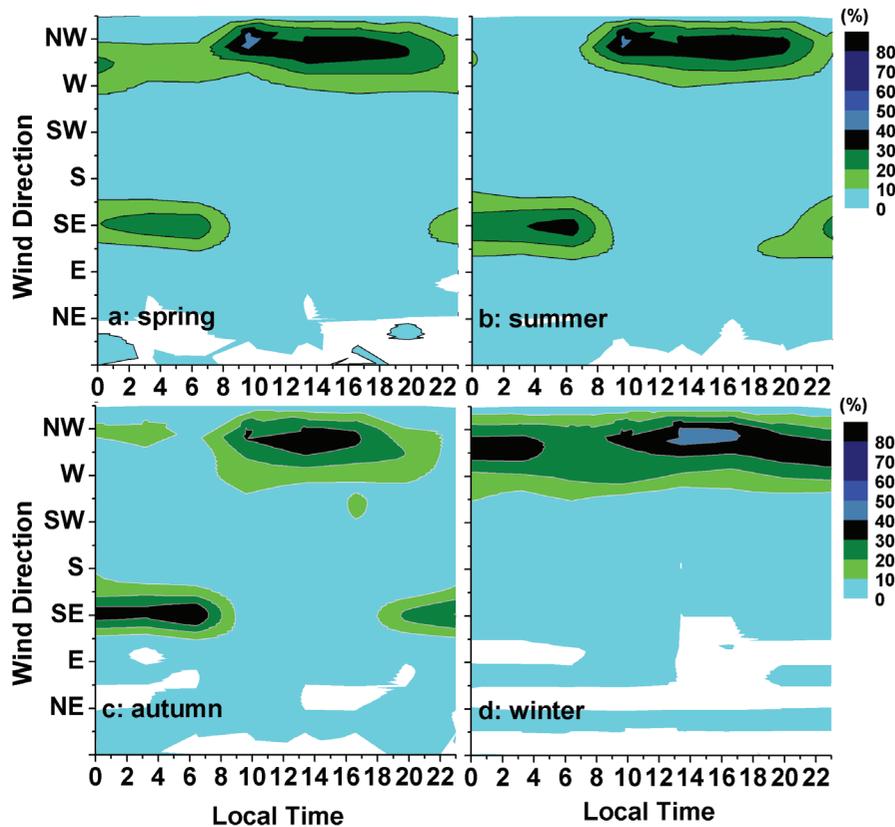810 / Arctic, Antarctic, and Alpine Research

FIGURE 4. Mean diurnal distribution of the wind direction frequency at site 3 in different seasons. The frequency was calculated with the same method as that in Figure 2. Note that frequencies add up to 100% at each given time. (a) Spring (March–May), (b) summer (June–August), (c) autumn (September–November), and (d) winter (December–February).

direction is also observed at site 4 from May to December 2007. On the Ruopula Pass at site 6, the accumulation zone of the East Rongbuk Glacier, the wind regime is dominated by northerly or northwesterly winds with the mean frequency of about 83% from October 2007 to January 2008 (not shown). The directional constancy increases as high as 0.93.

Overall, the mean frequencies of katabatic winds decrease from about 74% at site 1 to about 17% at site 3, and about 4% at site 6, whereas the same values of up-valley winds increase from about 13% at site 1 to about 50% at site 3, and about 83% at site 6 from October 2007 to January 2008. The directional constancy increases from 0.72 at site 1 to 0.76 at site 3, and 0.93 at site 6 during the same period.

Based on the sounding measurements at 5:00 and 17:00 LT from middle April through early May 2007 and 2008, mean frequencies of wind directions are also calculated between altitudes of 5200 and 10,000 m a.s.l. It is evident that wind directions exhibit a substantial change from SE and SSE to W and WNW between altitudes of 6000 and 6300 m a.s.l. (Fig. 5).

Although the available measurements at six sites do not cover the whole year, it could be argued preliminarily that the predominant wind is the katabatic flow at low-elevation areas of the Rongbuk Valley, while the up-valley wind dominates at high-elevation areas of this valley. More details will be discussed in the section Mechanism Analysis.

WIND SPEED

Daily average and maximum wind speeds for all sites exhibit pronounced variation with elevation (Fig. 6). Daily average and maximum wind speeds decrease toward higher elevation, whereas

maximum wind speeds are lower at site 2 than at sites 1 and 3 from May to October. During the rest of the measuring period, daily average wind speeds increase toward higher elevation with the exception of site 4, where wind speeds are lowest. Meanwhile, daily maximum wind speeds are higher at site 3 than sites 1, 4, and 6. Again, the average wind speeds are higher from November to April than the rest of the measuring period, and the highest wind speeds reach as high as 43.1 m s^{-1} and 57.1 m s^{-1} at sites 1 and 3 in February, respectively. The mechanism will be discussed in the section Mechanism Analysis.

Figure 7 shows daily cycles of wind speeds and air temperatures in annual and different seasons over the entire measuring period at sites 1 and 3. The daily maximum wind speed occurs in the late afternoon, slightly after the time that air temperature reaches its highest value at site 1, whereas it occurs earlier than the daily maximum air temperature at site 3 (Fig. 7, part a). The daily minimum wind speed occurs before sunrise at two sites. Seasonally, at site 1, the daily maximum wind speed occurs 3, 2, and 1 h later than the daily maximum air temperature in summer, spring, and autumn, respectively, and 1 h earlier in winter. In contrast to site 1, the daily maximum wind speed at site 3 occurs about 1 h earlier than the daily maximum air temperature from spring to autumn, and at the same time in winter (Fig. 7, parts b, c, d, and e). The diurnal variations of average wind speeds are 4.8, 4.3, 4.1, and 3.1 m s^{-1} at site 1, and 3.5, 3.6, 3.1, and 2.5 m s^{-1} at site 3 from spring to winter. Moreover, the variations decrease with elevation, ascending from 4.0 (site 1) to 3.2 (site 3), and to 1.2 (site 4) m s^{-1}. At site 6, the value is only 0.2 m s^{-1} and there is hardly pronounced diurnal variation in wind speed (not shown).
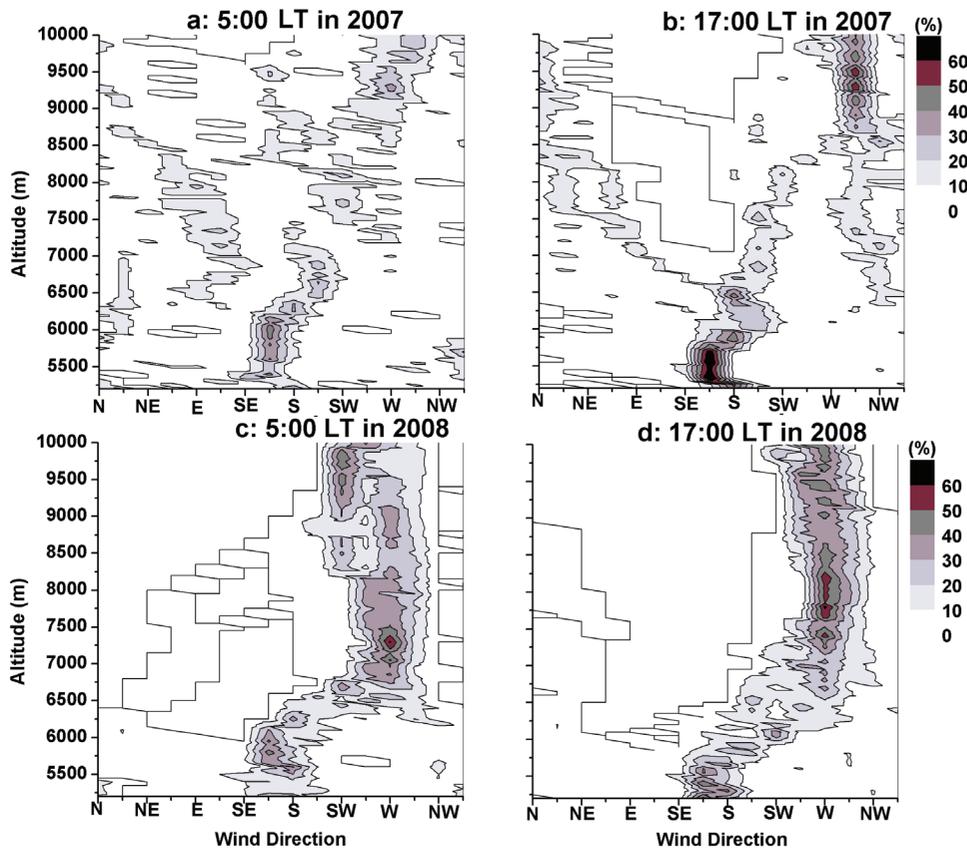
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FIGURE 5. Mean variations of wind directions between altitudes of 5200 and 10,000 m a.s.l. at 5:00 and 17:00 local time (LT) over the periods from middle April to early May of 2007 and 2008.

Based on the sounding measurements mentioned above, wind speeds increase sharply from the surface and attain their maximum at the altitude of about 5500 m a.s.l., then decrease with altitude ascending. Above 6000 m a.s.l., wind speeds increase again toward higher altitude (Fig. 8).

Mechanism Analysis

Generally, the wind regime over mountainous terrain covered with snow or glacier is determined with three systems: the mountain wind, the katabatic wind, and the synoptic-scale wind (Ar-
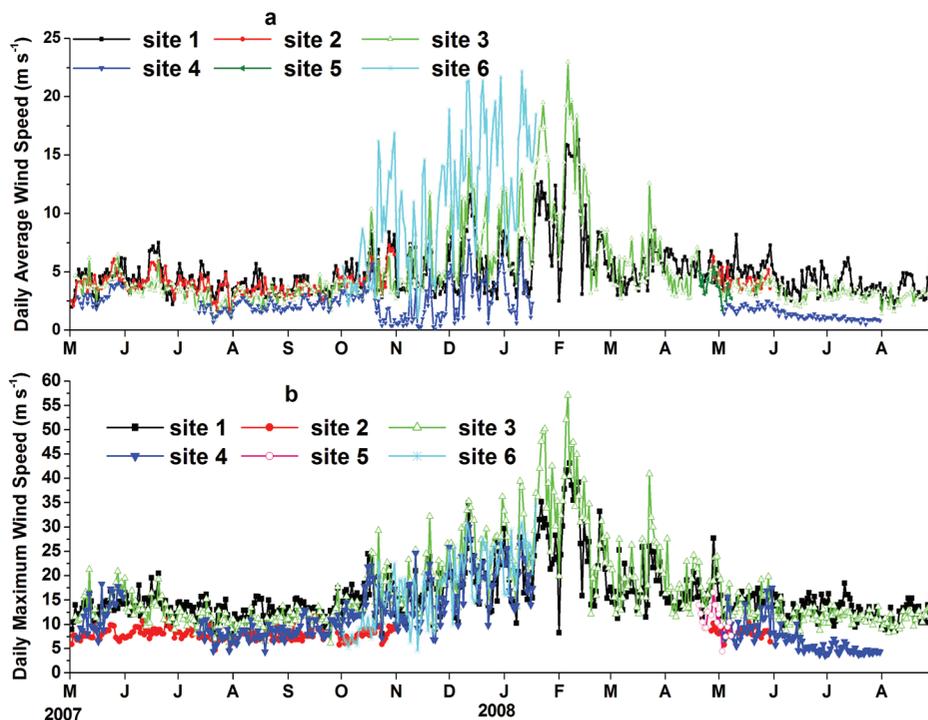

FIGURE 6. Temporal variations of (a) daily mean, and (b) maximum of wind speeds at all sites. All available data are used over the measuring period.
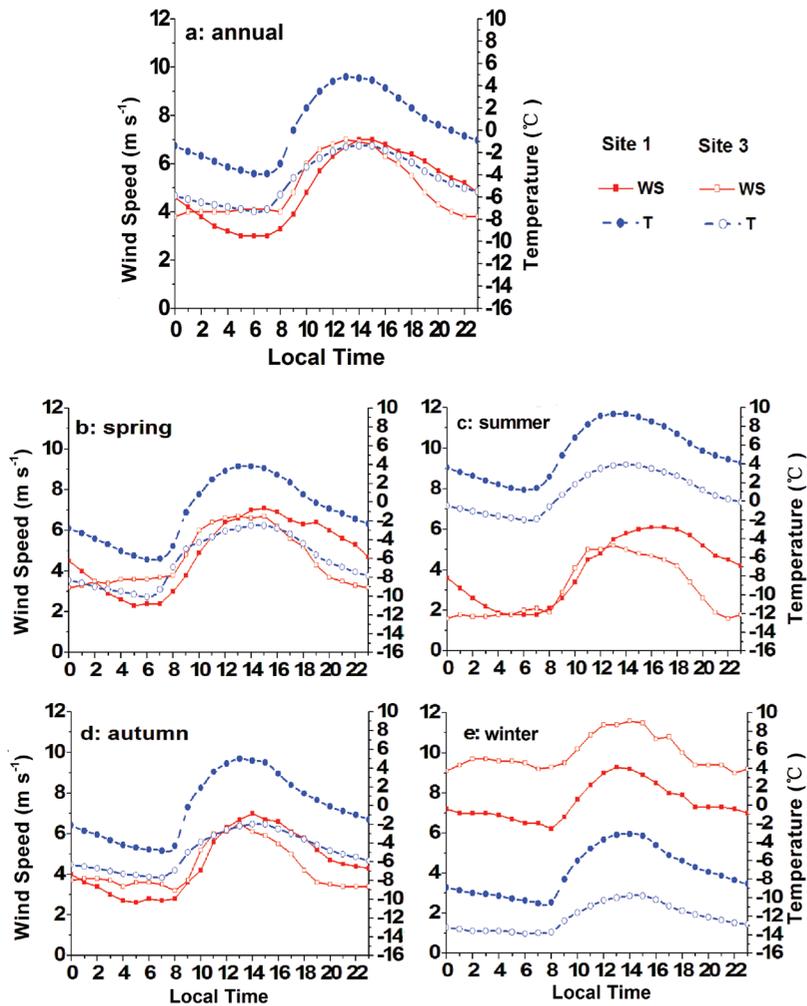
FIGURE 7. Mean diurnal variations of wind speeds and air temperatures at sites 1 and 3 over period from May 2007 to August 2008. (a) Annual; (b) spring (March–May), (c) summer (June–August), (d) autumn (September–November), and (e) winter (December–February).

ritt and Pielke, 1986; Greuell and Knap, 1997). As described in classical meteorological textbooks, winds generally flow up-valley in the daytime and down-valley at night in mountain regions due to radiational cooling and heating of sloping surfaces (Whiteman, 2000). Over the sloping glacier, due to the downward exchange of sensible heat with the surface, the air near the surface cools and starts to flow down the incline of the glacier under the influence of gravity, and the katabatic wind could be forced by its inertia farther down from the glacier terminus (Oerlemans and Grisogono, 2002; Strasser et al., 2004; Song et al., 2007). The observed wind regime on the north slope of Mount Qomolangma is related with the surface-to-air heating and cooling processes, as well as the synoptic-scale wind and the effect of local topography.

Over the ablation zone of the ice-covered Rongbuk Valley, there is a steady downward sensible heat flux toward the melting surface (Schneider, 1999; Greuell and Smeets, 2001; Reijmer and Oerlemans, 2002; Wagnon et al., 2003; Favier et al., 2004; Sicart and Wagnon, 2005), whereas in the adjacent rock-covered zone of the middle and downstream Rongbuk Valley, it is directed upward. Chen et al. (2012) observed that the upward sensible heat flux is 150–250 W m^{-2} around noon, and the ratio between sensible heat and net radiation flux is as high as 0.49 in the rock-covered Rongbuk Valley. Therefore, temperature gradients form between colder air in a shallow layer over glacier and warmer air at the same alti-

tude farther down the valley, as well as the buoyancy force over the glacier surface induces the katabatic wind at site 1 all year, and site 3 sometimes in spring, summer, and autumn.

On the other hand, solar radiation of valley areas induces heating of air layer near the ground and thermally driven up-valley flows in the daytime (Defant, 1951; Whiteman, 2000; Rampanelli et al., 2004). In the middle and downstream of the Rongbuk Valley, the up-valley wind occurs before 12:00 LT due to the intensive surface-to-air heating process in summer. Along the Rongbuk Valley, the up-valley flow propagates with higher speed than the wind speed from the downstream to the upstream of the valley, and the katabatic flow propagates with lower speed than the wind speed in a reverse direction from April to June (Zou et al., 2008). The up-valley wind appearing before noon was also simulated with the advanced regional prediction model by Song et al. (2007) in summer in this region. Thereafter, the katabatic wind overcomes the up-valley wind with the increasing gradients in temperature along the glacier-moraine-rock transition, and forms the observed katabatic wind. The along-valley larger temperature gradient causes the daily maximum wind speed in the late afternoon when the stratification near the ice surface is most stable with a stronger convective boundary layer over the rock-covered surface. It is probably the up-valley flow eroding the katabatic wind that causes the daily maximum wind speed to occur 3 h later than the maximum air
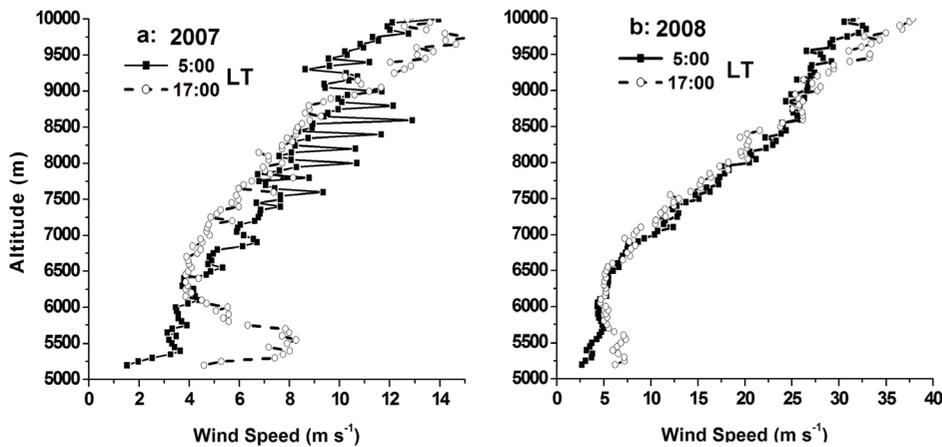
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FIGURE 8. Mean variations of wind speeds between altitudes 5200 and 10,000 m a.s.l. at 5:00 and 17:00 LT over period from middle April to early May of (a) 2007 and (b) 2008.

temperature, and the lowest directional constancy to occur in summer. At night, the formation of a stable boundary layer over the rock-coved surface probably causes the wind speed to decrease. The similar results were also observed along a mid-latitude glacier (Greuell and Knap, 1997; Strasser et al., 2004), and a tropical glacier (Sicart and Wagnon, 2005).

Daily average wind speeds being smaller at sites 2, 3, and 4 than that at site 1 from May to October may be for the following reasons: (1) the smaller fetch of the katabatic wind in the upper areas, (2) the smaller temperature contrast between the glacier surface and the ambient atmosphere at higher elevations, and (3) the open landscape of valleys and smaller area of glaciers. Vergeiner and Dreiseitl (1987) pointed out that the area-height distribution of a valley segment is a fundamental geometric factor, and the horizontal pressure gradient will vary according to the relief, side walls, and passes, and increase across narrow sections of a valley. The middle and downstream of the Rongbuk Valley is relatively narrow and could strengthen the wind speed. Furthermore, larger areas of the West and Middle Rongbuk Glaciers contribute significantly to the katabatic wind at site 1. This was also confirmed with the meso-scale numerical models (Song et al., 2007). As the air temperature near the melting ice surface depends on downward mixing of warm air, it is not surprising that the daily maximum air temperature appears shortly after the daily maximum wind speed at site 3. Furthermore, the maximum air temperature at site 3 occurs, on average, 1 h later than at site 1, which is also consistent with this view. The same result was observed in the melting zone of the Greenland Ice Sheet, where the katabatic wind was accelerated in the late afternoon due to the large temperature gradient at the border between tundra and ice (Oerlemans and Vugts, 1993).

Moreover, there is a positive correlation between the wind speed and the air temperature at sites 1 and 3 from spring to autumn. The highest values of linear correlation coefficients are 0.57 and 0.54 with significant $P < 0.01$ at sites 1 and 3 in summer respectively, and the second highest in spring. This result was also observed on the San Rafael Glacier of Southern Chile in warmer summer (Ohata, 1989). The correlations could explain the larger diurnal variations of wind speeds at sites 1 and 3 in spring and summer. The diurnal ranges of the air temperature are 9.9 and 8.1 °C at site 1, and 7.6 and 5.8 °C at site 3 in spring and summer, while the diurnal variations of wind speeds are 4.8 and 4.3 m s^{-1} at site 1, and 3.5 and 3.6 m s^{-1} at site 3, accordingly.

Therefore, we argue that the higher diurnal ranges of air temperatures could induce the larger diurnal variations of wind speeds to a certain extent.

The synoptic-scale gradient wind also plays an important role in the wind regime of mountain regions. The synoptic-scale wind interacts nonlinearly with the katabatic wind through the mechanical production of the turbulent kinetic energy (Arritt and Pielke, 1986). On the north slope of Mount Qomolangma, it is expected that the katabatic wind at site 1 should be weakening in winter because the whole snow-covered terrain and reduced incoming solar radiation could inhibit the temperature gradients along the valley (Song et al., 2007). But the observed results show that wind speeds are higher during this season than the rest of the measuring period (Fig. 6). From November to March, the Qomolangma region is usually controlled by the active westerly trough in the upper troposphere (Ye and Gao, 1979). The south branch westerly troughs always intrude into the West and Middle Rongbuk Valley from the west mountain pass and could strengthen the katabatic wind with the subsidence flows (Gao, 1980). This could maintain the strong katabatic wind with smaller diurnal variations of wind speeds and higher directional constancy at site 1. At higher elevation areas, the synoptic-scale wind can penetrate more easily because of the relatively open landscape. Therefore, under the control of the westerly regime, up-valley winds dominate at site 6 with larger value and smaller diurnal variation of wind speed, and with higher directional constancy than that at site 3. Moreover, from 5 to 8 January, the region is just on the south of the axis of the stronger subtropical westerly jet stream with very high wind speed (70 m s^{-1}). Under the combination of this strong jet stream and special topography, the wind speeds remain very high on these days (Fig. 6, part a), and the maximum wind speeds reach as high as 43.1 and 57.1 m s^{-1} at sites 1 and 3 (Fig. 6, part b), respectively. The highest hourly mean wind speed (10 m s^{-1}) was also observed under the synoptic-scale forcing at Haut Glacier in Switzerland (Strasser et al., 2004).

Discussion

Though theoretical analysis for simple, idealized mountain valleys reveals the general characteristics of the topographical flows (Defant, 1951; Whiteman, 2000), airflows over glacier-covered mountainous areas are complicated because of the different

effect of internal parameters (terrain, the scale of valleys, the distribution of glacier, etc.), and external parameters (the synoptic-scale wind, radiative flux, etc.) (Arritt and Pielke, 1986; Vergeiner and Dreiseitl, 1987; van den Broeke et al., 1994). As a result, research and particularly field experiments over different glacier-covered mountainous areas reveal very specific wind characteristics (Greuell and Knap, 1997; Strasser et al., 2004; Sicart and Wagnon, 2005). Along the mid-latitude glacier in the Alps region, although the katabatic wind prevails, the synoptic-scale gradient wind can cause the highest wind speed and reversal of wind direction over the Haut glacier d'Arolla in Switzerland (Strasser et al., 2004), and the valley wind erodes the katabatic wind occasionally at the lower end of the tongue on the Pasterze glacier in Austria (Greuell and Knap, 1997). In the southern hemisphere, the valley wind prevails during the daytime in wet season, whereas the katabatic wind is observed most of the day in the dry season, except a few hours around 14:00 LT over the tropical Bolivian Zongo glacier (Sicart and Wagnon, 2005). As mentioned above, the surface wind regime on the north slope of Mount Qomolangma also shows the special features.

On the other hand, the katabatic wind is also different between the Mount Qomolangma region and polar glacier due to their special conditions. Over the melting zone of the Greenland Ice Sheet, the adjacent tundra has a large influence on the katabatic wind. As a result, the horizontal pressure gradient plays a more important role than the buoyancy force near the edge of the ice surface, and the wind speeds can be accelerated in the late afternoon due to the large temperature gradient at the border between tundra and ice. The synoptic force is also of great importance for the onset and final strength of the katabatic wind (van den Broeke et al., 1994). In Antarctica, the strength of the katabatic wind, originating from the continental interior, is mainly dependent on the slope of the ice surface and the near-coastal environment (Parish and Bromwich, 1989, 1997). The katabatic flows with directional constancy of around 0.8 always follow orographic pathways from the interior of Antarctica to the coast (Parish and Bromwich, 1997). The pressure gradient force at the coast develops much more quickly than the corresponding interior and results in the strongest katabatic wind at the steep coastal terminus of the continent (Parish et al., 1987). As shown previously, the surface winds at different elevations show their special features due to the more complex terrain and different underlying surface in our research region. From site 1 to 3, the horizontal pressure gradient may play a more important role for driving the katabatic flow, whereas at higher elevation areas, both the local buoyancy and horizontal pressure gradient force are the significant factors in the surface wind regime. On the Ruopula Pass (site 6), the wind is mainly under control of the synoptic-scale gradient wind. The different underlying surface may also influence the wind speeds and directions at six sites. Nevertheless, some missing data at sites 2, 4, 5, and 6 limit the spatial and temporal coverage, and thus prohibit the more detailed analysis about the wind regime systematically on the north slope of Mount Qomolangma region. The different impacts on the katabatic wind of the horizontal pressure gradient and buoyancy force need to be estimated quantitatively in conjunction with numerical simulations in the future.

In combination with the wind direction and speed variation with altitude (Figs. 5 and 8), we argue that the depth of the katabatic wind in the Rongbuk Valley is about 800 m. The value is thicker than that in the melting zone of the Greenland Ice Sheet (100–200 m) (Oerlemans and Vugts, 1993) and in the eastern Alps (100 m) (van den Broeke, 1997). This difference can be attributed to stability, synoptic-scale winds, the angle and length of the slope, local topography, and surface roughness (Arritt and Pielke, 1986). On the north slope of Mount Qomolangma region,

the strong atmospheric instability usually led to a thorough mixing and exchange of momentum due to extremely high incoming shortwave radiation (Chen et al., 2012). This can induce the katabatic wind to develop thicker depth (Arritt and Pielke, 1986). It is pointed out this argument is only based on the observed data during one month period in the morning and evening. The depth is probably thicker or thinner than 800 m due to the effect of solar radiation, underlying surface, and synoptic-scale gradient wind in different seasons. Moreover, little is known about the vertical structure of the katabatic wind because of the limited sounding data. Therefore, more detailed sounding data and numerical simulations are necessary for analyzing the katabatic wind and the effect of external parameters (Zängl et al., 2001; Song et al., 2007; Zhong and Whiteman, 2008).

In glacier-covered regions, the wind is not only responsible for the redistribution of snow cover (van den Broeke et al., 1994; Moore, 2004; Gascoin et al., 2013), but is also a critical factor of the glacier ablation since it determines the turbulent exchanges of heat and moisture between the glacier surface and the atmosphere (Fountain et al., 1999; Aizen et al., 2002; Favier et al., 2004; Moore, 2004). The katabatic wind has a large impact on the local mass balance of the East Antarctica Ice Sheet, being responsible for the formation of blue ice areas (van den Broeke and Bintanja, 1995), and it also blows 6% of the annual accumulation on Antarctica into the sea (van den Broeke and van de Wal, 1997). In the high-elevation, semi-arid Andes, wind-transported snow accumulates preferentially and reduces the snow mass loss over the snow season (Gascoin et al., 2013). As for the impact on the mass balance of glacier, some research pointed out that the wind has a positive effect. On the northern slope of the Himalayas, strong katabatic winds suppress precipitation but favor evaporation, reducing glacier melting even in the ablation zone (Aizen et al., 2002). On the ablation zone of Antizana glacier in the Andes, the wind is also responsible for intense turbulent fluxes and causes reduction of glacier melting. Conversely, in the polar region of Antarctica, sublimation is the only significant process by which glaciers lose mass and its rate largely depends on wind speed (Fountain et al., 1999). Furthermore, the wind is also an important driver of the static-surface sublimation and melting (Dadic et al., 2013), and its transport of suspended snow increases sublimation and thus ablation (Liston and Sturm, 1998). In the great Himalayas, there is a total glacier area of about 35,110 km^2, with an estimated total ice volume of 3700 km^3 (Qin, 1999). The winds may have an impact on the accumulation of snow at the summit of Himalayan Mountains as well as on the mass balance of the surrounding glaciers (Harper and Humphrey, 2003; Moore, 2004). Glaciers in the Himalayas are retreating faster than the world average and are thinning by 0.3–1 m a^{-1} (Dyurgerov and Meier, 2005). The horizontal retreat rate of the Rongbuk Glacier terminus was about 5.5–8.7 m a^{-1} between 1966 and 1997 and 5.6–9.1 m a^{-1} between 1997 and 2001 (Ren et al., 2004). However, there are only sporadic studies about the wind-driven redistribution of snow cover and its impact on the glacier or snow ablation (Harper and Humphrey, 2003; Moore, 2004). A full assessment of all these processes for glaciers over a season or longer has not yet been achieved in this region.

Summary

Wind regime on the north slope of Mount Qomolangma is investigated using hourly wind measurements from six AWSs at elevations ranging from 5207 to 6560 m a.s.l., as well as sounding data. The predominant wind is the katabatic flow in the mid-

dle and downstream of the Rongbuk Valley, while the up-valley wind dominates at high-elevation areas of this valley because of the complicated terrain, the synoptic-scale wind, and the glacier-moraine-rock transition in the underlying surface. The katabatic wind at low-elevation areas is always eroded by the up-valley wind and causes the lowest directional constancy in summer in the middle bottom of the Rongbuk Valley. The smaller fetch and temperature contrast, as well as the relatively open landscape of the valley and smaller glacier area cause smaller daily average wind speeds at high-elevation areas from May to October. Moreover, the synoptic-scale wind also plays an important role in the wind regime on the north slope of Mount Qomolangma. From November to March, the active westerly troughs always intrude into the bottom of the Rongbuk Valley and could maintain the strong katabatic wind, while the westerlies can penetrate more easily at high-elevation areas, and dominate the wind regime.

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References Cited

Aizen, V. B., Aizen, E. M., and Nikitin, S. A., 2002: Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers). *Quaternary International,* 97–98: 27–39.

Arritt, R. W., and Pielke, R. A., 1986: Interactions of nocturnal slope flows with ambient winds. *Boundary-Layer Meteorology,* 37: 183–195.

Barry, R. G., 2008: *Mountain Weather and Climate.* 3rd edition. Cambridge: Cambridge University Press.

Bertolani, L., and Bollasina, M., 2000: Recent biennial variability of meteorological features in the eastern Highland Himalayas. *Geophysical Research Letters,* 27: 2185–2188.

Cai, X., Song, Y., Zhu, T., Lin, W., and Kang, L., 2007: Glacier winds in the Rongbuk Valley, north of Mount Everest: 2. Their role in vertical exchange processes. *Journal of Geophysical Research,* 112: D11102, doi http://dx.doi.org/10.1029/2006JD007868.

Chen, X. L., Su, Z. B., Ma, Y. M., and Sunt, F., 2012: Analysis of land-atmosphere interactions over the north region of Mt. Qomolangma (Mt. Everest). *Arctic, Antarctic, and Alpine Research,* 44: 412–422.

Dadic, R., Mott, R., Lehning, M., Carenzo, M., Anderson, B., and Mackintosh, A., 2013: Sensitivity of turbulent fluxes to wind speed over snow surfaces in different climatic settings. *Advances in Water Resources,* 55: 178–189.

Defant, F., 1951: Local winds compendium of meteorology. *American Meteorological Society,* 655–672.

Dyurgerov, M. D., and Meier, M. F., 2005: *Glaciers and the Changing Earth System: A 2004 Snapshot.* Boulder, Colorado: Institute of Arctic and Alpine Research, University of Colorado, Occasional Paper 58, 117 pp.

Favier, V., Wagnon, P., Chazarin, J. P., Maisincho, L., and Coudrain, A., 2004: One-year measurements of surface heat budget on the ablation zone of Antizana Glacier 15, Ecuadorian Andes. *Journal of Geophysical Research,* 109: D18105, doi http://dx.doi.org/10.1029/2003JD004359.

Fountain, A. G., Lewis, K. J., and Doran, P. T., 1999: Spatial climatic variation and its control on glacier equilibrium line altitude in Taylor Valley, Antarctica. *Global and Planetary Change,* 22: 1–10.

Gao, D., 1980: *Report on Scientific Expedition to Mt. Qomolangma Area (1975)—Meteorology and Environment.* Beijing: Science Press (in Chinese).

Gascoin, S., Lhermitte, S., Kinnard, C., Bortels, K., and Liston, G. E., 2013: Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile. *Advances in Water Resources,* 55: 25–39.

Greuell, W., and Knap, W. H., 1997: Elevational changes in meteorological variables along a midlatitude glacier during summer. *Journal of Geophysical Research,* 102(D22): 25941–25954.

Greuell, W., and Smeets, P., 2001: Variations with elevation in the surface energy on the Pasterze (Austria). *Journal of Geophysical Research,* 106(D23): 31717–31727.

Harper, J. T., and Humphrey, N. F., 2003: High altitude Himalayan climate inferred from glacial ice flux. *Geophysical Research Letters,* 30(14): 1764, doi http://dx.doi.org/10.1029/2003GL017329.

Kang, S., Mayewski, P. A., Qin, D., Yan, Y., Zhang, D., Hou, S., and Ren, J., 2002: Twentieth century increase of atmospheric ammonia recorded in Mt. Everest ice core. *Journal of Geophysical Research,* 107(D21): 4595, doi http://dx.doi.org/10.1029/2001JD001413.

Liston, G., and Sturm, M., 1998: A snow-transport model for complex terrain. *Journal of Glaciology,* 44: 498–516.

Ming, J., Zhang, D., Kang, S., and Tian, W., 2007: Aerosol and fresh snow chemistry in the East Rongbuk Glacier on the northern slope of Mt. Qomolangma (Everest). *Journal of Geophysical Research,* 112: D15307, doi http://dx.doi.org/10.1029/2007JD008618.

Moore, G. W. K., 2004: Mount Everest snow plume: a case study. *Geophysical Research Letters,* 31: doi http://dx.doi.org/10.1029/2004GL021046.

Oerlemans, J., and Grisogono, B., 2002: Glacier winds and parameterization of the related surface heat fluxes. *Tellus,* 54A: 440–452.

Oerlemans, J., and Vugts, H. F., 1993: A meteorological experiment in the melting zone of the Greenland ice sheet. *Bulletin of the American Meteorological Society,* 74(3): 355–365.

Ohata, T., 1989: Katabatic wind on melting snow and ice surfaces (I): stationary glacier wind on a large maritime glacier. *Journal of the Meteorological Society of Japan,* 67(1): 99–111.

Parish, T. R., and Bromwich, D. H., 1989: Instrumented aircraft observations of the katabatic wind regime near Terra Nova Bay. *Monthly Weather Review,* 117: 1570–1585.

Parish, T. R., and Bromwich, D. H., 1997: A case study of Antarctic katabatic wind interaction with large-scale forcing. *Monthly Weather Review,* 126: 199–209.

Parish, T. R., Kenneth, T., and Waight, I., 1987: The forcing of Antarctic katabatic winds. *Monthly Weather Review,* 115: 2214–2226.

Qin, D., 1999: *Map of Glacier Resources in the Himalayas.* Beijing: Science Press.

Rampanelli, G., Zardi, D., and Rotunno, R., 2004: Mechanisms of up-valley winds. *Journal of the Atmospheric Sciences,* 61: 3097–3111.

Reijmer, C. H., and Oerlemans, J., 2002: Temporal and spatial variability of the surface energy balance in Dronning Maud Land, East Antarctica. *Journal of Geophysical Research,* 107(D24): doi http://dx.doi.org/10.1029/2000JD000110.

Ren, J., Qin, D., Kang, S., Hou, S., Pu, J., and Jing, Z., 2004: Glacier variations and climate warming and drying in the central Himalayas. *China Science Bulletin,* 49: 65–69.

Schneider, C., 1999: Energy balance estimates during the summer season of glaciers of the Antarctic Peninsula. *Global and Planetary Change,* 22: 117–130.

Sicart, J. E., and Wagnon, P., 2005: Atmospheric controls of the heat balance of Zongo Glacier (16°S, Bolivia). *Journal of Geophysical Research,* 110: D12106, doi http://dx.doi.org/10.1029/2004JD005732.

Somervell, T. H., and Whipple, F. J. W., 1926: The meteorological results of the Mount Everest expedition. *Quarterly Journal of the Royal Meteorological Society,* 52: 131–144.

Song, Y., Zhu, T., Cai, X., Lin, W., and Kang, L., 2007: Glacier winds in the Rongbuk Valley, north of Mount Everest: 1. Meteorological

modeling with remote sensing data. *Journal of Geophysical Research*, 112: D11101, doi http://dx.doi.org/10.1029/2006JD007867.

Strasser, U., Corripio, J., Pellicciotti, F., Burlando, P., Brock, B., and Funk, M., 2004: Spatial and temporal variability of meteorological variables at Haut Glacier d'Arolla (Switzerland) during the ablation season 2001: measurements and simulations. *Journal of Geophysical Research,* 109: D03103, doi http://dx.doi.org/10.1029/2003JD003973.

van den Broeke, M. R., 1997: Momentum, heat, and moisture budgets of the katabatic wind layer over a midlatitude glacier in summer. *Journal of Applied Meteorology*, 36: 763–774.

van den Broeke, M. R., and Bintanja, R., 1995: The interaction of katabatic wind and blue ice area formation in East-Antarctica. *Journal of Glaciology,* 41: 395–407.

van den Broeke, M. R., and van de Wal, R. S. W., 1997: Representation of Antarctic katabatic winds in a high-resolution GCM and a note on their climate sensitivity. *Journal of Climate*, 10: 3111–3130.

van den Broeke, M. R., Duynkerke, P. G., and Oerlemnas, J., 1994: The observed katabatic flow at the edge of the Greenland ice sheet during GIMEX-91. *Global and Planetary Change,* 9: 3–15.

Vergeiner, I., and Dreiseitl, E., 1987: Valley winds and slope winds—observations and elementary thoughts. *Meteorology and Atmospheric Physics*, 36: 264–286.

Wagnon, P., Sicart, J. E., Berthier, E., and Chazarin J. P., 2003: Wintertime high-latitude surface energy balance of a Bolivian glacier, Illimani, 6340 m above sea level. *Journal of Geophysical Research,* 108(D6): doi: http://dx.doi.org/10.1029/2002JD002008.

Whiteman, C. D., 2000: *Mountain Meteorology: Fundamentals and Applications*. New York: Oxford University Press, 171–202.

Xie, Z., 1975: *The Scientific Investigation Report on Mt. Qomolangma Region (1966–1968)—Modern Glaciers and Sphysiognomy*. Beijing: Scientific Press (in Chinese).

Yang, X. G., Zhang, T. J., Qin, D., Kang, S., and Qin, X., 2011: Characteristics and Changes in Air Temperature and Glacier's Response on the North Slope of Mt. Qomolangma (Mt. Everest). *Arctic, Antarctic, and Alpine Research*, 43: 147–160.

Ye, D., and Gao, Y., 1979: *Meteorology of the Tibetan Plateau*. Beijing: Science Press (in Chinese).

Zängl, G., Egger, J., and Wirth, V., 2001: Diurnal winds in the Himalayan Kali Gandaki valley, part II: modeling. *Monthly Weather Review,* 129(7): 1062–1080.

Zhong, S., and Whiteman, C. D., 2008: Downslope flows on a low-angle slope and their interactions with valley inversions. Part II: numerical modeling. *Journal of Applied Meteorology and Climatology,* 47: 2039–2057.

Zhu, T., Lin, W. L., and Song, Y., Cai, X., Zou, H., Kang, L., Zhou, L., and Akimoto, H., 2006: Downward transport of ozone-rich air near Mt. Everest. *Geophysical Research Letters,* 33: L23809, doi http://dx.doi.org/10.1029/2006GL027726.

Zou, H., Li, Z., Shu, M., Li, P., Wang, W., Li, A., Jia, J., and Gao, D., 2008: Local wind system in the Rongbuk Valley on the northern slope of Mt. Everest. *Geophysical Research Letters,* 35: L13813, doi http://dx.doi.org/10.1029/2008GL033466.