Boundary layer effects above a Himalayan valley near Mount Everest

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[1] Periodical Wind Profiler and Radio Acoustic Sounding System observations have been commenced at the Himalayas’ northern slope nearby Mount Everest in September 2005. Primarily data sets obtained 25 km remote from the glacier edge are utilized for a preliminary discussion of planetary boundary layer circulation resembling high alpine mountainous regions. Substantial findings include the detection of two wind shears and the phenomenon of glacier wind at a distance of 25 km from the glaciers. The latter lead to a reversed compensatory flow in a vertical scale of up to 2000 m above ground level, pointing at supra regional impact. Citation: Sun, F., Y. Ma, M. Li, W. Ma, H. Tian, and S. Metzger (2007), Boundary layer effects above a Himalayan valley near Mount Everest, Geophys. Res. Lett., 34, L08808, doi:10.1029/2007GL029484.

1. Introduction

[2] Land surface - atmosphere interaction processes play an important role in the energy and matter cycles over a wide magnitude of scales. Considerable deficit exists concerning the ability to properly describe these processes in topographically complicated high alpine environments, which among others leads to systematically biased assessment of climate anomalies by Global Climate Models (GCMs). At this juncture, slope-winds represent the smallest scale of mountain wind systems [Vergeiner and Dreiseitl, 1987], providing a keystone of a higher scale process-related understanding.

[3] The Atmospheric and Environmental Comprehensive Observation and Research Station at Qomolangma (AECORSQ) aims at the long term atmosphere observation of the Himalayas’ northern slope nearby Mount Everest. Wind Profiler (WP) and Radio Acoustic Sounding System (RASS) measurements are part of the observation plan. Being efficient methods to obtain atmospheric wind and temperature profiles [Weber et al., 1990; Grimsdell and Angevine, 1998; Angevine et al., 1998], those technologies are not as weather sensitive as e.g., the radiosonde release and consequently a good choice for continuous measurements under contrary weather conditions as found in the area under investigation.

[4] Primarily WP and RASS data sets obtained 25 km remote from the glacier edge are just recently available for a preliminary discussion of atmospheric processes above AECORSQ. Data from 24 May to 21 June 2006 has been used in this study exclusively, since in this period no precipitation took place and the interdiurnal variation of the weather was slight. As the monsoon season in this region stretches from begin of July to the mid of September, the results of this study reflect the average structure of the planetary boundary layer (PBL) in pre-monsoon season, which is mainly influenced by local terrain and glacier wind [Gao, 1985]. Hence, thorough research on glacier wind in high altitude mountainous regions has been proposed in many cases [Lüdecke and Kuhle, 1991; Yoshino, 1984; Obleitner, 1994]. However, due to logistic conditions in Himalayas, only few atmospheric observations have been carried out, particularly, no routine sounding measurements had ever before been established in this area.

2. Field Observation and Instruments

[5] The AECORSQ, run by the Chinese Academy of Sciences (CAS), was set up in August 2005 in an s-shape valley north of Mount. Everest (Figure 1) at an altitude of 4300 m above sea level (asl). The crests along the valley slopes show a height of 600-800 m above ground level (agl), comparatively higher in the south of the valley crook, peaking at 7000 m asl and partially covered by glaciers.

[6] The setup utilized for this evaluation consists of a Vaisala LAP3000 WP/RASS, and a Vaisala MILOS520 Automated Weather Station (AWS) located next to the LAP3000 with the anemometer at 20 m height agl in a PBL tower.

[7] The WP operating frequency is 1290 MHz, performing in pulse mode with three beams (one vertical and two oblique). It is configured to operate in two modes (low mode and high mode), that correspond to two different vertical ranges (from 132 to 2180 m and from 315 to 3800 m respectively) and resolutions. In high mode, the profiler covers eighteen range gates with each 200 m width, starting at 315 m agl, while in low mode, 21 range gates with 100 m width are scanned. At this, range gates blank out all signals originating from ranges outside this at most narrow window, substantially increasing the signal-to-noise ratio and protecting the radar against unsynchronized jamming pulses. Interlacing both modes’ results assures a broad coverage of the PBL and even the free atmosphere, with an height coverage of about 3300 m agl in average, and a high spatial resolution for PBL scans in low mode. In 2006, the WP operated continuously from May 24 to June 30, with half hour averaging intervals.

[8] The RASS, as configured, shows a height coverage of about 1200 m with a resolution of 80 m for vertical temperature measurements. However, RASS didn’t have a satisfactory height coverage and accuracy in this primarily period of observation. one possible reason might be the serious dissipation of the acoustic signal by cold and dry air.
Since for technical reasons yet no data for the WP echo intensity and RASS virtual temperature is available, the PBL height is not discussed in this article.

3. Results

For the reason of instrumentation, Beijing Standard Time (BST) is used for all depictions in this study. As for interpretation, one must keep in mind, that local time is two hours behind BST. The wind data of a typical and therefore representative day for pre-monsoon weather condition, 19 June 2006, is used in the following to introduce the findings.

At surface level WP observation bears close analogy to AWS ground level measurement (Figure 2), whereat values exceeding 6 m/s only appear in a window from 15:00 to 21:00 (BST), peaking at 11 m/s at 20 m agl. In this window, wind speed in both observational heights increases until 16:00 (BST), after what the wind speed at 315 m agl begins decreasing, whereas wind speed at 20 m agl keeps increasing until 17:00 (BST). As the general wind direction, southerlies are found interrupted by north-westerlies around 02:00 and 20:00 (BST) and a window of northerlies to easterlies from 09:00 to 14:00 (BST).

At night-time a wind shear of comparatively slow westerlies (secondary minimum of wind speed) interrupts the general southerlies at an altitude of 1500 m (Figures 3a–3c). Below this level the logarithmic wind profile peeks around 5 m/s at an altitude of 1000 m. With passage of time, the general southerlies segment toward easterlies below and westerlies above the wind shear.

After sunrise the forenamed segmentation continues, leading to a wind direction distribution with height resembling the Ekman spiral with a sharpened wind shear at 1500 m agl (Figures 3d and 3e). With increasing wind speed in the boundary layer, the 13:00 (BST) measurement most of all displays a logarithmic wind profile up to the free atmosphere, despite at secondary minimum of wind speed at 1500 m agl.

In the afternoon, the wind direction at an altitude of 900 m agl suddenly turns, now boasting southwesterlies and creating a new secondary minimum of wind speed (Figure 3f). With passage of time, this wind shear descends down to 500 m agl and transforms to westerlies around 20:00 (BST) (Figures 3g and 3h).

From Figure 4 three horizontal flow layers can be distinguished from nighttime to forenoon. Above 1500 m southwesterlies are found, whereas southeasterlies dominate in a range from 500 m to 1500 m, and weak northeasterlies bestride below 500 m. The local boundary layer is disturbed at 15:00 (BST) for a period of approximately 6 hours at which the range of disturbance reaches up to 2000 m agl.

During the period of disturbance, southeasterlies were found at the surface, whereas northwesterlies dominate the region between 1000 and 1500 m agl (Figure 5).

4. Discussion

Below, all terms regarding boundary layer structure and dynamics follow [Seibert et al., 2000].

The valley under investigation stretches north-south with high mountains in the south, therefore, general surface layer circulation (Figure 2) agrees with the slope- and along-valley wind phenomenon as described by [Whiteman, 2000].

As for the sudden change of wind direction and increase of wind speed in the afternoon, the glacier wind phenomenon should be taken into account: Southerlies agree with the location of the most prominent glaciers. 

Figure 2. Variations of (a) wind speed and (b) wind direction near ground level, June 19, 2006 (BST). Gray symbols represent the AWS result with anemometer at 20 m high; black symbols represent the result of LAP3000 at a height of 315 m, which are not corrected for ground clutter.
nearby (Figure 1). In addition, the development and speed of glacier wind depends on the temperature difference between the ice surface and the air nearby. The maximum difference is to be expected around 14:00 (local time), 16:00 (BST) respectively, when the air temperature reaches its maximum. Considering the stretch of way from the glacier slope to the station, speckled with sizable roughness elements, it’s reasonable to detect a maximum of wind speed at the station approximately one hour later (Figure 2, 17:00 (BST)). Therefore, the glacier wind would have covered this distance at an average speed of $7 \text{ ms}^{-1}$. According to glacier wind theory, the peak value of the wind speed profile is to be expected near surface height. Yet, a decrease of wind speed at higher altitudes keeping the increase of surface wind is not reported, this phenomenon is still subject of investigation.

[20] Wind shears have been detected at 500 m and 1500 m agl (Figure 4). Since at all times wind directions between surface and middle layer are contorted for at least 90° the middle layer apparently displays a compensatory flow pattern preserving mass balance for the surface layer circulation. Besides, an altitude of 500 m agl for the first wind shear points to an influence of the crests along the valley. On the other hand, above the second wind shear southwestlies can be found at most of the times, the direction of the geostrophic wind and therewith pointing at the transition to the free atmosphere.

[21] The turning and powerful increase of surface wind from 15:00 to 21:00 in Figure 4b displays the vertical scale of the glacier wind in the valley, that reaches about 700 m agl, close to the average height agl of the crests along the valley. Figure 3f correspondingly shows a sudden turn of wind direction at and below a height of 900 m agl, with the new wind shear descending down to 500 m agl by and by (Figures 3g and 3h).

[22] Furthermore, the disturbance provoked by the glacier wind can reach up to 2000 m agl, since atop the glacier wind, a strong simultaneous inverse flow was found (Figure 5). Thus, a possible explanation is that the strong downslope glacier wind causes a lack of air around the

Figure 3. Wind profiles of June 19, 2006 (BST), to emphasize typical uniqueness of wind profiles, equidistant time intervals were renounced.

Figure 4. Vector maps of average wind speed variation for 29 days, from May 24 to June 21, 2006: (a) high mode and (b) low mode. The vector’s length represents its magnitude.
At this point, a compensatory flow is likely to set in from north, since the glacier wind has accumulated air in this direction. This compensatory flow, under the influence of the geostrophic wind, gains northwestern direction.

5. Conclusions

The key findings of this study are: (1) Two wind shears at 500 and 1500 m agl exist, seemingly providing compensatory flow patterns between surface and middle layer and geostrophic wind in the upper layer; (2) the phenomenon of glacier wind exists at a distance of 25 km from the glaciers, with a vertical impact up to 700 m agl; and (3) the glacier wind leads to a compensatory flow with a vertical scale of up to 2000 m agl, by far exceeding the valleys crests and even penetrating the free atmosphere, thereby pointing at a supra regional phenomenon.

By now, our understanding of the vertical atmosphere structure above high alpine terrain, such as the dimension of boundary layer and its relation to supra regional circulation is limited, aggravated by local topography and glacier wind effects. Consequently, findings derived from point measurements can not be simply upscaled in spatial and temporal manner.

All the more, multi-instrument point measurements (WP, RASS, radiosonde, Eddy Covariance) including cutting edge post field data processing routines (Quality Control and Footprint Analysis [Göckede et al., 2006; Metzger et al., 2006], Wavelet and Bispectral Analysis) can provide a high quality data basis corrected for violations of manifold assumptions brought along by the measurement techniques commonly in use. Only now, the application of a regional atmospheric model [e.g., Lu et al., 2005], fed with training areas supplying high quality time series and detailed terrain data, can help to reveal the spatial and temporal dynamics and impact of supra regional circulations in high alpine terrain. Therewith, an instrument for proper areal upscaling of energy and matter fluxes, so as to realize a more authentic assessment of climate anomalies by GCMs, can be created.

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