Diurnal Circulation of the Bolivian Altiplano. Part I: Observations

JOSEPH EGGER,* LUIS BLACUTT,+ FLAVIO GHEZZI,+ RICHARD HEINRICH,* PHILIP KOLB,* STEPHAN LÄMMLEIN,# MARTIN LEEB,* STEPHANIE MAYER,* EDUARDO PALENQUE,+ JOACHIM REUDER,* WOLFGANG SCHÄPER,@ JAN SCHWEEN,* RENE TORREZ,+ AND FRANCESCO ZARATTI+

*Meteorologisches Institut im Department für Physik der Universität München, Munich, Germany
+Laboratorio de la Fisica de la Atmósfera, Universidad Mayor de San Andres, La Paz, Bolivia
#Fachbereich Maschinenbau, Fachhochschule Regensburg, Regensburg, Germany
@Astrium, Friedrichshafen, Germany

(Manuscript received 6 April 2004, in final form 26 August 2004)

ABSTRACT

In July and August 2003 a field campaign was conducted to explore the diurnal circulation of the Bolivian Altiplano. Vertical soundings by remote-controlled aircraft yielded profiles of temperature, pressure, and humidity at six passes and in a valley. Pilot balloon observations provided wind profiles. Two permanent stations collected additional data. Typically, inflow toward the Altiplano commences a few hours after sunrise at about the time when the stable nocturnal layer near the ground is transformed by the solar heating into an almost neutrally stratified convective boundary layer. The depth of the inflow layer is comparable to but normally less than that of this boundary layer. There are indications of return flow aloft. The inflow continues at least until sunset. Moisture is imported at the passes leading to the Yungas in the east. Strong upvalley flows were found in the valley of the Rio de La Paz, which connects the wide canyon of La Paz with the tropical lowlands to the east. Inflow was absent at one of the passes despite favorable synoptic conditions. Cases of synoptically forced flows are presented as well where the diurnal signal is difficult to separate. A simple flow scheme is presented that fits the observations reasonably well.

1. Introduction

Plateaus are ubiquitous features of mountainous terrain. Their size ranges from a few square kilometers to almost planetary scale where the Zugspitzplatt in the Alps (Gantner et al. 2003) may be mentioned as an example of a plateau at the lower end of the scale; the Lake Tekapo Basin in New Zealand (McGowan and Sturman, 1996) as an example of intermediate size; and the Great Basin in the United States, the Andean Altiplano, and finally, the Tibetan Plateau as the grand plateaus on earth. It has long been recognized (e.g., Wagner 1932) that such plateaus induce a rich variety of thermally forced flows. In particular, it has been argued (e.g., Hann 1915) that the heating of the surrounding lowlands leads to an expansion of the air columns there and to a corresponding rise of the pressure surfaces. With that the surface pressure at the plateaus is relatively low and one may expect an inflow toward the plateau. Flohn (1953) stressed that the air above elevated plateau surfaces like the Altiplano is warmer than that above the lowlands at the same height because of sensible heat transfer from the ground and partly because of latent heat release above the plateau. With that, the pressure rises as well above the plateau so that the direction of the diurnal circulation is less obvious. Using radiosonde data, Flohn (1968) derived a diurnal inflow of 3.6 m s^{-1} toward the Tibetan Plateau for the 600–500-hPa layer (the corresponding figure is reproduced in Barry 1981). Flohn anticipated that most of this flow is channeled by passes. Note, however, that Flohn's inflow scheme depicts differences between morning and evening. The more detailed analysis of the winter wind fields by Murakami (1981) showed that it is only at the southeastern edge of the Tibetan Plateau where the inflow strength in the afternoon may be comparable to that estimated by Flohn (1968) for the whole plateau in the morning. However, Murakami (1981) relied on large-scale analyses and not on in situ observations; he did not discuss the role of passes.

At that time, Sang and Reiter (1982) presented the first simple model of the diurnal circulation of a large plateau. They considered a circularly symmetric plateau of 4000-m height connected to flat low-level terrain by a downward-sloping domain of rather small inclination (slope angle ~0.003). Given a diurnal heating cycle, Sang and Reiter (1982) numerically evaluated the

Corresponding author address: Joseph Egger, Meteorologisches Institut im Department für Physik der Universität München, Theresienstr. 37, München 80333, Germany.
E-mail: J.Egger@LRZ.uni-muenchen.de

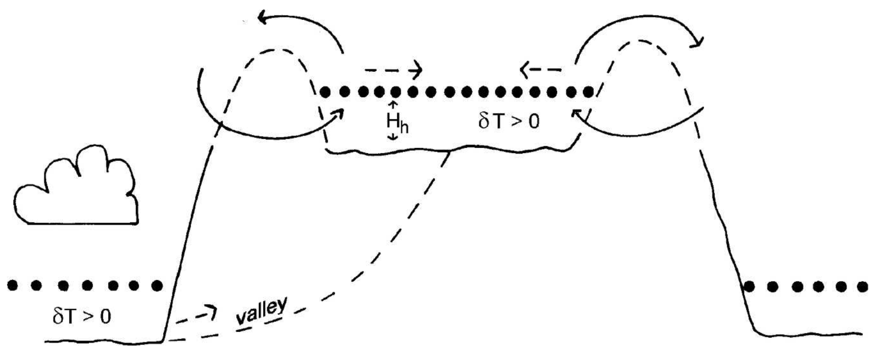

FIG. 1. Schematic of the hypothesized initial stages of the diurnal circulation of a plateau. The dashing of the terrain contour indicates the presence of passes. The dots mark the upper boundary of the convectively heated layer of depth H_h and temperature excess δT. The broken arrows give the anticipated inward motion of the circulation cells. A valley leads from the foreland up to the plateau.

corresponding diurnal circulation on the basis of the hydrostatic flow equations coupled to a state-of-the-art boundary layer scheme for conditions in the Northern Hemisphere. They found cyclonic upslope flow and inflow on the plateau itself near the ground during the day with corresponding outflow aloft. A low pressure system is established on the plateau. It is the reverse during the night. Egger (1987) considered a box model of a plateau with vertical sidewalls but with valleys incised into the plateau. Upslope flow is absent in this case but the inflow via the valleys is found to contribute strongly to the plateau's diurnal circulation. Gaertner et al. (1993) numerically investigated the diurnal circulation of the Iberian Peninsula that forms a plateau of 500–1000-m height (see Hoinka and Castro 2003 for climatological details). Using a two-dimensional model they demonstrated that cooler air penetrates from outside into the convective mixed layer above the plateau during the day in form of a shallow cold front. Moreover, they pointed out that the absence of a mixed layer above the surrounding sea helps to establish a heat low above the plateau. Portela and Castro (1996) extended this work by performing a three-dimensional numerical case study where they demonstrated inter alia that the air is flowing up the valleys and through mountain passes toward the center of the heat low above the plateau before noon.

Reiter and Tang (1984a,b) provided evidence for a diurnal cycle of the near-surface pressure field above the Great Basin in gross agreement with the model of Sang and Reiter (1982, see their Fig. 10 as a corresponding reference with respect to Tibet). However, the near-surface winds in the mountain massifs surrounding the Great Basin hardly resemble the spiraling up- and downslope patterns as found by Sang and Reiter (1982). Instead, the airflow is channeled by passes and valleys cut into the basin in accord with the calculations of Portela and Castro (1996). There is simply no softly inclined slope connecting the Great Basin with the Great Plains and the shores of the Pacific. The same is, of course, true with respect to the Altiplano and the Plateau of Tibet. We are, however, not aware of any attempts to explore the thermal circulation of these grand plateaus by in situ observations. It is still an open question as to what type of diurnal circulation is induced by these plateaus. A hypothesis with respect to this circulation is presented in Fig. 1, which is based on the numerical work mentioned and on simulations to be presented in a forthcoming paper (Egger et al. 2005, hereafter Part II). Low passes lead to an elevated basin surrounded by lowlands. There is also a valley connecting the lowlands with the plateau. The solar heating generates a convective boundary layer of depth H_h both above the plateau and the low terrain. The boundary layer at the plateau has a temperature excess δT with respect to the atmosphere at the same height above the lowlands. Altogether the heating induces "jumps" of temperature and pressure at the passes. The atmosphere adjusts to these steps and we expect that thermally direct circulations form at the passes, which protrude into the interior of the plateau later on. Eventually a grand circulation of the total plateau may emerge. In the case of the Bolivian Altiplano, clouds form in the east but not above the deserts in the west. Of course, Fig. 1 reminds us of the sea-breeze problem and the thermal circulation of heat islands (e.g., Miller et al. 2003; Baik 1992), but the topographic situation is more complex here mainly because of the passes.

The inflow through the valley must be partly caused by the buoyancy of the heated air above the sloping valley floor where the heating depends on local terrain geometry. However, the temperature in the valley tends to be larger than over the lowlands because of the volume effect (Steinacker 1984) so that there will be a jump in temperature at the valley's mouth. The valley winds are at least part of an adjustment to this temperature difference. Slope winds will also contribute to the circulation of the plateau but are beyond the scope of this paper. No corresponding observations have been

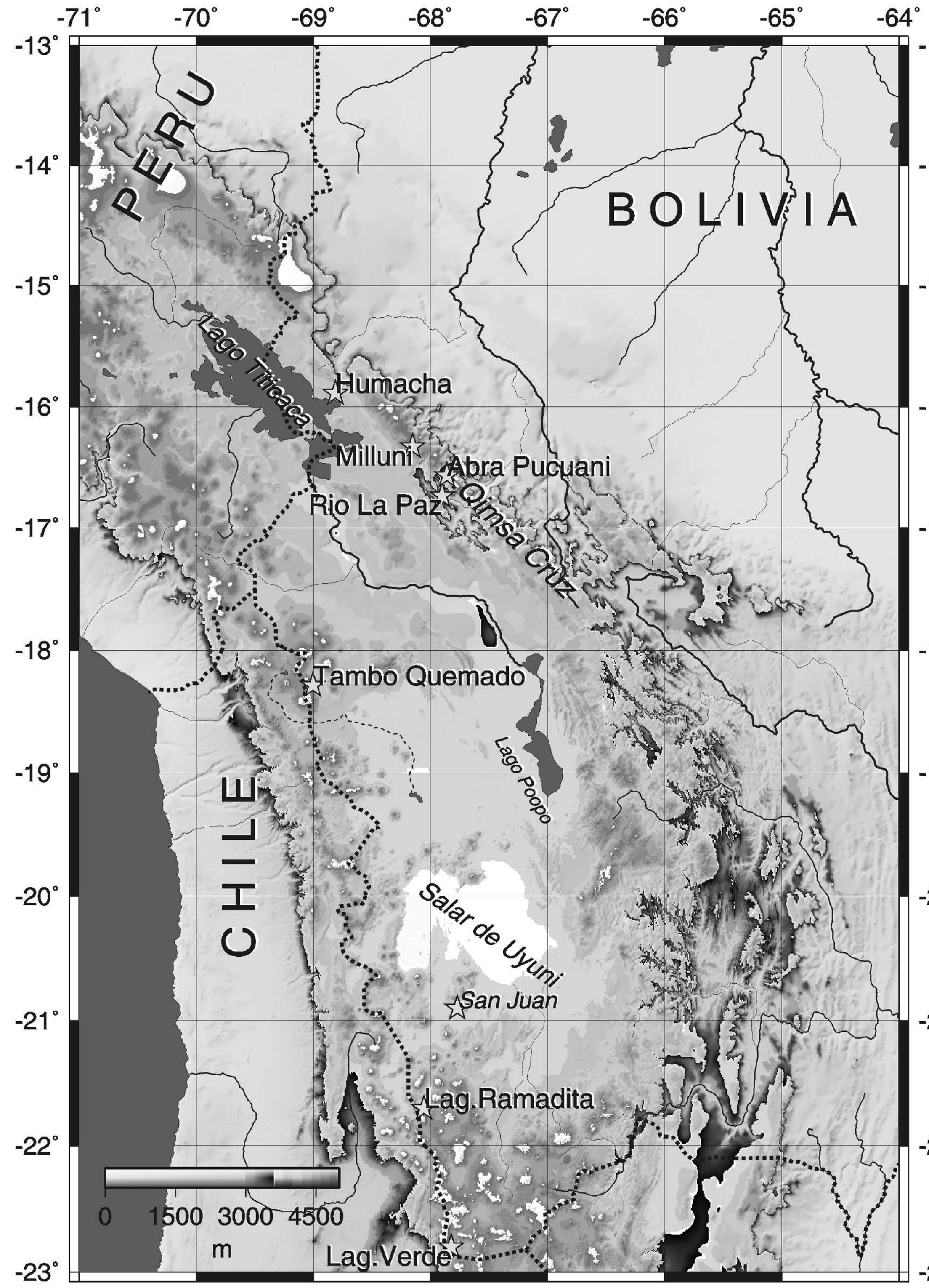

FIG. 2. Map of the Bolivian Altiplano with height shading. Also given are the observation sites and the names of a few towns and geographic features. The border (dots) separates Bolivia from Chile in the southwest, Peru (northwest), and Argentina (southeast). Darkest shading for the height line 3600 m, which roughly marks the boundary of the Altiplano. Larger heights have light shading. Areas above 5000 m are white as is the Salar Uyuni.

TABLE 1. Site location, length of the baseline for pilot balloons, and days of observations.

Site	Lat (S)	Lon (W)	Alt (m above MSL)	Base length (m)	Observation days
Laguna Ramadita	21°42′3″	68°3′12″	4299	2387.4	8–9 Aug
Laguna Verde	22°47′59″	67°49′12″	4370	1450.3	12–13 Aug
Milluni	16°19′49″	68°9′11″	4650	1526.2	28–30 Jul
Abra Pucuani	16°34′17″	67°51′32″	4556	469.9	22–23 Jul
Rio de La Paz	16°44′0″	67°54′0″	2457	342.8	19–20 Jul
Humacha	15°53′23″	68°48′41″	3947	662.4	26 Jul
Tambo Quemado	18°17′21″	69°0′17″	4681	620.0	18–19 Aug

made. Their role will be discussed in a forthcoming paper on numerical simulations (Part II).

In this paper we wish to report on a campaign during July and August 2003 that investigated the diurnal circulation of the Bolivian part of the Altiplano in austral winter. This season has been chosen because it is the only one throughout the year where one can expect to find mostly fair weather so that the Altiplano can be seen as an elevated sensible heat source during that time (e.g., Garreaud 1999). The topography of the Altiplano proper with its mean height of 4000 m is rather flat. Impressive Cordilleras to the east and west shield the high plains from inflow except through several passes (Fig. 2) and valleys connecting the Altiplano with the surrounding lowlands. Thus, the Altiplano is an almost ideal location for observations of the diurnal circulation of a grand plateau. Of course, anything like a reasonably complete coverage of all mountain passes and valleys of the Altiplano is impossible. Given limited resources one may decide to concentrate on one pass thought to be important and to observe the flows there, say, throughout one month. This way, a statistical evaluation of the observations becomes possible and confidence in the results increases. On the other hand, the situation at one pass is hardly typical of the Altiplano. For example, moist convection on the eastern side is a standard feature at all passes leading to the Altiplano from the Bolivian tropical and subtropical lowlands in the east. Moist convection is almost completely absent in the west where the passes connect the Altiplano with the coastal deserts of Chile and Peru. Moreover, the height of a pass with respect to the Altiplano is also an important factor. Finally, we decided to make observations for rather short periods at six passes and in one valley in order to capture part of the anticipated variability of inflow conditions. Although the thermal diurnal circulation was of key interest other types of inflow were not excluded a priori from observations during this campaign. Three passes lead to the east and three to the west (Fig. 2). Their exact location is given in Table 1 as well as that of the site in the valley of the Rio de La Paz. It must be stressed that this was the first attempt ever to study the thermally forced circulation of a large and high plateau by in situ flow observations at passes. Such an effort bears necessarily an exploratory character. In particular, a reasonably complete test of the flow scheme in Fig. 1 would require the installation of an array of stations leading from a pass into the interior of the altiplano. Even so, we can at least study the onset of the diurnal circulation at the passes in the morning, determine the depth of the inflow layers, and look for return flows. Theoretical aspects of the diurnal circulation and model results will be presented in subsequent papers. Of course, this is not the first attempt to observe airflow near mountain passes. However, the main emphasis of related work is on the response to large-scale flows as, for example, during Foehn events (e.g., Mayr et al. 2003).

A brief description of the instrumentation is given in the following section. The observations are described in section 3.

2. Equipment

The instrumentation for this campaign is the same as that used for the exploration of a Himalayan valley wind system described in detail in Egger et al. (2002). Helium-filled balloons were tracked by theodolites to derive the wind speed and direction. Battery-powered airplanes that were 1.29 m in length with a wingspan of 2.10 m, collected data on pressure, temperature, and humidity. Many of the remotely controlled flights reached heights of more than 2000 m above the ground. Pilots prefer thermals for climbing, which may introduce a small bias in ascent observations.

Permanent autonomous stations were installed at three sites described below. They contain instrumentation for temperature, wet-bulb temperature, pressure, wind speed, and direction. These instruments are mounted on a 3-m mast. Results from these stations will be mentioned only briefly. Because of logistic reasons, data collection always began after our visits to a site.

3. Observations

Although the weather was fair on most observation days, the air at upper levels was hardly ever at rest. The climatological mean flow above the Altiplano is westerly during austral winter (e.g., Kreuels et al. 1975) but variability from day to day is quite large. Nevertheless diurnal inflow was observed on several days. A day at a pass is counted as a day with diurnal inflow toward the Altiplano if there is little wind in the morning and if the inflow sets in before noon. In principle, one would like to also observe an end of the inflow regime in the evening but darkness prevents such observations. Seven out of 13 days of observations were inflow days. The corresponding measurements will be presented first where we also include the observations of up-valley flow in the valley of the Rio de La Paz. It follows a description of the days with forced flows where the diurnal signal is difficult to single out. Finally, a situation will be described where diurnal inflow was absent.

Table 1 gives the geographical coordinates, the altitude of the base camps, the lengths of the baseline for pilot balloon tracking, and the observation days for all seven observation sites. Note, that all sites are located within the Altiplano so that inflow can be easily detected.

a. *Diurnal inflow*

1) LAGUNA RAMADITA

Laguna Ramadita is one of the many lagunas in southwestern Bolivia on the southward track from San Juan to the Laguna Verde (see Fig. 2). Figure 3 shows the basin of the Laguna and the positions (T_1, T_2) of the theodolites. The pass is located west of the baseline in between two volcanoes, one to the northwest, the other one to the southeast. The ascent to the pass of ~4500-m height is fairly gentle and leads to the Bolivian border.

A low with its center at ~37°S reached South America on 5 August and moved toward the east. Correspondingly, 500-hPa winds were strong and southwesterly on 5 August. The following days, height gradients at 500 hPa were quite small in the area, the winds were weak and turned from mainly southerly flow on 8 August to northwesterly flow on 9 August.

The camp was installed near Laguna Ramadita in the evening of 7 August. On 8 August the air temperature at sunrise was - 12°C near the ground and rose slowly during the first morning hours. At 1000 LST, the first potential temperature profile of the day reflects a shallow cold pool of ~150-m depth in the basin of Laguna Ramadita (not shown). Above the pool, there is a stable layer of about 1500-m depth topped by an almost neutrally stratified layer. The dryness of the air is extreme with relative humidities below 30%. One hour later (Fig. 4a), the low-level inversion is completely eroded and a weakly stable layer extended up to an inversion at H_h ~1500 m above the ground. The temperature differences of 1–2 K between ascent and descent indicate convective activity. (They do not represent a hysteris effect, which can be seen from the almost perfect agreement of ascent and descent in Fig. 6a; see also Egger et al. 2002). The pilots seek to gain height by choosing thermals during ascent. Descent occurs mostly outside thermal updrafts. The first wind observations on that day in Fig. 4a reveal a shallow layer of easterly upslope winds (see Fig. 3 for the terrain) and weak southerlies aloft. At 1200 LST the southerlies are replaced by westerlies except close to the ground where northeasterly upslope winds prevail. From then on, winds are westerly also at the ground with speeds increasing there to 10 m s^{-1}. The depth of the layer of westerlies is ~2000 m at 1400 LST with northeasterlies above (Fig. 4b). The depth of the mixed layer is more than 2000 m. As time proceeds, the depth of the west wind layer is reduced to about 1000 m with layers of easterlies and again westerlies above. Figure 3 gives an example of a balloon trajectory in the afternoon, when the pass winds carry the balloon first toward the west, but easterly return flow moves the balloon back later on. Higher up, westerlies take over. This layer of easterlies persists throughout the afternoon. It is, of course, difficult to decide if we see here the return flow anticipated in Fig. 1

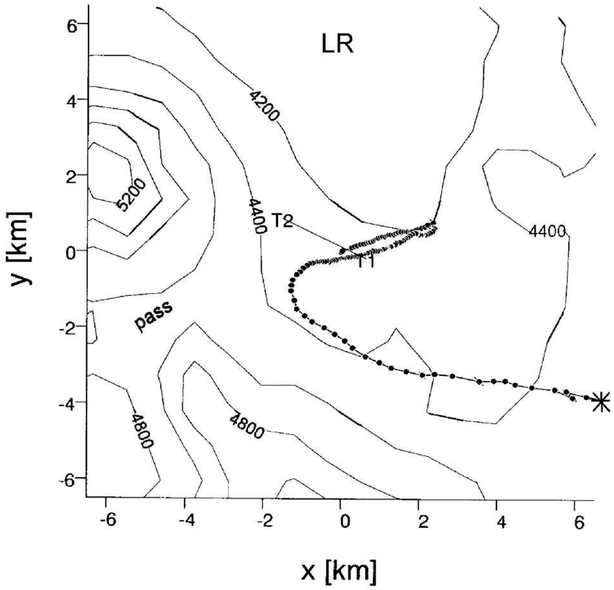

FIG. 3. Terrain and theodolite basis $T_1 - T_2$ near Laguna Ramadita (LR). Also shown is the track of the balloon released at 1456 LST 8 Aug; final balloon height is 8126 m above starting point. Contour interval 200 m; star: end of trajectory.

Altogether the observations at Laguna Ramadita fit Fig. 1 quite well. The replacement of the upslope winds by strengthening westerlies at low levels implies that the thermal circulation propagates westward. There are indications of a return flow. The inversion height coincides with the height of the shift of the wind direction, which is close to that of the mountain tops.

After a clear night, the erosion of the nocturnal inversion occurred again but northwesterlies of ~10 m s^{-1} prevailed aloft during this period (not shown). Spells of westerlies were observed but no continuous inflow. We speculate that this lack of definitive inflow was caused by a layer of stratiform clouds above the Altiplano visible on that day in the east. The corresponding satellite pictures show a cloud band over the Altiplano extending southeastward to the Atlantic.

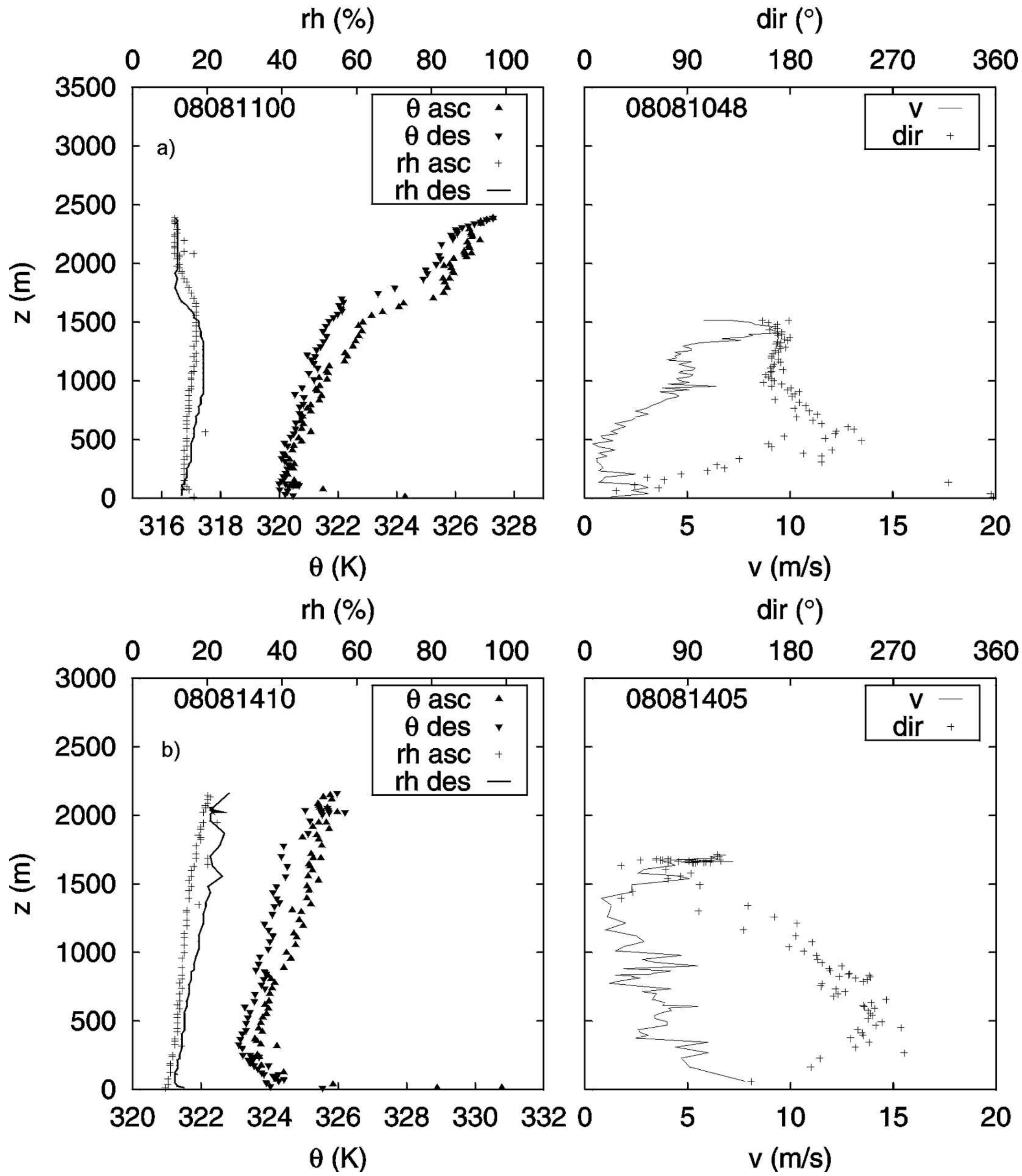

FIG. 4. Potential temperature θ (K) and relative humidity (rh; %) during ascent and descent at (a) 1100 and (b) 1410 LST 8 Aug observed at LR as a function of height. Also given are wind direction (crosses) and speed (bold; m s^{-1}).

This cloud layer hampered the establishment of a convective boundary layer and the evolution of a thermal circulation.

2) LAGUNA VERDE

Laguna Verde (Fig. 2) is located to the southeast of Laguna Ramadita within a relatively wide basin bordered by impressive volcanos (Fig. 5). The basin of Laguna Verde is also closed in the west. There is a shallow pass almost exactly to the west of the Laguna leading to Chile. The theodolite basis is oriented normal to the direction of the winds from the pass. It extends across the Laguna Verde.

The synoptic situation during our stay at Laguna Verde was dominated by a high pressure system approaching the coast from the west near 20°S. While 500-hPa winds were westerly on 12 August they became southwesterly on 13 August. The wind observations at Laguna Verde were in accord with this development and showed a slight turning from westerly to southwesterly at upper levels. There is no wind close to the ground until late in the morning of 12 August (Fig. 6). The nocturnal inversion is still quite pronounced at 1100 LST and its depth of ~500 m exceeds the height of the pass leading from the west toward the Laguna Verde (Fig. 5). Relative humidities above the cold pool are even smaller than at Laguna Ramadita. As mentioned above, ascent and descent profiles are quite close in this case at least for heights above 1000 m. The onset of low-level westerlies is easily observed on Laguna Verde because water surface waves that move toward the east are generated. The onset at about 1120 LST was clearly visible on all four days we were in the area. It was reported by other travelers as well (G. Hartjenstein 2004, personal communication). The low-level westerlies are quite intense in the afternoon of 12 August with speeds of more than 10 m s^{-1} near the ground (Fig. 6b). The inversion at about 400 m above the ground in Fig. 6b indicates that the surface westerlies are not the result of downward mixing from above but represent the cooling inflow across the pass toward the Altiplano. The trajectory in Fig. 5 demonstrates the rapid westward movement of the balloon. There are no signs of return flow. Given the strong westerlies aloft, observations of return flow are unlikely in any case.

The next morning, a strong inversion with a temperature increase of 6 K over a height distance of less than 100 m topped the basin of the Laguna Verde. Upper-level westerlies were strong at the heights above 1200 m above the Laguna in the morning but vivid surface westerlies developed on that day as well.

The observations at Laguna Verde are compatible with Fig. 1 but the strong westerlies aloft prevent statements on return flow and eastward propagation of the thermal circulation.

3) MILLUNI

Milluni is an old mine about 20 km to the north of La Paz (Fig. 2). It is located in a valley leading from the Altiplano to the Zongo pass (Fig. 7) with the valley's axis pointing toward the northeast. The valley bottom is about 2 km wide to become more narrow at the pass (Fig. 7). The peak of Huayna Potosi is towering in the north (outside of Fig. 7). The theodolite basis is oriented normal to the valley's axis.

A trough to the east of the Andes region moved slowly eastward in the period 28–30 July when measurements were made near the Zongo pass. The 500-hPa winds above the Altiplano were northwesterly and vivid on 28 July to abate and become westerly the next two days. When driving toward Milluni and the Zongo pass in the afternoon of 28 July strong northeasterlies were encountered and towering clouds were seen at the Zongo pass. Observations began at 1400 LST (Fig. 8a; see also Fig. 7). They indeed reveal vivid northeasterly inflow in a shallow stable layer. The stratification is almost neutral above the inflow layer. The relative humidity is large near the ground in the inflow layer. The clouds at the Zongo pass are the source region of this

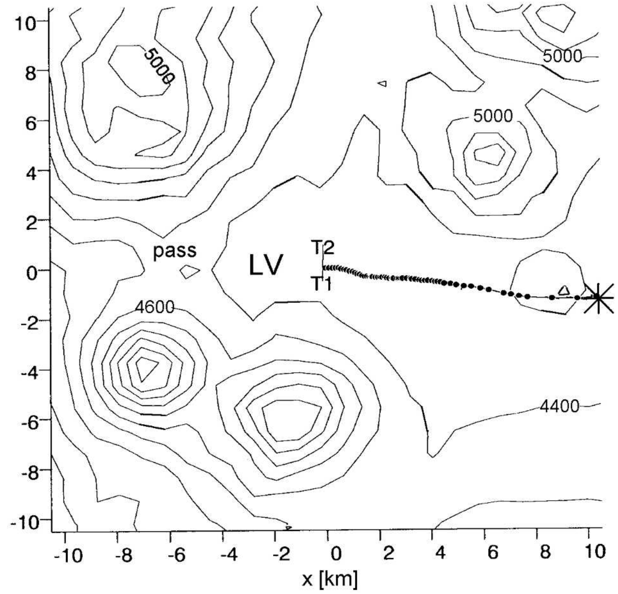

FIG. 5. Terrain and theodolite basis $T_1 - T_2$ near Laguna Verde (LV). Also shown is the track of the balloon released at 1401 LST 12 Aug; final balloon height above starting point is 2949 m. Contour interval 200 m; star: end of trajectory.

moist air. Well above this layer there is a maximum of relative humidity about 1200 m above the ground where clouds were encountered.

Snowfall of about 0.2-m depth occurred during the night and the snow cover was almost complete in the area during the next two days. Winter snowfall at the Altiplano is rare but known to produce sometimes considerable amounts of snow (Vuille 1999). This time, the snow covered the Milluni area but the Altiplano proper was free of snow. Temperatures were less than the day before. Winds remained westerly throughout those two days in layers of at least 1500-m depth but speeds were less than 5 m s^{-1} in the lowest 1000 m above the camp. Figure 8b demonstrates that there exists a moderately stable layer of 1500-m depth above the snow-covered ground topped by an extreme inversion. The plane briefly crossed a cloud during ascent to descend in relatively dry air. The relative humidity was small above the cloud layer.

The absence of inflow on both days suggests that the enhanced albedo due to snow cover reduced the sensible heat flux from the ground so that a thermal circulation did not develop. This observation is in keeping with our hypothesis that the inflow is induced by local conditions.

4) ABRA PUCUANI

Abra Pucuani is a pass at 4556-m altitude (Fig. 2) between the mountains Illimani in the south and Mururata to the north (map not shown). A road across the pass connects La Paz in the west with the Yungas in the east. The theodolite basis was established slightly to the east of the pass.

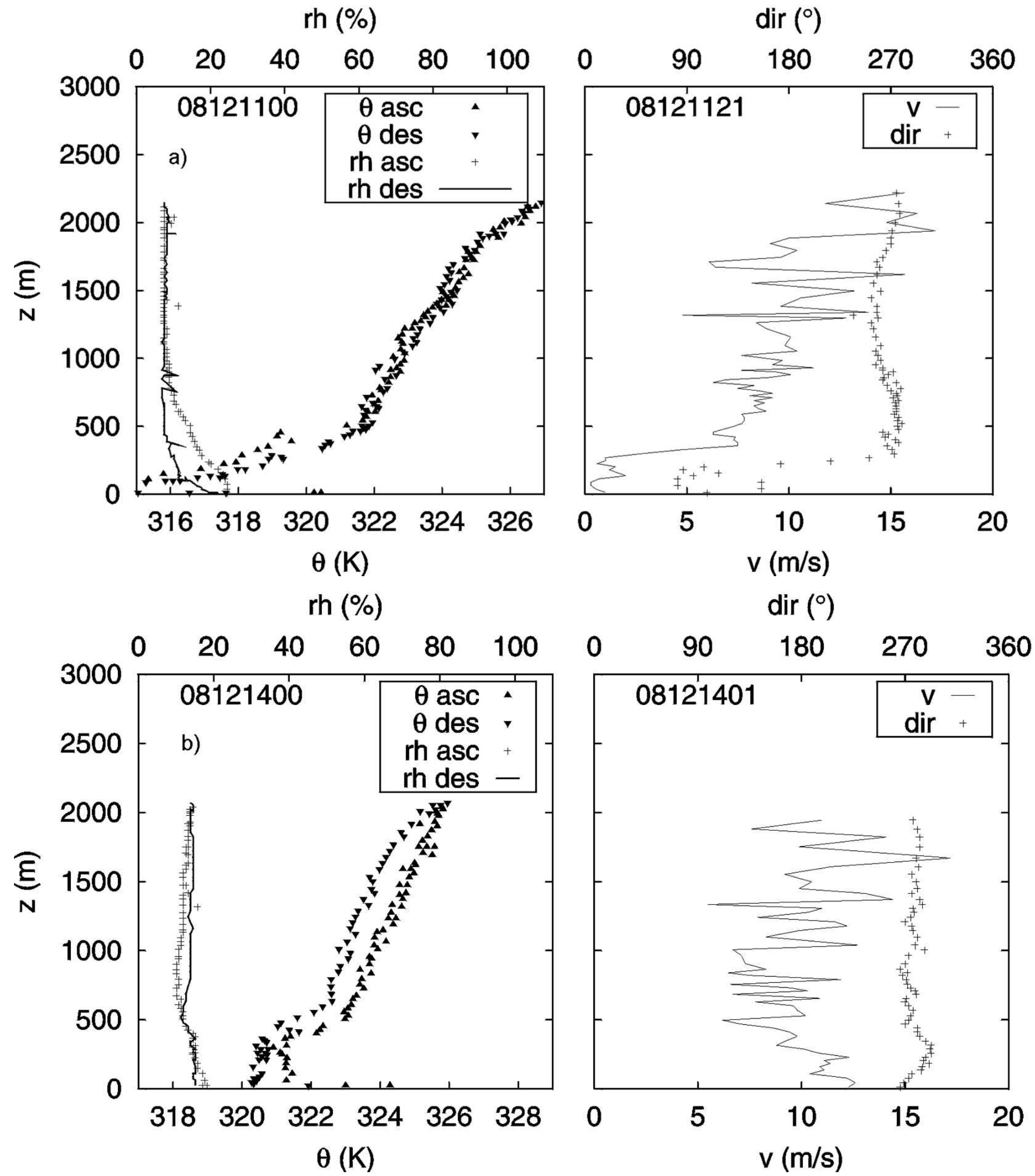

FIG. 6. Potential temperature and relative humidity at LV at 1400 LST 12 Aug during ascent and descent at (a) 1100 and (b) 1400 LST, respectively. Also given are wind speed (bold) and direction (crosses).

An interesting case of flow over the Abra Pucuani pass was encountered on 21 July on our way up to the pass in the afternoon. The 500-hPa winds were northwesterly on that day. Clouds, which originated at its eastern side, covered the pass and were dissolved on their way toward the Altiplano. Strong downslope flow led to a bending of the trees and people had to work hard to make their way against the downslope flow in a village several hundred meters below the pass. The cooling of the flow across the pass by evaporation presumably generated relatively dense air that accelerated rapidly on its way down the slope. The pass itself was covered by drizzling clouds. Wind speeds were moderate at the pass. It was, however, too late to start measurements on that day. This type of inflow represents a late stage not covered by Fig. 1 where humidity appears to affect the dynamics.

A permanent station was established at the pass but the solar panels were taken away a few days later so that no data are available.

5) Rio de La Paz

The site is located in the valley of the Rio de La Paz about 30 km to the southeast of La Paz and ~1300 m

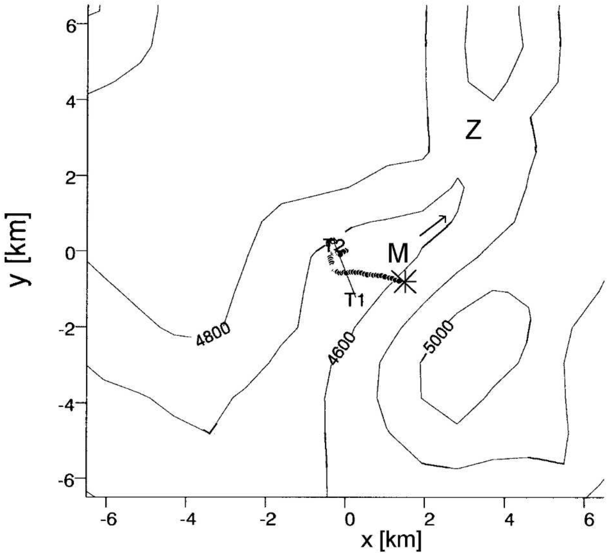

FIG. 7. Terrain and theodolite basis $T_1 - T_2$ near Milluni (M) and the Zongo pass (Z). The arrow follows the valley's axis. Also shown is the track of the balloon released at 1445 LST 28 Jul; final balloon height above starting point is 2023 m. Contour interval 200 m; star: end of trajectory. The available terrain data are incomplete in the northwest.

below the Altiplano (Figs. 2 and 9). This river connects La Paz with the lowlands of Bolivia. It belongs to a system of rivers and deep gorges that drain the Altiplano through a large gap separating the Cordillera Real and the Cordillera Qima Cruz (Fig. 2). The valley's orientation is roughly from east to west near the baseline, where its width is about a kilometer to become quite narrow farther east where a gorge leading toward the southeast makes farther passage difficult. The baseline is relatively short (Table 1) and is oriented across the valley. A permanent station is collecting data at the observation site.

As previously mentioned, the site has been chosen to measure inflow toward the Altiplano through a valley connecting the basin of La Paz with the Yungas to the east. On both days, there was no inflow in the morning. Cloud motion and generation of lenticular clouds showed that strong northwesterlies existed near the top height of the volcano Illimani. A strong vortex off Peru moved toward South America that day.

On 19 July, up-valley flow sets in before noon and quickly reaches speeds up to 15 m s^{-1}. Figure 10 presents the related profiles in the afternoon. A mixed layer of 600-m depth is topped by an inversion with a weakly stable layer farther up. Speeds in the lowest layer are 10–15 and 5–10 m s^{-1} above. The relative humidity in the lowest layer is much higher than above. The balloon first follows the valley wind but later enters the circulation of the north-facing slope (Fig. 9). Clearly, we observe here the inflow from the moist lowlands toward the canyon of La Paz. It appears, moreover, that the inflow toward the Altiplano at this point is captured reasonably well by the standard model of supercritical flow behind a contraction. This model accepts the inversion on top of the lowest layer as the top of shallow-water flow is affected by reduced gravity. As has been mentioned above, the valley is fairly narrow to the east of the point of observation (Fig. 9). We can assign the Froude number to Fig. 10:

$$F = |V|(g'H)^{-1/2}$$

with flow speed $|V| \sim 13$ m s^{-1}, layer depth $H = 600$ m, and reduced gravity $g' = \Delta\theta g/\theta \sim 2 \times 9.81/290 = 0.07$ to arrive at $F = 2.0$, so that supercriticality is ensured. Even if the flow is subcritical ($F < 1$) before the entry to the gorge, it becomes supercritical at the end of the gorge. A similar situation has been encountered in the Kali Gandaki valley in Nepal (Egger et al. 2002) where thermally driven subcritical up-valley flow in a gorge becomes supercritical at the gorge's exit where the valley is widening.

On the following morning, weak downvalley winds were found in a layer of 900-m depth (0930 LST). The ensuing up-valley flow was weaker than the day before with typical velocities of $\sim$8 m s^{-1} (not shown).

A permanent station was installed close to the theodolite basis (see Table 1). The data obtained so far reveal that the up-valley winds are an extremely stable phenomenon. No day without strong up-valley winds in the afternoon occurred from 21 July until the end of December. In January 2004, the wind system was less periodic. As an example, wind speeds and direction are displayed in Fig. 11 for 6 days. Clearly, there are strong up-valley winds during the day while nocturnal winds are always weak and tend to be directed down the valley. Wind observations at the Laboratorio de la Fisica de la Atmósfera close to the springs of the Rio de La Paz show similar features. This shows that the diurnal inflow in the valley reaches the Altiplano. These findings are in keeping with Fig. 1. On the other hand, it is unclear if there exists any dynamic coupling between the pass winds and the valley winds. For example, it is conceivable that pressure perturbations induced by the pass winds at the Altiplano affect the valley winds. More stations would be needed to see if the up-valley wind regime is propagating upward in a similar way to what has been found in the Kali Gandaki valley (Egger et al. 2002).

b. *Forced flows*

1) ABRA PUCUANI

On 21 July winds over the Abra Pucuani pass were westerly throughout the day in agreement with 500-hPa analysis. The next day, a rather shallow inflow layer developed before noon underneath a layer of relatively weak northwesterly flow. The layer of easterly inflow had a depth of 200 m and was stably stratified. The

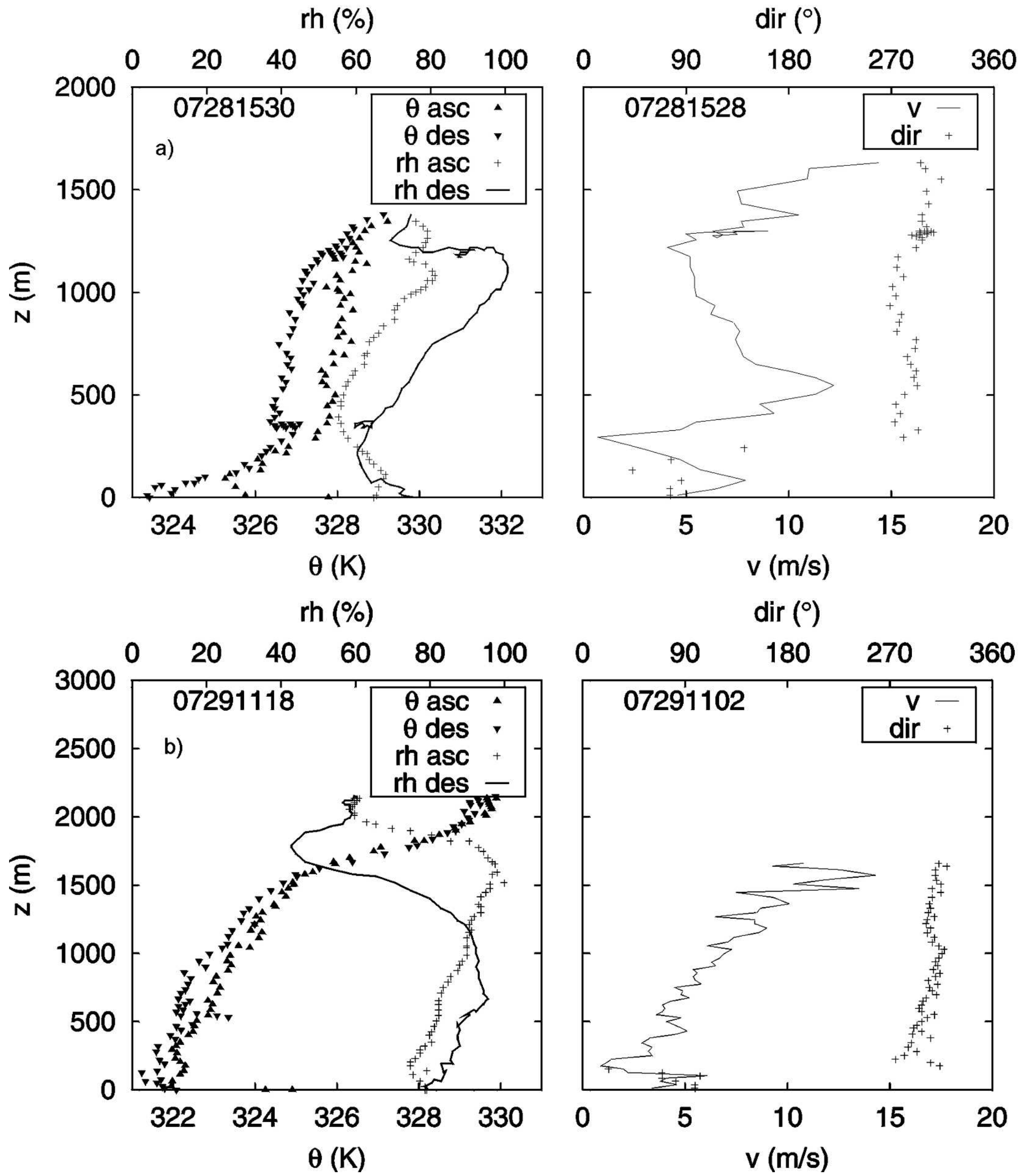

FIG. 8. Potential temperature and relative humidity at Milluni at (a) 1530 LST 28 Jul and (b) 1118 LST 29 Jul during ascent and descent, respectively. Also given are wind speed and direction.

airplane ascents failed to reach large heights on that day due to problems with the motor control system.

2) HUMACHA

As can be seen from Figs. 2 and 12 there exists a rather wide gap to the northeast of La Paz that connects the area of Lake Titicaca with the Yungas in the east with steep descent. The actual measurements took place near the village of Humacha on the western side of the pass. The pass height is less than 4200 m.

The wide pass leading from the Altiplano to the Yungas (see Fig. 12) was covered by low-level clouds on 25 and 26 July moving from the northeast toward the Altiplano. The cloud layer descended in the lee to disappear close to the village of Humacha. It is difficult to decide to what extent this inflow was thermally generated. A high pressure system in the east induced northwesterlies at 500 hPa above the Altiplano. The wind observations of 26 July (see Fig. 13) revealed almost northerly flow at upper levels. It is conceivable that this type of large-scale flow induces inflow at the pass. On the other hand winds at the pass were quite weak. Unfortunately, we had to leave the area around midnight

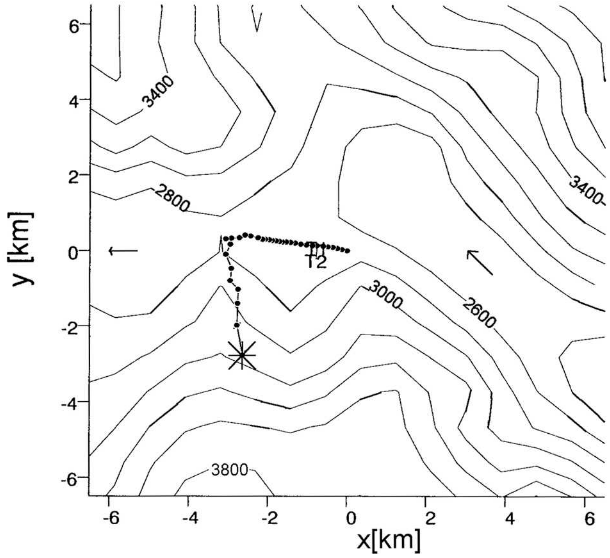

FIG. 9. Terrain and theodolite basis $T_1 - T_2$ near Rio de La Paz. Also shown is the track of the balloon released at 1653 LST 19 Jul; final balloon height above starting point is 2324 m. Contour interval 200 m; star: end of trajectory. The arrows follow the valley's axis upward.

of 26 July to avoid problems with the campesino movement centered in the nearly village of Achacachi. Further observations as planned were not possible. The observations on 26 July reveal a complicated flow structure at low levels (Fig. 13). Close to the ground, northeasterly cool flow prevailed in a layer of 200-m depth. The flow direction is determined by the orientation of the valley leading from the pass area toward Humacha (arrow in Fig. 12). Wind speeds are high in that layer so that it is likely that negative buoyancy due to cooling by evaporation accelerated the flow. Moisture content as well as relative humidity peak in the near-surface layer. An almost neutral layer of somewhat reduced wind speeds is found above the inversion where the winds are from north to northwest. There is another inversion at about 800-m height. This flow structure is found also in the ascents of 1402 LST, while that at 1458 LST contains the signature of the surface layer only. At 1210 LST, only the deep layer is present. Moreover, relative humidity is sometimes largest above the lowest layer.

The Froude number for the surface layer in Fig. 13 is large with $F \sim 3$–4 so that the flow down from the pass appears to be shooting. However, it may be more appropriate to apply a multilayer model in this case. This type of strong downslope wind appears to be common near this pass as can be deduced from the permanent bending of many trees toward the southwest in this area.

c. No inflow

TAMBO QUEMADO

The pass Tambo Quemado is located at the western border of Bolivia (Fig. 2). It connects the Altiplano with the Chilean deserts in the west and with the Pacific. The baseline near Tambo Quemado (Fig. 14) is located almost exactly to the east of the pass. The gap has a width of a few kilometers and is situated about 500 m above the Altiplano. A permanent station col-

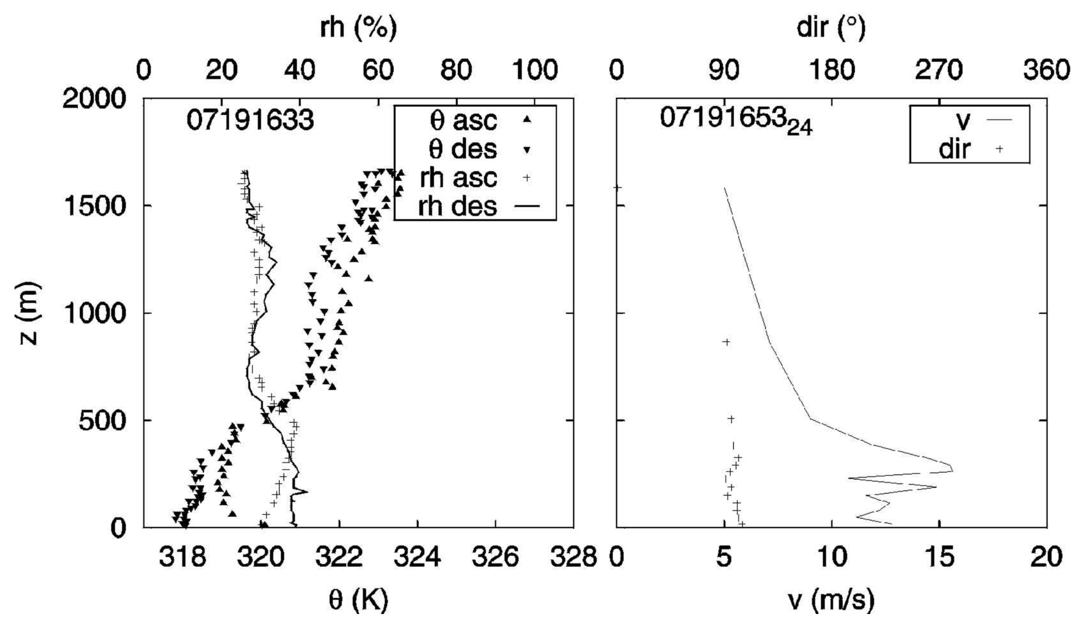

FIG. 10. Potential temperature and relative humidity at Rio de La Paz at 1633 LST 19 Jul. Also given are wind speed and direction at 1653 LST.

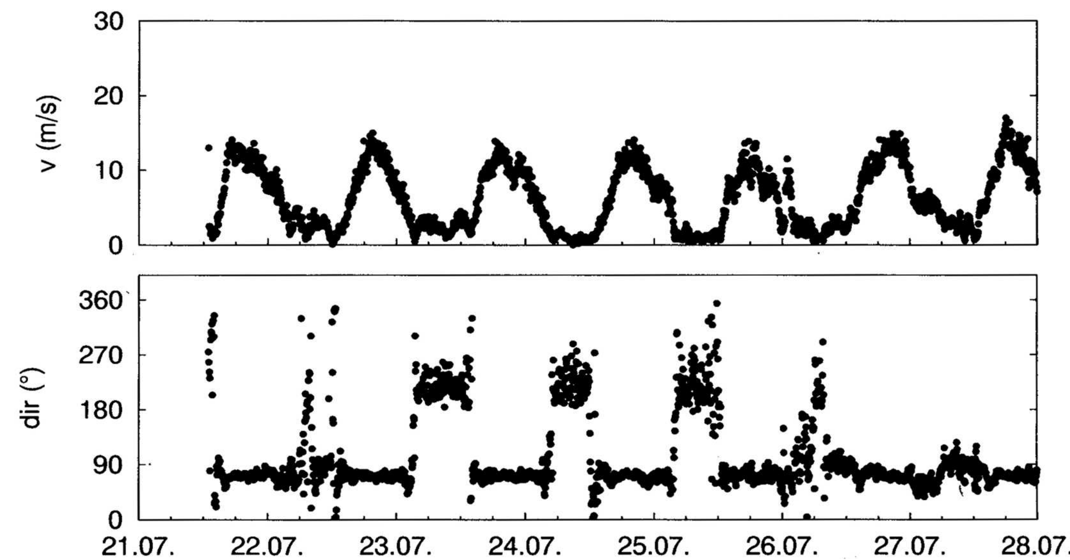

FIG. 11. Wind direction and velocity (m s^{-1}) as observed at the permanent station in the valley of the Rio de La Paz from 1200 UTC 21 Jul to 0000 UTC 28 Jul. Observations every 10 min.

lects data at the Bolivian border station about 5 km to the west of the pass.

On 18 August easterly flow prevailed at the pass throughout the day. At first, it was thought that we witnessed upslope flow but these easterlies continued after the solar heating of the slope had ended. Moreover the layer of easterlies was at least 2000 m deep in the morning. The next day, however, there was no appreciable airflow aloft. Spells of upslope flows occasionally interrupted a calm state (Fig. 14). In any case, no westerly inflow whatsoever has been observed despite the fact that this was a clear day without flow at larger scales. This result appears to contradict the flow scheme in Fig. 1. On the other hand the data from the permanent station show that the main wind direction late in winter is westerly with occasional easterly spells during the day. The numerical simulations to be described in a forthcoming paper will shed more light on the situation at Tambo Quemado (Part II).

4. Conclusions

Before drawing conclusions we have to stress again that all results are based on a small sample of observations. Moreover, we have chosen winter conditions. We cannot guarantee that our results apply in other seasons as well. With those caveats in mind we conclude the following:

1) The air above the Altiplano is stably stratified early in the morning at least near the passes. It takes about 3–5 h from sunrise to establish an almost neutrally stratified boundary layer of 1000–2000-m depth. There are, however, also days where the stratification remains stable.
2) Inflow through the passes sets in a few hours after sunrise. The inflow depth is comparable to but less than the depth of the convective layer. The inflow tends to continue at least until sunset. Return flow aloft has presumably been found in one case. Inflow from the east goes with substantial moisture transports. Evaporative cooling may help to accelerate inflow.
3) Snowfall near Milluni prevented the formation of inflows as did the low stratus near Laguna Rama-

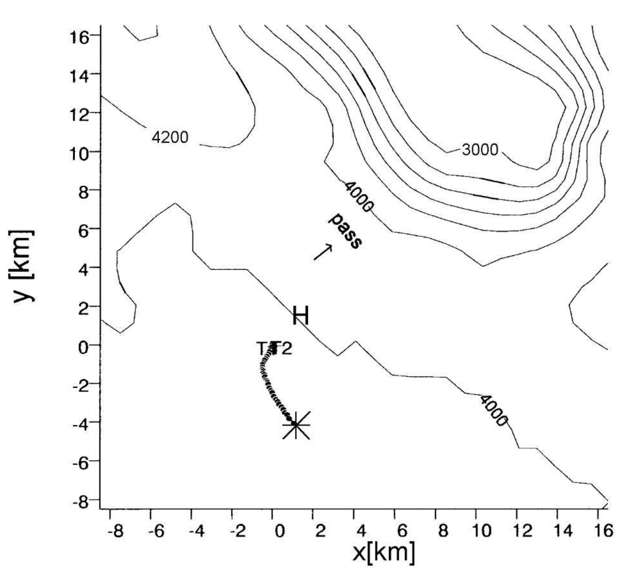

FIG. 12. Terrain and theodolite basis $T_1 - T_2$ near Humacha (H). Also shown is the track of the balloon released at 1653 LST 26 Jul; final balloon height above starting point is 1461 m. Contour interval 200 m; star: end of trajectory. The arrow follows the valley near Humacha.

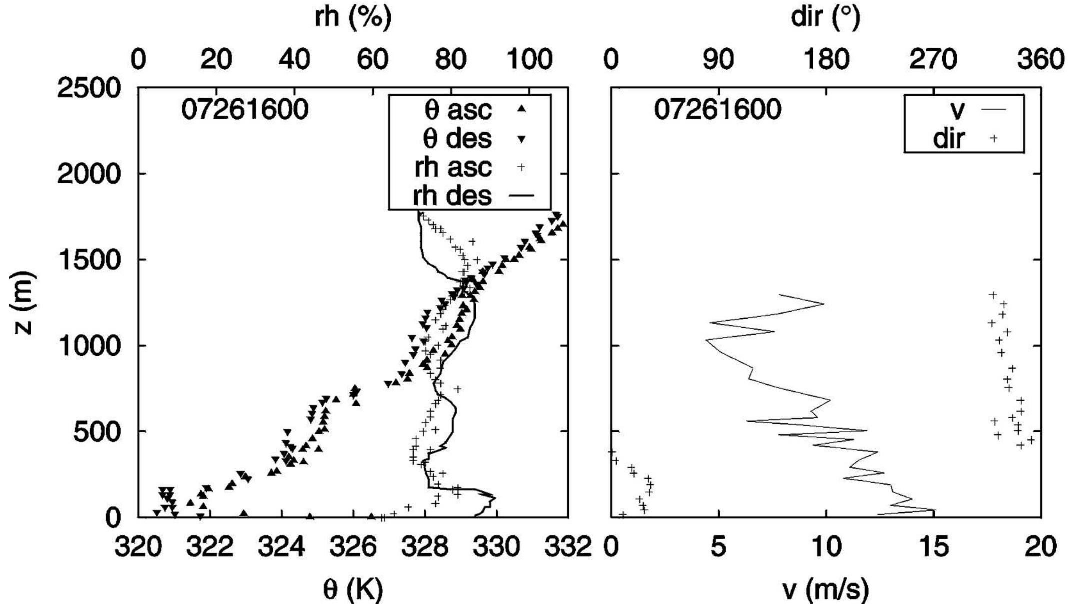

FIG. 13. Potential temperature and relative humidity near Humacha at 1600 LST 26 Jul. Also given are wind speed and direction.

dita. This suggests that the diurnal flow through passes is steered by local conditions and not by a huge heat low covering the Altiplano, which would generate inflow even if local conditions are not favorable.

4) Strong up-valley flow during the day is found in the valley of the Rio de La Paz, which transports moisture into the Altiplano. La Paz owes much of its ventilation to this valley wind.

So far, our findings are compatible with the hypothesis illustrated in Fig. 1. On the other hand, the observations at Tambo Quemado indicate that the topographic situation there is more complicated than assumed in Fig. 1. The numerical experiments to be described in Part II of this paper (Zängl and Egger 2005) will shed light on this problem.

Ambient flows are not included in Fig. 1. They may support the inflow (Humacha) or prevent it (Abra Pucuani). The climatological westerlies tend to suppress the inflow from the east.

As stated above this campaign must be seen as a first step toward an exploration of the diurnal circulation of the Altiplano. More observations are needed to fully capture this phenomenon. In particular, it would be interesting to find out how far the pass winds penetrate into the Altiplano proper. Additional measurements in the interior (5 August) at the Salar de Uyuni (Fig. 2) failed to shed light on this problem because the mean winds were too strong on that day. The detailed analysis of permanent station data will add further information.

It is tempting to calculate a mean vertical motion for the Altiplano for the situation of unperturbed diurnal inflow. Assuming a typical inflow speed of 5–10 m s^{-1} and a typical inflow depth of 1000 m, the average inflow at passes like the Zongo pass, Laguna Ramadita, and Laguna Verde is $\sim 1.5–3 \times 10^7$ kg s^{-1}. If we assume 4 passes per 100-km length of the Bolivian border we end up with a total of ~50 passes. The corresponding mean vertical motion above the Altiplano would be 0.003–

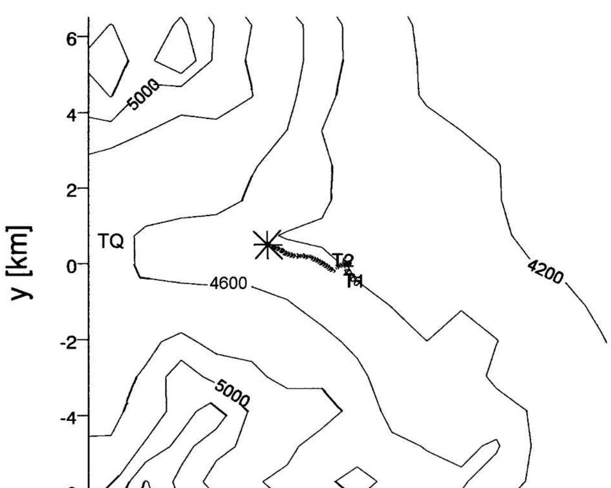

FIG. 14. Terrain and theodolite basis $T_1 - T_2$ near Tambo Quemado (TQ). Also shown is the track of the balloon released at 1500 LST 19 Aug; final balloon height above starting point is 1779 m. Contour interval 200 m; star: end of trajectory.

0.006 m s^{-1}. It has to be kept in mind, however, that it is far from obvious if the inflow at the passes will ever make it to reach the central parts of the Altiplano. The ascent is restricted to regions near the passes in the morning hours and is, therefore, stronger in those regions.

Acknowledgments. The authors are grateful to Volkswagenstiftung for support of the campaign and of the cooperation between our universities. The comments of two anonymous reviewers helped to improve this paper.

REFERENCES

Baik, J.-J., 1992: Response of a stably stratified atmosphere to low-level heating—An application to the heat island problem. *J. Appl. Meteor.,* **31,** 291–303.

Barry, R., 1981: *Mountain Weather and Climate*. Methuen, 309 pp.

Egger, J., 1987: Valley winds and the diurnal circulation over Plateaus. *Mon. Wea. Rev.,* **115,** 2177–2185.

——, and Coauthors, 2002: Diurnal winds in the Himalayan Kali Gandaki Valley. Part III: Remotely piloted aircraft soundings. *Mon. Wea. Rev.,* **130,** 2042–2058.

——, and Coauthors, 2005: Diurnal circulation of the Bolivian Altiplano. Part II: Theoretical aspects. *Mon. Wea. Rev.,* **133,** 911–924.

Flohn, H., 1953: Hochgebirge und allgemeine Zirkulation II. Die Gebirge als Wärmequellen. *Arch. Meteor. Geophys. Biokl.,* **A5,** 265–279.

——, 1968: Contributions to a meteorology of the Tibetan Highlands. Atmospheric Science Paper 130, Colorado State University, Ft. Collins, Colorado, 1–266.

Gaertner, M., C. Fernández, and M. Castro, 1993: A two-dimensional simulation of the Iberian summer thermal low. *Mon. Wea. Rev.,* **121,** 2740–2756.

Gantner, L., M. Hornsteiner, J. Egger, and G. Hartjenstein, 2003: The diurnal circulation of Zugspitzplatt: Observations and modelling. *Meteor. Z.,* **12,** 95–102.

Garreaud, R., 1999: Multiscale analysis of the summertime precipitation over the Central Andes. *Mon. Wea. Rev.,* **127,** 901–921.

Hann, J., 1915: *Lehrbuch der Meteorologie.* Tauchnitz, 847 pp.

Hoinka, K.-P., and M. Castro, 2003: The Iberian Peninsula thermal low. *Quart. J. Roy. Meteor. Soc.,* **129,** 1491–1511.

Kreuels, R., K. Fraedrich, and E. Ruprecht, 1975: An aerological climatology of South America. *Meteor. Rundsch.,* **28,** 17–24.

Mayr, G., and Coauthors, 2003: Gap flow measurements during the Mesoscale Alpine Programme. *Meteor. Atmos. Phys.,* **70,** 1–21.

McGowan, H., and A. Sturman, 1996: Interacting multi-scale wind systems within an Alpine basin, Lake Tekapo, New Zealand. *Meteor. Atmos. Phys.,* **58,** 165–177.

Miller, S., B. Keim, R. Talbot, and H. Mao, 2003: Sea breeze: Structure, forecasting, and impacts. *Rev. Geophys.,* **41,** 1–30.

Murakami, T., 1981: Orographic influence of the Tibetan plateau on the Asiatic winter circulation. Part II. Diurnal variations. *J. Meteor. Soc. Japan,* **59,** 66–84.

Portela, A., and M. Castro, 1996: Summer thermal lows in the Iberian peninsula: A three-dimensional simulation. *Quart. J. Roy. Meteor. Soc.,* **122,** 6–22.

Reiter, E., and M. Tang, 1984a: Plateau monsoon of the Northern Hemispheres: A comparison between North America and Tibet. *Mon. Wea. Rev.,* **112,** 617–637.

——, and ——, 1984b: Plateau effects on diurnal circulation patterns. *Mon. Wea. Rev.,* **112,** 638–651.

Sang, J., and E. Reiter, 1982: A numerical model of large-scale mountain-valley breeze on a plateau. *Proceedings of the First Sino-American Workshop on Mountain Meteorology,* E. Reiter, Z. Baoskhan, and Q. Yongfu, Eds., Science Press, 609–630.

Steinacker, R., 1984: Area-height distribution of a valley and its relation to the valley wind. *Contrib. Atmos. Phys.,* **57,** 64–71.

Vuille, M., 1999: Atmospheric circulation over the Bolivian Altiplano during dry and wet periods and extreme phases of the southern oscillation. *Int. J. Climatol.,* **19,** 1579–1600.

Wagner, A., 1932: Hangwind–Ausgleichsströmung–Berg- und Talwind. *Meteor. Z.,* **49,** 209–217.