ALMA Memo No.322
Comparison of Meteorological Data at the Pampa La Bola and Llano de Chajnantor Sites

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September 4, 2000

Abstract

We have been monitoring meteorological conditions since 1996 at two possible sites in northern Chile – Pampa La Bola and Llano de Chajnantor – for the future large millimeter and submillimeter array. The compiled meteorological data are here evaluated to compare the observing conditions at these sites. The sites at Pampa La Bola and Llano de Chajnantor are both known to be excellent for astronomical observations at millimeter and submillimeter wavelengths. There are, however, measurable differences in the meteorological conditions at these two sites. The wind was significantly weaker at Pampa La Bola than at Llano de Chajnantor during the nighttime (UT−4h = 22h–9h) of the summer (January–April) and marginally weaker during the daytime of the winter, while it was marginally stronger during the daytime of the summer and the nighttime of the winter. On the other hand, the wind flow appeared to be slightly less organized (as determined from the variation of wind direction) at Pampa La Bola than at Llano de Chajnantor, possibly because of the mountains located to the west of Pampa La Bola. The site at Pampa La Bola had a marginally larger fraction of clear days than did the site at Llano de Chajnantor. The near-surface temperature was lower at Llano de Chajnantor by 1.8 K on average, probably reflecting the 250 m height difference between the two sites. During many summer mornings, however, Pampa La Bola was colder than Llano de Chajnantor. This is likely due to a temperature inversion in the lower atmosphere at the altitude of the sites. The surface water vapor pressure was generally lower at Pampa La Bola than at Llano de Chajnantor. Since we know from other measurements that the total precipitable water above Llano de Chajnantor is generally lower than that at Pampa La Bola, the fact that the surface water vapor pressure is lower at Pampa La Bola must indicate that this quantity is dominated by local surface effects, and is not representative of the bulk atmosphere above the two sites.

1 Introduction

Meteorological data are among the most basic parameters that characterize suitability of a site for astronomical observations. With a commercial weather station, we can simultaneously monitor wind direction, wind velocity, atmospheric temperature, relative humidity, and solar radiation. We have been using four identical weather stations to evaluate potential sites for the LMSA project in northern Chile [1]. After several years of measurements, we selected the Altiplano around Cerro Chascón as the primary candidate site. This site was declared as a science preserve area by the Chilean President.

We now need to make a decision on the location of the array center within this well-defined area. There are at least two good candidate sites within the Cerro Chascón science preserve area: Pampa La Bola (4800 m a.m.s.l.) and Llano de Chajnantor (5050 m a.m.s.l.). Although these sites are only 8 km apart, significant differences in meteorological conditions might be expected due to the difference in altitude as well as their location relative to nearby volcanic peaks. Here we report results of a comparative study of these two sites from the viewpoint of measured meteorological data.

2 Measurements

We used identical weather stations to monitor wind direction, wind velocity, temperature, relative humidity, and solar radiation at the two sites. Identical weather stations have been operating near the NRO container at Pampa La Bola since 1996 March, and near the NRAO container at Llano de Chajnantor since 1995. Locations of these weather stations (SAm56) measured with a navigation GPS were 7459683N and 633165E for Pampa La Bola (B. Butler 1999, private communication) and 7453772N and 627772E for Llano de Chajnantor [2], respectively, and are illustrated in Figure 1.

The anemometer was Ogasawara Keiki WS-942, set atop a 3.0 m mast. Measurable ranges were 2 to 60 m s^{-1} for wind velocity and 0 to 540 deg for wind direction. The overall conversion factors were 16.67 mV (m $s^{-1})^{-1}$ for the anemometer and 1.852 mV deg^{-1} for the anemoscope, respectively. The accuracy of the wind velocity was specified to be ± 0.5 m s^{-1} at < 10 m s^{-1} and $\pm 5\%$ at > 10 m s^{-1}. The error of the repeatability of the wind direction measurement was specified to be ± 5 deg. There are, however, systematic offsets up to 10 deg in the wind direction, due to the uncertainty in setting the absolute position (relative to north, for instance) of each individual anemometer.

The actinometer was Ogasawara Keiki P-PCM-01 that measured difference in temperature of black and white receptors with a suite of thermocouples. The time constant was about 1 s. Sensible wavelength range was from 305 to 2800 nm. The overall conversion factor was 700 mV (kW $m^{-2})^{-1}$. The accuracy was specified to be $\pm 3\%$, but the absolute values need careful treatment because of a probable difference of azimuth-elevation setting of individual instruments that might result in different incident angles of solar radiation.

The thermometer/hygrometer was Ogasawara Keiki P-HMP 35A. The sensors were Pt 100 Ω for the thermometer and a thin film capacitor for the hygrometer, respectively. Measurable ranges were -40 to 40°C and 0 to 100%, respectively, and the accuracy was $\pm 5\%$. The overall conversion factors were 100 mV K^{-1} for the thermometer and 10 mV $\%^{-1}$ for the hygrometer, respectively.

Measured data in DC voltage were stored in an IC memory card every 20 minutes so that the data are not overwritten in a regular data pick-up period of half a year. Electric power was supplied by solar cells and a storage 12 V battery. The timing of the data acquisition refers to the internal clock of the data logger on each weather station, and thus the suite of data from each weather station is completely synchronized whereas there might be difference in timing up to a few minutes among those data taken with different weather stations.

3 Results and Discussion

3.1 Wind Velocity

We summarize in Figure 2 combined plots of diurnal and seasonal variations of the wind velocity at these sites. The instrument records 1-minute averaged data every 20 minutes, and these data were then binned and averaged every 30 minutes for the diurnal variation and every 15 days for the annual variation, respectively. At each site, there are notable diurnal and seasonal variations in the wind velocity. In general, the wind starts blowing at around 9h (local time UT$-$4h) in the morning and calms down at around 21h in the evening. The winter season (from May toNovember) is windier, with peak winds in June. The basic appearance of the diurnal and seasonal variations is similar at the two sites.

Figure 3 shows the cumulative distribution and histogram of the wind velocity observed during 1997. The maximum of the 1-minute averaged wind velocity in 1997 was 27.2 m s^{-1} recorded at Llano de Chajnantor. The median wind velocity in that year was 7.0 m s^{-1} at Pampa La Bola and 6.7 m s^{-1} at Llano de Chajnantor. The histogram of wind velocity is double-peaked at Pampa La Bola near 3 m s^{-1} and 9 m s^{-1}, whereas it is single-peaked near 6 m s^{-1} with broader wing at Llano de Chajnantor (though you can see the hint of a secondary peak around 9–10 m s^{-1} at Llano de Chajnantor as well). The lower and higher velocity peaks at Pampa La Bola roughly correspond to the median values of nighttime and daytime histograms, respectively.

There is a regular pattern in the ratio of wind velocities in these sites, as shown in Figure 4. The wind is significantly weaker (down to -0.4 dex) at Pampa La Bola than at Llano de Chajnantor during the nighttime (22h–9h) of the summer (January–April) and marginally weaker during the daytime of the winter, while it is marginally stronger during the daytime of the summer and the nighttime of the winter.

3.2 Wind Direction

The wind blows predominantly from the west, as shown in Figure 5. Occasionally, the wind blows from the east, but it is generally much weaker. Wind coming from either the north or the south is very rare. This tendency is clearer at Llano de Chajnantor than at Pampa La Bola. The larger scatter of the wind direction at Pampa La Bola displayed in Figure 5 may be due to the existence of Cerro Chajnantor and Cerro Toco, which are located upwind (to the west) of that site. The rms amplitude of a turbulent wake at the heights of these anemometers (3 m) estimated from amplitude distribution of wind to the north-south direction was found to be $\sim$1.5 times larger at Pampa La Bola than at Llano de Chajnantor, provided that the global flow of the wind above these sites is dominated by a uniform flow to the east-west direction. It will be interesting to compare these results to forthcoming numerical simulations and laboratory experiments of the behavior of the local turbulence in this region.

The diurnal variation of wind direction is shown in Figure 6, which is a plot of "normalized wind velocity" — the product of a probability and expected wind velocity toward a certain wind direction. As the wind becomes stronger in the daytime, the wind direction gradually shifts from WNW to W until the wind calms down at around 20h. Wind blowing from the east is generally restricted the morning hours (6h–12h) and rarely exceeds 10 m s^{-1}. This eastern wind also occurs more often (and has slightly higher velocity) at Llano de Chajnantor than at Pampa La Bola.

3.3 Temperature

The diurnal and seasonal variation of near-surface temperature is summarized in Figure 7. Because of the high altitude of these sites, the mean temperature is low: -0.96°C at Pampa La Bola and -2.73°C at Llano de Chajnantor, respectively, during the year 1997. The near-surface temperature drops below 0°C at night throughout the year. The lowest temperature recorded at Llano de Chajnantor during 1997 was -16.1°C. The peak-to-peak difference in the diurnal cycle of the near-surface temperature was typically 15°C on clear days and that in the annual cycle of the near-surface temperature approaches 30°C. The variation of the near-surface temperature is small at night (20h to 6h).

The near-surface temperature is lower at Llano de Chajnantor than at Pampa La Bola by 1.8°C on average as indicated in Figure 8. This general tendency is mostly explained by the 250 m difference in the height between the two sites and the 6.5°C km^{-1} temperature gradient in the vertical temperature profile of the atmosphere. There is a significant inversion of the temperature difference between the two sites (Pampa La Bola becomes colder than Chajnantor) in the summer mornings, reaching as high as -4°C as shown in Figure 8. This is most likely due to an atmospheric temperature inversion (where the temperature increases with altitude) in the summer mornings.

3.4 Solar Radiation

The solar radiation flux reflects the clarity of skies (amount of cloud cover) during the daytime. As shown in the combined diurnal and seasonal variation plots in Figure 9, the sky is mostly clear at both sites except for the afternoon during the summer (January–March). This period corresponds to the Altiplanic Winter, where the direction of the jet stream (and hence the surface winds) has turned around and comes from the east, bringing moist air from the Amazon basin over the sites.

To evaluate the fraction of clear skies from these data, we plot in Figure 10 the combined diurnal and seasonal variation of the ratio of the mean and maximum values of the solar radiation in each 30 min by 15 day bin. This value provides a rough idea of the sky coverage of clouds, provided that each bin contains at least one record reflecting unattenuated solar flux. Note that because of this effect, during long stretches of bad weather, the value estimated for the amount of clear skies will be overestimated (because there is no good "clear skies reference"). As illustrated in Figure 10, the seasonal variation of the fraction of clear skies is larger at Llano de Chajnantor. In particular, the optical sky is significantly clearer at Pampa La Bola during the high-precipitation summer season.

3.5 Surface Relative Humidity and Water Vapor Pressure

The diurnal and seasonal variation of surface relative humidity is summarized in Figure 11. The surface relative humidity is generally below 30% in the daytime — due to the warmer temperatures. The surface relative humidity during summer nights is very high, approaching 100%.

Water vapor pressure is a product of relative humidity and saturated water vapor pressure $p_{\mathrm{w,s}}$, whose value at a temperature T (°C) is approximated by:

$$p_{\mathrm{w,s}} = 6.11 \exp[17.27\, T/(T + 237.3)] \text{ hPa}. \quad (1)$$

The diurnal and seasonal variation of surface water vapor pressure calculated from the mean near-surface temperature and surface relative humidity is shown in Figure 12. There is, as expected, a significant seasonal variation of the surface water vapor pressure. The effects of the Altiplanic Winter during the summer season (January–March) — particularly in 1997 and 1999 — can be seen clearly in this figure. The large-scale effects of the 1997 El Niño are visible during August–September of 1997, as earlier reported [4]. On the contrary, the diurnal variation of the surface water vapor pressure is generally not very large. One noteworthy thing is that the water vapor pressure becomes slightly higher in the last half of the day, possibly reflecting the location of the inversion layer. The median of the surface water vapor pressure during 1997 was 1.6 hPa at Pampa La Bola and 1.8 hPa at Llano de Chajnantor. The histogram of the surface water vapor pressure is double-peaked near 0.7 hPa and 1.4 hPa, with marginally higher values at Llano de Chajnantor, as shown in Figure 13. Note that for an exponential distribution of water vapor in the atmosphere with a scale height of 1.5 km, the surface water vapor pressure in hPa is approximately equal to the total atmospheric precipitable water vapor in mm [5].

The fact that the median surface water vapor pressure is lower at Pampa La Bola would then seem to indicate that there is less total water in the atmospheric column above that site. We know from other measurements that this is not the case, however. Note that we also always measure a rather steep drop-off in the water vapor pressure with height during radiosonde experiments from Llano de Chajnantor (with a scale height of close to 1.5 km). This implies that the surface water vapor pressure is dominated by local and ground effects, and total atmospheric precipitable water vapor may not decrease so dramatically as a function of surface altitude as we might expect from the radiosonde measurements. Note that a similar effect was also reported at Rio Frio using the same instruments [6].

We thank all of the other members of the LMSA site testing team who jointly established and maintained the weather stations and collected the data in Chile with us.

References

[1] Nakai, N., Handa, K., Kato, T., Otárola, A., Bronfman, L., & Vallada, G. 1995, “Measurement of Meteorological Data in Northern Chile (August – October 1994),” LMSA Memo 1995-001

[2] Radford, S. J. E. 2000, “Refined Position of ALMA Equipment on Chajnantor,” ALMA Memo 312

[3] NRAO 1999, “Topographical Map of CONICYT Science Preserve”

[4] Otárola, A., Delgado, G., Booth, R., Belitsky, V., Urbain, D., Radford, S., Hofstadt, D., Nyman, L., Shaver, P., & Hills, R. 1998, “European Site Testing at Chajnantor: A Step Towards The Large Southern Array,” ESO Messenger 94, 13

[5] Butler, B. 1998, "Precipitable Water at KP – 1993-1998," ALMA Memo 238

[6] Holdaway, M. A., Ishiguro, M., Nakai, N., & Matsushita, S. 1996, "Correlation Between Opacity and Surface Water Vapor Pressure Measurements at Rio Frio," NROTR 52 (also ALMA Memo 158)

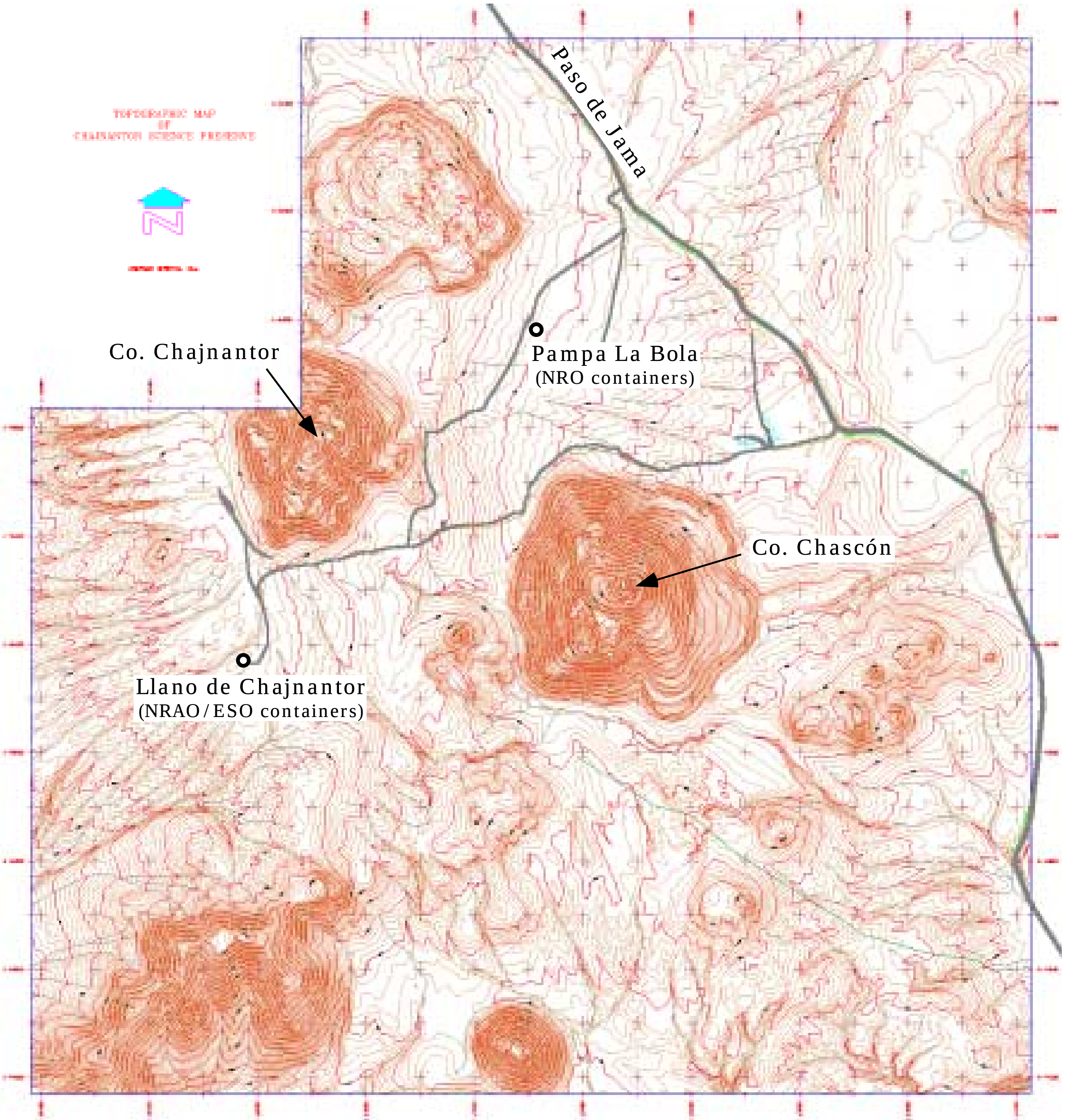

Figure 1: Location of the weather stations overlaid on the topographic map of the Cerro Chascón science preserve area [3]. Ticks are spaced by 1 km. Contour spacing is 10 m with thick contours every 50 m. The international highway (Paso de Jama) and some of the unpaved roads are marked with thick grey lines. The volcanic peak in the middle of this area is Cerro Chascón. Cerro Chajnantor is to the WNW of Cerro Chascón, and Cerro Toco is just above Cerro Chajnantor.

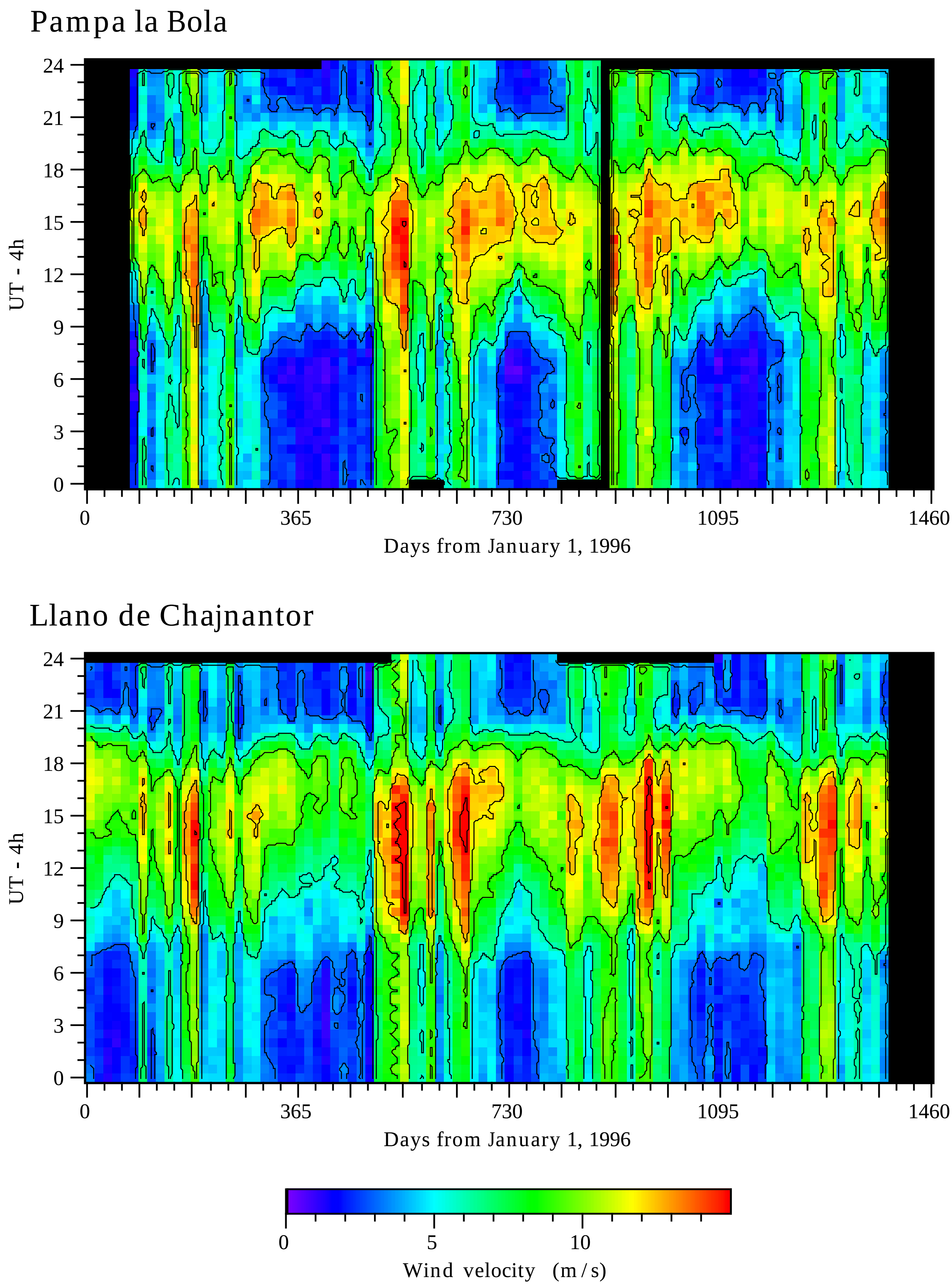

Figure 2: Combined diurnal and seasonal variation plots of wind velocity Contour interval is 3 m s^{-1} starting from 3 m s^{-1}.

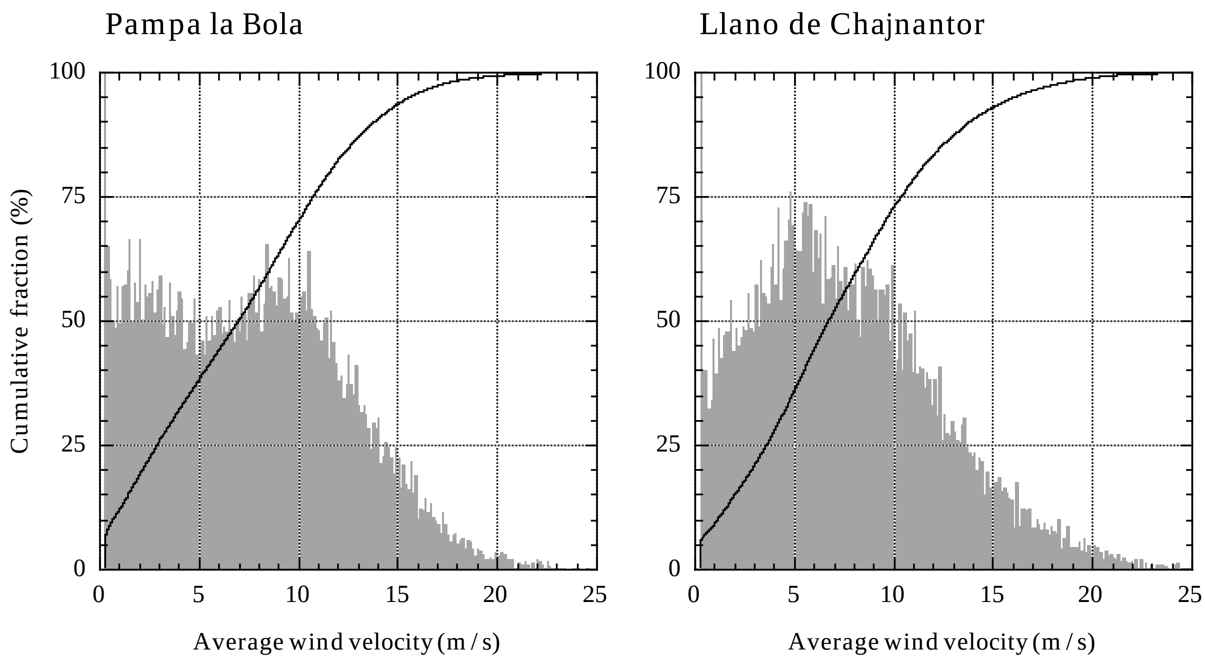

Figure 3: Cumulative distribution of wind velocity (1 min average) at Pampa La Bola and Llano de Chajnantor observed during 1997, overlaid on the corresponding histogram of wind velocity in arbitrary units. Note that wind velocities below 2 m s^{-1} are not accurately measured by the anemometer.

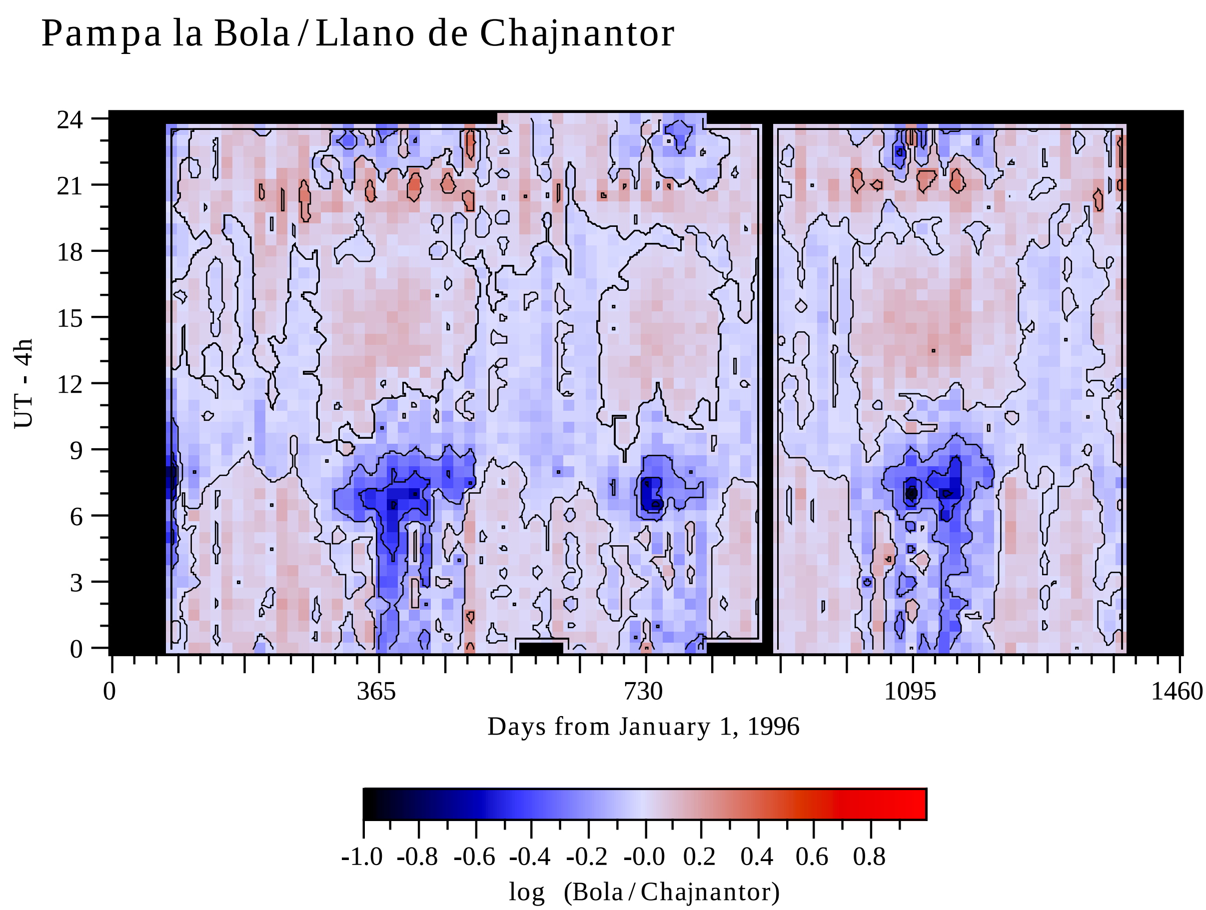

Figure 4: Combined diurnal and seasonal plots of the difference in wind velocity between the Pampa La Bola and Llano de Chajnantor sites. Contour interval is 0.2 dex starting from −0.4 dex.

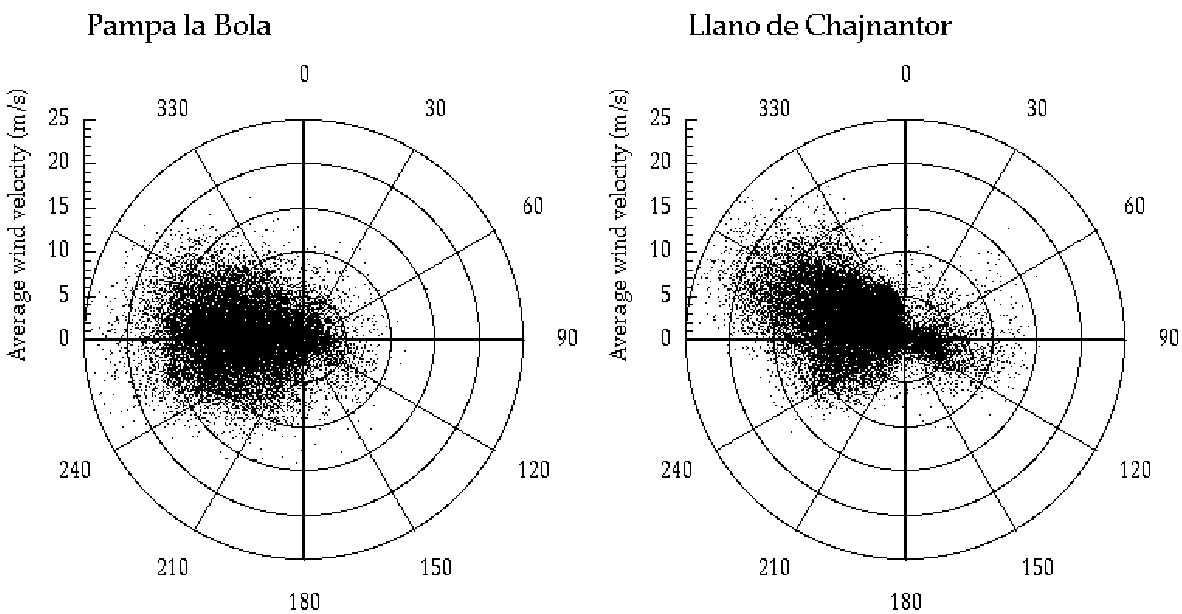

Figure 5: Wind direction and velocity observed at Pampa La Bola and Llano de Chajnantor during 1997. Note that the absolute values of wind direction may include systematic offsets of up to 10 deg due to an uncertainty in the absolute direction setting.

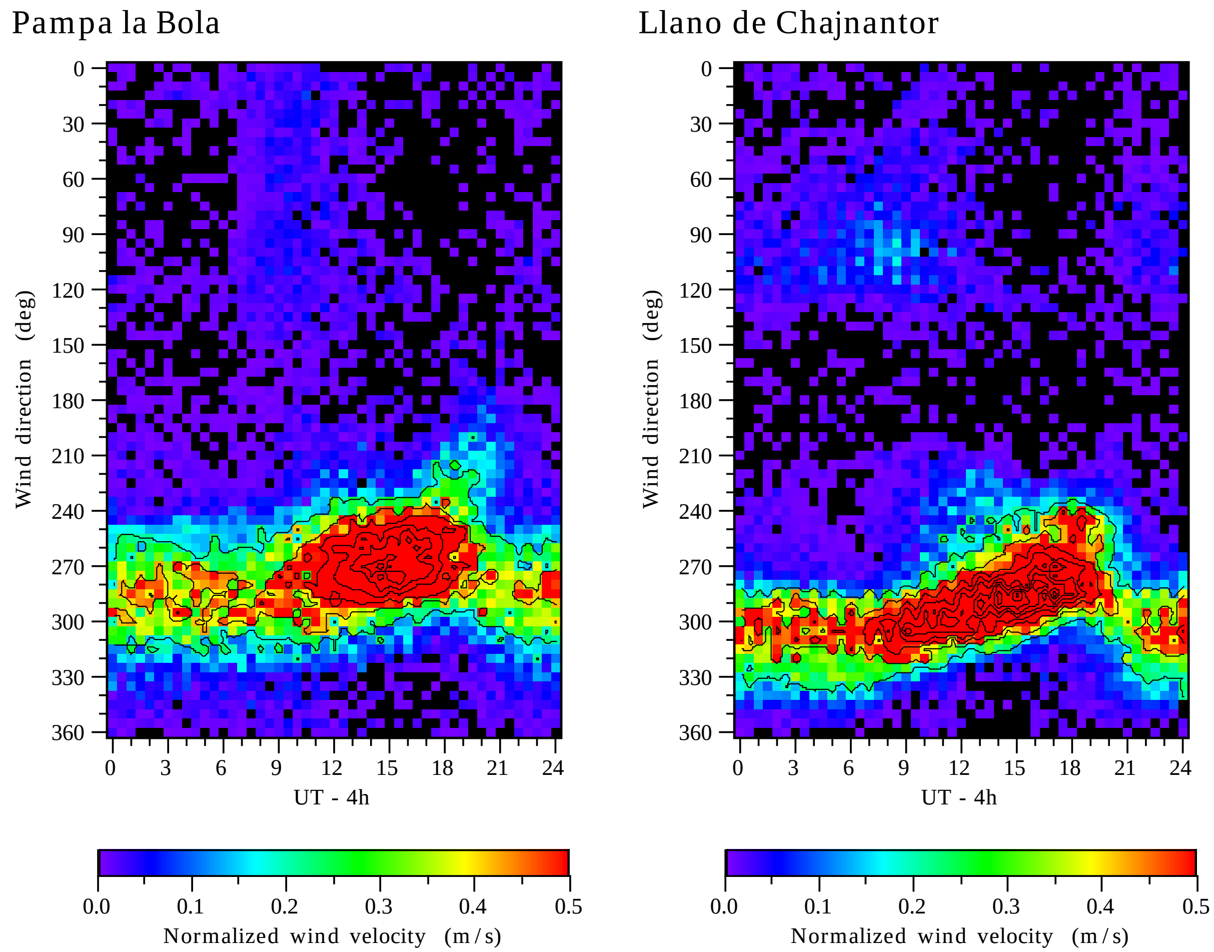

Figure 6: Diurnal variation of wind direction at Pampa La Bola and Llano de Chajnantor. Note that the absolute values of wind direction may include systematic offsets of up to 10 deg due to an uncertainty in the absolute direction setting.

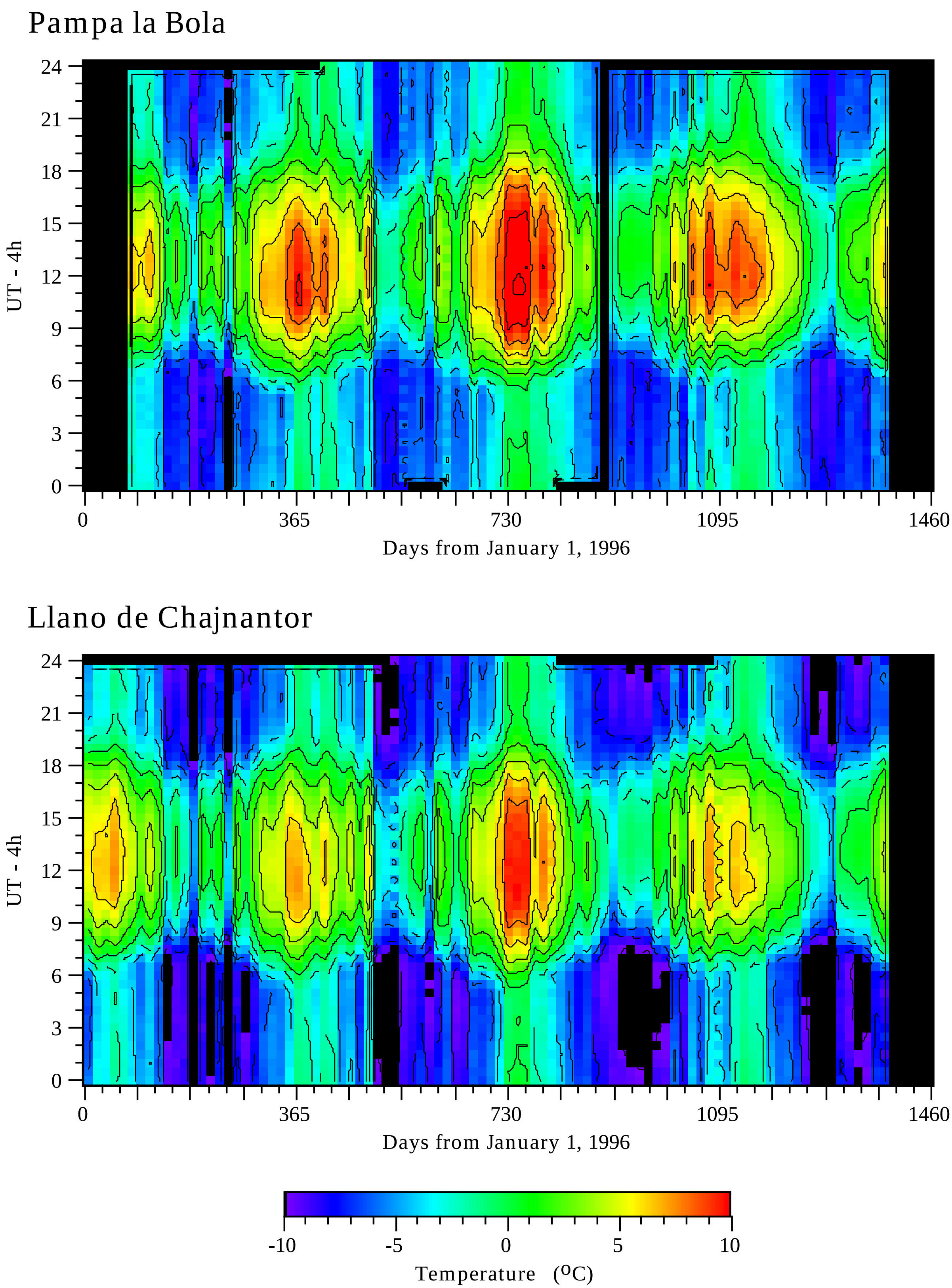

Figure 7: Combined diurnal and seasonal variation plots of near-surface temperature. Contour interval is 2°C starting from −10°C. Negative contours are dashed.

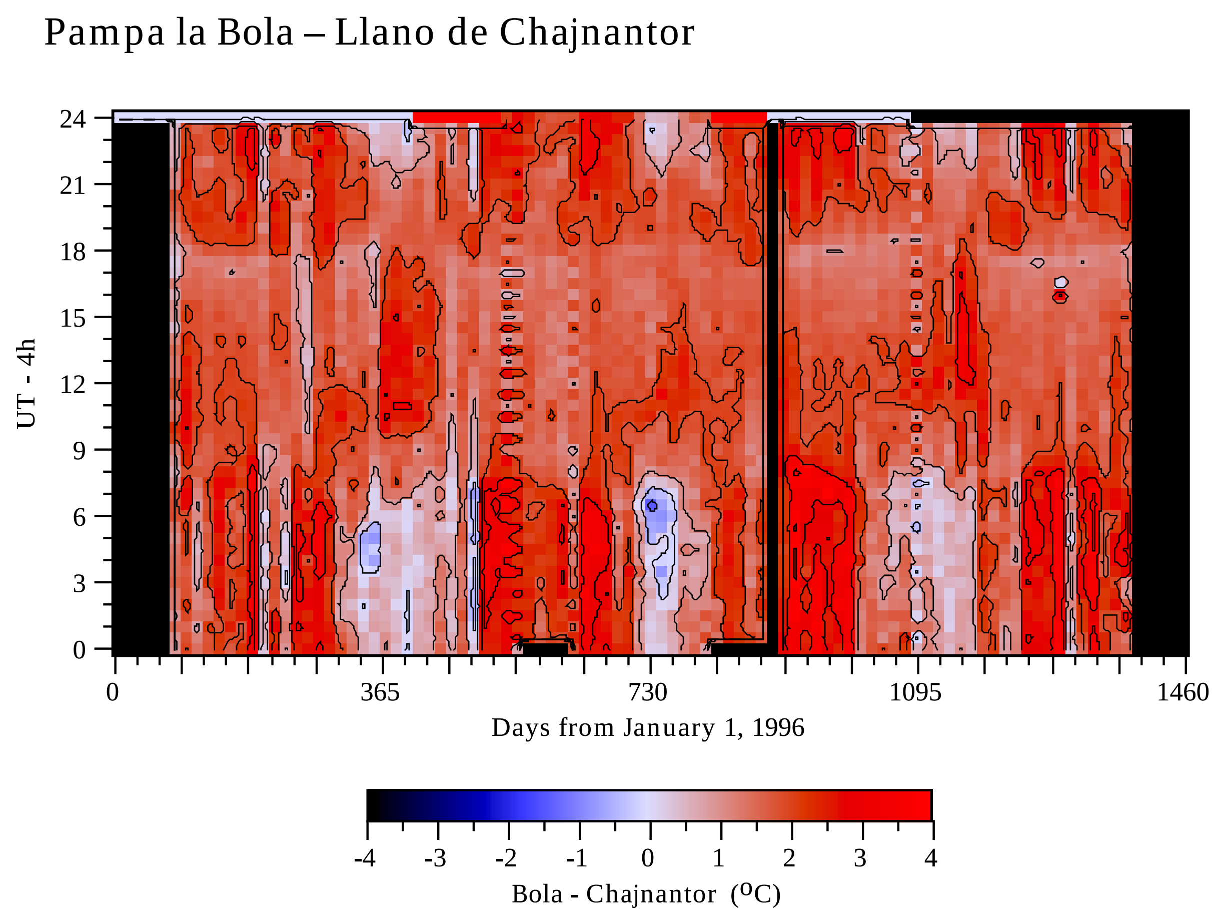

Figure 8: Combined diurnal and seasonal plots of the difference in near-surface temperature between the Pampa La Bola and Llano de Chajnantor sites. Contour interval is 1°C starting from −1°C.

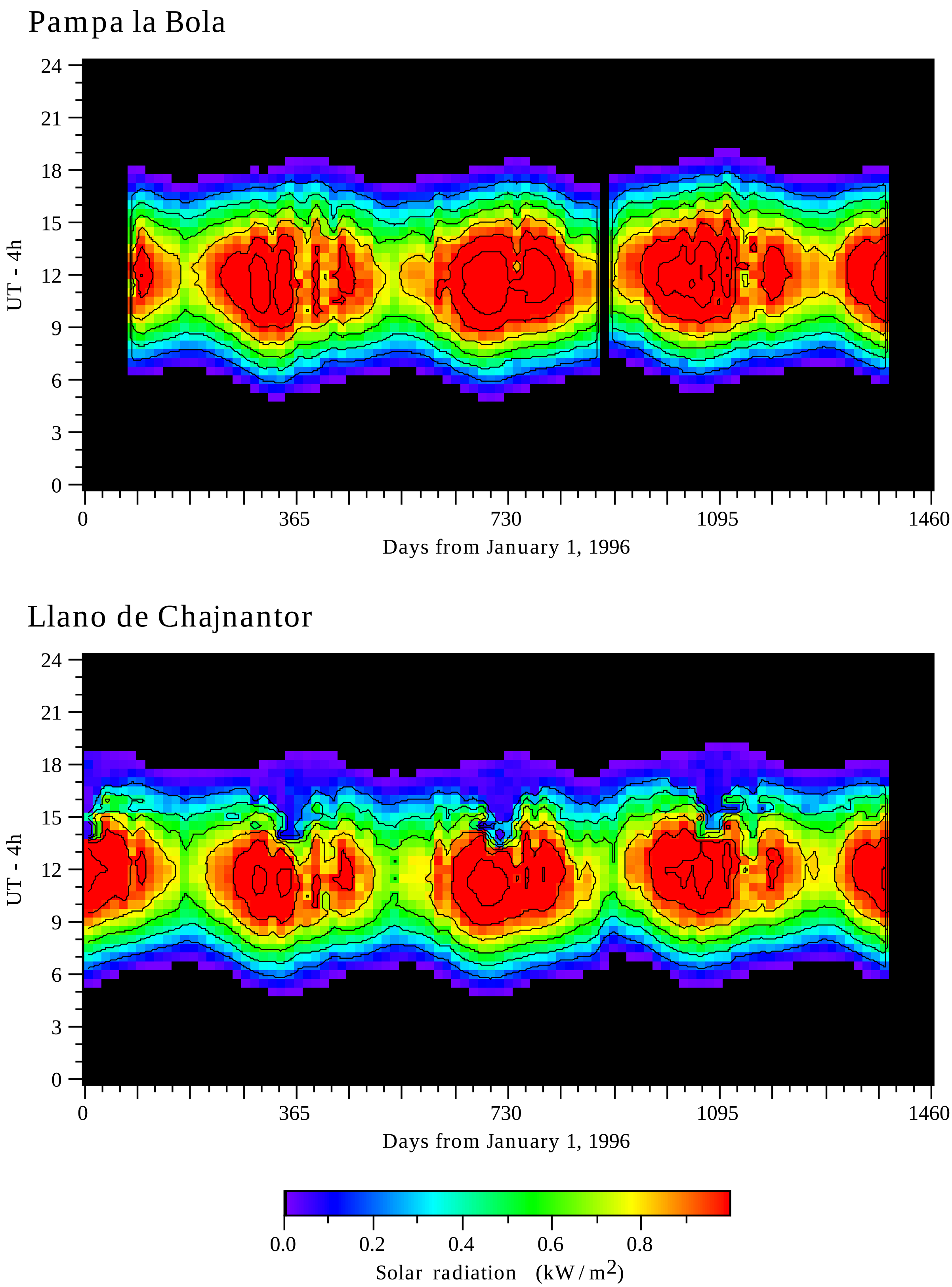

Figure 9: Combined diurnal and seasonal variation plots of solar radiation. Contour interval is 0.2 kW m^{-2} starting from 0.2 kW m^{-2}. There has been no correction for incidence angle effects. V-shaped features with their roots near 14h in December, seen in the diagram for Llano de Chajnantor, are artifacts.

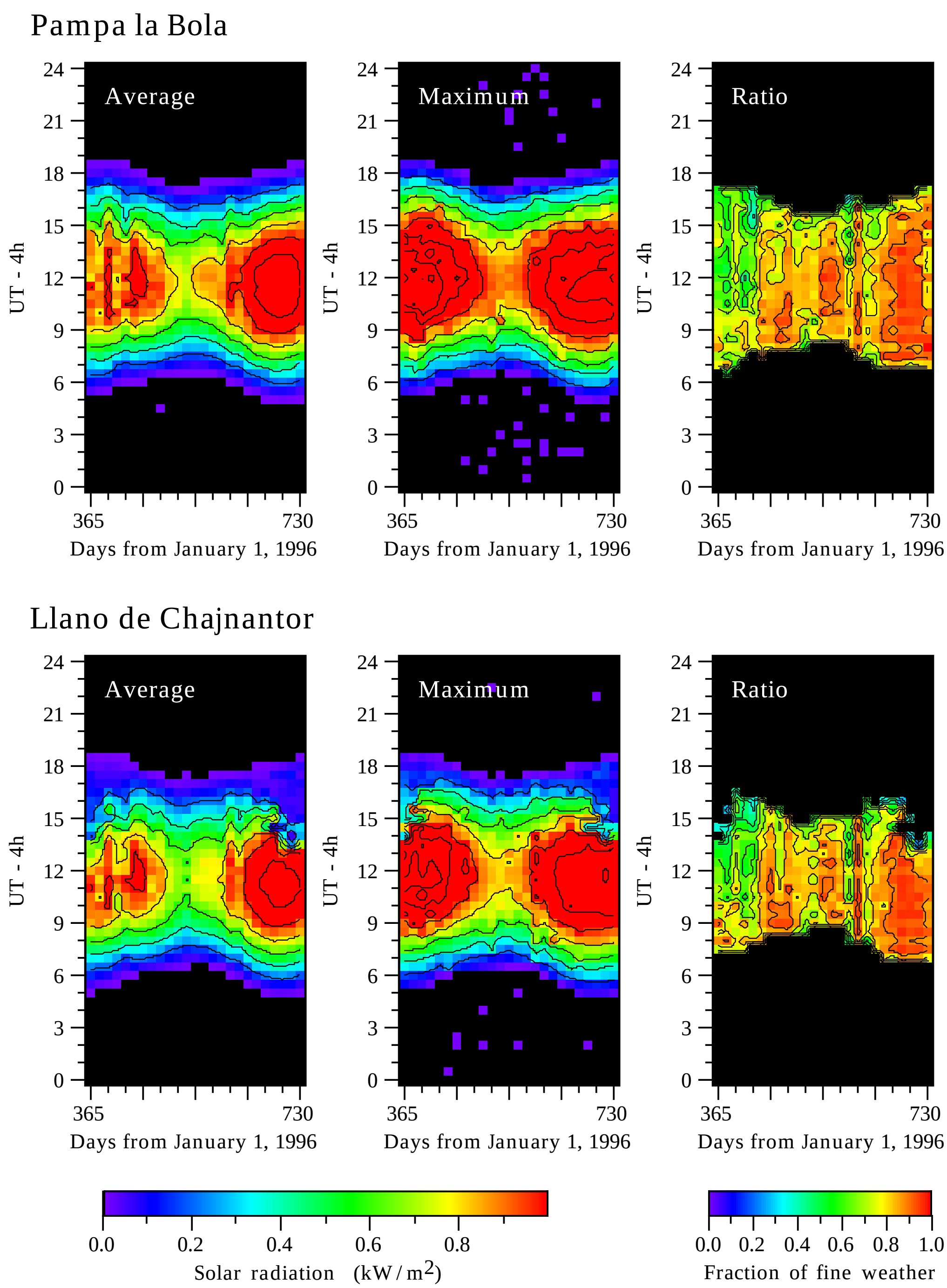

Figure 10: (*a*: *left*) Combined diurnal and seasonal variation plots of the mean value of the solar radiation during 1997. Contour interval is 0.2 kW m^{-2} starting from 0.2 kW m^{-2}. There has been no correction for incidence angle effects. V-shaped features with their roots near 14h in December, seen in the diagram for Llano de Chajnantor, are artifacts. (*b*: *middle*) Same as (*a*) but for the maximum value of the solar radiation in each 30-min by 15-day bin. (*c*: *right*) Combined diurnal and seasonal variation plots of the fraction of clear skies estimated from the ratio of the mean and maximum values of the solar radiation in each 30-min by 15-day bin. Those data in each bin with their maximum solar radiation flux less than 0.2 kW m^{-2} were clipped. Contour interval is 0.1 starting from 0.1. Note that there was an El Niño during August–September of 1997 and the weather was significantly worse than average year during this period.

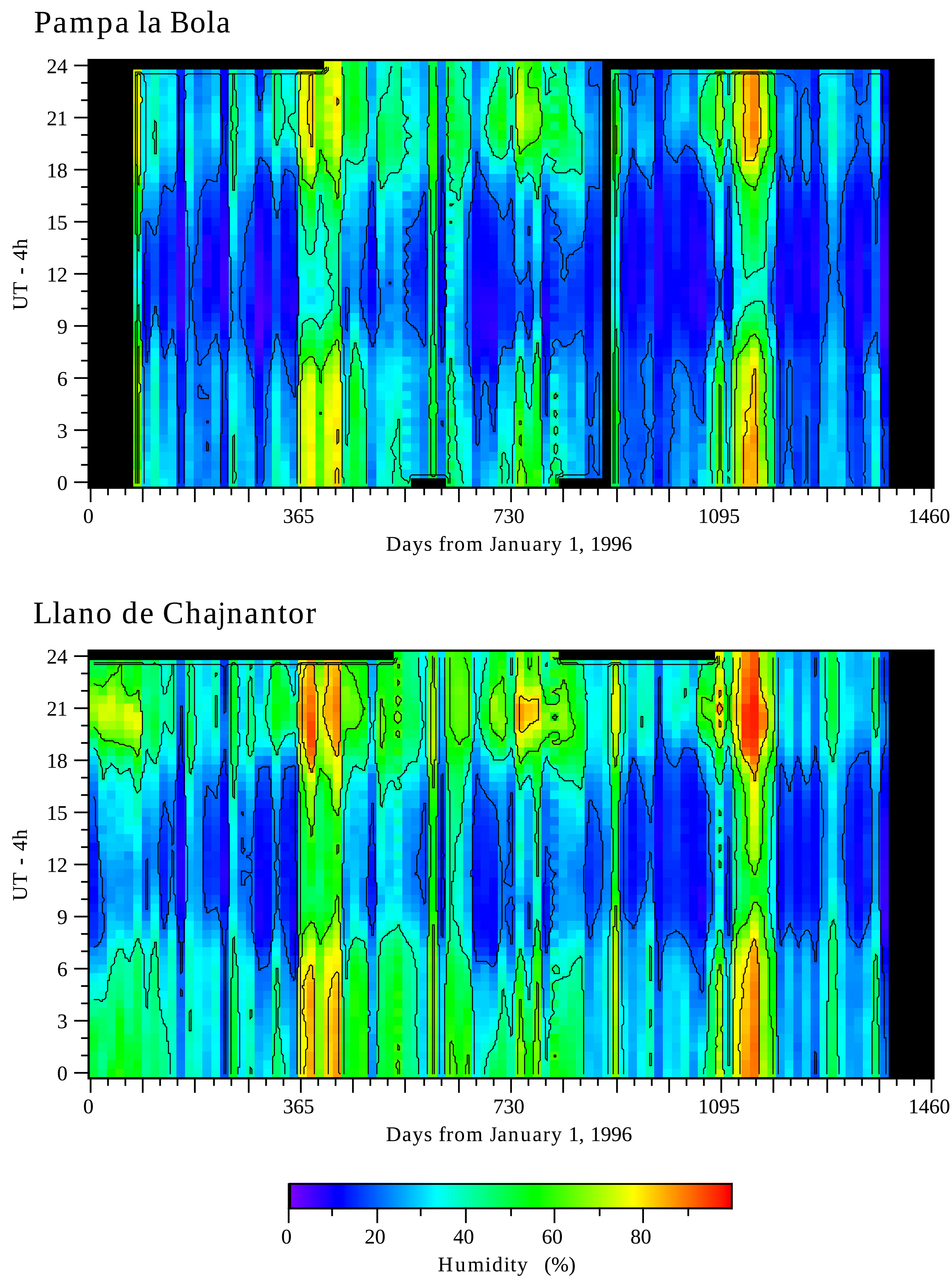

Figure 11: Combined diurnal and seasonal variation plots of surface relative humidity. Contour interval is 20% starting from 20%.

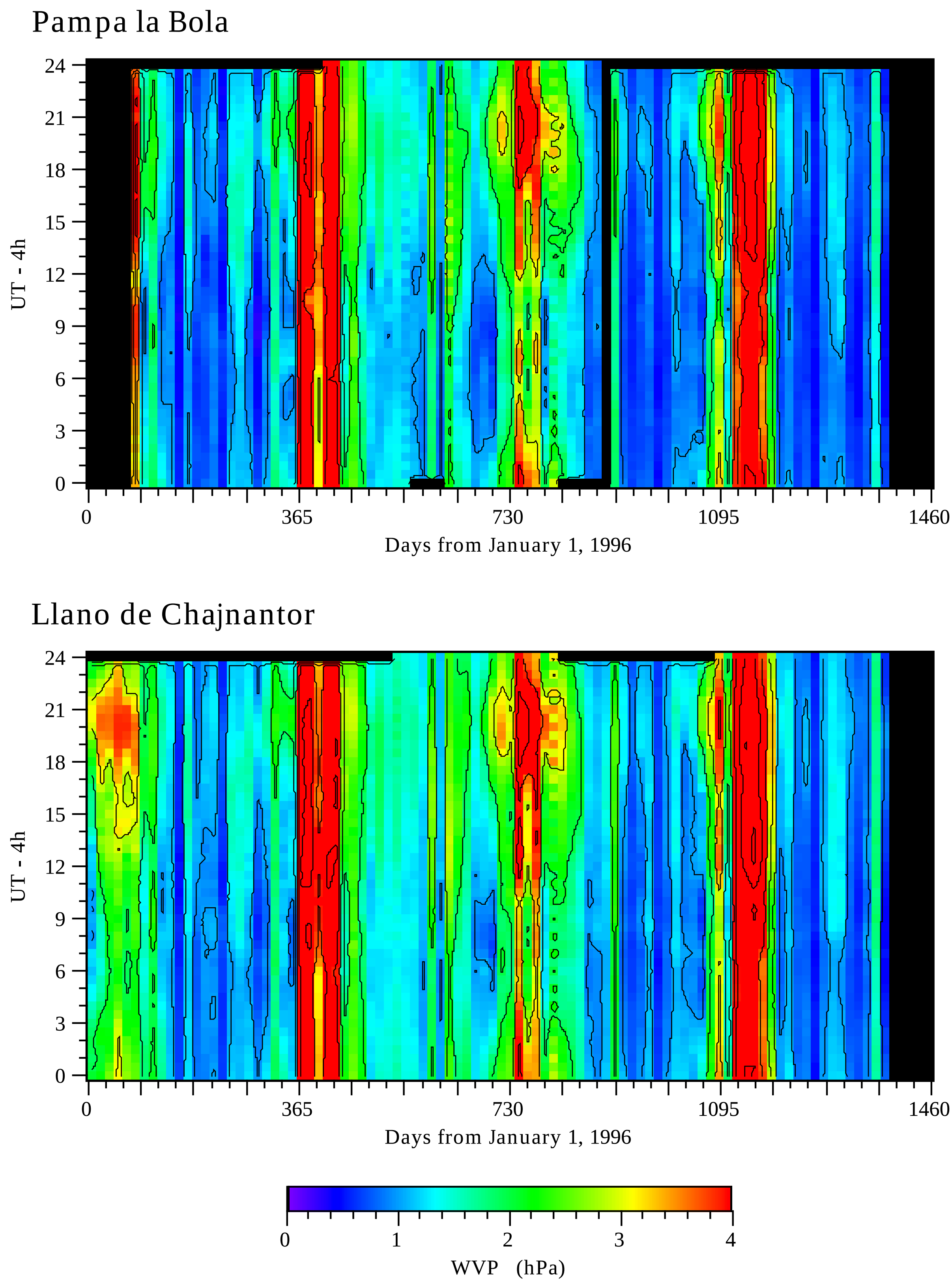

Figure 12: Combined diurnal and seasonal variation plots of surface water vapor pressure calculated from mean near-surface temperature and surface relative humidity. Contour interval is 1 hPa starting from 1 hPa.

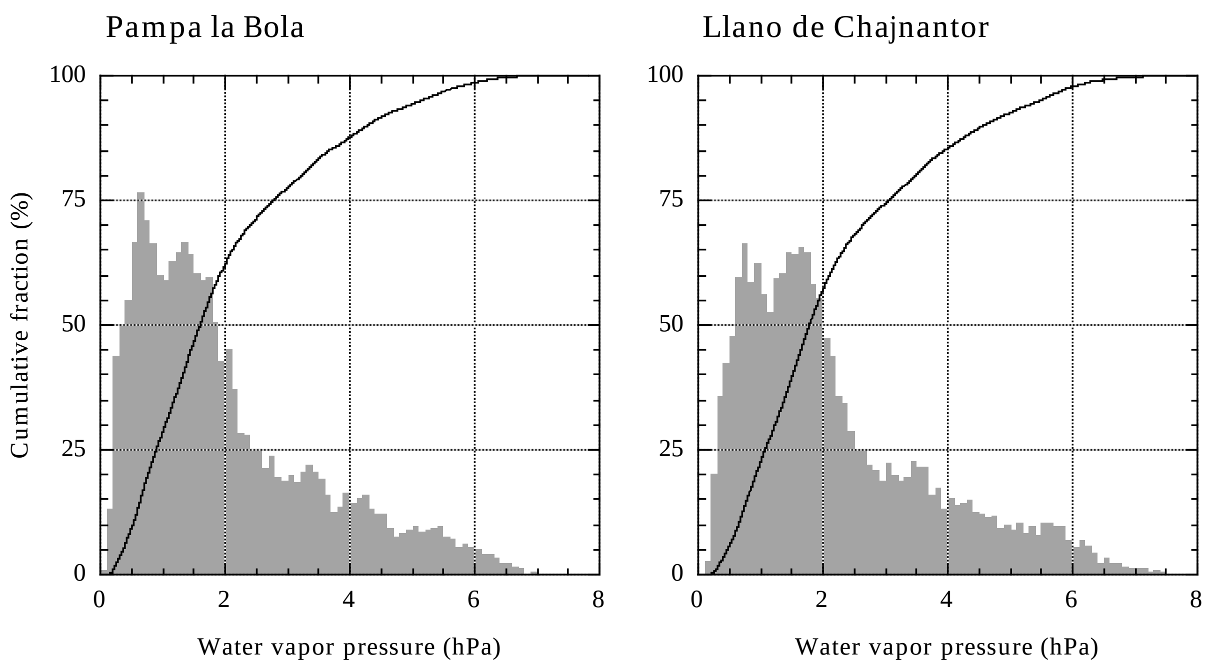

Figure 13: Cumulative distribution of surface water vapor pressure at Pampa La Bola and Llano de Chajnantor observed during 1997, overlaid on the corresponding histogram of surface water vapor pressure in arbitrary units.