3.5 MOUNTAIN-VALLEY FLOW OBSERVATIONS WITH A BOUNDARY LAYER WIND PROFILER

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1. INTRODUCTION

For over 4 years, a boundary layer wind profiler and surface anemometer have collected measurements in Juneau, Alaska's Lemon Creek Valley. While synoptic flow and wind storms around Juneau have been described by Colman, (1986), Dierking (1998), and Colman and Dierking (1992), thermally driven flows have received less attention. Recent statistical analysis of the 4 years of anemometer wind directions has revealed daytime up-valley flow, nocturnal down-valley flow, and also a daytime cross-valley flow (Cohn 2004), all of which vary with season. These flows are expected based on the daytime solar forcing and nighttime radiative cooling of the surface.

In this paper, we extend these observations in altitude using wind profiler measurements. The wind profiler, using advanced signal processing to function in a mountain (high-clutter) environment, shows direct thermally forced flows up to about 500 m, and reveals a return flow aloft. There are a few observations of return flow in the literature, and where available they are generally made using pibals. The continuous, long-term monitoring by a wind profiler clearly shows the return flow, and provides many examples for further study. This is an example of value wind profiler observations add to mountain observations.

2. BACKGROUND AND DATA SUMMARY

The Lemon Creek valley of Juneau, Alaska is relatively small, on the order of 10 km long and 3 km wide with steep walls rising to about 1 km. Figure 1 shows the terrain of this valley with the 2000 foot and 3000 foot contours highlighted. The up-valley axis is toward approximately 50 degrees (true), with a branch of the Taku glacier to the west of the valley and its east end opening into the Gastineau Channel. Juneau's latitude is 58 degrees so there are large seasonal variations as the amount of solar heating changes. The noontime solar elevation angle varies from 55 degrees at the summer solstice to only 9 degrees at the winter solstice, and the length of day also varies from about 18.5 hours (dawn to dusk) to only 6.7 hours. Figure 2 shows a photo of the Lemon Creek valley taken from the Juneau airport. The ridge on the left is the head of Heintzleman Ridge on the north side of the valley, and the ridge on the right is the valley's south wall formed by Blackerby Ridge.

The data set used is a subset of that described in Cohn (2004). An R. M. Young propeller-vane anemometer and a Vaisala, Inc. boundary layer radar wind profiler were located at the site marked "*" in figure 1. Anemometer data are collected with 1-s resolution, processed to remove outliers, and averaged to 1-min values. The wind profiler is a 915-MHz nine-panel phase array profiler similar to the four-panel system described in Carter et al. (1995). It collects measurements in 5 beam directions with 60-m range resolution. These data are processed with the NCAR NIMA-NWCA software whose algorithm and performance are described in Morse et al. (2002), Goodrich et al. (2002) and Cohn et al. (2001).

3. DIURNAL FLOW AT 10-m

The Lemon Creek anemometer wind direction probability density function (PDF) and histogram of wind speed and direction occurrence are shown in Fig. 3. Note that the histogram uses a nonlinear color scale to emphasize smaller values. As described in Cohn (2004), there are three flow modes. A mode centered from 50 degrees is consistent with down-valley drainage flow but also with gap flow into the Lemon Creek valley. Gap flow (and a more severe flow known as the Taku) is known to occur in other valleys along the Gastineau Channel. A mode centered at 150 degrees is consistent with southeast flow in the Gastineau Channel turning slightly into the valley, and a mode near 250 degrees is consistent with both up-valley flow and on-shore synoptic flow. To investigate the relative importance of forcing by thermally driven diurnal flow and by synoptically driven flow with no diurnal component, we examine the occurrence of each wind direction (in 5 degree increments) as a function of local time (in 1-hr increments). Examples of this are shown in Fig. 4. Typically about 25000 1-min measurements were available for creating these distributions, P(t), which were then normalized. This plot shows a nocturnal signal within the 50-degree mode, and a daytime flow from the 250 degree mode. The diurnal nature of the 150-dgree mode varies. There is essentially no diurnal signal at its SE edge (130 degrees) but diurnal flow forced by solar heating from the SSE edge (160 degrees),

To quantify the diurnal flow we fit a truncated sine function plus constant

$$P(t) = A\sin\left[2\pi\left(t+\varphi\right)/24\right]+K \quad \text{if } P(t) > C;$$

$$\text{else } P(t) = K \tag{1}$$

to the measured PDF, where t and ϕ are in hours. This fit is overplotted in red in figure 4. We fit for the four quantities A, ϕ, C, and K. The truncation (using only the segment of the sine curve above C) mimics the solar thermal forcing, which is sinusoidal during

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the day and zero at night, and has the effect of varying the duration of the sine. This function also fits the distributions of nighttime flows if negative amplitudes are allowed. The strength of the diurnal signal (diurnal fraction) can be represented by the fraction of the fit curve above K, and the phase of the maximum diurnal signal is ϕ. The diurnal fraction and phase for all wind directions are shown in figure 5. The apparent outliers in diurnal fraction between 5-30 degrees are due to the crude fit routine not fully converging. This plot confirms the nature of the dominant flow modes. The phase shows remarkable consistency with the earliest down slope flow centered around midnight from the north, and broadening to include NE, NW, and even easterly flow as the night progresses. Note that the indicated phase for a given direction is near the peak of the PDF but the PDF widths indicate that flow from that direction is also seen several hours earlier and later. Based on the occurrence distribution, most of the down-valley winds are in the 60-degree mode, aligned with the valley and with a maximum occurrence near 3 am. By contrast, the upslope flow occurs between about 135-270 degrees, and between 11-17 LT (although some signal is seen several hours before and after these times). These winds encompass the southern part of the 135-degree mode and the 225-degree mode. We identify the first as a cross-valley flow caused by solar heating of the south face of Heintzleman Ridge while the north face of Blackerby Ridge is shadowed, and the second as the valley aligned up-valley mode. These results essentially show the presence of drainage flow from all directions where there is high terrain (from about 290 degrees clockwise through 120 degrees) and upslope flow from the remaining sector (135-270 degrees) with small transitions between.

Additional notes on this analysis are (1) that the fitting process does not allow for a PDF with simultaneous daytime and nighttime diurnal signals that may be important in the transition regions. However, there are very few winds from the transition directions; and (2) these results combine anemometer winds from all seasons, and it has already been pointed out that the solar forcing varies greatly during the year. A brief seasonal analysis will be presented in section 5.

4. DIURNAL FLOW ALOFT: RETURN FLOW

The wind profiler measurements at each altitude have been analyzed in the same way as the anemometer time series. Direction PDF and speed-direction occurrence histograms appear in figure 6 for selected 300-m thick layers. The wind profiler reliably shows modes similar to those seen with the anemometer, and changing in a continuous way with height. The histograms show reduced occurrence of profiler winds below 1-2 m s^{-1}, which is a known bias of the NIMA software. However, figure 6 gives us confidence that the profiler accurately measures winds within the mountain environment.

Figure 7 shows the diurnal fraction and phase ϕ of the diurnally resolved histograms of wind profiler time series. Again the resolution used was 1-hr by 5 degrees, and for this figure the full profiler resolution (60 m) was used rather than grouping into 300 m layers. In the phase plot bins with diurnal amplitude less than 0.15 are omitted. Below 500 m the diurnal amplitude shows two modes. A strong, compact mode has a diurnal cycle in winds from 240 degrees, and a second, broader mode has winds from a range around 40 degrees (occurrences between 310 and 55 degrees). These are consistent with the valley aligned modes seen in the anemometer data. The phase of the upslope (first) mode is centered in the early to mid-afternoon, and the down slope (second) mode is centered from just before midnight through about 4 am. As with the anemometer analysis, the corresponding PDF show significant occurrence for several hours before and after the central time. The wind profiler statistics show that these flows occur up to about 500 m.

Further examining the phase, it appears that the up valley flow below 500 m has an analog with similar phase above 800 m and from the north. Similarly the down valley flow from the northeast around midnight has an analogous flow from the northwest just before midnight. The times and directions of these analogs suggest they are a form of return flow. In larger valleys a closed circulation has sometimes been measured (typically using pibals) with flow aloft opposing the surface up valley or down valley flows. This upper level flow has been called the return flow (e.g. Whiteman 2000). The Lemon Creek valley is relatively small and the nearby valleys, ridges, and glaciers will lead to complex circulations. Although the directions of the observed flow aloft are not directly opposite the surface flow, their phase and diurnal nature strongly suggest they have a role as a compensating flow to the surface circulations.

5. SEASONAL EFFECTS

In section 3 it was noted that seasonal differences in forcing can be large in Juneau. In figure 8 we present the diurnal fraction and phase of anemometer results for each month. The same direction modes are seen (up valley from 225 degrees, cross valley flow from 135 degrees, and down valley flow from a broad range of directions centered around 50 degrees), but the seasonal dependence is also clear. There is no diurnal component during Nov-Feb. The strongest diurnal flows are in June (the month of the summer solstice) with daytime flows also quite strong in May and nighttime flow quite strong in July. Both are present and fairly strong from April through August.

6. RETURN FLOW CASE

In figure 9 we present a single day observation of return flow for June 7, 1999. There are many similar days in the 4-year data set. In this figure, the wind vector is plotted with 15-min time resolution and 60-m altitude resolution. As a guide, vectors have been colored based on their quadrant, with winds from 0-90 degrees colored cyan; 90-180 blue; 180-270 red; and 270-360 green. The daytime up-valley flow is seen as the predominantly red vectors beginning at low altitudes around 9 LT, building to about 450 m, and continuing through about 16 LT. The yellow vectors aloft indicate the corresponding return flow during the same time period. This NE return flow is embedded in a prevalent NW flow. Similarly the down valley flow begins at low levels in the evening at 19 LT as indicated by the yellow vectors growing to 500 m by 22 LT, at which time a synoptic disturbance with SE flow intrudes into the valley.

7. DISCUSSION

Diurnal flows within Juneau's Lemon Creek valley show up clearly in the 4-year time series of both an anemometer and wind profiler measurements. The wind profiler shows the valley aligned flows persist to about 500 m above the surface. The wind profiler data also show evidence of a compensating return flow aloft. This analysis has been primarily statistical, based on distributions of wind occurrence over 4 years. While we have shown one example of these flows in a daily wind pattern, the data set is richly populated with similar examples. Further study of these individual days may show a pattern of growth and decay of the low level flow and also of the return flow.

A significant result from this analysis is simply that boundary layer wind profilers work well in a mountainous environment and can be used to document and study flow patterns above a valley floor. We attribute this at least in part to improved software to reject ground clutter (in this case the NIMA/NWCA software). Winds available from profilers are more frequent and of longer duration than pibal winds, and are not affected by clouds or darkness.

Areas for further investigation include an examination of the temporal evolution of the diurnal flow and return flow with altitude; exploration of seasonal differences in this evolution; and consideration of the role of the glacier (permanent ice surface) to the west of the valley in providing cool air for nocturnal flow;

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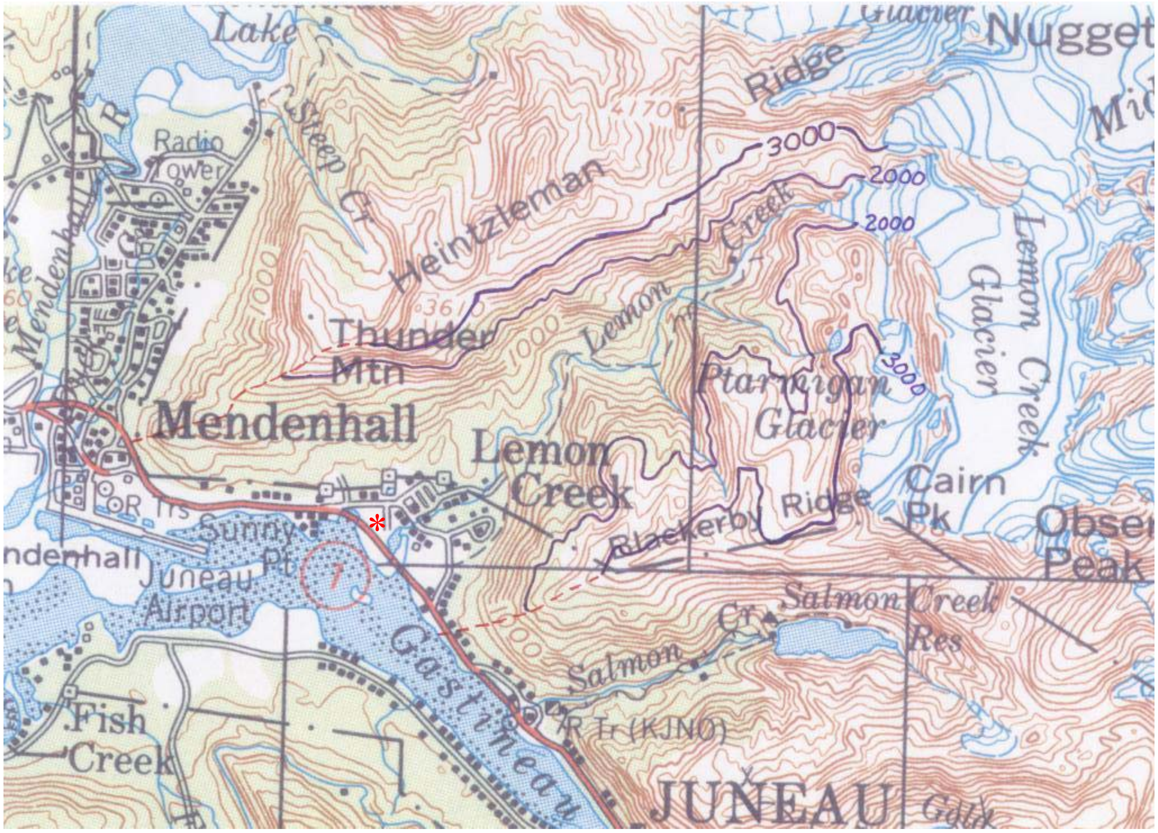

Figure 1: Map of the Lemon Creek Valley. The 2000' and 3000' contours (blue), and the extended ridgeline (red dash) have been highlighted. The wind profiler and anemometer location is at the *

Figure 2: The Lemon Creek Valley viewed from the Juneau International Airport looking to the east.

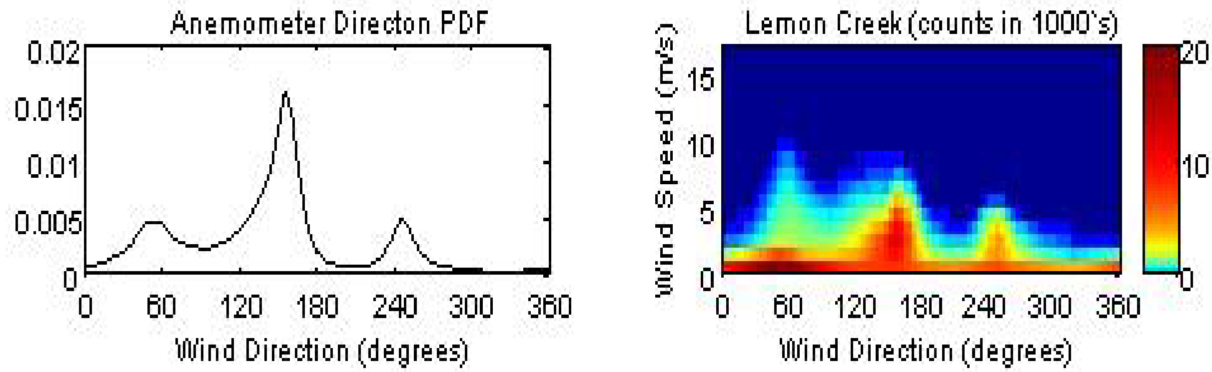

Figure 3: Wind direction probability density function (left) and wind rose histogram (right) for the Lemon Creek anemometer. The color scale emphasizes smaller values and represents number of occurrences in thousands.

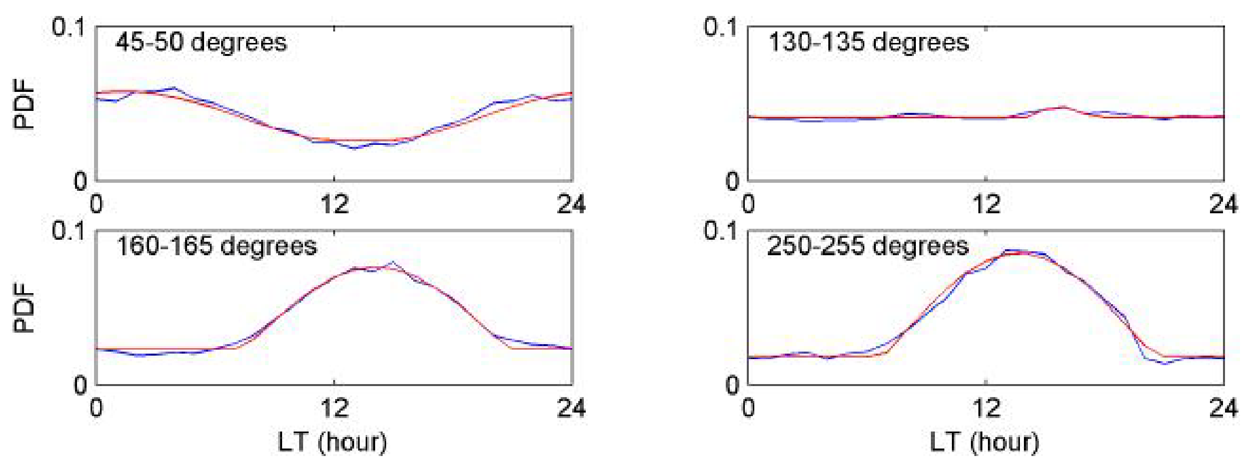

Figure 4: Diurnal variation of wind direction occurrence (normalized) from four 5-degree intervals: (a) 45-50 deg.; (b) 135-140 deg; (c) 160-165 deg; (d) 250-255 deg. A fit curve of the form (1) is in red.

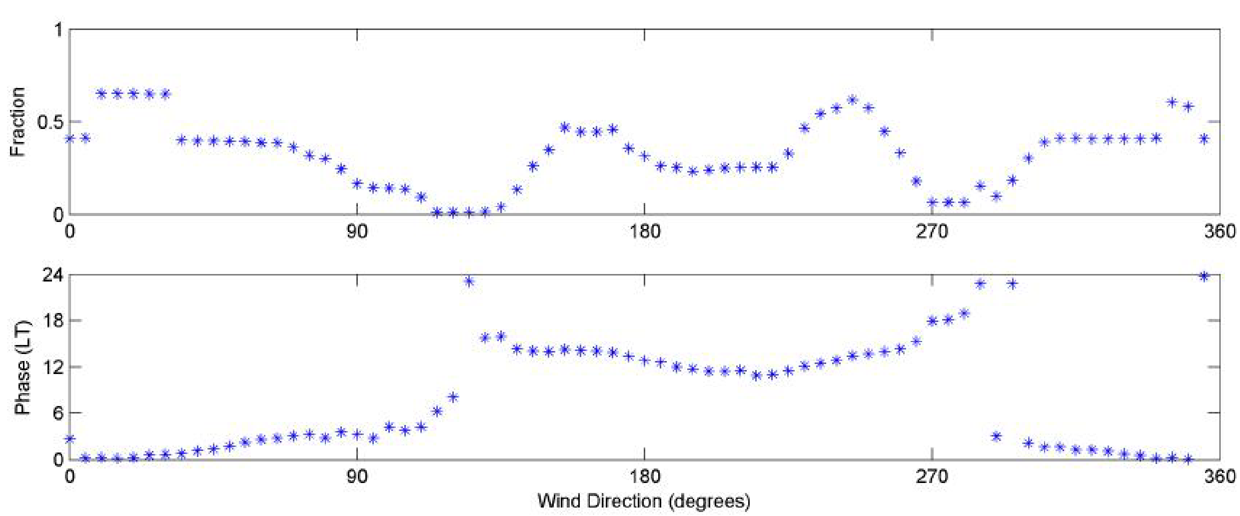

Figure 5: Diurnal fraction and phase of fits to each anemometer PDF as a function of wind direction.

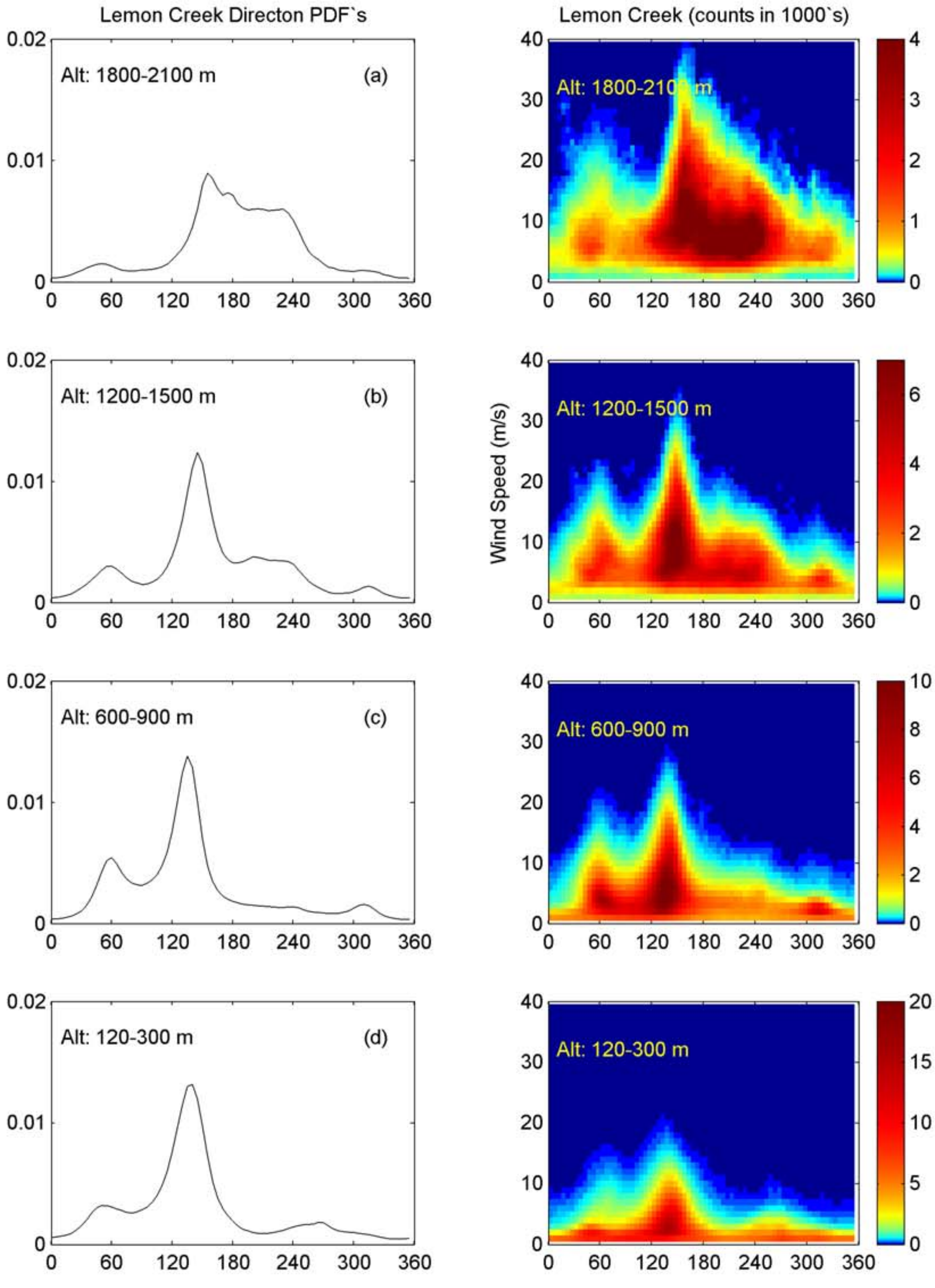

Figure 6: Wind direction probability density functions (left) and wind rose histograms (right) for four altitude ranges from the wind profiler at Lemon Creek. The nonlinear wind rose color axis represents number of occurrences in thousands. Following the meteorological convention, wind directions are clockwise from true north.

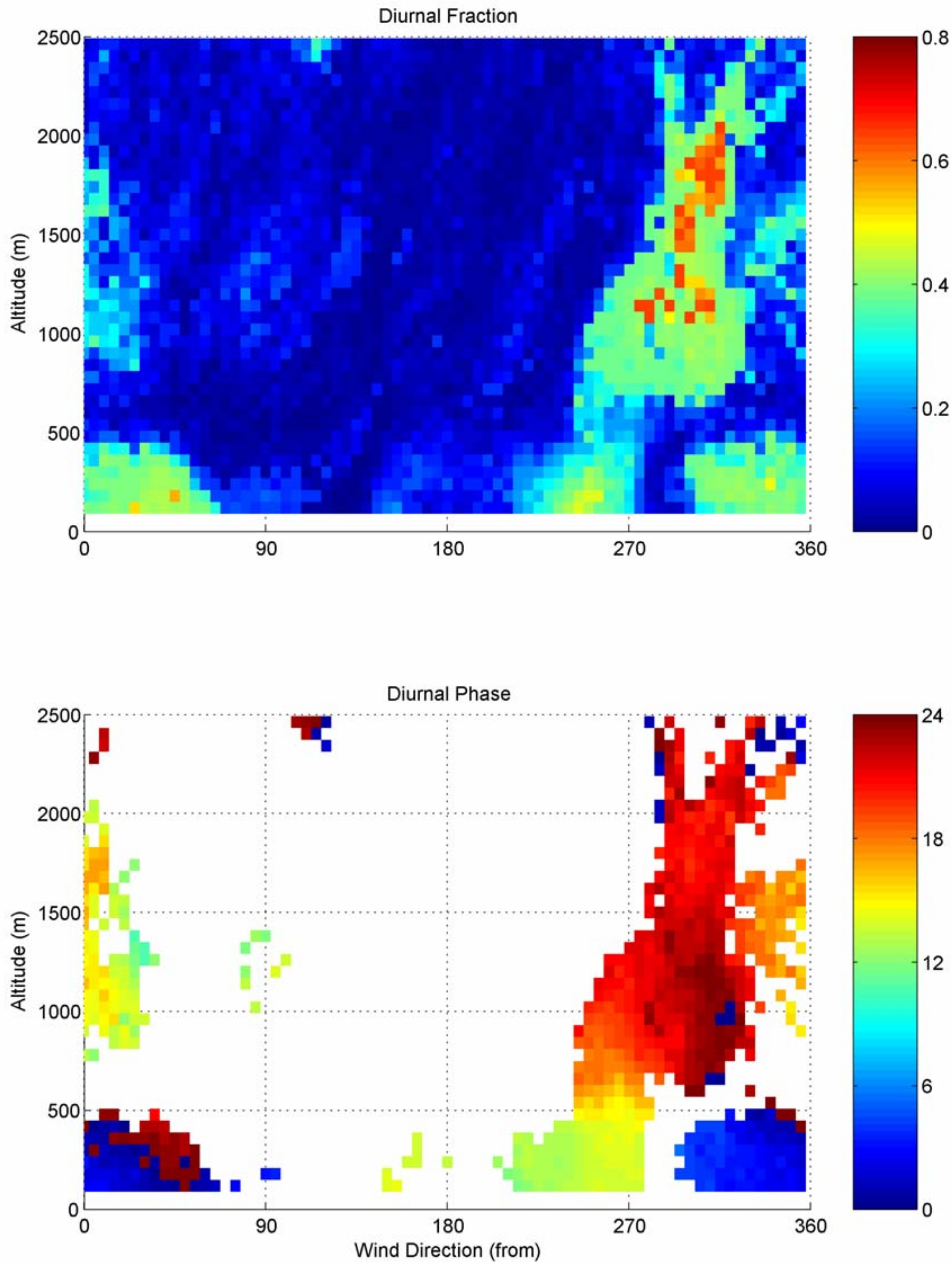

Figure 7: Diurnal fraction (top) and phase (bottom; local time, hours) of the fit to the Lemon Creek profiler PDF as a function of wind direction and altitude.

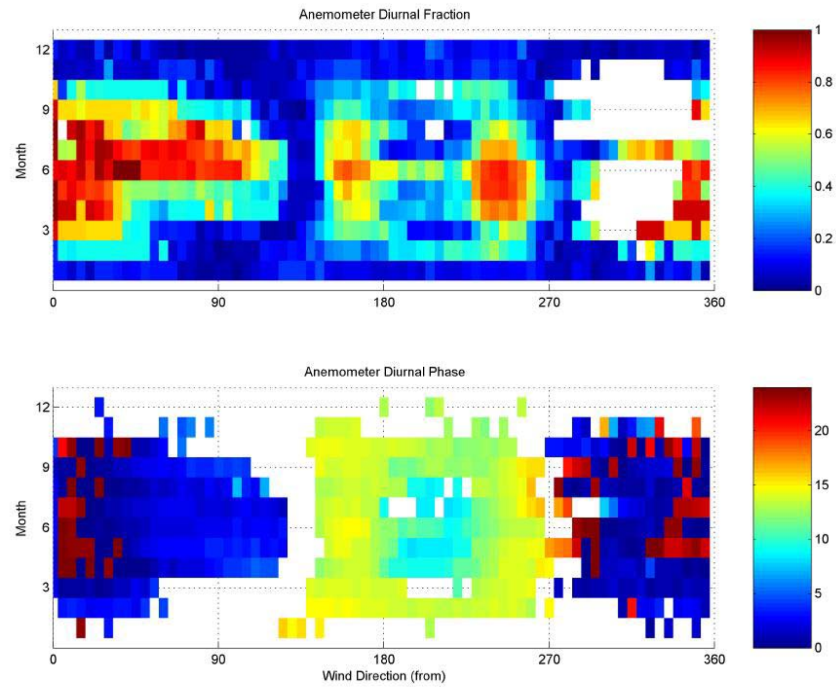

Figure 8: Amplitude and phase of the Lemon Creek anemometer diurnal signal as a function of wind direction and month. A minimum of 400 points was required in the diurnal PDF for a valid result, and the phase is only plotted where the diurnal fraction exceeds 0.15.

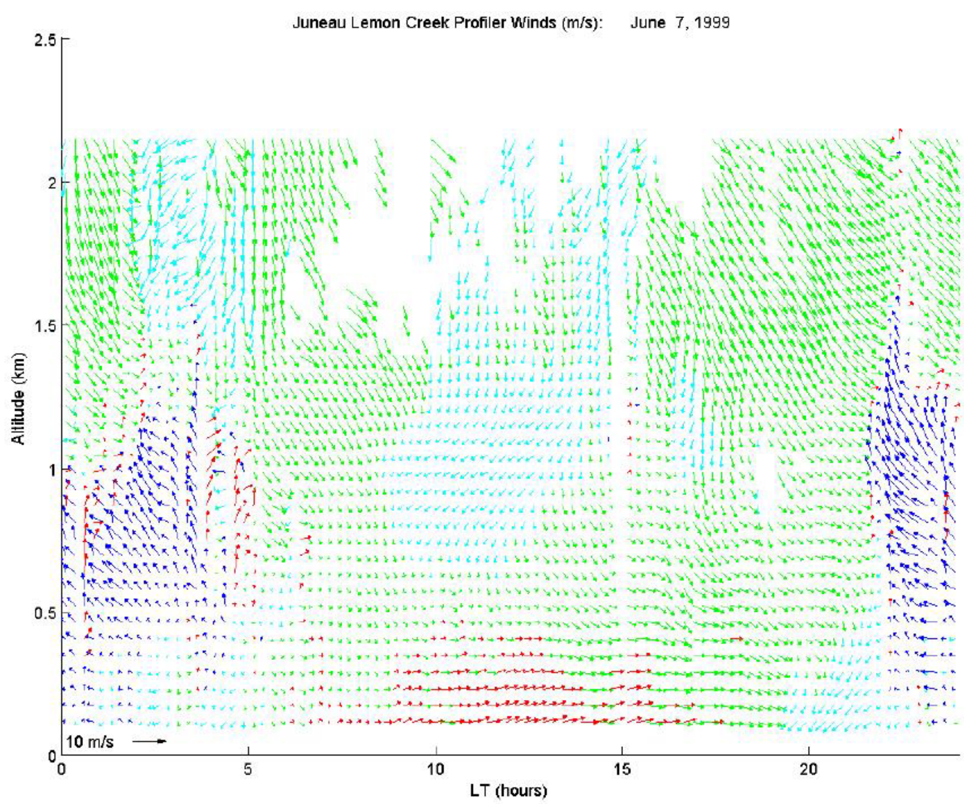

Figure 9: Winds measured at Lemon Creek on June 7, 1999, and averaged to 15-min resolution. The vectors are color coded according to direction quadrant.