Flow in Complex Terrain: Observations by Radar Wind Profilers and Anemometers near Juneau, Alaska

STEPHEN A. COHN

National Center for Atmospheric Research, Boulder, Colorado*

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ABSTRACT

Four years of data from three radar wind profilers and collocated anemometers are used to examine the airflow regimes near Juneau, Alaska. Wind direction probability density functions and wind rose histograms show the dominant wind speeds and directions from a long time series of observations. Analysis of diurnal variation separates mountain–valley flow events from synoptically driven events. Flow constrained by the Gastineau Channel dominates the winds near downtown Juneau, and the wind profilers document the rotation of this flow as it merges with the synoptic flow above the surrounding mountains. Strong flows from the northeast over the Taku Glacier, locally known as ‘‘Taku flows,’’ are also documented. These flows are less frequent but can cause strong wind storms at the surface. In addition, local flow effects are seen, including winds turning in response to terrain influence, drainage flows in creek valleys, and cross-valley flows. This analysis also demonstrates that radar wind profilers, using recently developed data-processing algorithms [in this case the National Center for Atmospheric Research (NCAR) Improved Moments Algorithm–NCAR Winds and Confidence Algorithm (NIMA–NWCA)], can provide valuable data even at low altitudes near complex terrain and sources of ground clutter.

1. Introduction

Juneau, Alaska, is surrounded by dramatic terrain. Mountain peaks rise steeply from sea level to over 1000 m; the Taku Glacier flows from the Juneau ice field, which is the fifth largest ice field in North America; and the Gastineau Channel provides a long, narrow conduit between high peaks. Located on the coast of southeast Alaska between the Coast Mountains and the Alexander Archipelago, Juneau's weather is influenced by both moist maritime air masses and cold, dry continental air masses (Colman 1986). The Aleutian low in the Gulf of Alaska guides storms with strong pressure gradients on to the shore, and the interaction of these storms with the precipitous terrain generates strong local flows. Dry continental air traverses the Coast Mountains to reach Juneau and arrives as strong northeast winds from density currents, known as gap flow, or from downslope windstorms from amplified mountain waves, known locally as the ‘‘Taku’’ (Dierking 1998; Colman and Dierking 1992). During synoptically quiet periods, mountain–valley flows are common. There are no road connections to Juneau, and so aviation and boating are common and essential for transportation between Juneau and outside communities. Weather has a significant effect on the local population, and pilots and boaters, as well as the local meteorologists, take a keen interest in the weather patterns that cause strong winds.

Since 1998, three radar wind profilers and numerous anemometers have been collecting data near Juneau as part of an aviation safety project. Although there are some gaps in the time series, this dataset has undergone thorough quality checks and represents a substantial quantity of wind information. The locations of these wind sensors expose each of them to different flows around this rugged terrain. Wind profilers are often affected by ground clutter when sited in a mountainous environment. They have been used to study deep flows affected by large-scale terrain (e.g., mesoscale circulations and atmospheric waves), but they seldom have been used to study smaller-scale flows close to terrain.

In this paper, the wind-profiler and anemometer dataset is used to reveal flows by using probability density functions of measured wind directions and by using wind rose histograms (a statistical composite of wind speed and direction occurrences) for each site. The wind rose histogram can show dominant directions of flow and also the dominant wind speeds from each direction. Less-frequent phenomena also appear in these plots. Although the length of the dataset (about 4 yr) is too short to provide a long-term climatological description of

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Corresponding author address: Stephen A. Cohn, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307.
E-mail: cohn@ucar.edu

winds, it is sufficient to show the prevailing flow features. Each of the wind profiler sites has a collocated anemometer, and wind profiles from the surface to well above the terrain show flow changes with height. Flows constrained to within the Gastineau Channel at low levels rotate and merge with the background synoptic-scale flow aloft. Northeast flows (gap flow through the Coast Mountains, and Taku wind storms) are also diagnosed from these wind rose histograms. Drainage flows from creek channels and thermally driven cross-valley flows are distinguished from synoptically driven flows by examining the diurnal distribution of the winds.

In the following section, the pertinent terrain features, weather, and measurement systems are described. Observations by the wind profilers and anemometers are presented and discussed in sections 3 and 4. Section 5 presents conclusions about flow in Juneau and about the use of wind profilers in complex terrain.

2. Background

a. Terrain description

The Juneau region is divided by the Gastineau Channel, which is oriented northwest–southeast between the mainland and Douglas Island (Fig. 1). The orientation of this channel plays a key role in airflow characteristics, both when flow is from the Gulf of Alaska to the west and when it comes over the Taku Glacier to the northeast. Downtown Juneau is located near the midpoint of this channel on the northeast side, with the town of Douglas located on the southwest side. The northwest outlet of the channel opens into a basin, oriented approximately east–west, in which the Juneau International Airport is located. On both sides of the channel the terrain rises steeply, with mountain peaks over 1000 m above sea level. On the east side there is a series of ridges and peaks separated by creek drainages. These drainages are important in the case of Taku flow. Just east of the northwest end of the channel is the Lemon Creek valley, in which the Lemon Creek wind profiler and anemometer (LC) are located. To the south, there is a valley that contains Salmon Creek and then there is the Gold Creek valley, where downtown Juneau is located. South of downtown Juneau are a ridge of Mount Roberts, the Sheep Creek valley, and then a broad ridge that extends to the south end of the channel. Inland from these ridges and valleys are more high peaks, the Juneau ice fields, and the Taku Glacier. All of these features affect the airflow around Juneau.

The major axis of Douglas Island is approximately parallel to the Gastineau Channel. The Fish Creek valley originates near the center of the island, with flow down to the northwest. This valley is also nearly parallel to the Gastineau Channel. Several high peaks dominate the east side of the island between Fish Creek and the channel, with more peaks on the west side of the island. The North Douglas wind profiler and anemometer (ND) are located at the outlet of the Fish Creek valley. The third wind profiler and anemometer site, South Douglas (SD), is located on a pier that extends over the Gastineau Channel from the town of Douglas. This site has excellent exposure to flows within the channel.

b. Weather and airflow around Juneau

The maritime and continental flows generated by the dominant weather patterns of Juneau are well known to local meteorologists, pilots, and boaters. Colman (1986) describes these flows in terms of temperature and moisture, including a relatively warm and moist maritime flow and a much colder and very dry flow of continental air from the interior of Canada. Both flow regimes can include strong winds. In this paper, a description of weather scenarios is based on wind measurements rather than temperature but is similar.

Weather events that are known locally as Taku winds have strong winds aloft from the north or northeast. This situation can occur with high pressure over northern Canada and low pressure approaching Juneau from the Gulf of Alaska. As an alternative, flow from the northeast can be generated by the cyclonic flow from a low pressure system that has passed to the southeast of Juneau. As described by Colman and Dierking (1992) and Dierking (1998), strong flow over the barrier of mountains northeast of Juneau creates mountain waves. In the case of a Taku wind, conditions at a critical level aloft amplify the wave energy and amplitude. A critical level is defined as an altitude at which the wind component in the direction of cross-barrier flow is zero, causing wave energy to be reflected and concentrated below this level. This wave activity usually generates strong winds, wind gusts, and turbulence within the Gastineau Channel. Taku winds also cause strong flow down the creek valleys on the northeast side of the channel. Gap winds have characteristics similar to those of Taku winds in Juneau but are often weaker. A critical layer is not present, and mountain waves, if present, are not amplified. Often, gap flow will occur when a shallow layer of cold air dammed behind the high peaks becomes deep enough to spill through mountain passes. This cold air will accelerate down the creek valleys on the east side of the Gastineau Channel, generating localized strong winds and turbulence. Flow will sometimes also occur over the ridge along the southern part of the Gastineau Channel.

Flow that is known locally as ‘‘southeast’’ winds occurs with winds aloft that are strong and from the southeast, south, or west, bringing moist air from the Gulf of Alaska. Within the Gastineau Channel, winds are confined by the terrain to be from the southeast. Similar southeast flow is occasionally observed in the Fish Creek valley on Douglas Island.

This paper will use the local nomenclature, referring to Taku or gap flow or to southeast flow. In addition, there are times when the flows aloft and in the channel

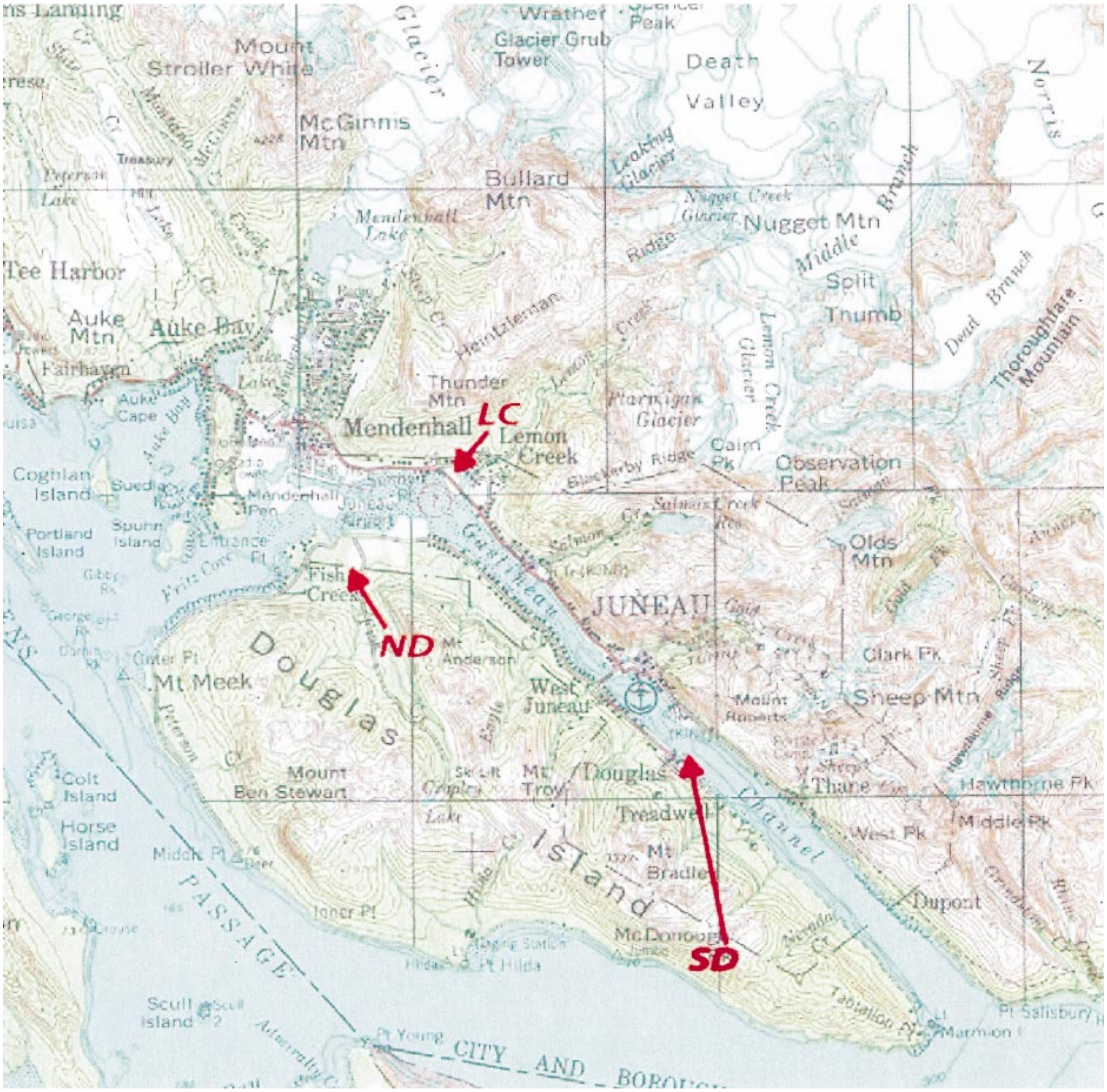

FIG. 1. Map of Juneau and southeast Alaska. Labels SD, ND, and LC show the locations of radar wind profilers with collocated anemometer at the South Douglas, North Douglas, and Lemon Creek sites.

have characteristics of southeast flow but approaching low pressure also induces gap flow. This situation will be referred to as a ‘‘mixed flow’’ case.

These wind regimes represent only strong wind cases and fall within the regimes of Colman (1986), with the gap flow and mixed flow both belonging to his ‘‘transition’’ flow regime. The statistical analysis presented here identifies Taku, gap, and southeast flows but does not identify mixed-flow events, which would require case studies or a statistic that combines winds from different altitudes. Weak winds in the valleys around Juneau are generated by mountain–valley wind systems. These winds have not previously been studied in the Juneau area but are documented here through diurnal patterns of the wind direction.

c. Sensor description and data processing

Instruments at the Lemon Creek, North Douglas, and South Douglas sites are essentially identical. Each site has an R. M. Young Company propeller-vane anemometer and a Vaisala, Inc., boundary layer radar wind profiler. Anemometer data are collected with 1-s resolution, processed by a quality-control algorithm to remove outliers, and averaged to 1-min values. The wind profilers are 915-MHz nine-panel phased-array Doppler wind profilers [Vaisala Lower Atmosphere Profiler (LAP)-3000], similar to the four-panel system described in Carter et al. (1995). In Juneau, they are operated with a range resolution of 60 m. Data are processed using the National Center for Atmospheric Research (NCAR) Improved Moments Algorithm–NCAR Winds and Confidence Algorithm (NIMA–NWCA) quality-control and wind analysis software. This software produces a vector wind measurement from the past 10-min of collected data but updates this wind with each new radial velocity measurement (dwell). Therefore, vector winds are produced approximately every 30 s, but winds produced within a 10-min period are not independent. The NWCA also provides a confidence index that is used to identify measurements contaminated by ground clutter or weak signal strength. These algorithms are described by Morse et al. (2002) and Goodrich et al. (2002), and an evaluation of their effectiveness is presented in Cohn et al. (2001).

3. Measurements of wind flow regimes

Figures 2–4 show the distribution of winds measured with the wind profiler and anemometer at the three sites for several altitude layers. The left column in each plot shows the probability density function (PDF) for wind direction, and the right column is a wind rose histogram showing the frequency of occurrence of wind speed and wind direction. Wind directions associated with speeds of less than 1 m s^{-1} are not well defined and are excluded from the PDF. In the wind rose histogram, the color axis represents number of occurrences in 1000s, and the color scale is chosen to emphasize the less frequent modes. The wind rose histogram shows measurements as a function of both wind speed and direction, accumulated in bins of 1 m $s^{-1} \times 5°$. Both depictions are useful, because the PDF will show dominant wind directions unbiased by the range of wind speeds from each direction and the wind rose histogram will show the directions of the highest wind speeds, even if these directions are rare. In these figures, the bottom plot (panel e) is from the anemometer and higher plots (panels a–d) are profiler data, increasing in altitude. Note that the anemometer wind rose histogram uses a smaller velocity interval than do the wind profiler wind rose histograms.

a. Winds in the Gastineau Channel

Wind direction PDF and wind rose histograms from the South Douglas site are shown in Fig. 2. The anemometer distributions (Fig. 2e) are derived from about 1.5×10^6 1-min measurements collected between 1998 and 2002. About 30% of these measurements have wind speed of less than 1 m s^{-1}, and these data were not used in the wind direction PDF. The South Douglas anemometer is near sea level in the Gastineau Channel, and the axis of the channel is 135°–315°. Strong peaks are seen in the PDF aligned with the channel, with flow primarily up channel (labeled SE in Fig. 2e), and a significant peak also down channel (labeled NW). Another less prominent but significant direction of wind flow is from 50° (labeled Taku). This flow is nearly perpendicular to the channel and is the flow direction expected during Taku or gap flow from the northeast. By examining the anemometer wind rose histogram, it can be seen that this northeast flow occurs almost exclusively with high wind speeds. This condition is shown by the light blue region in the figure centered at 50° and 8 m s^{-1}, although many northeast wind observations exceed 15 m s^{-1}. For Taku or gap flow to penetrate to the surface on the Douglas Island side of the channel, the wind must have considerable momentum.

Closer examination of the down-channel (northwest) part of the PDF shows that it is skewed toward more westerly directions. The wind rose histogram suggests that this down-channel flow is a combination of two distributions. The high wind speeds are closely aligned to the channel direction, but there is a population of lower wind speeds with a more westerly component. In section 4 it will be shown that these lighter winds are likely flow out of the Bear Creek valley directly west of the anemometer. The southeast flow is also skewed, with faster wind speeds having a more easterly component. Evidence of separate synoptic and diurnal components of this flow will be presented in section 4.

The dominant flow directions, closely aligned with the channel, show little variation in direction. Winds are deflected to flow along the channel from either the northwest or southeast, depending on the synoptic wind direction. Because the dominant incident wind direction above the terrain is from the south-southwest, there are many more occurrences of southeast than northwest flow in the channel.

Figures 2a–d show wind direction PDF and wind rose histograms measured by the South Douglas wind profiler. Although measurements were collected with 60-m altitude resolution, data have been grouped into 300-m layers for clarity. Also for clarity, we show only four of these layers. Each of these plots includes about 10^7 30-s wind measurements. Values with low confidence (as determined by NWCA) were not included, and so only high-quality data are plotted. These plots illustrate the observed pattern of winds in the Gastineau Channel and trends with increasing altitude. As expected, higher wind speeds are seen with increasing altitude.

The Taku flow direction is much less distinct in the lowest wind profiler wind rose histogram (Fig. 2d) than in the anemometer plot (Fig. 2e). This result is due to marginal data quality in Taku conditions. The cold and dry continental air in Taku and gap flows has weak radar reflectivity, and at low altitudes the strong winds generate ground clutter. Both result in low NWCA confidence, and so many of these values have been excluded. The northeast winds are seen more clearly at higher

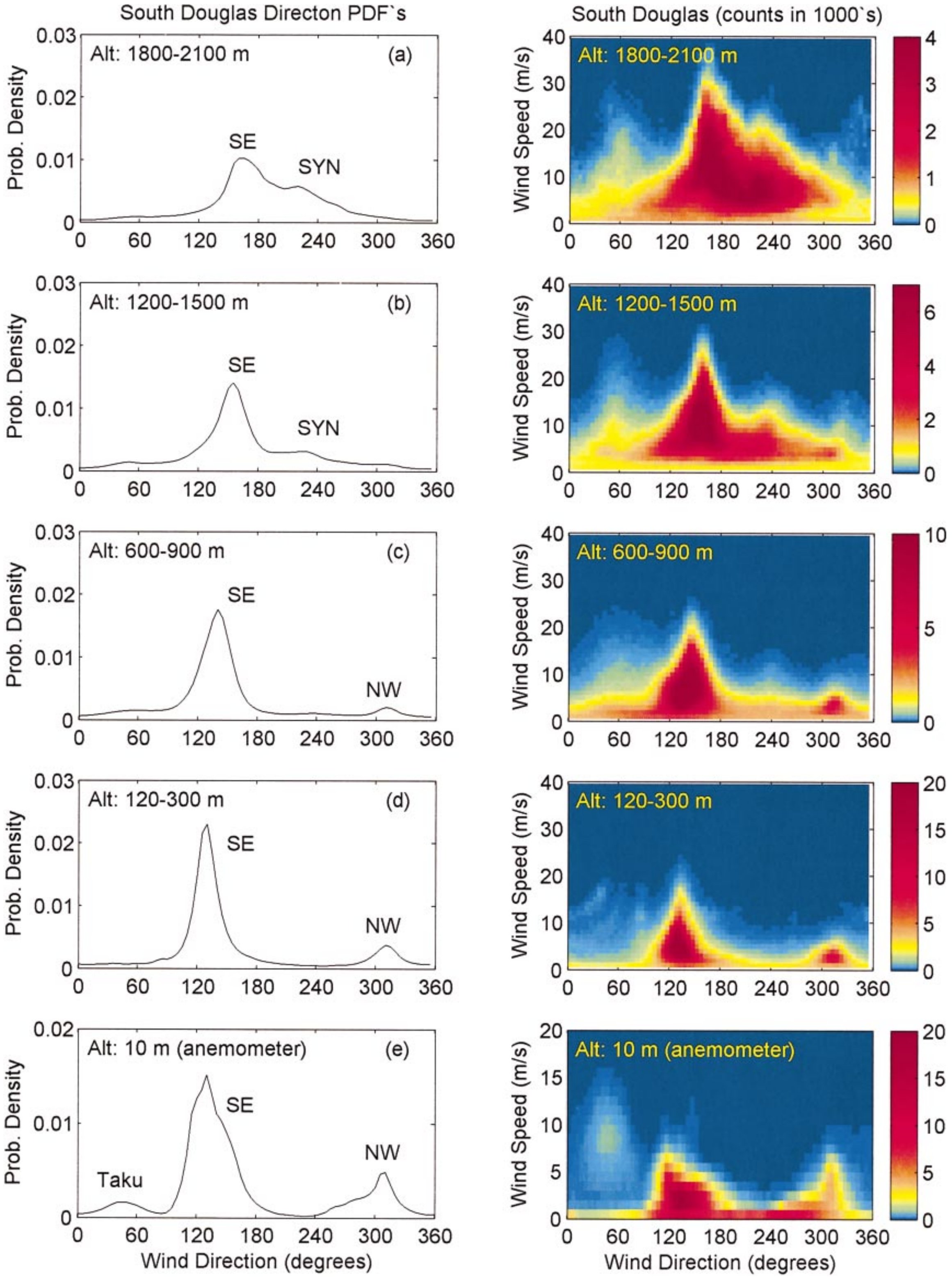

FIG. 2. (left) Wind direction PDFs and (right) wind rose histograms for the (bottom) anemometer and four altitude ranges from the wind profiler at the South Douglas site. The wind rose color axis represents number of occurrences in thousands. Following the meteorological convention, wind directions are clockwise from true north.

altitudes where ground clutter is less severe, and, as altitude increases, this mode has stronger wind speeds. There are also an increasing number of weaker northeast (Taku direction) wind observations at higher altitudes, because these winds can be present aloft without penetrating down into the channel. There is no apparent rotation with altitude of the highest wind speeds observed for this wind mode, but the lighter wind speeds seen aloft are more northerly than the high wind speeds are (Fig. 2a).

The southeast and northwest flows are very distinct in the lowest wind profiler PDF and wind rose histogram (Fig. 2d). The southeast mode becomes more southerly with increasing altitude. This rotation is most prominent between the 600–900- and 1200–1500-m layers, which include the transition from within the channel to above it. Also, the narrowest PDF modes are seen below 600 m, where the flow is most restricted. Above 1500 m, the direction PDF has become much more broad, centered near 170°, and has merged with a broader background flow. The northwest flow in the lowest wind profiler observations does not show the skewness introduced by flow out of the Bear Creek valley that was seen by the anemometer, which suggests that the Bear Creek outflow events are shallow.

In the 900–1200-m layer (not shown), which is near the height of the local mountain ridges, a mode begins to emerge from about 220°. These winds are closer to the synoptic wind direction that is above the influence of the mountains on Douglas Island and is labeled SYN on Fig. 2. In the highest measured layer, this mode is broad and has partially merged with the southeast flow direction. Winds from the south and west are more frequent, and the PDF and wind rose histograms are more representative of the prevailing winds above the local terrain. Although there are still many observations aligned with the channel, its influence is less than at lower altitudes.

Overall, the South Douglas PDF and wind rose histograms document the local wind patterns around Juneau very well. Near the surface, the winds are parallel to the Gastineau Channel from the northwest or southeast. The strongest winds are from the southeast direction. The Taku wind mode is seen at all altitudes but is most visible at or above 900–1200 m. South to southwest winds are evident in the highest levels of data, as is expected farther above the influences of the channel.

In the midlatitudes in the Northern Hemisphere, the prevailing wind above the boundary layer is from the west. Above Juneau, the position of the Aleutian low over the Gulf of Alaska can deflect westerly winds, creating a southwesterly prevailing synoptic wind direction over Juneau. The wind profilers in Juneau do not collect measurements above 2100 m, but it is expected that winds at higher altitudes are dominated by a southwest synoptic flow.

b. *Winds at the North Douglas site*

Figure 3 shows wind direction PDF and wind rose histograms from the anemometer and wind profiler at North Douglas. Whereas the dominant feature of the terrain around the South Douglas wind profiler site is the Gastineau Channel, the North Douglas site is located at the north end of the Fish Creek valley between the substantial mountains on Douglas Island. The anemometer PDF of Fig. 3e shows three dominant flow directions. The most frequently occurring wind directions are a broad easterly mode near 100°, which is also the direction of the highest wind speeds. This mode results primarily from the southeast flow in the Gastineau Channel as it turns more easterly, curving around the northeast side of Douglas Island (labeled SE). A slight skewness from the east-northeast may be from gap or Taku flow out of the Lemon Creek valley, but specific case studies are needed to investigate this surmise. A second wind direction mode includes southerly winds (labeled FC). These winds are usually less than 2 m s^{-1} and are most likely drainage flow from the Fish Creek valley rather than mechanical channeling of the synoptic wind by the terrain. The third wind direction mode occurs from the west-southwest. This flow probably includes onshore winds, which are more southerly and have flowed around the north slopes of mountains on the northwest side of Douglas Island. However, as will be shown in section 4, some flow from this direction is also associated with up-valley or cross-valley flow (labeled VF). A fourth, less distinct, flow mode can be seen in the wind rose histogram of Fig. 2e as the light blue area of higher wind speeds around 60°. This mode appears to be Taku or gap winds reaching the surface at the North Douglas site. It is particularly interesting because Taku winds near the surface are thought to occur mostly in the southern half of the Gastineau Channel.

The North Douglas wind profiler wind direction distributions and wind rose histograms (Figs. 3a–d) extend these patterns in altitude. There is no clear signature of drainage flow from Fish Creek (VF) in the lowest wind profiler measurements, and so this flow is probably a shallow process like the flow from Bear Creek. The lowest profiler measurements are dominated by winds from the southeast, which are significantly rotated from the dominant mode of surface measurements and include greater wind speeds. This southeast flow rotates clockwise with increasing altitude, and by the highest layer the distribution is very broad and is centered about 170°. The southwest flow (labeled VF) in the anemometer distribution has an analog that is broad and slightly more westerly in the lowest wind profiler measurements. This part of the distribution continues to rotate with altitude to about 315° by the highest measurements. At midlevels, this distribution may be from flow deflected up the Fish Creek valley (from 315°; labeled VF). This supposition is supported by observations at a moun-

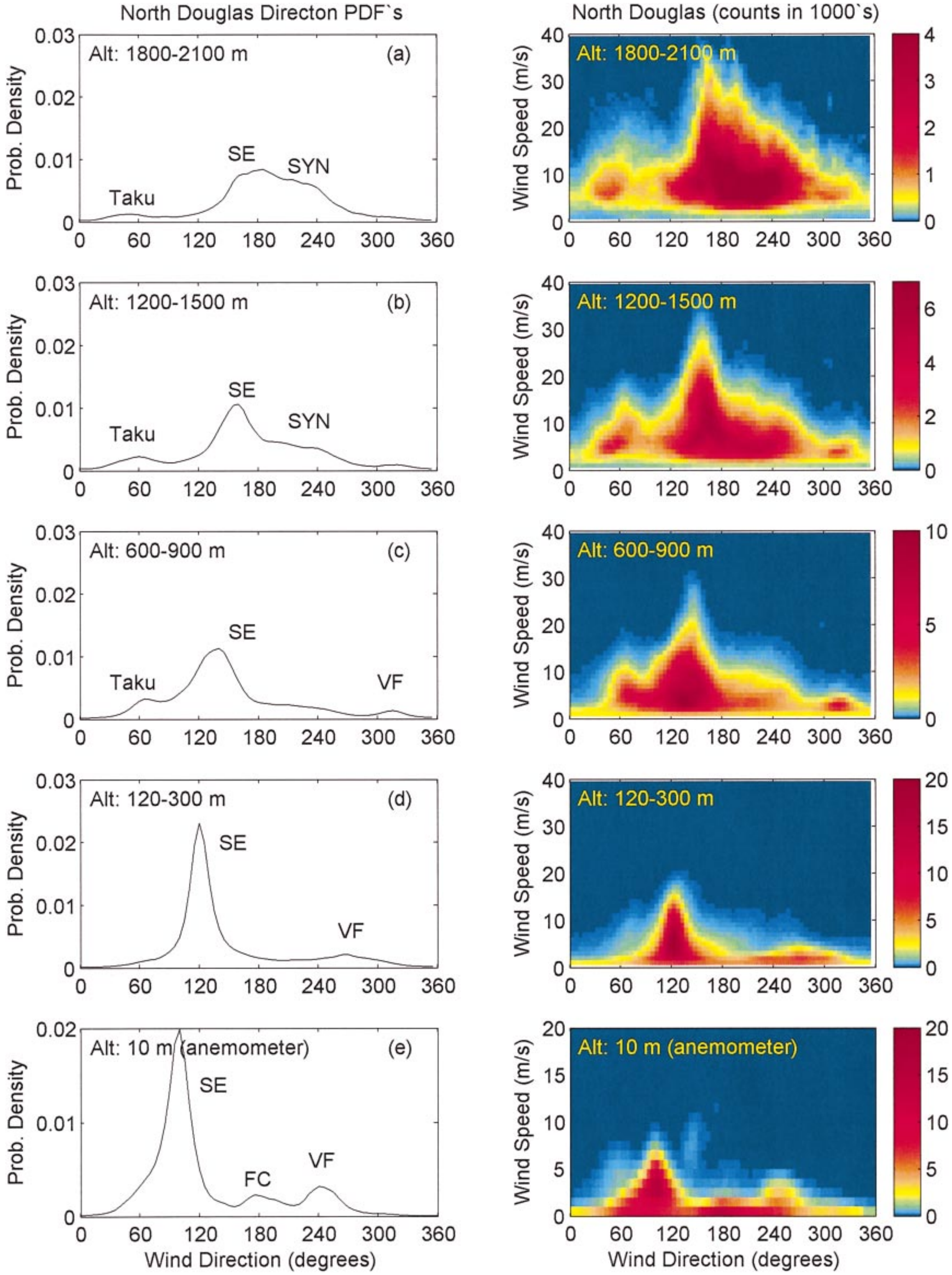

FIG. 3. As in Fig. 2, but for the North Douglas anemometer and wind profiler.

taintop anemometer site near the upper end of the Fish Creek valley (not shown). A northeast (Taku direction) grouping of winds becomes clearly visible in the North Douglas wind rose histogram at and above the 600–900-m layer. It is noteworthy that these northeast winds sometimes do not penetrate to the surface at North Douglas but are prominent aloft.

c. Winds at the Lemon Creek site

As at the other sites, the direction of the low-level winds at Lemon Creek (Fig. 4) is determined by the local terrain. As seen by the Lemon Creek anemometer (Fig. 4e), the dominant direction is again southeasterly flow, slightly more southerly than at South Douglas as the southeasterly flow turns into the Lemon Creek valley. As will be shown in section 4, some of the weaker winds in this mode are from a cross-valley circulation. Another mode is from the west-southwest. This flow appears to be onshore flow, which will turn into northwesterly (down channel) flow as it flows past the Lemon Creek valley (labeled ‘‘onshore’’). However, as will be seen in section 4, many of these observations are from diurnal valley flows. There is also a grouping of winds from the northeast (labeled Taku). This is the Taku or gap flow direction, but it is also the down-valley direction for the Lemon Creek valley. Most of the winds from this direction are light, less than about 3 m s^{-1}, and consistent with drainage flow, but some are much faster and could be part of Taku or gap flow events.

The Lemon Creek wind profiler PDF and wind rose histograms at the lowest level (Fig. 4d) are similar to the anemometer distributions. The southeast mode is initially more easterly, but it rotates with altitude and is more southerly by 2100 m. The onshore mode seen in the anemometer data has an analog that rotates to the west-northwest and merges at the tail of the broad synoptic distribution. The Taku or drainage flow direction mode becomes more prominent above 600 m, and wind speeds become stronger. As at the North Douglas site, these winds appear to be from Taku or gap flow events but should be studied in more detail through case studies.

The highest altitudes of Figs. 2–4 show similar wind distributions above all three wind profiler sites. In each, a broad synoptic wind distribution is seen with directions from the southwest through the west. A peak of stronger winds is seen from the southeast that is caused by channeled winds in strong wind events, and another peak is seen from the northeast Taku or gap flow direction.

4. Observed diurnal effects

The diurnal pattern of the observed wind directions may be examined to investigate further the flows described in the previous section. Mechanisms that generate diurnal flows are considered in detail in, for example, Whiteman (2000). In valleys, circulations with a diurnal pattern occur where there is differential heating (or cooling) between air in contact with a slope and air farther from it. For example, during the day the slope of a mountain exposed to sunlight and the air in contact with the slope warm, and this air becomes less dense than air at the same altitude but farther from the slope. Hence, winds will tend to flow up slope during the day. Nocturnal drainage flow in valleys is also common, occurring as the valley walls and air in contact with them cool more quickly than the air farther from the walls. Cross-valley flows occur when the geometry is favorable for differential heating of opposite walls of a valley. For example, consider a valley with steep walls oriented east–west at a latitude and season for which the maximum solar elevation is well below zenith. During the day, the side of the valley facing the sun will warm more than the side away from the sun. There will be an up-slope flow to the sunward side with compensating flow coming from the shadowed side, which will produce a cross-valley flow during the day.

Wind speeds associated with diurnal flows are often only a few meters per second—much weaker than winds in the dominant modes described in section 3. However, by considering the distribution of wind directions as a function of local time, a diurnal pattern can emerge. The diurnal analysis presented here is useful to separate flows forced by the large-scale synoptic situation from those driven by differential heating or cooling.

Figure 5 shows the diurnal distribution of 1-min anemometer winds from selected direction sectors as a function of local time. The distributions are generated with 1-h resolution and are normalized so that each is a PDF. Distributions were examined for each 5° direction interval, and the direction sectors shown in this figure are a composite of contiguous 5° intervals with similar characteristics. The top plot shows the diurnal variation from five sectors around the South Douglas anemometer. One can relate this figure to the flow characteristics seen in Fig. 2e—there is a strong diurnal trend in winds from the southwest and west (240°–285°). This pattern is the more westerly portion of the down-channel (northwest) flow. The great majority of winds from this sector occur at night, with a minimum during the day (in fact, at local noon). This result is strong evidence that many winds from this direction are drainage flow from the Bear Creek valley or from the steep slopes to the west of the South Douglas site. By contrast, the main part of the northwest flow distribution, from 285° to 330°, as well as each 5° interval within this sector, shows almost no diurnal variation and is caused by channeling of the synoptic flow. Examination of the sectors around the South Douglas site also shows diurnal variations in winds from 115° to 135°, the more easterly part of the southeast mode. Winds from this direction tend to occur during the daytime, with a maximum near local noon, and there are many fewer occurrences at night. It is likely that this flow is either up-valley or cross-valley

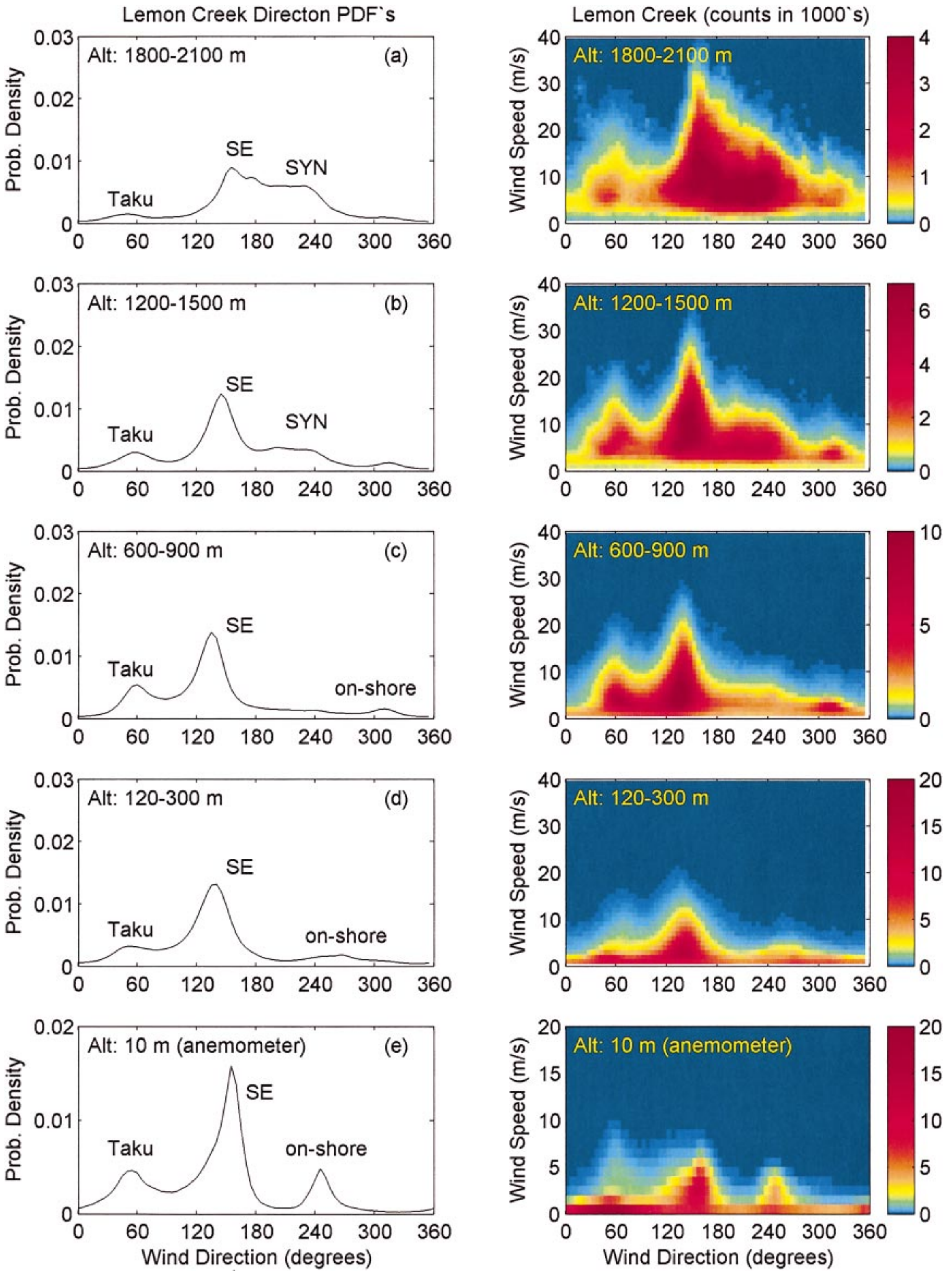

FIG. 4. As in Fig. 2, but for the Lemon Creek anemometer and wind profiler.

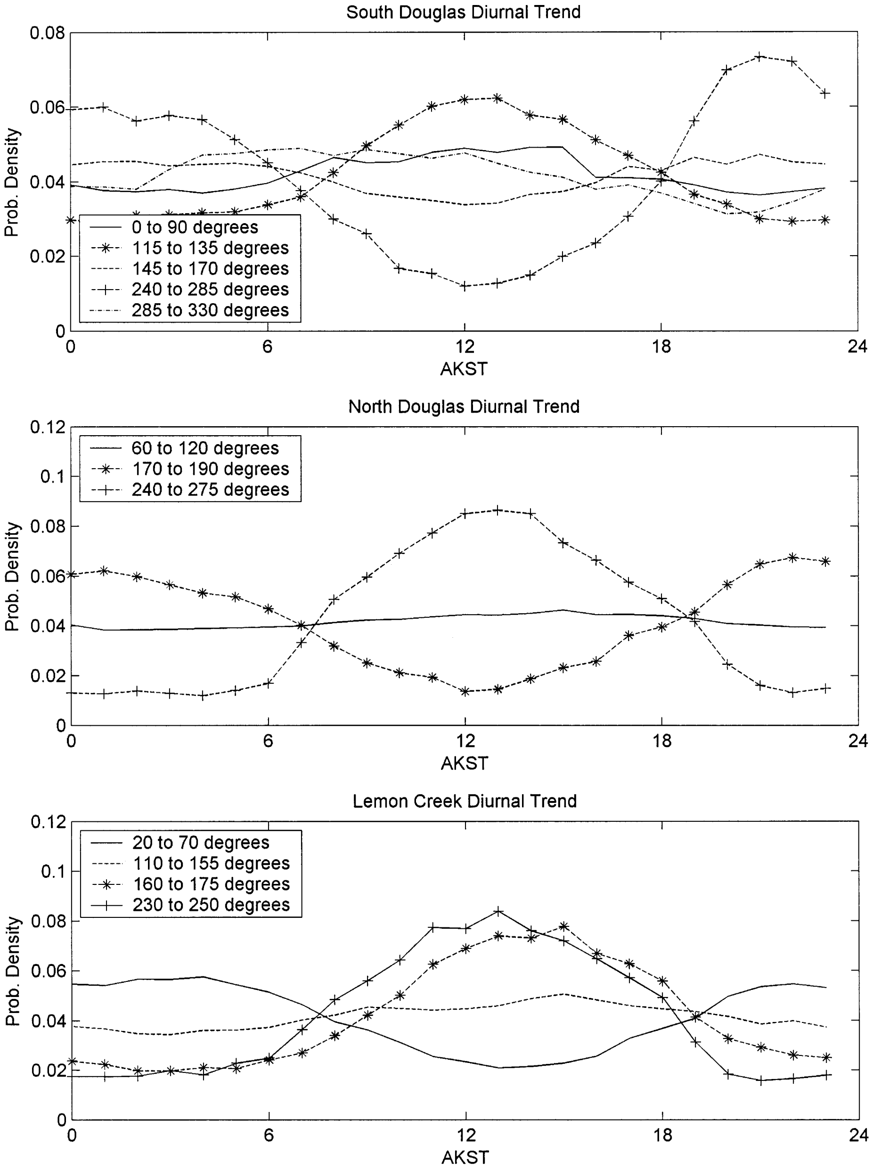

FIG. 5. PDFs as a function of local standard time for various wind direction sectors, from the anemometers. PDFs with a daytime minimum are expected from valley drainage flows, those with a daytime maximum are expected from up-valley or cross-valley flows, and those with no diurnal variation are expected from synoptic or other nondiurnal flows.

as described in Whiteman (2000) and is due to heating of the slopes north and west of the anemometer. By integrating the directionally invariant component of this PDF (in this case below a value of about 0.03 h^{-1}), it is estimated that the diurnal winds represent about 25% of the measurements from this sector. This plot also shows that the more southerly part of the southeast flow, from 145° to 170°, does not have a significant diurnal variation. Last, it is seen that the flow from the Taku direction, from 0° to 90°, does not have a diurnal trend, which is consistent with Taku and gap flows being driven by synoptic events rather than differential cooling or solar heating.

The pattern of winds at the North Douglas anemometer is examined in the center plot of Fig. 5. The southeast mode of Fig. 3, the most common flow direction observed at the North Douglas site, has no diurnal variation (60°–120°). However, two flow directions at this site do exhibit a diurnal variation. Winds from a cross-valley mode, from 240° to 275° (labeled VF in Fig. 3), occur preferentially during the day. This flow appears to be another example of a flow caused by differential solar heating, in which the northeast slope of Mount Meek (to the southwest of the anemometer) receives little insolation while the flat shelf surrounding and to the north of the North Douglas site receives more solar heating. This differential heating drives flow from the slopes of Mount Meek past the anemometer site. Also, winds from the down-valley direction, from 170° to 190° (labeled FC in Fig. 3), show a nocturnal flow pattern that suggests some down-valley flow down the Fish Creek valley. However, it is noteworthy that winds from 195° to 235° (not shown), which include part of the down-valley mode, do not show a diurnal variation. Therefore, it is likely that the down-valley flow mode includes both nocturnal drainage flow and synoptic flow forced down the valley.

The bottom plot of Fig. 5 shows a similar analysis for the Lemon Creek anemometer. Flow within the Taku sector (20°–70°) occurs mostly at night and is due to drainage down the Lemon Creek valley (centered about 50° from the anemometer) broadened by drainage flow directly from the valley sidewalls. The diurnal component from this direction accounts for more than 50% of occurrences, with the remainder probably during gap flow or Taku events. These events are likely to be the higher–wind speed events. This plot also shows that the flow labeled onshore (from 230° to 250°) is primarily a daytime flow that represents a classic up-valley flow situation. The southeast flow mode is also examined. Winds from the easterly portion of this mode between 110° and 155° were found to have no diurnal component and are generated by channeling of synoptic flow by the Gastineau Channel. However, winds from the southerly portion (160°–175°) have a very strong diurnal pattern dominated by daytime flow, and this pattern appears to be a cross-valley flow. From this analysis, it is seen that the major southeast flow mode of Fig. 4e is actually composed of both cross-valley (diurnal) flow and flow up the Gastineau Channel (not diurnal). With a latitude of about 58°N, the noontime solar zenith angle in Juneau ranges between about 55° at the summer solstice to only 9° at the winter solstice. The south wall of the Lemon Creek valley faces away from the sun and receives very little solar heating, whereas across the valley the north slope receives much more insolation. This contrast in heating generates a cross-valley flow seen as part of the southeast mode by the Lemon Creek anemometer.

5. Summary and discussion

Flows around Juneau are complex both because of its location at the intersection of coastal and mountain climates and because of complicated terrain with a long channel, high mountains, and many creek valleys. The wind profilers and anemometers installed in this area for an aviation safety project have provided an opportunity to study these complex flows. It is unusual to have three wind profilers so closely located and is also unusual to have high-quality wind profiler measurements at low altitudes from profilers located so near steep terrain. The NIMA–NWCA signal processing used by the Juneau wind profilers was successful in measuring winds, even in the challenging Taku wind situation with weak radar signals and strong clutter.

Wind direction PDF and wind rose histogram plots that show statistical occurrences of wind speed and direction clearly document flow restricted by the Gastineau Channel. These plots show flow primarily restricted to be from the southeast or northwest directions and show rotation with altitude to a dominant southwest flow above the terrain. Similar flow effects are seen at the North Douglas and Lemon Creek sites, with up-channel winds turning slightly into the Lemon Creek valley, and these same winds appearing with a more easterly component at the North Douglas site. It is noteworthy and reassuring that the upper-level winds from all three wind profilers have very similar distributions.

Northeast Taku or gap flow within the channel and above is also documented in these plots. The northeast winds at the surface are seen most clearly at the South Douglas site. Surface flows from the northeast also appear at the other wind profiler sites, but wind speeds are smaller. Surface observations of Taku events have not previously been documented on North Douglas Island or in the Lemon Creek valley. Northeast winds are seen by all three wind profilers, most clearly above 600 m, with speeds increasing with altitude. Some drainage flow and mechanical channeling of flow direction by terrain is also seen in the anemometer measurements: for example, drainage flow from the Bear Creek valley and deflection of the southeast flow into the Lemon Creek valley. These features are shallow—they are seen clearly in the surface anemometer measurements but are not apparent in the profiler data.

Overall, this analysis shows the major flow patterns around Juneau, along with some less prominent and very local (e.g., drainage and cross valley) flows. Details of these dominant flows differ over relatively small distances, underscoring the importance of local terrain effects. Wind profilers using the NIMA–NWCA software provide valuable wind information down to 120 m AGL, even in close proximity to terrain clutter sources. With improvements in signal processing, it is expected that wind profilers will be used in future studies in complex terrain. Wind direction PDF and wind rose histograms provide a summary of the frequency of observed wind speed and direction occurrences. These histograms effectively show clearly separated flow regimes.

Examination of the diurnal nature of the observed flows is used to reveal directions for which flow is dominated by nocturnal drainage, up-valley, or cross-valley flows rather than by synoptically forced flow. This analysis shows that many of the wind measurements at the South Douglas site coming from the direction of Bear Creek are nocturnal drainage flows, and other winds are likely to be caused by solar heating of the slopes to the northwest of this site. Similar diurnal effects were seen at the North Douglas site, revealing nocturnal drainage flow down the Fish Creek valley and a daytime circulation caused by differential solar heating. At the Lemon

Creek site, a more traditional nocturnal down-valley and daytime up-valley flow was seen in addition to a daytime cross-valley flow. The analysis of diurnal trends is useful in understanding the nature of flow modes exposed by the wind direction PDF and wind rose histograms. Synoptically driven flows do not show a diurnal trend, whereas valley flows show a strong diurnal trend.

The dataset used here continues to grow and contains much more information waiting to be examined. Future work with these data will include case studies to document specific situations of the dominant flows and the observable drainage flows and will include further statistical examination of the conditions under which the diurnal-flow directions are seen. In addition, the altitude variation of diurnal drainage and cross-valley flows will be investigated, making use of the low-level wind profiler measurements.

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