Characteristics of Nocturnal Low-Level Jets Observed in the North Florida Area

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ABSTRACT

The seasonal and interannual variability of the nocturnal low-level jets over the north Florida region are investigated using sodar measurements spanning 540 nights. On average, jets are present in 62% of the nocturnal periods examined. The observed jet speeds range between 3 and 21 m s^{-1} and heights are between 80 and 700 m. Observations show that the low-level jet occurs more frequently (70% of the nocturnal periods) during the colder months November–February in contrast with the warmer months June–August (~47%). The presence of southerly jets dominates the summer months, whereas northerly jets are more frequent during winter. Colder months frequently exhibit jets with speeds exceeding 14 m s^{-1}, often associated with the passage of frontal systems. The interannual variability observed using the North American Regional Reanalysis (NARR) wind profile data during a 4-yr period shows only minimal differences in jet characteristics. A comparison of jet heights with NARR planetary boundary layer heights suggests that jets at the north Florida location frequently occur within the planetary boundary layer. The occurrence and speed of observed low-level jets are linked to both the land–ocean temperature contrast and to the strength and orientation of surface pressure gradients over the region. A high occurrence of large-amplitude oscillations with approximately a 24-h period near the jet height is shown using the Hilbert–Huang transform analysis, suggesting that inertial oscillations are one possible cause of jet formation in north Florida.

1. Introduction

Low-level jets are important atmospheric processes frequently observed in the earth's planetary boundary layer. A low-level jet (LLJ) generally forms during the evening, strengthens during the course of the night, and dissipates shortly after sunrise because of enhanced vertical mixing generated by the warming of the surface. One of the pioneering theories on the LLJ formation is Blackadar's (1957) inertial oscillation mechanism associated with frictional decoupling during evening hours followed by an acceleration of boundary layer winds. Several authors have suggested that inertial oscillations constitute an important cause of jet formation (Parish et al. 1988; Smedman et al. 1995; Whiteman et al. 1997; Mahrt 1999; Andreas et al. 2000; Banta et al. 2002; Song et al. 2005; Zhang et al. 2006).

Several other mechanisms also explain the formation of a low-level jet. Throughout the world, studies have shown that the presence of low-level jets results from a combination of several effects depending on both geographic location and terrain characteristics. Holton (1967) showed that alternating differential heating and cooling of the sloping terrain is linked to the evolution of the U.S. Great Plains jet. Barrier jets however, result from a geostrophic adjustment as stable air is advected against an elongated topographic ridge (Parish 1983; Li and Chen 1998). King and Turner (1997) show that katabatic winds also cause low-level jets. And jets observed along coastal regions originate from baroclinic effects associated with land–sea temperature gradients (Zemba and Friehe 1987; Burk and Thompson 1996; Holt 1996; Parish 2000). Uccellini (1980) studied the role of upper-tropospheric features and upper- and lower-tropospheric jet coupling as a cause of LLJ formation at the Great Plains. The nocturnal LLJ characteristics discussed here consider LLJs associated with boundary layer processes.

The pioneering study on LLJ climatology across the United States by Bonner (1968) showed that boundary layer jets are most frequent over the Great Plains. Several observational and theoretical studies have been reported on their characteristics (Blackadar 1957; Hoecker 1963; McNider and Pielke 1981; Parish et al. 1988;

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Zhong et al. 1996; Arritt et al. 1997; Whiteman et al. 1997; Song et al. 2005). An earlier study (Whiteman et al. 1997) provided a detailed climatological description of LLJs over north-central Oklahoma using a 2-yr dataset. Their results showed only minor seasonal differences of jet occurrence. Song et al. (2005) used an extensive dataset collected using sodars and wind profilers in Kansas and found that jets occurred during 63% of the nocturnal periods throughout their study. It has been shown that water vapor transported by LLJs from low to midlatitudes and their subsequent condensation modulates rainfall events over the Great Plains (McCorkle 1988; Mitchell et al. 1995; Higgins et al. 1997; Wu and Raman 1998).

A recent study by Zhang et al. (2006) discussed warm season LLJ features over the mid-Atlantic states using a combination of profiler observations and model simulations. They found the presence of jets with speeds 8–23 m s^{-1} at an average altitude of 670 m on 15–25 days of each month. Bonner (1968) presented a geographical distribution of LLJ frequency across the United States, including the eastern United States using twice-daily rawinsonde observations. Mathieu et al. (2005) reported the occurrence of LLJs predominantly below 100 m in Ottawa, southeastern Canada. In two recent studies (Karipot et al. 2006, 2008), at the north Florida AmeriFlux site near Gainesville, Florida, we investigated the influence of LLJs on measured CO_2 fluxes over a forest canopy. To our knowledge, there has been no other study focused on the characteristics of low-level jets in the southeast. This study is of significance in the light of the fact that jets close to the surface lead to the generation of turbulence and increased surface–atmosphere gaseous exchange in the nocturnal boundary layer (NBL); it is also of significance given their potential influence on weather phenomena throughout the region.

In this paper, LLJ characteristics such as speed, height and direction are examined using sodar measurements in the north Florida peninsula over a 2-yr period. The analysis focuses on the frequency of occurrence of LLJ characteristics and their nocturnal, seasonal, and interannual variability. Mechanisms favorable for the formation, strength, and seasonal variations of LLJ are also investigated.

2. Measurements and data

The present study uses sodar data collected at the Florida AmeriFlux site (29°45′N, 82°10′W) located 10 km northeast of Gainesville, Florida. The geographical location of the site is shown in Fig. 1. The shortest distance from the site to the Atlantic coast on the northeast–southeast sector as well as to the Gulf of Mexico coast on the southwest–west sector is approximately 100 km. The topography at the site is flat and is located in a managed slash pine (*Pinus elliottii* Engelm. var. *elliottii* L.) plantation.

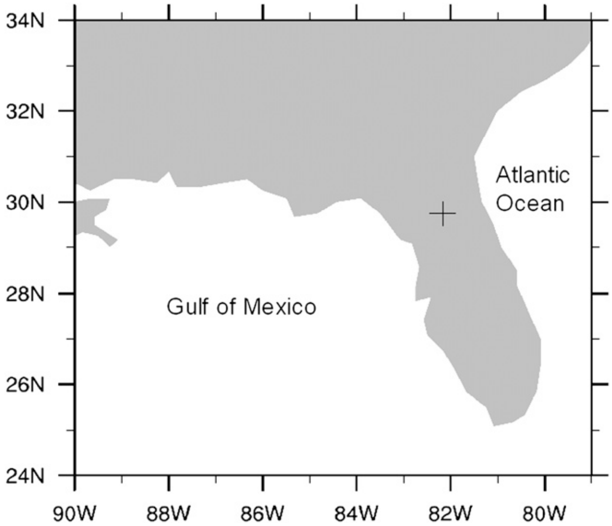

FIG. 1. Map of the Florida peninsular region showing measurement location.

The wind profiles were measured using a boundary layer monostatic Doppler sodar (Model PA2, Remtech Inc., Paris, France). The instrumentation was deployed in a forest clearing, 200 m off the forest edge. Profile measurements were made up to a height of 1000 m with a 20-m vertical resolution, starting at 20 m above ground. Thirty-minute average profiles of wind speed, direction, and standard deviations of three-dimensional velocity components were archived in a computer. A quality check on the collected data showed that nearly 70% of the nocturnal periods have good data up to 700 m during moderate-to-high wind conditions (speed >6 m s^{-1} at least at one level below 300 m). The analysis presented in this study uses data up to 700 m for maximum signal quality. Measurements were conducted during several months spanning the years 2001–05, as part of micrometeorological experimental campaigns. A total of 540 days of data, which includes quasi-continuous measurements during July 2003–June 2004 and data from different months of 2001, 2002, 2003, and 2005, are used in the analysis. The selection of different months from 2001 to 2005 is made based on the number of days of sodar measurements available within each month of the field campaign. The reader is referred to Table 1 for details. The nocturnal periods considered for the study are 2000–0500 eastern standard time (EST). This range was determined by considering seasonal changes in sunrise and sunset times. A total of 8785 half-hourly nocturnal periods are used for this analysis.

TABLE 1. Details of the sodar dataset used for the study.

2003/04 sodar dataset				Sodar data from other years			
Yr	Month	No. of days	No. of 30-min nocturnal periods	Yr	Month	No. of days	No. of 30-min nocturnal periods
2004	Jan	28	432	2002	Jan	18	305
2004	Feb	24	386	2002	Feb	22	366
2004	Mar	28	445	2002	Mar	16	269
2004	Apr	28	460	2005	Apr	20	345
2004	May	31	509	2002	May	22	361
2004	Jun	30	492	2003	Jun	17	287
2003	Jul	24	375	2001	Jul	15	254
2003	Aug	31	498	2001	Aug	16	261
2003	Sep	23	375	2002	Sep	17	273
2003	Oct	30	477	2002	Oct	26	427
2003	Nov	26	412	2002	Nov	20	331
2003	Dec	28	445				

In this study, the term ‘‘low-level jet’’ refers to any lower-tropospheric elevated wind maximum in the vertical profile at least 2 m s^{-1} greater than speeds both above and below it. This criterion is similar to that used by Andreas et al. (2000) and it differs from earlier studies by Bonner (1968) and by Whiteman et al. (1997) in which a jet speed threshold was used in addition to a shear criterion. The reason for this choice in the present study lies in the fact that the use of a threshold speed criterion filters out many of the low-speed jets. Although weak jets play only a modest role in the long-range transport of atmospheric constituents, many such jets observed below 200 m are important in generating turbulence in the surface layer and thus influence nocturnal surface–atmosphere exchange (Mathieu et al. 2005; Karipot et al. 2006, 2008).

Low-level jets satisfying the above criterion are identified in wind profiles averaged over 30 min. Jet periods are counted regardless of whether they are continuous or intermittent in the time series. Several of the jets observed during the summer months exhibit intermittency; accounting for them is nonetheless important given their role in turbulence generation and in mass transport in the NBL. In the case of missing data in some of the atmospheric layers, the profile is still used provided the dataset of the jet core and the shear layers above and below the core is complete. For each period, LLJ characteristics such as maximum wind speed in the profile, the height of the jet core, and its wind direction are tabulated.

Interannual variations in jet characteristics are studied using North American Regional Reanalysis (NARR) wind profile data (Mesinger et al. 2006) corresponding to the experiment site coordinates, as continuous sodar measurements were conducted only during July 2003–June 2004. The NARR data have 32-km horizontal resolution and 3-h temporal resolution. The wind speed and direction profiles are calculated from the longitudinal (u) and lateral (v) wind components at 30 m above the surface and at five levels between 1000 and 900 mb (hPa) at a 25-mb interval. The heights corresponding to the five pressure levels vary between 100 and 900 m. The criterion used in identifying an LLJ is the same as that used for sodar data (i.e., the presence of a maximum in the wind profile that is at least 2 m s^{-1} higher than speeds both above and below it). Three nocturnal periods, 2200, 0100, and 0400 EST from each night, are used in the present analysis. The four NARR datasets used to study interannual variability correspond to the periods July 2001–June 2002, July 2002–June 2003, July 2003–June 2004, and July 2004–June 2005. NARR planetary boundary layer (PBL) height data and surface pressure and surface temperature data are also used in the study.

3. Results and discussion

a. General nocturnal LLJ characteristics

In the present analysis, jets are classified into four categories based on the maximum speed: weak (<6 m s^{-1}), moderate (6–10 m s^{-1}), strong (10–14 m s^{-1}), and very strong (>14 m s^{-1}). Examples of different nocturnal jet scenarios are presented in Fig. 2. Some nights exhibit weak and moderate jets (Figs. 2a,b) either throughout the night or only during a portion of the night, while well-defined strong and very strong jets throughout (Figs. 2c,d) are persistent on other nights. On some weak-to-moderate jet nights, large variations in jet heights are observed during the course of the night (Fig. 2b). Overall, during the complete periods given in Table 1, 62% of the total nocturnal periods (5430 of the total 8785 half-hour periods) exhibit jets. This is significantly higher

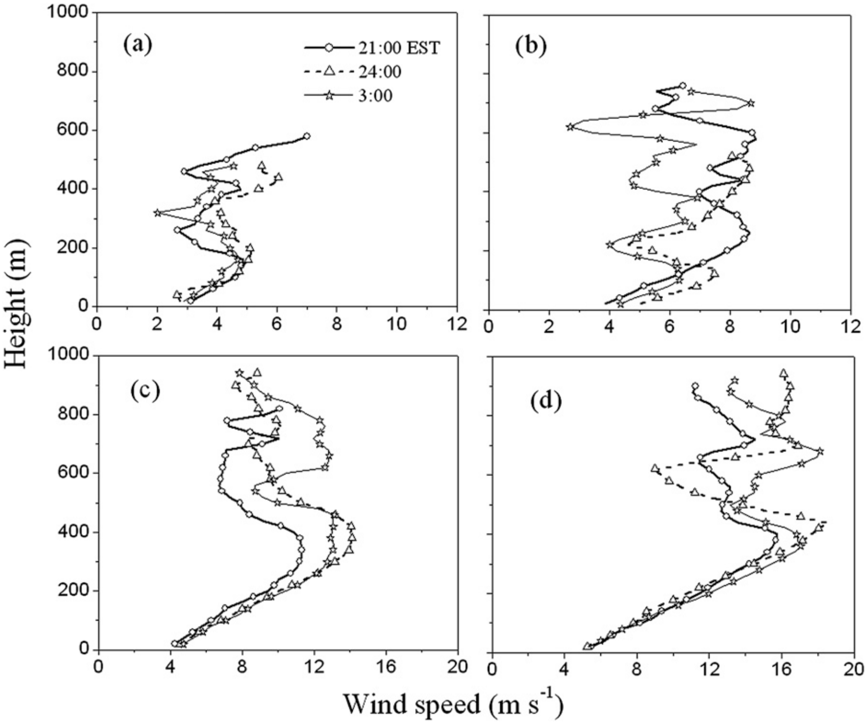

FIG. 2. Sample nocturnal wind profiles exhibiting different categories of low-level jets: (a) weak, (b) moderate, (c) strong, and (d) very strong.

than the 46% observed by Whiteman et al. (1997) in the Great Plains states, but identical to the 63% noticed by Song et al. (2005) at the Atmospheric Boundary Layer Experiment (ABLE) facility in Kansas. It is worthwhile to note that both Whiteman et al. (1997) and Song et al. (2005) used a higher maximum wind threshold and shear criteria to define a LLJ and their study was conducted at a different geographical location. In terms of the number of LLJ nights, 446 of the total 540 nights (82%) have at least one period of jet activity in any of the four jet categories. In total, 64% of the nights have at least one strong or very strong jet period and 18% showed only weak to moderate jets. The number of nights characterized by the presence of strong LLJs (64%) is roughly equivalent to that of Song et al. (2005), which included only jets with maximum speed >10 m s^{-1}. Some LLJ periods also feature multiple maxima in the wind profile. Approximately 18% of the LLJ periods exhibit a secondary peak and 4% exhibit a third peak. Most of these peaks occur above 500 m and are not as well defined as the first peak. The present study focuses only on the first jet maximum above the surface.

The frequency of occurrence of jet speed, height, direction, and shear (between 20 m above ground and the jet height) is estimated using the jets detected in the 30-min interval sodar data. The histograms of the above four parameters are presented in Fig. 3. Results show that jet speeds (Fig. 3a) range between 3 and 21 m s^{-1}, with the majority of them between 6 and 14 m s^{-1}. Nearly 12% of the total observed jets are weak, 44% are moderate, 33% are strong, and the remaining 11% are very strong. Overall, 44% of total LLJs have speeds greater than 10 m s^{-1}, a finding comparable with those of Whiteman et al. (1997), for a similar maximum wind speed threshold. Banta et al. (2002) observed a lower number of jets with speed >10 m s^{-1} at the Kansas site, but their study was limited to a 1-month period during October.

The jet height distribution (Fig. 3b) shows that the heights range between 80 and 700 m. The majority (70%) of jets are below 400 m with 300–400 m being the single height class with the largest number of LLJ occurrence. Several jets during the colder months (November–February) with heights above 400 m belong to the ‘‘very strong’’ jet category. Banta et al. (2002) found jet peaks to hover at levels of approximately 100 m, whereas Song et al. (2005) in the southern Great Plains ABLE study observed most jets at 200–400 m. Over the Great Plains, Bonner (1968) found a much higher mean height (785 m), whereas Whiteman et al. (1997) observed that 57% of the jets occur below 500 m. The warm season LLJ study over the mid-Atlantic states showed jets moving at an average 670-m level (Zhang et al. 2006). The frequency of occurrence of jet

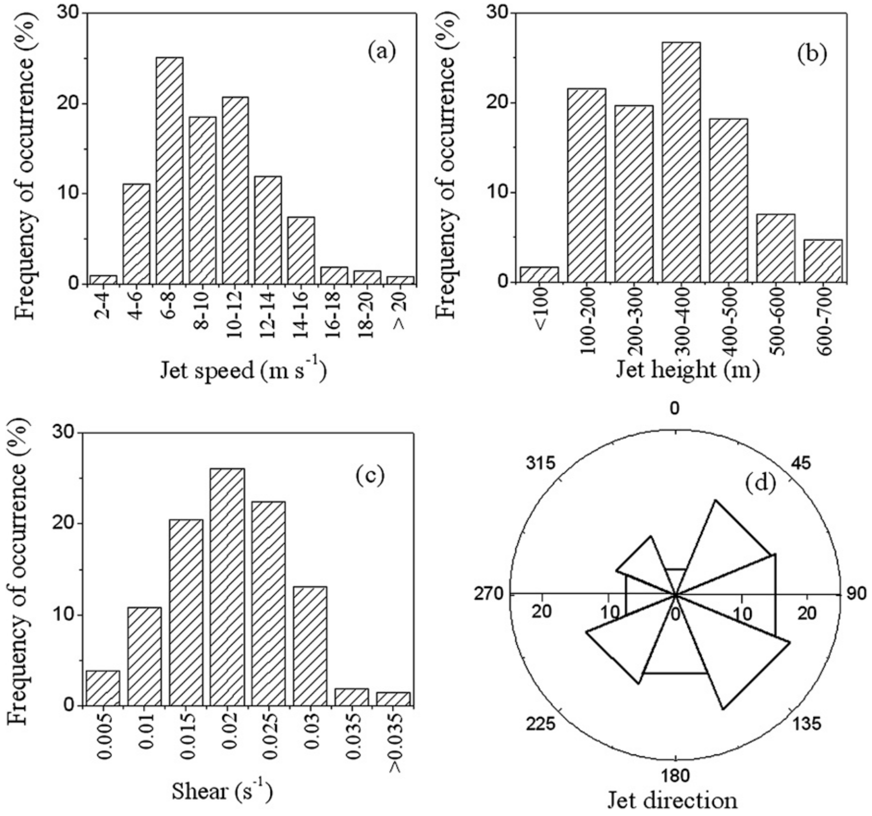

FIG. 3. Histograms of (a) jet speed, (b) jet height, (c) jet shear, and (d) jet direction for all available 30-min periods in the dataset spanning years 2001–05.

shear (Fig. 3c) suggests that approximately 39% of the LLJ periods exhibit a shear greater than 0.02 s^{-1}. Data show that shear increases linearly with wind speed and that a greater shear jet generally occurs below 400 m.

The results further show that southerly jets (wind direction at jet height 90°–270°) are predominant at the site (Fig. 3d). Of the total nocturnal LLJ periods, 62% are either southeasterly or southwesterly. Northeasterly (45°–90°) jets are observed approximately 17% of the total LLJ periods. The north-northwest–north-northeast (315°–360° and 0°–45°) directions have the least LLJ occurrence. The above wind direction distribution indicates that most of the observed jets in this study come from either from the direction of Atlantic Ocean on the northeast–south-southeast or from the direction of Gulf of Mexico on the south-southwest–west-northwest sector. Jets originating from the direction of the Atlantic sector are more frequent than those originating from the Gulf of Mexico sector.

b. *Nocturnal and diurnal variations*

The availability of continuous sodar observations allows us to examine the variability in nocturnal LLJ characteristics. The frequency of LLJ occurrence during hourly nocturnal periods (2000–0500 EST), estimated from two half-hour observations corresponding to each hour, is depicted in Fig. 4a. The frequency increases gradually during evening hours and attains the maximum occurrence of 72% at 0100 EST. The jet occurrence decreases gradually thereafter. The figure also shows that jets are present more frequently during the second half of the night. The histogram of the time of occurrence of the greatest jet speed each night (Fig. 4b), on approximately 63% of the nights, is found during 2300–0200 EST. This suggests that jets observed at the site strengthen gradually following the evening transition to attain maximum strength during midnight hours and then weaken during early morning hours. The maximum number of jets and the greatest jet speed occurs approximately an hour later at night in June–August relative to November–February because of the late sunset in the summer months.

Although our study focuses on the nocturnal LLJ characteristics, it is worthwhile to have a broad understanding of its diurnal behavior. At the Florida AmeriFlux site near Gainesville, the presence of jets is generally less frequent during the daylight hours than at night as

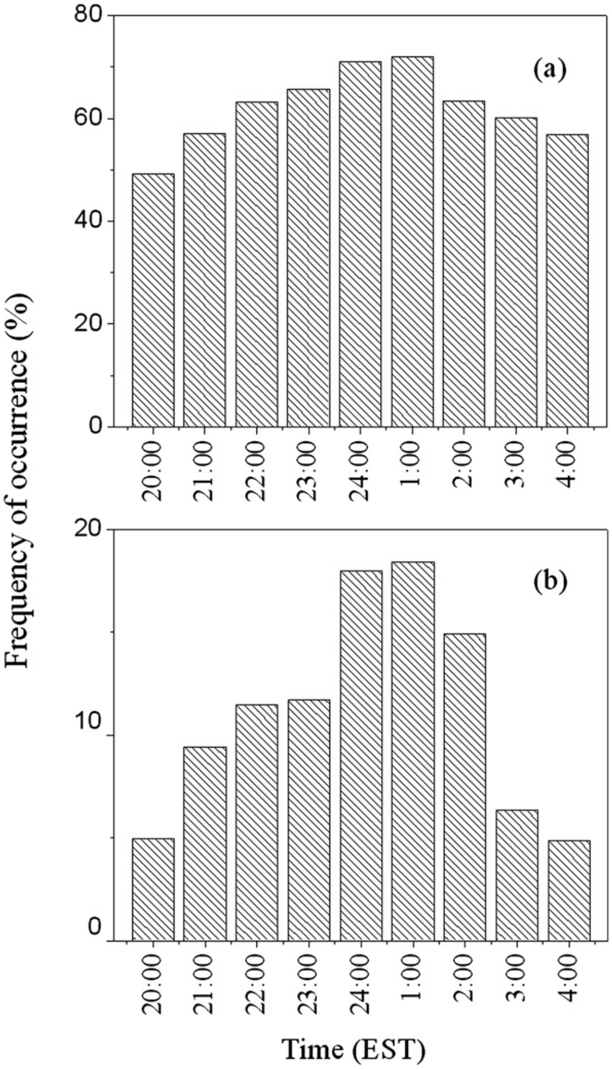

FIG. 4. Nocturnal variations of (a) jet occurrence and (b) occurrence of maximum speed jet in the dataset spanning years 2001–05.

enhanced turbulence and mixing in the daytime unstable boundary layer erodes the jets. Jets present during daylight hours are generally weak and generally occur at a higher elevation. More than 60% of the jet heights during daylight hours are above 500 m and 60%–80% of the daytime jets belong to weak-to-moderate (<10 m s^{-1}) category. The majority of daytime jets below 500 m and greater speeds are from the colder months, mostly under the influence of frontal systems. The daytime jets during warmer months are less frequent, exhibit lower speeds, and occur at higher elevation.

c. Seasonal variations

The frequency of occurrence of the observed jets in each month is presented in Fig. 5a. The months are presented from January to December, and include all the months from the dataset mentioned in Table 1. Approximately 70% of the nocturnal periods during the colder months January–April, November, and December exhibit jets. The occurrence of those jets decreases from May throughout the warmer months June, July, and August in contrast with the colder months. The difference in the frequency of LLJ occurrence between July and the colder months is nearly 27%. The analysis also shows that the duration of warm season jets is shorter than that of the cold season jets and that the presence of jets is more intermittent on several warm season nights. Whiteman et al. (1997) did not see any notable seasonal difference in the LLJ occurrence (45% in winter and 47% in summer) at the Great Plains site. Bonner (1968) noticed that 55%–60% of the total jets occurred during the warm season. Over the mid-Atlantic states, LLJs were observed over an average of 15–25 days of the warm season months May–September (Zhang et al. 2006). The differences between the LLJ definition used by Bonner (1968), Whiteman et al. (1997), and Zhang et al. (2006) and those of the present study should be kept in mind; the reader is also reminded that previous studies alluded to above were conducted at different geographical locations.

The monthly frequency distribution of LLJ speed classes is presented in Fig. 5b. In the present dataset, weak and moderate LLJs dominate (70%–80% combined) the warmer months (June–August). During other months (October–December and January–May), weak LLJs occur during less than 10% of the periods and moderate LLJs occur 30%–50% of the time. Strong LLJs occur 40%–50% throughout most of the colder months. Another notable feature is that very strong LLJs (speed >14 m s^{-1}) occur more frequently (20%–30%) during the colder months November–February. Whiteman et al. (1997) also noticed a more frequent occurrence of weak jets during the warm season and stronger jets in wintertime, although their jet detection criteria was set at a higher jet speed threshold. The estimated shear grouped into two classes 0–0.02 s^{-1} and 0.02–0.04 s^{-1} (Fig. 5d) shows that low-shear jets occur far more frequently during June–September than during the other months, matching the jet speed pattern. The monthly jet height class distribution (Fig. 5c) does not show any significant warm–cold month differences. Most months have nearly 70% of jets below 400 m.

The distribution of wind direction at the jet height (Figs. 6a,b) and a related result on the monthly variation of southerly jet occurrence (Fig. 7a) suggest that close to 80% of the jets are southerly (wind direction at jet height 90°–270°) during the months April–August.

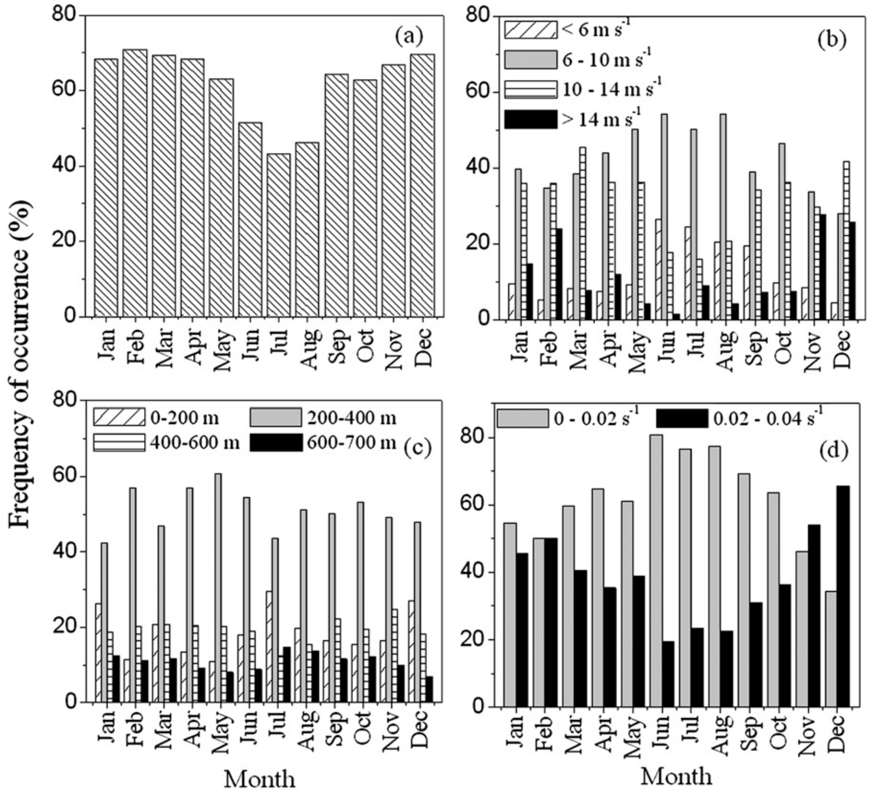

FIG. 5. Monthly distribution of (a) jet occurrence, (b) jet speed, (c) jet height, and (d) jet shear for all available 30-min periods in the dataset spanning years 2001–05.

Among these months, April and May have a higher percentage of southeasterly jets, and June, July, and August have higher southwesterly occurrences. The dominant wind direction follows a steadily rotating clockwise motion from northeasterly in February to southwesterly in August. These wind direction shifts seem to be linked with the variation in the positioning of subtropical high pressure center over the North Atlantic Ocean and the associated synoptic circulation pattern. Most of the colder months have less than 50% of southerly jets (Fig. 7a). September, October, and November have dominant northeasterly jets, and March and April have dominant easterly winds. The colder months are often influenced by the low pressure systems over the southeastern United States and passing frontal systems. As a result, several days in colder months have very strong northeasterly jets with speeds often close to 20 m s^{-1} and small diurnal variations. Song et al. (2005) observed that the occurrence of southerly jet nights increased from the cold season to the warm season with a peak in July at the ABLE facility in Kansas. No significant seasonal difference between northerly and southerly stronger jet (speed $>$10 m s^{-1}) occurrences is noticed in the data (Fig. 7b). However, stronger jets in both categories occur far less frequently during June–August when compared with winter months.

d. Interannual variations

In the present study, continuous sodar measurements from consecutive months throughout the year are limited to the period July 2003–June 2004 (Table 1). Measurements from other years are spread over months from different seasons of the years 2001–05, giving rise to a more challenging meaningful interannual comparison. The NARR wind profile data are used in this study for interannual comparison as a continuous data stream is available for all months during 2001–05, although only at 3-h intervals and at 25-mb vertical resolution. A comparison between LLJ characteristics derived from NARR data and sodar measurements during July 2003–June 2004 showed broadly similar features and seasonal patterns. The NARR data were also used in earlier studies to analyze the variability of the Great Plains LLJ (Weaver and Nigam 2008).

The important features of interannual comparison performed using NARR datasets are summarized in Table 2. Results do not show any significant differences in the yearly mean LLJ characteristics among the four

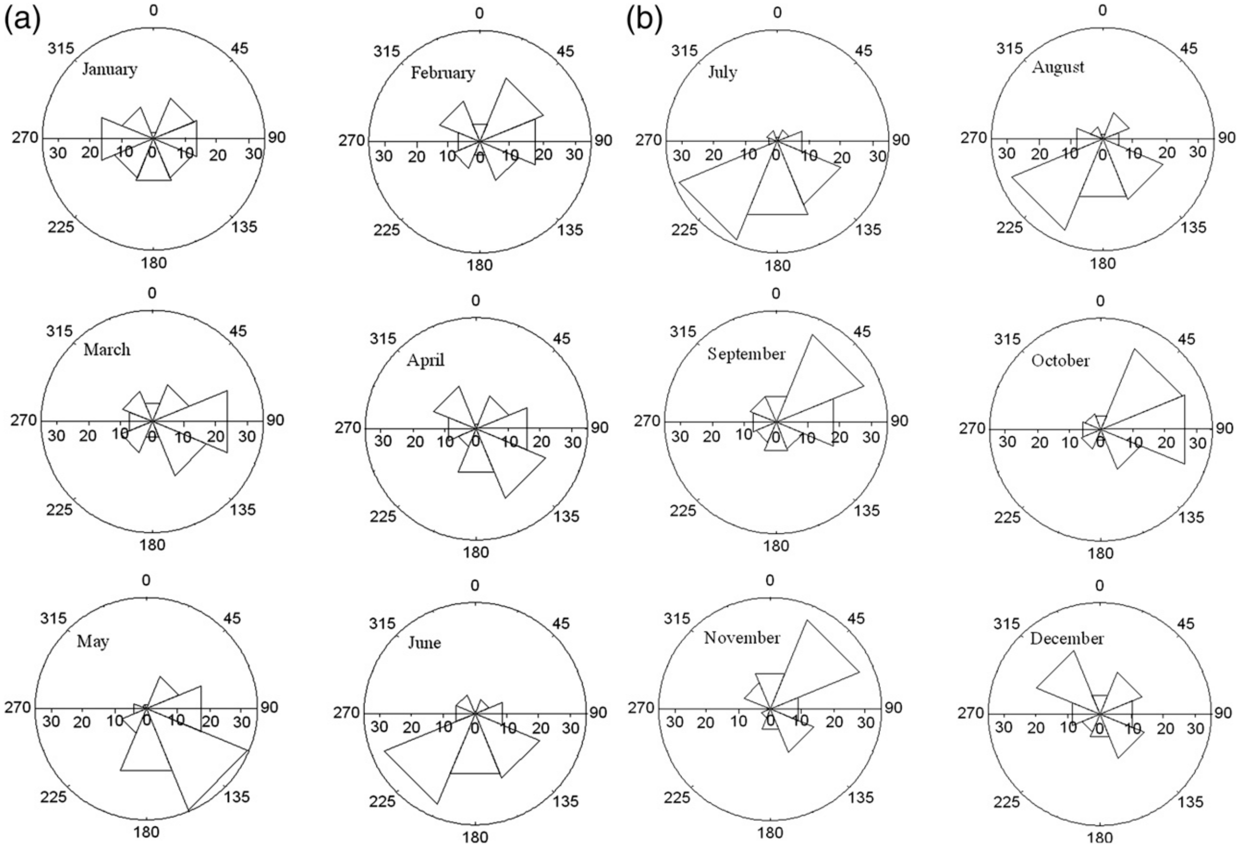

FIG. 6. The frequency of occurrence of wind directions at the jet core for (a) January–June and (b) July–December.

datasets. All four datasets have jet occurrence >63% of the total nocturnal periods, with warmer months showing fewer jet occurrences than do colder months. More than 40% of all jets have speeds >10 m s^{-1} and more than 65% of all jets occur below 400 m. Southerly jets dominate all years, with slightly less occurrence during 2004–05. The monthly distributions of jet occurrence, jets with heights <400 m, stronger jets, and southerly jets presented in Fig. 8 show some variations among the corresponding months of different years, but no clear trend in variations or significant difference is noticed. Most months in 2004–05 have fewer occurrences of southerly jets when compared with other years.

The strength of surface pressure gradients over the region (some of them associated with frontal systems during colder months) is found to strongly influence the occurrence and strength of LLJs at the site. Locations and the strength of the large-scale synoptic patterns and pressure gradients [National Oceanic and Atmospheric Administration (NOAA) surface weather map] show broadly similar patterns with only slight variations among months in the four datasets, which could be one possible reason for the small interannual variations noticed in LLJ characteristics. It is reasonable to expect notable differences in LLJ characteristics during 2002–03, as that year was an El Niño year possibly resulting in some variability in relation to large-scale climatic variations. However, our results do not show any clear differences in particular for this year. In the observations over the mid-Atlantic states, Zhang et al. (2006) noticed that the LLJ was present for 20–25 days of each month during the 2001 warm season and 15–19 days during the 2002 warm season, suggesting a significant variability in frequency from year to year. They attributed the small number of LLJ occurrences in 2002 to the fact that 2002 was an El Niño year with more cloudy/rainy days in the mid-Atlantic states. Our results indicate that nocturnal LLJs at the north Florida site are consistent features, with little year-to-year variability.

e. *Relationship to planetary boundary layer height*

Previous LLJ studies over the U.S. Great Plains (Bonner 1968; Whiteman et al. 1997) and the Antarctic regions (Andreas et al. 2000) have contributed mixed information on the altitude of jets (i.e., whether they occur within or above the nocturnal boundary layer). These

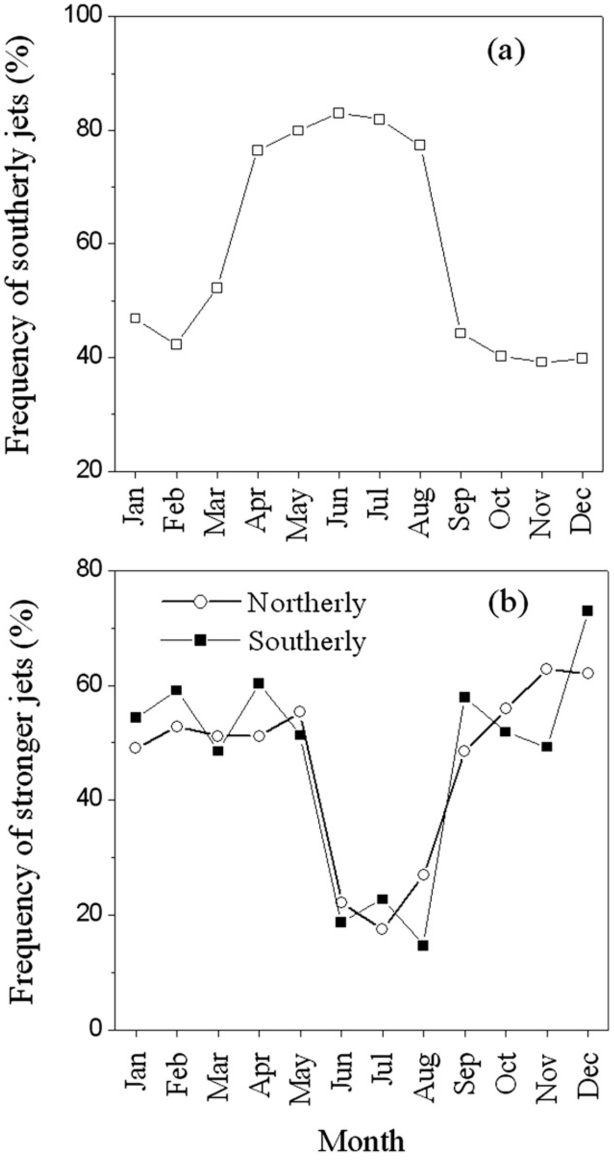

FIG. 7. Variations in the monthly occurrence of (a) southerly jets and (b) stronger (>10 m s^{-1}) northerly and southerly jets.

studies mostly looked at whether jets form below the inversion layer using air temperature soundings. In the present study, the PBL height, which is one of the parameter in the NARR dataset, is analyzed to get an understanding of the occurrence of jet peaks in relation to the boundary layer height. The NARR PBL data have some uncertainty because they are derived from model outputs. The PBL height corresponding to the grid point closest to the site coordinates on the NARR domain during three nocturnal periods (2200, 0100, and 0400 EST) is compared with the observed jet heights during the corresponding hours in the dataset spanning 2001–05. The scatter diagram in Fig. 9 shows that, in approximately 62% of cases, jet heights are at or below the PBL heights. Bonner (1968) examined the relationship between temperature inversions and LLJ development over 60 stations in the Great Plains region for a single jet case. He noticed that, in cases with a distinct inversion, 60% of jets formed either below the inversion top or at about the same height. Whiteman et al. (1997) found that jets generally occurred above the nocturnal inversion, with significant variability from case to case. Andreas et al. (2000) noticed that 91% of jets occurred within the inversion layer. Since our results show that a significant number of jets occur at or below the PBL height, it can be presumed that boundary layer processes play an important role in jets observed at the north Florida location.

f. Causes of jet formation and seasonal variation

Several processes are known to cause LLJs. The most widely studied LLJs are those observed over the Great Plains and attributed to inertial oscillation (Whiteman et al. 1997; Song et al. 2005) and baroclinically induced by the presence of Rocky Mountains (Holton 1967; Bonner 1968). Zhang et al. (2006) also outlined the cause of mid-Atlantic states jets as a combination of inertial oscillation together with land–ocean temperature contrast. In the sections below, possible influences of land–ocean temperature contrast, horizontal pressure gradient, and inertial oscillations on jet formation and seasonal variations are discussed.

1) LAND–OCEAN TEMPERATURE CONTRAST

Baroclinicity associated with horizontal temperature gradient is an important factor in the formation and strength of low-level jets. An analysis of seasonal variations of land–ocean temperature contrast is carried out using NARR surface temperature data during nocturnal periods at 3-h intervals. Surface temperatures at four grid points surrounding the site coordinates (29°45′N, 82°10′W) on the NARR domain are averaged to obtain land surface temperature. Similarly, sea surface temperatures over the Atlantic Ocean and Gulf of Mexico are obtained using averaged surface temperatures at four grid points surrounding locations with coordinates 29°45′N, 80°10′W and 28°45′N, 84°10′W, respectively. The difference in surface temperatures is found by subtracting land surface temperatures from ocean surface temperature during the corresponding nocturnal periods. The monthly average land–ocean temperature difference (Fig. 10) shows that the temperature contrast is smallest during June–August for both Atlantic–land difference as well as Gulf of Mexico–land difference. The colder months have more than 80% of the nocturnal periods with temperature differences >4 K, whereas

TABLE 2. Interannual variations in the low-level jet features between the annual NARR datasets.

Parameter	2001/02	2002/03	2003/04	2004/05
Total LLJ nights (%)	83	85	86	85
Total LLJ events (%)	63	66	64	64
Jet events during warmer months (%) (Jun–Aug)	51	57	52	56
Jet events during colder months (%) (Nov–Feb)	65	70	67	66
Stronger jet (speed >10 m s^{-1}) events (%)	42	40	45	46
Large shear (>0.02 s^{-1}) events (%)	51	50	47	47
Jet heights below 400 m (%)	65	68	71	66
Southerly jet events (%)	60	60	61	54

it is less than 30% in warmer months for the Atlantic–land difference. The temperature difference between the Gulf of Mexico and the site follows the same pattern, except for June–October, the number of periods with temperature difference >4 K is smaller than that of Atlantic–land difference for the corresponding months. The LLJ characteristics discussed earlier (section 3c) showed that June–August have a small number of low-level jets with the majority of them either of weak or moderate strength. These months also have the lowest average ocean–land temperature difference. In contrast, stronger jets are frequent in colder months when the temperature difference is large. In this analysis, a significant percentage of jet periods show veering of wind with height, possibly an indication of warm-air advection. Thus, considering the geographical location of our site, baroclinicity resulting from ocean–land temperature contrast in favorable synoptic conditions is a possible element contributing to the jet formation and its seasonal variation.

2) RELATIONSHIP TO SURFACE PRESSURE GRADIENT

Synoptic forcing coupled to the surface pressure gradient is another important factor that influences jet characteristics. An analysis of the NOAA daily surface

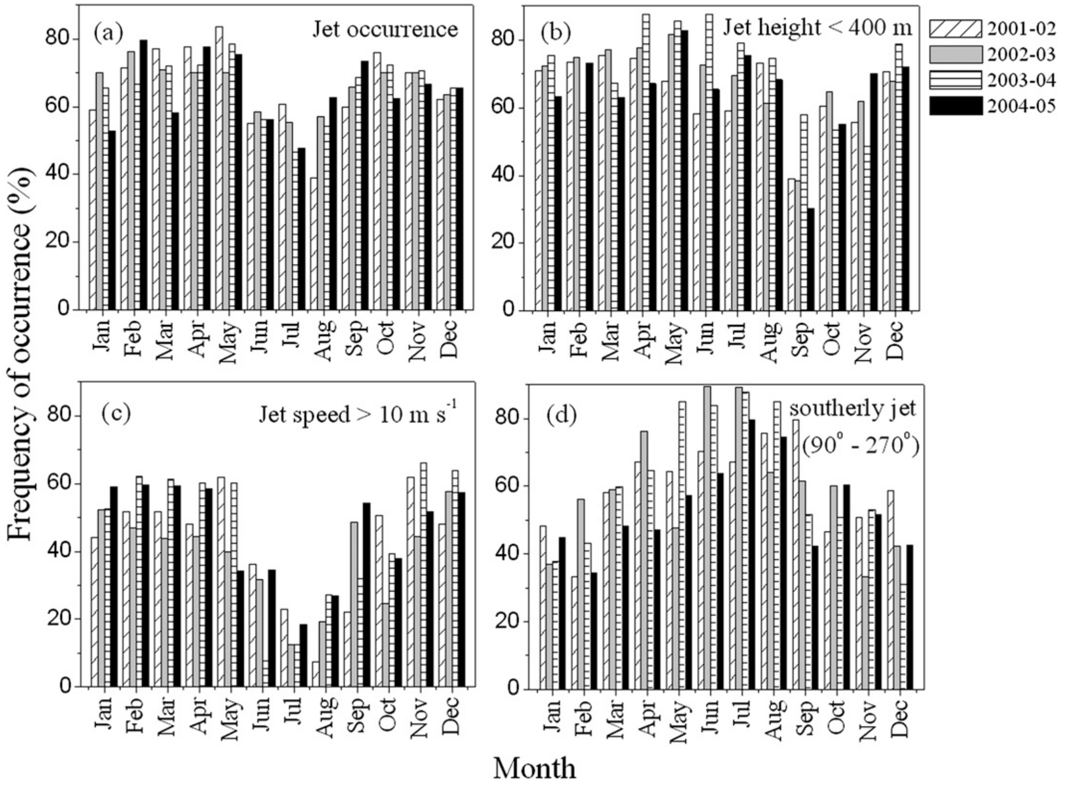

FIG. 8. Comparison of monthly variations in LLJ characteristics among four yearly NARR datasets: (a) jet occurrence, (b) jets occurring below 400 m, (c) stronger jets of speed >10 m s^{-1}, and (d) southerly jets (wind direction 90°–270°).

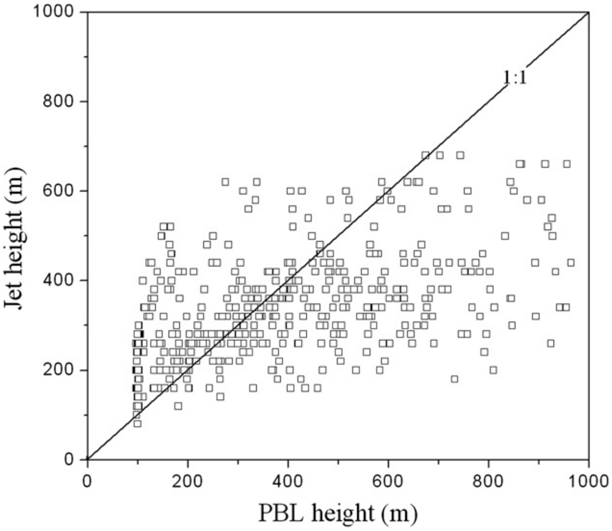

FIG. 9. A comparison of observed jet heights with NARR PBL heights of corresponding periods in the dataset spanning 2001–05.

weather maps shows that the prevailing surface pressure gradient and orientation of isobars in the southeastern United States exert a significant influence on the occurrence, strength, and direction of jets at the Florida AmeriFlux site near Gainesville. Moderate-to-strong high/low pressure systems are frequently observed over the continental United States or over Atlantic Ocean and off the coastal Carolinas during colder months. The subtropical high is very well defined during the summer months June–August in the region with weak pressure gradients, a situation conducive to weak winds and fewer number of jet occurrences during those months. Jets of moderate-to-strong speed (6–14 m s^{-1}) and their directions accompany these pressure systems. The majority of very strong jets (>14 m s^{-1}) are observed during the colder months November–February and they are coincident with large pressure gradients associated with frontal passages.

An analysis on seasonal horizontal surface pressure gradient over the study location is carried out using NARR surface pressure data. The pressure gradient is estimated for a 2° latitude × 2° longitude domain centered on the study location as

$$\sqrt{\left(\frac{\partial p}{\partial x}\right)^2 + \left(\frac{\partial p}{\partial y}\right)^2},$$

where p is the surface pressure and ∂x and ∂y are the distance between the grid points in the east–west and north–south directions, respectively. Periods exhibiting a larger pressure gradient [>0.75 mb (100 km)$^{-1}$] occur more frequently (>60%) during colder months than

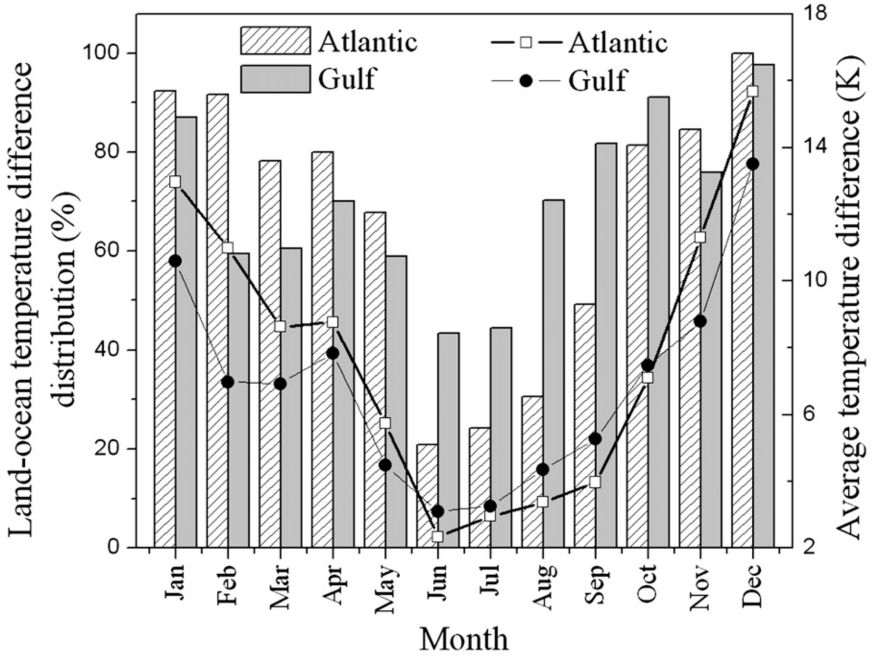

FIG. 10. Monthly distribution of nocturnal periods with land–ocean surface temperature difference >4 K (bars) and variation of average land–ocean temperature difference (lines with symbols). Surface temperature difference between the Atlantic Ocean and land and the Gulf of Mexico and land are shown.

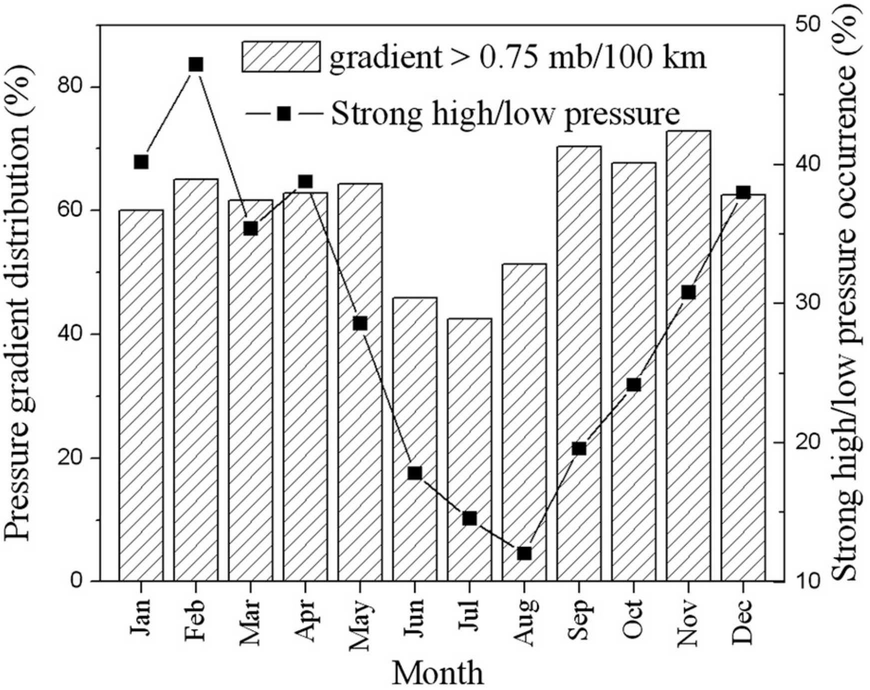

FIG. 11. Monthly distribution of nocturnal periods with surface pressure gradient >0.75 mb $(100\ \mathrm{km})^{-1}$ (bars) and periods of strong high/low pressure systems (line with symbol).

warmer months (Fig. 11). Analyses also reveal that all months except June–August have more than 10% of the periods with pressure gradients >1.5 mb $(100\ \mathrm{km})^{-1}$. The large pressure gradients during colder months result from the prevalence of large number of high or low pressure systems over the region. More than 30% of periods in colder months have ±4-mb pressure difference with the standard atmospheric pressure (i.e., 1013 mb), whereas during June–August such periods are less than 15% (Fig. 11). These results indicate that seasonal variations in the LLJ occurrence and strength correspond to the variations in the prevailing pressure gradient over the region.

3) INERTIAL OSCILLATION MECHANISM

(i) Wind oscillations

Horizontal wind speed hodographs constructed using the jet speed and direction show a distinct diurnal variation on the majority of the stronger jet (>10 m s^{-1}) nights examined. The general behavior is that the mean speed at the jet height undergoes an oscillation as the wind turns clockwise with time during nocturnal periods. On nights with stronger jets, the wind vector oscillation shows a complete circle with clockwise rotation during night. Most daytime periods, except for several winter cases, are seen to deviate from this oscillation pattern due to disruption of jets from enhanced mixing in the unstable boundary layer. During weak-to-moderate wind nights with intermittent jet activity, clockwise turning is noticed only during a fraction of the night and rest of the periods show abrupt jumps. The clockwise turning of wind at the jet height during the night is generally taken as evidence of the presence of inertial oscillations (Whiteman et al. 1997; Zhang et al. 2006; Karipot et al. 2008). Approximately 40% of nights characterized by low-level jets show clear oscillation patterns. This supports the idea that inertial oscillations constitute one of the mechanisms associated with LLJ formation at the study location.

(ii) Hilbert–Huang transform analysis of inertial oscillations

The strength of the Hilbert–Huang transform (HHT) lies in providing better time–frequency localization of events in nonstationary time series, particularly useful in the detection of inertial oscillation events. This relatively new approach, developed by Huang et al. (1998), was previously applied in atmospheric data analysis (Wu et al. 1999; Duffy 2004), including the analysis of boundary layer data (Lundquist 2003). Details on this technique along with a comparison with Fourier and wavelet transforms and their strengths were given in a series of papers by Huang et al. (1998, 1999, 2003). The HHT technique involves a two-step procedure to analyze a time series. The first step, known as the empirical mode decomposition (EMD), deconstructs the original time series into a finite set of intrinsic mode function (IMF) components based on local characteristic time scales of the data. In the second step, the Hilbert transform is applied to each of the IMFs to extract instantaneous frequency and amplitude information as a function of time, known as the Hilbert spectrum. When the Hilbert spectrum is integrated over time, it generates the marginal Hilbert spectrum (Huang et al. 1998), which provides a measure of the total amplitude or energy from each frequency spanning the entire dataset. The HHT method preserves time localities of events and allows exploration of regular and intermittent occurrences of motions with specific frequencies (Huang et al. 1998). Lundquist (2003) used this method to investigate the presence of inertial oscillations in the atmospheric boundary layer at the Kansas site and found that inertial oscillations are frequent with frontal passages.

In the present study, the HHT method is applied to the sodar data at 18 levels between 20 and 700 m, at an interval of 40 m. The data from all 12 months of July 2003–June 2004 are used for the HHT analysis. The month of May 2004 has 30 days of continuous data and has 14 stronger jet nights exhibiting clear oscillation pattern in the wind speed hodograph. For this reason, May 2004 is chosen for this analysis. Figure 12 demonstrates the EMD process in which the wind speed time series at 300 m (Fig. 12a) is broken into a series of IMFs (Figs. 12b–i). The time series shows flow patterns with a periodicity of nearly 24 h as well as larger-scale oscillations with a periodicity of approximately 12 days. The EMD technique resolves intrinsic time scales of the dataset. High-frequency motions are contained in the lower numbered IMFs and the low-frequency motions are resolved in the successive higher IMFs. The inertial oscillation periodicity corresponding to the site latitude 29°45′N is approximately 24 h and events of this periodicity are mostly contained in the IMFs 4 and 5. The eighth IMF (Fig. 12i) corresponds to the low-frequency oscillation visible in the data with a periodicity of 12 days. One difficulty with the present analysis is that the inertial periodicity coincides with the diurnal period, making it hard to distinguish whether the contributions are from inertial oscillations or from diurnal oscillations. The analysis differentiates the two by looking at the specific altitudinal and temporal patterns of events.

The Hilbert transform is applied to each of the eight IMFs independently to determine the local frequencies and amplitudes, thus to generate the Hilbert spectrum of characteristic motions in the dataset (Huang et al. 1998). The Hilbert transforms of all eight IMFs are integrated over time to produce the marginal Hilbert spectrum (Huang et al. 1998), which yield the total energy contribution for each frequency. The marginal Hilbert spectrum is similar to the traditional Fourier spectrum, except that the marginal spectrum does not conserve variance. Figure 13 depicts the marginal Hilbert spectrum of the sodar data at three selected heights: 20, 300, and 500 m. Two distinct peaks are present in the spectra at all three levels; the first one at 1 day^{-1} corresponding to 24-h diurnal–inertial oscillation periodicity and the second one at 0.08–0.1 day^{-1} corresponding to the large-scale pattern observed in the data with a periodicity of approximately 12 days. Although these peaks are seen at all three levels, the peak for 300-m height (which also corresponds to the average jet height observed in May 2004) has greater energy at a 1 day^{-1} frequency (24-h periodicity). If the peak is purely due to diurnal variations, the energy would have been the highest at levels close to the surface as observed by Gupta et al. (1997). Lundquist (2003) argued that spectral peaks associated with inertial oscillations should have preferred levels of occurrence related to the LLJ height. The preference for a higher energy corresponding to the jet height level noticed in our analysis can be taken as evidence to differentiate between diurnal and inertial oscillation contributions.

To explore this aspect further, events with local frequency between 0.95 and 1.05 day^{-1} and nonzero amplitude are selected from sodar data at 18 levels considered for the HHT analysis. The finer resolution possible with HHT technique allows the identification of a narrow frequency range corresponding to the inertial oscillation. The events of greater local amplitude in the above frequency range are further selected by separating only those events that exceed the mean amplitude estimated by averaging instantaneous amplitudes at all levels for the entire time series. The profiles of the percentage of events in the frequency range 0.95–1.05 day^{-1} detected from both these selections are presented in Fig. 14. The profile that includes events of all amplitudes shows that the lowest levels have approximately 25% of events in the frequency range 0.95–1.05 day^{-1} and the largest (~35%) number of events are present at 300 m. The marginal Hilbert spectra (Fig. 13) also show large amplitudes at levels close to jet altitudes. The second profile in Fig. 14, corresponding to the amplitude filtered events, shows a reduced number of events at all levels. The most notable feature is that the large number of events at levels close to the surface has vanished because of amplitude filtering. This is further indication that events of different amplitudes occur in the diurnal–inertial frequency range, but those corresponding to the inertial oscillation associated with LLJ have a large amplitude close to the jet height.

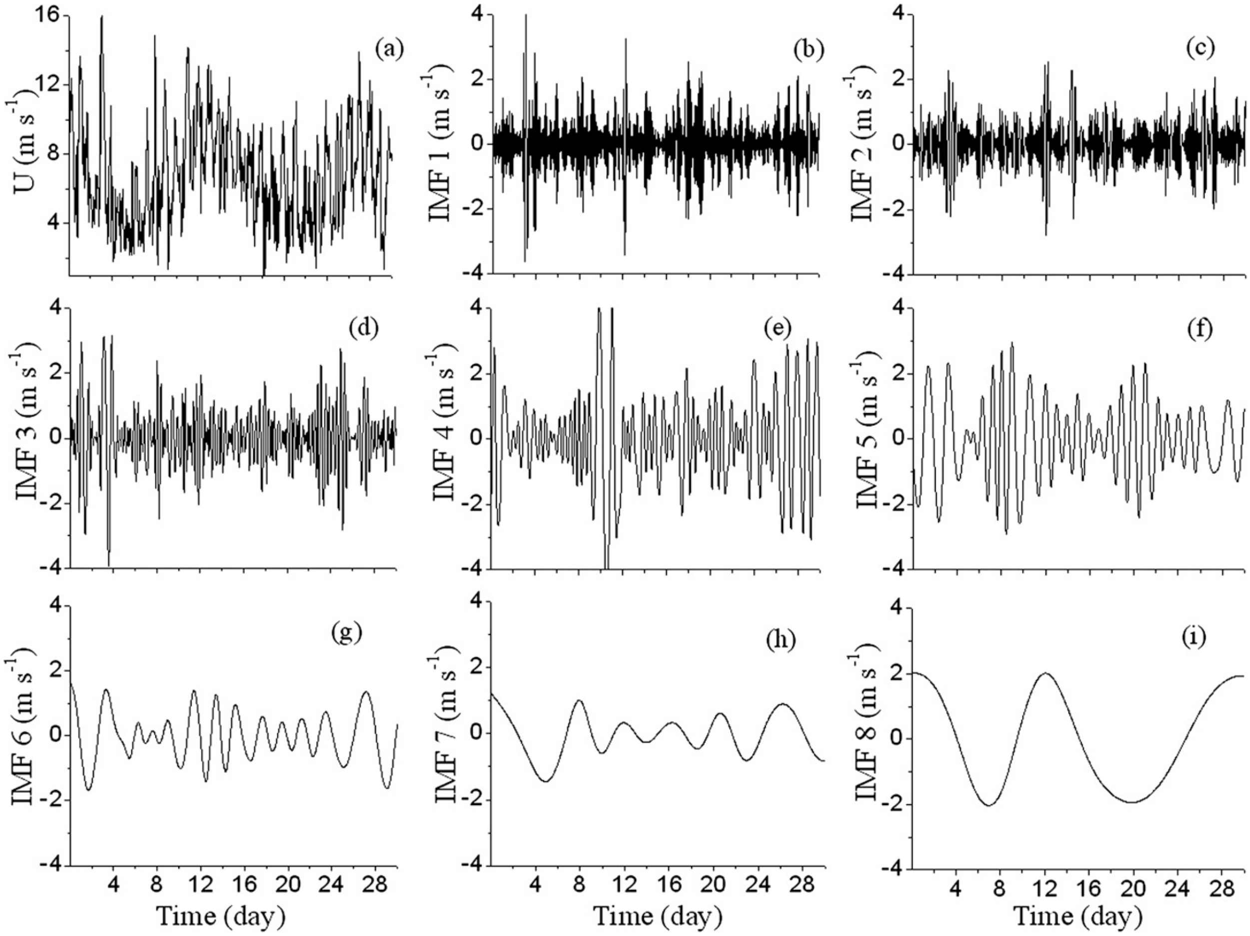

FIG. 12. (a) Time series of wind speed at 300 m during May 2004 and (b)–(i) eight intrinsic mode function components (IMF 1–IMF 8) obtained using empirical mode decomposition.

Inertial oscillations, if present, should exhibit temporal as well as altitudinal variations in the amplitude of an event during the course of the night (Lundquist 2003). The diurnal distribution of hourly-averaged amplitudes of events with frequency in the range 0.95–1.05 day^{-1} during May 2004 is depicted in Fig. 15. As evident from the figure, large-amplitude motions dominate levels 140–500 m and significant diurnal variations are also present at these heights. Large-amplitude motions initially appear close to 140 m during early evening hours and at levels close to 300–400 m later in the night. Amplitudes are generally small during daylight hours. Large-amplitude events (0.95–1.05 day^{-1}) occur at elevations near the jet height.

The detection of inertial-motion events of frequency in the range 0.95–1.05 day^{-1} and of nonzero amplitude exceeding the mean amplitude of all events in the above frequency range is carried out using sodar data during all months in July 2003–June 2004. If an event is thus detected within ±40 m of the LLJ height, it is counted as an inertial-motion event. The percentage of inertial-motion events with respect to the total LLJ occurrence during each month is estimated and given in Table 3. The result shows that a significant number of inertial motion events are present during most months. Although we cannot exclusively conclude that the inertial oscillation mechanism is the sole cause of LLJ at the study location, our analysis suggest that it plays an important role in the generation of at least a part of LLJs observed.

4. Conclusions

The boundary layer sodar data collected during several months in 2001–05 are used to examine the characteristics of the low-level jet observed over north Florida. The results suggest that nearly 62% of the total nocturnal periods have the presence of jets. Stronger jets with speeds exceeding 10 m s^{-1} are observed on 44% of the nocturnal periods. The jet heights range between 80 and

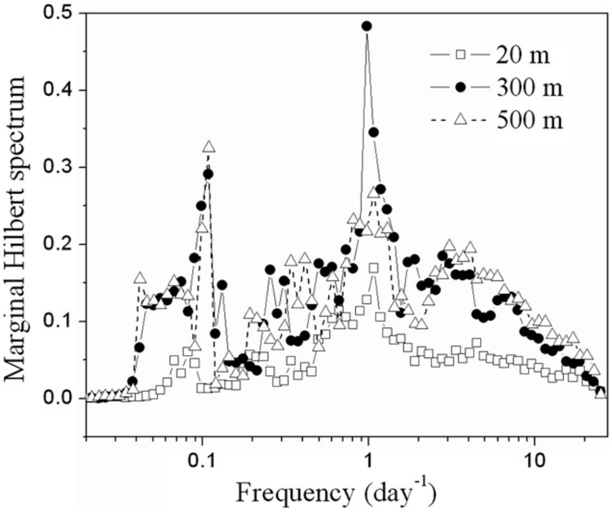

FIG. 13. Marginal Hilbert spectrum of wind speeds at heights 20, 300, and 500 m. All periods during 1–30 May 2004 are used for the analysis. Jet peaks are observed in the vicinity of 300 m during most nights in that month. Peaks at 1 day^{-1} correspond to the inertial oscillation period (24 h) at the study location.

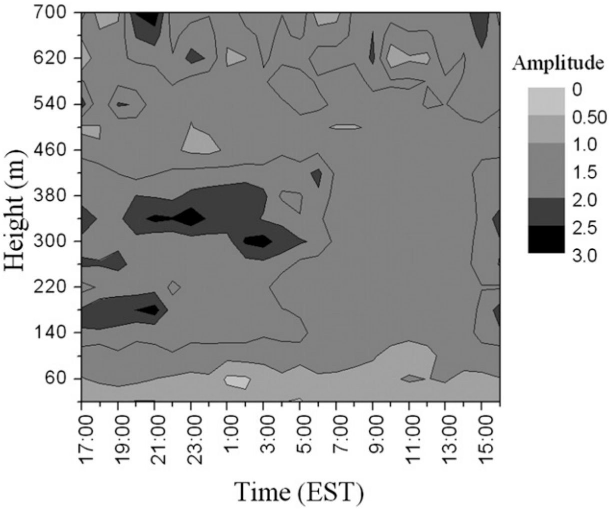

FIG. 15. Diurnal variation of hourly averaged 0.95–1.05 day^{-1} event amplitudes during 1–30 May 2004.

700 m and a majority of them occur below 400 m. The southerly jets occur much more frequently than northerlies, especially during summer months. The positioning of high or low pressure systems and associated pressure gradients over the region contributes to the domination of southerly jets.

The seasonal variations in LLJ occurrence indicate that LLJs are present in approximately 70% of the cold season (November–February) nocturnal periods, whereas the warmer months (June–August) have the least occurrence (~47%). The stronger jets (>10 m s^{-1}), found more frequently in winter, appear to be related to the presence of strong pressure gradients over the region. Several of them are associated with frontal systems as observed at the Great Plains states (Whiteman et al. 1997). The large ocean–land temperature gradient and the associated baroclinicity may be another reason for the high frequency of occurrence of stronger jets in the winter months. The interannual comparison of jet characteristics using North American Regional Reanalysis data during a 4-yr period shows broadly similar features. A comparison of NARR planetary boundary layer heights and observed jet heights indicates that jets frequently occur within the boundary layer.

A clockwise turning of the wind at the jet height and an oscillation in speed are noticed during several nights

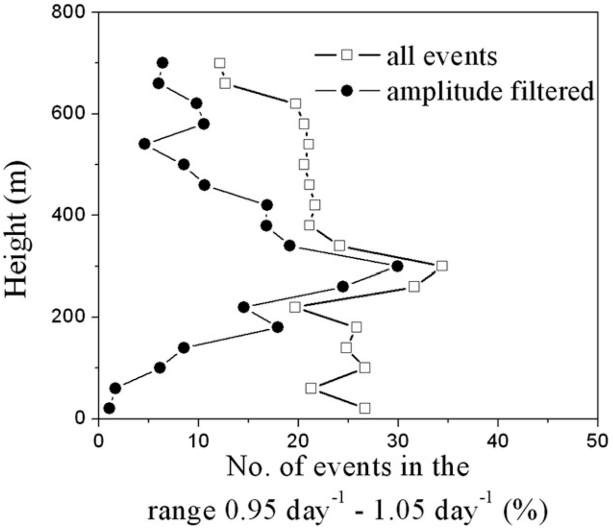

FIG. 14. Variation of 0.95–1.05 day^{-1} events with height for the wind profiles observed during 1–30 May 2004.

TABLE 3. Monthly occurrence of inertial oscillation events during Jul 2003–Jun 2004.

Month	Inertial oscillation events (%)
Jan	42
Feb	46
Mar	42
Apr	39
May	44
Jun	10
Jul	12
Aug	15
Sep	28
Oct	38
Nov	45
Dec	44

with strong jets. The Hilbert–Huang transform analysis indicates preference for a higher number of occurrences of large-amplitude 24-h periodic motions at heights corresponding to the jet core. Our results suggest that, in the presence of a strong pressure gradient over the region, the jet formation appears to be related to inertial oscillations and baroclinicity associated with ocean–land surface temperature gradient.

The low-level jet characteristics estimated from both in situ sodar measurements as well as the NARR wind profile data categorically demonstrate that LLJs are a dominant nocturnal atmospheric feature over north Florida. In light of the above findings and considering the ability of LLJs to transport moisture and other atmospheric constituents, spatial variations of the jet characteristics, along with their influence on weather events in the region, should be examined.

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REFERENCES

Andreas, E. L, K. J. Claffey, and A. P. Makshtas, 2000: Low-level atmospheric jets and inversions over the western Weddell sea. *Bound.-Layer Meteor.,* **97,** 459–486.

Arritt, R. W., T. D. Rink, M. Segal, D. P. Todey, C. A. Clark, M. J. Mitchell, and K. M. Labas, 1997: The Great Plains low-level jet during the warm season of 1993. *Mon. Wea. Rev.,* **125,** 2176–2192.

Banta, R. M., R. K. Newsom, J. K. Lundquist, Y. L. Pichugina, R. L. Coulter, and L. Mahrt, 2002: Nocturnal low-level jet characteristics over Kansas during CASES-99. *Bound.-Layer Meteor.,* **105,** 221–252.

Blackadar, A. K., 1957: Boundary-layer wind maxima and their significance for the growth of nocturnal inversions. *Bull. Amer. Meteor. Soc.,* **38,** 283–290.

Bonner, W. D., 1968: Climatology of the low level jet. *Mon. Wea. Rev.,* **96,** 833–850.

Burk, S. D., and W. T. Thompson, 1996: The summertime low-level jet and marine boundary layer structure along the California coast. *Mon. Wea. Rev.,* **124,** 668–686.

Duffy, D. G., 2004: The application of Hilbert–Huang transforms to meteorological datasets. *J. Atmos. Oceanic Technol.,* **21,** 599–611.

Gupta, S., R. T. McNider, M. Trainer, R. J. Zamora, K. Knuff, and M. P. Singh, 1997: Nocturnal wind structure and plume growth rates due to inertial oscillations. *J. Appl. Meteor.,* **36,** 1050–1063.

Higgins, R. W., Y. Yao, E. S. Yarosh, J. E. Janowiak, and K. C. Mo, 1997: Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. *J. Climate,* **10,** 481–507.

Hoecker, W. L., 1963: Three southerly low-level jet systems delineated by the Weather Bureau special pibal network of 1961. *Mon. Wea. Rev.,* **91,** 573–582.

Holt, T. R., 1996: Mesoscale forcing of a boundary layer jet along the California coast. *J. Geophys. Res.,* **101,** 4235–4254.

Holton, J. R., 1967: The diurnal boundary layer wind oscillation above sloping terrain. *Tellus,* **19,** 199–205.

Huang, N. E., and Coauthors, 1998: The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis. *Proc. Roy. Soc. London,* **454A,** 903–995.

——, Z. Shen, and S. R. Long, 1999: A new view of nonlinear water waves: The Hilbert spectrum. *Annu. Rev. Fluid Mech.,* **31,** 417–457.

——, M. L. Wu, S. R. Long, S. S. Shen, W. D. Qu, P. Gloersen, and K. L. Fan, 2003: A confidence limit for the empirical mode decomposition and the Hilbert spectral analysis. *Proc. Roy. Soc. London,* **459A,** 2317–2345.

Karipot, A., M. Y. Leclerc, G. Zhang, T. Martin, G. Starr, D. Hollinger, J. H. McCaughey, and G. R. Hendrey, 2006: Nocturnal CO_2 exchange over a tall forest canopy associated with intermittent low-level jet activity. *Theor. Appl. Climatol.,* **85,** 243–248.

——, ——, ——, K. F. Lewin, J. Nagy, G. R. Hendrey, and G. Starr, 2008: Influence of nocturnal low-level jet on turbulence structure and CO_2 flux measurements over a forest canopy. *J. Geophys. Res.,* **113,** D10102, doi:10.1029/2007JD009149.

King, J. C., and J. Turner, 1997: *Antarctic Meteorology and Climatology*. Cambridge University Press, 409 pp.

Li, J., and Y.-L. Chen, 1998: Barrier jets during TAMEX. *Mon. Wea. Rev.,* **126,** 959–971.

Lundquist, J., 2003: Intermittent and elliptical inertial oscillations in the atmospheric boundary layer. *J. Atmos. Sci.,* **60,** 2661–2673.

Mahrt, L., 1999: Stratified atmospheric boundary layers. *Bound.-Layer Meteor.,* **90,** 375–396.

Mathieu, N., I. B. Strachan, M. Y. Leclerc, A. Karipot, and E. Pattey, 2005: On the use of NBL budget technique: Delineating optimum atmospheric conditions. *Agric. For. Meteor.,* **135,** 35–43.

McCorkle, M. D., 1988: Simulation of surface-moisture effects on the Great Plains low-level jet. *Mon. Wea. Rev.,* **116,** 1705–1720.

McNider, R. T., and R. A. Pielke, 1981: Diurnal boundary-layer development over sloping terrain. *J. Atmos. Sci.,* **38,** 2198–2212.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.,* **87,** 343–360.

Mitchell, M. J., R. W. Arritt, and K. Labas, 1995: A climatology of the warm season Great Plains low-level jet using wind profiler observations. *Wea. Forecasting,* **10,** 576–591.

Parish, T. R., 1983: The influence of the Antarctic Peninsula on the wind field over the western Weddell Sea. *J. Geophys. Res.,* **88,** 2684–2692.

——, 2000: Forcing of the summertime low-level jet along the California coast. *J. Appl. Meteor.,* **39,** 2421–2433.

——, A. R. Rodi, and R. D. Clark, 1988: A case study of the summertime Great Plains low level jet. *Mon. Wea. Rev.,* **116,** 94–105.

Smedman, A. S., H. Bergstrom, and U. Hogstrom, 1995: Spectra, variances and length scales in a marine stable boundary layer dominated by a low-level jet. *Bound.-Layer Meteor.,* **76,** 211–232.

Song, J., K. Liao, R. L. Coulter, and B. M. Lesht, 2005: Climatology of the low-level jet at the Southern Great Plains atmospheric boundary layer experiment site. *J. Appl. Meteor.,* **44,** 1593–1606.

Uccellini, L. W., 1980: On the role of upper tropospheric jet streaks and leeside cyclogenesis in the development of low-level jets in the Great Plains. *Mon. Wea. Rev.,* **108,** 1689–1696.

Weaver, S. J., and S. Nigam, 2008: Variability of the Great Plains low-level jet: Large-scale circulation context and hydroclimate impacts. *J. Climate,* **21,** 1532–1551.

Whiteman, C., D. X. Bian, and S. Zhong, 1997: Low-level jet climatology from enhanced rawinsonde observations at a site in the southern Great Plains. *J. Appl. Meteor.,* **36,** 1363–1376.

Wu, M. L. C., S. Schubert, and N. E. Huang, 1999: The development of the South Asian summer monsoon and the intraseasonal oscillation. *J. Climate,* **12,** 2054–2075.

Wu, Y., and S. Raman, 1998: The summertime Great Plains low-level jet and the effect of its origin on moisture transport. *Bound.-Layer Meteor.,* **88,** 445–466.

Zemba, J., and C. A. Friehe, 1987: The marine boundary layer jet in the coastal ocean dynamics experiment. *J. Geophys. Res.,* **92,** 1489–1496.

Zhang, D.-L., S. Zhang, and S. J. Weaver, 2006: Low-level jets over the mid-Atlantic states: Warm-season climatology and a case study. *J. Appl. Meteor. Climatol.,* **45,** 194–209.

Zhong, S., J. D. Fast, and X. Bian, 1996: A case study of the Great Plains low-level jet using wind profiler network data and a high resolution mesoscale model. *Mon. Wea. Rev.,* **124,** 785–806.