Meteorologische Zeitschrift, Vol. 23, No. 3, 295–304 (published online August 27, 2014)

Wind speed and shear associated with low-level jets over Northern Germany

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(Manuscript received November 22, 2013; in revised form February 19, 2014; accepted April 11, 2014)

Abstract

Nearly two years of SODAR measurements in Hannover, Northern Germany have been analysed for the frequency of occurrence of low-level jets and their properties. Characteristic properties such as the height of the jet core above ground, maximum wind speed, and wind shear underneath the jet core have been derived from the data set. The occurrence of these jets, which appear in a bit more than 20 % of all nights, is correlated with the occurrence of typical large-scale weather patterns ("Großwetterlagen"). Maximum wind speed and height of the jet are positively correlated to each other and both increase with increasing geostrophic forcing. The evaluations further show that low-level jet wind speeds tend to develop until the bulk shear underneath the jet core reaches a critical threshold of about 0.08 s^{-1}. Further increase in speed of the jet is then assumed to be linked to a growing height of the jet core above ground keeping the shear at its critical value.

Keywords: stable boundary layer, low-level jet, climatology, SODAR data, critical shear, energy meteorology

1 Introduction

Low-level jets (LLJ) considered in this paper are wind speed maxima which form at the top of surface air layers that underwent a sudden change from a state of fully-developed turbulence to a low-turbulence or even quasi-laminar flow (evening transition). The friction-induced downward momentum flux is very much decreased in such a layer with strongly reduced turbulence. The considered jets are thus inertial oscillations which come into existence due to the sudden disappearance of the retarding frictional force exerted by the underlying surface while the driving geostrophic pressure force is unchanged. These jets are usually characterized by super-geostrophic wind speeds and a gradual turning of the wind direction with time due to the influence of the Coriolis force (see Fig. 1 and, e.g., Lettau 1954; Blackadar 1957). Nocturnal LLJs frequently form over land when the surface layer turbulence decreases following the stabilization due to radiative cooling of the underlying surface. Usually, this happens, when the near-surface cooling after sunset occurs rather fast (i.e., more than about 0.5 degrees per hour which leads to inversion strengths of more than 1 K per 100 m (these were the LLJ identification criteria used in Kottmeier et al., 1983). These jets disappear the next morning after radiative warming of the surface by incoming solar radiation produced thermally induced turbulence again.

A similar feature are offshore LLJs which form in flows where surface-layer turbulence is strongly reduced due to the transit of the flow from rough land surfaces to smooth water surfaces (Smedman et al. 1993). This coastal phenomenon is especially pronounced when the water is cooler than the air (Garratt and Ryan 1989). Marine LLJs only disappear gradually when the newly formed internal boundary layer over the sea surface finally fills the full depth of the marine boundary layer.

LLJs have been observed in many parts of the world. Wippermann (1973) reported observations from the United States (see Bonner (1968) as well), from Canada, Western Peru, the Saharian desert, Kenia, other parts of tropical Africa, the Sovjet Union, the Indian Ocean and from the Antarctic Plateau. LLJs can only form at higher latitudes than of 20° (Wippermann 1973; Krishna 1968), because otherwise the development of the inertial oscillation takes too much time. Please note that Bonner (1968) dealt with LLJs over the Great Plains east to the Rocky Mountains chain in the USA. Over the Great Plains, due to orographic forcing, the LLJ phenomenon is much more frequent than, e.g., in Central Europe. Here, in this study, we stick to the purely stability related phenomenon first described by Lettau (1954) and Blackadar (1957).

LLJs over Northern Germany have already been analysed from mast measurements at Gartow (Kottmeier et al. 1983). They found a frequency of occurrence of 10 % of all nights. This rather low frequency is mainly due to the fact that they only included cases where the maximum jet speed was at least one and a half times larger than the geostrophic wind speed. The present study will not use this criterion and will show that then the frequency is about double as high. A first indication for a higher frequency of roughly 20 % of all

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DOI 10.1127/0941-2948/2014/0551
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

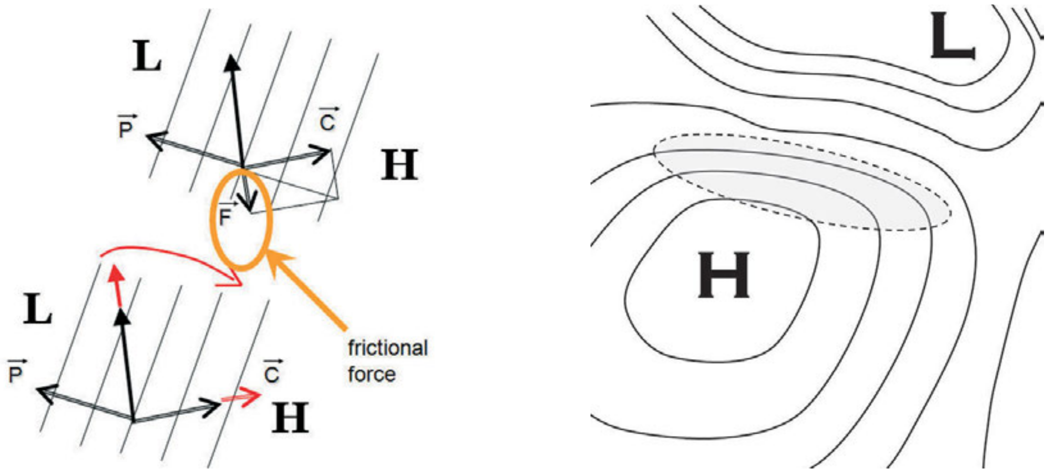


Figure 1: Left: Balance of forces during the formation of a LLJ (top: daytime, bottom: after sunset, red arrows indicate the change from day to night, *F*: frictional force, *P*: pressure gradient force, *C*: Coriolis force, no label: resulting wind vector). Thin straight lines are isobars; low pressure is to the left. Right: the shaded area at the fringe of a high pressure area ("H") close to a low pressure system ("L") is a favourable area for LLJ formation.

nights was already given by Baas et al. (2009) who evaluated data from the 200 m tower and a wind profiler in Cabauw in the Netherlands. SODAR data from Northern Germany were also used by Beyrich (1994). He detected that LLJs coincide with a typical temporal development of the height of the stable nocturnal boundary layer, i.e., an increase of this height in the first half of the night and a decrease in the second half. This decrease is associated with the occurrence of the jet.

LLJs are currently becoming increasingly important for wind energy (Emeis 2012; Emeis, in print) and this paper will focus on this. Apart from this, they are important for nocturnal longer distance transports of air pollutants in the residual layer, for increased vertical mixing at night-time (Reitebuch et al., 2000) and also for nocturnal noise propagation (Heimann et al. 2010). Therefore, reliable information on the factors which govern maximum jet wind speed, jet height, and wind shear underneath the jet axis are needed.

Therefore, SODAR data will be evaluated here. The used long-range SODAR can detect wind speeds up to about one kilometre in ideal conditions. LLJ core heights up to about 600 m have been identified in the data set that is presented here. The nearly two-year-long data set available from SODAR measurements in Northern Germany seems to be well-suited for a LLJ study. Existing investigations on LLJs were either mostly (a notable exception is the 7-year study by Baas et al. (2009)) confined to shorter measurement campaigns (e.g., Banta et al. 2003, 2006; Banta 2008), limited to tower data with limited height and height resolution (e.g., Kottmeier et al. 1983), confined by a limited temporal resolution (e.g., Bonner (1968) used radiosonde data with 6 hour resolution), or were case studies with numerical models (e.g., a LES study by Cuxart and Jiménez 2007). Mesoscale numerical models still have systematic deficiencies in simulating LLJs. For instance, WRF simulations can capture some of the essential characteristics of LLJs, but give too large heights of the jet core and simultaneously too low core wind speeds (Storm et al. 2009). The counteracting aims in representing stable surface layers and large-scale pressure patterns in these models are discussed in detail in Sandu et al. (2013).

This paper will start with a short overview on the measurements, the SODAR instrument, the evaluation method, and on additional data sources. The following Results section is split in an investigation of the favourable large-scale weather situations for the occurrence of LLJs, the correlation of LLJ properties with local meteorological parameters, and the correlation between different parameters of the LLJs themselves. Hub heights of modern multi-MW wind turbines between 100 and 150 m above ground and rotor diameters of more than one hundred metres now frequently expose modern wind turbines to LLJs. Therefore, this paper will address especially this height by analysing the SODAR data at 160 m. The paper is finalized with Conclusions and a short Outlook.

2 Measurement site, instrumentation, evaluation method and additional data sources

The SODAR used in this study is a METEK DSDR3x7 three antenna SODAR which was operated on a large industrial area close to the city centre of Hannover, Northern Germany, from mid May 2001 to mid April 2003. Hannover is situated in essentially flat terrain. The siting in an industrial area caused some interference with environmental noise during daylight hours on weekdays. Nevertheless, it is assumed that the nocturnal LLJ measurements are uncorrupted. The SODAR data were obtained at 1674 Hz and have a temporal resolution of 30 min and a vertical resolution of 25 m. The lowest range gate was at 60 m. Data are completely missing from mid of May to end of July 2002 because the instrument was operated at another site during this period. All in all, 620 days of SODAR data were available with a height range for Doppler wind speed data between 250 and 800 m. 132 LLJ cases were identified. Further details on the campaign in Hannover and the operation of the SODAR can be found in Emeis and Türk (2004) and Emeis et al. (2004). The fact that the data were obtained over a city with a very rough surface is not corrupting the evaluation, because LLJs are a regional phenomenon which form over larger areas (Corsmeier et al. 1997).

LLJs were identified by visual inspection from time-height cross-sections (sodargrams) of horizontal wind speed, vertical velocity variance, and acoustic backscatter intensity in this study. Visual inspection instead of an objective search criterion was used due to two specific properties of Doppler SODAR wind data. Quite often, wind data are retrieved only for the lower half of LLJs. I.e., the LLJ is found at the upper bound of the retrieved data. Furthermore, the height of the available uppermost wind data is changing frequently due to the varying atmospheric conditions which influence the signal-to-noise ratio of the retrieved SODAR data. Additionally, LLJs show a large variability and already Beyrich (1994) stated that there is no overall accepted definition of the nocturnal jet. Here, in this study, an event has been characterized as LLJ event when wind speed in the height range between 150 m and the upper bound of the available wind data increased and vertical velocity variance simultaneously decreased during the hours around or shortly after sunset of days which had previously shown the development of a convective boundary layer (indicated by high vertical velocity variance and simultaneously high acoustic backscatter intensity close to the ground). This rapid reduction of the vertical velocity variance is typical for calm weather conditions. By applying this criterion, wind speed increases due to worsening weather is usually excluded. An additional necessary criterion was the disappearance of the nocturnal wind speed maximum around sun rise at the next morning.

Jet core height and maximum jet speed were identified by searching the highest wind speed value during the selected nights. When the highest wind speed value was the uppermost information available, we then assumed that the height of this value was the jet core height. The reason for this choice is that SODAR instruments need a certain level of turbulence at night-time to detect wind speed, because otherwise the signal-to-noise ratio is too low for the algorithm detecting the Doppler shift. Shear and thus turbulence usually is higher below the jet core than above so that jet core height is often the height from which the uppermost wind speed information is available in SODAR data. Therefore, the decrease of the wind speed above the core height was not included in the criteria to identify the jet.

In the next step the highest wind speed at 160 m above ground was searched during LLJ nights within three hours of the occurrence of the maximum jet speed. This height is relevant, because it will become a typical hub height of large onshore wind turbines in Germany. Wind shear below and above 160 m were determined from the wind speed gradients between the surface (zero wind speed assumed) and 160 m and between 160 m and the jet core height (taking the maximum speed observed during this night).

The driving pressure gradient force is usually described by the surface geostrophic wind. Here, midnight (00 UTC) 850 hPa winds were obtained from radiosonde data measured at Bergen (WMO number 10238, roughly 60 km north of Hannover) as driving wind speeds. They are available on the internet on the pages of the University of Wisconsin. This wind speed is probably a good representation of the lower tropospheric pressure gradient, because it is from a height of approximately 1500 m above ground, which should be well above the nocturnal boundary layer. Beyrich (1994) used 850 hPa winds as an estimate of geostrophic winds as well. Geostrophic wind speeds may vary with height due to baroclinity. Baas et al. (2009), who used the 1500 m wind speed from a weather model output in their LLJ study, investigated this and demonstrated that the bias to the geostrophic wind speed during their ten years of data was only 0.1 ms^{-1} (standard deviation was 1.6 ms^{-1}). Relative humidity at 850 hPa was extracted from this radiosonde data as well.

The typical weather patterns ("Großwetterlagen") are available from subjective classification as daily values. Here, the classification of Gerstengarbe and Werner (2005) was used which is mainly based on the 500 hPa flow patterns and the surface pressure patterns.

3 Results and discussion

3.1 Correlation with typical weather patterns

Before looking into the specific properties of the LLJs, the frequency of their occurrence is analysed. This frequency is linked to the appearance of certain weather or circulation types ("Großwetterlagen", Gerstengarbe and Werner, 2005), because the development of a LLJ requires situations with nocturnal radiative surface cooling and a non-vanishing large-scale horizontal pressure gradient (Fig. 1 right). Fig. 2 left shows the frequency of occurrence of LLJs over Hannover as function of these 29 large-scale weather types. LLJs were detected for 19 (65.5 %) out of the 29 circulation types. The highest number of LLJs appears for the type "bridge over Central Europe (BM)". The objective weather type classification of the German Meteorological Service (Bissoli and Dittmann 2001) gives a less sharp classification, i.e., 30 (75 %) out of the 40 circulation types offer favourable conditions for the formation of a LLJ. Therefore, this latter classification has not been used here.

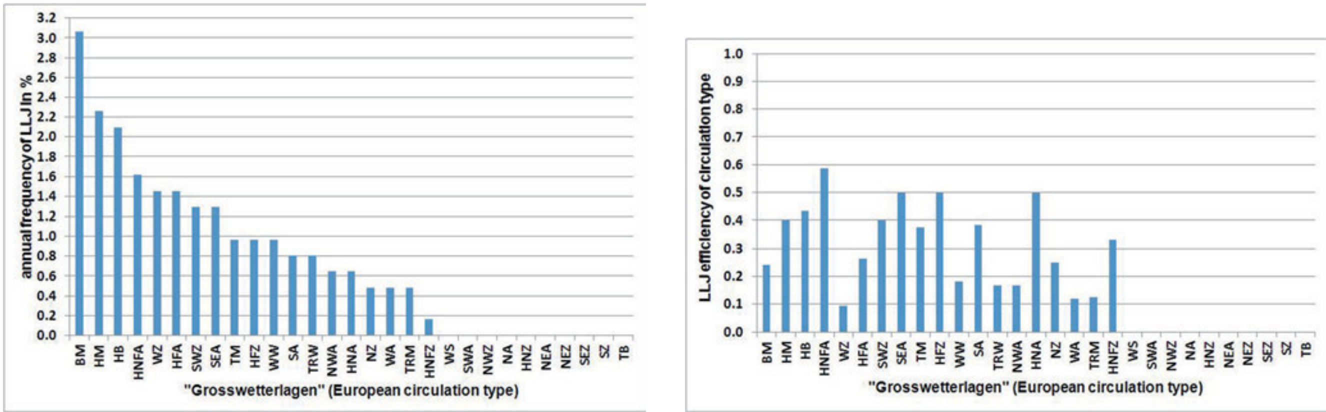


Figure 2: Left: Frequency of occurrence of LLJs over Hannover, Germany as function of European circulation types (Großwetterlagen, see Gerstengarbe and Werner 2005 for definitions and details). Right: Efficiency of European circulation types to develop a LLJ.

The cumulated frequency over all circulation types is about 21.3 % (132 of 620 nights). Normalizing the frequencies in Fig. 2 left with the overall occurrence probability of the circulation types within these 620 days gives a measure for the efficiency of each of these circulation types to favour the formation of LLJs. This efficiency is depicted in Fig. 2 right. The most efficient circulation type with respect to the occurrence of LLJs is HNFA (high pressure over the North Atlantic and Scandinavia with anticyclonic curvature of the pressure isolines over Central Europe). A LLJ appeared in nearly three out of five nights with this circulation type. Germany is situated at the southern fringe of a Scandinavian anticyclone during the occurrence of this weather pattern. Three further anticyclonic circulation types (SEA (flow from the Southeast, anticyclonic), HFZ (high pressure over Scandinavia with cyclonic curvature of the pressure isolines over Central Europe) and HNA (high pressure over Iceland with anticyclonic curvature of the pressure isolines over Central Europe)), during which the anticyclone is to the North or the East of the area of interest exhibit the development of the jet in every second night.

3.2 Correlation with meteorological parameters

An important driving force for the formation of LLJ is the large-scale synoptic pressure gradient. Therefore, Fig. 3 shows the correlation between the maximum LLJ core wind speed and the 850 hPa winds. Fig. 3 top shows a reasonable correlation which explains 24 % of the variance of the LLJ core wind speed data. Most jets form for 850 hPa wind speeds below 14 ms^{-1}. Only twelve events formed at higher 850 hPa wind speeds and none of these exhibited higher core speeds than the maximum speed which was found at 13ms^{-1}. A possible explanation for this feature is that boundary layer turbulence tends to increase with higher synoptic forcing which suppresses the formation of stronger LLJs.

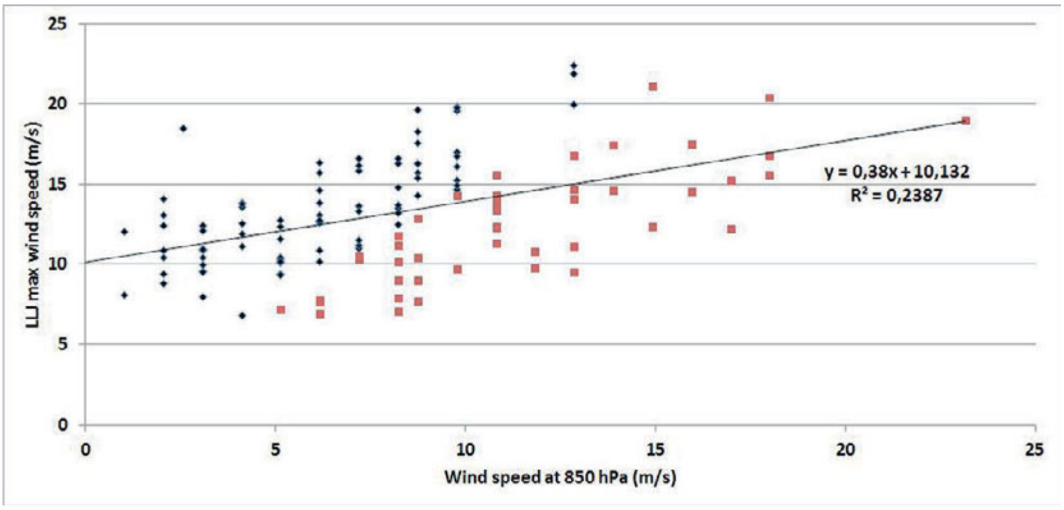
Fig. 3 also explains why Kottmeier et al. (1983) only found LLJs in about 10 % of all nights and not in more than 21 % as in the present study. Kottmeier et al. (1983) only considered LLJs with a super-geostrophy ratio larger than 1.5. Looking at the data for Fig. 3, it is noticeable that 69 (i.e., 11.1 % of all nights) of all cases are above a ratio of 1.5 (blue) and 63 below 1.5 (red). Only 13 of the latter jet events in the present analysis were actually sub-geostrophic. Therefore, the present study is not in contradiction to the study of Kottmeier et al. (1983) but confirms it's results.

The next relevant variable for LLJ formation is cloud cover, because no nocturnal radiative cooling takes place for overcast conditions. Unfortunately, regional cloud cover data are not available. Therefore, as a surrogate, the correlation with 850 hPa relative humidity is investigated and shown in Fig. 4. As expected, LLJ core wind speeds weakly decrease with increasing relative humidity. Increasing relative humidity is not only an indicator for an increased cloud cover but also – and this is probably more important here – for increased thermal counterradiation from the atmosphere towards the surface, which inhibits nocturnal surface cooling as well. Assuming that 850 hPa wind speed and 850 hPa relative humidity are uncorrelated (R^2 is 0.0058 in the present data set), another 14 % of the LLJ core wind speed is explained by the correlation with relative humidity.

There are more meteorological influences, but they cannot be investigated from the available data. One interesting correlation exists with the season (Fig. 5). Nearly no LLJs appear within the three months of November to January. This is probably due to the widely missing diurnal change between a convective daytime boundary layer and a stable nocturnal boundary in winter. The fewer data for the months May to July is an artificial effect due to the fact that for these months only data from one year were available while all other months are based on data from two years.

3.3 Correlation between different properties of the LLJs

The main jet properties are the maximum core wind speed and the height of the jet core above ground. The ratio of these two properties defines the bulk wind shear



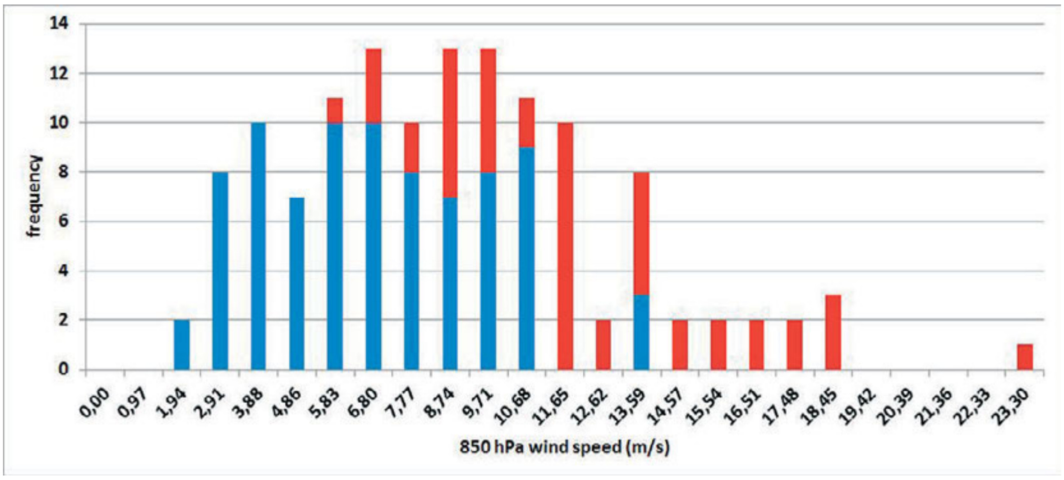


Figure 3: Top: LLJ core wind speed over Hannover, Germany as function of 850 hPa wind speed from the Bergen radiosonde (roughly 60 km north of Hannover). Blue markers: LLJ speed more than 1.5 times the 850 hPa wind speed, red markers: LLJ speed less than 1.5 times the 850 hPa wind speed. Bottom: Absolute frequency of LLJ events as function of 850 hPa wind speed (upper bounds of intervals are given on the x-axis, non-integer bounds have been chosen, because the original data were recorded in knots). Blue bars: LLJ speed more than 1.5 times the 850 hPa wind speed, red bars: LLJ speed less than 1.5 times the 850 hPa wind speed.

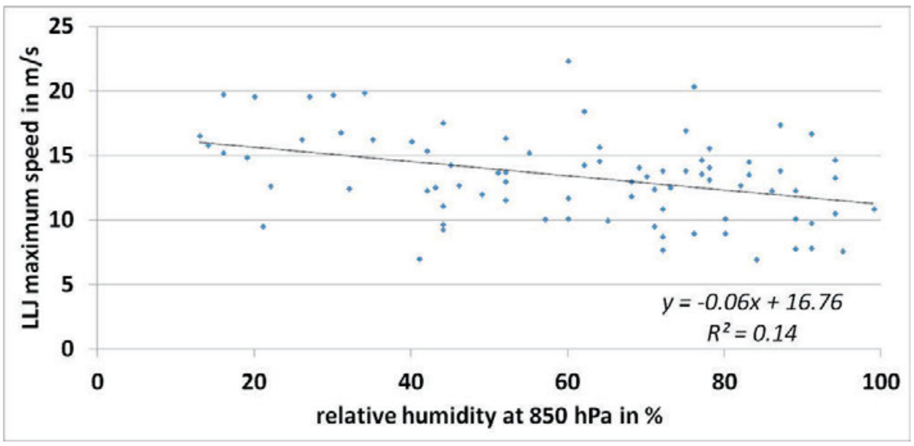


Figure 4: LLJ core wind speed over Hannover, Germany as function of 850 hPa relative humidity from the Bergen radiosonde (roughly 60 km north of Hannover).

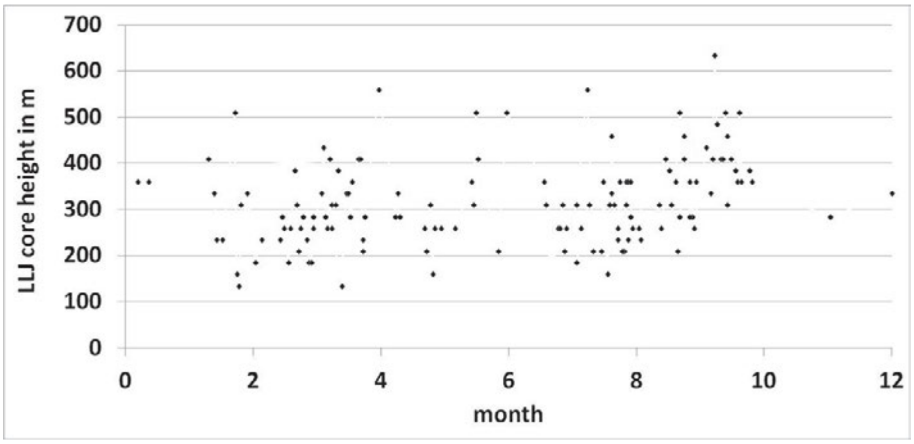


Figure 5: LLJ height over Hannover, Germany as function of the month of the year.

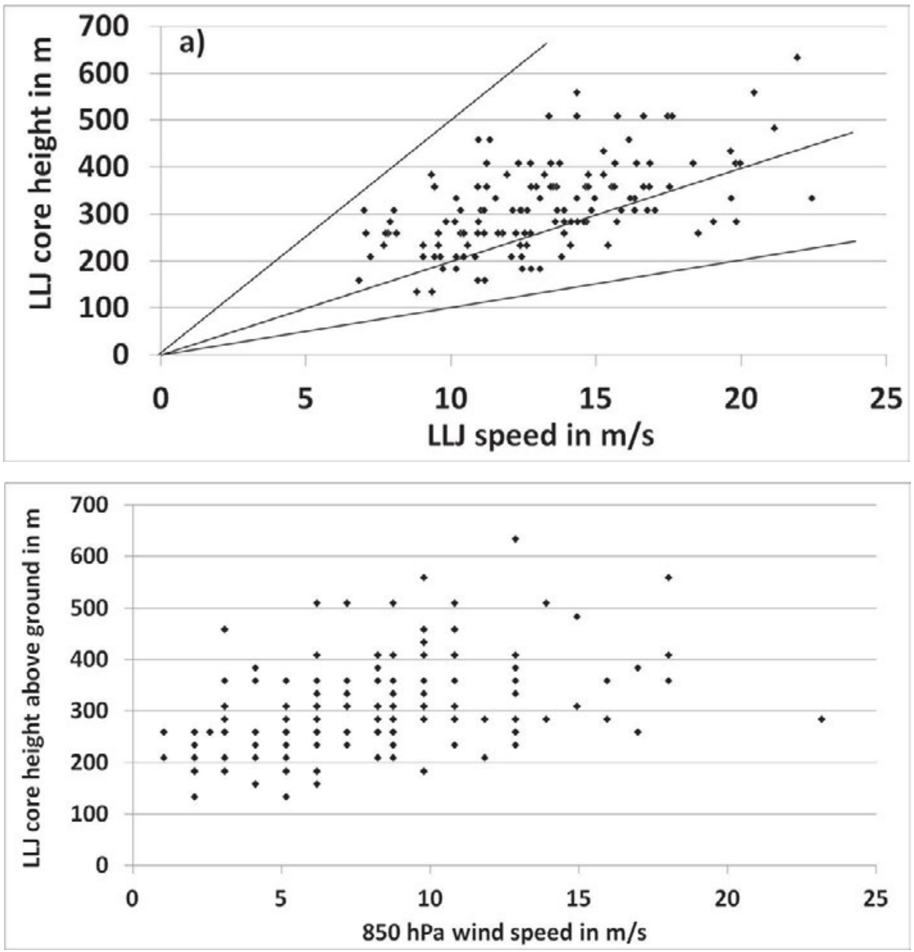


Figure 6: Top: LLJ height over Hannover, Germany as function of LLJ core wind speed. The lines indicate a vertically mean wind speed shear of 0.02 s^{-1} (upper line), 0.05 s^{-1} (middle line), and 0.10 s^{-1} (lower line) underneath the jet core. Bottom: LLJ height versus 850 hPa wind speed.

in the layer underneath the LLJ core. Fig. 6 top shows that increasing jet core wind speeds partly correlate with increasing core heights. The magnitude of the bulk wind shear in the entire layer underneath the jet core is indicated by straight lines. The uppermost line corresponds to a mean shear of 0.02 s^{-1}, the middle line corresponds to a shear of 0.05 s^{-1} and the lower line to a shear of 0.10 s^{-1}. It is notable that there seems to be an upper limit to this bulk shear which is close to 0.1 s^{-1} and which bounds the cloud of dots in this Figure to the lower right. The LLJ core height also seems to be a weak function of the driving geostrophic wind speed (Fig. 6 bottom) as it slightly increases with the 850 hPa wind speed.

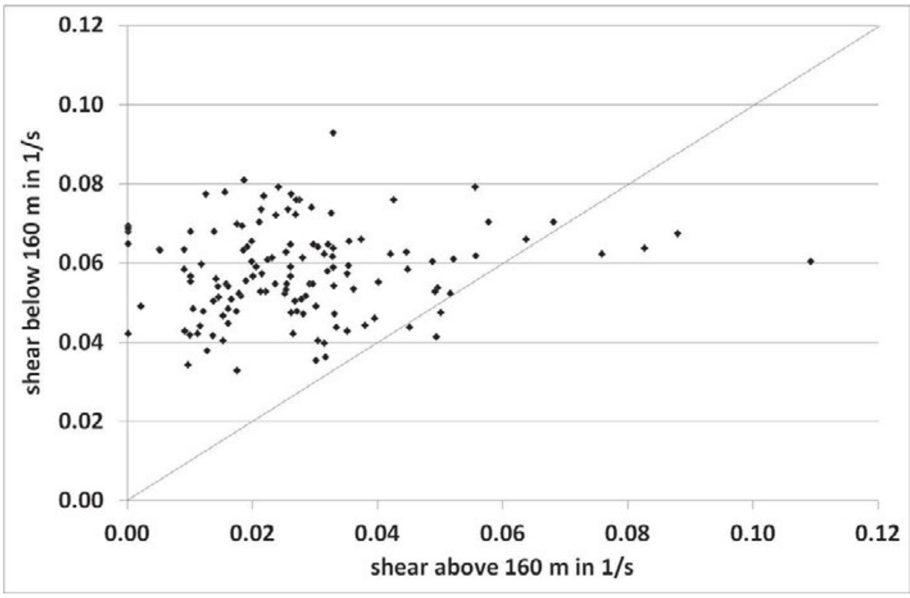


Figure 7: Mean vertical wind shear below 160 m above ground versus wind shear between 160 m and the LLJ core during LLJ events over Hannover, Germany.

Wind shear over the rotor area is especially important for wind energy applications. Because of this fact, the bulk wind shear underneath LLJs plotted in Fig. 6 top needs further investigation. Fig. 7 compares the mean vertical wind shear in the entire layer below 160 m to the mean shear in the layer above this height but below the LLJ core. While the shear above 160 m underneath the jet core turns out to be quite variable between essentially zero (in cases where the jet core height is close to 160 m) and about 0.08 s^{-1}, the mean vertical shear in the layer below 160 m varies much less. Except a few events the shear in this lower layer is always between 0.04 and 0.08 s^{-1}.

These shear values fit to other evaluations. Wind shear in stable surface layers can be estimated by assuming Monin-Obukhov similarity (Stull 1988):

$$\frac{\partial u}{\partial z} = \Phi_M \frac{u_*}{\kappa z} \tag{3.1}$$

where κ is the van Kármán constant, u_* is the friction velocity, u is wind speed and z is height. This holds as long as it is not too strongly stable, because then a z-less description would be more appropriate (see, e.g., Nieuwstadt, 1984). Equation (3.1) can be solved for the friction velocity if the stability function for stable stratification is given. Choosing:

$$\Phi_M = 1 + 5\frac{z}{L_*} \tag{3.2}$$

where L_* is the Obukhov length, $z = 160$ m, $\kappa = 0.4$, a stability measure of $z/L_* = 2$ (by putting $L_* = 80$ m), and inserting a mean shear of 0.06 s^{-1} yields a value for the friction velocity of 0.35 ms^{-1} which is in good agreement with the values used for the friction velocity under stable stratification for Hannover in Emeis et al. (2007a). Making the usual assumption of a ratio between the standard deviation of the vertical wind component, σ_w and the friction velocity, i.e. $\sigma_w = 1.26u_*$ (Stull 1988), we get $\sigma_w = 0.44\,ms^{-1}$. This again is in good agreement with SODAR observations of σ_w underneath LLJs (see, e.g., Fig. 6 in Reitebuch et al. 2000). The ratio between σ_w and the jet core speed is close to 0.05 which is comparable to results from lidar measurementspresented in Banta et al. (2006)

The clear upper bound of 0.08 s^{-1} for the shear in the entire layer below 160 m seems to be a limiting shear. Stronger shear leads to more mechanically produced turbulence. More turbulence leads to more vertical momentum exchange and thus to a reduction of the shear back to the limiting value. This finding which was already visible from Fig. 6 left. It indeed turns out from the data evaluation that 160 m wind speeds during LLJ events do not exceed values between 11 ms^{-1} for low 850 hPa and 13 ms^{-1} for high 850 hPa wind speeds. This upper bound for the ratio of the maximum 160 m wind speed, $u_{160,\max}$ to the 850 hPa wind speed is easily computed from the critical shear value found above, $\frac{\partial u}{\partial z_{\text{crit}}} = 0.08\,ms^{-1}$, the height $z = 160$ m and the 850 hPa wind speed, u_{850}:

$$\frac{u_{160,\max}}{u_{850}} = \frac{\frac{\partial u}{\partial z_{crit}} z}{u_{850}} = \frac{0.08 \cdot 160}{u_{850}} = \frac{\text{const.}}{u_{850}} \tag{3.3}$$

Directional shear is also an issue for wind energy applications. The SODAR data were analysed for the directional shear between 110 m and 160 m above ground as well. The values found scatter between −0.4 and 0.6 degrees per metre with the majority of the values being between 0.0 and 0.2 degrees per metre. Positive values mean a veering of the wind with height. This means that a turning of the wind direction over a rotor plane of 100 m diameter of 0 to 20 degrees can be expected. No correlation with any of the available meteorological data could be found. There was a slight dependence of this turning angle on the wind direction which could be a hint that differences in upstream land use may have a slight influence on this turning angle.

4 Conclusions

Nearly two years of data from measurements with a far-range SODAR instrument in Northern Germany have been evaluated with respect to the occurrence and properties of LLJs. The instrument was able to detect LLJs up to a height of about 600 m above ground.

The main results are:

- LLJs appear in about 21 % of all nights
- LLJs mainly occur between February and October
- LLJs are linked to certain weather and circulation types (the generic circulation type classification "Großwetterlagen" is better suited to identify weather patterns generating LLJs than the new automated circulation type classification of the German Meteorological Service)
- LLJ core heights are partly a function of the driving large-scale wind speeds and range between 150 and 650 m with maximum jet wind speeds between 7 and 23 ms^{-1}; core heights and maximum wind speeds are positively correlated as they are in Baas et al. (2009)
- LLJ core speeds are usually super-geostrophic (in about 90 % of the detected cases), they reach several times the geostrophic speed for low geostrophic winds (i.e., 850 hPa winds in this evaluation)
- LLJs occur for 850 hPa wind speeds up to 18 ms^{-1} (one isolated event with 23 ms^{-1} was found as well), here the maximum LLJ core wind speed was found for a 850 hPa wind speed of 13 ms^{-1}
- the mean wind shear in the entire layer underneath the LLJ has an upper bound limited by a critical shear of about 0.08 s^{-1}
- the two-year data set exhibited a minimum value for the mean shear in the entire layer underneath a height of 160 m above ground during LLJ events of about 0.04 s^{-1}

Comparison of the results presented here to other studies points to the strong influence of the chosen criteria for the identification of LLJs. For instance, the occurrence frequency found here is about double as large as the one found by Kottmeier et al. (1983). This is mainly due to the fact that Kottmeier et al. (1983) limited their study to those LLJs which have at least a maximum core speed of 1.5 times the geostrophic wind speed. We waived this criterion here, because we were interested in all cases where wind speed after sun set increased due to the rapid reduction of retarding surface friction, regardless whether the geostrophic speed was exceeded or not. This interest was mainly driven by the interest in the production of electrical energy from the wind. We wanted to identify those situations where the energy yield has a nocturnal maximum. These nocturnal yield maxima are interesting but somewhat unwanted, because they do not fit to the daily variation of electrical power consumption which usually peaks at daytime.

A comparison to the results of Baas et al. (2009) is more difficult. Their data base had much higher data availability in greater heights and regularly supplied the decrease of wind speed above the jet maximum, which was not regularly available in the present study. The amount of this wind speed decrease was a major criterion in their analysis. Otherwise, their objective criteria and the present subjective visual criteria were similar. In contrast to Kottmeier et al. (1983), Baas et al. (2009) did not require a minimum ratio with respect to the geostrophic wind speed. This is probably the reason why our results and the results of Baas et al. (2009) are quite similar in terms of occurrence frequency.

The following conceptual model for the formation of LLJ seems reasonable from the analysed data: the core wind speed of LLJs increase after sunset until a critical threshold value of the wind speed shear underneath the LLJ is reached. A further increase of the jet core wind speeds is then possible only if the core speed is still sub-geostrophic and if the jet core can move to greater heights in order to keep the shear underneath the jet below the critical value of about 0.08 s^{-1}. This interpretation is also supported, e.g., by the temporal evolution of wind profiles after sunset shown in Fig. 7 in Banta (2008).

The here presented results have practical applications. Among these are:

- there exists a certain predictability of LLJ events. If a suitable circulation type and clear skies are forecasted, the formation of a jet can be expected with a given probability that depends on the circulation type. This is advantageous, because numerical models still have problems to predict LLJs. This is because there is a lower limit to computed nocturnal diffusivities due to the non-zero numerical diffusion in these models (see, e.g., Banta et al. 2003; Storm et al. 2009 or Sandu et al. 2013)
- during LLJ cases, the wind speed at a given height above ground is bounded by the relation given in Equation (3.3) but will – as this evaluation has shown – reach at least half of this value. For a height of 160 m above ground, this wind speed will be between 7 and 13 ms^{-1}
- if the critical shear value underneath the jet is reached (we found 0.08 s^{-1} for this critical shear in this evaluation), mechanical production of turbulence sets in which leads to vertical mixing. Air pollutants from the residual layer can be mixed down into the nocturnal surface layer in this case (see, e.g., Reitebuch et al. 2000)
- long distance transport of pollutants in the residual layer can happen during LLJ events. Wind speeds

of about $10\,\mathrm{ms}^{-1}$ which last for about six hours can transport air masses of the residual layer over distances of more than 200 km.

Outlook

The evaluations presented in this paper show considerable scatter. Future investigations should try to include further meteorological variables such as the vertical temperature profile (in order to compute critical Richardson numbers which are more significant for the assessment of the production of turbulence and vertical mixing than just the vertical shear) and radiation and cloud cover data. The attempt to use midnight temperature profile data from the Bergen radiosonde 60 km north of Hannover was not satisfying.

Wind profile measurements should be made by remote sensing instruments with a sufficient height range. Larger wind LIDARs usually have this height range and are principally much better suited for this purpose than SODARs (Emeis et al. 2007b). A recent example of an observation of a LLJ event by a 'virtual tower' consisting of two Doppler lidars is described in Damian et al. (2014). Optical remote sensing techniques though may be unfavourable in situations with strong nocturnal cooling, because fog formation could hamper optical remote sensing.

A long-range SODAR-RASS could be quite a good solution as such an instrument could supply wind and temperature profiles simultaneously, and measurements can be continued in fog situations. The disadvantage of a RASS is that for LLJs in greater heights with larger wind speeds the sound pulses are blown away from the focus of the radar antenna of this measurement system.

Further LLJ studies are desirable, because this wind phenomenon will continue to be of interest in wind energy generation as well as in regional and larger-scale air pollution studies and in noise propagation studies. Such studies will also help to improve numerical modelling of LLJs with mesoscale (Storm et al. 2009; Sandu et al. 2013) and LES (Cuxart and Jiménez 2007) models.

Acknowledgements

The SODAR measurements in Hannover were funded by the German Research Ministry (BMBF) in the framework of the project VALIUM (reference number 07ATF12) which was part of the greater German atmospheric research initiative AFO2000 of BMBF. I especially thank one of the reviewers for directing my attention to the work of Baas et al. (2006) and Sandu et al. (2013) and both reviewers for their many helpful critical comments. We acknowledge support by Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of Karlsruhe Institute of Technology.

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