J1. 7 CLASSIFICATION OF LOW-LEVEL JETS AT CABAUW

Peter Baas*, Fred C. Bosveld, Henk Klein Baltink
Royal Netherlands Meteorological Institute, De Bilt, The Netherlands

1. INTRODUCTION

Low Level Jets (LLJs) are frequently occurring phenomena in the nocturnal stable boundary layer (SBL). Knowledge of the characteristics of the LLJ is relevant for aviation, the transport of pollutants and from a wind energy perspective. Moreover, the strong shear below the jet can influence the turbulent exchange between the surface and the atmosphere (Banta et al., 2002).

Often model evaluation is based on 'ideal' case studies. However, in this way hardly a good picture can be obtained for the model performance in operational practice. The goal of this study is to produce relevant statistics on the behavior of nocturnal LLJs that can be used to evaluate the bulk performance of atmospheric models in stable conditions.

The availability of long term observations make the Cabauw site very suitable for deriving a climatology of LLJs. We classify vertical profiles of wind speed to the major forcing terms of the SBL, the geostrophic wind speed and the nocturnal cooling. Next for each class we determine characteristics of the LLJ including frequency of occurrence, height and turning.

2. DEFINITION AND EXAMPLE

In literature many definitions for LLJs are applied. For example, Andreas et al. (2000) define a LLJ as a local maximum in the wind speed profile that is at least 2 m/s higher than speeds both above and below it. Instead of this fixed 2 m/s threshold we prefer a relative threshold of 20% for our analysis. Both definitions are compared in Section 5.

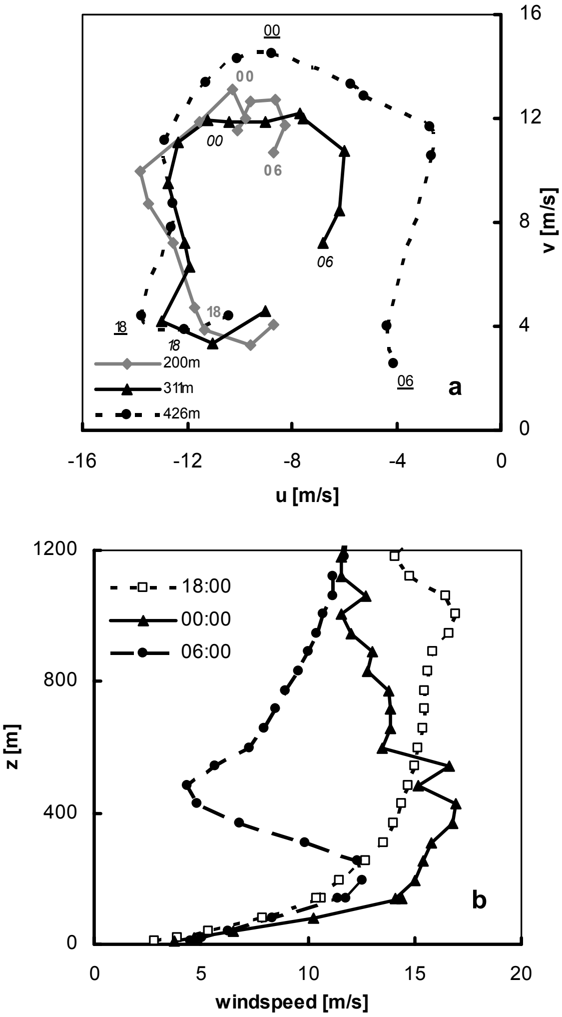

Figure 1 *Example of a LLJ induced by an inertial oscillation. a) Hodograph for three levels. Hourly data, numbers indicate time. b) Vertical profiles of wind speed for three points in time during the night.*

LLJs can form by a variety of mechanisms (Stensrud, 1996). For Cabauw, the two most important ones are strong baroclinicity and the inertial oscillation. When in strongly baroclinic conditions the geostrophic wind speed decreases with height, a LLJ is likely to occur since friction causes the wind near the surface to slowdown.

---

* *Corresponding author address:* Peter Baas, KNMI, Dept. of Atmos. Res., PO Box 201, 3730 AE, De Bilt, The Netherlands; e-mail: peter.baas@knmi.nl

In this study, we focus on LLJs caused by an inertial oscillation (Blackadar, 1957). In the mixed layer, during daytime the pressure gradient force is balanced by the coriolis force and friction, resulting in sub-geostrophic winds. When after sunset stable stratification develops, turbulence dies out and the upper part of the former mixed layer becomes decoupled from the surface. In this layer, where friction does not play a role anymore, the balance of forces is disturbed since the coriolis force and the pressure gradient force are not in equilibrium. Because the coriolis force is always perpendicular to the wind vector and proportional to the wind speed, the resulting net force induces an oscillation in the wind vector around the geostrophic wind. Consequently, a super-geostrophic LLJ will form later during the night.

An example of such a LLJ is presented in Figure 1. The type of hodograph as in Figure 1a is very typical for the inertial oscillation: the tips of the wind vector oscillate around the geostrophic wind. Figure 1b gives three vertical profiles of wind speed for the corresponding night. As can be inferred from this example, the corresponding time series of wind speed and wind direction will show a clear nighttime maximum in the speed and veering in the direction. At Cabauw the period of the inertial oscillation amounts to 15.2 hours.

3. DATA

We use 6 years of hourly data from the 200 meter mast and a 1290 MHz wind profiler in operation at Cabauw (1995, 1996, 2001-2004). On the mast wind speed and wind direction are measured at 10, 20, 40, 80, 140 and 200 m. The wind profiler gives wind speed and direction with a resolution of roughly 60 m. We use data from 200 m up to 1420 m.

Availability of the mast measurements is close to 100%. For the wind profiler data this is different. The availability decreases steadily with height from about 80% at 200 m to about 30 – 60% at 1400 m. Differences between combined classes of geostrophic wind speed and nocturnal cooling are small, especially below 600 m. Above this level, classes with lower wind speed and higher cooling tend to have lower availability.

We rejected all profiles for which the difference in wind speed at 200 m between the mast and the wind profiler exceeded 2 m/s. By this a reasonably smooth transition between the two measuring systems is guaranteed.

4. CLASSIFICATION

Vertical profiles of wind speed are classified to geostrophic wind speed and the nocturnal cooling. This classification is based on the one of Bosveld and Beyrich (2004). As a measure of the cooling the net radiation at the surface could be used. However, this quantity is influenced by local thermal characteristics of the surface. Therefore we prefer to use the iso-thermal net radiation at the top of the SBL (Monteith, 1981). Since the temperature at the top of the SBL is not readily available we use the temperature at 200 m height. The geostrophic wind is derived from surface pressure observations collected from the network of synoptic stations around Cabauw.

We limit our analysis to one moment of time each night, namely 6 hours after sunset. This time is chosen because the maximum jet speed can be expected around this time when we assume that the moment of decoupling occurs shortly before sunset. The fixed point in time has the advantage that we presumably classify LLJs that are in the same stage of development.

For the geostrophic wind we define three classes: $Vg < 5$ m/s, $5 < Vg < 10$ m/s and $Vg > 10$ m/s. Also three classes for the long wave cooling are defined: $Q < 3$ K, $3 < Q < 6$ K and $Q > 6$ K. Here Q is the temperature drop that the net iso-thermal long wave cooling (integrated over the first 6 hours after sunset) would cause in a 200 m high column of air. For each class of geostrophic wind speed and nocturnal cooling we determine how often a LLJ occurs. Also the average height of the jets and the average turning of the wind vector between the jetnose and the 10 m wind are calculated. Of the 2187 nights considered, 1778 fell into one of the defined classes. After we rejected all profiles for which the difference in wind speed at 200 m between the mast and the wind profiler exceeded 2 m/s 1332 nights remained. The numbers of nights in each class combination are listed in Table 1.

Table 1 *Number of nights for each class combination*

	Vg<5	5<*Vg* <10	*Vg*> 10	Total
Q<3	62	154	210	426
3<*Q*<6	107	144	169	420
Q>6	141	196	139	476
Total	310	494	518	1332

5. RESULTS

Figure 2 presents the results for the different class combinations for two definitions of the LLJ: the 20% and the 2 m/s criteria. As can be expected the difference in occurrence between the two definitions is large. At low wind speeds the 2 m/s criterion is much more stringent than the 20% criterion. For high wind speeds the opposite is true.

Figure 2a shows that in general the number of LLJs increases with decreasing geostrophic wind speed and increasing nocturnal cooling. This result is consistent with the theory since conditions with low geostrophic wind speed and high cooling promote decoupling of the boundary layer, creating favorable circumstances for the formation of inertial oscillation induced LLJs.

In Figure 2b the average height of the LLJs is shown for each class. The height varies from about 130 m for the most stable class, to about 400 m for the class with the weakest stability. Decreasing wind speed combined with increasing radiative cooling gives lower LLJs. This tendency agrees with the theoretical concept that the jets form on top of the decoupled boundary layer. The turning of the wind vector between the jetnose and the 10 m wind (Figure 2c) seems to increase with increasing cooling. However, the dependency on the wind forcing seems to be small.

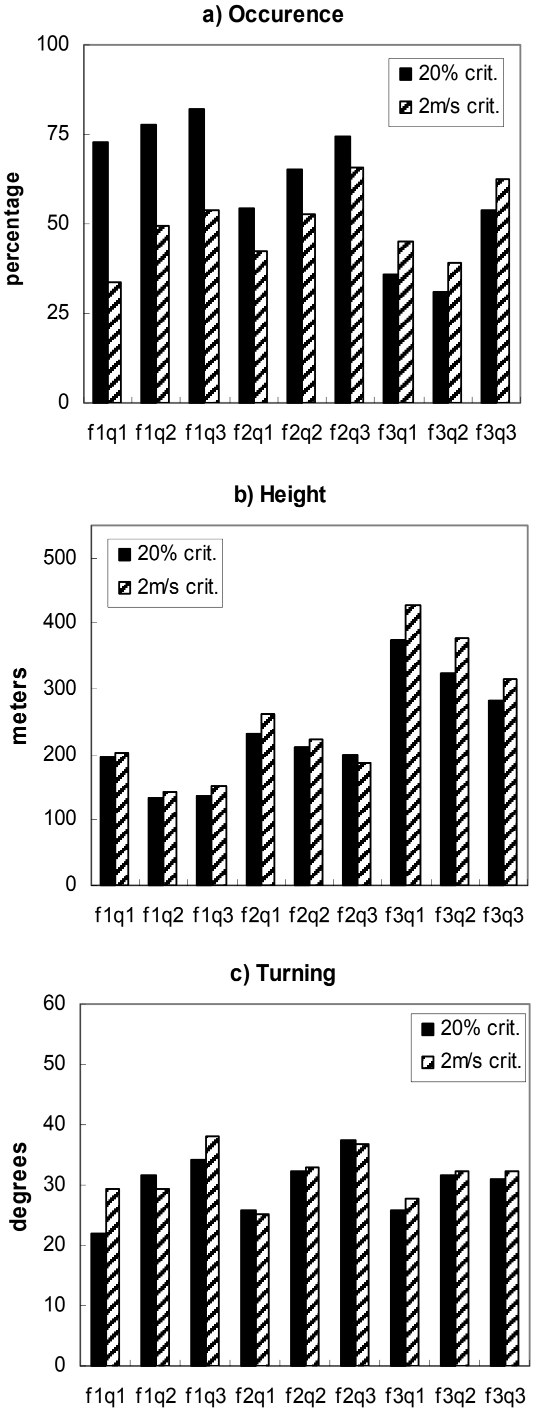

Figure 2 *Characteristics of LLJs (for two definitions) for classes of geostrophic wind speed and nocturnal cooling. a) Occurrence, b) height and c) turning.*

Classes:

f1 : Vg < 5 m/s	*q1 : Q < 3 K*
f2 : 5 < Vg < 10 m/s	*q2 : 3 < Q < 6 K*
f3 : Vg > 10 m/s	*q3 : Q > 6 K*

6. CONCLUSIONS AND FUTURE WORK

At Cabauw long time series of atmospheric parameters exist of atmospheric parameters for stable conditions. Bringing this large amount of valuable information together in a practical form, may contribute to the evaluation and improvement of stable boundary layer representation of atmospheric models. Applying comparable classifications for different sites in the world, would give useful insight in the reaction of the stable boundary layer on the different boundary conditions at the various sites (Bosveld and Beyrich, 2004).

Using 6 years of data we classify profiles of wind speed into nine classes of SBL forcing. To be independent of local boundary conditions, we choose the geostrophic wind speed and the cumulative isothermal long wave cooling as the forcing variables. For each class we determined how often a LLJ occurs. Also the average height and the turning of the jet with respect to the 10 m wind were calculated. In general the more stable classes show up more LLJs, which occur at a relatively low altitude and exhibit a larger turning compared to the surface.

The current statistics can be refined by taking into account the changes of the geostrophic wind with height. In this way, LLJs which result from strong baroclinicity can be dismissed from the statistics. In the future we also want to compare the derived statistics with model output in order to evaluate model climatology of LLJs.

REFERENCES

Andreas, L. A., 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.

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.

Bosveld, F. C. and F. Beyrich, 2004: Classifying observations of stable boundary layers for model validation. Preprint, *16th Symposium on Boundary Layers and Turbulence*, Portland, ME, Amer. Meteor. Soc., P4.13.

Monteith J. L., 1981: Evaporation and surface temperature. *Quart. J. Roy. Meteor. Soc.*, **107**, 1-27.

Stensrud, D. J., 1996: Importance of low-level jets to climate: a review. *J. Climate*, **9**, 1698-1711.