Turbulent coherent structures in the atmospheric surface layer: a 13-month study of dynamics based on Doppler lidar observations in mid-latitude coastal city

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Abstract: Turbulent coherent structures such as streaks play a crucial role in turbulent flows' behavior and pollutants' dispersion in the surface layer. This research is based on ~40,000 horizontal Doppler lidar scans recorded during a 13-month campaign in Dunkirk, France, an industrial harbor city on the North Sea. Similarly to Cheliotis et al. [1], this work is based on the results of automated classification, detailed in a companion abstract. This approach which is based on texture analysis and supervised machine learning, facilitated the distinction between organized and disorganized streaks, which appeared, respectively, mainly during the day and at dawn and dusk. There was no significant seasonal variation in the appearance of the two streak types, beyond the fact it followed the sunrise and sunset times. Organized streaks were typically associated with neutral to unstable atmospheric conditions and characterized by higher motion and thermal fluxes than their disorganized counterparts. Conversely, disorganized structures were more narrowly associated with stable conditions and higher friction velocity. The classification parameters also allowed retrieving the streaks' direction misalignment with the mean wind and their periodicity. The misalignment was more pronounced for disorganized streaks and varied between 0 and 20°. Organized streaks tended to be slightly narrower than disorganized ones, with periods of 0.48 ± 0.22 km and 0.42 ± 0.25 km, respectively (average ± 1σ standard deviation). The aspect ratio of streaks (width-to-height ratio) could only be determined during a few night-time case studies, due to difficulties in differentiating the surface and mixed layers using Doppler lidar data only. The retrieved aspect ratio of 1.64, therefore, corresponds to disorganized streaks.

1. Introduction

Studying turbulent structures in the surface layer is essential for understanding small-scale atmospheric flows. These flows are crucial in the parameterization of weather prediction models or chemistry-transport models. Understanding the properties of surface turbulence is important for better planning and management of urban areas to mitigate problematic weather conditions and improve air quality. Furthermore, the emergence of wind farms in a known and analyzed environment can enhance the prediction of their performance and assess their impact on turbulence within the superficial layer. Turbulent streaks are among the most common and studied turbulent structures. They form due to the shear produced throughout the surface layer. These structures are recognizable by their alternation between bands of higher and lower speeds, generating linear vortices that align, in most cases, with the direction of the average wind [2].

This study aims to understand how streaks in the surface layer are influenced by surface conditions and local meteorology, using statistics derived from 13 months of Doppler lidar measurements recorded near the North Sea in 2021 and 2022. In the first part of the study, the collected data, comprising a set of 40,000 lidar scans, were classified by supervised machine learning. This classification encompasses three categories: organized streaks, disorganized streaks, and a third category labeled 'others' for cases devoid of identifiable structures. In this part, the objective is to highlight the physical properties and characteristics of the streaks, from the classified images.

2. Experimental setup and methodology

The campaign was conducted in Dunkirk, France, a coastal location situated between the English Channel and the North Sea, from May 18, 2021, to June 13, 2022. The region features flat topography at a low elevation of 5 meters. The study area encompasses both industrial and urban zones.

Three instruments were used for this campaign: a scanning Doppler lidar, an ultrasonic anemometer, and a weather station. The lidar, a scanning WindCube WCS100 from Leosphere / Vaisala, was situated 1 km from the coastline (51°02'15.3"N 2°21'57.6" E), on the roof of a 16 m high building. This lidar is built around a 1.543 µm laser and operates for radial wind speeds ranging from −30 to +30 $m.s^{-1}$ with an accuracy of ± 0.1 $m.s^{-1}$. The turbulent structures were detected from quasi-horizontal conical scans of the Plan-Position Indicator (PPI) type. The lidar performed complete 360°-azimuth sweeps at 1° elevation, with an angular resolution of $2°.s^{-1}$, an axial resolution of 50 m and a maximal range of 7.2 km, with a 100 m blind zone in the center. Profiles of the horizontal wind and horizontal turbulent kinetic energy were derived from pairs of perpendicular vertical scans or the Range-Height Indicator (RHI) type, following Bonin et al. [3]. The RHIs were oriented in the North-South and East-West directions, with a resolution of 2° in elevation and 25 m in range, and a maximal range of 3.3 km. The accumulation time was 1 s per beam for both scan types, so a PPI scan or a RHI pair of scans took about 3 minutes to record. The measurement cycle was repeated every 14 minutes.

The ultrasonic anemometer, a METEK USA-1, was positioned close to the sea, about one km North of the lidar, on a 15-m mast taller than any surrounding building. The anemometer operated at a 10-Hz frequency and computed 15-minute averages. It was used to retrieve the fluxes of sensible heat and momentum, as well as the Monin-Obukhov length (MOL). Six atmospheric stability classes were defined from the inverse of the MOL, using modified Pasquill stability classes as in Dieudonné et al. [4]. A weather station (Vantage Pro2 from Davis Instruments Corp) located about 250 m south-east from the lidar atop a 10 m building was used to complete the ultrasonic anemometer observations. It provided 15-minute averages of the relative humidity, precipitation and solar radiation.

In the first part of the study, an automated classification method by supervised machine learning was developed to manage the extensive PPI dataset (37,809 scans). Each image was represented by a vector of statistical ‘texture’ parameters computed from the wind data following Haralick et al. [5]. A training dataset of 399 scans was used to train a Quadratic Discriminant Analysis (QDA) classification algorithm. This classification contains three categories: organized streaks, disorganized streaks, and ‘other’ corresponding to the absence of identifiable structures.

One of the image texture parameters, named ‘contrast’, was also used in this part of the study. The variation of contrast upon the pixel pair orientation used to compute it allowed to retrieve the streaks direction, and thus their misalignment with the mean wind direction. Besides, for pixel pairs oriented perpendicular to the mean wind, the variation of contrast upon distance provided the transverse periodicity of the image, i.e. the turbulent structures’ width. The height of the streaks corresponds to the nocturnal boundary layer depth during night-time and to the surface layer depth during daytime. Distinguishing the surface layer from the mixed layer proved challenging using only the Doppler lidar observations, so the streaks’ height, and thus their aspect ratio (width-to-height ratio of a single roll) was only determined during night-time. The nocturnal boundary layer top was defined as the altitude where the horizontal turbulent kinetic energy dropped by an empirically set 25%-threshold from its low-altitude maximal value [6].

3. Results

3.1. Seasonal and diurnal variability

Figure 1 shows the frequency of occurrence of the three structure categories, averaged over the different seasons. During all seasons, organized streaks predominantly appeared during daytime, which suggests they are formed in thermally driven turbulence. Disorganized streaks tended to occur more frequently during the dawn and dusk transitions, suggesting either they are a temporary pattern, or they need a minimum amount of turbulence to form. Indeed, the 'others' category, often associated with weak or shifting winds, was more frequent during night-time, which suggests reduced turbulence impedes the formation of coherent structures.

The shape of the diurnal cycles remained the same during the four seasons, but the time at which the different categories peaked or dropped varied following the seasonal cycle of the sunrise/sunset time. Except during the short winter days, the share of organized streaks increased slowly along the day (from ~40 to ~70%) suggesting that the accumulated heat also matters to form coherent structures. The winter diurnal cycle exhibited a higher frequency of disorganized streaks and a matching lower frequency of ‘others’, compared to other seasons. This may be due to the higher number of storms in winter, making low or changing wind conditions favorable to the ‘others’ category less frequent in this season.

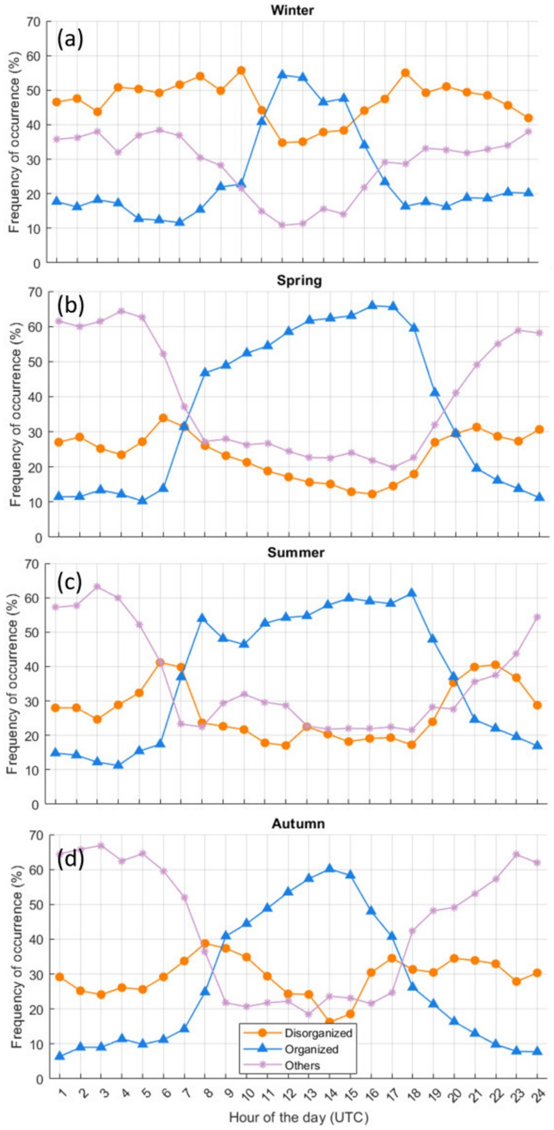

Figure 1. Diurnal cycle (hourly averages) of the frequency of occurrence of the structure classes, for the four seaons.

3.2. Streaks’ properties and conditions of occurrence

Figure 2 presents the structures’ evolution during a four-day case study in spring. With few exceptions, the classification forms a continuous and coherent pattern of structures over time. Fronts passed during the first and third mornings, and a sea breeze formed during the third afternoon; these low and shifting wind periods associated with low friction velocity impeded the development of streaks, resulting in a persistent ‘other’ category. On the second and fourth day, the heat flux reached higher values and organized streaks formed. Disorganized streaks appeared mainly at dawn and dusk (fourth day), after a frontal passage (first day) or after the sea breeze extinction (third day), confirming their association with transition periods. Organized streaks also formed on the first afternoon despite the low heat flux, but with higher friction velocity values, suggesting that the offshore or onshore origin of the air mass, and thus the surface roughness may also play a role in turbulence organization.

Over the whole period, disorganized streaks formed in a very predominant way under neutral stability conditions (Figure 3), which is coherent with their association with transition periods. Organized streaks formed in both neutral and slightly unstable atmospheres (Figure 3). A more marked association with unstable conditions could be expected given the daily cycle of organized streaks’ occurrence (Figure 2), but moderately or extremely unstable atmospheres are rare altogether in a coastal site such as Dunkerque.

The angle between the mean wind and the streaks directions varied between 0° and 20°, like simulated streaks by Drobinski and Foster [7]. The misalignment tended to be stronger for disorganized streaks than for organized streaks (respective average angle of 1.5° and 3.2°). In terms of size, organized streaks were very slightly wider than the disorganized variety, with a single-roll width (half periodicity) of 0.48 ± 0.22 km and 0.42 ± 0.25 m respectively (average ± 1σ-standard deviation). The boundary layer height, and thus the aspect ratio of streaks could be determined only 3.4% of the time, and only by night. Consequently, the retrieved aspect ratio of 1.64 is indicative of disorganized streaks.

4. Conclusion and perspectives

This study presents a year-long analysis of turbulent coherent structures in the surface layer using Doppler lidar data from Dunkirk, France. The automated classification algorithm produced coherent time-series of structure categories and effectively distinguished between organized and disorganized streaks. Organized streaks were predominant during the day and in slightly unstable atmospheric conditions, while disorganized streaks appeared primarily during neutral conditions and transition periods, at dawn and dusk or after a front.

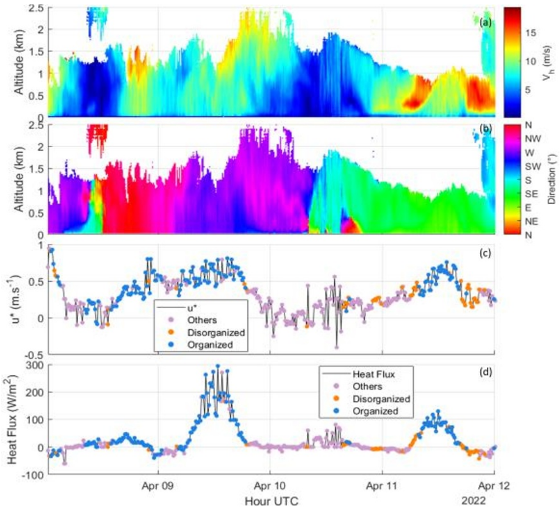

Figure 2. Evolution of turbulent structures from April 8 to 11, 2022: time-height cross section of (a) the wind speed and (b) the wind direction; time-series of (c) the friction velocity and (d) the turbulent heat flux, colored following the structure category.

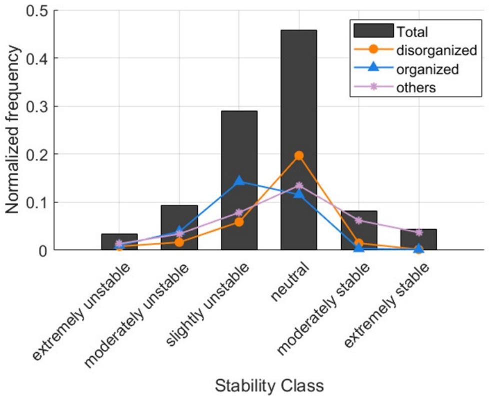

Figure 3. Frequency of occurrence of the atmospheric stability classes for the three structure categories.

Future research will investigate over more cases and longer periods the transitions between the non-coherent turbulence, disorganized streaks and organized streaks regimes. The dependency to the weather conditions will also be explored in more detail, which should help improve our understanding of the streaks' formation mechanisms.

5. References

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