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CHARACTERISATION OF LOW-LEVEL JETS AND THEIR INFLUENCE ON LOW-LEVEL CLOUDS OVER THE BALTIC SEA; ÖSTERGARNSHOLM OBSERVATORY, SWEDEN

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DIVISION OF COMBUSTION PHYSICS

Supervisors:
Metodija SHAPKALIJEVSKI
Elna HEIMDAL NILSSON

Candidate:
Johan LUNDBERG

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Abstract

In this study, about two years of data from Östergarnsholm in the Baltic Sea are used to analyse offshore low-level clouds (LLCs) influenced by low-level jets (LLJs) in the marine atmospheric boundary layer. The LLJs are passages of strong horizontal winds near the surface and are measured using a Doppler LiDAR, which provides information about the wind speed and wind direction up to 300 meters. In this study we define two groups of LLJs depending on the height at which they occur; 1) LLJs with maximum wind speed at heights below 300 meters that are clearly identified from the LiDAR data, and 2) LLJs that occur at heights around 300 meters or higher and are not clearly captured by the LiDAR but are assumed by visual inspection. The clouds are quantified using a ceilometer which provides information about the cloud base heights (CBH). The main objectives of this study were to identify periods of coincident LLJs and LLCs, to classify these identified LLJs and LLCs and to provide general statistics of their interaction. The combination of LLJ- and LLC presence, and the interaction between these, are new research. The analysis showed that the highest LLJ frequency regarding all LLJs was 47.7 %, with a maximum speed of 17.5 ms^{-1} and occurred during winter. Only 4.38 % of these LLJs occurred below 300 m. The largest share of all LLJs below 300 m occurred during summer (75.6 %), where the mean maximum speed was 11.1 ms^{-1}. Largest LLC presence during active LLJs occurred during the winter (56.0 % regarding all LLJs, 64.5 % regarding LLJs below 300 m). The possible LLJ influence on the formation of LLCs was large during late autumn, winter, and early spring since the LLJ mean height and the CBH were at approximately the same height. It was also found that the LLJs induced an increased turbulence intensity below and above the LLJs cores. The increased mixing above the jet core could lead to turbulent transport of cold and humid air, leading to LLC formation. The results of this study may contribute to improved weather forecasts for the processes related to LLJ- and LLC interaction.

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Data representing marine conditions in the Baltic Sea was provided from the ICOS (Integrated Carbon Observation System) site Östergarnsholm. I would like to acknowledge the data provision by the Gotland observatory team, managed and operated by Anna Rutgersson and Erik Nilsson from Uppsala University.

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Contents

Acronyms

ABL	**A**tmospheric **B**oundary **L**ayer
AOD	**A**erosol **O**ptical **D**epth
CBH	**C**loud **B**ase **H**eight
CCN	**C**loud **C**ondensation **N**uclei
ESRL	**E**arth **S**ystem **R**esearch **L**aboratories
ICOS	**I**ntegrated **C**arbon **O**bservation **S**ystem
LiDAR	**Li**ght **D**etection **A**nd **R**anging
LLJ	**L**ow-**L**evel **J**et
LLC	**L**ow-**L**evel **C**loud
NOAA	**N**ational **O**ceanic and **A**tmospheric **A**dministration
NWP	**N**umerical **W**eather **P**rediction
SMHI	**S**veriges **M**eteorologiska och **H**ydrologiska **I**nstitut
TI	**T**urbulence **I**ntensity
TKE	**T**urbulent **K**inetic **E**nergy

1 Introduction

1.1 General overview

This study will deal with winds and clouds, namely low-level jets (LLJs) and low-level clouds (LLCs) respectively, that have been measured over the Baltic Sea.

Winds and clouds have a significant importance for the Earth. Winds are important due to their influence on current and future weather. To understand and predict the winds are key for weather forecasts since they can transport moisture and heat between different areas and therefore contribute to a change in weather conditions as the wind direction change. Clouds are important due to their influence on the radiation and energy balance of the Earth. Thus, they are the key regulator of the average temperature globally. For example, during daytime, clouds on a low level keep the surface temperatures cool as they often reflect heat from the sun back to space while higher-level clouds can contribute to keep surface temperatures warm. This reflective ability is called albedo and especially thick clouds on a low level have a relatively high albedo. The albedo is defined as the ratio of the total reflected light to the incident light. Except for the received solar radiation, the albedo is also dependent on the radiating temperature and the greenhouse effect (Donev et al., 2020). It is important, especially for meteorologists, to know the physical processes of winds and cloud formation in order to ameliorate weather forecasts and global climate predictions. By presenting a specific characterisation of the Baltic Sea meteorology with a focus on LLJs and LLCs, this study provides a base for further advances in the understanding of the LLC-LLJ interaction.

LLJs are corridors of fast wind which move horizontally above the surface and are usually quantified as wind speed maxima at a certain lower height above the surface. An LLJ profile (blue line) versus a representative general wind profile (red line) is schematically illustrated in Figure 1. The height of the wind speed maximum typically occurs at a height between 100 and 1000 meters (Tuononen et al., 2015) with the first wind speed minimum at the ground and the second a few hundred meters above the jet core (Hallgren et al., 2020). LLJs modify the thermodynamics of the ambient air by advecting moisture and heat, often leading to LLC formation and precipitation (Su et al., 2016). Due to their multi-scale character, the LLJ- and LLC interaction processes are not fully understood and often not well represented in numerical weather prediction (NWP) systems. Consequently, this can lead to uncertainties in weather predictions. The main goal of this study is to provide a detailed observational analysis of offshore LLCs influenced by LLJs above the Baltic Sea, as measured at the Östergarnsholm observatory situated on a small island east of Gotland, Sweden.

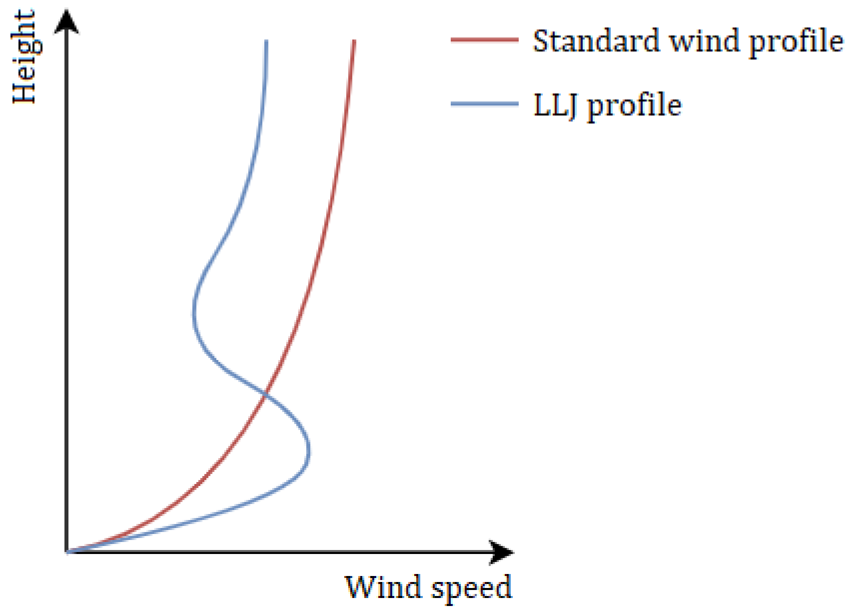

Figure 1: A schematic representation of a typical wind profile in red and the low-level jet (LLJ) wind profile in blue.

A large share of the global surface area is sea: more than 70% according to Svensson (2018). Locations on these sea surfaces are though often more remote and less accessible. Hence, meteorological measurements are a scarce commodity over the sea. But despite this fact, it is important to study atmospheric conditions above sea surfaces in order to obtain accurate weather forecasts mainly needed for more safe offshore transport, but also for other socioeconomic and energy developments. For instance, the offshore wind energy has recently increased in use very rapidly: from 11 small wind turbines in 1991 in the seas around Denmark, with capacity of only a few megawatts, to 19 gigawatts installed capacity worldwide nowadays (Svensson, 2018). Therefore, the amount of measurement sites has increased mainly due to this increase in offshore wind energy. Thus, an improved understanding about LLJs and how they operate could be useful for a more effective distribution of energy resources.

LLJs over the Baltic Sea are due to different kinds of contrasts between the land and sea. Due to a more homogeneous surface over the sea than over land, stronger and more uniform wind speeds are experienced over the sea. This is favourable for offshore wind energy as there are reduced frictional effects over sea, which in turn makes it possible to set up wind turbines with lower hub heights (Svensson, 2018). Since LLJs usually operate at higher wind speeds than the normal winds do, they have more power to provide to the wind turbines which is also an advantage for more efficient offshore wind energy. However, a higher occurrence of LLJs increases the turbulence intensity and wind shear (spatial difference in wind velocity) and can affect the loads on the wind turbines and shorten their lifetime (Svensson et al., 2019). There is also a large contrast in heat capacity. The heating and cooling of the sea are much slower compared to the land. This leads to a large temperature contrast between land and sea which can induce LLJs and other mesoscale processes such as sea breezes. These sea breezes can in turn induce LLJs as the sea breeze circulation commonly occur across coastlines and across these temperature gradients (Svensson, 2018). In addition, weak winds on the synoptic scale can trigger sea breeze circulations which then can create an LLJ with onshore winds (Svensson et al., 2019). As the day progresses, the winds may change direction and become more parallel to the coast due to the Coriolis force (Svensson et al., 2019). Contrasts between land and sea are thus an important condition for LLJs to be formed.

The Baltic Sea is of particular interest since it is largely influenced by the surrounding land areas. This is because it is a semi enclosed area, and it is at a high latitudinal location. This means that the temperature contrasts between land and sea can be up to 20°C in spring and LLJs are therefore very frequent (Svensson, 2018; Smedman et al., 1997). With a higher frequency of LLJs, more horizontal advection of warm or cold (or humid or dry) air will take place from one place to another. Consequently, larger temperature differences cause more horizontal advection. During spring and summer, the air over the land surface is almost exclusively warmer than the sea water. Since the Baltic Sea is an inland sea with widths of just a few hundreds of kilometres, it almost does not matter from which direction the wind blows: the air will almost always flow from heated land over the colder water during the day (Smedman et al., 1993). Furthermore, Hallgren et al., 2020 showed through LiDAR (Light Detection And Ranging, a method commonly used for determining properties of winds) measurements over the Baltic Sea that the most LLJ frequent month was May. During this month, LLJs were present almost 60% of the time over a small island at the southern parts of the Finnish archipelago called Utö and had a 40% presence over the Östergarnsholm observatory. LLJs are more frequent by night and early mornings. As the sun rises, however, convective heating of the land will eventually lead to a decrease in the LLJ strength (Su et al., 2016) and the LLJ will eventually dissipate. To conclude, the analysis of LLJs over the Baltic Sea is relevant as the land-sea interaction can have large impacts on offshore conditions. Also, the Baltic Sea is well situated for future expansion of wind power with its proximity to so many countries. With the increasing need for more sustainable energy resources, this would be a good area for wind power deployment in the future.

As mentioned earlier, LLJs work as a carrier of moisture (and heat) at low altitudes. They also facilitate the transport of aerosols, that can act as cloud condensation nuclei (CCN). Aerosols and moisture can be transported by LLJs and converge and may eventually lead to the development of clouds and precipitation (Su et al., 2016). Clouds require water vapor and aerosols to exist. The aerosol particles work as condensation nuclei for water vapor, where the water molecules in the atmosphere are drawn to the aerosols like magnets, and cloud droplets are formed and eventually also clouds. Su et al. (2016) observed that enhanced night-time atmospheric turbulence can be triggered by LLJs, and very strong disturbances can be induced between different layers at low altitudes. Furthermore, they observed that these disturbances can lead to vertical transport of water vapor and aerosols between these layers. When they examined the turbulent kinetic energy (TKE) and the size of the aerosols, they concluded that a region that is strongly exposed of LLJ induced turbulence, leading to vertical transport, can be composed of potential CCN to a very large extent. Therefore, a region like that is very favourable for cloud formation and thus, LLJs can be drivers of LLCs and subsequent precipitation.

The connection between LLJs and LLCs can be broadened and even more understood when looking at the speed of an LLJ. An increase in the horizontal wind speed causes an increase in the aerosol optical depth (AOD). The AOD is a function of altitude and aerosol extinction coefficient (Su et al., 2016). This extinction coefficient is the sum of absorption and scattering of insolation and is a measure of the attenuation of the light from the solar irradiance travelling through the atmosphere. Optical depth is a measure of transparency of a specific material and the AOD measures how much of the direct sunlight aerosol particles are preventing from reaching the ground. For example, a very clean atmosphere has an AOD of 0.01 and a very hazy atmosphere has an AOD of 0.4 (NOAA ESRL, n.d.). Further, this increase in AOD suggests that an LLJ of higher speed will induce stronger turbulence and entails increased vertical transportation of aerosols (more aerosols available that can be transported) into a region and produce more CCN, which ultimately leads to more LLCs (Su et al., 2016).

There are several studies regarding LLJs over the Baltic Sea (e.g., Smedman et al., 1993;

Dörenkämper et al., 2015) and there are also a number of studies regarding LLCs (e.g., Stenlid, 2019; Sporre et al., 2014). There are however not much research dealing with LLJ-LLC interaction, especially not over the Baltic Sea. Su et al. (2016), for example, had the motivation to gain a better understanding of how LLJs influence cloud formation. To do so, they looked at one single LLJ case, lasting ten hours, in the end of May 2020 in Virginia in USA. Babić et al. (2019), for example, had the motivation to find what controls the formation of nocturnal LLCs during the monsoon season over West Africa. They found that the onset time of the nocturnal LLJ, horizontal cold-air advection and background moisture level, and the interplay of these mechanisms is crucial for LLCs to form during monsoon season. Regarding the Baltic Sea however, there is no specific research about the LLJs-LLCs interaction. The novelty in the present study is the analysis of the LLCs as possibly influenced by LLJs over the Baltic Sea. By looking at the atmospheric boundary layer (ABL, 2 km above the surface) over the Baltic Sea, the analysis of the interaction of LLJs and LLCs can be made as it is in this layer where their formation, development and dissipation take place.

1.2 Aim and objectives

This project will deal with the presence of marine LLCs and the significance of ambient LLJs, and the main goal is to give an observational analysis of these clouds over the Baltic Sea, as influenced by the LLJs. The specific objectives of this study are:

- to identify periods with LLC presence during operating LLJs;
- to provide a classification of these LLCs and LLJs: cloud base heights, height of LLJ core and its magnitude, and the LLJ direction; and
- to provide general statistics of the LLJ-LLC interaction over the observatory.

To do so, high-quality datasets from the Östergarnsholm observatory will be analysed. The results of this study can be used for model validation (e.g., the operational NWP system at SMHI) or to further improve the knowledge about the interaction between the LLJ and LLC processes and thereby produce better weather forecasts.

2 Methods and methodology

In this study, observations from the ICOS (Integrated Carbon Observation System)[1] site Östergarnsholm are processed and analysed (Rutgersson et al., 2020). Data from the ZephIR 300 LiDAR is used to analyse profiles of the wind speed, while backscatter data from the ceilometer CBME80B is used to identify the cloud presence and estimate the height of the cloud base. The wind direction, extracted from the LiDAR, was compared, and if needed corrected, with the data from the tower wind measurements (Rutgersson et al. 2020). All processed data is visualized using MATLAB.

2.1 Östergarnsholm site

The measurement site is the Östergarnsholm observatory, situated on the small island Östergarnsholm about 3.7 km east of Gotland (Figure 2). This station, which is run by Uppsala University, consists of anemometers, temperature- and humidity censors but also other instruments that can quantify the sea-atmosphere interaction with respect to different scalars. All measurements conducted at the Östergarnsholm observatory are primarily used for studies regarding the marine boundary layer. In cooperation with the Östergarnsholm site and SMHI, this study has dealt with wind- and cloud data from 26th June 2018 to 24th June 2020.

Figure 2: LEFT: The Östergarnsholm island and its orientation in the Baltic Sea. **RIGHT:** The measurement site Östergarnsholm marked with a white "X". (Google Maps, 2021)

[1] https://www.icos-sweden.se/

2.2 ZephIR 300 LiDAR

The Doppler wind LiDAR releases a laser beam into the air, which is sooner or later reflected from aerosols, dust, and other moving particles (Hallgren et al., 2020). The motion of these particles is assumed to follow the motion of the wind flow. This is an assumption that is very appropriate due to the fact that viscous forces are dominant for such small particles (Peña et al., 2015). The laser is aimed at an angle relative to the vertical direction in at least three various directions, and the frequency of the backscattered signal is recorded. Then, the wind speed can be calculated using the Doppler shift - the wave-frequency change in relation to an observer. The Doppler shift in frequency, which the scattered light experiences, is given by

$$\delta \nu = \frac{2V_{LOS}\nu}{c} = \frac{2V_{LOS}}{\lambda}$$

where c is the speed of light, ν is the laser frequency and λ is the laser wavelength. V_{LOS} is the component of aerosol speed along the beam direction. For the LiDAR at (0, 0, 0), measuring at location (x, y, z) with wind components (u, v, w), the V_{LOS} is given by the dot product

$$V_{LOS} = \left| (\boldsymbol{u} + \boldsymbol{v} + \boldsymbol{w}) \cdot \left(\frac{\boldsymbol{x} + \boldsymbol{y} + \boldsymbol{z}}{\sqrt{x^2 + y^2 + z^2}} \right) \right|.$$

Problems with the LiDAR measurement technique do exist, when investigating LLJs. For a very dry atmosphere, there are few aerosols which is the case over the Baltic Sea when northerly winds are occurring (Hallgren et al., 2020) which implies that the wind will not be measured accurately as there are not enough particles in the air reflecting the beam. Additionally, LLCs can be present which can block the path of the laser beam from the LiDAR, resulting in a weak backscattered signal. These are two reasons that to some extent can inhibit the backscattered signal and measurements can be discarded (Hallgren et al., 2020) as there are certain atmospheric conditions that can lead to bias in the data. In the long term, this can make a data set unusable. But since the LLCs are mostly generated at heights above 300 meters, they should not interfere the LiDAR signal in its operating range (up to 300 meters in this case).

The particular LiDAR used for detecting the LLJs is called ZephIR 300 and is situated about 3 meters above sea level. A ZephIR 300 is shown in Figure 3. The ZephIR 300 is a continuous-wave laser LiDAR, meaning that the emitted laser beam is continuous (uninterrupted), opposed to a pulsed laser beam (laser emitted in short bursts). The emitted continuous laser beam has a wavelength of 1.5 µm (Mann et al., 2010). The ZephIR 300 operates with a power consumption of 69 W (ZX Lidars, n.d.), and measures up to ten different heights to support the quantification near the surface, from ten to 300 meters height (Svensson et al., 2019). These heights are defined by the user. The most common set of heights for the measurements used in this study is 27, 38, 49, 99, 149, 199, 249 and 299 meters, but other slightly different combinations are applied as well. The ZephIR 300 used for the measurements is a conically scanning LiDAR with an inclination from the vertical of around 30° (Hallgren et al., 2020) (i.e., the beam elevation angle is around 60°). It adjusts its focus for each of the user-defined heights, which entails an increased probability of that the backscattered signal comes from particles on each of the pre-set heights. Consequently, the measurement volume is strongly a function of the measurement distance, where the narrowest focus is enabled on the shortest distance. Also, the ZephIR 300 makes three horizontal revolutions, or scans, per height before it scans at another height. When it has scanned all heights, it starts all over again. Each completed scan takes 1 second with a frequency of 50 measurements s^{-1} (Svensson et al., 2019). It has a direction variation of less than 0.5° and the wind speed accuracy is 0.1 ms^{-1} (ZX Lidars, n.d.).

Figure 3: A photography of the ZephIR 300 LiDAR measuring winds and connected properties (Uppsala Universitet, n.d.).

2.3 Ceilometer CBME80B

The cloud presence was determined from data from a ceilometer, which is a device operating in the same way as a pulsed laser LiDAR. Its transmitter is a semiconductor laser diode, and its receiver detector is an avalanche photo diode. The transmitter operates with a pulse power of 50 W. It emits very short light pulses with a wavelength of 905 $\pm$ 5 nm, a pulse frequency of 1000 s^{-1} and pulse lengths of 100 ns (properties specific for the ceilometer used at Östergarnsholm) and receive backscatter. From this, the measurement distance can be determined through the time elapsed between the emitted pulse and the received backscattered pulse. The amplitude of the backscattered pulse (the "backscatter signal") is also measured as the laser beam travels back to the ceilometer and gives a backscatter profile. That is, the backscatter signal strength versus time. The time and the backscatter profile are then stored and processed by software and the cloud base height can be determined. With known time delay δt between the time of emission of the laser beam and the time of detection of its backscatter signal, and the speed of light c, the cloud base height CBH can be calculated as

$$CBH = \frac{c \cdot \delta t}{2}.$$

The ceilometer for this study was a CBME80B ceilometer and is shown in Figure 4. The CBME80B measures the clouds' base heights or, if no clouds are present, the vertical visibility up to 7600 meters. The CBME80B has the ability to detect up to four CBH simultaneously. However, it is only the first CBH that is of interest for this study. This pulsed LiDAR, which the CBME80B is and as opposed to the continuous-wave LiDAR, maintain the same vertical measurement volume independent on height. Additionally, the pulsed laser LiDAR will present a higher uncertainty than the ZephIR 300 on lower levels but a lower uncertainty on higher levels. All technical properties of the ceilometer have been taken from the CBME80B manual (Björn Eliasson Ingenjörsfirma AB, 2017).

Figure 4: Figure showing the ceilometer model used in the study (Björn Eliasson Ingenjörsfirma AB, 2018).

2.4 Data treatment

The ZephIR 300 data available for this study concerns about two years of data: from June 1st, 2018, to June 24th, 2020. However, all days are not covered. For example, around 6 months of the 2019 data is missing completely. Consequently, some months only have data available for 2018 and 2020, or just one of those years. In addition to this, some days have too many gaps in the data to conclude anything from. In accordance to how Hallgren et al. (2020) treated gaps in the data: if more than around 70% of the data was missing, the wind profile was dismissed. The LiDAR data provides information about the wind speed U (given in ms^{-1}) and wind direction WD (given in °). Additionally, turbulence intensity TI (dimensionless) is calculated as the standard deviation of the horizontal wind speed σ_U (given in ms^{-1}) divided by the mean wind speed. If the vertical component of the wind speed and standard deviation of the wind speed would be included, the TKE could be obtained. But here, only the horizontal components are considered. An LLJ is in this study defined to be a wind speed maximum at a certain lower height or winds exceeding 12.8 ms^{-1}, according to National Weather Service (n.d.). The latter criterion was primarily applied at 300 meters height. Since the LiDAR only provides data up to 300 meters, but LLJs can have their maximum jet core above that height, there are LLJs that cannot be detected for this study and thus not treated here. Both Hallgren et al. (2020) and Tuononen et al. (2017) states however that the vast majority of LLJs they identified over the Baltic Sea were below that level. There are also wind speeds exceeding the threshold of 12.8 ms^{-1} at the 300 meters level but are having their maximum jet core higher up. In that case, the jet core is assumed to be at 300 meters.

In this study, the only cloud bases in the atmosphere that were considered were the ones located in the ABL. Hence, only cloud base heights below 2000 meters (LLCs) were included in the analysis. The CBME80B data available was between June 25th, 2018, to June 25th, 2020. Also here, not all days were covered. In total around 2 months were missing data completely but almost all these days coincided with missing data in the LiDAR. Two years of data were in the end reduced to 501 days due to corresponding 230 days of completely or partly missing data (in total 5519.5 hours) in either the LiDAR data, ceilometer data or in both.

When determining the CBHs, the procedure was as follows:

1. Look for CBHs for every day of interest (that is, when the CBH was coincident with operating LLJs).
2. Due to variation of the CBH in time, a "lowest CBH" and a "highest CBH" were defined.
3. When all the data was reviewed, all "lowest CBH" were combined with each other, and all "highest CBH" were combined with each other, for each month.
4. With these lists of "lowest CBHs" and "highest CBHs", the "median lower CBH" was calculated from the "lowest CBH" values and the "median higher CBH" from the "highest CBH" values.
5. The mean of the "median lower CBH" and the "median higher CBH" was then calculated for the months involved in each season to get the "LLC mean CBH span".

3 Results

3.1 Properties of LLJs and LLCs

In this subsection, the LLJs and LLCs are defined with their properties on selected cases. As defined in the methodology (subsection 2.4), every LLJ has the following properties: i) a jet core, defined as a wind speed maximum at a certain lower height, after which the wind speed decreases with increasing altitude; ii) a wind strength, defined as the magnitude of the wind speed at the jet core; iii) a duration, defined as the time elapsed between the formation and dissipation of the LLJ; and iv) a wind direction, defined at the start of the LLJ. Figure 5 shows the diurnal cycle of the wind speed in the left panel and the wind direction in the right panel as measured from the Doppler wind LiDAR on the 22nd of June 2020. The light yellow represents the highest wind speeds and the dark blue the lowest wind speeds. For the wind direction figure, the colour scale goes from 0 to 360 degrees (°). Two nocturnal LLJs are identified for this selected day: one in the early morning from 00:00 to 09:00 UTC and another in the late afternoon from 17:30 to at least 00:00 UTC. Regarding the first LLJ, the wind maximum is 11.3 ms^{-1} 100 m above the surface at around 00:30 UTC. Its direction is 53° as shown in the right panel of Figure 5 (light blue colour), which means that it has a north-easterly (NE) or an east-north-easterly (ENE) direction. The max of the second LLJ is at around 180 m above the surface 11.6 ms^{-1} at 21:00 UTC and then the LLJ rises to higher levels. In this case (as opposed to the LLJ in the morning), the wind direction has changed. The direction of this LLJ is 276° (burgundy colour), which means that it has a westerly (W) direction. The white regions (e.g., around 12:00 UTC between 200 and 300 m height) are regions of missing data. Both these LLJs were nocturnal, and this is consistent with the fact that LLJs are more common when the sun has set, as said in section 1.1.

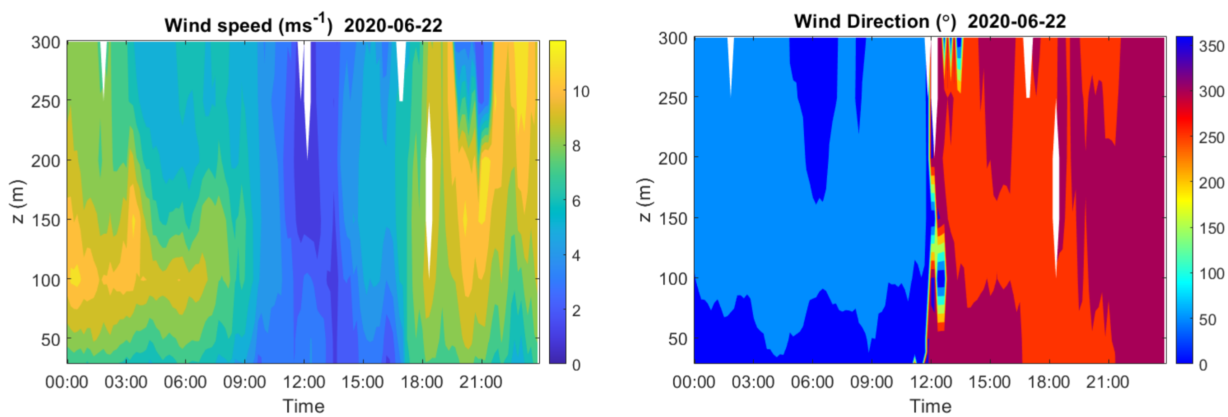

Figure 5: The horizontal wind speed, in the left panel, for the 22nd of June 2020 with one low-level jet (LLJ) present at 100 m between 00:00 and 09:00 UTC. A second LLJ is present at least between 17:30 and 00:00 UTC at 100 m in the entry of the LLJ. The wind direction for the wind profile is in the right panel.

Another property that an LLJ can have, as defined in the subsection 2.4, is that it measures at least 12.8 ms^{-1}. In Figure 6, all measuring points exceed the threshold of 12.8 ms^{-1}. This wind profile (from the ninth of February 2020) shows an example of an LLJ that probably has its jet core at around 300 m height. The uncertainty of the wind profile above the 300 m height is replaced with an assumption that the wind speed decreases above this level. This assumption is justified with previous studies (Tuononen et al., 2017; Hallgren et al., 2020) showing that the LLJs cores is usually at lower levels. This LLJ has its maximum speed of 32.7 ms^{-1} at just before 24:00 UTC. The direction of this LLJ is 200° as shown in the right panel of Figure 6. That is, south-south-westerly (SSW) wind that has the direction of along the eastern coast of Gotland.

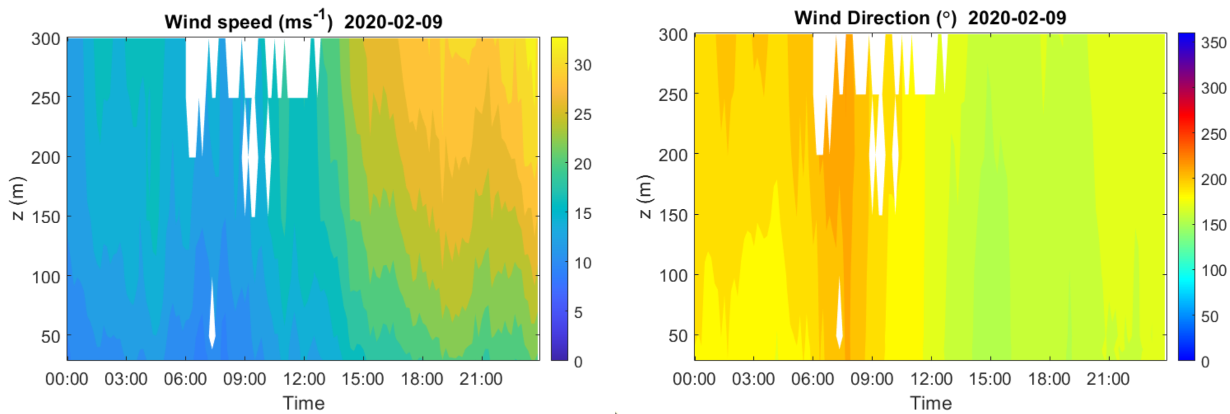

Figure 6: The horizontal wind speed, in the left panel, for ninth of February 2020 with a low-level jet (LLJ) present all day with a jet core probably around 300 m. The wind direction for the wind profile in the right panel.

As defined in the methodology (subsection 2.4), LLCs have their bases below 2000 m above the surface. In the lower panel of Figure 7, the CBHs are shown as black dots together with the strength of the backscatter signal (plotted using colours). In the upper panel is the same wind profile as in Figure 5 since LLJs might contribute to the formation of LLCs (as hypothesized). There is LLCs during the first LLJ only around 03:00 UTC at 1200 m. LLCs are also present during almost the whole LLJ in the evening, at different levels. Early in the LLJ, an LLC appear with a CBH at 220 m and when the LLJ has reached its maximum speed, the CBH is present at 1560 m. After this, the CBH continue to rise.

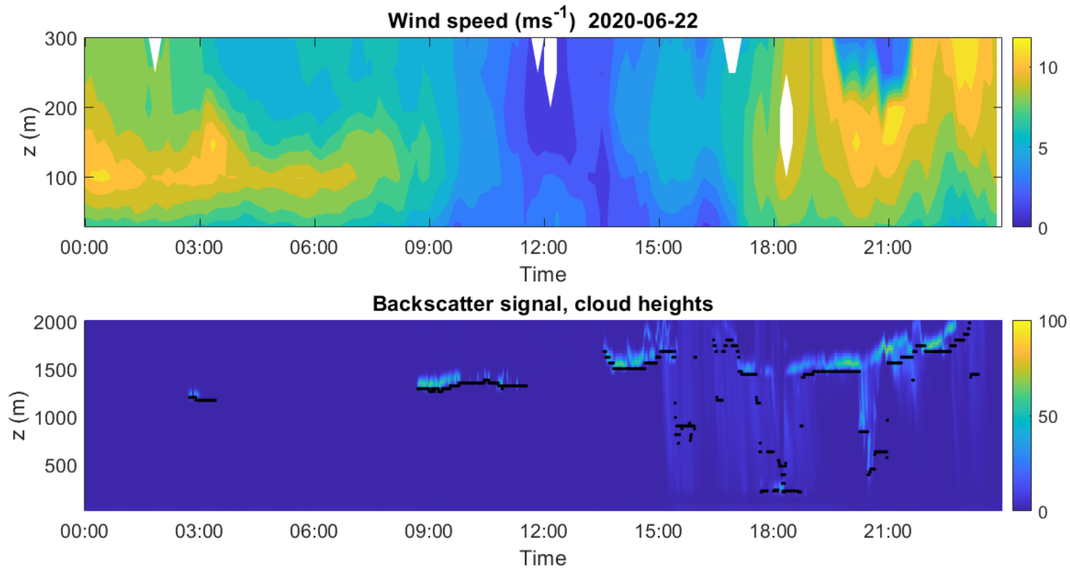

Figure 7: The upper panel shows the wind profile for the 22nd of June 2020. The lower panel shows the cloud base heights (CBH) from the backscatter for the same date. Most of the lower CBH values (below 1000 m) in this case are from rain, and future studies may need to distinguish better between influence from clouds and precipitation on the CBH. Note that the y-axes in the two panels are different.

3.2 Monthly and seasonal characterisation

In this subsection, a general monthly and seasonal characterisation is first provided for the LLJs, and then for the presence of LLCs during operating LLJs. These characterisations are based on the definitions made on the LLJs and LLCs in the previous subsection 3.1.

3.2.1 LLJs

Figure 8 shows the LLJ frequency in percent (of the total measured hours) for each month during the period of measurements and their associated LLJ maximum speeds. The upper panel in Figure 8 regards all LLJs while the lower panel regards just LLJs below 300 m. The values of the orange bars are the share of LLJs below 300 m as calculated from the total LLJ occurrence per month. The most LLJ frequent month proved to be February where LLJs occurred around 52.8 % of the time and the least LLJ frequent month was August where LLJs occurred around 23.6% of the time. It can also in general be said that the median max speed is significantly higher for more LLJ frequent months, even though it is not true in every case. The median max speed was highest in December with about 17.9 ms^{-1} and lowest in July with about 10.3 ms^{-1}. The largest share of LLJs below 300 m belong to the summer months where LLJs below 300 m contributes 78.9 % of the total LLJs in June. LLJs below 300 m show a pretty small contribution to the LLJs in the winter months (< 7.5 %). There is also no clear trend in the speed of these LLJs below 300 m.

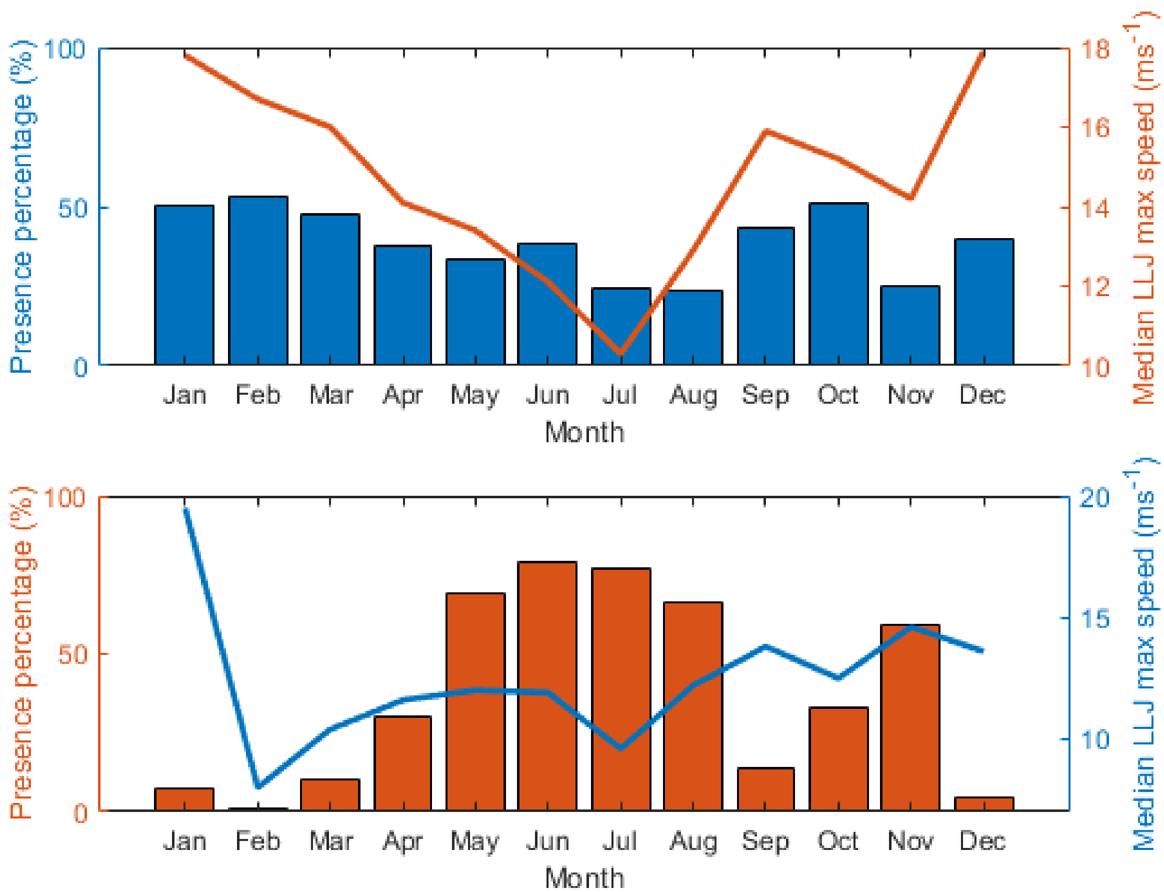

Figure 8: The low-level jet (LLJ) frequency regarding all LLJs per month and their associated max speeds in the upper panel. The share of LLJs below 300 m as calculated from the total LLJ occurrence per month and their associated max speeds is shown in the lower panel. Note that the right y-axes in the two panels are different.

Combining months into seasons give the LLJ seasonal characteristics according to Table 1, including properties as frequency, mean height, mean max speed, and mean direction. The table is distinguishing between LLJs below 300 m and all LLJs (including those at 300 m or higher up). In other words, it distinguishes between characteristics of the LLJs that are certain (frequency, mean height, mean max speed, and mean direction of LLJs below 300 m) and characteristics about LLJs that are more of a guess, as no data above 300 m is available. The numbers without parentheses concern all LLJs while the numbers with parentheses concern the LLJs below 300 m. The numbers in parentheses in the frequency column show the percentage of LLJs that are below 300 m as calculated from the total LLJ occurrence per season. The LLJ frequency seems to be direction dependent. The highest frequency occurs in the winter months December-February with a mean direction of 222°. That is, wind travelled from southwestern Gotland, pretty much along the east coast (onshore) where large roughness- and temperature contrasts occur. The latter is especially valid during spring. The second and third most LLJ-frequent season was autumn and spring respectively where the wind had a mean direction of 204° and 213° respectively. That is, wind coming a little bit more from the south but still very close to the coast but mostly offshore. The least LLJ-frequent season was summer with a 28.8% frequency and a mean wind direction of 154°. That is, wind coming from about SSE which is purely water between Östergarnsholm and the southern part of the Baltics. The mean height of the jet core and the mean maximum speed are also higher during the more LLJ-frequent seasons. That is, the LLJ frequency seems to be dependent of those parameters as well

Table 1: Low-level jets (LLJs) seasonal characteristics: frequency, mean height of the jet core, maximum speed, and wind direction. The numbers without parentheses concern all identified LLJs and the numbers inside the parentheses concern LLJs below 300 m. The numbers inside the parentheses in the LLJ frequency column are the percentages of LLJs that are below 300 m as calculated from the total LLJ occurrence per season.

Season	LLJ frequency (%)	LLJ mean height (m)	LLJ mean max speed (ms^{-1})	LLJ mean direction (°)
Dec-Feb	47.7 (4.38)	300 (195)	17.5 (14.9)	222 (223)
Mar-May	39.5 (40.0)	267 (128)	14.5 (11.9)	213 (196)
Jun-Aug	28.8 (75.6)	167 (135)	11.8 (11.1)	154 (127)
Sep-Nov	39.6 (30.9)	217 (150)	15.1 (13.3)	204 (203)

3.2.2 Presence of LLCs during LLJs

Figure 9 shows the LLC occurrence during operating LLJs for each month and their associated median CBH spans. The CBH median span is found by taking the lowest and highest CBH respectively (see subsection 2.4), during active LLJs of each day in a specific month and then taking the median of those values separately. The highest LLJ-LLC presence (concerning LLJs at any height) occurs in December with about 68.1% and lowest LLJ-LLC presence (concerning LLJs at any height) occurs in June with about 25.9%. Generally, higher LLJ-LLC presence percentage coincides with lower LLC base heights. This is apparent in for example December which both has the highest LLJ-LLC presence and the lowest average *CBH*. June, that has the lowest LLC presence during LLJs at all heights, has a high average *CBH* (around 1000 m).

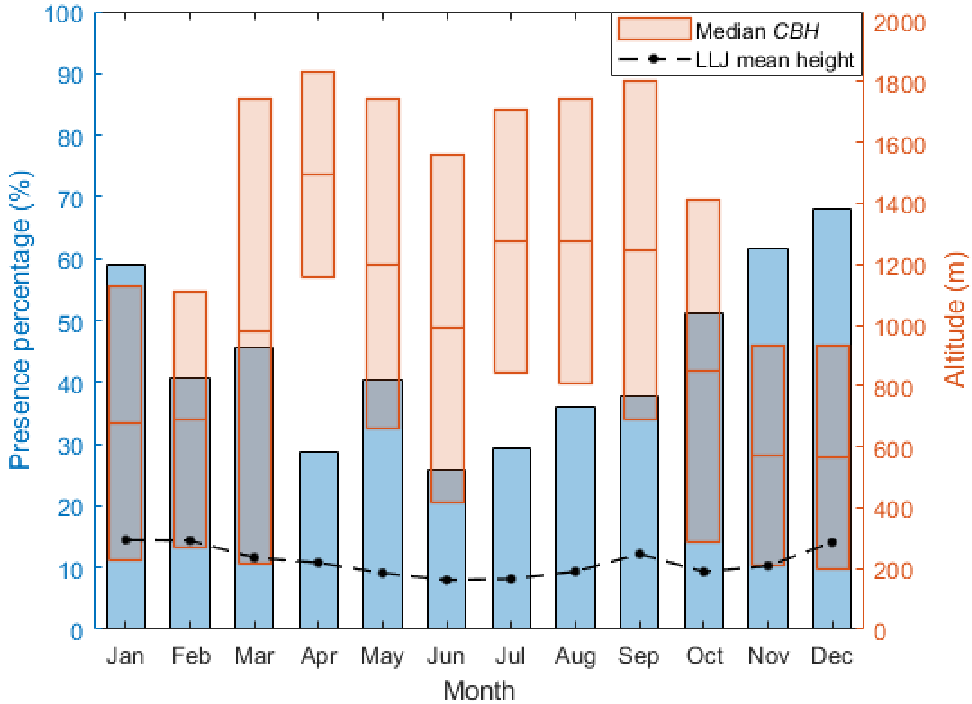

Figure 9: The low-level clouds (LLCs) appearance during operating low-level jets (LLJs) for each month (in blue bars) and their associated median cloud base heights (*CBH*) spans (in red boxplots). The lower part of the boxplot shows the lower median *CBH*, and the upper part of the boxplot shows the upper median *CBH*. The LLJ mean height is displayed in the black dash-dotted line.

Combining months into seasons yields the following Table 2. The LLJ-LLC presence column is telling us how much of the time LLCs appear when LLJs are active, presented as a percentage. The LLC mean *CBH* span column gives us the mean lower height and the mean upper height for each season. The numbers in parentheses show the presence percentage of LLCs during operating LLJs below 300 m and the mean *CBH* span of these LLCs, respectively. The highest presence of LLCs during operating LLJs at any height and during LLJs below 300 m both occur in the winter (56.0 % and 64.5 % respectively). They have a high appearance in the autumn as well but less in spring and summer. Least appearance is during the summer, with 30.4%, where LLCs during LLJs below 300 m also has a low presence (21.9 %). The *CBH* height is inversely proportional to the LLJ-LLC presence: higher appearance of LLCs during LLJs means lower LLC mean height. Hence, lower mean height in the winter (lower CBH was 233 m) and higher mean height in the summer (lower CBH was 692 m). From Table 2, it can also be observed that those months with higher LLJ-LLC presence (winter, autumn, and spring), are the seasons with higher LLJ frequencies, higher LLJ mean heights, higher wind speeds and are also originating from approximately the same direction (along the east coast of Gotland). This implies that not only the LLJ gets triggered by different contrasts between sea and land, but also the LLC appearance gets triggered by that.

Table 2: Seasonal presence of low-level clouds (LLCs) under operating low-level jets (LLJs), and the mean cloud base height (CBH). The numbers in parentheses show the presence percentage of LLCs during LLJs under 300 m (middle column) and the mean CBH span of these LLCs (right column).

Season	LLJ-LLC presence (%)	LLC mean CBH span (m)
Dec-Feb	56.0 (64.5)	233-1055 (170-651)
Mar-May	38.3 (19.4)	677-1770 (823-1606)
Jun-Aug	30.4 (21.9)	692-1670 (818-1531)
Sep-Nov	50.2 (23.6)	397-1380 (638-1199)

The information about the characteristics of the LLJs and the LLJ-LLC presence can be combined in order to be able to draw even more careful conclusions about the LLJ-LLC interaction. If one would look deeper into each month, and seek for the monthly LLJ median directions, it could be easier to see a connection. Since when the median direction was other than along the shore of the east coast of Gotland, the LLJ-LLC presence was lower (lower than 30%) than it was when the LLJ direction was along the coast (more than 35%), except for one case (November). For example, during the month with the highest percentage of LLJ-LLC presence (December), the LLJ median direction was 210°; and during the month with the lowest percentage of LLJ-LLC presence (June), the LLJ median direction was 139°. Why November has so high LLJ-LLC presence but a southerly LLJ direction (175°) is a suitable question to ask. There are no other factors that clearly impacts the presence. Neither the LLJ median speed maximum (14.2 ms^{-1}) nor the LLJ median height (200 m) is particularly distinctive from the other months. But it might be because of there was much data missing for November and thus, not enough occasions to identify LLJs and LLCs. Therefore, the median LLJ direction might have been significantly different with more data to analyse. To conclude, a lower LLJ-LLC presence implies in general that the wind direction is other than close to the shore of Gotland and a higher presence means that it is close to the coast. The monthly LLJ-LLC presence combined with the LLJ median direction is visualised in Figure 10.

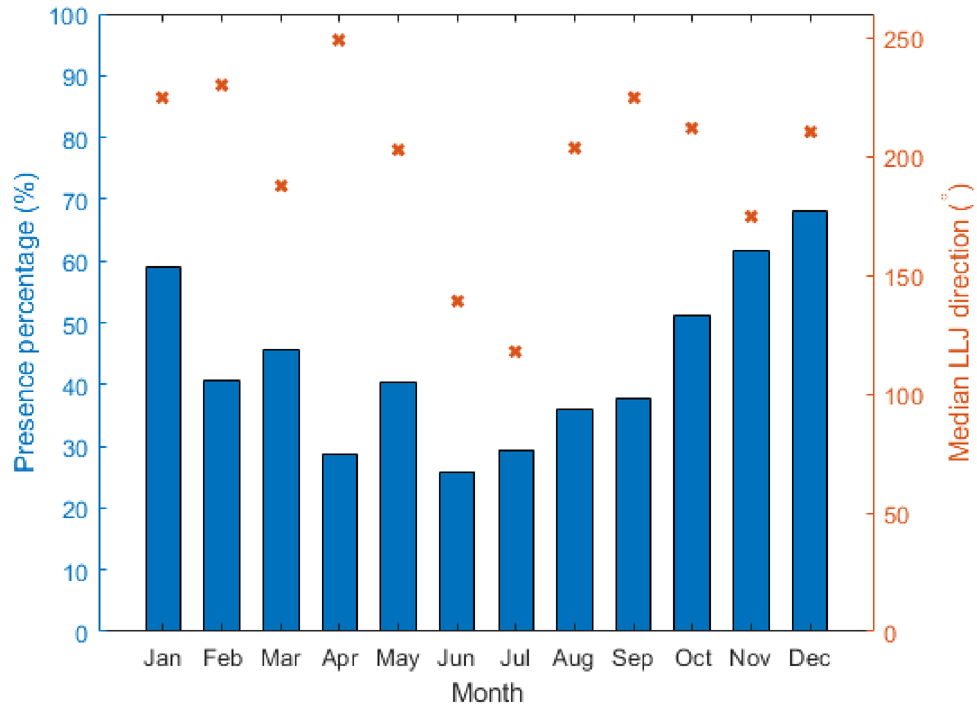

Figure 10: Monthly presence of low-level jets (LLJs) at all levels in combination with present low-level clouds (LLCs) (both calculated as hours) and the direction of the LLJs.

In Figure 11, it is shown even more how the LLJs are influencing the overall LLC appearance. The two visualisations show the total cloud appearance by season and month respectively for the 501 days of used measurement data, divided into blue bars (LLCs present during active LLJs below 300 m), red bars (LLCs present during active LLJs at 300 or above) and yellow bars (LLCs present when no LLJs are operating). For each month (or season), the blue, red, and yellow bars together represent 100 % of the total LLC appearance for that individual month (or season). The LLC appearance percentage during other hours than during operating LLJs is up to 80.7 % in November (and thus 19.3 % during LLJs where 49.5 % of these appear during LLJs below 300 m).

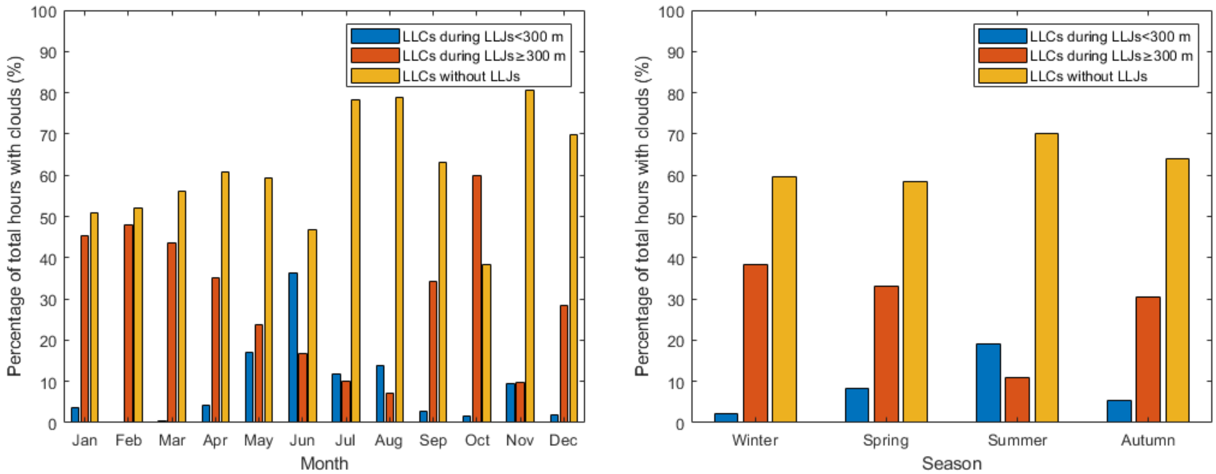

Figure 11: The percentage of when the low-level clouds (LLCs) occur for each month and season (in respective figure): during operating low-level jets (LLJs) below 300 m (bars in blue), during operating LLJs at 300 m or above (bars in red) or during hours without LLJs (bars in yellow).

3.3 Discussion

In Figure 12 are the panels for the wind profile and the LLCs now presented together with a panel for the TI for the 22nd of June 2020. In an early stage of the second LLJ, the TI lowers around the core of the LLJ. The TI goes from a value of 0.0795 just before the LLJ starts to operate, to 0.0148 in an early stage of the LLJ. At most, the TI has increased to 0.0853 at 27 m height and to 0.370 at 250 m. Thus, the maximum turbulence intensity is occurring around 100 m above the jet core (at 20:00 UTC). This increase in TI below and more important above the LLJ suggests that the increase is induced by the LLJ. The LLJ is causing strong turbulent mixing. The standard deviation of the horizontal wind speed is being increased owing to the LLJ and consequently, also the TI. This could further entail transportation of aerosols and moisture aloft to the upper part of the ABL. In general, the temperature decreases with height. Colder temperatures are needed in order for cloud droplets or ice crystals to be formed. Since when the air cools, the air cannot hold all the water vapor that is in the air (the air becomes saturated), whereupon this water vapor changes into liquid or solid state. Thus, formation of clouds can take place.

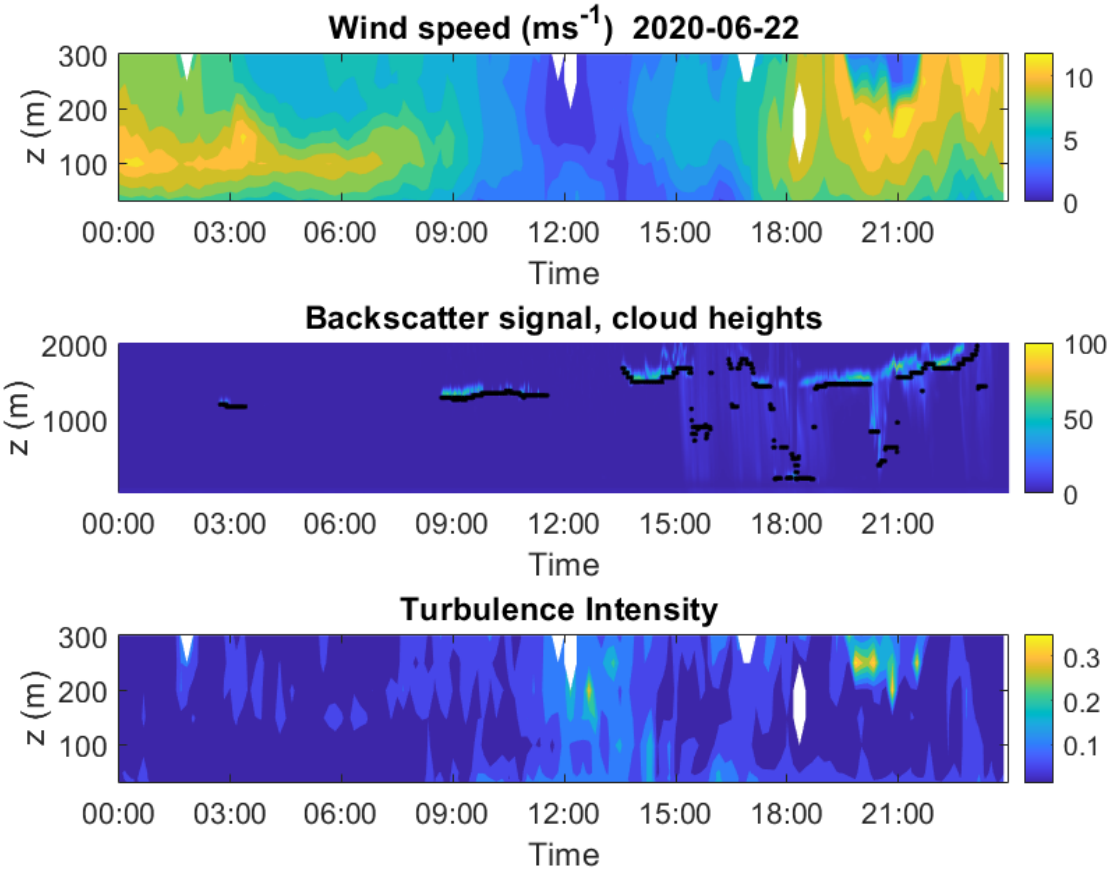

Figure 12: The wind profile for the 22nd of June 2020, with the wind profile in the upper panel. The middle panel shows the cloud base heights (CBH) and the lower panel shows the turbulence intensity (TI) for this date. Note that the y-axes between the middle panel and the other two panels are different.

4 Conclusions and outlook

This study has dealt with low-level jets (LLJs) and low-level clouds (LLCs) as measured over the Baltic Sea. The LLJs are measured by the ZephIR 300 LiDAR which calculates the wind speed and wind direction at ten different heights up to 300 m. Due to limitation of the LiDAR signal in height, the LLJs were defined in two ways based on the height they occurred. The first group identifies LLJs below 300 m that are clearly measured by the LiDAR, while in the second group the LLJs higher than 300 m are assumed and added in the statistics. The uncertainty of the guessed LLJs (above 300 m) was replaced with an assumption that the wind speed decreased above that height. The LLCs are measured by the ceilometer CBME80B which is another kind of LiDAR. The CBME80B measures cloud base heights or vertical visibility up to 7600 m. All these measurements have been obtained from about two years of data from the Östergarnsholm observatory, east of Gotland.

Highest seasonal LLJ frequency, regarding all LLJs, was during the winter period (47.7 %). The season with the largest share of LLJs below 300 m was however summer (75.6 %). The season with the highest LLC presence during operating LLJs was the winter period December to February. This applies both concerning all LLJs (56.0 %), and LLJs below 300 m (64.5 %). The lowest LLC presence during all LLJs was in summer (30.4 %), while the lowest LLC presence during LLJs below 300 m was in spring (19.4 %). For all seasons, the majority of the LLCs were present other times than during active LLJs: around 60 to 70 %. Summertime, 29.8 % of the LLCs appeared when the LLJs were active. 19.0 % of the LLCs were present during LLJs below 300 m and 10.9 % were present during LLJs around 300 m this season.

During the winter period the LLJs were stronger compared to summertime (around 17 ms^{-1} vs 12 ms^{-1}, respectively). The same applies for LLJs below 300 m (15 ms^{-1} vs 11 ms^{-1}). In both cases, the dominant wind direction was from southwest. Only during the summer was the southeast wind the dominant wind direction. The mean height of the LLJ core was around 300 m during winter season and was decreasing down to 170 m during the summer. Only concerning LLJs below 300 m, the height of the LLJ core decreased from 200 m in the winter to around 130 m in spring and summer. The average height of the CBH was lower during wintertime (around 650 m) then during spring and summer (around 1200 m). The same applies for the CBHs of the LLCs present during LLJs below 300 m (400 m vs 1200 m).

Indications that the LLJ influence on LLC formation is larger during late autumn, winter, and early spring, than during other times, were found. This is since the LLCs average cloud base heights are in the range between 300 and 700 m above the jet core. It has been shown that this is the layer where the increased turbulence intensity was recorded. Thus, the maximum transport of cold and humid air caused by turbulence, which is relevant for cloud formation and development, can be expected above the jet. During the summer months, the difference in height between the average CBH and the LLJs maxima is often larger than 1000 m, thus the direct LLJ influence on cloud formation is less plausible (although there are separate cases recorded with lower CBH during night-time).

To prove the hypothesis about LLJs possible influence on LLC formation, detailed process-wise study should be performed. Possibly by using high-resolution turbulence-resolving atmospheric models (e.g., large-eddies simulations) with included cloud microphysics modules to understand the LLJs-LLCs influencing mechanisms. This study has had its directed focus on the macroscale. Future research could go more into the microscale, and thus into more detail. Are the LLCs convective clouds, stratiform clouds or a mix between those? Are they cumulus, stratus, or stratocumulus clouds? Do they consist of water droplets, ice crystals or both? Do they produce precipitation and if so, what kind of precipitation (e.g., rain, drizzle, snow, hail)? Future studies should also be better in distinguishing between influence from clouds and precipitation on the CBH. Further research within the area could then strengthen global climate models and weather forecasts even more.

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A Appendix

A.1 Example of LLJ induced turbulence

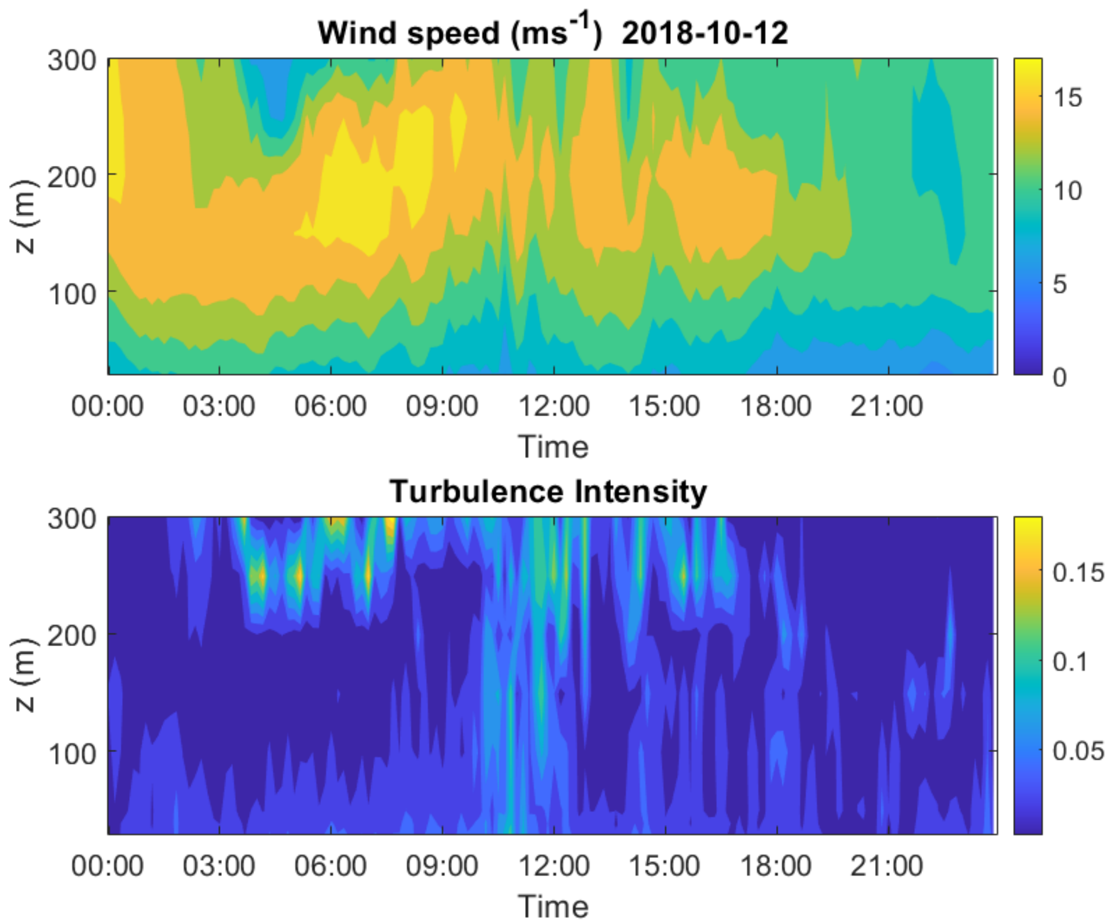

Figure A1: The wind profile for the 12th of October 2018 in the upper panel. A nice low-level jet (LLJ) is shown from 00:00 to around 20:00 UTC, with a max speed of 17.0 ms^{-1} at 07:00 UTC, 150 m above the surface. The turbulence intensity for the same date is shown in the lower panel. It is clear that the LLJ has induced an increased mixing below and above the jet core, where the latter could lead to turbulent transport of cold and humid air and eventually, clouds. No clouds were however present in this case. The sun rises at around 07:00 UTC at this time of the year, so the increase in turbulence intensity early in the LLJ is not due to convection.

A.2 Examples of LLJ-LLC presence

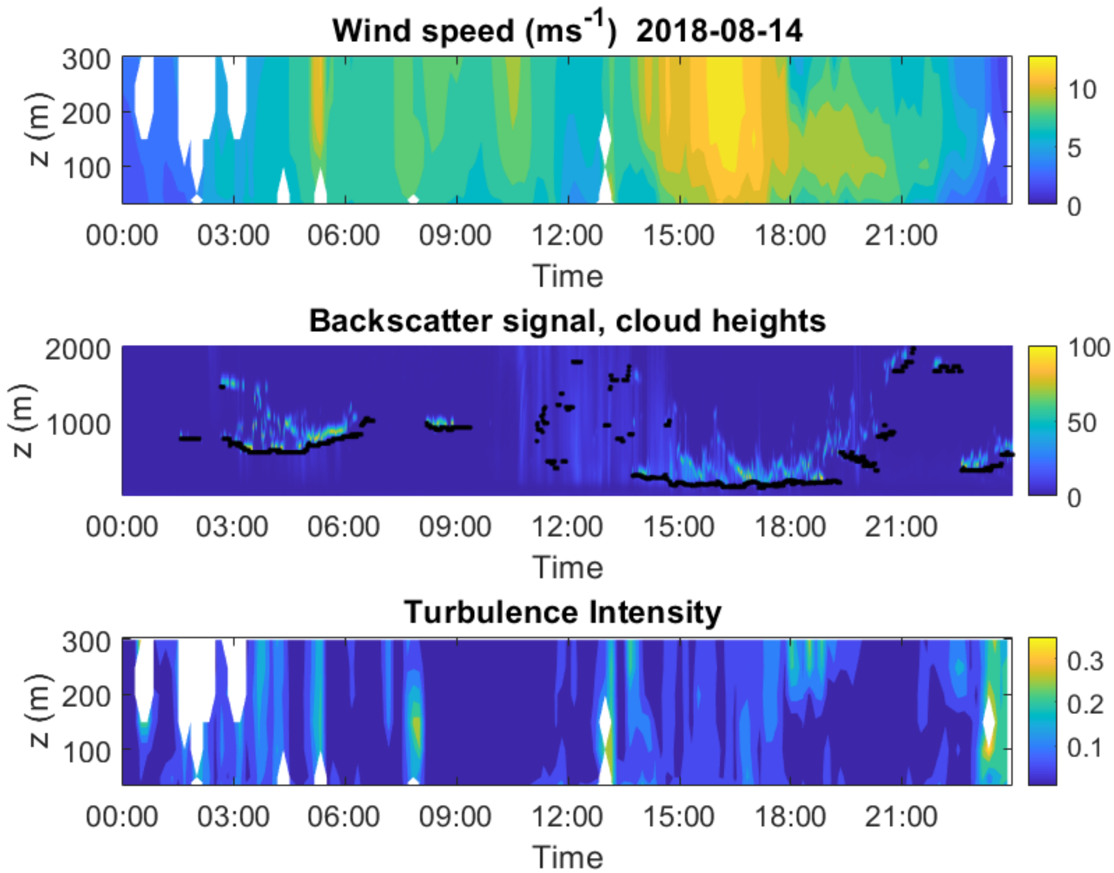

Figure A2: The wind profile for the 14th of August 2018, with a low-level jet (LLJ) between 18:00 and 21:00 UTC in the upper panel. The LLJ max speed is 10.0 ms^{-1} at 100 m height, at 19:30 UTC. The middle panel shows the cloud base heights (CBH) for the same date, with present clouds at around 230 m in the beginning of the LLJ. The lower panel shows the turbulence intensity (TI) for this date. The TI is lower at the jet core than below and above it.

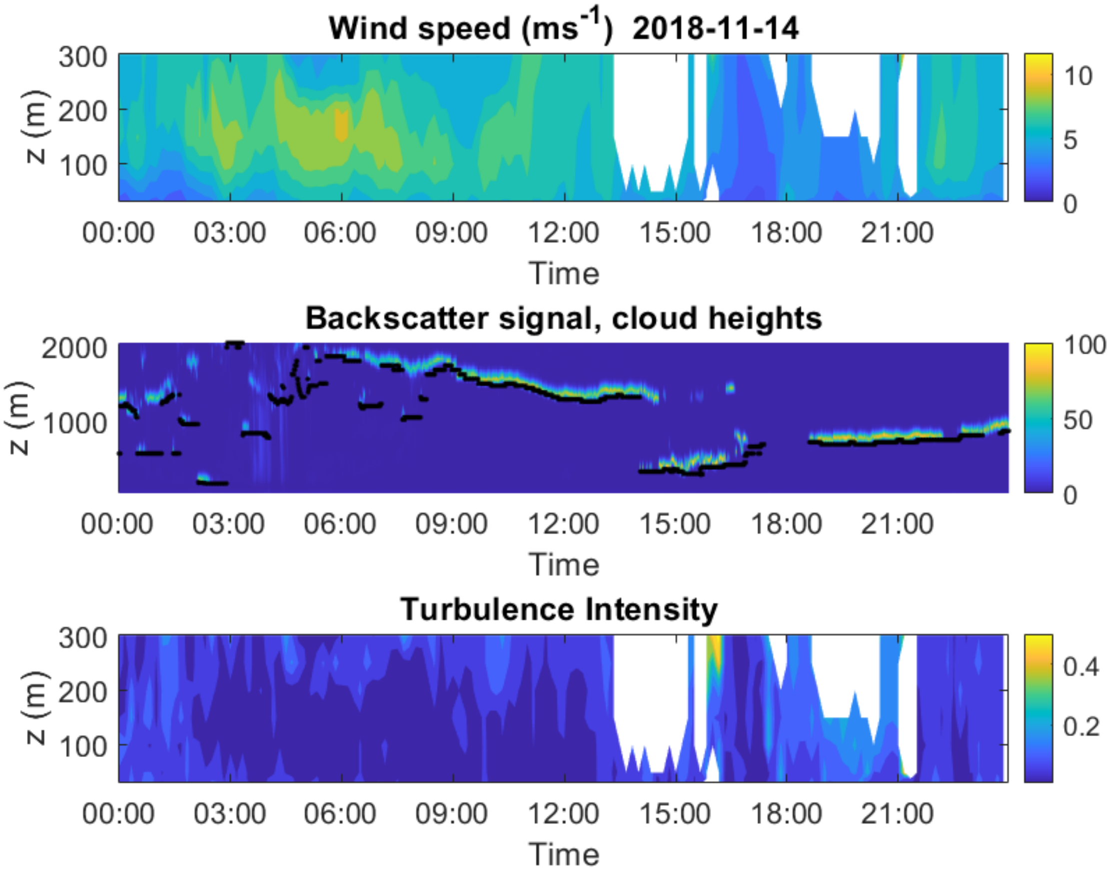

Figure A3: The wind profile (upper panel) for the 14th of November 2018, with a low-level jet (LLJ) at least between 00:30 and 11:00 UTC. The LLJ max speed is 9.3 ms^{-1} at 150 m height, at 06:00 UTC. There are low-level clouds (LLCs, middle panel) from 170 m height up to 2000 m, but just after 00:00 UTC the cloud base height (CBH) is at 570 m and just after 03:00 UTC the CBH is at 840 m. It is clear that after 02:00 UTC, the turbulence intensity (TI, lower panel) is lower at the jet core than below and above the core. A second weak LLJ occurs around 22:00-23:00 UTC, with a max speed of 7.5 ms^{-1} at 150 m height. LLCs occur at 750 m at this time.

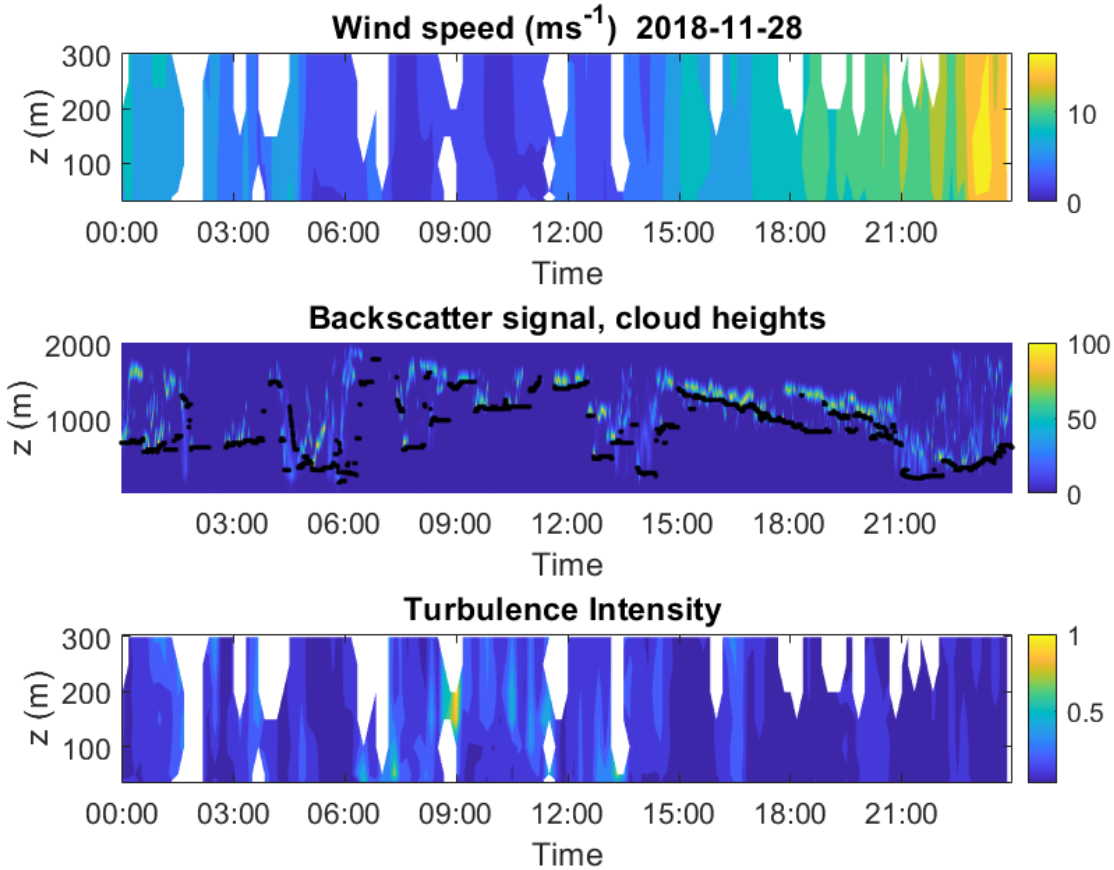

Figure A4: The wind profile for the 28th of November 2018, with a low-level jet (LLJ) between 23:00 UTC and midnight in the upper panel. It has its max 16.7 ms^{-1} at 150 m around 23:00 UTC. This LLJ continues in the next day (Figure A5). The middle panel shows the cloud base heights (CBH) for the same date, with present clouds at around 390-660 m in the beginning of the LLJ. The lower panel shows the turbulence intensity (TI) for this date.

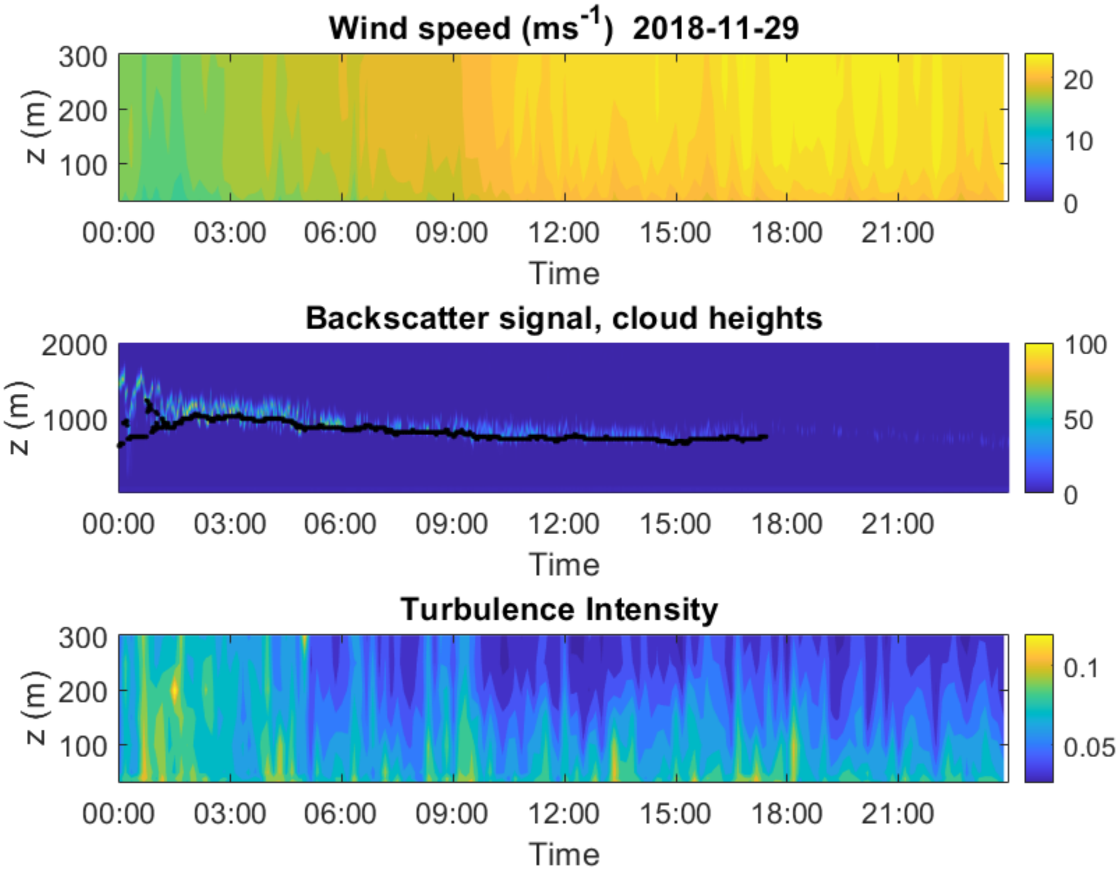

Figure A5: The wind profile (upper panel) for the 29th of November 2018, with probably a low-level jet (LLJ) all day (at 300 m or above). Between around 00:00 and 01:30 UTC however, the LLJ max is at 150 m (17.2 ms^{-1}), and this probably belongs to the LLJ just before midnight as seen in Figure A4. The middle panel shows the cloud base heights (CBH) for the same date, with present clouds at around 630-1230 m during the lower LLJ. The lower panel shows the turbulence intensity (TI) for this date.

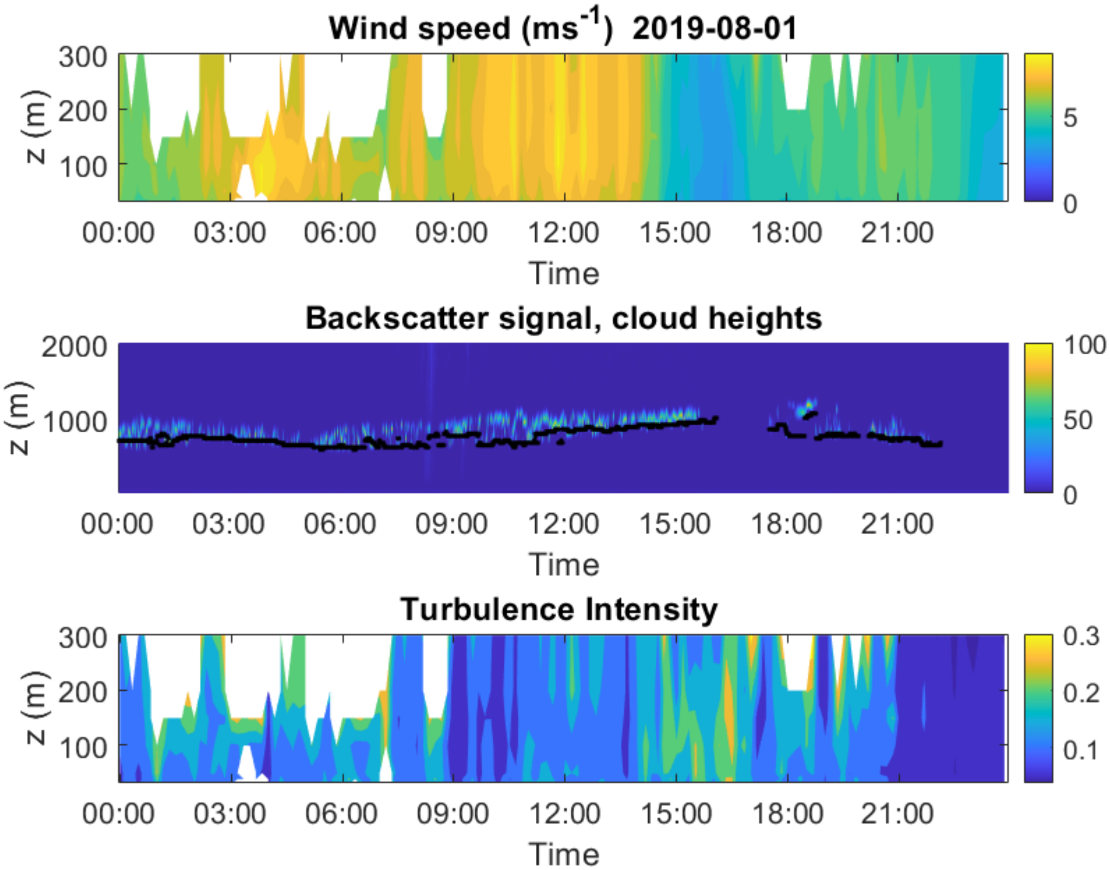

Figure A6: The wind profile (upper panel) for the 1st of August 2019. A low-level jet (LLJ) probably occurs at least between 03:00 and 06:00 UTC, with a visible max speed of 8.6 ms^{-1} at 100 m height at 04:00 UTC. During this LLJ, there is low-level clouds (LLCs, middle panel) present at 750 m. The turbulence intensity (TI, lower panel) shows an increase above the jet core (although most of the increased is "hidden" in the missing data region).

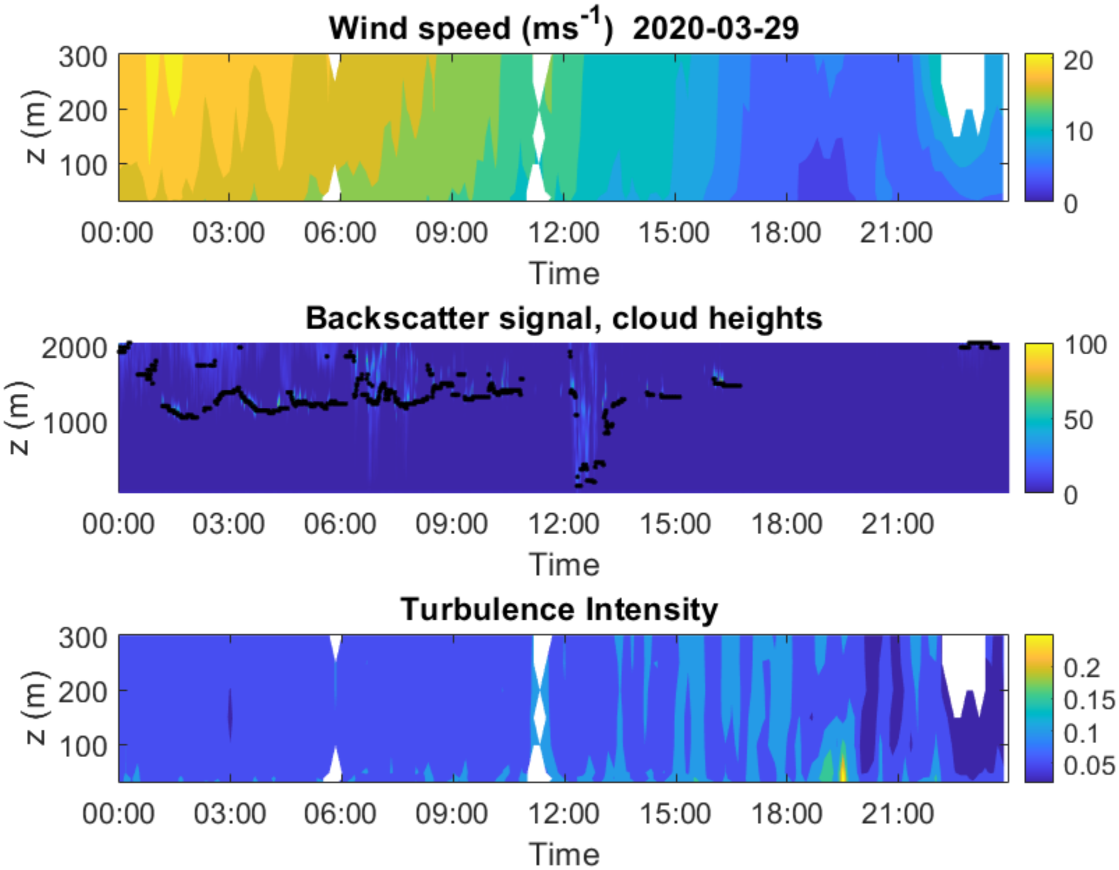

Figure A7: The wind profile (upper panel) for the 29th of March 2020, where there probably is a low-level jet (LLJ) between before midnight to 12:00 UTC. Its max speed is 20.7 ms^{-1} around 300 m at 01:00 UTC. During the LLJ, there are LLCs (middle panel) around 1250 m and higher. The lower panel shows the turbulence intensity (TI) for the same date.

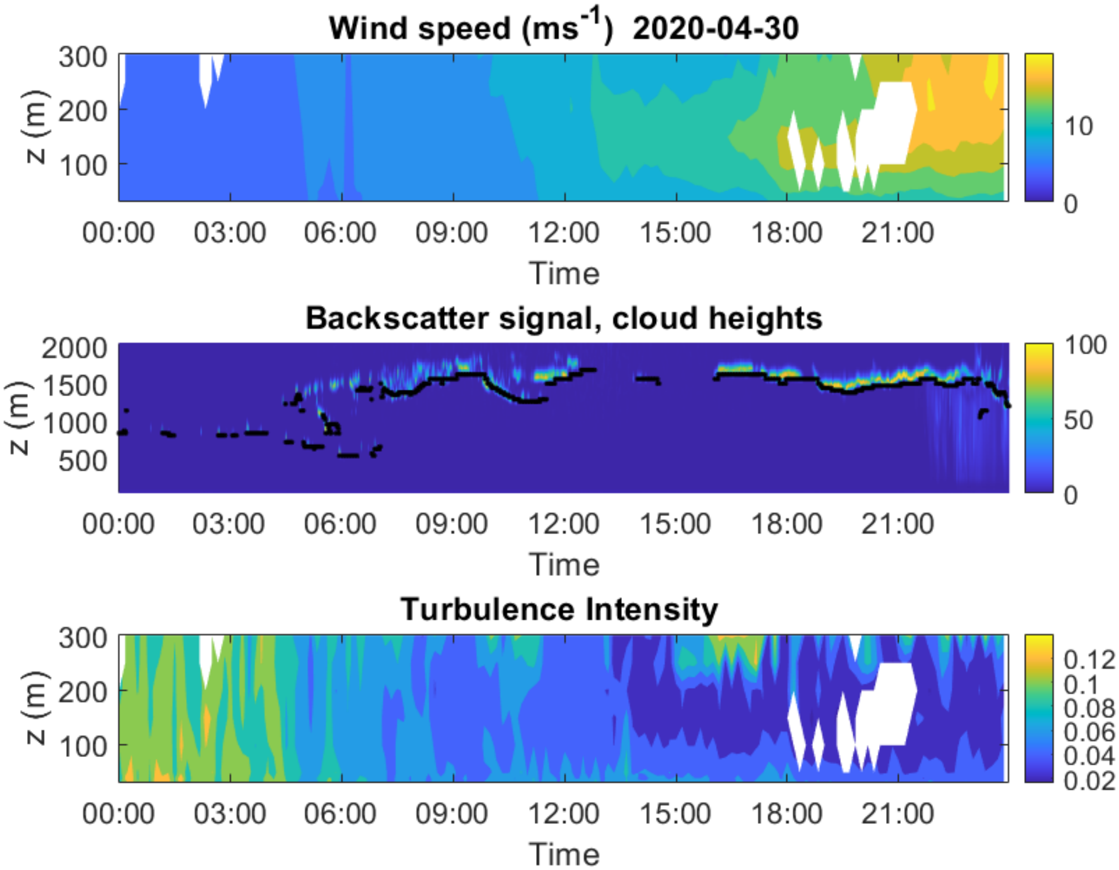

Figure A8: The wind profile (upper panel) for the 30th of April 2020, where there is a low-level jet (LLJ) between 13:00 and 24:00 UTC. Its max speed is 19.0 ms^{-1} at 250 m at 23:30 UTC. From 16:00 UTC, there are LLCs (middle panel) around 1500 m which sinks down to 1200 m at 23:00 UTC when the LLJ rises to 250 m. The lower panel shows the turbulence intensity (TI) for the same date, showing lower TI at the jet core, at least until 22:00 UTC.

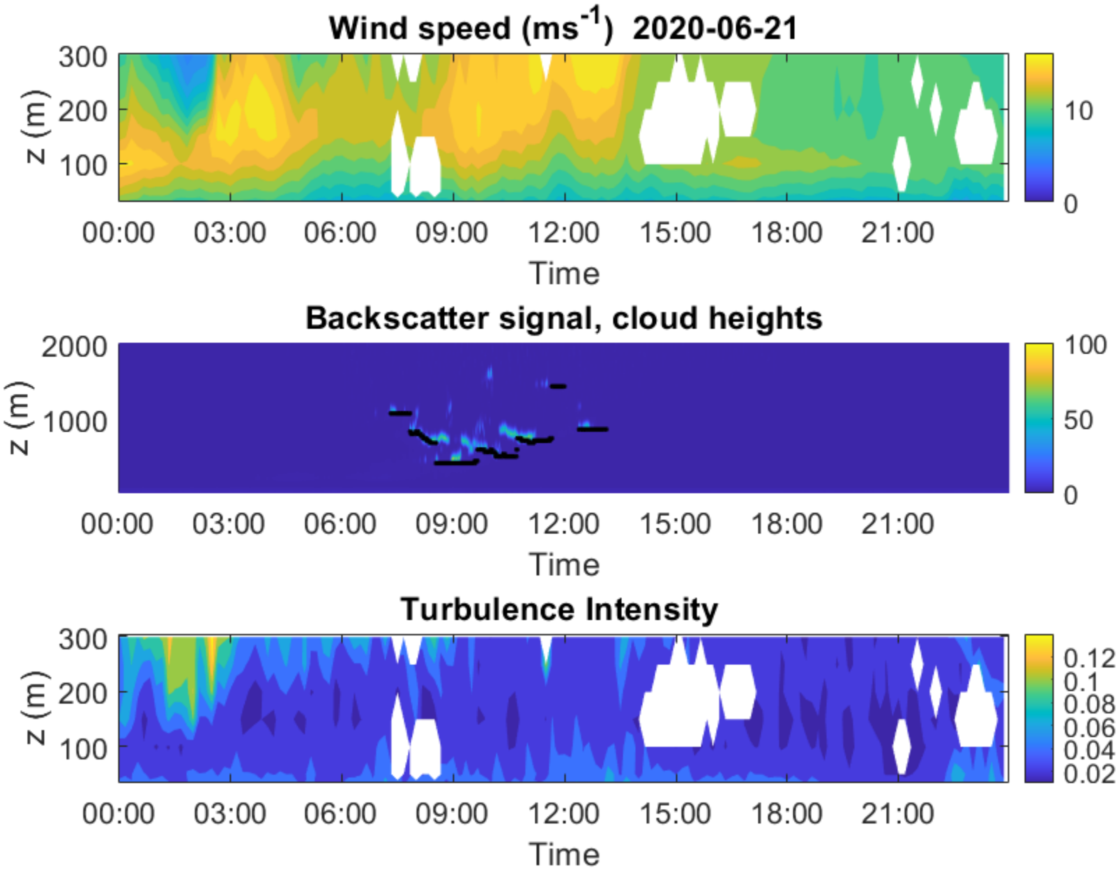

Figure A9: The wind profile (upper panel) for the 21st of June 2020, where there is a low-level jet (LLJ) at least between 00:00 and 12:00 UTC. Its max speed is 15.6 ms^{-1} at 200 m at 04:00 UTC. From 07:30 UTC, there are LLCs (middle panel) around 1100 m which sinks down to 420 m at 09:00 UTC and then rise again to 870-1440 m. The lower panel shows the turbulence intensity (TI) for the same date, showing lower TI at the jet core.