



Lidar measurements of Bora wind effects on aerosol loading



Maruška Mole^{a,*}, Longlong Wang^a, Samo Stanič^a, Klemen Bergant^{a,b},
William E. Eichinger^c, Francisco Ocaña^d, Benedikt Strajnar^b, Primož Škraba^e,
Marko Vučković^a, William B. Willis^c

^a University of Nova Gorica, Vipavska cesta 11c, Ajdovščina, Slovenia

^b Slovenian Environment Agency, Vojkova 1b, Ljubljana, Slovenia

^c University of Iowa, 523B C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA, USA

^d Universidad Complutense de Madrid, Avda. Complutense s/n, Madrid, Spain

^e Jožef Stefan Institute, Jamova cesta 39, Ljubljana, Slovenia

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ABSTRACT

The Vipava valley in Slovenia is well known for the appearance of strong, gusty North-East Bora winds, which occur as a result of air flows over an adjacent orographic barrier. There are three prevailing wind directions within the valley which were found to give rise to specific types of atmospheric structures. These structures were investigated using a Mie scattering lidar operating at 1064 nm, which provided high temporal and spatial resolution backscatter data on aerosols, which were used as tracers for atmospheric flows. Wind properties were monitored at the bottom of the valley and at the rim of the barrier using two ultrasonic anemometers. Twelve time periods between February and April 2015 were selected when lidar data was available. The periods were classified according to the wind speed and direction and investigated in terms of appearance of atmospheric structures. In two periods with strong or moderate Bora, periodic atmospheric structures in the lidar data were observed at heights above the mountain barrier and are believed to be Kelvin–Helmholtz waves, induced by wind shear. No temporal correlation was found between these structures and wind gusts at the ground level. The influence of the wind on the height of the planetary boundary layer was studied as well. In periods with low wind speeds, the vertical evolution of the planetary boundary layer was found to be governed by solar radiation and clouds. In periods with strong or moderate Bora wind, convection within the planetary boundary layer was found to be much weaker due to strong turbulence close to the ground, which inhibited mixing through the entire layer.

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1. Introduction

Due to its complex orography, the Vipava valley (100 m a.s.l., Figs. 1 and 2), positioned between the ridge of Trnovski gozd (1500 m a.s.l.) and the Karst plateau (500 m a.s.l.), is a good location for observations of atmospheric structures related to the airflow over the mountain barrier.

Orographic barriers are known to cause the air to oscillate downwind of the barrier and form so-called mountain waves [1–3]. A direct consequence of such waves is drag which appears toward the upper atmospheric level, and possible clear-air turbulence which can be dangerous for aviation. Associated with these phenomena are strong surface winds (so-called downslope winds, [4,5]) blowing down the lee side of the mountains. In the case of the Vipava valley, this wind is called Bora. It is a consequence of the stably stratified air-masses flowing from the northeast over the ridges of the Trnovski gozd, Nanos and

* Corresponding author.

E-mail address: maruska.mole@ung.si (M. Mole).

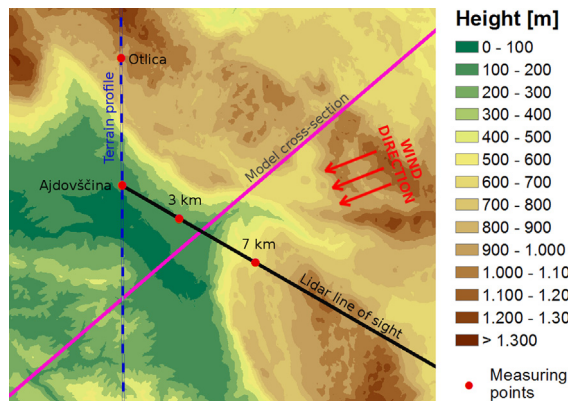


Fig. 1. An orographic map of the Vipava valley region. Anemometers were located in Ajdovščina and at Otlica, with the lidar line of sight oriented towards the south-east at an elevation angle of 20° . The markers 3 km and 7 km along the lidar line of sight show lidar measurement locations at the heights of 1.1 km and 2.5 km. The terrain profile along the dashed line is shown in Fig. 2 and the two-dimensional model prediction of the wind velocities along the pink line is shown in Fig. 9. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

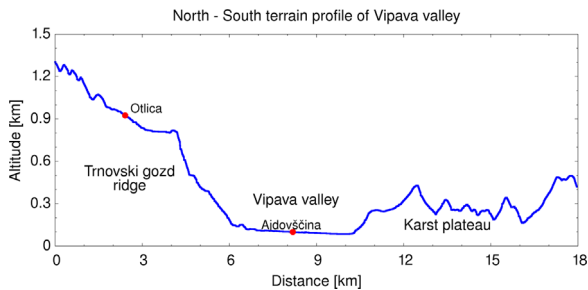


Fig. 2. The terrain profile of the Vipava valley along the north-south direction. Red points represent the locations of surface wind measurements. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Javorniki plateaus into the Vipava valley and over the Karst region [6,7]. The flow of cold air down the slopes causes strong winds on the lee side of the barrier [8,9], with the strongest wind gusts observed directly below the barrier. During Bora events, wind gusts commonly reach velocities above 30 m/s [9]. The preliminary study of winds within the Vipava valley, performed on the data set acquired in 2015 at the valley floor, shows three prevailing wind directions – northeast (NE) winds, corresponding to Bora, southwest (SW) winds, which are usually mild and do not exceed 5 m/s, and southeast (SE) winds, which usually occur when Bora weakens and rarely exceed 20 m/s. Wind conditions within the valley affect the vertical distribution of aerosols and structures, forming in and above the planetary boundary layer (PBL). Due to their small size (few tens of nm to few tens of μm), aerosols may be assumed to follow airflow streamlines, and can therefore be used as tracers for the study of airmass motion. Elastic lidar measurements provide information on the vertical distribution of aerosols and its evolution in time [10–13]. They can, therefore, reveal atmospheric structures within the troposphere and above, which provides valuable



Fig. 3. The Mie scattering lidar system used in the observations (top) and an ultrasonic anemometer, positioned on the rooftop of the University of Nova Gorica building in Ajdovščina (bottom).

information for characterizing the behavior of the atmosphere under various weather conditions [14].

2. Instrumentation and experimental setup

Lidar observations were performed between February and April 2015 in Ajdovščina (Fig. 2), a small town at the edge of the Vipava valley floor, which is ideally located to observe cold airflow over the mountain barrier. Atmospheric structures were observed using the Mie scattering lidar system and two ultrasonic anemometers. The lidar system and one of the anemometers were positioned in the urban environment of Ajdovščina, while the second anemometer was located at the Otlica observatory at the top of the mountain barrier, 6 km north of Ajdovščina. The University of Nova Gorica's Mie scattering lidar (Fig. 3, Table 1) uses an Nd:YAG pulsed laser with a wavelength of 1064 nm, pulse energy of 40 mJ and pulse length of 9 ns at a 10 Hz repetition rate as a transmitter. It employs a Newtonian telescope with 300 mm diameter mirror as a receiver, an avalanche photodiode as a detector, and a digitizer, which enables data sampling with a spatial resolution of 3.75 m. Each lidar measurement is an average over 10 laser pulses, resulting in a sampling rate of about 1.3 Hz [15]. The range of the lidar system is approximately 10 km under clear weather conditions.

Table 1

A summary of main lidar and anemometer parameters used in the presented research.

Lidar system	
Transmitter	Nd:YAG pulsed laser
Wavelength	1064 nm
Pulse energy	40 mJ
Pulse duration	9 ns
Repetition rate	10 Hz
Receiver	Newtonian telescope
Diameter	300 mm
Focal length	1500 mm
Detector – APD	EG&G C300954/5E
Quantum efficiency	38%
Data recorder	Licel TR40-160
Sampling rate	40 MSPS
A/D resolution	12 bit
Range resolution	3.75 m
Anemometers	
Ultrasonic 2D device	Vaisala WMT702
Wind speed range	0–65 m/s
Resolution	0.01 m/s (speed) 0.01° (direction)
Accuracy	± 0.1 m/s or 2% of reading, whichever is greater (speed) ± 2° (direction)
Sampling rate	1 s (Ajdovščina) 10 min (Otlica)

Measurements of wind speed and wind direction were performed using two-dimensional ultrasonic anemometers (Fig. 3, Table 1), which measure the variations in the time of flight of ultrasonic pulses due to the presence of wind. The anemometer positioned in Ajdovščina provided data with a sampling rate of 1 s, while the one at Otlica was operated at a 10 min sampling rate and was mainly used to confirm the presence of Bora. Wind properties were continuously monitored 10 m above the ground from February to December 2015, while the lidar measurements were performed on selected days, corresponding to different weather situations. The days with simultaneous wind and lidar measurements are presented in Table 2.

3. Lidar observations of atmospheric structures

Between February and April 2015, twelve case studies based on lidar measurements were performed. The lidar was pointing towards the SE (azimuth 120°), alongside the mountain barrier, with a different fixed elevation angle for each specific case. Wind conditions and elevation angles are summarized in Table 2. Six of the investigated cases represent Bora outbreaks and are written in bold. Periodic structures, which are expected to appear in the atmosphere in the presence of strong air flow over the mountain barrier, were observed in the lidar data in two of these cases.

Table 2

Selected lidar measurement periods in 2015 and corresponding wind conditions. The second column presents the duration (Dur.) of each lidar measurement, the third the elevation angle (El.) of the lidar scan, the fourth the prevailing wind direction (WD), the fifth type of wind event and the sixth the maximum wind speed (Max. WS) during the lidar data taking period. Wind events were classified according to the position of the peak value of the wind speed distribution as follows: mild – peak is between 0 and 3 m/s, moderate – peak is between 3 and 6 m/s and strong – peak is between 6 and 9 m/s. Bora events (NE wind) are written in bold.

Date	Dur. (h)	El. (deg)	WD (deg)	Wind	Max. WS (m/s)
Feb 24	1	20	60	Strong NE	20.0
Feb 26	1	20	130	Mild SE	9.7
Feb 27	2	20	60	Moderate NE	11.7
Mar 5–6	30	70	130	Mild SE	20.6
Mar 9	2	48	130	Mild SE	12.2
Mar 10	8	48	60	Mild NE	14.3
Mar 12	5.5	24	60	Mild NE	9.5
Mar 17	8	23	60	Strong NE	18.9
Apr 5	1	35	130	Mild SE	9.6
Apr 13	3	33	270	Mild SW	7.2
Apr 14	8.5	30	60	Mild NE	13.7
Apr 16–17	33	22	270	Mild SW	8.8

3.1. Mild wind situations

Nine out of the twelve lidar observations were performed during low surface wind speed conditions with the peak of the wind speed distribution below 3 m/s, when atmospheric behavior was strongly governed by solar radiation [16]. The height of the PBL was low in the morning (at about 100–200 m), increasing up to 2 km during the day and dropping back to its initial value after sunset. The observed convective towers, reaching the top of the layer, indicate that the PBL was well mixed. Lidar measurements for one of the mild wind cases (April 13, 2015) are presented in Fig. 4. The wind was blowing from the SW with wind speeds mainly below 3 m/s (Fig. 4, right), enabling convective evolution of the PBL. At the beginning of the scan, solar radiation was still providing enough energy for vertical mixing to reach the top of the layer, producing a strong backscattering signal throughout the entire layer. Later in the afternoon, vertical mixing started to decay along with the PBL height.

3.2. Bora outbreaks

Three out of the twelve observation periods covered strong or moderate Bora cases, when the PBL structure was affected both by the wind and by the solar radiation. In the presence of strong wind, the PBL height remained constant despite increasing radiation during the day, since vertical mixing did not reach the top of the PBL. With decreasing wind speeds, the convective evolution of the PBL started to occur and growth of the PBL was observed. In two out of the three Bora cases, periodic structures slightly above the mountain barrier height were observed. Vertical airflow oscillations (often referred to as mountain waves) often occur after air masses are forced to rise over a mountain barrier [2]. In the first case, lidar data from February 27, 2015 in clear sky and

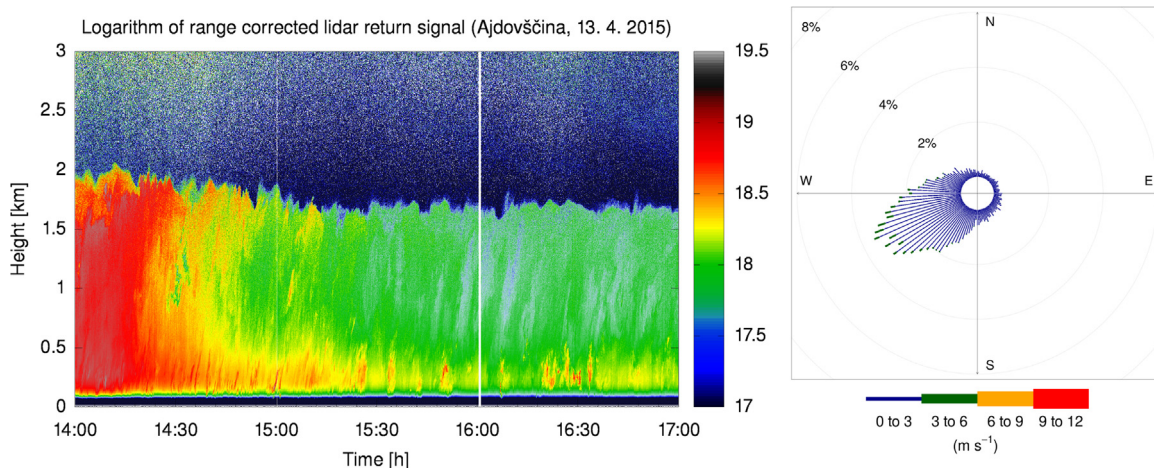


Fig. 4. The temporal evolution of the vertical profile of aerosol loading in the atmosphere (left) and wind distribution in Ajdoščina (right) for the mild SW wind case on April 13, 2015. The lidar measurements were performed at an elevation angle of 33° . The color scale in arbitrary units represents the logarithm of the range-square corrected lidar return signal after background subtraction. Height above the ground was obtained as a product of the measured range and the sine of the elevation angle. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

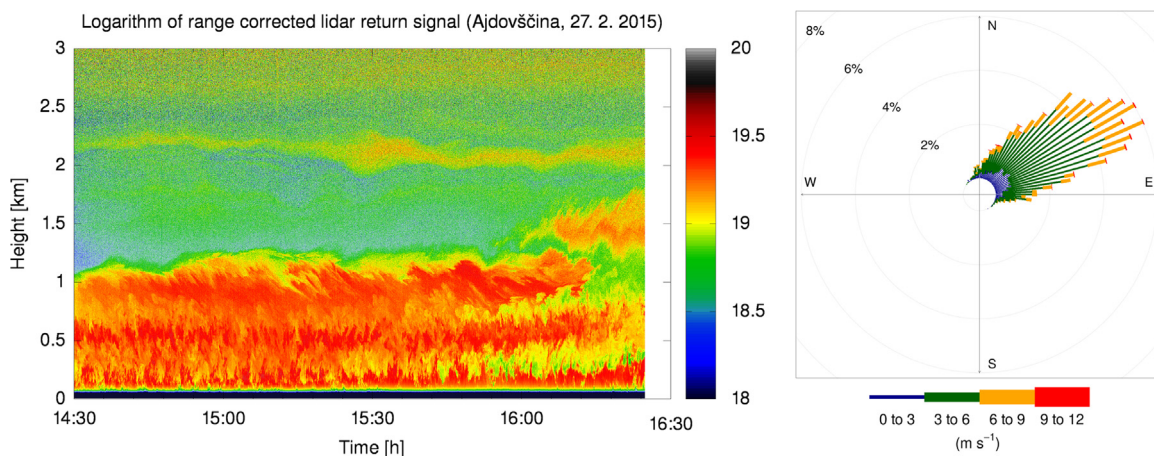


Fig. 5. The temporal evolution of the vertical profile of aerosol loading in the atmosphere (left) and wind distribution in Ajdoščina (right) for the moderate Bora outbreak on February 27, 2015. The lidar measurements were performed at an elevation angle of 20° . The color scale in arbitrary units represents the logarithm of the range-square corrected lidar return signal after background subtraction. Height above the ground was obtained as a product of the measured range and the sine of the elevation angle. The PBL height was found to be around 1.2 km in clear sky conditions. Periodic structures are visible directly above the PBL, up to 2.5 km. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

moderate Bora conditions (Fig. 5) clearly shows periodic structures in the layer above the PBL, between 1.2 km and 2.5 km above the ground. The PBL was stratified into 3 well-defined sublayers, within which vertical mixing took place, but the layers themselves do not appear to mix. The second case, referring to strong Bora conditions on February 24, 2015 (Fig. 7), shows the presence of a cloud layer at 2.5 km, almost directly above the PBL, and strong periodic oscillations of the top of the PBL itself. In order to analyze the flow behavior revealed in the lidar data, additional information on wind profiles was obtained from radiosonde data and from a detailed meteorological model [17] used for operational forecasting in Slovenia by the Slovenian Environmental Agency. General details

about the model can be found in [18,19] or online at <http://www.cnrm.meteo.fr/aladin> and in the references therein.

4. Atmospheric properties in Bora episodes

Based on continuous wind data, a total of 19 Bora episodes were identified between February and April 2015. With respect to wind speed and direction, 5 episodes were classified as strong (peak of wind speed distribution in the range 6–9 m/s), 9 as moderate (3–6 m/s) and 5 as mild Bora events (0–3 m/s). An event was classified as Bora if more than 10% of the wind direction data was between the

NE (45°) and ENE (77.5°) direction. Bora is known for its strong gusts with no predictable periodicity, characteristic of a specific location. Older studies report typical periods of wind gusts to be from 3 to 8 min [21,22]. The study performed on wind data collected with cup anemometers in the Vipava valley in 2012 confirmed the periodicity range [23]. It also showed that the period of the gusts is characteristic for shorter periods of time, not for the entire event or as a general rule. As both Bora and mountain waves are a consequence of the same airflow over the same orographic barrier, we investigated possible correlations between the resulting structures in the atmosphere above the PBL and wind properties. In particular, we searched for the possible influence of mountain waves on turbulence within the PBL, which is reflected in wind gusts at the ground level. Using the two Bora cases with simultaneous lidar observations of periodic atmospheric structures directly above the PBL, correlations between the wind speed at the ground and aerosol loading at a number of fixed heights within these structures were investigated, as well as the correlation of the wind speed with the height of the PBL itself. The correlations were all found to be small, ranging from 0.1 to 0.2. This may be due to horizontal displacement of wind and lidar measurements at low elevation angles of the lidar (Fig. 1).

4.1. Moderate Bora – February 27, 2015

On February 27, 2015, the lidar image (Fig. 5) shows three distinct layers (below 700 m, 700–1200 m and above 1200 m) with a clear presence of wave-like structures between the upper two layers.

Based on the wind speed and direction data from Ajdovščina, the lower layer (below 700 m) corresponds to a jet of air close to the ground, coming down the mountain side from the NE (at $\sim 60^\circ$) with velocities of 4–8 m/s. The layer thickened at about 16:15, when the wind increased in speed. Radiosonde data from Udine (45 km away), taken two hours before the lidar scan (Fig. 6 left) provided information about the elevated layers. The middle layer (700–1200 m) was found to be almost at rest (0.5 m/s at 1400 m) and particulate rich, probably as a residual from previous days. The top layer was found to be moving at

speeds of up to 6 m/s in a distinctly different direction than the other two layers. Air masses above 1400 m were arriving from the south ($\sim 190^\circ$) with significantly higher relative humidity and a 3 °C increase in potential temperature, forming a stable lid above the underlying atmosphere, that kept its height approximately constant.

Wave-like structures appearing at about 1200 m are believed to be Kelvin–Helmholtz waves caused by wind shear due to large difference in air flow speeds and directions between the adjacent well defined layers [22,24,25]. Periodic properties of the observed wave-like structures were investigated using least-squares spectral analysis (LSSA) [26], employing the implementation available in [27]. Streamline data between 1.2 and 2 km was extracted from the lidar scan (Fig. 5) based on the observed contrast between layers with higher and lower aerosol loading (Fig. 6 center) [28]. Spectral analysis of streamline properties confirmed the presence of wave-like structures with periods between 9 and 16 min. Best results were obtained between 14:30 and 15:30, when the observed periodic structures appeared to be stable. A statistically significant period of 12 min (Fig. 6 right) and an amplitude of about 50 m were found for waves at two different heights (the red streamline with $p=0.001$ and the orange streamline with $p=0.003$ in Fig. 6 center).

4.2. Strong Bora – February 24, 2015

In the strong Bora case on February 24, 2015, lidar data again revealed three distinct layers, with an evident periodic structure in the middle layer (Fig. 7). Atmospheric modeling predicted highest wind speed values in the observed middle layer (between 1 and 1.5 km above the ground), reaching up to 22 m/s at the end of the observational period. In the lower layer, which was predicted to be about 650 m deep, wind speeds close to the ground were expected to reach up to 10 m/s, and in the top layer above 1500 m about 8 m/s. Soundings from Udine indicate a 35° change in wind direction and a strongly stable temperature profile in the upper layer (above 1400 m), a profile typical for days when a low level jet is present. In this case, both the upper and the lower jet boundary

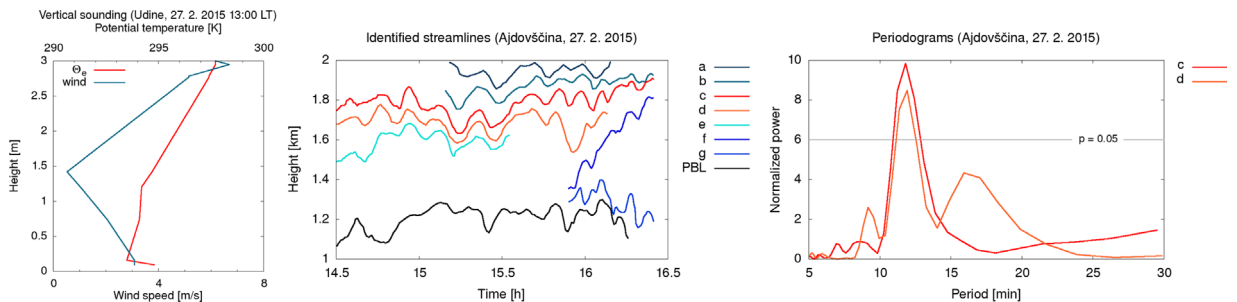


Fig. 6. Vertical sounding of wind speed and potential temperature (Θ_e) from Udine on February 27, 2015 at 13:00 UT (left), streamline data, extracted from the lidar scan on February 27, 2015 between 1.2 and 2 km (center) and periodograms for two selected streamlines (right). Streamlines were extracted from THI plot of the same day (shown in Fig. 5, left) based on the contrast between higher and lower aerosol loading. The observed wavelike structures, which were processed using least-square spectral analysis, have periods between 9 and 16 min. Periodograms of two selected streamlines, obtained from the lidar scan on February 27, 2015 between 14:30 and 15:30 reveal a period of 12 min, which is statistically significant at $p=0.001$ level for the red line and at $p=0.003$ for the orange line. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

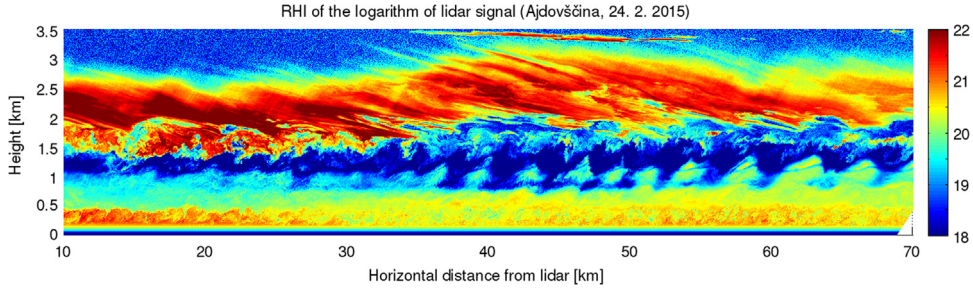


Fig. 7. Range-height indicator (RHI) of the background subtracted, range-square corrected lidar signal for the strong Bora case on February 24, 2015. Horizontal distance was obtained from the temporal evolution of the vertical aerosol profile, for a fixed observer, where the data was corrected for the lidar elevation angle and the wind speed. We assumed a constant vertical wind velocity profile and the applicability of Taylor's frozen turbulence hypothesis [20]. Kelvin–Helmholtz instabilities can be seen forming at the heights of 800 m above the ground with the clear-air area above. Note the presence of waves also at the top of the clear air area.

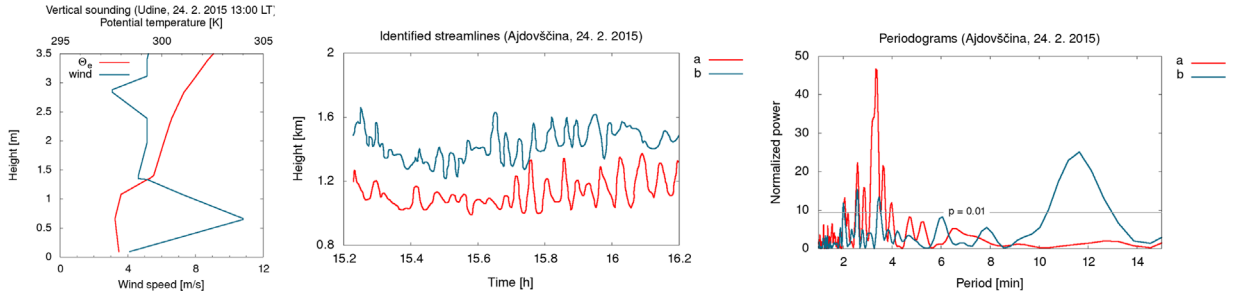


Fig. 8. Vertical sounding of wind speed and potential temperature (θ_e) from Udine on February 24, 2015 at 13:00 UT (left), streamline data extracted from the lidar scan on February 24, 2015 (center) and periodograms of the observed wave structures (right). Streamlines were extracted from THI plot of the same day (not shown) based on the contrast between higher and lower aerosol loading. The gray horizontal line in the periodogram plot represents the significance level of $p=0.01$. (For interpretation of the references to color in the text, the reader is referred to the web version of this paper.)

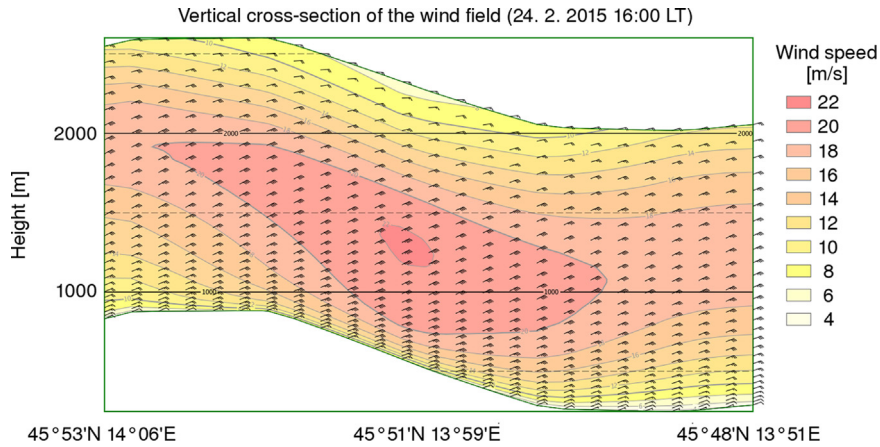


Fig. 9. A cross-section of the modelled wind field in the direction perpendicular to the mountain barrier for the Bora case on February 24, 2015. The colors represent the absolute value of the wind speed, while the arrows indicate the horizontal wind direction at each height [17]. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

experienced strong shear which led to the formation of Kelvin–Helmholtz waves.

The LSSA method was also applied to the streamlines from February 24, 2015. The waves at the upper boundary of the jet (at about 1400 m above the ground) have periods of approximately 11.6 min (blue line in Fig. 8 right), comparable to those observed on February 27, 2015 in clear weather conditions. The periods for the waves at the lower jet boundary (at about 800 m above the ground) are

considerably shorter, their periodogram reaching its peak value at 3.3 min (red line in Fig. 8 right). In both cases, other statistically significant periods were also present (2, 2.6, 3.5 min for the upper waves and 2.6, 3.6 min for the lower waves). Using Taylor's assumption of frozen turbulence [20] and assuming constant wind speed of 20 m/s, the wavelength of the lower waves was estimated to be $4(1 \pm 0.1)$ km.

5. Conclusions

The behavior of the atmosphere in the Vipava valley is strongly affected by wind properties. In the case of Bora, wind properties are the dominant factors governing both the aerosol loading and the formation of atmospheric structures such as mountain waves. Periodic atmospheric structures, observed during one moderate and one strong Bora episode investigated in this study, are believed to be Kelvin–Helmholtz waves caused by shear between atmospheric layers moving at different speeds and directions. Their properties were analyzed with spectral analysis and their periodicity was found to be between 2 and 12 min. In the strong Bora case with a distinct high-speed jet between 1 and 1.5 km above the ground, the periodicity of the waves at the lower jet boundary was found to be 4 min and their wavelength approximately 4 km. Although the Bora layer close to the ground is expected to be, to a certain extent, affected by the propagation of the waves towards lower levels, only a low correlation between gust periodicity and periodicity of the Kelvin–Helmholtz waves was found.

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