Influence of lee waves and rotors on the near-surface flow and pressure fields in the northern foreland of the Tatra Mountains

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ABSTRACT: This study presents the results of a field campaign aimed at observing near-surface flow and pressure fields downwind of the Tatra Mountains. The general objective was to study low-level turbulence associated with lee waves and rotors and to improve weather forecasts for aviation. The main instrumentation consisted of a network of nine weather stations arranged as a transect perpendicular to the Tatra Mountains. The stations recorded the wind speed and direction (at 10 m), atmospheric pressure, temperature and humidity (at 2 m) for ~2 years. Gliding flights and cloud cover observations using two digital sky cameras also formed part of the campaign. The measurements were supported by data from atmospheric soundings in Poprad (Slovakia) and satellite images provided by the Moderate Resolution Imaging Spectroradiometer (MODIS). During a stable southerly flow, episodes of flow separation were observed, which are associated with lee-wave and rotor activity aloft. Based on data from the selected period, surface-pressure perturbations arranged as alternate positive and negative anomalies with extreme values of up to ~0.7 hPa were detected. Positive (negative) anomalies are assumed to be a response of the surface-pressure field under the influence of descending (ascending) wave or rotor currents because of the downward (upward) component of the air movement in the atmosphere. The relationship between the decreasing magnitudes of the pressure perturbations with the distance from the Tatra Mountains was exposed. It was also possible to demonstrate the dependence of the position and intensity of pressure anomalies in relation to changes in wind conditions.

KEY WORDS atmospheric pressure; foehn; gliding; lee wave; rotor; Tatra Mountains

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1. Introduction

When stably stratified air flows over a mountain ridge, downwind gravity waves may be triggered. These buoyancy perturbations are propagated away from the mountains and significantly affect the meteorological conditions on the lee side of the topographical barrier. The vertical air movement and occurrence of lenticular clouds are examples of such an influence (Durran, 2003). Large-amplitude waves can generate clear-air turbulence and strong winds that blow down the lee slope (Lilly, 1978; Clark et al., 1994). Mountain waves too manifest themselves in the disturbances of the pressure field. Lyra (1943) was one of the first to note that trapped mountain waves may determine local adverse pressure gradients. This factor greatly facilitates the boundary-layer separation and the formation of recirculation regions underneath the wave crests (Doyle and Durran, 2002; Vosper, 2004). These vortices, called rotors, typically measure a few hundred metres to a few kilometres across and usually form below the elevation of the mountaintops. The presence of rotors may be revealed through the existence of a reversed flow at its base and sometimes by cloud formations, such as a ragged cumulus.

The first observations and studies of lee waves and rotors were made in the Sudetes (Hirth, 1935), the Alps (Kuettnner, 1938, 1939) and the Pennines (Manley, 1945). Pioneering gliding measurements contributed significantly to this effort. Early theoretical investigations of mountain wave and rotor dynamics were conducted by Lyra (1943), Queney (1948) and Scorer (1949). More recently, new measurement techniques were applied in the studies, such as Doppler Lidar (Ralph et al., 1997; Darby and Poulos, 2006). New insight into interactions between lee waves and rotors is also provided by modern numerical models (Doyle and Durran, 2002; Vosper et al., 2006). The wide enhancement of knowledge of both phenomena comes from field experiments involving the collaboration of many organizations and performing extensive ground-based and airborne in situ and remote-sensing measurements. Examples of these experiments include the Sierra Wave Project (Holmboe and Klieforth, 1957) followed by studies in the Colorado Rockies (Lilly, 1978) and the Alpine Experiment (ALPEX, Davies and Pichler, 1990). More recent investigations include the Terrain-Induced Rotor Experiment (T-REX, Grubišić et al., 2008) and field campaigns in the Falkland Islands (Mobbs et al., 2005) and the Pennines (Sheridan et al., 2007). The Mountain Wave Project (MWP) is aimed at the global classification and analysis of mountain waves (Heise et al., 2014).

During periods of stable southerly flow, lee-wave activity occurs when the Podhale region lies downwind of the Tatra Mountains (Figure 1). This phenomenon is well known to the local aero club in the city of Nowy Targ (26 km north of the main ridge of the Tatra Mountains). In 1958, in the Nowy Targ airport, the Centre of Wave Soaring, a specialized unit of the Polish Aero Club, was formed. It has remarkable achievements such as many record flights approved by the World Air Sports Federation (FAI). Despite a good realistic background, lee waves on the northern foreland of the Tatra Mountains are rather poorly recognized, and
few scientific papers have been published so far concerning this subject (Mozdyniewicz, 1976; Schmidt, 1982, 2002).

The lee-wave activity on the northern foreland of the Tatra Mountains is often associated with severe near-surface turbulence. This activity is expressed as rapid changes in wind speed and direction, including the occurrence of northerly flow, opposite to the prevailing air masses advection. Such events are thought to be caused by rotor activity (Mozdyniewicz, 1976; Schmidt, 2002). This air structure is known to be a dangerous hazard to aviation in the region. Passage through the zone of descending rotor currents, especially during take-off or landing, can affect flight safety. However, ascending rotor currents can be used to acquire greater height by gliders. Therefore, the study of lee-wave and rotor activity in the research area is of great practical importance, and the results can be applied in meteorological forecasting. Because the mountain waves in the Tatra Mountains remain poorly understood and no reliable method of rotor forecasting has been applied so far, results of the field campaign may provide the basic knowledge for further detailed studies.

The present study describes the results of a field campaign aimed at measuring the near-surface flow on the northern foreland of the Tatra Mountains during periods of lee-wave and rotor formation. The essential part of the research was the analysis of the surface-pressure perturbations to determine the relationship between the location (intensity) of pressure anomalies and lee waves (rotors) aloft. The field campaign description and details of the instrumentation are presented in Section 2. Section 3 describes the methods that were used in this study. The meteorological background of the selected study period is provided in Section 4, while the results and discussion are in Section 5. Conclusions are drawn in Section 6.

2. Description of the field campaign

The field campaign was performed in the Tatra Mountains and in the Podhale region of southern Poland. The area of research included a mountain range with a height of up to 2655 m asl (Gerlach Peak) and its northern foreland, inclined towards the
The accuracy of the first sensor was constant (was almost equal to the outside air temperature. Therefore, the temperature of 15–25°C, while Vaisala PTB110 barometers were housed in a radiationshield. The AWS instruments measured the 2m air temperature and relative humidity in addition to the atmospheric pressure and the 10 m wind speed and direction (at AWS 1, 16 m; at AWS 2, 15 m). The air temperature and humidity were measured using the following sensors: Vaisala HMP45A/45D (AWSs 1–3) and Vaisala HMP155 (AWSs 4–9), housed in a radiation shield. The wind speed and direction were registered by Vaisala WS425 (AWSs 1–2), Vaisala WMS302 (AWS 3) and A-STER W-104 (AWSs 4–9) anemometers. The atmospheric pressure was measured by the barometers Vaisala PA11 (AWSs 1–2) and Vaisala PTB110 (AWSs 3–9). Vaisala PA11 barometers were installed inside the synoptic station buildings (with a constant air temperature of 15–25°C), while Vaisala PTB110 barometers were housed in a meteorological shelter where the air temperature was almost equal to the outside air temperature. Therefore, the accuracy of the first sensor was constant (±0.3 hPa), while the accuracy of the second sensor depended on the air temperature (±0.3 hPa at +15...+25°C, ±0.6 hPa at 0...+40°C and ±1.0 hPa at ±20...+45°C). Data from AWSs that were owned by IGSO PAS and PPWSZ were recorded every 10 min throughout the entire experiment. Free access to data from stations that were operated by the IMGW was limited to 24 synoptic observations per day (AWSs 1–2) and to three climatic observations per day (0600, 1200, and 1800 UTC at AWS 3, except for the 10 min of atmospheric pressure data). During certain intensive measurement periods (IMPs) (see below), access to the 10 min data from these stations was also available.

Data on cloud cover over the study area were provided by images from the Moderate Resolution Imaging Spectroradiometer (MODIS) that was installed on satellites Terra and Aqua. For each day, two images were available with a 250 m resolution. During the field campaign, cloud patterns were also recorded by two sky cameras that were placed ~11 km east from the AWS’s transect (Figure 1). The locations for the cameras were chosen at sites with conditions conducive for observing clouds occurring over the meteorological array and for technical reasons. Images were collected automatically every 10 min simultaneously with the measurements that were made at the AWSs. However, data from the cameras were not used in this study.

Measurements were supported by routine atmospheric soundings by the Slovak Hydrometeorological Institute in the city of Poprad. The site is located on the southeastern foreland of the Tatra Mountains, ~33 km from AWS 1 (Figure 1). Radiosondes were released each day at 0000 and 1200 UTC. During the southerly flow, the radiosonde profiles represent the upwind conditions.

Gliming flights over the study area also formed part of the field campaign. These flights were organized into three occasions, called intensive measurement periods (IMPs), when forecast conditions were favourable for strong lee-wave formation. Flights were performed from the Nowy Targ airport (AWS 8) using Polish double-seat training and an acrobatic glider, SZD-50 Puchacz. The master plan of the flights consisted of three stages: (1) towing from the airport over the Tatra Mountains ending with the glider releasing, (2) gaining altitude associated with a reconnaissance tour over the Tatra Mountains ending over Kasproy Wierch Peak (AWS 1) and (3) flying to the north along the meteorological transect ending with landing at the airport. The flight objective was to determine the location and speed of the ascending and descending lee-wave and rotor currents over the study area, in particular over the AWSs 2–9. Measurements were performed using on-board instruments and a GPS receiver.

In the present study, only data from IMP1 (4–5 November 2014) are presented. During this period, due to technical problems, the wind speed and direction at AWS 9 were not measured. However, the failure of the anemometer did not largely affect the possibility of studying the near-surface flow.

3. Methods

To determine the surface-pressure perturbations that occurred on the northern foreland of the Tatra Mountains during periods of a stable southerly flow, it was necessary to remove two components from the pressure measurements at AWSs 2–9: hydrostatic and regional. The first component is derived from the differences in height above sea level between the barometers that were included in the surface array. As a reference level to barometric equalization, the height of the AWS 5 barometer (728.64 m asl) was chosen because it was located almost in the middle of the vertical profile set by the AWSs 2–9 barometers (732.36 m asl). To compute the hydrostatically corrected pressure, the following Laplace-Rühlmann barometric formula was used (Niedźwiedź, 2003):

\[
\log \left( \frac{p_1}{p_2} \right) = \left[ 1 - 0.00366 \cdot \bar{t} \right] \cdot \left( 1 - 0.377 \cdot \frac{\bar{p}}{p} \right)
\]

\[
/ \left( 1 - 0.00000196 \cdot \frac{\bar{h}}{18400} \right)
\]

where \(p_1\) is the atmospheric pressure at a lower level (hPa); \(p_2\) is the atmospheric pressure at a higher level (hPa); \(\bar{t}\) is the mean

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air temperature between the higher and lower levels (°C); \( e \) is the mean vapour pressure between the higher and lower levels (hPa); \( \overline{\rho} \) is the mean atmospheric pressure between the higher and lower levels (hPa); \( \varphi \) is the latitude (rad); \( \overline{h} \) is the mean height above sea level between the higher and lower levels (m); and \( \Delta h \) is the height difference between the higher and lower levels (m).

For AWSs 2–4, the higher level is the height of the AWSs 2–4 barometers and the lower level is the height of the AWS 5 barometer. For AWSs 6–9, the higher level is the height of the AWS 5 barometer and the lower level is the height of the AWSs 6–9 barometers.

The geographical location and height above sea level of AWSs 3–9 were measured in the study area using a precise GPS receiver (Trimble R4 GNNS System). The practical accuracy of the measurements was <2 cm. Data on the location and height above sea level of AWSs 1–2 were reported by the IMGW. \( \overline{\varphi} \) and \( \overline{\varphi} \) were calculated as the arithmetic average of data taken from AWS 5 and one of the other AWSs (2–4, 6–9). The vapour pressure \( (e) \) was calculated using the following equation (Masterson and Richardson, 1979):

\[
e = 0.06112 \cdot f \cdot 10^{\frac{\Delta T}{237.7}}
\]

(2)

where \( f \) is the relative humidity (%) and \( T \) is the air temperature (°C).

The regional component was obtained by simply averaging the hydrostatically corrected pressure values across AWSs 2–9.

Initially, the third component, synoptic, was also included in the calculations. This component comprises a differentiation of the pressure field over the study area related to atmospheric circulation (location of highs and lows). To estimate the synoptic component, the horizontal hydrostatically corrected pressure gradient between the synoptic stations in Kraków (Poland) and Eger (Hungary) was calculated. The stations were selected because of their location (plain area on the outskirts of the Carpathians, roughly the same distance from the Tatra Mountains, almost the same height above sea level) and the almost parallelism of the AWSs 1–9 and Kraków–Eger lines. The location of AWSs 2–9 was projected on the pressure-gradient line, and the distances between the following sites were calculated. Finally, an adequate synoptic component was subtracted from the hydrostatically corrected pressure measurements at AWSs 2–9.

Including the synoptic component in the calculations affected the results significantly. Towards the south, at the high-pressure system located upwind of the Tatra Mountains, the component values become increasingly greater (from 0hPa at AWS 9 to an average of ~0.6 hPa at AWS 2). Surface-pressure perturbations in the study area are demonstrated as strong and stable positive anomalies in the north that are gradually replaced by negative anomalies in the south. These results were considered incorrect (only small changes in anomalies were found despite a large variation in meteorological conditions) and restrictive to detect the perturbations caused by the lee-wave and rotor activity. Therefore, the subtraction of the synoptic component in the final calculations was rejected.

To estimate the potential possibility of the lee-wave occurrence, the Scorer parameter \( \ell^2(z) \) (Scorer, 1949) was calculated using quantities from atmospheric soundings upstream of the Tatra Mountains. The following equation was used (Gill, 1982):

\[
\ell^2(z) = \frac{N^2}{U^2} - 1 \cdot \frac{1}{U} \cdot \frac{\partial U}{\partial z}^2
\]

(3)

where \( N \) is the Brunt-Väisälä frequency (rad s\(^{-1}\)), \( N = (\frac{\varphi}{\Phi} \cdot \frac{\partial \theta}{\partial z})^{0.5} \) where \( g \) is the gravitational acceleration; \( \theta \) is the potential temperature (K); \( U \) is the wind speed component perpendicular to mountain range (m s\(^{-1}\)); and \( z \) is the height (m).

In general, when the Scorer parameter is nearly constant with the height, the conditions are favourable for vertically propagating mountain waves. A decrease in the height of the parameter indicates that trapped lee waves can be expected.

The location and speed of lee-wave and rotor currents were determined using GPS data from gliding flights. During each flight, the position of the sailplane and the flight altitude were recorded for every second. To determine current speed, initially the difference of height between the following points was calculated, and then the glider rate of the sink was subtracted. The value of the glider rate depends on the relative-to-air glider speed, and for SZD-50 Puchacz, it is 0.72 m s\(^{-1}\) at 80 km h\(^{-1}\), 0.95 m s\(^{-1}\) at 100 km h\(^{-1}\) and 1.33 m s\(^{-1}\) at 120 km h\(^{-1}\). To facilitate the calculations, a constant value of 1 m s\(^{-1}\) was assumed.

4. Meteorological background of the selected study period

The meteorological conditions over the study area during IMP1 were formed under classic synoptic situations, inducing intense lee-wave activity on the northern foreland of the Tatra Mountains.

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Over northwest Europe, a large low-pressure system was present, while over southeast Europe, an extensive high-pressure system was formed (Figure 2). On the eve of IMP1, a low-pressure centre was situated over northern United Kingdom and started to move slowly in an easterly direction. It was followed by enlargement in terms of the area of the low-pressure system (a result of the secondary cyclone generation over the Gulf of Lion and southern Norway) along with gradual cyclosis. The pressure difference between the low and high centres (∼2500 km apart) reached up to 50 hPa. The high-pressure system consists of a stationary anticyclone located over the Black Sea. Following its appearance, typical westerly flows were blocked, and strong southerly and southwesterly warm advection occurred over central Europe. Incoming air masses were initially polar maritime and tropical, beginning on the morning of 5 November 2014.

Profiles of the wind, temperature and Scorer parameter taken from upstream radiosonde ascents during IMP1 are shown in Figure 3. On both days, the wind direction was close to southwesterly. Initially, the western component was dominating, but the southern component prevailed over time. The wind speed profiles indicate generally strong winds but varying with height. From the surface to the mountaintops, the wind strengthened, reaching ∼25 m s$^{-1}$ at 2–3 km. Above this zone, the wind speed decreased gradually to ∼10 m s$^{-1}$, peaking once again at 10–12 km (∼30 m s$^{-1}$). The potential temperature profiles confirm that the conditions were stable on both days. At the mountain peaks, a temperature inversion occurred. In the beginning, the temperature inversion was stronger (1.1 K/100 m) and was located lower (2000–2300 m), gradually weakening to isothermy and ascending to a maximum level of 3200 m. Smaller inversions were also present in the troposphere (3300–3500, 6800–7100 m). The occurrence of these inversions was likely associated with the anticyclone, southeast of the study area. The Scorer parameter on 4 November strongly varied with the

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Figure 3. Vertical profiles of wind direction, wind speed, potential temperature and Scorer parameter as measured by radiosondes released from Poprad on (a) 4 November 2014 and (b) 5 November 2014 at 0000 UTC (solid lines) and at 1200 UTC (dashed lines).
dominance of the positive peaks, indicating that the profile was unfavourable for lee-wave trapping. On 5 November, the parameter was rather constant with height, demonstrating better conditions for lee-wave propagation.

Satellite images of the study area during IMP1 are shown in Figure 4. On the southern foreland of the Tatra Mountains, clouds are visible in each image and are formed in regular and equally spaced bands arranged parallel to the mountain ridges. These features along with cloud stationarity indicate that the lee-wave activity was induced by the flow over the Low Tatra Mountains (30 km south of the Tatra Mountains). In contrast, the northern foreland is almost free of clouds; only on 5 November did a single cumulus cloud occur in the vicinity of AWS 2 (Figure 5). During the time between taking the images (0905 and 1050 UTC), almost no horizontal movement of this rotor cloud could be observed; however, its size increased notably (a detailed analysis of this period will be discussed in Section 5.3.3). The absence of clouds on the northern foreland can be explained by a low content of water vapour in the air after crossing the Tatra Mountains and by very low amplitude of the waves to reach the water vapour condensation level. The gliding flight track seen in Figure 4(d) will be discussed in Section 5.3.3.

5. Results and discussion

5.1. Air temperature and humidity

The air temperature during IMP1 in the study area was significantly differentiated (Figure 6). At the foot of the Tatra Mountains (AWS 2), the temperature for almost the entire period remained stable at 12–15 °C. A completely different temperature course occurred 20 km further to the north (AWS 8). At night, the temperature there was low (minimum −5.2 °C on 4 November at 0450 UTC), while during the daytime, it was high (maximum 17.5 °C on 5 November at 1140 UTC). Additionally, short warming periods appeared at night, 4 and 5 November (e.g. 2020–2250 UTC). In the southerly direction, these periods became longer and more intense (see AWS 5 data), and from AWS 4, the temperature course corresponded to the foothill-type (AWS 2) rather than to the foreland-type (AWS 8).

The relative humidity also exhibited high spatial variability. The relationship between the humidity and temperature courses is clearly visible: high (low) humidity corresponded to low (high) temperature. At the foot of the Tatra Mountains (AWS 2), humidity remains low (<60%) almost for the entire period, while further ahead in the foreland (AWS 8), unsteadiness is well pronounced.

Figure 4. Visible satellite images of the study area as recorded by MODIS from the satellites Terra ((a) and (c)) and Aqua ((b) and (d)) on (a) 4 November 2014 at 1000 UTC, (b) 4 November 2014 at 1145 UTC, (c) 5 November 2014 at 0905 UTC, and (d) 5 November 2014 at 1050 UTC. The meteorological transect and Polish–Slovakian border are marked in white. Part of gliding flight track in (d) is marked by a dashed line. The flight along the track was performed on 5 November 2014 at 1024–1033 UTC. Source: NASA Worldview.
The differentiation of air temperature and humidity in the study area was caused by the occurrence of the foehn wind. A strong advection of warm air resulted in high temperature and low humidity in the vicinity of the mountains, where it remained stable throughout the entire period. In contrast, the northern part of the area was only slightly influenced by the foehn wind, which was manifested as short-term warming periods in normal daily courses of temperature (minimum at night, maximum at midday). The small influence of the foehn wind could be associated with topography because AWSs in the north are located in an area of extensive depression, where descents of cold air are common.

Under such conditions, the foehn wind could be blocked from the ground by inversion layers.

5.2. Wind direction and speed

The wind conditions at the mountaintops (AWS 1) during IMP1 varied in a narrow range. The wind direction for almost the entire period was southerly with only short-term periods of a stronger western or eastern component (Figure 7(a)). Conditions became stable on 4 November before noon and on the evening of 5 November. Larger variability was characteristic for the middle period during which short-term changes in wind direction reached up to 62° (4 November, 2140–2240 UTC).

During IMP1, strong and very strong winds occurred on the mountaintops in the Tatra Mountains (Figure 7(b)). The average wind speed at AWS 1 was 18.6 m s⁻¹, and gusts reached up to 44 m s⁻¹. During this period, three stages can be identified. Initially, the average wind speed remained rather stable at 15–20 m s⁻¹. From 2000 UTC on 4 November, this speed increased quickly, peaking (25.6 m s⁻¹) at 0230 UTC on 5 November. Then, the wind speed began to decrease slowly to 15 m s⁻¹ by 5 November night.

To study wind conditions on the foreland of the Tatra Mountains, data from AWSs 2–9 were used; however, in this section, a detailed analysis was performed only for AWSs 2 and 3 because these sites are under the greatest influence of the mountains.

Timeseries of the wind direction at AWS 2 differs significantly from the flow at AWS 1 (Figure 7(a)). During almost the entire period, the wind direction was northwesterly, i.e. nearly reversed with respect to the flow at the mountaintops. This wind direction indicates the rotor influence. The rotor has suitable orographic conditions to form in the vicinity of AWS 2 because the site is located in a valley surrounded on the north and south by high elevations. The unsteadiness of the wind direction at AWS 2 on 4 November at 0000–0740 UTC can be explained by the mixing of colder and moister residual air with warmer and drier air inflowing from the mountains (see variations in air temperature and humidity at AWS 2 in Figure 6). The wind direction at AWS 3 was more consistent with the flow at the top of the Tatra Mountains. The southwest wind dominated for almost the entire period. The western component may have been caused by orography as AWS 3 is located in a valley that is open to the west. The wind speed on the foreland of the Tatra Mountains was clearly lower than that on the mountaintops. The average wind speed at AWS 2 was 5.0 m s⁻¹ and gusts reached up to 25 m s⁻¹, while at AWS 3, the values were 4.6 and 20 m s⁻¹.

During IMP1 at AWSs 2 and 3, few short periods of unsteadiness and spatial variability in wind conditions occurred. These periods were manifested as rapid changes in the wind direction up to 180° (e.g. flow reversal at AWS 3 on 5 November, 2120–2150 UTC, Figure 7(a)). The wind acceleration at some of the AWSs was also characteristic, while it was slow at other AWSs (e.g. on 4 November, 2020–2320 UTC, Figure 7(b)). These periods may be associated with changes in the location, altitude and intensity of the rotors. Similarly, unsteadiness and spatial variability of the near-surface flow were also observed during strong lee-wave events in the Falkland Islands (Mobbs et al., 2005) and downwind of the Pennines (Sheridan et al., 2007) and assumed to be linked with the position of the lee-wave crests and troughs.
occurred. The mean values of these perturbations were similar (0.13–0.18 hPa in absolute values). At sites that were located further from the mountains, a sequence of positive and negative anomalies was detected, but their mean values were significantly lower (0.02–0.06 hPa in absolute values). An analogous succession of pressure perturbations during lee-wave activity was also detected by Mobbs et al. (2005) and Sheridan et al. (2007). At the foot of the mountains, a negative anomaly was found usually, replaced downwind by a positive anomaly. Because the meteorological measurements on the lee side of the topographic barrier were collected along a distance of ∼10 km, observations of pressure perturbations further downwind were limited. The maximum absolute values of the pressure perturbations in the Pennines reached ∼1 hPa while those in the Falklands Islands reached up to 4 hPa.

Extreme values of pressure perturbations during IMP1 were recorded at AWS 2: +0.69 hPa (5 November, 1520 UTC) and −0.71 hPa (4 November, 2010 UTC) (Figure 8(b)). The relationship between the magnitude of the extreme anomalies and the distance from the mountains is clearly visible. The greater the distance from the mountains, the smaller the extreme perturbations. Based on the trend lines shown in Figure 8(b), it can be assumed that at IMP1, surface-pressure perturbations appeared on the foreland of the Tatra Mountains, probably up to ∼50 km from the mountaintops.

Precise barometric formula and accurate GPS measurements of barometer height above sea level have been applied; hence, these two factors cannot explain the differentiation in the pressure field that was detected in the study area. A greater potential impact on the results may be associated with the accuracy of barometers. Although it is rather low (at best ±0.3 hPa), the magnitude of many of the anomalies exceeds the accuracy error significantly.

Less uncertainty in results is typical for AWSs that are located in the southern part of the study area because the intensity of perturbations is bigger, and pressure measurements are more accurate (as a result of the higher air temperature).

5.3.2. Periods with specific set-up of the anomalies

A time series of the surface-pressure perturbations at AWSs 2 and 3 on IMP1 is presented in Figure 7(c). Six periods with a characteristic set-up of anomalies at the sites were identified. The most common arrangement of the perturbations, represented by periods ‘a’, ‘d’ and ‘f’, is a positive anomaly at AWS 2 and a negative anomaly at AWS 3. During IMP1, an inverted situation also occurred (period ‘c’). Simultaneous strong negative anomalies at AWSs 2 and 3 were recorded (period ‘b’), while there were no strong positive anomalies coincident at both sites. Period ‘e’ represents weak perturbations, which occur between two periods with strong anomalies. The mean values of pressure perturbations at AWSs 2–9 for all the six periods are shown in Figure 9.

Surface-pressure perturbations detected on the foreland of the Tatra Mountains during periods ‘a’, ‘d’ and ‘f’ exhibit a
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Figure 7. Time series of (a) wind direction and (b) wind speed at AWSs 1–3 and (c) pressure perturbations at AWSs 2–3, on 4 and 5 November 2014. Periods with a characteristic set-up of the pressure perturbations are separated using vertical lines (in panels (a)–(c)) and labelled with letters a–f (in panel c).

high degree of resemblance. Positive anomalies were detected at AWSs 2 and 5, while negative anomalies were detected at AWSs 3 and 4 (except for a small positive anomaly at AWS 4 during period ‘a’). Towards the north, the situation was more complicated, but some patterns in the distribution of perturbation were detected. The characteristic succession of alternately arranged positive and negative anomalies can be explained by lee-wave and rotor activity. Positive anomalies are assumed to be a response of the surface-pressure field under the influence of descending wave or rotor currents because of the downward component of the air movement in the atmosphere. Similarly, the negative anomalies should be in response to ascending wave or rotor currents as a result of the upward wind component. Generally decreasing values of mean pressure perturbations with the distance from the mountains can be explained by the weakening intensity of the lee-wave or rotor activity aloft.

During period ‘b’, a strong negative anomaly occurred at AWS 2. Negative anomalies were also detected at AWSs 3 and 4, while positive anomalies appeared at AWSs 5–9. Difficulties in interpretation may arise while analysing the distribution of perturbations during this period. No typical sequence of positive and negative anomalies might indicate that near-surface-pressure perturbations were not caused by lee-wave and rotor activity. Such explanations can be confirmed by changes in the flow over the Tatra Mountains that occurred at period ‘b’ (Figure 7(a) and (b)). The wind direction at the mountaintops
turned westward (up to 69°), while the wind speed significantly decreased (down to 11.5 m s\(^{-1}\)), being only slightly higher than the minimal value that is needed to generate a lee wave on the northern foreland of the Tatra Mountains (9.5 m s\(^{-1}\), Schmidt, 2002). These factors usually lead to wavelength reductions, resulting in a shift of anomalies towards the mountains as well as a shortening of its horizontal width. Decrease in speed of lee-wave and rotor currents over the study area is also expected. The deterioration of wind conditions over the Tatra Mountains was expected to result in a reduction rather than intensification of the anomaly magnitude, which however did not occur.

Because the magnitude of anomalies during period ‘b’ is relatively high, the distribution of perturbations cannot be explained by the accuracy of the barometers. A gradual change in the air pressure associated with the regional synoptic situation is also not an option because including the synoptic component into the calculations will result in an increasing rather than decreasing differentiation of anomalies in the study area (see reflections in Section 3). Therefore, other factors causing near-surface-pressure perturbations should also be considered. Sheridan et al. (2007) concluded that a stronger wind at a given downstream station corresponded to a lower pressure perturbation. During period ‘b’, decrease in wind speed with distance from the mountains was observed (Figure 9(b)), suggesting that this interpretation may be correct. However, the pressure anomaly at AWS 8 was higher than that at AWS 4 despite the fact that the mean wind speed at both the sites was roughly the same. The submitted relationship between wind speed and pressure perturbations in the other five analysed periods is not fulfilled.

During period ‘c’, the increased wind speed and return of wind direction to near southerly at the mountaintops (Figure 7(a) and (b)) were characteristic. An improvement of conditions for lee-wave propagation is expected to determine the wavelength increase, which leads to a shift in anomalies towards the north as well as an extension of its horizontal width. As a result, negative anomalies appeared at AWSs 2, 4 and 8, while positive anomalies occurred in the vicinity of AWSs 3, 5, 6, 7 and 9.

Period ‘e’ can be interpreted as a temporary weakening of the lee waves and rotors. Thus, the wind conditions at the mountaintops did not change significantly (Figure 7(a) and (b)), and disappearance of pressure anomalies can be associated with changes in the vertical equilibrium of the atmosphere. Available data from aerological soundings (Figure 3) are not applicable to verify this assumption. Weak anomalies may also be a result of rotor ascent or reduction of its intensity due to unknown reasons; thus, it did not cause significant pressure perturbations at ground level.

5.3.3. Application of satellite pictures and aviation data

Based on the almost stationarity of the rotor cloud between 0905 and 1050 UTC on 5 November 2014 (see satellite images in Figure 4), it can be assumed that no significant movement of lee waves or rotors occurred during that time in the study area. Access to data on surface-pressure perturbations allowed the verification of this hypothesis. In relation to the cloud, the nearest site of meteorological measurements is AWS 2. Thus, this location is in the vicinity of the cloud on its northern side, and descending rotor currents are expected to occur above the site. Positive surface-pressure anomalies, which may demonstrate its existence, were detected at AWS 2 at the time of taking both the images (Figure 10(a) and (d)). The distribution of anomalies throughout the entire period between 0905 and 1050 UTC on 5 November 2014 was very similar and resembled a sinusoid distribution (Figure 10(b) and (c)). Only small changes in the anomaly magnitude were revealed as well as a shift of perturbations near AWSs 6–8. Based on the distance between consecutive positive (negative) anomalies, assumption of the wavelength was made as 11 km. The absence of rotor clouds on the northern part of the research area prevents the complete verification of the relationship between the position of the rotor clouds and surface-pressure anomalies.

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During IMP1 eight gliding flights were organized: three on 4 November and five on 5 November. Data from the flight that was performed on 5 November at 1005–1034 UTC were selected for presentation because the pressure perturbations in the study area at the time were rather strong (Figure 7(c)) and also because it was possible to refer the aviation data to the location of the rotor cloud (Figure 4(d) and flight track therein). The flight entry into the zone of strong descending rotor currents in the vicinity of AWS 2 resulted in an aircrew decision (Piotr Mateja – pilot, author – passenger) to return to the airport in the shortest possible way (straight line coincident with the meteorological transect), avoiding passage over AWS 9. Data from the flight represent air circulation associated with rotors but not lee waves because the transition over the study area began at 1701 m asl and ended at 825 m asl (∼900 and ∼200 m above ground, respectively).

Data from the gliding flight demonstrate the occurrence of ascending and descending air currents over the area of research (Figure 10(c)). These currents were arranged alternately, beginning with strong descending currents near AWS 2 on the northern side of the rotor cloud. A generally decreasing current speed with increasing distance from the mountains was observed. The maximum upward current speed over the study area reached 7 m s$^{-1}$ (near AWS 4), while the downward speed was 10 m s$^{-1}$ (near AWS 2). The arrangement of the air currents shows high compliance with the distribution of the near-surface-pressure perturbations. Descending currents were situated above positive anomalies, while ascending currents were located over negative anomalies. Some inconsistency between the distribution of vertical air movements and pressure perturbations (e.g. stronger negative anomaly at AWS 7 than that at AWS 4, with a reverse arrangement of the current speed at the sites) might be explained using aviation data acquired not exactly from the location of the AWSs (glider passed above each AWS at some horizontal distance) as well as from differences in terms of measurements (pressure data for 1030 UTC, aviation data for 1024–1033 UTC).

6. Conclusions

In the present study, the results of a field experiment focusing on the impact of lee waves and rotors on near-surface flow are presented. The main objective was to detect episodes of flow...
separation and analyse their location and intensity in relation to lee-wave and rotor activity aloft. This study was conducted on the northern foreland of the Tatra Mountains in a region known for frequent occurrence of these phenomena, well documented by aviation data but poorly recognized so far.

During stable cross-ridge flow, local adverse pressure gradients in the study area were observed. Based on the alternate arrangement of positive and negative pressure anomalies along a meteorological transect, it has been assumed that their occurrence is associated with lee waves and rotors, which repeat themselves several times aloft. Positive (negative) anomalies are thought to be the response of the surface-pressure field under the influence of descending (ascending) currents because a downward (upward) component of the air movement is present in the atmosphere. For specific cases, when the position and intensity of the vertical air movement in the atmosphere were known due to gliding flight data and rotor cloud presence, the verification of this hypothesis was positive. The coincidence of both the intensity of vertical air movement and the magnitude of the near-surface-pressure perturbations decreasing over distance may also indicate the correctness of the interpretation.

Because clouds may not always be present to identify rotors visually, the surface-based array of weather stations becomes an important data source of low-level potential turbulence. A meteorological network may also be applied to the planning and execution of the gliding flights, which can provide information on the position and intensity of ascending rotor currents. An enlargement of the network would be beneficial both for aviation and science. An additional number of stations should be located, especially in the vicinity of the mountains, where the potential occurrence of rotors and hazards for aviation are more likely. Positive results are also expected due to the use of more accurate barometers as well as more frequent measurements. While the field campaign was restricted to mostly surface-based measurements, little can be said about the internal structure of the rotors, and remote-sensing techniques would be necessary to further investigate the problem in the future.

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