Temporal structure of thermal inversions in Łeba (Poland)

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Abstract

This study presents the detailed characteristics of thermal inversions based on a 10-year aerological measurement series (2005–2014) conducted in Łeba (Poland). The analyses included surface-based inversions (SBIs) and elevated inversions (ELIs) in the atmospheric layer up to 3000 m. In the case of SBIs, this layer extended directly from the ground level to an altitude above which the air temperature decreases with altitude, whereas for ELIs, which have a base above ground level, only the lowermost inversion layer was taken into consideration. The results of the monthly and seasonal variations in the selected parameters for air temperature inversions (thickness— ΔZ , strength— ΔT , base— Z_B) were analysed separately at night-time (00 UTC) and daytime (12 UTC). The thermal structure of the boundary layer up to 3000 m was primarily determined by ELIs, which occurred at a frequency of approximately 70% at both times during the 24-h period. The SBIs showed a pronounced temporal structure that occurred every second night throughout the year and from April to September, with a frequency similar to that of the ELI (approximately 60%). The worst vertical air exchange conditions, which resulted from the simultaneous occurrence of SBIs and ELIs, were found in 30% of nights from April to October. Elevated inversions generally formed in a layer from approximately 820 to 1200 m, which was the lowermost ELI in winter and the highest ELI in summer; however, in all seasons, the lowest base height was characteristic of daytime inversions. Both surface-based and elevated inversion layers were distinguished by comparable thicknesses, particularly for those occurring at night-time (generally within the range of 150–200 m). From November to March, greater thicknesses were identified in ELIs with lower occurrences, whereas SBIs were identified in the remaining months of the year.

1 Introduction

Temperature inversions (TIs) are natural phenomena and may occur at any time of the year. TIs are usually defined by a layer of the atmosphere where the vertical temperature gradient changes from negative to positive (Whiteman 2000; Stryhal et al. 2017; Czarnecka et al. 2016). Based on formation mechanisms, atmospheric inversions can usually be classified as radiation inversions, advection inversions, turbulence inversions, subsidence inversions, frontal inversions, 0 °C inversions, tropopause inversions and mesospheric inversions (Schnelle and Brown 2002; Nodzu et al. 2006; Randel et al. 2007; Kumar et al. 2001; Gramsch et al. 2014; Brümmer and Schultze 2015).

When considering the vertical range of this phenomenon, thermal inversions are classified as either surface inversions or elevated inversions present in the free atmosphere (Niedzwiedz 2003). It should be noted that most studies on inversions are restricted to surface inversions or initial elevated inversions only (e.g. Knozová 2008; Iyer and Nagar 2011; Brümmer and Schultze 2015; Stryhal et al. 2017; Czarnecka et al. 2016). The analysis of the long-term measurement series has shown a decrease in the frequency of surface inversions and a simultaneous increase in the frequency of elevated inversions. Such opposing trends have been demonstrated by Knozová (2008) and Stryhal et al. (2017) for the city of Prague and by Bailey et al. (2011) for the USA. According to these authors, the underlying reasons for such changes are atmospheric circulation and local topographical considerations such as, but not limited to, the intensity of urban heat islands and the geometry of buildings. The influence of local conditions has been noted by Stryhal et al. (2017) in a trend analysis over Prague (the Czech Republic) and Kümmersbruck (Germany), which was located at a distance of approximately 200 km. In turn, according to Iyer and Nagar (2011), the results from a majority of stations (20 total) in the Indian region showed

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surface inversions with decreasing depth and increasing strength in the period 1970–2000.

In respect to duration, two types of inversions associated with different boundary layer processes have been distinguished: diurnal and persistent (Whiteman et al. 2001). The diurnal cycle of inversion (Garratt 1994; Whiteman 2000) is well known and has been substantially documented. A ground-based stable layer usually forms every night, which ends when solar rays reach a maximum or when the wind speed exceeds 20 km/h. After sunset, stability increases again until sunrise. In valleys, however, there are days when a residual inversion layer persists throughout the entire diurnal cycle. This characterises the second type of inversion (persistent), which is long-lasting and not fully destroyed by daytime insolation (Largerón and Staquet 2016). According to Gillies et al. (2010), while it is relatively easy to predict the onset of an inversion, features such as duration or the eventual breakup of a persistent inversion event are unforeseeable. Based on numerically simulated temperature inversions during the daytime in an idealised valley, Leukauf et al. (2015) found that a minimum amplitude of 450 W m^{-2} was required to reach the breakup point, 11 h after which an inversion dissipates.

It has been proven that TIs have a significant effect on weather and climate because their strength controls energy and mass transfers in the atmosphere and cloud formation in the boundary layer (Dong et al. 2005; Devasthale et al. 2010; Zhang et al. 2011). When considering climate change observed at higher latitudes, a substantial amount of attention has been given to TIs in both polar regions (Bourne et al. 2010; Devasthale et al. 2010; Zhang et al. 2011; Zhang and Seidel 2011).

An inversion in the lower atmosphere creates stable atmospheric conditions that inhibit vertical movement, which can play a crucial role in the accumulation of air pollution. Generally, serious pollution episodes are attributed to unfavourable meteorological conditions rather than sudden increases in the emission of pollutants. Temperature inversions are often responsible for these events (Kukkonen et al. 2005; Olofson et al. 2009; Nidzgorska-Lencewicz and Czarnecka 2015). Consequently, numerous studies have discussed temperature inversions with respect to air quality, particularly regarding conditions in urban valleys. For instance, heavy air pollution events in the Cache Valley (Logan, Utah, USA) (Malek et al. 2006; Silva et al. 2007) and Alpine valleys in the area of Grenoble (Largerón and Staquet 2016) have been associated with low-level inversions. Based on data collected from a valley in Santiago, Chile, Gramsch et al. (2014) stated that on days with surface and subsidence inversions, $\text{PM}_{2.5}$ was 84% higher than that on days without any type of inversion. In turn, Wallace and Kanaroglou (2009) demonstrated increases of 49 and 54% in NO_2 and $\text{PM}_{2.5}$, respectively, during night-time inversion episodes in Hamilton. According to Czarnecka and Nidzgorska-

Lencewicz (2017), unfavourable conditions for pollutant dispersions on days with excessive PM_{10} levels in winter are mainly attributed to greater surface inversion thicknesses. However, levels of SO_2 recorded in winter seasons are shaped not only by the thickness but also by the height of inversion layers (Czarnecka et al. 2016). Moreover, as shown by Katsoulis (1988) in a study on SO_2 levels, the intensity of inversions also has an effect on the pollution concentration. According to Milionis and Davies (1992), the intensity of an inversion is directly proportional to its ability to inhibit the vertical movement of pollutants. The results from Czarnecka et al. (2016) and Czarnecka and Nidzgorska-Lencewicz (2017) also show that high location of an elevated inversion base contributes to the improvement of air quality, whereas a significant thickness in both surface-based inversions and elevated inversions result in the deterioration of air quality.

Recently, temperature inversions have been linked to negative health effects. A study conducted by Beard et al. (2012) during winter seasons in Salt Lake County (USA) revealed an association between inversions and emergency visits to the hospital for asthma. Abdul-Wahab et al. (2005) states that the daily average number of hospital visits in Oman increased with an increase in the inversion depth and strength of surface-based inversions.

Apart from investigating the effects of inversions on environmental changes and human health, Gramsch et al. (2014) and Li et al. (2015) rightly note that better understanding temperature inversions and their effect on pollutant levels is necessary in order to control pollutant emissions and prevent pollution episodes. It is worth noting that apart from the models used only in studies on thermal inversion (Leukauf et al. 2015), most models for air pollutant diffusion already incorporate the characteristics of inversions (Milionis and Davies 2008; Morbidelli et al. 2011; Rendón et al. 2015).

This study presents detailed characteristics on the temporal variability of thermal inversions and is based on a dataset from the aerological station in Łeba, Poland. It is generally known that thermal inversions play a role in the development of processes occurring in the boundary layer (e.g. they play a key role in limiting vertical mixing), which is a significant factor that determines air quality and has already been reported. Given the results of previous studies (Nidzgorska-Lencewicz and Czarnecka 2015; Czarnecka et al. 2016; Czarnecka and Nidzgorska-Lencewicz 2017), which show contrasting and statistically significant roles of inversion layers depending on the height of occurrence, this paper provides a separate analysis for surface-based inversions (SBIs) beginning immediately at ground level (Sect. 3.1) and elevated inversions (ELIs) that have bases above the ground (Sect. 3.2) (Parczewski 1976; Stryhal et al. 2017) and form in the atmospheric layer up to 3000 m. It should be emphasised that the principal aim of this study is to determine the temporal structure of the basic characteristics of both types of inversions.

2 Materials and methods

The basis of this study was a 10-year radiosonde measurement series, which was conducted at Hydrological and Meteorological Station IMiGW—PIB in Łeba (No. WMO: 12120) during 2005–2014. The measurements were taken at 00 UTC and 12 UTC. The analyses are based on TEMP messages from the database for upper-air data at the University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>). In the analysed period, measurements were taken using Vaisala radiosondes RS92-KL, RS92-SGP and RS92-SGPD. The station in Łeba (54.75°N, 17.53°E) is one of three aerological stations operating in Poland. It is located by the Baltic Sea and is 90 km northwest of the Agglomeration of Gdańsk (Fig. 1).

Characteristics for the temporal variability of an inversion occurrence in a year included surface-based inversions (SBIs) and elevated inversions (ELIs). The following parameters were determined separately for night-time (00 UTC) and day-time (12 UTC): the height of the inversion base (Z_B), the inversion top (Z_T) and the thickness of the inversion layers ($\Delta Z = Z_T - Z_B$). Additionally, when characterising SBIs, the strength of inversion ($\Delta T = T_T - T_B$) and the mean temperature gradient for the inversion layer ($\Delta T / \Delta Z$) in K per 100 m were determined.

Inversion layers were identified twice a day (00 and 12 UTC) by analysing the vertical changes in air temperature for each day during the adopted 10-year study period, which resulted in a total of 7304 cases. In the analysed measurement series, there were 51 cases (1.4%) where the measurements did not exist; there were more cases at 12 UTC (33) and less at 00 UTC (18).

Fig. 1 Location of the aerological station in Łeba (Poland)

The heights of the inversion layers were determined with an analysis of aerological data presented in the form of a table, which is partially illustrated in Fig. 2. The thicknesses of the SBIs and ELIs were equivalent to the thickness of a layer with a positive vertical temperature gradient. In the case of SBIs, this layer extended directly from the ground level to an altitude above which the air temperature showed a continuous decrease. The example in Fig. 2 shows that on the 26th of January 2006 at 00 UTC, there was a surface-based inversion with a strength of 3.2 K and a thickness of 222 m (ΔZ). At the same time, the base of the elevated inversion (Z_B) was located at a height of 530 m, and the layer reached 912 m (Z_T) (i.e. the thickness was 382 m ($\Delta Z = Z_T - Z_B$)).

On several occasions, it was found that in the atmosphere (especially over urban and industrial areas), there were many ELI layers that were separated by layers of air when the temperature decreased with altitude; therefore, this study takes into consideration only the lowermost ELI. The relatively scarce available literature on the subject includes numerous methods for both the identification of inversions and the classification of ELIs. According to Parczewski (1976), only inversions occurring at heights up to 1000 m were classified as elevated inversions. A study by Kozová (2008) regarding the influences of the frequency of occurrence, thickness, strength and duration of thermal inversions on the concentrations of major air pollutants in Prague identified layers that formed at heights from 201 to 3000 m as inversions in the free atmosphere. However, this was debated by Stryhal et al. (2017), who provided different values (up to 2000 m). Considering the aforementioned classification, this paper provides an analysis on ELIs with bases at altitudes up to 3000 m.

The temporal structure of daytime and night-time inversions has been characterised monthly according to the annual calendar seasons: winter—Dec., Jan., Feb.; spring—

12120 Leba Observations at 00Z 26 Jan 2006

PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg	SKNT knot	THTA K	THTE K	THTV K
1020.0	6	-11.1	-13.9	80	1.29	175	4	260.6	264.1	260.8
1018.0	21	-8.9	-11.3	83	1.59	163	5	262.9	267.3	263.2
1005.0	120	-6.3	-13.3	58	1.37	86	9	266.5	270.4	266.7
1004.0	128	-6.0	-13.0	58	1.40	80	10	266.8	270.8	267.1
1000.0	159	-4.9	-11.9	58	1.54	75	12	268.2	272.6	268.5
992.0	222	-3.9	-6.3	83	2.42	73	12	269.9	276.6	270.3
982.0	302	-4.6	-6.4	88	2.43	70	12	269.9	276.7	270.3
959.0	489	-6.3	-6.5	99	2.46	80	14	270.0	276.8	270.4
957.0	505	-6.5	-6.5	100	2.47	81	14	270.0	276.9	270.4
954.0	530	-6.3	-7.6	90	2.27	83	14	270.5	276.8	270.8
950.0	563	-4.5	-15.5	42	1.21	85	14	272.6	276.2	272.8
942.0	630	-3.7	-18.7	30	0.93	89	14	274.1	276.9	274.2
940.0	647	-3.6	-19.0	29	0.91	90	14	274.3	277.1	274.5
925.0	774	-3.1	-21.1	23	0.77	85	12	276.1	278.5	276.3
909.0	912	-2.7	-22.7	20	0.68	85	10	277.9	280.1	278.0
901.0	982	-3.3	-16.3	36	1.19	89	9	278.0	281.6	278.2
879.0	1177	-4.1	-17.1	36	1.15	100	9	279.1	282.6	279.3
874.0	1222	-4.1	-26.1	16	0.52	103	9	279.6	281.3	279.7
865.0	1304	-4.5	-15.5	42	1.33	107	8	280.0	284.0	280.2
850.0	1441	-5.3	-22.3	25	0.76	115	8	280.6	282.9	280.7
849.0	1450	-5.3	-22.3	25	0.76	115	8	280.7	283.0	280.8
827.0	1655	-7.3	-13.3	62	1.67	113	6	280.7	285.6	281.0
815.0	1769	-7.7	-21.7	32	0.83	112	5	281.4	284.0	281.6
811.0	1807	-7.7	-15.7	53	1.40	112	4	281.8	286.0	282.1
784.0	2069	-10.0	-13.7	74	1.70	110	2	282.1	287.2	282.4

□ surface inversion layer (SBI) □ elevated inversion layer (ELI)

Fig. 2 An example of highlighting inversion layers based on radiosonde measurement (www.weather.uwyo.edu/upperair/sounding.html)

Mar., Apr., May; summer—Jun., Jul., Aug.; and autumn—Sep., Oct., Nov.

This paper provides two separate analyses over a 24-h period (i.e. daytime and night-time), which are represented by the results of the aerological measurements at 12 UTC and 00 UTC, respectively. Therefore, all characteristics concerning the frequency of occurrence for inversions at both times during the 24-h period refer to the number of days or nights, analysed separately, in the individual months (Figs. 4, 8 and 10) or calendar seasons in a year (Figs. 6, 9, 12 and 14).

3 Results and discussion

3.1 Surface-based inversion (SBI)

3.1.1 Frequency

In the area of Łeba, SBIs occur in approximately 50% of nights and only 4% of days throughout the year (Fig. 3). In turn, Katsoulis (1988) reported a slightly lower frequency of inversions in Athens (44%), which was determined from measurements taken at 00 UTC. In the only publication to date on the temporal and spatial variabilities of inversions in Poland (Parczewski 1976), the phenomenon was characterised with isotherms and cases of slight vertical temperature gradients (0.2 °C/100 m), which were classified as thermal inhibition layers. The number of days in Poland with night-time thermal inhibition layers identified by the aforementioned definition equals approximately 60% (approximately 6% for daytime).

In the period 2005–2014, the number of nights with SBIs ranged from 167 to 205, and the number of daytime SBIs ranged from 8 to 18. By far, the smallest number of SBIs was recorded at both times during the 24-h period in 2007, and the highest number was recorded at both times in 2012. A large number of inversions (only night-time) were recorded in 2014. It was found that such a variation in the number of SBIs is characteristic for years with very similar thermal conditions. According to the Bulletin of Monitoring Climate in Poland, the years 2007 and 2014 were classified as extremely warm, and the year 2012 was classified as warm.

Fig. 3 Frequency (%) of SBI and ELI in Łeba (2005–2014)

From April to October, SBIs recorded in Łeba were more frequent every second night; from May to September, the frequency was approximately 65% (Fig. 4). The smallest frequency of night-time SBIs (approximately 30%) was found in December and January. For comparison, in Prague at 00 UTC, inversions were recorded with a frequency of 38% in the colder half of the year (ONDJFM), and more than 60% were recorded in the warmer half of the year (AMJJAS) (Stryhal et al. 2017). In turn, earlier studies by Knozová (2008) showed that night-time inversions at height up to 50 m formed most frequently in July and August and least frequently in November and December. The identified downward trend in the frequency of inversion occurrences in the lowermost layer of the troposphere during 1992–2006 was also confirmed by the results of Stryhal et al. (2017), which were obtained for a longer period (1992–2012).

Daytime inversions not only occur far less frequently than those at night-time, but they also show opposing distribution patterns throughout the year. Daytime inversions are recorded mainly in December and January (approximately 8–9% of days), whereas in the remaining months, the frequency of daytime inversions is generally no more than 4%. The fewest occurrences of these events are recorded in September and October.

3.1.2 Thickness (ΔZ)

The average seasonal thickness of a night-time surface-based inversion ranges from 150 to 200 m; during most seasons of a year, it is 50–80 m greater than that of daytime inversions (Fig. 5). According to Parczewski (1976), significant factors of varied thickness in night-time and daytime SBIs represent the very different causes of their formations. This study argues that a greater thickness in night-time inversions is connected with stronger vertical air mixing in radiative-advective inversion layers, which are twice as thick as radiative layers. These layers form at night and do not occur during the day. Spring is the only atypical season in the region of Łeba. It is distinguished not only by the greatest average thickness of night-time

Fig. 4 Frequency (%) of SBI according to the months in Łeba (2005–2014)

Fig. 5 Thickness (ΔZ) of SBI according to the seasons in Łeba (2005–2014)

inversions, but also by equally thick, yet far less frequent, daytime inversions (Figs. 3 and 4). This could be linked to a very high frequency of stable equilibrium states in this season, which was shown in climatic simulations over the Baltic Sea (Svensson et al. 2016). Average lower thicknesses of night-time inversions (00 UTC) in the winter season (DJF) and greater thicknesses in the spring (MAM) in the northern part of Poland were also presented by Palarz et al. (2017) based on the ERA-Interim reanalysis over a 35-year period.

Similar inversion thicknesses occur in summer and autumn; however, these thicknesses are dissimilar in winter and spring (Fig. 4), which is not confirmed by the diagrams in Fig. 6. Due to the frequency distribution of the adopted inversion layer thickness ranges, as well as the separate assessment of daytime and night-time inversions, greater similarities can be found between winter and autumn seasons, just as the spring season is found to be similar to that of summer. In the calendar winter season at both times during the 24-h period, inversions with a thickness up to 100 m are markedly

Fig. 6 Thickness (ΔZ) of SBI—frequency (%) of adopted ranges according to the seasons in Łeba (2005–2014)

predominant. In autumn, inversion layers with the smallest thicknesses form only in the daytime, whereas thicknesses of night-time inversions can similarly reach up to 100 m or even extend from 100 to 200 m. Moreover, approximately $\frac{1}{4}$ of the cases of night-time inversions occurring in autumn shows thicknesses from 200 to 300 m, which is similar to that of spring and summer. In spring and summer, the most predominant inversions are those with thicknesses ranging from 100 to 200 m. Large average thicknesses of daytime inversions in calendar spring (Fig. 5) are determined by the greatest annual proportion of layers with thickness of 200–300 m.

Considering the lower frequency of daytime inversions, characteristics of the primary phenomenon features, presented in Table 1, refer only to the night-time inversions. In most months, the mean average thickness of night-time inversion ranged from approximately 170 to 190 m and exceeded 200 m only in April and May. In Athens, inversions with thicknesses greater than 200 m were observed more frequently from April to October (Katsoulis 1988). Night-time inversions with the smallest thicknesses (143 m) occurred in December. Despite the fact that the mean monthly thickness of night-time inversions generally did not exceed 200 m, as indicated by the values of the upper quartile (Q3) in Table 1 for almost all months of the year (with the exception of January and December), 25% of cases showed night-time inversion thicknesses ranging from 230 to approximately 280 m. In the period 2005–2014, inversions with maximum thicknesses were recorded, on average, during the coldest and warmest months of the year. In January, night-time SBI thicknesses amounted to 1632 m, whereas in July, thicknesses equalled 1397 m. In the remaining months, the maximum thickness ranged, on average, from 600 to 800 m, indicating that the thickness was 3–5 times greater than the average thickness. The highest relative variation in night-time SBI thickness (125%) was found in January.

3.1.3 Strength (ΔT)

The mean seasonal strength of night-time SBIs ranged from 1.5 to 2.3 K, and daytime SBIs ranged from 1.1 to 1.6 K (Fig. 7). Greater strength in the night-time inversions was characteristic during spring and summer, and the weakest strength (by as much as approximately 1 K) was characteristic during winter. The results of the night-time inversions showed high compliance with the results of Palarz et al. (2017) for the Baltic Sea region. The calendar winter season was distinguished by the greatest strength of daytime inversions. Moreover, winter was the only season where daytime inversions showed even a slightly higher strength than that of night-time inversions. In spring, summer and autumn, the mean strength of daytime inversions was approximately two times lower than that of night-time inversions. The distinct characteristic of the winter season caused by the strength of

Table 1 Statistics of thickness and intensity of the surface inversions at night (hour 00 UTC) in Łeba (2005–2014)

Thickness ΔZ (m)					Strength ΔT (K)			
Month	Average	Max	Q3	Vs	Average	Max	Q3	Vs
Jan	177	1632	199	125	1.4	5.2	1.9	70
Feb	180	761	251	95	1.5	4.6	2.0	70
Mar	180	734	246	70	2.0	9.8	2.8	80
Apr	218	777	273	56	2.4	11.0	3.2	70
May	202	578	277	55	2.5	15.7	3.3	81
Jun	186	639	249	59	2.4	9.0	3.2	69
Jul	182	1397	255	71	2.4	10.1	3.1	68
Aug	176	778	235	58	2.1	7.3	2.7	63
Sep	182	617	239	55	2.1	8.2	2.6	74
Oct	200	944	270	78	2.0	10.0	2.7	86
Nov	169	881	229	82	1.6	17.1	2.1	109
Dec	143	663	183	81	1.5	8.6	2.1	86

Q3 upper quartile, Vs coefficient of variation (%)

inversions was confirmed by the data presented in Fig. 8. Inversion layers forming in winter showed strengths of 0–1 K and 1–2 K with similar frequencies—both ranges comprised approximately 77% of cases for both daytime and night-time inversions. In the remaining seasons, 70–80% of inversions (only night-time inversions) showed strength from 0 to 3 K; yet in spring and summer, there was a slight tendency toward the 1–2 K range. Night-time inversions with a strength greater than 5 K occurred mainly in spring. Among the daytime inversions, the most predominant (60–75%) strength was less than 1 K. A large proportion (approximately 27%) of daytime inversions with greater strength (1–2 K) was characteristic only in spring.

In most months of the year, the average strength of night-time inversions ranged from 2 to 2.5 K (Table 1). Weaker strength (1.4–1.6 K) was determined for inversions occurring in calendar winter (Dec–Feb) and November. However, according to the Q3 value, in approximately 25% of cases, the strength of night-time inversions for almost all months exceeded 2 K, and from April to July, it even exceeded 3 K.

Fig. 7 The strength (ΔT) of SBI according to the seasons in Łeba (2005–2014) **Fig. 8** The strength (ΔT) of SBI—frequency (%) of the adopted ranges according to the seasons in Łeba (2005–2014)

In the period 2005–2014, the maximum 24-h period strengths of night-time inversions showed a very wide range (from 4.6 to 17.1 K); however, in most months, the values did not exceed 10 K. Extreme strength was determined for a 15-m thick inversion layer that occurred in November. A slightly lower strength ($\Delta T = 15.7$ K) was identified for a less thick (8 m) inversion in May; both cases were recorded in 2008. The strength of the night-time inversion typically showed greater variability than that of thickness.

3.1.4 24-h surface inversions

Particularly unfavourable conditions for the dispersion of pollutants from low-emitting sources occur during inversions that persist throughout daytime and night-time (i.e. 24-h inversions) (Köber 2013; Walczewski 2009; Czarnecka et al. 2016). A catalogue of morning transitions of the atmospheric boundary layer (Walczewski 2009) lists 24-h inversions as one of the two main phenomena that foster the emergence of smog. However, data presented in Fig. 9 show that in Łeba, such situations occur rather sporadically. In the analysed 10-year period, there were only 81 of these situations, most of which occurred in January and December, as well as in May. The winter season, which is when 24-h inversions occur most frequently, were also mentioned in this respect by Köber (2013). In Łeba, inversions with a 24-h duration were the least reported in the period from June to November, with a minimum in September. Most cases of 24-h inversions (18) were recorded in 2009 and 2012. In contrast, in southern Poland in the area of Kraków, the mean annual number of days with 24-h inversions was 99, and many individual years during 1994–2005 experienced 24-h inversions that were recorded over as many as 20 days in winter (Walczewski 2009). In Prague during 1992–2012, 24-h inversions were determined for 9.6% of days, yet there were cases that exhibited inversions

Fig. 9 24-h SBI—the number of days and the average thickness in Łeba (2005–2014)

lasting 2–8 subsequent days (Stryhal et al. 2017). Even though 24-h inversions in the area of Łeba were recorded more frequently in the winter months, the average thickness did not exceed 150 m and was smaller than that recorded in the remaining months of the year. By far, the greatest 24-h SBI thickness was identified in April, followed by September.

3.2 Elevated inversions (ELIs)

3.2.1 Frequency

Throughout the year, elevated inversions with base heights reaching 3000 m are common—approximately 70% of days (12 UTC) and 69% of nights (00 UTC) (Fig. 3). In comparison to SBIs, the frequency of ELIs shows only a small variation between the seasons, months and the given times of a 24-h period (Fig. 10). The distribution of annual ELIs is opposite that of SBIs; the occurrence of ELIs is slightly more frequent in the colder half of the year, particularly in December and January, and less frequent in August and September. Elevated inversions form mainly as a result of stagnant high-pressure areas under stable equilibrium conditions, but they also result from propagating low-pressure areas along the front surface, which separates the cold air mass from the warm air mass. The aforementioned processes occur more frequently in the colder half of the year, which results in a higher frequency of ELIs from October to February. The role of advection in the

Fig. 10 Frequency (%) of ELI to 3000 m according to the months in Łeba (2005–2014)

formation of front elevated inversions in Łeba is suggested by the location of the town on the coast of the Baltic Sea, which is in the vicinity of one of the main passages for propagating low-pressure systems.

In most months of the year, the difference between the frequencies of night-time and daytime inversions does not exceed 6%. There are slight differences in the frequencies of daytime and night-time inversions in the layer extending 2000 m AGL; however, differences are markedly greater between the colder (ONDJFM) and warmer (AMJJAS) halves of the year, which were presented by Stryhal et al. (2017) when analysing Prague.

3.2.2 Base (Z_B)

Elevated inversions typically form in a layer approximately 820 to 1200 m AGL; the lowermost inversions are recorded in winter, higher inversions are recorded in spring and the highest are recorded in summer (Fig. 11). In autumn, the average inversion base height is marginally lower than that in summer, and both occurrences during the 24-h period exceed 1000 m. During all seasons of the year, bases with lower heights were characteristic for daytime inversions; however, greater differences were found in spring (approximately 190 m), and markedly smaller differences were found in autumn (approximately 50 m).

Radiative processes play a significant role in the formation of elevated inversions. These processes are a fundamental factor in the transformation of night-time surface structures into elevated layers after sunrise. Under the condition of a sufficiently high surplus in the radiative balance, developing convection transforms a surface inversion into an elevated inversion in the vertical due to the surplus of radiative energy. The characteristics of the temperature inversion regime in Prague showed that at 06 UTC, there was a significant increase in the frequency of elevated inversions, while the frequency of surface-based inversions decreased below 50% (Stryhal et al. 2017). Intensified processes of transforming night-time surface-based inversions into morning elevated layers occurred in the analysed boundary layer up to 2000 m

Fig. 11 The base (Z_B) of the first (located at the lowest level) ELI—average height according to the seasons in Łeba (2005–2014)

from April to September and particularly in June and July. In winter, with insufficient supply of solar energy, the elevated layers, which are the continuum of night-time surface structures, occurred relatively low to the ground. Such weakening in the transformation of SBIs into ELIs, in conjunction with the large-scale downward movement in low-pressure areas, may provide an explanation for lower base heights for elevated inversions during winter.

Variations in the height of ELI occurrences between colder and warmer half-years are more clearly shown in diagrams representing the frequency of base heights in the adopted height ranges (Fig. 12). Often, inversions form at heights no greater than 500 m and, depending on the season, constitute as much as 30–45% of all cases. Compared with inversions forming at greater heights, the greatest frequency of the lowermost inversions (up to 500 m) is found mainly in spring and summer and less in winter; for autumn, the difference is minimal, particularly regarding daytime inversions. Consequently, there are differences in the frequency distribution of ELI base heights between warmer and colder half-years. In summer and spring, after the predominant occurrence of inversions with base heights reaching 500 m, there is a rapid and almost three to fourfold decrease in the frequency of inversions occurring at greater heights. In winter and autumn, however, the decrease is gradual (particularly in winter). It should be noted that the calendar summer, which is a season with the highest occurrence of unstable equilibrium and thus has the deepest mixing layer, is distinguished by markedly less frequent occurrences of inversions forming at heights from 500 to 1500 m and at least twice as many occurrences of inversions at heights from 2000 to 3000 m.

Fig. 12 The base (Z_B) of the first (located at the lowest level) ELI—frequency (%) of the adopted ranges according to the seasons in Leba (2005–2014)

Data presented in Table 2 show that the lowermost inversion base heights during both daytime and night-time are characteristic during, on average, the coldest month of the year (January), whereas higher base heights are recorded in September then August. In the period from June to September, the average inversion base heights exceed 1000 m at both times during the 24-h period, whereas from February to May, these heights only exceed the 1000 m threshold at night-time. However, the values of the upper quartile (Q3) indicate that in almost all months of the year (75% of cases), daytime and night-time inversions form in layers with heights reaching 2000 m. In two summer months, ¼ of cases have inversion bases occurring at heights greater than 2000 m: in August at both times during the 24-h period and in July during the daytime. However, in the analysed decade 2005–2014, in almost every month of the year, ELIs with base heights greater than 2900 m were recorded at both times during the 24-h period.

3.2.3 Thickness (ΔZ)

A rather stable increase in ELI base heights from winter to summer (Fig. 11) is accompanied by a decrease in average thickness (Fig. 13). The thickest inversion layers occur during winter; at both times during the 24-h period, the ELI thickness amounts to approximately 210 m. In summer, the thickness of night-time inversions is smaller by 50 m, and the daytime thickness is smaller by as much as approximately 70 m. The thicknesses of inversions occurring in transitional seasons (i.e. spring and autumn) are similar.

Although the average seasonal thicknesses of inversions occurring in winter are markedly higher, the most frequently recorded range is from 100 to 200 m, which is similar to those in other seasons during the year (Fig. 14). Only daytime inversions occurring in the summer season are distinguished by thicknesses not exceeding 100 m. Generally, thicknesses up to 200 m are recorded in more than 80% of cases. In spring and autumn, daytime and night-time inversions with the smallest thicknesses (up to 100 m) occur more frequently than those with 200–300 m thicknesses; in winter, the frequency is comparable. Winter is the season distinguished by the highest frequency of inversions, with thicknesses greater than 400 m.

The dominance of inversions with thicknesses up to 200 m is confirmed by the results obtained for most months of the year, in seasonally adjusted terms (Table 2). During both times in the 24-h period, average maximum inversions (greater than 200 m) are recorded not only in January but also in the last month of the autumn season (November). In December and February, thicknesses of approximately 210 m are recorded only for night-time inversions. However, the values of the upper quartile (Q3) show that in 25% of cases during most months of the year (with the exception of summer months), thicknesses for daytime and night-time inversion layers exceed 200 m; from

Table 2 Statistics of elevated inversions (ELI) layers occurred below 3000 m in Łeba (2005–2014)

Months/time of day		Base Z_B (m)				Thickness ΔZ (m)			
		Average	Max	Q3	Vs	Average	Max	Q3	Vs
January	Night	800	2954	1145	79	209	937	269	71
	Day	806	2882	1169	74	221	1297	268	83
February	Night	1064	2886	1555	66	207	1649	257	91
	Day	870	2714	1255	66	197	718	256	66
March	Night	1006	2942	1600	76	197	705	254	64
	Day	980	2974	1377	71	187	824	234	72
April	Night	1135	2996	1831	79	173	624	217	59
	Day	786	2996	1373	105	159	602	203	64
May	Night	1095	2919	1955	85	177	792	217	75
	Day	904	2950	1782	102	157	638	192	70
June	Night	1143	2915	1990	81	162	779	200	71
	Day	1010	2985	1892	94	148	591	189	69
July	Night	1091	2960	2001	87	160	634	201	56
	Day	1034	2978	1816	89	126	597	162	69
August	Night	1339	2986	2084	70	154	541	192	60
	Day	1361	2955	2063	65	132	653	168	72
September	Night	1354	2891	1918	56	176	786	214	72
	Day	1409	2965	1872	49	155	609	194	68
October	Night	1125	2957	1654	69	183	910	256	75
	Day	1099	2968	1613	63	179	899	234	73
November	Night	956	2997	1426	75	209	1234	243	68
	day	805	2969	1206	77	202	759	252	67
December	Night	941	2953	1355	71	208	1040	253	72
	Day	794	2988	1163	80	190	834	254	68

Q3 upper quartile, Vs coefficient of variation (%)

October to March, they exceed 230 m, and in the winter months, they exceed heights as greater as 250 m.

In the analysed period of 2005–2014, the maximum inversion layer thickness was generally 4–5 times greater than the average inversion layer thickness. A record thickness ($\Delta Z = 1649$ m) was identified during a night-time inversion in February 2009. Over 1000-m thick inversion layers also occurred at night-time in November and December. The only occurrence of a comparable thick daytime inversion layer ($\Delta Z = 1297$ m) occurred on 29 January 2011.

Fig. 13 Average thickness (ΔZ) of the first (located at the lowest level) ELI according to the seasons in Łeba (2005–2014)

Relative variations in the monthly thicknesses of ELIs were generally due to the height of the base. Variation coefficients of the two features (daytime and night-time inversions) fell within a range from 60 to 80% for most months of the year. However, thickness, particularly for daytime inversions, showed slightly weaker variability throughout the year.

3.3 The simultaneous occurrence of SBIs and ELIs

In the lower troposphere (up to 3000 m), the simultaneous occurrence of surface-based and elevated inversions accounted for 34% of nights and only 2.5% of days during the year, which was obviously determined by the small frequency of surface-based inversions. Nights when both SBIs and ELIs occurred were found most often from April to October (Fig. 15). On most nights during the aforementioned period, the simultaneous occurrence of SBIs and ELIs had a frequency greater than 30%, and on many nights (approximately 70), the frequency was at least 50% (mainly in May; 21 days). For individual 24-h time periods, such situations occurred in as many as 7–8 years of the study period.

Fig. 14 Thickness (ΔZ) of the first (located at the lowest level) ELI—frequency (%) of the adopted ranges according to season in Łeba (2005–2014)

The simultaneous occurrence of daytime SBIs and ELIs is very rare, and it occurs mainly in the winter season. Often, such situations are recorded in January and December (6 and 4% of days, respectively). For almost all days from 25 December to 28 January, the phenomenon occurred at least once, yet on individual days, the phenomenon occurred 2–3 times. From mid-June to mid-November, daytime SBIs and ELIs were recorded only during a few days. For individual years during the period of 2005–2014, the simultaneous occurrence of SBIs and ELIs was identified 29–36% of nights and merely 1–3% of days; night-time had the largest frequency in 2008 and 2014, and daytime had the largest frequency in 2009 and 2012.

The exemplary occurrence of inversion layers is illustrated by the results from 2012 (Fig. 16). In the analysed decade of 2005–2014, 2012 was distinguished by the highest frequency of surface-based inversions (night-time (56%) and daytime (5%)) and the greatest proportion of nights (34%) and days (3%) with the additional occurrence of elevated inversions.

4 Conclusions

The results presented in this study show that temperature inversions are a common phenomenon in the area of Łeba and can occur throughout the whole year. The thermal structure of the boundary layer up to an altitude of 3000 m is determined both by surface-based and elevated inversions. However, elevated inversions are dominant and occur throughout the year, with similar (approximately 70%) frequencies examined at both times during the 24-h period. These inversions are characterised by a slight frequency variation between seasons and months. In comparison to elevated inversions, surface-based inversions show a pronounced temporal structure. Surface-based inversions form primarily at night-time—specifically, every second night throughout the year; from April to September, the frequency of occurrence is comparable (approximately 60%) to that of elevated inversions. Daytime surface-based inversions occur very rarely (mainly in January and December). Therefore, the long-term hindrance of vertical pollutant dispersion due to surface-based inversions during a 24-h period is negligible, and even in winter months, it occurs rather sporadically. Unfavourable conditions for vertical air mixing are related to the simultaneous occurrence of surface-based and elevated inversions. These were recorded for more than 30% of nights, particularly from April to November; daytime occurrences were very rare.

Surface-based and elevated inversion layers are characterised by comparable thicknesses, particularly during night-time inversions, which range from 150 to 200 m. Similar thicknesses are also recorded for inversions occurring during the daytime; however, due to lower frequencies of occurrence for surface-based inversions, the results of such a comparison are treated as purely indicative. Elevated inversions, which occur from November to March, occur at lower heights than those in the remaining months of the year and have greater thicknesses compared to those of surface-based inversions. However, in the period from April to October, the situation is reversed—thicker layers form directly above ground level.

Variability of the main characteristics of inversion occurrences in Łeba is generally consistent with that presented in the relevant literature. The 24-h and seasonal inversion

Fig. 15 Frequency (%) the simultaneous occurrence of SBI and ELI in Łeba (2005–2014)

Fig. 16 The average thickness of the SBI and ELI during the simultaneous occurrence in a layer of up to 3000 m in Łeba in 2012

occurrences are primarily influenced by radiative processes and the vertical advection of heat, depending on the type of inversion either at ground level or in the higher layers of the troposphere. Topographical conditions play a significant role regarding the types and properties of the surface or its cover. The significance of radiative processes that determine both the 24-h and annual basic characteristics of surface-based inversions occurring across the European continent is presented in numerous studies (Brümmer and Schultze 2015; Kassomenos et al. 2014; Palarz et al. 2017; Stryhal et al. 2017). Intense and effective radiation emissions under anticyclonic weather conditions, particularly on cloudless nights or night with small cloud cover and little wind, are the underlying cause of the frequent occurrence of inversion layers with great thicknesses and high vertical temperature gradients during the warmer months of the year. Regardless of the adopted classification for pressure systems and types of circulation, numerous studies note that conditions for strong radiative cooling at the surface occur under pressure systems with small horizontal pressure gradients at the centre of the anticyclone, wedge or anticyclonic ridge (Bailey et al. 2011; Kassomenos et al. 2014; Katsoulis 1988; Prezerakos 1998; Palarz 2014; Walczewski 1994, 2009; Vitasse et al. 2017).

This assessment on the 24-h and annual occurrence of temperature inversions refers to the area of Poland distinguished by increased dynamics in the lower atmosphere, which primarily manifest from the occurrence of unstable equilibrium influenced by the inflow of the maritime polar air mass (Parczewski 1971). The role of advection in the formation of inversion layers during winter is demonstrated by comparing the frequency and thickness of inversions occurring in Łeba and Wrocław (Czarnecka et al. 2016). In the area of Łeba, night-time surface-based

inversions occur half as much as those in Wrocław; however, the thickness in Łeba is greater. This certainly results from higher frequencies of radiative-advective inversion occurrences, which show greater thicknesses than those of typical radiative inversions (discussed in Sect. 3.1.2).

The temporal structure of temperature inversions in the area of Łeba is modified by mesoscale phenomena due to the location of the town along the Baltic Sea coast (between lakes Łebsko and Gardno), which is a very dynamic natural environment. Temperature contrasts between land and sea contribute to the development of local circulation, including sea breezes (Brümmer et al. 2005, 2014; Johansson et al. 2005; Katsoulis 1988). Markedly lower frequencies, thicknesses and strengths of SBIs during all seasons for the coastal area of the Baltic Sea are illustrated on maps in Palarz et al. (2017). The effect of the sea breeze on the vertical distribution of temperature inversions was demonstrated by Milionis and Davies (2008). According to the authors, in the lower section of the atmospheric boundary layer (approximately 850 hPa), local factors overwhelm synoptic conditions. This means that the results of the assessment on inversions occurring at one location can be considered representative for larger areas only under similar synoptic conditions. Therefore, it would be difficult to compare the quantitative characteristic results of the basic features for both types of inversion in the area of Łeba with data presented in the relevant literature. Several other reasons, such as incomparable data and method sources for the identification of inversions, also pose a significant problem with the interpretation of results. Several authors identify layers up to 280 m as both surface-based and elevated inversions (Brümmer and Schultze 2015); others consider all

inversions in layers up to 5500 m to be surface-based inversions (Palarz et al. 2017). Results that were obtained by observation series of various lengths are often rather short (Pekour and Kallistratova 1993) and refer to various climatic zones (Ramírez-Sánchez et al. 2013). For example, a frequency analysis on the occurrence of surface inversions in winter during 1971–2000 at 20 stations in India (Iyer and Nagar 2011) showed an extreme variation from 4 to 95%, depending on the latitude. Numerous studies have adopted gradient masks as the basis for the assessment of inversions (Bokwa 2011; Brümmer and Schultze 2015), which is of particular importance regarding elevated inversions. At times, inversions are mentioned merely as a phenomenon without distinguishing the height of its occurrence and only with reference to increased or excessive pollutant concentrations (Ramírez-Sánchez et al. 2013). Therefore, the results were confronted with just only a few items of literature, which are primarily based on the results of aerological soundings from long measurement series, as presented by Knozová (2008), Palarz et al. (2017), Parczewski (1971, 1976), and Stryhal et al. (2017).

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References

- Abdul-Wahab SA, Bakheit CS, Siddiqui RA (2005) Study the relationship between the health effects and characterization of thermal inversions in the Sultanate of Oman. *Atmos Environ* 39:5466–5471. <https://doi.org/10.1016/j.atmosenv.2005.05.038>
- Bailey A, Chase TN, Cassano JJ, Noone D (2011) Changing temperature inversion characteristics in the US southwest and relationships to large-scale atmospheric circulation. *J Appl Meteorol Climatol* 50:1307–1323. <https://doi.org/10.1175/2011JAMC2584.1>
- Beard JD, Beck C, Graham R, Packham SC, Traphagan M, Giles RT, Morgan JG (2012) Winter temperature inversions and emergency department visits for asthma in Salt Lake County, Utah, 2003–2008. *Environ Health Perspect* 120:1385–1390. <https://doi.org/10.1289/ehp.1104349>
- Bokwa A (2011) Influence of air temperature inversions on the air pollution dispersion conditions in Krakow. *Prace Geograficzne Instytut Geografii i Gospodarki Przestrzennej UJ Kraków* 126:41–51
- Bourne SM, Bhatt US, Zhang J, Thoman R (2010) Surface-based temperature inversions in Alaska from a climate perspective. *Atmos Res* 95:353–366
- Brümmer B, Schultze M (2015) Analysis of a 7-year low-level temperature inversion data set measured at the 280 m high Hamburg weather mast. *Meteorol Z* 24:481–494. <https://doi.org/10.1127/metz/2015/0669>
- Brümmer B, Kirchgäßner A, Müller G (2005) The atmospheric boundary layer over Baltic Sea ice. *Bound-Layer Meteorol* 117:91–109. <https://doi.org/10.1007/s10546-005-0906-4>
- Brümmer B, Kirchgäßner A, Müller G (2014) The atmospheric boundary layer structure over the open and ice-covered Baltic Sea: in situ measurements compared to simulations with the regional model REMO. *Theor Appl Climatol* 118:641–653. <https://doi.org/10.1007/s00704-009-0177-y>
- Czarnecka M, Nidzgorska-Lencewicz J (2017) The impact of thermal inversion on the variability of PM10 concentration in winter seasons in Tricity. *Env Prot Eng* 43:157–172. <https://doi.org/10.5277/epe170213>
- Czarnecka M, Nidzgorska-Lencewicz J, Rawicki K (2016) Thermal inversions and sulphure dioxide concentrations in some Polish cities in the winter season. *J Elem* 21:1001–1015. <https://doi.org/10.5601/jelem.2016.21.1.1038>
- Devasthale A, Willén U, Karlsson K-G, Jones CG (2010) Quantifying the clear-sky temperature inversion frequency and strength over the Arctic Ocean during summer and winter seasons from AIRS profiles. *Atmos Chem Phys* 10:5565–5572. <https://doi.org/10.5194/acp-10-5565-2010>
- Dong XQ, Minnis P, Xi BK (2005) A climatology of midlatitude continental clouds from the ARM SGP central facility: part I: low-level cloud microphysical, microphysical, and radiative properties. *J Clim* 18:1391–1410
- Garratt JR (1994) *The atmospheric boundary layer*. Cambridge University Press, Cambridge
- Gillies RR, Wang SY, Booth MR (2010) Atmospheric scale interaction on wintertime intermountain west low-level inversions. *Wea Forecasting* 25:1196–1210. <https://doi.org/10.1175/2010WAF2222380.1>
- Gramsch E, Cáceres D, Oyola P, Reyes F, Vásquez Y, Rubio MA, Sánchez G (2014) Influence of surface and subsidence thermal inversion on PM 2.5 and black carbon concentration. *Atmos Environ* 98:290–298. <https://doi.org/10.1016/j.atmosenv.2014.08.066>
- Iyer US, Nagar SG (2011) Variability in surface inversion characteristics over India in winter during the recent decades. *J Earth Syst Sci* 120:73–84. <https://doi.org/10.1007/s12040-011-0069-2>
- Johansson C, Hennemuth B, Bösenberg J, Linné H, Smedman AS (2005) Double-layer structure in the boundary layer over the Baltic Sea. *Bound-Layer Meteorol* 114:389–412
- Kassomenos PA, Paschalidou AK, Lykoudis S, Koletsis I (2014) Temperature inversion characteristics in relation to synoptic circulation above Athens, Greece. *Environ Monit Assess* 186:3495–3502. <https://doi.org/10.1007/s10661-014-3632-x>
- Katsoulis BD (1988) Aspects of the occurrence of persistent surface inversions over Athens Basin, Greece. *Theor Appl Climatol* 39:98–107. <https://doi.org/10.1007/BF00866395>
- Knozová G (2008) Temperature inversions at Prague-Libuš aerological station (1975–2006). In: Klysik K, Wibig J, Fortuniak K (eds) *Klimat i bioklimat miast*. Wydawnictwo Uniwersytetu Łódzkiego, Katedra Meteorologii i Klimatologii UŁ, Łódź, pp 65–80 (in Polish)
- Köber AU (2013) The influence of temperature inversions on the air pollution in the city of Sibiu. *Riscursi si catastrofe* 12:113–122. <http://riscursicatastrofe.reviste.ubbcluj.ro>
- Kukkonen J, Pohjola M, Sokhi RS, Luhana L, Kitwiroon N, Fragkou L, Rantamäki M, Berge E, Ødegaard V, Slørdal LH, Denby B, Finardi S (2005) Analysis and evaluation of selected local-scale PM 10 air pollution episodes in four European cities: Helsinki, London, Milan and Oslo. *Atmos Environ* 39:2759–2773. <https://doi.org/10.1016/j.atmosenv.2004.09.090>
- Kumar VS, Kumar YB, Raghunath K, Rao PB, Krishnaiah M, Mizutani K, Aoki T, Yasui M, Itabe T (2001) Lidar measurements of mesospheric temperature inversion at a low latitude. *Ann Geophys* 19:1039–1044. <https://hal.archives-ouvertes.fr/hal-00316897/>

- Largerone Y, Staquet C (2016) Persistent inversion dynamics and winter-time PM10 air pollution in alpine valleys. *Atmos Environ* 135:92–108. <https://doi.org/10.1016/j.atmosenv.2016.03.045>
- Leukauf D, Gohm A, Rotach MW, Wagner JS (2015) The impact of the temperature inversion breakup on the exchange of heat and mass in an idealized valley: sensitivity to the radiative forcing. *J Appl Meteor Climatol* 54:2199–2216. <https://doi.org/10.1175/JAMC-D-15-0091.1>
- Li J, Chen H, Li Z, Wang P, Cribb M, Fan X (2015) Low-level temperature inversions and their effect on aerosol condensation nuclei concentrations under different large-scale synoptic circulations. *Adv Atmos Sci* 32:898–908. <https://doi.org/10.1007/s00376-014-4150-z>
- Malek E, Davis T, Martin RS, Silva PJ (2006) Meteorological and environmental aspects of one of the worst national air pollution episodes (January, 2004) in Logan, Cache Valley, Utah, USA. *Atmos Res* 79:108–122. <https://doi.org/10.1016/j.atmosres.2005.05.003>
- Milionis AE, Davies TD (1992) A five-year climatology of elevated inversions at Hemsby (UK). *Int J Climatol* 12:205–215. <https://doi.org/10.1002/joc.3370120209>
- Milionis AE, Davies TD (2008) A comparison of temperature inversion statistics at a coastal and a non-coastal location influenced by the same synoptic regime. *Theor Appl Climatol* 94:225–239. <https://doi.org/10.1007/s00704-007-0356-7>
- Morbiddelli R, Corradini C, Saltalippi C, Flammini A (2011) Atmospheric stability and meteorological scenarios as inputs to air pollution transport modeling. *Water Air Soil Pollut* 218:275–281. <https://doi.org/10.1007/s11270-010-0640-5>
- Nidzgorska-Lencewicz J, Czarnecka M (2015) Winter weather conditions vs. air quality in Tricity, Poland. *Theor Appl Climatol* 119:611–627. <https://doi.org/10.1007/s00704-014-1129-8>
- Niedźwiedz T (ed) (2003) Dictionary meteorological. Polskie Towarzystwo Geofizyczne, Instytut Meteorologii i Gospodarki Wodnej, Warszawa
- Nodzu MI, Ogino SY, Tachibana Y, Yamanaka MD (2006) Climatological description of seasonal variations in lower-tropospheric temperature inversion layers over the Indochina peninsula. *J Clim* 19:3307–3319. <https://doi.org/10.1175/JCLI3792.1>
- Olofson KFG, Andersson PU, Hallquist M, Ljungström E, Tang L, Chen D, Pettersson JB (2009) Urban aerosol evolution and particle formation during wintertime temperature inversions. *Atmos Environ* 43:340–346. <https://doi.org/10.1016/j.atmosenv.2008.09.080>
- Palarz A (2014) Variability of air temperature inversions over Cracow in relation to the atmospheric circulation. *Prace Geograficzne* 138:29–43. <https://doi.org/10.4467/20833113PG.14.016.2698> (in Polish)
- Palarz A, Celiński-Mysław D, Ustrnul Z (2017) Temporal and spatial variability of surface-based inversions over Europe based on ERA-interim reanalysis. *Int J Climatol* 38:158–168. <https://doi.org/10.1002/joc.5167>
- Parczewski W (1971) Thermo-dynamic stability of vertical air in Poland. *Pr Inst Meteorol Gosp Wodnej* 102, Warszawa. (in Polish)
- Parczewski W (1976) Thermal blocking layers in Poland. *Pr Inst Meteorol Gosp Wodnej* 8. (in Polish)
- Pekour MS, Kallistratova MA (1993) SODAR study of the boundary layer over Moscow for air-pollution application. *Appl Phys B Lasers Opt* 57:49–55. <https://doi.org/10.1007/BF00324100>
- Prezerakos NG (1998) Lower tropospheric structure and synoptic scale circulation patterns during prolonged temperature inversions over Athens, Greece. *Theor Appl Climatol* 60:63–76
- Ramírez-Sánchez HU, García-Guadalupe ME, Ulloa-Gódinez HH, García-Concepción O, Gutierrez JA, Brito SJL (2013) Temperature inversions, meteorological variables and air pollutants and their influence on acute respiratory disease in the Guadalajara metropolitan zone, Jalisco, Mexico. *J Environ Prot* 4:142–153. <https://doi.org/10.4236/jep.2013.48A1016>
- Randel WJ, Wu F, Forster P (2007) The extratropical tropopause inversion layer: global observations with GPS data, and a radiative forcing mechanism. *J Atmos Sci* 64:4489–4496. <https://doi.org/10.1175/2007JAS2412.1>
- Rendón AM, Salazar JF, Palacio CA, Wirth V (2015) Temperature inversion breakup with impacts on air quality in urban valleys influenced by topographic shading. *J Appl Meteor Climatol* 54:302–321. <https://doi.org/10.1175/JAMC-D-14-0111.1>
- Schnelle KB, Brown CA (2002) The air pollution control technology handbook. CRC Press, Boca Raton 386 pp
- Silva PJ, Vawdrey EL, Corbett M, Erupe M (2007) Fine particle concentrations and composition during wintertime inversions in Logan, Utah, USA. *Atmos Environ* 41:5410–5422. <https://doi.org/10.1016/j.atmosenv.2007.02.016>
- Stryhal J, Huth R, Sládek I (2017) Climatology of low-level temperature inversions at the Prague-Libuš aerological station. *Theor Appl Climatol* 127:409–420. <https://doi.org/10.1007/s00704-015-1639-z>
- Svensson N, Bergström H, Sahlée E, Rutgersson A (2016) Stable atmospheric conditions over the Baltic Sea: model evaluation and climatology. *Boreal Environ Res* 21:387–404
- Vitasse Y, Klein G, Kirchner JW, Rebetez M (2017) Intensity, frequency and spatial configuration of winter temperature inversions in the closed La Brevine valley, Switzerland. *Theor Appl Climatol* 130:1073–1083. <https://doi.org/10.1007/s00704-016-1944-1>
- Walczewski J (Eds) (1994) Characteristics of the atmospheric boundary layer over an urban area—the case of Cracow. Materiały badawcze, Seria: Meteorologia, 22, IMGW, Warszawa (in Polish)
- Walczewski J (2009) Some data on occurrence of the all-day inversions in the atmospheric boundary-layer in Cracow and on the factors stimulating this occurrence. *Przegląd Geofizyczny* 54:183–191 (in Polish)
- Wallace J, Kanaroglou P (2009) The effect of temperature inversions on ground-level nitrogen dioxide (NO₂) and fine particulate matter (PM_{2.5}) using temperature profiles from the atmospheric infrared sounder (AIRS). *Sci Total Environ* 407:5085–5095. <https://doi.org/10.1016/j.scitotenv.2009.05.050>
- Whiteman CD (2000) Mountain meteorology: fundamentals and applications. Oxford University Press, New York
- Whiteman CD, Zhong S, Shaw WJ, Hubbe JM, Bian X, Mittelstadt J (2001) Cold pools in the Columbia basin. *Weather Forecast* 16:432–447. [https://doi.org/10.1175/1520-0434\(2001\)016%3C0432:CPITCB%3E2.0.CO;2](https://doi.org/10.1175/1520-0434(2001)016%3C0432:CPITCB%3E2.0.CO;2)
- Zhang Y, Seidel DJ (2011) Challenges in estimating trends in Arctic surface-based inversions from radiosonde data. *Geophys Res Lett* 38. <https://doi.org/10.1029/2011GL048728>
- Zhang Y, Seidel DJ, Golaz J-C, Deser C, Tomas RA (2011) Climatological characteristics of Arctic and Antarctic surface based inversions. *J Clim* 24:5167–5186