



# The ground-level ozone concentration in forest and urban environments in central Slovakia

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Received: 6 May 2022 / Accepted: 7 October 2022 / Published online: 24 October 2022  
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**Abstract** This paper analyses data by summarising the concentration values of ground-level ozone (GLO). The study area is situated in central Slovakia and is part of the Western Carpathians. These measurements were carried out between 2015 and 2020, implementing Werner's method working with passive samplers. The highest average and the highest absolute GLO deposition values were 30.93 ppb and 61.06 ppb, respectively, recorded in August 2015 in the forest in the Kremnické vrchy Mts. The lowest average GLO value in the whole measuring period was 17.72 ppb, measured in the town of Zvolen; the absolute minimum was 4.43 ppb, recorded in April 2016 on an open plot in the Kremnické vrchy Mts. The GLO formation over the study area has not yet reached a steady rate. Since 2007, the developmental trend has been increasing. Statistically significant differences in GLO concentrations were confirmed between the localities with different airborne pollutants. However, the analysis of the existing ozone concentration values showed considerable differences, especially related to the time pattern. The

spatial variability was equalised. The extreme values, while remarkable, were dangerous, especially in the forest stands in the Kremnické vrchy Mts., where they were 14 times above the critical level of 32.5 ppb O<sub>3</sub>. The dominant factor influencing the GLO concentration was global radiation. The effects of average temperature and rainfall total were less important.

**Keywords** Ground-level ozone · Beech forest · Carpathian Mts. · Town and rural plots

## Introduction

Ozone (O<sub>3</sub>) is a naturally occurring gas in the Earth's atmosphere. It is an important constituent in a whole complex of reactions running in this system. O<sub>3</sub> is a very unstable chemical substance that easily emits atomic oxygen. The oxidative effects of ozone are stronger than those of molecular oxygen (O<sub>2</sub>).

The natural sources of O<sub>3</sub> are UV radiation, storms and electrical discharges generated by lightning.

GLO is formed from nitrogen oxides (NO<sub>x</sub>) and volatile organic compounds (VOCs), which are present in the atmosphere and react chemically with solar radiation. NO<sub>x</sub> and VOCs are emitted from cars, power plants, caldrons and boilers, refineries, chemical plants and similar sources.

One of the primary biogenic VOC sources (BVOCs) is vegetation (Guenther, 2002). BVOCs are specific carbohydrate compounds (isoprene, terpenes,

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hemiterpenes and oxidic compounds) reacting reciprocally (photolysis) with other chemical substances and influencing the atmospheric chemistry not only at the ground level but also within the whole troposphere (Lin et al., 2021). They also significantly affect the vegetation phenology and protect vegetation against negative physical influences (Anav et al., 2017; Baggesen et al., 2021). In Central Europe, the dominant BVOC-releasing species are *Fagus sylvatica* L., *Quercus ilex* L., *Quercus robur* L., *Pinus alba* Tebeuf and *Myrtus communis* L. (Kramer et al., 2010; Meeningen et al., 2016).

Due to its strong oxidative power and high molecular instability, O<sub>3</sub> can destroy cell membranes, serving as a life substrate for viruses, microbes, small insects and other pathogens. In this context, we can address a “good” ozone, as the low O<sub>3</sub> concentrations and short-lasting contacts with this substance do not represent danger for humans. O<sub>3</sub> is a disinfecting agent; however, it is stronger and more intensive than chlorine. From an ecological viewpoint, O<sub>3</sub> is a better choice. However, a problem arises when the O<sub>3</sub> concentrations surpass the allowable threshold value. In such a case, O<sub>3</sub> is considered a dangerous substance that negatively influences human health. The World Health Organization (WHO, 2000) has reduced the allowed 8-h average value to 50 ppb. For damage to plants, the UN/ECE (2004) set a critical threshold of 32.5 ppb.

In such a way, higher GLO concentrations are characteristic of urban areas, in which abundant O<sub>3</sub> precursors generated from industry and traffic are assumed.

From the analysis of the time trends of the GLO concentrations in Slovakia, a relatively balanced course was evident in the years 2008–2020, with a small increase in values in recent years, depending primarily on altitude (Kremler et al., 2021).

The O<sub>3</sub> in forest ecosystems can influence all its performance. Most plants use stomata—small openings in their cuticula—for interchanging water, vapour and gases, which are irreplaceable for plant existence in the environment. Normally, the stomata are open during the day and closed at night. As the GLO concentrations reach their maximum in the day, O<sub>3</sub> can easily penetrate inside of the plants and attack their interior cells.

Spots are the first visible symptom of damage, predominantly on leaves. In certain cases, the damaged

leaves fall down. Damaged plants exhibit enhanced sensitivity against climatic changes and are more frequently attacked by pests or diseases. At high GLO concentrations, several plants struggle. The GLO reduces the yields of many agricultural crops by impacting their photosynthesis and hampering normal plant growth. The ozone effects in trees are similar (Augustaitis et al., 2010; Schaub et al., 2005, 2015; Zhu et al., 2021).

Our research aims were to quantitatively express the GLO deposition in forest environments and compare the values with the ozone amounts in urban and rural environments; examine the dynamics and differences between the plots and years; and analyse the developmental trends in the GLO concentrations. Additionally, we evaluated the impacts of temperature, global radiation and total rainfall amount on the O<sub>3</sub> concentrations.

## Materials and methods

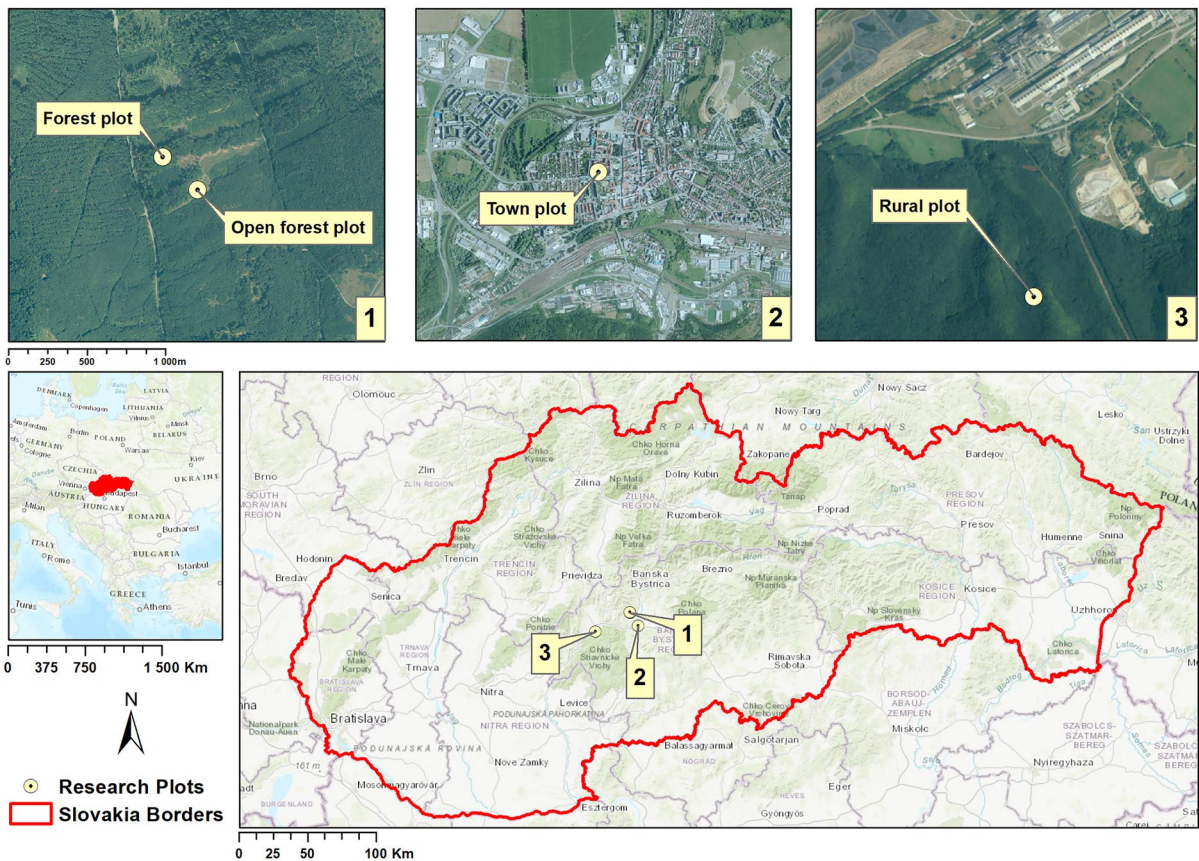
### Study sites

The research plots (RP) in the Kremnické vrchy Mts. are outside of the impact of long-range pollution transport, even though there are energy plants, industrial parks, highway systems and a large railway crossing relatively close by, i.e., within approximately 10 km (Fig. 1). At present, the localities are part of an international network, LTER. Geobiocoenologically, the RP belongs to the 3rd forest vegetation grade, mesotrophic, edaphic-trophic order of geobiocoenes, and the forest type is *Carex pilosa-nudum* (Kukla, 1990). The dominant tree species is *Fagus sylvatica* L., with an average height of 28 m (Barna & Bošela, 2015).

The research plot in the town of Zvolen is situated in the central part of the city without vegetation. There are adult lindens nearby, with a height of up to 15 m, and there are some city transport links.

All the RPs are situated in the moderately warm or warm (Štiavnické vrchy Mts.) climatic district of Slovakia (Kubov et al., 2022).

Contrary to the plots in the Kremnické vrchy Mts., the rural plot there was exposed to a decent emission load. The plot is located near the city of Žiar nad Hronom in the Žiar basin belonging to the Štiavnické vrchy Mts. (Fig. 1). The main



**Fig. 1** Location of the research plots in the Slovakia Republic. Numbers represent the following: (1) Forest plot and Open forest plot (Kremnické vrchy Mts.), (2) Town plot (Zvolen), (3) Rural plot (Žiar basin in Štiavnické vrchy Mts.)

contaminating substances in the Žiar basin are generated from regional sources (aluminium plant, energy production, traffic, communal waste dump), and they included fluoride, sulphur and nitrogen oxides, arsenic, cadmium, solid particles and others. The long-term deposition of air pollutants has had a negative effect on the quality of the surroundings, mostly beech forests. This part of the Štiavnické vrchy Mts. belonged to the most polluted territories in Slovakia. However, as a result of the upgrading of industrial processes and novel legislation, a noticeable decrease in pollutants has been evident since the 1990s. The flourine concentration has been reduced to an acceptable limit of  $1 \mu\text{g m}^{-3}$  (Urminská et al., 2000). Geobiocoenologically, the forest stands are in close proximity to the RP. This RP belongs to the 3rd forest vegetation grade and has a waterlogged edaphic-hydric order of geobiocoenes, mesotrophic

edaphic-trophic order of geobiocoenes and forest type *Dentaria bulbifera-nudum* (Kukla, 1990). More detailed characteristics and locations of all RPs are given in Table 1.

**Methods**

For the evaluation of airborne ozone deposition, we applied Werner’s method working with passive samplers (Werner et al., 1999). The principle of this method is the adsorption of gaseous particles on the activated surface. The adsorbents are paper filters with indigo solution applied on their surface. The exposed paper sheets were extracted with ethanol in the laboratory. The reaction between indigo and ozone causes the formation of isatin, inducing conspicuous colour changes in the exposed filter papers. The isatin content was assessed by spectrophotometry

**Table 1** The basic characteristic of research plots

	Forest plot Kremnické vrchy Mts	Open forest plot Kremnické vrchy Mts	Town plot Zvolen	Rural plot Štiavnické vrchy Mts
Latitude (Nord, East)	48° 38', 19° 04'	48° 38', 19° 04'	48° 34', 19° 07'	48° 35', 18° 51'
Exposition	W	SW	NW	NW
Altitude (m a.s.l.)	450	445	374	470
Slope (°)	17–20	17–20	0	5–8
Geological substrate	Andesites, tuffs	Andesites and tuff agglomerates	Andesites, sediments	Rhyolite tuffs
Soil type	Typical cambisol	Eutrophic andosolic cambisol	Typical fluvisol	Andic cambisol
Humus form	Acid mull	Acid mull	Not done	Not done
Group of forest types	Fagetum pauper inferiora	Fagetum pauper	-	Fagetum pauper superiora
Average temperature in VP (°C)	15.64	16.38	16.90	19.37
Precipitation in VP (mm)	39.09	66.73	66.69	57.83
Global radiation in VP (W)	23.87	139.78	140.75	157.49
Trees/age	Beech/100	Near beech and fir/100–110	Near Linden/100	Near beech and pine/110–80
Prevailing wind	Northern	Northern	Northern	Northern

VP vegetation period

at a wavelength of 408 nm. Paper extinction is proportional to the isatin content. The measured values reflect the ozone sums corresponding to the calibration curve. Papers in the collectors were exposed continually for 7–10 days. The research ran over the vegetation period from April 1st until September 30th, under full tree foliage (Schieber, 2006). Ozone maxima usually occur during this period. There were two passive ozone collectors placed on each plot, each at a height of 1.5 m above the soil ground. Then, the O<sub>3</sub> concentration values were given in the standard unit ppb. From these values, we calculated the average monthly O<sub>3</sub> concentration. The equipment for indigo paper exposition consisted of a roofed pole and a perforated protective cylinder (passive sampler), with the indigo-coated papers coated in a laboratory. This method is especially suitable for not-so-easily accessible localities, with lower demands on technical and financial costs, while it guarantees satisfactory precision comparable with continual measuring equipment (5% measuring error). Details can be found in Janík et al. (2015, 2020).

The individual GLO samplers were placed on four plots along an environmental gradient encompassing a forest, an open forest area close to the forest, a town

and a rural zone. The seasonal dynamics and variations in O<sub>3</sub> concentrations influenced by external factors were evaluated with the aid of our original linear model employing the generalised least square (GLS) concept (Littel et al., 1996; Pinheiro & Bates, 2000). The advantage of GLS is its power to analyse time series for which there is a high probability of the presence of time-related (auto) correlation and/or unequal variances.

The subsequent variance analysis applied to our model detected the relevance of the differences between the individual variance values, summarised in Table 2 and expressed graphically (average values predicted within 95% confidence intervals). The GLO concentration dataset was also subjected to a Holt-Winters time series filter (Holt, 1957; Winters, 1960) and to time series decomposition, specifying observed trends and seasonal and irregular components (Fig. 2a–d), with the aid of moving averages (Kendall & Stuart, 1983). The aim was to isolate the dominant seasonal O<sub>3</sub> concentration patterns.

Atmospheric precipitation was collected in funnels (each with a catchment area of 660 cm<sup>2</sup>) and driven into enclosed collectors. The sampling was carried out at regular intervals and after each precipitation episode. The samplers were spaced regularly on forest plots and in open areas.

**Table 2** Descriptive statistics of ground-level ozone in the Kremnické vrchy Mts., Zvolen and Žiar basin in the Štiavnické vrchy Mts. in years 2015–2020

	Years					
	2015	2016	2017	2018	2019	2020
Forest plot Kremnické vrchy Mts						
Mean	34.46	32.97	24.50	26.89	32.33	34.45
Minimum	23.47	20.66	14.44	9.02	25.97	16.18
Maximum	61.06	49.37	29.34	42.93	37.40	43.07
Std <sup>A</sup>	12.92	9.98	1.93	10.57	4.55	9.08
Vx% <sup>B</sup>	37.50	30.28	20.11	39.33	14.07	26.35
Open plot Kremnické vrchy Mts						
Mean	26.24	24.40	19.95	28.98	27.86	33.53
Minimum	18.64	4.43	13.23	12.10	23.60	23.19
Maximum	38.25	44.32	23.89	36.41	30.61	45.61
Std	6.94	12.13	3.59	8.27	2.56	7.56
Vx%	26.44	49.69	17.99	28.55	9.19	22.53
Town plot Zvolen						
Mean	22.15	17.79	8.86	23.50	16.21	17.80
Minimum	18.40	14.03	4.74	5.92	12.43	9.53
Maximum	38.25	25.75	12.79	40.40	20.46	26.61
Std	6.94	4.02	2.61	12.59	2.88	6.42
Vx%	20.08	22.57	29.46	53.57	17.79	36.05
Žiar basin, Štiavnické vrchy Mts						
Mean	28.07	23.15	16.45	18.16	23.87	26.31
Minimum	22.03	15.52	11.90	10.86	19.69	13.81
Maximum	38.73	43.75	20.25	30.36	30.98	35.38
Std	5.49	9.45	2.84	7.27	3.67	7.48
Vx%	19.56	40.82	17.29	40.05	15.38	28.44

<sup>A</sup>Standard deviation

<sup>B</sup>Coefficient of variation

The temperature data were provided by the SHMI station Sliach. The climatic characteristics were relevant for 2015–2020.

A very simplified assessment of the effects of selected meteorological variables was performed using correlation analysis.

All statistical procedures were performed in the “R” programming language environment version 3.6.3 (R Core Team, 2014) using the packages “nlme” version 3.1–152 (Pinheiro et al., 2021) and “forecast” version 8.15 (Hyndman & Khandakar, 2008; Hyndman et al., 2021). Graphic outputs were edited in Inkscape (Harrington, 2004).

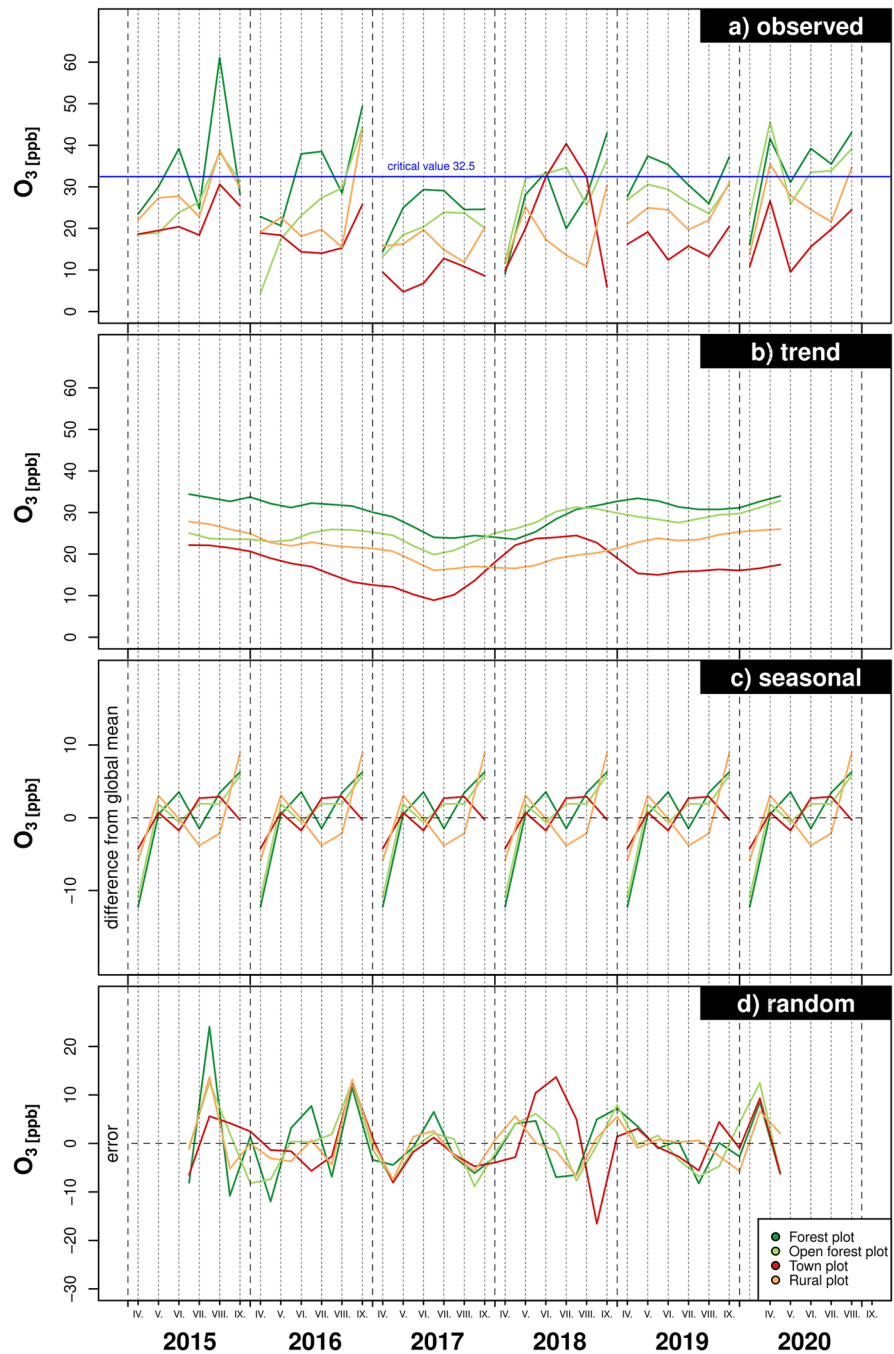
## Results

The highest GLO values, which were 30.93 ppb, were recorded in the forest stand. The maximum for

the whole research period was observed in August 2015, with a value of 61.06 ppb. The average values in the other research plots were lower, ranging from 17.72 to 26.83 ppb (Fig. 2a). In the adult forest stand, the ecological limit (32.5 ppb) established for ozone exceeded 14 times, mainly in autumn. In 2020, the only value not surpassing the threshold was measured in April, i.e., at the beginning of the growing season (16.18 ppb). The corresponding events on the other plots were less frequent, from three (in the town) to eight times (in the open forest plot). On all plots, the limit values were exceeded at least once, except in 2017. In this year, all the values measured on all of the plots were below the allowance limit (Table 2).

Diagnostics of the GLS model resulted in detecting considerable seasonal variability in the GLO concentrations ( $F=9.353$ ;  $p<0.001$ ) and large locality-dependent differences ( $F=22.893$ ;  $p<0.001$ ; (Table 2; Fig. 3).

**Fig. 2** Diagnostic of time series decomposition of ground-level ozone concentration in the Kremnické vrchy Mts., Zvolen and in the Žiar basin in years 2015–2020

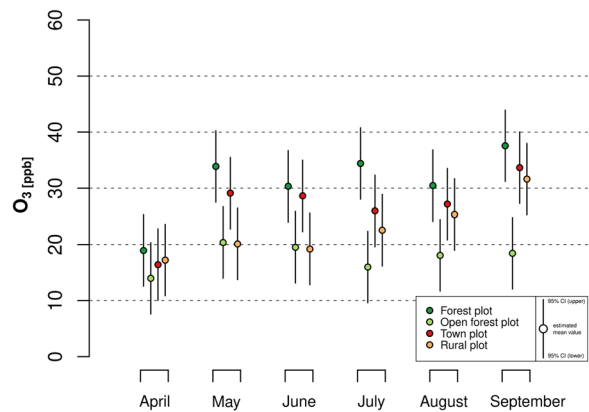


The diagnostics of time series decomposition indicated that the GLO concentration dynamics strongly differed along the environmental gradient, with the ozone concentration values being the highest in the forest areas and the lowest in the urban areas (with the exception of 2018). The significantly lowest GLO

concentrations occurred in April (in comparison to most of the other months).

From the research beginning in 2015 until 2017, the developmental trends of the GLO concentrations exhibited a decrease (Fig. 2b). The average values obtained for all plots in this year were the lowest,

**Fig. 3** Fitted values of average O<sub>3</sub> concentrations for different localities (environmental gradient from forest to urban area over the growing season (vertical lines visualise 95% confidence intervals, whereas overlaps of these intervals indicate non-significant differences)



ranging from 8.86 ppb in the town to 24.5 ppb in the forest. Then, there was an increase from 2017 to 2020, with relatively high values: from 17.8 ppb in the town to 34.45 ppb in the forest. The value measured in the town represented an increase of 100%. In the forest, the critical level of 32.5 ppb was exceeded in all months except April.

The variability in the GLO concentration deposition was lower in the forest environment in the Kremnické vrchy Mts., at just above 32%. The value in the town was 45% (Table 3). This result demonstrates that the GLO concentration production was also influenced by more climatic, chemical and environmental factors entering such complex biochemical processes as GLO formation.

The results of the correlation analysis and the values of the correlation coefficients (up to -0.48) showed that in the zone of submountain beech forests, global radiation, together with temperature, had a more significant effect on the formation of the GLO concentration than did the total precipitation (Table 4, Fig. 4). The average air temperature at the Kremnické vrchy Mts. research site in the forest ranged from 16.0 to 17.1 °C during the growing season. Compared to the long-term average of 14.8 °C reported from the meteorological station Sliač for the years 1961–1990, an increase was evident (Kubov et al., 2022).

**Discussion**

In accordance with Mangoni and Buffoni (2008), our study confirmed that the GLO concentration method (using passive samplers) is an appropriate tool for assessing the air quality at localities with

low technical and financial provisions. Moreover, this method guarantees that the results are obtained with sufficient precision. As such, the method is suitable for forests and not easily accessible localities. Such equipment can serve as an alternative for or ancillary to continual analysers in the case when a denser monitoring network is necessary (Sanz et al., 2007).

Research carried out in the High Tatras Mts. (Šabláturová & Bičárová, 1995) (measuring O<sub>3</sub> concentrations by using passive samplers and continual measuring equipment at the same time) exhibited a precision of ± 20% in real time. These results met the requirements set for ecological and environmental

**Table 3** Model GLS, the influence of the environmental gradient and seasonal dynamics on ground-level ozone concentrations

ANOVA (significance of terms)			
	numDF	F-value	p-value
<b>Intercept</b>	1	247.397	<0.001
<b>Locality</b>	3	22.893	<0.001
<b>Time (month)</b>	5	9.353	<0.001
Model diagnostics (estimates)			
	Coefficients	Std. error	t-value p-value
<b>Intercept</b>	30.932	1.866	16.573 <0.001
<b>Town plot</b>	-13.213	1.673	-7.897 <0.001
<b>Open forest plot</b>	-4.105	1.673	-2.453 0.0154
<b>Rural plot</b>	-8.264	1.673	-4.939 <0.001
<b>Time (month)</b>	8.359	1.673	5.769 <0.001

AIC, 974.199; BIC, 1006.157; logLik, -476.099

Correlation structure parameter estimate: Rho, 0.198

**Table 4** Correlation between ground-level ozone and radiation, air temperature and precipitation depth on the research plots in years 2015–2020

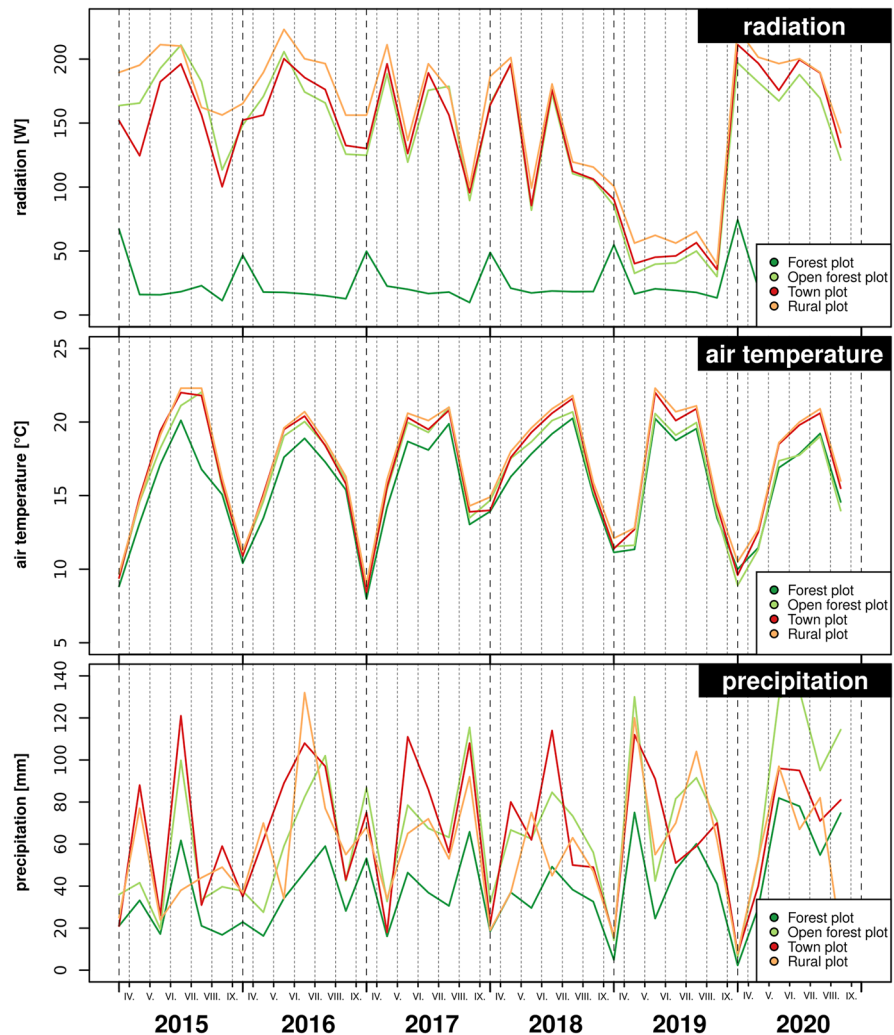
	Forest plot Kremnické vrchy Mts	Open forest plot Kremnické vrchy Mts	Town plot Zvolen	Rural plot Štiavnické vrchy Mts
Radiation	-0.48	-0.11	-0.04	-0.12
Air temperature	0.24	0.26	0.9	0.4
Precipitation depth	0.3	0.1	-0.04	0.02

studies, allowing differences of 15–20% between passive samplers and continual analysers (Krupa & Legge, 2000). Gerboles et al. (2006) demonstrated that passive samplers were in good accordance with the referential methods of the European Environment Health Safety (EC, 2002) guidelines, and they also fulfilled the requirements for O<sub>3</sub> monitoring

precision. The same conclusions were drawn for the Jizerské hory Mts. by Hůnová et al. (2016).

In our study, the highest average GLO concentrations were recorded in the adult forest stand in the Kremnické vrchy Mts. (Fig. 2a.). Furthermore, the lowest concentrations were measured in the town plot in Zvolen, with only 55% O<sub>3</sub> produced compared to

**Fig. 4** The radiation, air temperature and precipitation depth on research plots in years 2015–2020





the forest plot. The inter-plot differences were significant (Table 2), despite the short distances between them (the total transect length was almost 40 km).

Our results are comparable with the GLO values measured in polluted localities in southern Europe (Gerosa et al., 2007), Central Europe (Borowiak, 2013) and at higher altitudes (De Vries et al., 2014). In the Czech Republic, ppb values ranging between 38 and 39 have been observed over the course of several years (Hůnová & Schreiberová, 2012).

Considering the summary GLO concentration, this value also includes the BVOCs produced by vegetation, as they also act as significant precursors of their formation (Sicard et al., 2018).

Fitzky et al. (2019) stated that deciduous forests produced mainly isoprene (C<sub>5</sub>H<sub>8</sub>), and coniferous forests produced monoterpene (Kramer et al., 2010). According to Cortinovis et al. (2005), biogenic VOCs released by Mediterranean forests can significantly (up to 30%) affect GLO levels. The forest in our study area consisted mainly of *Fagus* sp. considered a strong producer of isoprene by Benjamin and Winer (1998) and, at the same time, is less affected by ozone stress (Göttlein et al., 2009). Lime trees and low vegetation grow in the immediate vicinity of the inner city, both emitting a large amount of BVOCs. This shows that the GLO levels in specific, especially urban, areas can be reduced by selecting and growing suitable trees that release low levels of BVOCs while ensuring their appropriate distribution and density (Calfapietra et al., 2013; Gu et al., 2021). In the case of forestland and open land approximately 50 m from the first, the corresponding difference was smaller, with a value 11% higher in the forest. The relations between BVOCs and GLO are complex, so it is not easy to specify the share of BVOC emissions in GLO formation (Calfapietra et al., 2013). Systems are also influenced by additional factors operating in the contexts of physiology, chemistry, meteorology and others (Paoletti et al., 2021).

Therefore, it is not possible to declare unequivocally that the GLO is primarily harmful to vegetation, in accordance with Jakovljevič et al. (2021). Cailleret et al. (2018) stated that no significant long-term effect of tropospheric ozone has been identified, explaining the current state and trend in the health state and production of forests in the Alps because the adaptation capability of these forests cannot be excluded. Together with Grote et al. (2019) and Cailleret et al. (2018), they stated that

important forest condition influencing factors are biotic and abiotic damage, nutrient cycling and locality. Nevertheless, it is necessary to separate the long-term and short-term effects of these factors.

Significant differences in the GLO concentrations between the plots were confirmed in the forest environment in the Jizerské hory Mts. by Hůnová et al. (2016), who observed differences in the O<sub>3</sub> levels between the stand interior and the stand edge. Despite a very small distance between the two environments (20 m), those differences were smaller by almost 14 ppb.

A study by Bičárová et al. (2016) implied that the seasonal dynamics of O<sub>3</sub> concentrations at high altitudes over Central Europe exhibited maxima: first in April and second in August, and usually, the second was higher than the first. Our research revealed that the same result may not be the case for lower situated localities, with the maximum average GLO values being 2015–2020 recorded in September. It is evident that the former spring GLO concentration peak shifted to the late summer or early autumn, which was also confirmed by Chevalier et al. (2007).

The episodes of high concentrations of BVOCs and GLO were mostly associated with high atmospheric pressure, characteristic high temperature, solar radiation power, low precipitation air flow and other factors.

A positive correlation between air temperature and photochemical processes in the atmosphere has been documented by several authors (Juráň et al., 2021; Hertig, 2020).

In our study, the influence of the mean temperature on the GLO concentration was not confirmed so explicitly. The correlation coefficient in the regression analysis was low in the open forest plot (0.26) and even lower in the other plots (Table 4). Similar values were obtained by Boletí et al. (2020), who found that the GLO concentrations were less sensitive to temperature and that the governing ozone formation factor was the amount of ozone precursors emitted in the air.

Air temperature is closely linked to global and solar radiation (Hůnová et al., 2019; García et al., 2021). Consequently, it can drive photochemical reactions at lower temperatures. In the forest stand, the maximum global radiation values were recorded in spring or in winter months in the absence of tree leaves.

Our research confirmed the highest impact of radiation on the forest plot (Table 4).

Other factors influencing the GLO levels in forests were air flow and air mass exchange. Insufficient air flow

in a forest with a completely closed canopy may cause GLO levels (at the given forest locality) to increase compared to the area without vegetation (Vranckx et al., 2015).

Wind disperses air pollutants and GLO precursors over long distances, where their photochemical transformation is possible. This may be one of the reasons for the occurrence of higher GLO concentrations in rural localities than in urban ones.

The occurrence of limit-topping values and the increasing trend of ozone concentrations in the final research years (2017–2020) showed progressive tendencies, despite the former trend, which decreased before 2017. The same has been confirmed in a study accomplished by Proietti et al. (2021). The authors reported that in 2000–2014, the production of ozone precursors was reduced and the ozone concentrations decreased over large areas of Europe. This fact reflected the legislative measures forced by the individual countries. However, Sicard et al. (2020) noted consequent increases in GLO concentrations, mainly in urban areas, despite the conspicuous drop in NO<sub>x</sub> emissions associated with the COVID-19 pandemic. GLO values above 32.5 ppb can exert negative impacts on vegetation (WHO, 2000).

All the discussed factors and proximity (2–5 km) of a busy motor way connecting the Adriatic and the Baltic Seas, as well as other factors not specified, influenced the creation and performance of GLO to various extents. Agathokleous et al. (2019) declared that the analysis of O<sub>3</sub> requires using an analytic approach working with nonlinear relations and regressions. However, linear regression in our study was employed with only one aim: to assign weights to the factors. Furthermore, forest and soil ecosystems are in themselves well working multi-components and appropriately structured systems. Consequently, it is not easy to assess their historical or seasonal trends. Realistic evaluation requires more time (Jonson et al., 2006) and a more sophisticated statistical approach (Paoletti et al., 2021).

## Conclusions

An analysis of the average annual concentrations revealed that values were high, with considerable seasonal variability. The spatial variability between the plots seems fairly level, partially due to their similar

altitudes. Serious and risky concentrations above the critical threshold of 32.5 ppb were recorded for all plots, with the exception of the plot situated in the town.

The GLO concentration trends decreased from 2015 until 2017. In this year, we recorded the lowest GLO concentrations from all of the study plots. Since 2017, however, an evident increase has followed: in 2020, the GLO concentration value in the forest was 41% higher and 100% higher in the town than in 2017.

The main factors definitely influencing the GLO concentration were stand age, tree species composition and density. For silvicultural measures, global radiation is an important climatic factor. The highest GLO concentration was measured in the original beech stand; the GLO deposition load in the town's centre was the lowest. The value recorded in rural areas in the Žiar basin, exposed to the most serious airborne pollution, was near the centre of this interval.

**Acknowledgements** The authors wish to thank to Dr. Dagmar Kúdelová for translating and to Barbora Janíková and Jamie Ley Williams for correcting the English of the manuscript.

**Author contribution** The authors equally contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

**Funding** This research was supported by the Science Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Sciences (VEGA), project no. 2/0050/21.

**Data availability** The datasets analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

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