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Spatio-temporal variations of cave-air CO_2 concentrations in two Croatian show caves: natural *vs*. anthropogenic controls

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Abstract

Carbon dioxide (CO_2) concentration (CDC) plays an important role in karst processes, governing both carbonate deposition and dissolution, affecting not only natural processes, but also human activities in caves adapted for tourism. Its variations due to various controlling parameters was observed from 2017 to 2021 in two Croatian show caves (Manita peć and Modrič) where we examined inter- and within-cave correlation of internal aerology regarding the sources, sinks and transport mechanism of CDC in a karst conduit setting. In both caves, the main sources of CO_2 are: i) plant and microbial activity i.e. root respiration and organic matter decay within soil horizons and fractured epikarst, and ii) degassing from CO_2-rich percolation water. The main sink of CO_2 is dilution with outside air due to cave ventilation. Chimney-effect driven ventilation controlled by seasonal differences between surface and cave air temperatures shows winter ($T_{out}<T_{cave}$) and summer ($T_{out}>T_{cave}$) ventilation regime, which are modulated by the geometry of cave passages, the transmissivity of the overlying epikarst, and occasionally by the external winds, especially the gusty north-eastern bora wind. In these terms, the Modrič Cave appears to be more confined and less ventilated, with a substantial CDC difference between the left (550-7200 ppm) and right (1475- >10,000 ppm) passages. The Manita peć Cave is, in contrast, ventilated almost year-round, having 7 months of CDC equilibrated with the outside atmosphere and the highest summer CDC values of ~1415 ppm. In both caves, at the current level of tourist use, anthropogenic CO_2 flux is not a matter of concern for cave conservation. In turn, in the innermost part of the right Modrič Cave passage visitors' health might be compromised, but the tourists are allowed only in the left passage.

Speleothem growth rate, recognized as a useful palaeoenvironmental proxy for speleothem-based palaeoclimate studies, strongly depends on CDC variations, so the high CDCs recorded in the Modrič Cave indicate the potential periods with no speleothem deposition due to the hampered degassing of CO_2 from the dripping groundwater. The opposite effect i.e. enhanced ventilation (that supports calcite precipitation) during the windy glacials/stadials, as well as substantial vegetational changes must also be taken into consideration when interpreting environmental records from spelean calcite.

Keywords: show cave, CO_2, cave ventilation, anthropogenic impact, Croatia

1. INTRODUCTION

Caves are natural underground voids formed predominantly by the dissolution of soluble (mostly carbonate) bedrock and they act as natural windows to the Earth's Critical Zone (ECZ). The ECZ is a relatively thin, but extremely heterogeneous zone that extends from the bottom of the groundwater body to the uppermost parts of the surface vegetation in which life can be sustained by coupled chemical, biological, physical and geological processes (BRANTLEY et al., 2007) and which is most exposed to environmental changes. The natural functioning of this system is strongly regulated by climate and associated hydrological and vegetational changes which can be reliably archived within speleothems (REGATTIERI et al., 2019). Therefore, speleothem-based research is increasing globally (COMAS-BRU et al., 2020), complemented by the monitoring of cave properties such as hydrogeology, hydrogeochemistry, microclimate, cave air composition, etc., the understanding of which is essential for the appropriate interpretation of the palaeoenvironmental signals recorded in spelean carbonate.

Although it is just a trace gas in the atmosphere (416.49 ppm in May 2021, NOAA accessed on 30 August 2021), CO_2 plays an important role in the overall Earth system, especially when misbalanced from the natural state. On an incomparably smaller scale, CO_2 in cave air is, in an underground environment, also important and interesting for its various sources, sinks and effects that occur with or without human interaction. Generally, CO_2 partial pressure is one of the most important factors that controls both carbonate dissolution and speleothem deposition (DREYBRODT, 1999) and the understanding of CO_2 distribution and dynamics in the underground is essential for various aspects of cave science including the aforementioned speleothem-based palaeoclimate studies (BALDINI et al., 2008; COWAN et al., 2013; GREGORIČ et al., 2013). Cave air CO_2 concentration (CDC) is controlled by dynamic equilibrium between different CO_2 sources and sinks and their competing influences depending on both spatial and temporal particularities of the cave environment. The main natural sources of underground CO_2 are: i) diffusion of CO_2-rich air generated by root respiration and organic matter decay transmitted from the soil through the joints and fissures, ii) degassing from the groundwater which was enriched by CO_2 on its way through the soil and epikarst, iii) biological productivity i.e. decomposition (micro-organisms feeding on organic matter, usually guano) within the cave, and iv) deep-seated (thermal) geogenic sources (BALDINI et al., 2008; FAIRCHILD & BAKER, 2012; PRELOVŠEK et al., 2018). In addition to the aforementioned natural sources, show caves may receive extra anthropogenic CO_2-flux from visitors breathing (e.g. DRAGOVICH & GROSE, 1990; LIÑÁN et al., 2008). The most substantial sinks of cave air CO_2 are: i) ventilation i.e. dilution of the CO_2-rich cave air with relatively CO_2-poor outside air, and ii) uptake by groundwater i.e. CO_2 dissolution in under-saturated cave water (COWAN et al., 2013).

Elevated cave air CDC, increased either naturally or anthropogenically, may affect the cave environment in several ways. First, when percolating groundwater (in which CO_2 is controlled predominantly by soil pCO_2) reaches the air-filled voids, equilibration with lower pCO_2 cave air occurs and degassing of CO_2 can cause calcite precipitation from the water saturated with respect to calcite (HOUILLON et al., 2017). However, elevated pCO_2 in cave air can hamper degassing of CO_2 from the dripping groundwater resulting in either the absence or cessation of calcite deposition (BALDINI et al., 2006; 2008). Second, cave air CO_2 dissolved in water condensed within the cave produces carbonic acid which may dissolve bedrock or already crystallized spelean calcite, a process known as condensation corrosion (DUBLYANSKY & DUBLYANSKY, 1998; FAIMON et al., 2006; BALDINI et al., 2006; GABROVŠEK et al., 2010). Thirdly, high cave air CDC values are related to health issues, so already a CDC of 5000 ppm is regarded as the occupational exposure limit (ILO, 2006), and it must be considered for all visitors in show caves, including tourists, guides, cavers and scientists. The majority of caves have elevated CDCs, usually in summer, which in some cases reach extremely high values, such as ~14,000 ppm in the Romanian Urșilor Cave (CONSTANTIN et al., 2021), ~22,000 ppm in Galeria das Lâminas, Portugal (BENSON et al., 2021), ~35,000 ppm in Béke Cave, Hungary (CZUPPON et al., 2018), ~31,000 ppm in District Park Cave and ~38,000 ppm in Natural Bridge Caverns in the USA (COWAN et al., 2013), even up to >44,000 in Chauvet Cave (BOURGES et al., 2020) and ~60,000 ppm in Causse d'Aumelas (BATIOT-GUILHE et al., 2007) in France. In Croatia, the first records of elevated CDC were published by MALEZ (1954) and BOŽIČEVIĆ (1966), and afterwards numerous occurrences of high CDC have been reported by cavers, but systematic monitoring began only in 2016 within 5 show caves in the continental part of Croatia (BOČIĆ & BUZJAK, 2018).

Here, we present the first results of multi-year monitoring of the cave environment aimed at estimating spatial and temporal variations of cave air CDC in two show caves located in the coastal zone of the Dinaric karst in Croatia – the Manita peć and Modrič caves, both considered to be small and simple caves with relatively low numbers of visitors. The obtained data sets enabled us to: i) reveal cave ventilation dynamics in order to detect possible seasonal speleothem growth patterns crucial for palaeoenvironmental studies; ii) estimate the anthropogenic contribution to the cave CO_2 background levels and potential effects on the cave interior, and iii) assess the possible health hazard for the visitors from an elevated CDC.

2. STUDY SITE

The Dinaric karst in Croatia is characterized by relatively high mountain ranges (up to 1831 m) stretching parallel to the coast, one of which is Velebit Mountain – the host of the two studied caves. Modrič Cave is located in its foothill at 32 m a.s.l., while the entrance of Manita peć Cave is at 570 m a.s.l., on the side of the canyon perpendicular to the mountain range (Fig. 1). Given their geographical position and geological settings, some specific meteorological features (e.g. bora events) are expected to influence the cave atmospheres i.e. ventilation.

The Modrič Cave (44° 15' N, 15° 32' E) is situated 120 m from the shoreline on the SW slope of the central part of Velebit Mountain. The cave is formed within a 2.5 km wide fault zone, in well-bedded Upper Cretaceous limestone (MIKO et al., 2002), and consists of two, mostly horizontal, passages with a total length of 829 m and a single narrow entrance (KUHTA et al., 1999). Overlying bedrock is 1-27 m thick and vegetation cover above the cave is sparse trees, bush and grassland. Soon after its discovery in 1985 and an initial topographic survey, Modrič Cave came to the attention of various scientific disciplines and has since become one of the most investigated Croatian caves (SURIĆ, 2018). Palaeontological research of Quaternary vertebrate faunal remnants (MALEZ, 1987; AGUILAR et al., 2004) was followed by a thorough speleological and geological survey and partial geochemical and hydrogeological investigations (KUHTA et al., 1999); the geochemical aspect was focused on sediments, percolating water and bat guano influences (MIKO et al., 2001; 2002). Because the cave has been open for adventure tourism since 2004, radon activity in the cave air was occasionally monitored (BUZJAK et al., 2010; SRŠEN, 2019). For the purpose of palaeoclimate reconstruction, thorough microclimate monitoring, along with speleothem and dripwater stable isotope analyses, were conducted in several campaigns from 2003 onwards (SURIĆ et al., 2010; 2017; 2020; RUDZKA et al., 2012).

The Manita peć Cave (44°18' N, 15°28' E) is located on the steep flank of the Velika Paklenica canyon carved perpendicularly into the Velebit Mountain. It is a simple, 175 m long, descending spacious chamber formed in Upper Jurassic limestone, with a height up to 38.5 m and total volume of 67,510 m^3 (KUHTA, 2010). The overburden is up to 80 m thick and heavily fractured. Ground surface cover is sparse patches of terra rossa, shrubs and grass. Scientific interest for this cave had already begun in 1900 with the first biospeleological investigation, followed by geological and speleological surveys in 1929, which also included preliminary notes on its microclimate and hydrogeology. Due to its rich speleothem formations, in 1937 it was adapted for visitors with construction of the first pathway and a new artificial entrance (Action Plans National Park Paklenica, 2007). In the following decades the cave has been the site of occasional environmental research projects, one of which was the monitoring of radon activity in the cave atmosphere (RADOLIĆ et al., 2012). This was fundamental for assessing the health and safety of visitors and guides.

Although both caves are open for visitors, there is a significant difference in the approach to touristic management between them. Modrič Cave is available for individually arranged visits year-round, but the peak numbers of visitors occurs between April and October, with an annual maximum of 727 visitors in 2019. Organized as an adventure tour with caving equipment, visitors in groups of up to 30 people spend approximately 1.5 to 2 hours within the left passage of the Modrič Cave. Manita peć Cave operates as a "classical" show cave with guided tours and no need for special equipment. According to the current timetable, during the summer (July, August, September), Manita peć Cave is open every day, then three days a week through the late spring and early autumn (May, June, October), finally in April only one day per week. It is closed for visitors during the winter season, except for organized groups on demand. In order to minimize anthropogenic impact, it has been open just for three hours per day, except during 2017-2018 when it was open for 4 hours per day. A maximum of ~13,000 visitors per year was reached in 2017. The usual visiting time in Manita peć Cave is up to 30 minutes for groups of 25-30 visitors.

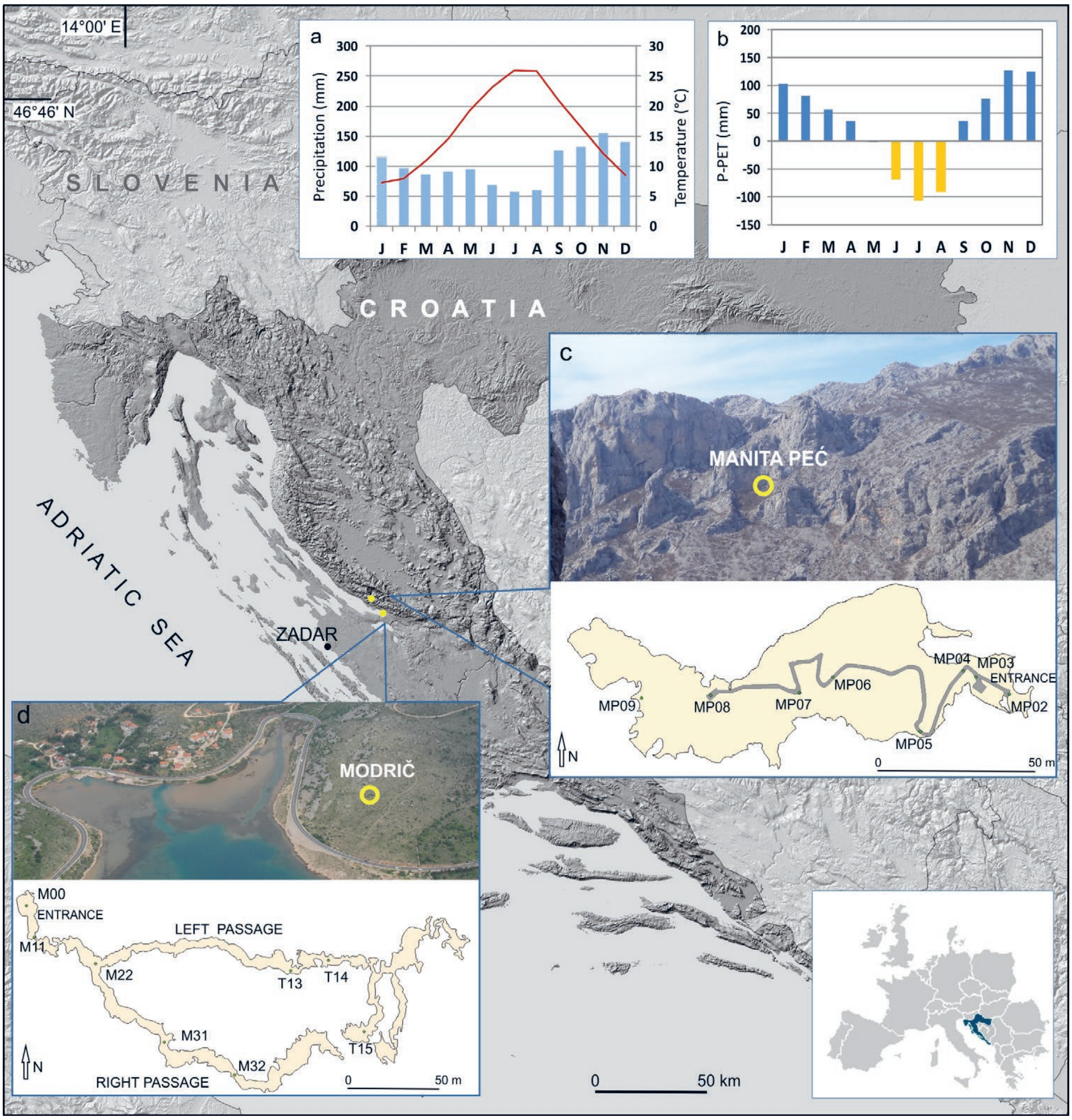

Figure 1. Study area with cave locations and basic climatic data for the meteorological station in Starigrad Paklenica (ca. 4 km SW of the Manita peć Cave and ca. 9 km NW of the Modrič Cave) for 1992-2018: a) air temperature and precipitation; b) difference between precipitation and potential evapotranspiration (Croatian Meteorological and Hydrological Service /CMHS/, 2021); c) east-facing entrance of Manita peć Cave and the plan with measurement points; d) north-facing entrance of Modrič Cave and the plan with measurement points. Water balance (potential evapotranspiration) was calculated using the Thornthwaite evapotranspiration model (THORNTHWAITE, 1948; MCCABE & MARKSTROM, 2007).

3. METHODS

Monitoring of cave air CDC was conducted in Modrič Cave from March 2017 to March 2021 in the right passage and from July 2018 to March 2021 in the left passage. In Manita peć Cave CDC monitoring covered the period between January 2018 and March 2021. Measurements were performed on a monthly basis using a *7755 AZ Handheld CO_2 & Temperature & Relative Humidity Meter* (CO_2 range 0-9999 ppm; resolution 1 ppm; accuracy ±50 ppm or ±5% of reading (0-2000 ppm); air temperature range -10-60 °C; resolution 0.1 °C; accuracy ±0.6 *°C*). The measurements were carried out at the beginning of each month, on the same day in both caves. Along with regular monthly monitoring, CDC was measured on several occasions before and after tourist group visits (usually 20-30 people) in spring and summer, to assess anthropogenic impact on the cave air properties. Eight measurement points were established in Manita peć Cave, and 7 in Modrič Cave, distributed at approximately even distances from the entrance to the innermost parts, with additional measurement points in front of each cave (Figs. 1c &1d).

Additionally, in the Modrič Cave's right passage, air temperature and relative humidity were also continuously recorded (1-hour intervals) using Onset Hobo® PRO-V2 U23-001 data loggers (T range -40 to 70 °C; accuracy ±0.25 °C from -40 to 0 °C; ±0.2 °C from 0 to 70 °C; resolution 0.04 °C; RH range 0 to 100%, accuracy ±2.5% from 10% to 90% RH, ±5% <10% or >90% RH, resolution 0.05%). External temperatures and precipitation data were obtained from the Croatian Meteorological and Hydrological Service (CMHS) for the station in Starigrad Paklenica (ca. 4 km SW from Manita peć Cave and ca. 9 km NW from Modrič Cave). However, due to the station's technical failure, from December 2018 onwards, data for the station in Novigrad (ca. 16.5

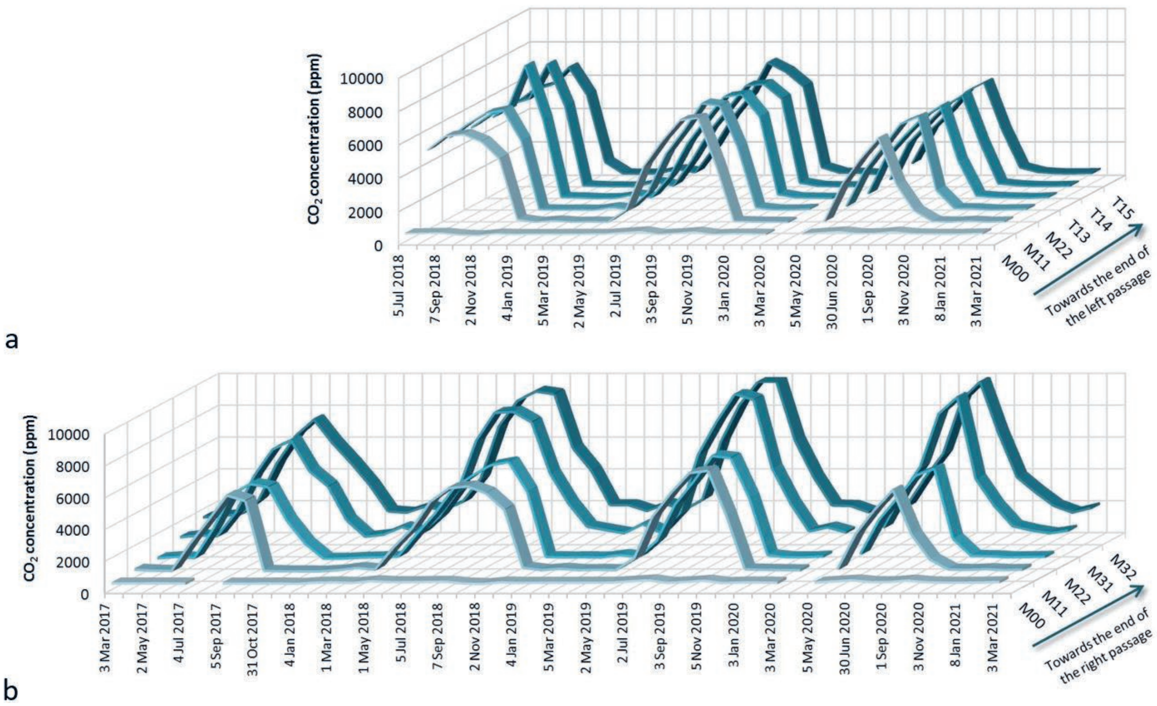

Figure 2. Variation of CO_2 concentrations along a) the left passage (July 2018 - March 2021) and b) the right passage (March 2017 - March 2021) of the Modrič Cave. Note that both plots contain the same values for the first three measurement points, i.e. exterior point M00 and main passages' points M11 and M22.

km SE from Manita peć Cave and ca. 8 km S from the Modrič Cave) was used instead. Both stations share similar topographic location and climate properties, so no significant changes in data representativeness are expected.

4. RESULTS

4.1. Spatio-temporal variations of the cave air CO_2 concentration

Spatial and temporal variations of Modrič Cave air CDC are presented in Fig. 2 and the complete data set is provided in Tab. 1A in the Appendix. At the first measurement point M00 in front of the cave, during the period between March 2017 and March 2021 we recorded CDCs from 350 ppm to 590 ppm. Cave air CDC of the main passage measured at points M11 and M22 varied between 412 ppm and 6868 ppm; similar to that in the left passage, values between 480 ppm and 7228 ppm were recorded at points T13, T14 and T15. Meanwhile, along the right passage, at measurement points M31 and M32, the CDC range was from 994 ppm to >10,000 ppm (i.e it exceeded the measurement limit of instrument).

Spatio-temporal variations of cave air CDC in the Manita peć Cave between January 2018 and March 2021 are given in Fig. 3 and in Tab. A2 in the Appendix. The first measurement point (MP 01) was ~100 m away from the cave entrance at the most exposed part of the mountain slope, at the lookout, and provides values of the outside CDC, while point MP 02 was at the very entrance of the cave, right in front of the gate bars with a CDC range of 339-664 ppm (Fig. 4). The remaining measurement points (MP 03 – MP 09), which were distributed evenly along the descending channel, had CDC values ranging between 325 ppm and 1415 ppm.

Temporal variations of CDC in both caves are seasonal, with the highest values in summer/autumn, and the lowest during the winter/spring, which is the opposite of natural atmospheric CDC fluctuations (Pearman & Hyson, 1981). Namely, due to the phytoplankton bloom and plant photosynthesis in the warmer part of

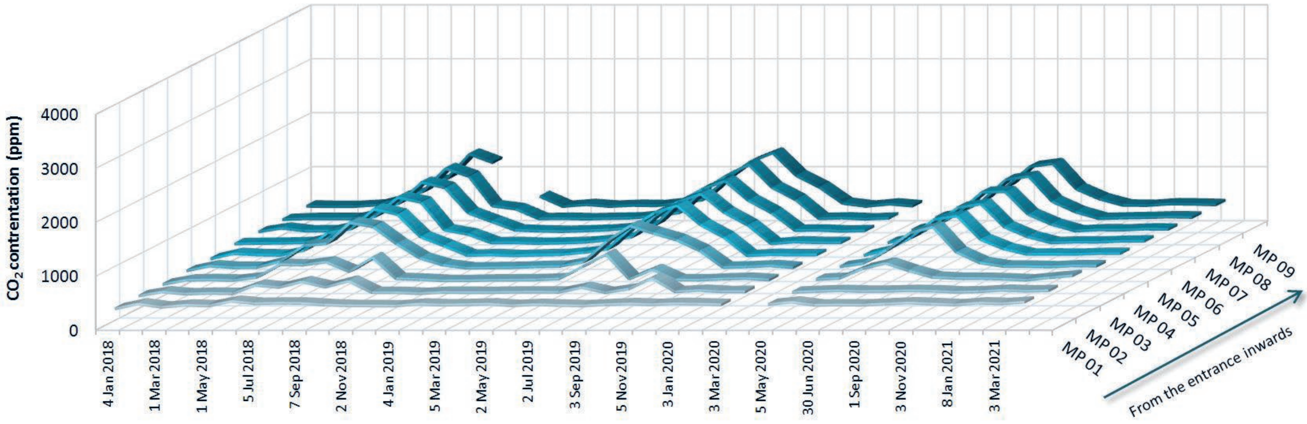

Figure 3. Variation of CO_2 concentration in the Manita peć Cave (January 2018 – March 2021).

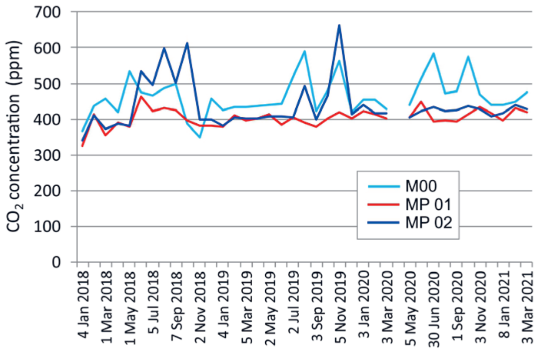

Figure 4. Variation of air CO_2 concentration in the vicinity of the cave entrances; measurement point M00 was several metres in front of the Modrič Cave, MP 01 was at the lookout ~100 m away from Manita peć Cave and MP 02 was at the very gate of the same cave. Note the relatively invariant MP 01 values in relation to the covariance of M00 and MP 02.

Table 1. Effect of groups of visitors on air CO_2 concentration (in ppm) measured before and immediately after the visitor groups in Manita peć Cave and in the left passage of the Modrič Cave, in spring and summer seasons. Only locations with longer tourists' residence time are considered. For measurement points, see Fig. 1.

	Modrič Cave			
Measurement point	6 April 2018		20 July 2018	
	Before	After	Before	After
M11			5169	5178
M22	588	705	5132	5172
T13	575	715	5068	5158
T14	594	761	5034	5044
	Manita peć Cave			
Measurement point	1 May 2018		1 August 2018	
	Before	After	Before	After
MP03	452	577	740	1230
MP04	524	600	1243	1246
MP05	505	614	1270	1257
MP06	512	607	1259	1267
MP07	510	602	1315	1317
MP08	502	612	1346	1313

the year, CO_2 is absorbed from the atmosphere, so the CDC in the northern hemisphere decreases, while in autumn decaying plants release their CO_2 back into the atmosphere, which along with elevated fossil fuel consumption leads to an atmospheric CDC increase. Surprisingly, the CDC variations in the surface air in front of our studied caves at M00 and MP 01 do not follow that pattern. Instead, they coincide with in-cave CDC variations, as demonstrated in Fig. 4, showing the influence of the in-cave environment on the nearest surroundings.

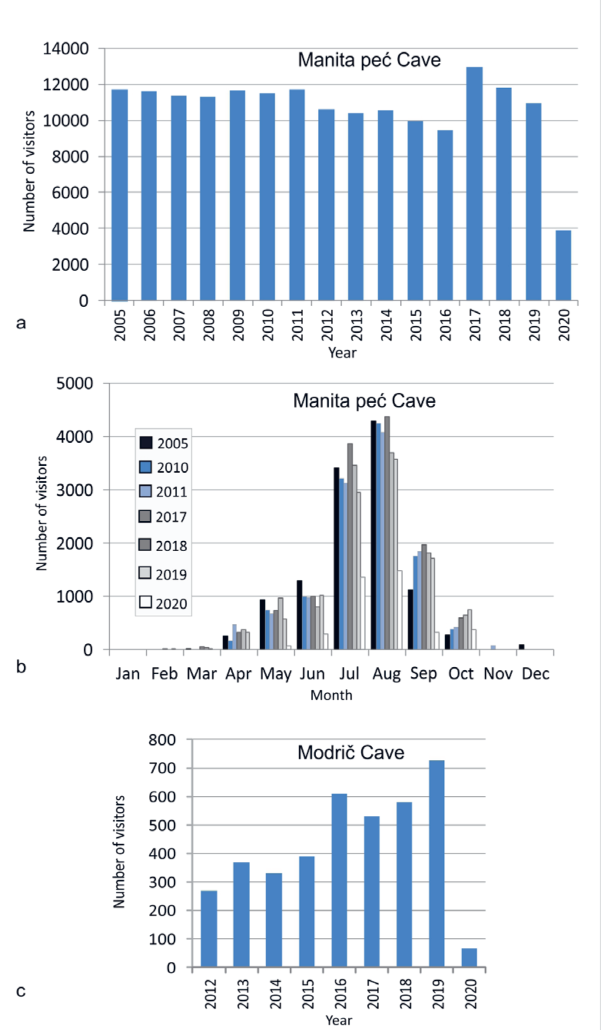

Figure 5. Number of visitors a) annually in Manita peć Cave (2005-2020); b) monthly distribution in Manita peć Cave, and c) annually in Modrič Cave (2012-2020). Note the significantly different y-axes scales in a and c. Sudden decrease of number of visitors in 2020 reflects the COVID-19 pandemic. (Sources: NP Paklenica for Manita peć Cave and M. Buzov, pers. comm. for Modrič Cave).

4.2. Visitor numbers and their impact on cave air CO_2 concentration

The total annual numbers of visitors in the caves are given in Figs. 5a and 5c, and the monthly distribution of the Manita peć Cave visitors is presented in Fig. 5b. The highest annual values reached in 2017 and 2018 are due to the prolonged working hours (4 hours per day instead of 3 hours) of Manita peć Cave, and the sudden decrease of visitor numbers in both caves is a direct response to the COVID-19 pandemic.

Measurements of CDC before and after groups of tourists were conducted in spring and summer season at the sites where the visitors pause for the sightseeing or explanations, and the results are given in Table 1. During the spring season, the increase of CDC measured immediately after the groups was 14-22% and 20-28% for Manita peć Cave and Modrič Cave, respectively. However, due to the relatively low initial CDC, absolute values after the visitors are still within safety limits. High CDCs in the summer season remained after the visitors at similar levels, ~1250 ppm in Manita peć Cave and ~5100 ppm along the left passage of Modrič Cave. The exception was measurement point MP03 in Manita peć Cave with an increase of 66% (from 740 ppm to 1230 ppm), but due to its location near the entrance, the CDC probably quickly reduced to the previous values.

5. DISCUSSION

Distribution and variations of cave CO_2 are controlled by an interplay of different sources and sinks and their spatial and temporal evolution, which are in the case of Modrič and Manita peć caves, relatively simple. There are no underground rivers or geogenic sources of CO_2, and in-cave decomposition of organic matter does not play an important role, since there are no large de-

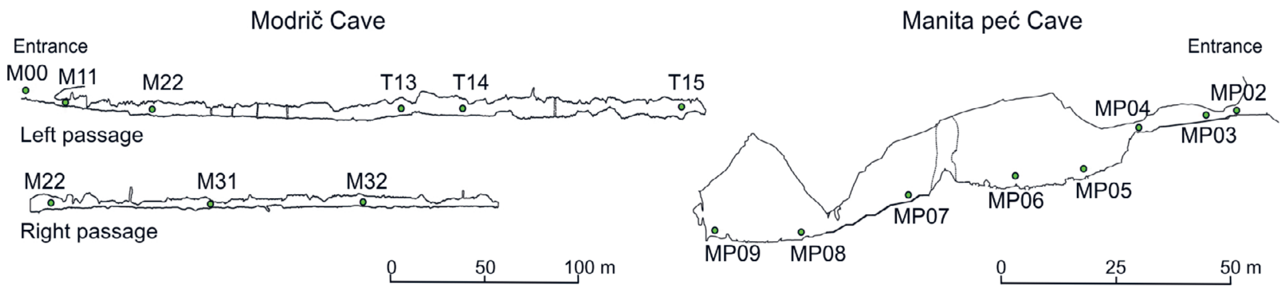

Figure 6. Cross section of Modrič and Manita peć caves with marked measurement points.

posits of organic matter such as guano. The main factors controlling CDC are transport of CO_2-rich air from the soil horizon and epikarst, along with CO_2 degassing from drip water, and its dilution by the external CO_2-poor air, i.e. cave ventilation (EK & GEWELT, 1985). Cave ventilation dynamics follow several patterns controlled predominantly by seasonal temperature variations, cave morphology, and potentially by anthropogenic CO_2-flux, while the ventilation itself is mainly triggered by differences between outside (T_{out}) and cave air (T_{cave}) temperatures (SPÖTL et al., 2005; BALDINI et al., 2006), and wind (RIECHELMANN et al., 2019; KUKULJAN et al., 2021). These particular features are discussed bellow.

5.1. Impact of cave morphology and epikarst structure on spatial CDC variations

Substantial differences between the Modrič and Manita peć cave morphology are depicted in their cross sections (Fig. 6). Modrič Cave is almost horizontal except for the small descent near the entrance, and a short ascent at the beginning of the right passage. Although relatively similar in dimensions, the two passages differ by their accessibility. Along the left passage during the winter time, there are only small variations of CDC, with values <100 ppm higher that those outside the cave (Fig. 7a). Similarly, CDC values are also relatively evenly distributed in the summer-autumn season (Fig. 7b), which is likely caused by unobstructed movement of the air through the left passage due to its larger dimensions compared to the right one. In the right passage, CDCs are substantially higher both during the warm and cold seasons, and spatial variations are more pronounced. The entrance section of the right passage (after M22) is only slightly ascending, but obviously enough to prevent or at least mitigate the inflow of the cool outside air during the cold season. Additionally, the more diverse morphology of the right passage with several smaller chambers connected by narrow corridors makes this passage more constrained. An abrupt increase in CDC occurs ca. 50 m inside the passage, which is in accordance with the findings of BALDINI et al. (2006) and MILANOLO & GABROVŠEK (2009) who generally recorded such sudden increases in CDC right after constrictions in their studied caves.

There is another difference in the spatial distribution of CDC between the two passages in the Modrič Cave. The left one has evenly distributed either summer (higher) or winter (lower) CDC values throughout the whole passage, while in the right passage the CDC values increase towards the end (Fig. 7). This partially reflects the structure of the overlying bedrock, which is apparently more fractured, and hence easily ventilated, due to the fault zone along the left passage. The sets of small stalactites and sodastraws in the second part of this passage additionally point to the matrix porosity (FAIRCHILD & BAKER, 2012) of that part of the cave and can be regarded as a *macrofissural network* cf. BOURGES et al. (2006), defined as fissures of less than 1 mm aperture which transfer both rainwater and CO_2-rich soil air towards the cave. Conversely, the bedrock of the right passage is more compact, or maybe even sealed by the spelean carbonate which is also reflected in more homogenous drip rates, sometimes unresponsive to surface rain events (SURIĆ et al., 2018). The apparent differences of the atmospheric regimes in the relatively similar passages underline that the volume of the critical zone involved in the control of in-cave atmosphere is much larger than the volume of the underground chambers and includes also the voids of the surrounding karstified bedrock (BOURGES et al., 2006).

On the other hand, the Manita peć Cave consists of one large descending chamber that begins with two relatively large openings (1.7×2.5 m and 1.3×2.0 m), and the height difference from the entrances to the lowest point of the cave is 35 m. In addition, heavily fractured overlying bedrock detected in some places by the immediate rain fracture-flow infiltration (SURIĆ et al., 2017),

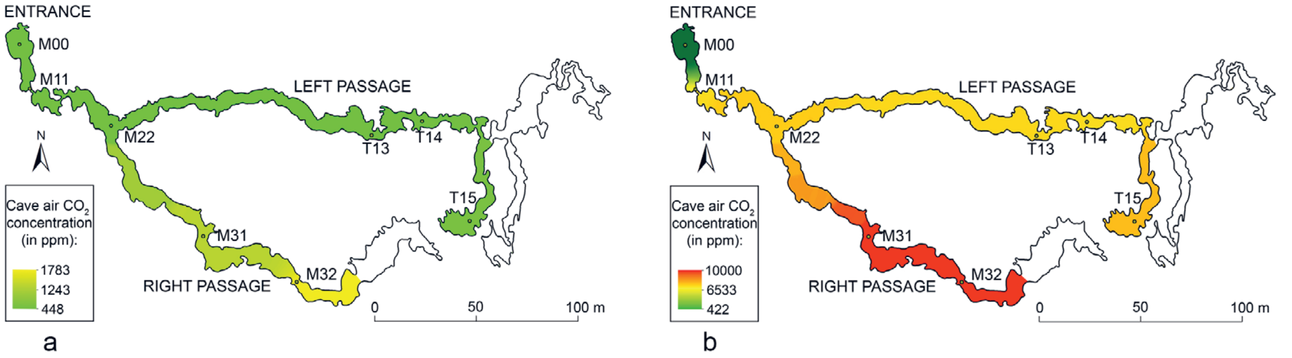

Figure 7. Spatial distribution of cave air CO_2 concentration in Modrič Cave passages during the: a) winter season – measured 1 February 2021; b) summer season – measured 3 September 2019.

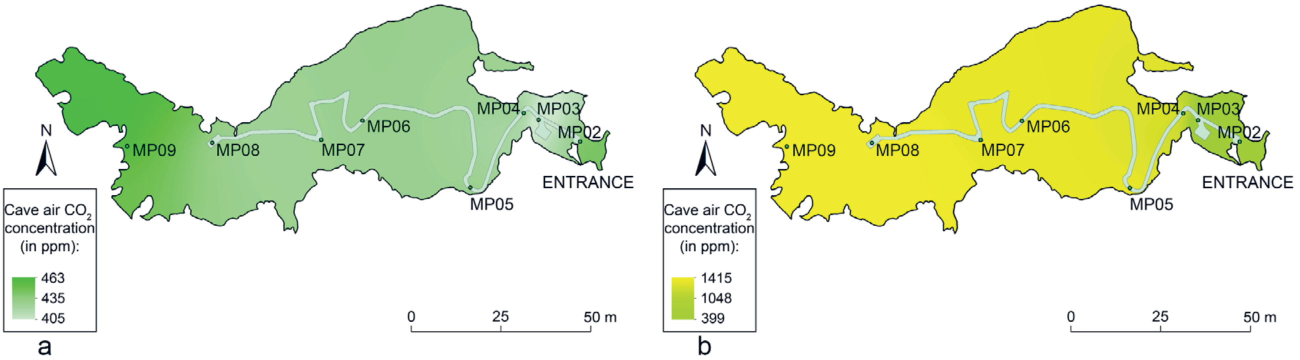

Figure 8. Spatial distribution of cave air CO_2 concentration in Manita peć Cave during the: a) winter season – measured on 1 February 2021; b) summer season – measured on 3 September 2019.

enables considerable air circulation via epikarst. Given the fulfilled prerequisites for significant ventilation, the spatial variations of CDC remain relatively minimal, particularly during the winter when cold air descends into the cave and CDC values within the cave are practically equal to the external ones (Fig. 8a). Summer spatial CDC variations are also relatively small (the maximum recorded value was 1415 ppm), specifically when compared to those in Modrič Cave. For the summer CO_2 distribution, the vertical dimension of the cave plays the leading role, with the inflow of the outside air being obstructed by the cold and dense air trapped at the cave bottom. This phenomenon has already been identified in the Manita peć Cave by the pocket of cold air having a year-round stable temperature of 9.0 °C ($1\sigma=0.4$ °C), while the external mean annual air temperature (MAAT) in front of the cave was 13.7 °C (2014-2015) (SURIĆ et al., 2017). Such a stable thermal stratification during warm periods in aerodynamically closed *cold trap* systems has been discussed in e.g. BOURGES et al. (2006), LUETSCHER et al. (2008), MILANOLO & GABROVŠEK (2009) etc.

5.2. Temporal controls of the cave air CO_2 concentration

Temporal variations of CDC given in Tabs. A1 and A2 and presented in Figs. 2 and 3 point to the strong seasonal mode in both studied caves. Given the constant air cave temperature, during the warm season the cave air temperature is lower than outside, and during the cold season the situation is the opposite. Correlation between ΔT ($T_{out} - T_{cave}$) and CDC implies that air temperature differences govern the air density gradients between the outside and cave air and also control air exchange i.e. ventilation (FAIRCHILD & BAKER, 2012). Studies conducted in caves with a comparable temperature regime and morphology in Germany (Bunker Cave; RIECHELMANN et al., 2019), Puerto Rico (Cueva Larga; VIETEN et al., 2016) and Bosnia and Herzegovina (Srednja Bijambarska Cave; MILANOLO & GABROVŠEK, 2009) revealed the same driving mechanism of seasonal CDC variations; that is ventilation driven by an air density gradient between external and cave air. Such circulation is known as a chimney effect, usually ascribed to the caves with two or more entrances at different altitudes (FAIRCHILD & BAKER, 2012). During the summer, warm surface air enters the cave via an upper entrance, cools down and with increased density it descends and emerges at a lower entrance as cold cave air. In winter time, cold dense outside air inflows through the lower entrance, warms up and, because it is less dense, appears at the upper opening (SPÖTL et al., 2005). Despite the fact that our studied caves have only one passable entrance, the chimney effect can be attributed to them, particularly to the Modrič Cave since it has only 2-30 m overburden thickness of faulted and heavily fractured limestone bedrock, which practically acts as an upper entrance. Therefore, we identified two ventilation regimes and associated CDC variation patterns:

– summer: with $T_{out}>T_{cave}$ – warm surface air on its way through the epikarst is enriched by CO_2, downdraft occurs and cool cave air flows outwards from the caves, as proven by measured elevated CDC in front of the caves (Fig. 4).

– winter: with $T_{out}<T_{cave}$ – cool CO_2-poor outside air flows into the cave and decreases CDC within the caves, leading even to the complete equalization of CDC throughout the whole Manita peć Cave for seven months (Fig. 3).

Variations of temperatures and CDCs shown in Figs. 9 and 10 provide an insight into the periods of transition between $T_{out}>T_{cave}$ and $T_{out}<T_{cave}$ considered to be crucial for the behaviour of the cave CDC (LIÑÁN et al., 2018), additionally modulated with some site-specific features related to the geometry of the caves, wind etc. Generally, such thermal convective instability (BOURGES et al., 2006) with changes in cave air CDC was argued to occur rapidly and at precisely the time when the difference in temperature between the surface and cave air reverses sign (FRISIA et al., 2011). However, in the Postojna Cave it was shown that reversal from updraft to downdraft airflow occurs even while T_{cave} is more than 10 °C higher than T_{out} (KUKULJAN et al., 2021). In the Modrič Cave, in autumn when T_{out} drops below T_{cave} the decreasing trend of the CDC closely follows that of the T_{out}, apparently due to the strong inflow of the dense external CO_2-poor air into the cave. However, spring conversion displays an evident lag of the CDC peaks behind T_{out} maximum (Fig. 9). This might be because biological activity (the main driving mechanism of the CDC increase) increases more slowly than the temperature, which is particularly the case with deciduous plants which take time to grow leaves in the spring. The highest CDCs (>10,000 ppm) were recorded during the late summer of 2019 which was the coolest summer between 2017–2020, but the long-lasting warmth with above-average precipitation in July (CMHS, 2021) obviously triggered intensive biological activity inducing the CDC increase.

The aforementioned impact of different morphology of the left and right passage in the Modrič Cave is also evident when considering temporal variations in CDC distribution. Namely, the sudden drop in CDC values recorded in the left passage during the autumn/winter transition period (e.g. November and December 2018) with CDC values decreasing from >5000 ppm to 500-600 ppm (Fig. 9 & Tab. A1) coincides with the drop of the

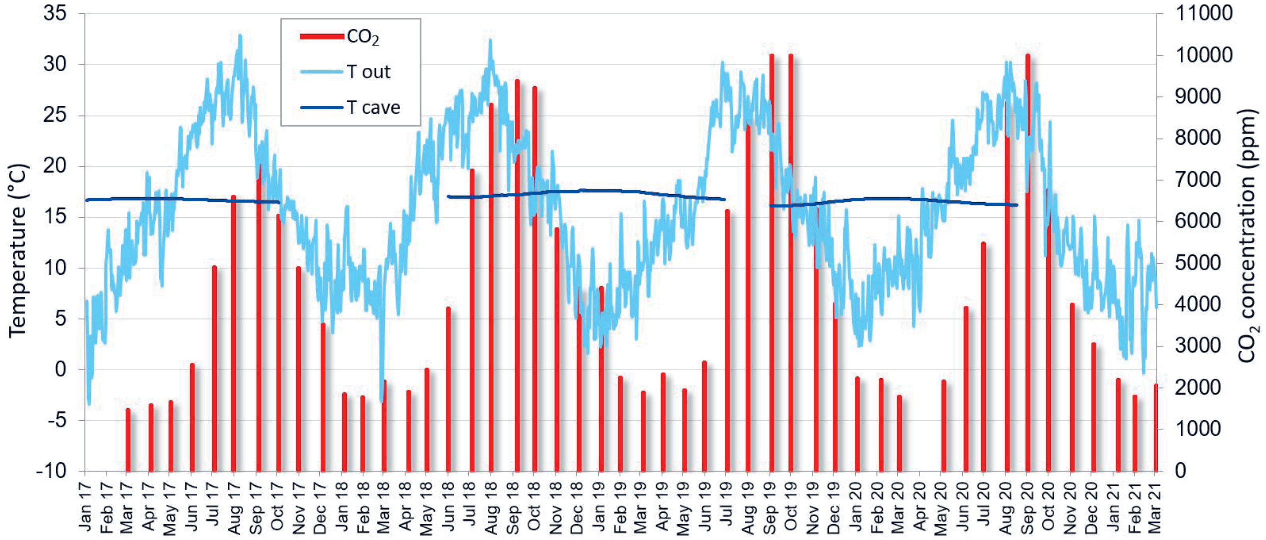

Figure 9. Time series of the surface (T_{out}) and cave air temperature (T_{cave}) and air CO_2 concentration at M32 – the innermost measurement point within the right passage where the highest CDC values were recorded, never falling below 1450 ppm. Surface temperature is compiled from the Starigrad (1/2017-7/2018) and Novigrad stations (8/2018-8/2020), equally distant from Modrič Cave. Data for April 2020 are missing due to the COVID-19 pandemic.

T_{out} below $T_{cave,}$ which usually occurs during October and November and triggers the inflow of the CO_2-poor outside air into the cave. At the same time, the decrease of the CDC in the right passage is much smoother as values drop from ca. 5000-6000 ppm to 3000-4500 ppm owing to the right passage's tight spots preventing the rapid inflow of cooler outside air, but also because of apparently more compact bedrock and therefore reduced outflow.

The transition between higher summer and lower winter CDC values in the Manita peć Cave (Fig. 10) is governed by both the chimney effect and the cold trap responsible for the cave's site-specific temperature regime. The cold trap is present during most of the year, so T_{out} remains below T_{cave} only relatively briefly during the winter (December to February/March). Still, the innermost part of the cave retains unchanged CDC until May/June when T_{out} increases to approximately 15-17 °C (Fig. 10). Presumably, because of the large volume of that part of the cave (cave ceiling is ca. 30 m high), it takes a longer time for the CDC to increase. Also, the surface above the cave is over 600 m a.s.l., so increased biological activity in the soil lags behind that on the surface above the Modrič Cave.

5.3. Impact of specific meteorological events

Occasionally, ventilation can be further modulated, and more rapid changes in CDC values are expected during specific meteorological episodes such as strong winds (RIECHELMANN et al., 2019; KUKULJAN et al., 2021) and intense precipitation events (BOURGES et al., 2020). Modrič and Manita peć caves have northward- and eastward-facing entrances, respectively, exposed to the north-eastern bora – a gusty downslope windstorm characteristic for the eastern Adriatic coast (GRISOGONO &

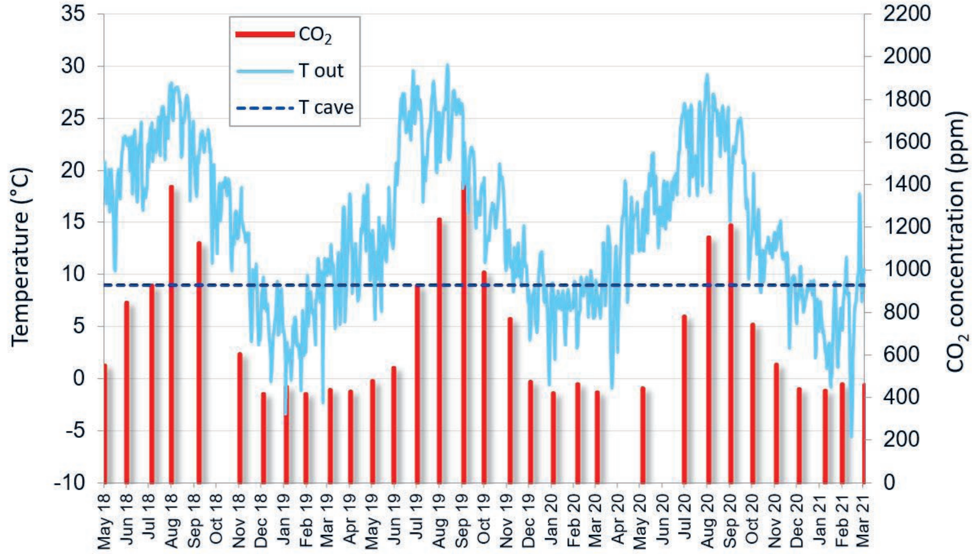

Figure 10. Time series of the surface (T_{out}) recorded in front of the Manita peć Cave, and air CO_2 concentration at MP09 - the innermost measurement point where the highest CDC values were recorded. Cave air temperature (T_{cave}) is an average value recorded between 7/2012 and 7/2014. Note the significantly shorter duration of $T_{out} < T_{cave}$ than $T_{out} > T_{cave}$. Data for October 2018 are missing due to device failure, for April 2020 due to the COVID-19 pandemic, and for June 2020 due to the drowning of the innermost part by the extreme rainfall.

BELUŠIĆ, 2009). During the bora episodes, which are particularly frequent in March (e.g. IVANČAN-PICEK & VUČETIĆ, 1990; COLUCCI & PUCILLO, 2010) (anecdotally, three in a row), chimney circulation is disturbed in the Modrič Cave and surface air is pushed into the caves through the fractured bedrock due to the pronounced barometric high. Similar reversed airflow is recorded in the Postojna Cave during the strong NE wind with gusts of >10 m/s (KUKULJAN et al., 2021). If airflow is not measured, such events can be distinguished by sudden decreases of cave air relative humidity, as recorded in March 2013 in Manita peć and two other adjacent caves (SURIĆ et al., 2017). An immediate lowering of CDC can be revealed by continuous daily measurement as it was conducted e.g. in Bunker Cave during the strong southern winds (RIECHELMANN et al., 2019), while our monthly measurement registered only the slight decrease of CDC after the onset of the warm season increase (5/2017, 4/2018, 5/2019, 3/2020) (Tab. A1). Impact of the south-eastern scirocco wind was not perceived, but probably might be instrumentally measured, similar to the Postojna Cave where the southern wind increases the winter updraft (KUKULJAN et al., 2021). In fact, these reversal and/or amplifying effects can occur in all seasons, but the predominant chimney effect can be overridden only by the strongest wind gusts (KUKULJAN et al., 2021). This secondary wind-induced ventilation may have ramifications for speleothem record interpretation when it comes to dry and windy glacial periods in which summer high CDC could have been suppressed, enabling speleothem precipitation.

An opposite effect, i.e. an increase of CDC, may be related to intense precipitation that increases groundwater infiltration in the cave, which in turn elevates the CO_2 concentration through degassing from the drip water (HOUILLON et al., 2017; BOURGES et al., 2020). Although two extreme rain events occurred during the monitoring period (daily precipitation of 229 mm on 11 Sept 2017 and 151 mm on 5 Jun 2020), increased CDC values were not observed during the monthly visit. This implies that short-term rain (and infiltration) events do not affect CDC on a monthly scale in terms of consequent growth cessation, particularly when site-specific settings of the aquifers are considered. Stalagmate® drip logger data point to a wide range of flow regimes (BAKER et al., 1997), from an immediate response due to fracture flow in the Manita peć Cave (SURIĆ et al., 2017) to practically unresponsive homogenised drip rates in the right passage of the Modrič Cave (SURIĆ et al., 2018).

5.4. Influence of visitors on cave CDC and/or the opposite impacts

Any human presence in the caves can elevate air temperature, relative humidity and dust content in the air, as well as disturb its chemical composition which can all potentially threaten speleothem formation. Upon cessation of the use of open fire and acetylene lighting in show caves (in Modrič Cave it was part of an adventure offer until 2015), breathing remains the only direct human influence on the cave air chemical composition. In exhaled human breath, CO_2 concentration is ~20,000-58,000 ppm (BYRNES et al., 1997), and in specific circumstances in the caves, it appears to serve as a high-concentration source of CO_2 (PRELOVŠEK et al., 2018). Individual production, i.e. CO_2 exhalation rate, depends on a person's age and physical activity. Some estimated and calculated values are: 0.2-1.2 L_{CO_2} min^{-1} person^{-1} (DRAGOVICH & GROSE 1990), 0.39 ± 0.11 L_{CO_2} min^{-1} person^{-1} (FAIMON et al., 2006) and 0.35-0.45 L_{CO_2} min^{-1} person^{-1} (MILANOLO & GABROVŠEK, 2009). The contribution of CO_2 from human breathing (ΔC_{CO_2}) can be calculated by the expression (1) (PRELOVŠEK et al., 2018):

$$\Delta C_{CO_2} = J_A \times t \times n_v / V_{est} \qquad (1)$$

where ΔC_{CO_2} is change of CDC due to the exhalation (in ‰), J_A is CO_2 production (exhalation) rate (in L_{CO_2} min^{-1} person^{-1}), t is the residence time of the visitor (in minutes), n_v is number of visitors, and V_{est} is estimated volume of the cave/passage (in m^3).

In the Manita peć Cave, with its relatively short working hours, in August there are only ~130 visitors per day (2020 not taken in account due to COVID-19 pandemic), and with their average residence time of 30 minutes in the total cave volume of 67,510 m^3, they contribute to the overall CDC with 12-26 ppm per day. Seasonal peak attendance in the Modrič Cave is 30 visitors per day and their trip takes place in the left passage, roughly estimated at 10,000-13,000 m^3 of total volume. During the 2-hour tour, their contribution to the natural CDC is approximated to 55-162 ppm, which is six times higher than in Manita peć Cave. Both of these estimations are calculated with a theoretical absence of ventilation. A similar increase of 5.6 to 28 ppm per adult-equivalent person per hour was measured in the Grotta di Ernesto (FRISIA et al., 2011). Our calculated values corroborate the measurements given in Tab. 1 and reflect prudent management of both caves in the sense of environmental protection.

An opposite effect, i.e. the impact of high cave air CDC on visitors, can be expected in summer since the high tourist seasons coincides with the period of the elevated naturally occurring CO_2 (Figs. 2a, 3 and 5b). In the Manita peć Cave, the highest recorded CDC value of 1415 ppm has no influence on visitors, as that is around the level commonly reached indoors, but values that occur along the Modrič Cave tourist path are already 20-25 times higher than those of the outside atmosphere. Luckily, CDC peaks are reached only in September, after the tourists' peak in August. Potentially harmful CDCs >10,000 ppm that can cause increased respiratory rate, respiratory acidosis, metabolic stress, increased brain blood flow and increased minute ventilation (AZUMA et al., 2018) have been recorded in the right passage which is only of scientific interest and not visited by tourists. However, there is an additional health risk in that part of the cave. It relates to the radioactive gas radon which is emitted from the deeper Earth's crust without any surface input. According to preliminary observation (SRŠEN, 2019), given its good correlation with CDC, and dependence of its concentration exclusively on dilution with surface air, we may expect potentially dangerous values during the summer season in the right passage.

5.5. Potential impact of long term natural and anthropogenic environmental changes to the surface on speleothem-based palaeoclimate interpretation

Contemporary vegetation cover that consists of scrubby Mediterranean maquis-like plants has been subject to permanent natural, and more recent human-induced, changes that result in pro- or degradation of the soil horizon and plant density – the main source of CO_2 in our studied sites. On decadal to centennial scales, the earliest anthropogenic impact manifested by enhanced erosion due to deforestation can be detected in marine sediment from Modrič Bay back to 1715 cal BP, with maximum at 160-265 BP (HASAN, 2017). Velebit woodlands across the wider region experienced drastic changes, as they were overused during the 16th-17th c. not only by the Venetians, Habsburgs and Otomans (ŠTEFANEC, 2000), but also by the growing local population

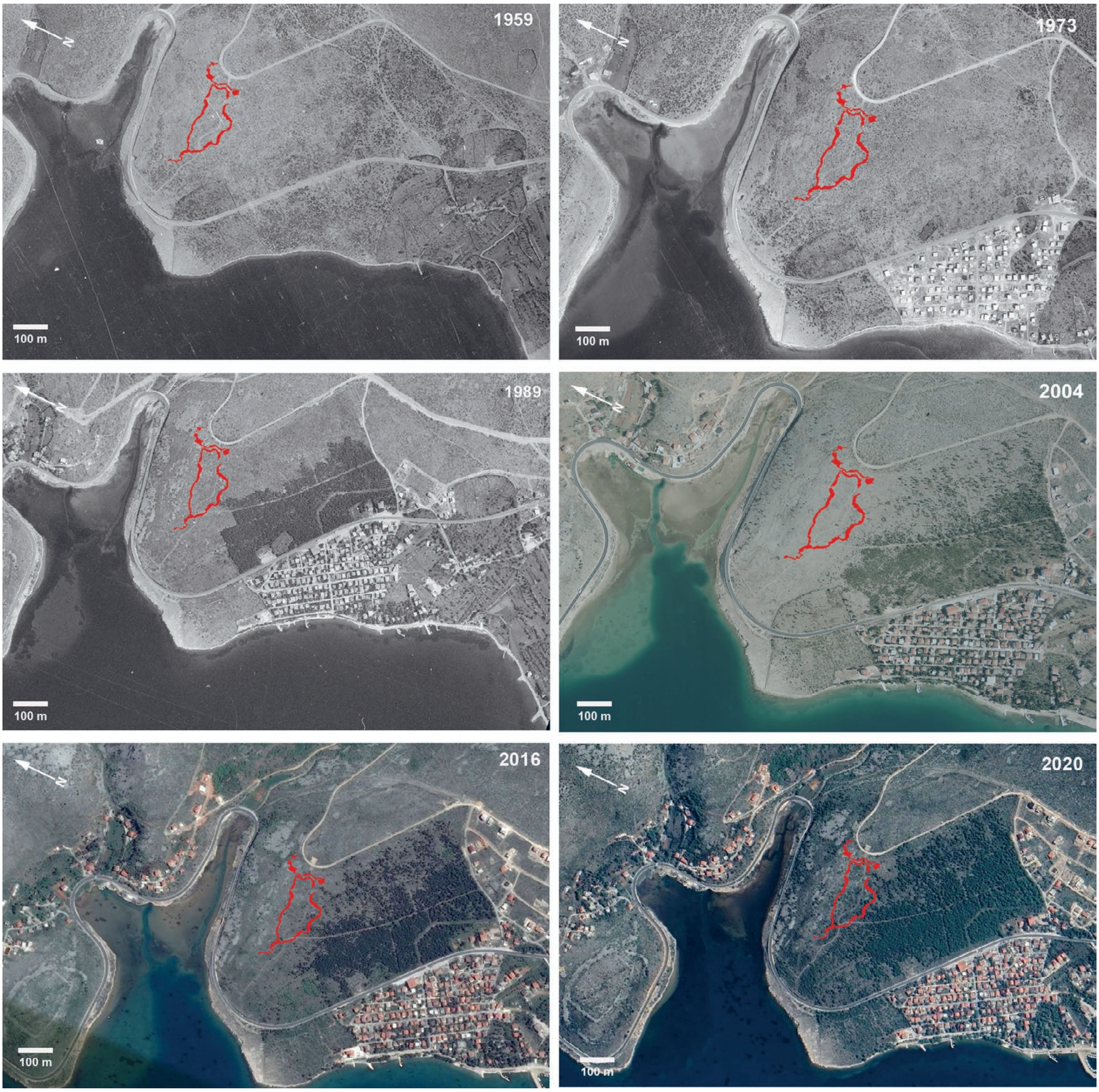

Figure 11. Natural and anthropogenic environmental transformations on the surface above the Modrič Cave between 1959 and 2020. Modrič Cave plan is given in red.

(RUKAVINA, 1990). This also coincided with the Little Ice Age with increased demands for firewood (KUŽIĆ, 1999). Under the French government starting at 1805, and with ameliorated climate conditions, erosion and/or deforestation declined (HASAN, 2017). Organized reforestation began in the late 19th century (KASER, 1987) and was intensified during the ban on goat breeding in 1954-1982, but the recovery has been relatively slow. Evident changes of vegetation cover on the decadal scale have been documented by aerial photography (Fig. 11). Bare karst scenery that dominated in 1959 and 1973 was partially changed by planned reforestation (recorded in 1989), followed by natural (and occasional anthropogenic) forestation during the last three decades. Each of these soil or/and vegetation alterations might have left an imprint in CO_2-controlled speleothems growth rate.

Going farther back into the past, beyond human interference, climate changes at the centennial to millennial scale controlled environmental settings in terms of temperature and/or humidity variations and hence cave ventilation, which, in turn, forced or ceased speleothem precipitation. Throughout the glacial periods, commonly regarded as cold, dry and windy, in ice-covered and some periglacial regions, speleothem deposition completely ceased (BAKER et al., 1995; LOWE & WALKER, 1998). This was due to the lack or negligible input of pedogenic CO_2 into the karst system because of the absence of a soil cover (SPÖTL et al., 2006; LI et al., 2021). However, that was not the case in littoral Croatia, as evidenced in currently submerged speleothems that precipitated during the Last Glacial Maximum (SURIĆ & JURAČIĆ, 2010), and particularly in speleothems from the Manita peć Cave where sufficient pedogenic CO_2 sustained karst processes, including speleothem deposition, throughout the last glacial cycle (SURIĆ et al., 2021). Presumably, the possibility of growth cessation caused by a diminished gradient between $p\mathrm{CO}_2$

in drip water and cave air was compensated by enhanced wind activity (WACHA et al., 2013; DURN et al., 2018; KOVAČIĆ et al., 2013) which promotes cave ventilation (RIECHELMANN et al., 2019). As for the past interglacials, likewise today, growth interruptions due to enhanced biological activity, elevated CDCs and hindered degassing have been possible in the Modrič Cave. Given that the potential growth cessation occurs only seasonally, the winter signal may dominate in other speleothem climate-related properties and proxies driven by CO_2-flux, as well (GENTY et al., 2001; BALDINI et al., 2008; FRISIA et al., 2011). One such commonly used proxy is $\delta^{13}C$, which increases with vegetation decline related to climate deterioration, accompanied finally by the cessation of speleothem growth (FRISIA et al., 2011). In addition, cave ventilation forces degassing of CO_2 from dripwater, prior to any calcite precipitation onto the stalagmites (FRISIA et al., 2011). Prior calcite precipitation leads to ^{13}C-enrichment in the speleothems (FAIRCHILD & BAKER, 2012) during deposition within the cave atmosphere obviously favourable for their growth. These similar signals, but supported by opposite conditions, underscore the importance of a multiproxy approach to verify palaeoclimate interpretations.

6. CONCLUSIONS

We presented the results of multiyear monitoring of CDC in the Modrič and Manita peć show caves, which was conducted in order to identify spatio-temporal CDC variations, their controlling mechanisms and potential mutual influence and interrelationships between cave atmosphere and visitors.

i) The main sources of CO_2 in both caves are plant- and microbial-derived CO_2 produced in the soil horizon by root respiration and decay of organic matter that is transported downward, and in-cave CO_2 degassing of the dripping groundwater. Underground streams are absent and CO_2 production by cave biota is considered negligible. The main sink for the cave air CO_2 is dilution with outside air due to the cave ventilation which is governed by air density differences derived from different air temperature, and by occasional wind-induced air flow.

ii) General ventilation patterns are seasonal and mimic the chimney-type circulation with associated CDC variations: the winter mode includes inflow of cold, dense CO_2-poor outside air into the caves due to the $T_{out} < T_{cave}$, while in summer mode, warm surface CO_2-rich air enters into the caves during $T_{out} > T_{cave}$. The key events are abrupt transitions from $T_{out} > T_{cave}$ to $T_{out} < T_{cave}$ followed by a sudden CDC drop. Occasionally, NE bora wind-induced air flow, as a secondary ventilation pattern, overprints the primary ventilation model, while the influence of wind-driven ventilation of the SE scirocco was not noticed.

iii) Superimposed upon the ventilation driven by air density gradient are circulation effects controlled by cave geomorphology and epikarst architecture, so the similar seasonal ventilation patterns result in large differences between absolute CDC values in the inclined and spacious Manita peć Cave, and the horizontal and more confined Modrič Cave. Moreover, within the same cave, the right and left Modrič Cave passages are ventilated differently due to the fractured fault zone of passable left passage (more ventilated) and more constrained right one (less ventilated).

iv) Although these caves are only 8 km apart, belong to the same type of climate (Cfa) and vegetation zone (Mediterranean), and spatio-temporal CDC variations within them are generally controlled by the same dynamic (seasonal) ventilation patterns, the magnitude of CDC variation appears to be site-specific. Due to the dependence of calcite precipitation on CDC variation, careful selection of the samples for speleothem-based palaeoenvironmental studies is essential. In particular, the Manita peć Cave generally does not experience major CO_2 fluctuations, so neither deterioration by condensation corrosion of the already deposited calcite, nor growth inhibition due to the CDC fluctuations is expected. On the other hand, the very high summer-autumn CO_2 concentration within Modrič Cave could reduce CO_2 degassing from the dripwater and thus hamper calcite precipitation.

v) Due to the low number of visitors, anthropogenic impacts on cave CDC is negligible even in the confined Modrič Cave passages, when compared to the natural CO_2 input which is higher by two orders of magnitude. In the Manita peć Cave episodes with slightly elevated human-induced concentrations are occasional and temporary short-duration events, with insignificant contribution to the natural CO_2 content.

vi) Conversely, given the site-specific nature of CDC and known temporal patterns, cave management should maintain the same practice of short visits of small groups in Manita peć Cave and the left passage of Modrič cave, while the right one should be avoided at least in late summer and during autumn.

vii) Elevated CDC values and similar preliminary results of radon measurements urge high-resolution (daily to hourly) monitoring of both parameters, measurement of velocity and the direction of air flow, along with collection of modern calcite to assess its precipitation in relation to the ventilation dynamics.

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APPENDIX

Table A1. Modrič Cave air CO_2 concentration (in ppm) measured during the 2017-2021 period. April 2020 data are missing due to the COVID-19 pandemic lockdown. For the measurement points, reader is referred to the Fig. 7.

	Main passage			Left passage			Right passage	
	M00	M11	M22	T13	T14	T15	M31	M32
3 Mar 2017	385	490	441				994	1475
4 Apr 2017	385	427	528				1107	1580
2 May 2017	393	412	458				1067	1666
2 Jun 2017	393	2115	2244				2536	2558
4 Jul 2017	380	3600	4450				4850	4900
31 Jul 2017		5155	5110				6517	6600
5 Sep 2017	386	4800	4900				7070	7620
3 Oct 2017	373	415	2813				5138	6145
31 Oct 2017	383	388	1358				4180	4892
5 Dec 2017	387	382	411				2060	3522
4 Jan 2018	366	378	416				1028	1858
30 Jan 208	438	454	485				1161	1769
1 Mar 2018	459	606	504				1640	2153
6 Apr 2018	418	492	545				1230	1915
1 May 2018	534	1886	1940				2278	2434
1 Jun 2018	475	3081	3247				3879	3903
5 Jul 2018	466	4772	4812	4713	4645	4752	7058	7228
1 Aug 2018	487	5605	5620	5459	5432	5576	8810	8805
7 Sep 2018	498	5723	6273	5781	5738	5871	8874	9386
2 Oct 2018	388	5286	6485	8441	7831	6955	8215	9213
2 Nov 2018	350	4252	4635	5200	5310	5293	4995	5812
4 Dec 2018	458	614	521	554	551	1252	3095	4404
4 Jan 2019	425	462	496	529	504	572	1657	2247
31 Jan 2019	433	548	506	480	493	559	1447	2251
5 Mar 2019	434	463	491	501	498	580	1245	1880
2 Apr 2019	436	481	647	702	754	829	1820	2317
2 May 2019	440	461	525	540	544	640	1269	1940
31 May 2019	444	1170	1548	1808	2036	2098	2505	2613
2 Jul 2019	520	3817	3846	3818	3849	3889	6195	6250
1 Aug 2019	590	5313	5276	5214	5149	5211	8263	8550
3 Sep 2019	422	6565	6868	6556	6533	7228	>10000	>10000
1 Oct 2019	482	6702	6731	6709	6636	6680	9614	>10000
5 Nov 2019	564	3877	4220	5377	5752	5789	5314	6310
3 Dec 2019	418	510	627	715	711	944	3104	4015
3 Jan 2020	454	480	509	533	525	610	1358	2226
6 Feb 2020	455	465	506	517	497	612	1617	2200
3 Mar 2020	427	456	554	500	504	551	1293	1795
1 Apr 2020								
5 May 2020	439	513	705	759	900	1174	1590	2149
5 Jun 2020	513	2755	2845	3030	3095	3150	3689	3924
30 Jun 2020	584	4242	4234	4224	4212	4206	5420	5473
3 Aug 2020	473	5495	5635	5317	5300	5481	8750	8867
1 Sep 2020	477	2700	6070	6015	5960	6028	9790	>10000
1 Oct 2020	574	1128	1680	2730	3100	3190	4670	6763
3 Nov 2020	468	500	592	636	665	930	2976	4005
4 Dec 2020	440	475	571	562	560	649	1698	3052
8 Jan 2021	441	525	504	518	512	584	1425	2197
1 Feb 2021	448	467	517	505	512	580	1243	1783
3 Mar 2021	476	491	537	557	548	601	1419	2064

Table A2. Manita peć Cave air CO_2 concentration (in ppm) measured during the 2018-2021 period. April 2020 data are missing due to the COVID-19 pandemic lockdown. For the measurement points, reader is referred to the Fig. 8.

	MP 01	MP 02	MP 03	MP 04	MP 05	MP 06	MP 07	MP 08	MP 09
4 Jan 2018	325	339	325	351	348	400	397	398	421
30 Jan 2018	414	411	404	441	444	407	464	414	413
1 Mar 2018	354	373	412	411	422	412	413	415	415
6 Apr 2018	391	387	400	414	415	422	414	415	441
1 May 2018	378	380	452	524	505	512	510	502	551
1 Jun 2018	463	535	693	814	825	812	816	821	845
5 Jul 2018	422	497	684	855	900	903	920	911	924
1 Aug 2018	430	599	740	1243	1270	1259	1315	1346	1387
7 Sep 2018	426	501	563	1166	1173	1170	1212	1198	1226
2 Oct 2018	397	612	824	851	753	655	745	650	
2 Nov 2018	382	400	432	585	588	578	586	595	604
4 Dec 2018	380	400	418	457	411	419	428	412	416
4 Jan 2019	377	381	394	401	424	421	412	419	450
31 Jan 2019	411	405	395	407	405	406	402	409	417
5 Mar 2019	395	402	404	412	418	414	415	418	435
2 Apr 2019	402	401	407	428	426	429	431	427	429
2 May 2019	413	407	411	435	465	469	471	466	476
31 May 2019	383	409	430	515	527	523	525	523	538
2 Jul 2019	404	406	657	897	914	917	946	933	925
1 Aug 2019	389	493	884	1185	1196	1179	1186	1210	1237
3 Sep 2019	379	399	423	1048	1335	1323	1338	1415	1410
1 Oct 2019	402	465	600	923	979	978	979	990	988
5 Nov 2019	418	664	410	722	747	747	747	767	770
3 Dec 2019	402	414	407	414	407	402	424	415	472
3 Jan 2020	422	439	426	425	428	435	427	427	418
6 Feb 2020	413	416	435	445	420	421	408	407	460
3 Mar 2020	401	417	408	410	424	422	418	426	424
1 Apr 2020									
5 May 2020	405	405	419	428	409	420	428	435	442
6 Jun 2020	448	422	437	488	513	514	505	519	
30 Jun 2020	392	435	616	738	738	762	758	746	778
3 Aug 2020	397	422	718	1054	1076	1072	1127	1137	1152
1 Sep 2020	394	424	576	1164	1140	1137	1142	1198	1210
1 Oct 2020	415	436	458	696	706	712	719	734	740
3 Nov 2020	434	428	436	500	533	530	535	539	554
4 Dec 2020	416	407	435	434	431	420	413	416	438
8 Jan 2021	397	416	425	434	434	433	434	428	433
1 Feb 2021	432	441	405	424	431	431	430	435	463
3 Mar 2021	420	427	450	444	446	448	448	447	458