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Prelimminary communication

Night sky brightness trends above Zagreb, 2012–2022

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The night sky brightness at the RGN site (near the centre of Zagreb, Croatia) was monitored from January 2012 to August 2022. The first data set, covering the period 2012 to 2017, has already been analysed and the conclusions were published in Andreić (2018). The main conclusions are repeated here for comparison and completeness. The results of the analysis of the second dataset, covering the period from January 2018 to July 2022, are reported here.

The first data analysis showed that the average night sky brightness did not change significantly from 2012 to 2017, excluding differences due to annual variations in meteorological parameters. The second data set (2018 to 2022) showed a slight decrease in night sky brightness compared to the first data set. The difference is small, about 0.2 mag/arcsec^2 (mean values). In the second data set, there is a trend toward darker nights in later years that began three or four years ago (around 2019 or 2020). It is attributed to the modernisation of the public lighting network, where old, often very poor lighting fixtures are slowly being replaced by modern LED lighting fixtures, and to the effects of climatic changes leading to warmer winters with more clear nights.

Keywords: light pollution, night sky brightness, site testing, atmospheric effects

1. Introduction

The brightness of the night sky above the city of Zagreb, Croatia has been monitored for the last 10 years from the roof of the Faculty of Mining, Geology and Petroleum Engineering in Zagreb (RGN site). The results of the first 6 years (2012-2017) of monitoring were published in 2018 (Andreić, 2018). The average brightness of the night sky in this period was found to not change significantly, apart from the differences caused by annual variations in meteorological parameters. The seasonal probability curves were used to obtain additional information on the light pollution at the RGN site. They showed that the night sky brightness concentrates around two values, one of about 15.0 mag/arcsec2 and the other of about 18.2 mag/arcsec2. These two values were attributed to cloudy and clear nights, respectively, the difference in brightness between them being about 3 magnitudes. The tendency to slightly lower brightness values in spring and summer was also seen in the data.

Since that paper, another 5 years of data were accumulated and they are analysed in this paper. The motivation behind this extended measuring period is to monitor the evolution of light pollution in Zagreb, deduce the trend of its intensity and get some insight into possible future evolution.

The same instrument was in continuous use. Unfortunately, many power and hardware failures resulted in significant data loss, especially in 2020, the first year of the COVID pandemic. The instrument in question is an SQM-LE instrument (Unihedron, 2022) permanently placed on the roof of the building of the Faculty of Mining, Geology and Petroleum Engineering in Zagreb (45.80701° N, 15.96398° E, approx. 150 m above sea level), which is located near the centre of the town with approximately one-million population. We kept the data analysis pipeline the same as in the first article, so only a short description is provided here.

A lot of articles about light pollution appeared in the last five years, covering very different aspects of it. If we select only articles concerning monitoring the light pollution, the number reduces to around a hundred. An extensive recent review of LP monitoring methods is given in Mander et al. (2023). If we limit ourselves to methods using SQM in long-term measurements (longer than several years), significantly less papers can be found (for instance, Puschnig et al. (2023), Kyba et al. (2015)).

Only other method that is used for long term studies consistently is the analysis of satellite images (Yerli, 2021). However, this method uses light that escapes the earth atmosphere into the space, and depends on elaborate modelling to infer the amount of light pollution produced, while on-ground methods measures the light pollution directly, so the results obtained are not directly comparable. Actually, the on-ground measurements are used to calibrate the satellite based analyses.

To keep it reasonably compact, and as this article is a continuation of the previous one, we will not go deeper into the analysis to the topics not relevant for this study.

2. Materials and methods

The SQM-LE is aimed straight at the zenith. The sensitivity cone of the instrument has a Full Width Half Maximum (FWHM) of about 20°. As the faculty building is among the highest in the surrounding area, the instrument is well shielded from the influence of lights from nearby buildings or street lighting. Data are read and stored by a remote PC connected to the SQM-LE by an Ethernet cable. The instrument operates continuously and takes measurements every 5 minutes. The SQM measures the sky brightness in standard astronomical units of magnitudes per square arc-second. This brightness scale is used throughout the paper. SQM instruments are popular due to their affordability and ease of use. However, they are not strictly professional instruments, with accuracy of the order of 10%, which is quite satisfactory for this type of measurements.

During the analysis, the raw data are reduced in size by rejecting measurements taken during daytime, at the same time being arranged into sets covering individual months. To simplify the further procedure, time stamps of individual data points are replaced by the ordinal number in the current data set. To retain basic information about the dates of the measurements in question, the day number of the month is stored too. From these datasets, monthly plots were created and analysed.

It was already concluded in the first paper that for a heavily light polluted site like Zagreb clouds scatter far more light downward than the clear atmosphere, and consequently, the clear/cloudy conditions can be discerned in the data. For this particular site, the brightness of the cloudy night sky is generally 3 or more magnitudes larger than the brightness of the clear sky. The effect of the moonshine can also be detected as slow, and rather smooth, rise (or drop) of the sky brightness. The presence and the brightness of the Moon can easily be found with the help of any planetarium or astronomical ephemerides program, if needed.

Now, if we are interested in clear sky brightness values, the datasets are searched for the minimum brightness, as this determines the best clear sky conditions. The frequency of occurrence of such conditions, and the duration of periods of good sky conditions is also determined during this analysis.

On the other hand, if we are trying to determine the influence of light pollution on the environment, we will be more interested in the maximal sky brightness (during the night, of course) and again in the frequency of occurrence and the duration of such conditions. The mean values of sky brightness on nightly, monthly and yearly basis could also be of importance. For such purposes the cloudiness and presence/absence of the Moon are of secondary interest, or not relevant at all. For this purpose, minima, maxima and average values of sky brightness on a nightly basis were calculated from the datasets. The results of these calculations are given in Figs. 1 to 3. Finally, yearly statistics is extracted from the datasets and is summarized in the Tab. 1.

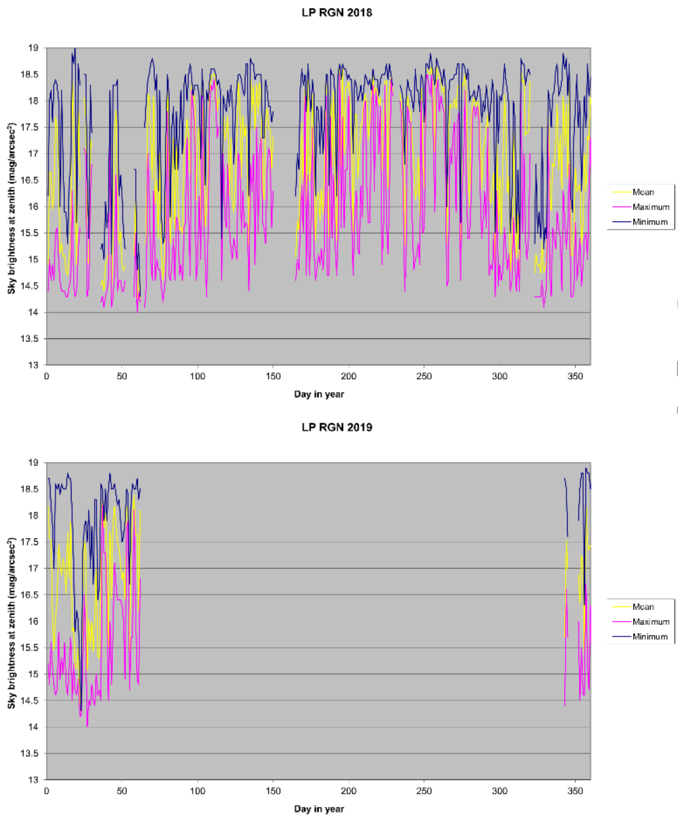

Figure 1. The nightly minima, maxima and average values of sky brightness for years 2018 and 2019.

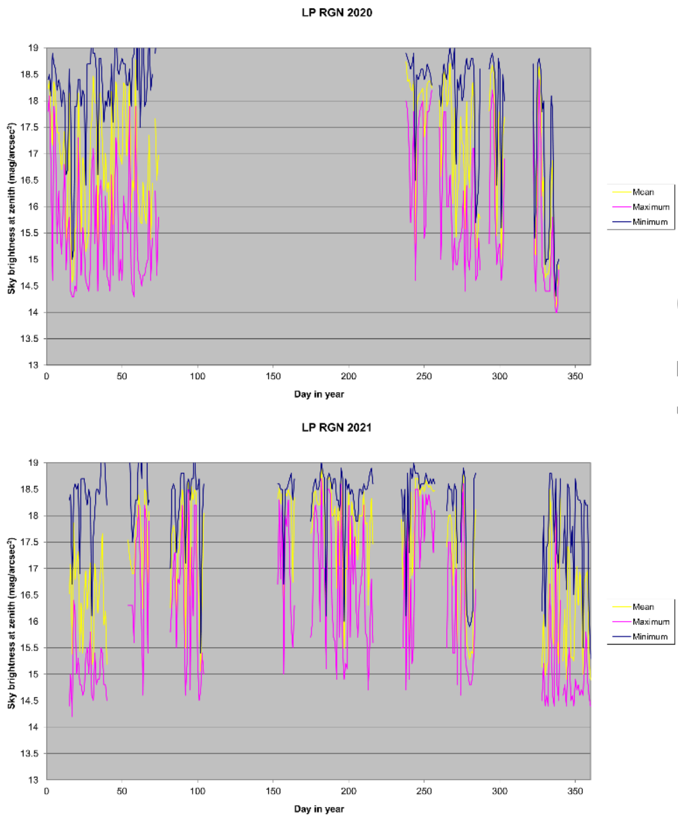

Figure 2. The nightly minima, maxima and average values of sky brightness for years 2020 and 2021

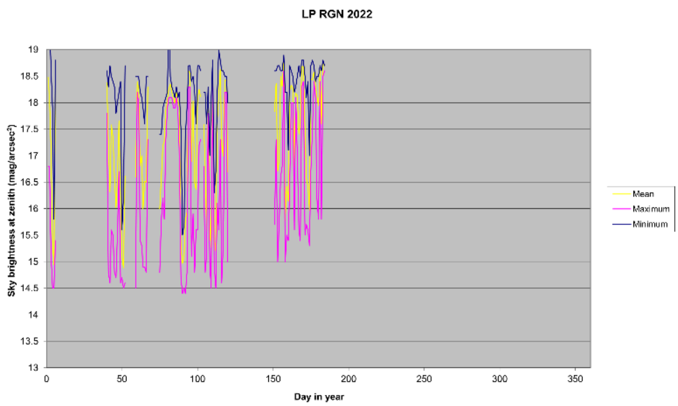

Figure 3. The nightly minima, maxima and average values of sky brightness for year 2022.

Table 1. Yearly statistics of nightly minima, maxima and average values of sky brightness and its nightly changes (variations) for years 2012 to 2017 (values taken from Andreić (2018)) and for years 2018 to 2022 (new data). All brightness values are expressed in magnitudes per arc-second squared. The mean values for the whole periods of measurements (2012–2017 and 2018–2022) are given in bold. The last recorded data in 2022 was on July 3rd, 2022. The missing days for 2022 are for the period when measurements were taken (January 1st to July 3rd).

Year	Sky brightness			Nightly variations			Number	Missing
	max.	min.	mean	min.	max.	mean	of nights	nights
2012	13.01	18.67	16.80	0.08	5.17	1.66	346	20
2013	13.00	18.73	16.64	0.07	4.18	1.70	276	89
2014	13.63	18.89	16.66	0.06	3.87	1.94	244	121
2015	13.27	18.84	16.90	0.08	4.33	1.78	161	204
2016	14.20	18.94	16.99	0.06	4.27	1.83	324	42
2017	14.15	19.03	17.08	0.07	4.20	1.88	227	138
mean	**13.54**	**18.85**	**16.85**	**0.07**	**4.34**	**1.80**	**263**	**102**
2018	14.00	19.00	16.88	0.10	4.70	1.98	331	34
2019	14.00	18.90	16.89	0.10	4.30	2.48	79	286
2020	14.00	20.00	16.98	0.10	5.10	2.30	149	217
2021	14.20	19.90	17.21	0.20	5.10	2.09	197	168
2022	14.40	20.00	17.31	0.10	4.10	1.97	108	76*
mean	**14.12**	**19.56**	**17.05**	**0.12**	**4.66**	**2.16**	**173**	**156**

3. Results and discussion

In the period between January 2012 and December 2017, about a quarter (28%) of the data was lost for different reasons. The most problematic in this aspect are years 2015 and 2016, for which only data for the first half of the year exist. In the second period (January 2018 to July 2022) data loss was even larger, being about 43%, mostly due to 2019 and 2020, other years being much better covered. Again, as in the first article, we remain by the conclusion that the remaining data are sufficient for a sound analysis, and summary statistics (see Tab. 1) do not show any significant differences from year to year that could be related to the missing data.

The Tab. 1 summarises yearly minima, maxima and average values of the measured sky brightness followed by the nightly variation of these values (also expressed as minimal, maximal and mean values observed over the year), together with information on number of nights that provided the data for the statistics. The main conclusion for the first period was that the average level of light pollution at the RGN site did not change significantly during the years 2012 to 2017.

In the second period (2018–2022) data show small decrease in sky brightness of about 0.2 mag/arcsec^2 (mean values) and about 0.1 mag/arcsec^2 (maximal values). It should be reminded here that the astronomical brightness scale is reversed, *i.e.*, maximal magnitude values represent the minimal sky brightness and vice versa.

Apart from the basic information collected in the Tab. 1, the probability that at any given moment (at night of course!) the sky brightness will be smaller (or greater) than a certain value was accordingly calculated in the first article and presented in Fig. 4 together with the new data for the period 2018–2022. Again, the seasonal variations are quite large from year to year, so these curves can be used as a rough guide only. The meteorological seasons are used here and in this article.

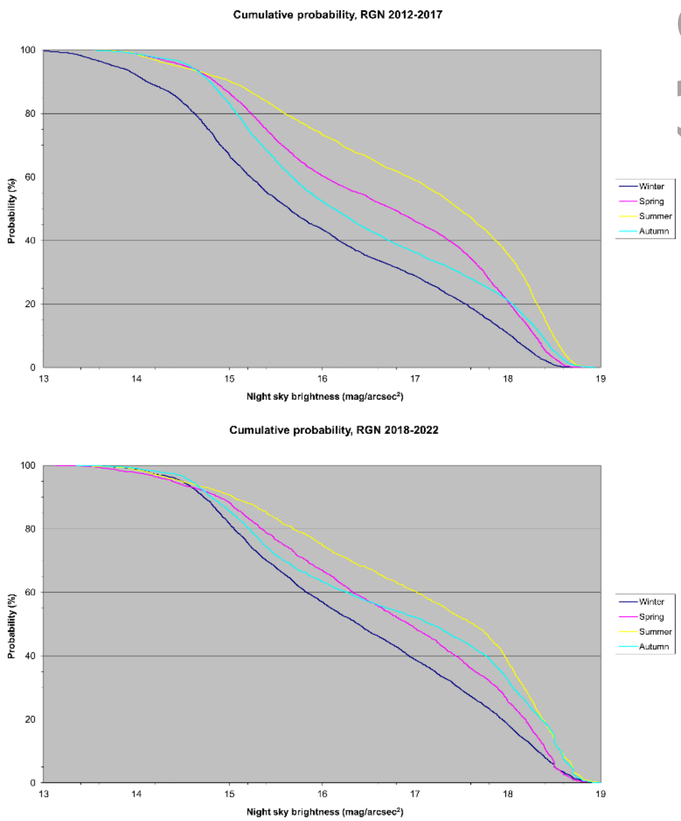

Figure 4. The average cumulative probability that the night sky brightness will be smaller than a given value, derived from all measurements available during the 2012–2017 period (reproduced from Andreić (2018)) and corresponding cumulative probabilities for the period 2018–2022.

Probability curves from Fig. 4 show the obvious: the summer (and spring) provide better observing conditions (less light pollution) than autumn and winter. One should also consider that duration of the night changes considerably over the year, and that in winter/autumn nights quite often start as clear and end as clouded or fogged, which worsens the nightly mean values in comparison to mostly fully clear summer nights. So, the seasonal differences are mostly caused by meteorological conditions prevailing in the season in question.

To gain a better understanding of possible improvement in night sky light pollution, as implied by the data in Tab. 1, we constructed all-year probability curves for the whole monitoring period (see Fig. 5).

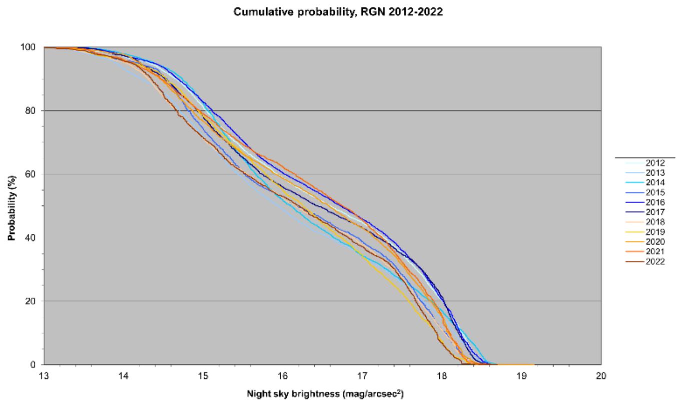

Figure 5. The average yearly cumulative probabilities that the night sky brightness will be smaller than a given value, derived from all measurements available during the 2012–2022 period.

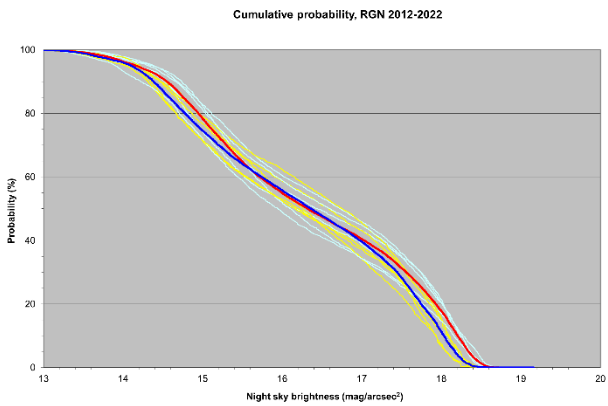

Figure 6. The average yearly cumulative probabilities that the night sky brightness will be smaller than a given value, derived from measurements during the 2012–2017 period (dark blue) and the 2018–2022 period (red). The individual yearly cumulative probabilities from the first period are shown in light blue and, for the second period in light yellow, for comparison. They are directly taken from the Fig. 5.

The yearly curves in Fig. 5 show a trend to progressing towards the right side of the graph (*i.e.* towards the less sky brightness) as the time passes, even as the yearly variations are obvious and sometimes quite large. To facilitate the interpretation of these curves, we repeated them in Fig. 6 in two groups.

The first group contains data from the 2012 to 2017 period, and all curves are plotted with the same colour, light blue. Similarly, the second group, containing data from 2018 to 2022 period is plotted with light yellow colour. Additionally, the averages for the whole time periods for both groups were constructed and are plotted on the same graph; the average for the first group in dark blue, and for the second group in red. These two curves are partially separated, in areas of high probability of occurrence (65%–95%) and in areas of low probability of occurrence (0%–40%) and the curve for the second group slightly shifted to the right, supporting the conclusions drawn from the data in Tab. 1.

The reason for the partially lower sky brightness in the later years may be due to several facts. First, due to climatic changes, the colder season becomes warmer, there are fewer clouds and fog, and the weather becomes clearer, meaning more clear, dark nights. Numerous scientific studies confirm the thesis of climatic changes that began to manifest themselves in the last 40 years and were particularly pronounced in recent times. For example, Pavlić et al. (2017) confirmed the hydrological manifestations of climate change in the area of Gorski kotar in Croatia in the 1980s, and Pavlić and Jakobović (2018) showed the intensification in the late 1990s. All this also indicates atmospheric changes affecting the brightness of the night sky. Second, the switch to better LED based lighting fixtures is gaining momentum, and more and more old and poor HP metal vapour fixtures are being replaced by much better shielded LED lighting fixtures. As the later emit significantly less (or nothing at all) light upwards, consequently, the sky brightness is reduced. Finally, as LED light sources do not produce infrared emissions at all, the change to LED outdoor lighting should be most pronounced in the IR part of the spectrum. This was predicted by authors more than decade ago in a paper about light pollution in the infrared (Andreić et al., 2012) and repeating this study is currently in plan. It should provide a final answer to the cause of observed reduction in the night sky brightness.

Recently a claim appeared that the SQM devices lose the sensitivity with age (Puschnig et al., 2020). However, the authors used a very awkward and unreliable calibration method and obtained quite different ageing constants for each of the three devices that they considered. To be sure, we contacted the SQM manufacturer, Unihedron, about this problem. They informed us that they regularly recalibrate used devices sent back by users and did not notice any noticeable ageing-related changes in instrument calibration (Unihedron, 2022b). Last, but not least, ageing would produce a gradual shift in measured data, opposite to what we see in the data: a rather rapid change to lower brightness values. Putting it all together, we dismissed the possibility of ageing effects in our data.

Lastly, to be sure that the observed effects are real, we performed a quick preliminary analysis of data from the second device, which monitors the night sky from a nearby rural location (the device and its results for the period 2014–2017 were reported in Pavlić and Andreić (2020)). The yearly probability curves obtained are similar to those for the RGN site (see Fig. 6), and the similar drop in the night sky brightness was observed in the two monitoring periods at the rural site (Fig. 7). However, the decrease in brightness in the recent period is visible in the area of lower probability of occurrence (up to 55%), while above this probability of occurrence the brightness is even higher. This increase can be explained by the large scattering of brightness values in recent years, and this is especially shown by the curve from 2018, so that difference is not significant. This is to be expected, as most light pollution at the rural site originates from the town of Zagreb. A few measurements taken during local power failures show only small drops in LP levels, about 0.1 mag/arcsec^2, or less, confirming that most LP at rural site comes from the town of Zagreb. Again, this supports the conclusion that devices function properly even after a decade of (almost) continuous operation.

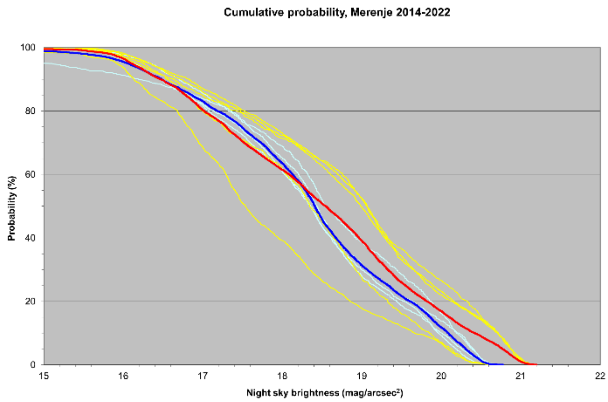

Figure 7. The average yearly cumulative probabilities that the night sky brightness will be smaller than a given value for the rural site near Zagreb. Cumulative probabilities were derived from measurements during the 2014–2017 period (dark blue) and the 2018–2022 period (red). The individual yearly cumulative probabilities from the first period are shown in light blue and, for the second period in light yellow, for comparison.

4. Conclusion

The compact statistical data from the Table 1 show that for the first monitoring period (2012–2017) the average level of light pollution at the RGN site did not change significantly. In the second period (2018–2022) a small decrease in sky brightness of about 0.2 mag/arcsec^2 (mean values) and about 0.1 mag/arcsec^2 (maximal values) was observed.

The yearly probability curves confirm these conclusions. These curves give the probability that at any given moment (at night of course!) the sky brightness will be smaller than a certain value. However, the seasonal variations are quite large from year to year, so the curves can be used as a guide only. First, they show the obvious: the summer (and spring) provide better observing conditions (less light pollution) than autumn and winter. Second, the curves generally slowly progress towards the right side of the graph (*i.e.* towards the less sky brightness) as the time passes. The 5-year average curves show the dimming effect more clearly and confirm the slight 0.2 mag/arcsec^2 drop in the night sky brightness over the monitoring period.

The cause for this can be attributed to several factors: First, the climatic changes make the colder part of the year warmer, with less clouds and fog and more clear weather. Second, switching to better LED luminaries results in less skyward light emissions.

A quick preliminary analysis of data from the second device, which monitors the night sky from a nearby rural location confirms the validity of our conclusions drawn from the device at the RGN location (the first device).

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References

Andreić, Ž. (2018): Night sky brightness above Zagreb, Croatia, 2012–2017, *Rudarsko-geološko-naftni zbornik*, **33** (3), 85–94, https://doi.org/10.17794/rgn.2018.3.9.

Andreić, Ž., Andreić, D. and Pavlić, K. (2012): Near infrared light pollution measurements in Croatian sites, *Geofizika,* **29**, 143–156.

Kyba, C., Tong, K., Bennie, J. et al. (2015): Worldwide variations in artificial skyglow, *Sci. Rep.*, **5**, 8409, https://doi.org/10.1038/srep08409.

Mander, S., Alam, F., Lovreglio, R. and Ooi, M. (2023): How to measure light pollution – A systematic review of methods and applications, *Sustain. Cities Soc.*, **92**, 104465, https://doi.org/10.1016/j.scs.2023.104465.

Pavlić, K., Kovač, Z. and Jurlina, T. (2017): Trend analysis of mean and high flows in response to climate warming - Evidence from karstic catchments in Croatia, *Geofizika,* **34**, 157–174, https://doi.org/10.15233/gfz.2017.34.11.

Pavlić, K. and Jakobović, D. (2018): High flows from Gornja Dobra basin, *Rudarsko-geološko-naftni zbornik,* **33**(3), 45–52, https://doi.org/10.17794/rgn.2018.3.5.

Pavlić, K. and Andreić, Ž. (2020): Comparison of night sky brightness above Zagreb and a nearby rural location 2014–2017, *Rudarsko-geološko-naftni zbornik,* **35**(2), 45–56, https://doi.org/10.17794/rgn.2020.2.5.

Puschnig, J., Naslund, M., Schwope, A. and Wallner, S. (2020): Correcting Sky Quality Meter measurements for aging effects using twilight as calibrator, *Mon. Not. R. Astron. Soc.,* **502**, 1095–1103, https://doi.org/10.1093/mnras/staa4019.

Puschnig, J., Wallner, S., Schwope, A. and Naslund, M. (2023): Long-term trends of light pollution assessed from SQM measurements and an empirical atmospheric model, *Mon. Not. R. Astron. Soc.*, **518**, 4449–4465, https://doi.org/10.1093/mnras/stac3003.

Yerli, S. K., Aksaker, N., Bayazit, M., Kurt, Z., Aktay, A. and Erdogan, M. A. (2021): The temporal analysis of light pollution in Turkey using VIIRS data, *Astrophys. Space Sci.*, **366**(4), 34–49, https://doi.org/10.1007/s10509-021-03942-6.

Internet sources:

Unihedron (2022a): http://www.unihedron.com/projects/sqm-le/ (last accessed on December 3rd, 2022).

Private communications:

Unihedron (2022b): e-mail discussion of ageing effects of SQM devices with the Unihedron company (December 2022).

SAŽETAK

Trend svjetline noćnog neba iznad Zagreba u razdoblju 2012.–2022.

Krešimir Pavlić and Željko Andreić

Svjetlosno onečišćenje iznad zgrade RGN fakulteta (u blizini središta Zagreba) mjereno je od siječnja 2012. do kolovoza 2022. Prvi dio podataka, od 2012. do 2017., je već bio obrađen i zaključci su objavljeni u Andreić (2018). Glavni zaključci te analize su ponovljeni ovdje radi usporedbe i kompletnosti. Rezultati analize preostalih podataka, od siječnja 2018. do srpnja 2022., su izneseni u ovom radu.

Prva analiza je pokazala da se prosječna svjetlina noćnog neba nije znatno mijenjala u periodu od 2012. do 2017., osim razlika zbog godišnjih varijacija meteoroloških parametara. Drugi niz podataka (2018. do 2022.) pokazuje maleno smanjenje svjetline noćnog neba u usporedbi s prvim nizom. Smanjenje je malo, oko 0.2 mag/arcsec^2 (srednje vrijednosti). Drugi set pokazuje lagani trend prema tamnijim noćima u kasnijim godinama koji je započeo prije tri ili četiri godine (oko 2019. ili 2020.). On je pripisan modernizaciji javne rasvjete, kod koje se zastarjele i loše svjetiljke pomalo zamjenjuju modernim LED svjetiljkama, i utjecaju klimatskih promjena koje donose toplije zime i vedrije noći.

Ključne riječi: svjetlosno onečišćenje, svjetlina noćnog neba, testiranje lokacije, atmosferski efekti

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