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CO LEVEL OVER THE REPUBLIC OF CROATIA USING SENTINEL-5P

Abstract: This paper deals with the issue of air pollution in the territory of the Republic of Croatia by monitoring the level of one of the largest air pollutants – carbon monoxide. For the study area, total carbon monoxide levels observed by the TROPOMI SENTINEL-5P mission device were taken and used to show carbon monoxide levels for the period from January to September 2020 for every fifteenth day of the month. The entire process of downloading, georeferencing and processing TROPOMI data is described. The analysis examines the relationship between carbon monoxide levels and urban areas, major roads, and altitude. Also, the time frame of observation covers the period of the most severe measures and lockdown due to the coronavirus pandemic and studies the impact of these measures on the level of carbon monoxide in the territory of the Republic of Croatia.

Keywords: air pollution, carbon monoxide (CO), GIS, remote sensing, TROPOMI

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Introduction

With the rapid increase of the World`s population rises the problem of air pollution. Some of the main causes of air pollution are urbanization, energy consumption, transportation, and motorization. Population growth and exposure to air pollutants also have a negative impact on the quality of the environment and human health (Kaplan & Avdan, 2020). With the smog hanging over cities, as well as the smoke inside home, air pollution poses a major threat to health and climate. The combined effects of ambient (outdoor) and household air pollution cause about seven million premature deaths every year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections. WHO (World Health Organization) data show that 9 out of 10 people breathe air that exceeds WHO guideline limits containing high levels of pollutants, with low- and middle-income countries suffering from the highest exposures (Air pollution, URL 1).

Together with climate change, air pollution has been one of the most serious threats to global health (Kaplan & Avdan, 2020) until the emergence of a new strain of coronavirus in late 2019, which the WHO called SARS-CoV-2, and a disease caused by it COVID-19. Patients with SARS-CoV-2 infection may present symptoms ranging from mild to severe with a large portion of the population being asymptomatic carriers. The most common reported symptoms include fever (83%), cough (82%) and shortness of breath (31%). Gastrointestinal symptoms such as vomiting, diarrhea, and abdominal pain are described in 2–10%, and in 10% of patients, diarrhea and nausea precede the development of fever and respiratory symptoms (Ciotti et al., 2020).

From the first industrial revolution in 1760 until today, man has taken many things for granted, ignoring the consequences of technological progress. One of these things is clean air which is a key element for human health, the future and ultimately for life in general. For this reason, this paper deals with the issue of clean air in the territory of the Republic of Croatia by monitoring the level of one of the largest air pollutants – carbon monoxide.

For the purposes of this paper, carbon monoxide level data for the territory of the Republic of Croatia measured by the device TROPOMI (TROPOspheric Monitoring Instrument) of the SENTINEL-5P satellite mission were used. The data collected from January to September 2020 for every fifteenth day of the month were downloaded and processed. The problems addressed by this research are presented by three main issues. What is the total carbon monoxide pollution in the Republic of Croatia? Which area is the least polluted? Did the lockdown due to the coronavirus pandemic affect the level of pollution? The subject of the research is modeling and monitoring the level of carbon monoxide on the territory of the Republic of Croatia using the data of the SENTINEL-5P mission, the comparison of the obtained models and drawing conclusions based on them. This paper sets out two assumptions or hypotheses. It is assumed that urban areas and areas of major roads have higher carbon monoxide pollution and that the lockdown due to the coronavirus pandemic has had the effect of reducing the level of carbon monoxide pollution.

Material and methods

Air pollutants. Outdoor air pollution originates from natural and anthropogenic sources. While natural sources contribute substantially to local air pollution in arid regions more prone to forest fires and dust storms, the human activities contribution far exceeds natural sources (Fig. 1). Although concern has been raised regarding the emission of air pollutants from anthropogenic sources, our society still relies heavily on fossil fuels for various applications such as electricity generation, transportation, industrial and domestic heating, and so on (Leung, 2015). To date, road traffic constitutes the major source of air pollution in the large cities of industrialized countries. Combustion of carbon constituted fuels (coal, fuel oil, wood, natural gas) is never complete, and it produces carbon monoxide (CO) and hydrocarbons. NOx result from the combination of air nitrogen and oxygen from combustion of fossil fuels contained in motor fuel at high temperature (Pénard-Morand & Annesi-Maesano, 2004). Outdoor air pollutants mainly consist of NOx, SO_2, O_3, CO, HC, and particulate matters (PM) of different particle sizes. In urban areas, these pollutants are mainly emitted from on-road and offroad vehicles, but there are also contributions from power plants, industrial boilers, incinerators, petrochemical plants, aircrafts, ships and so on, depending on the locations and prevailing winds (Leung, 2015).

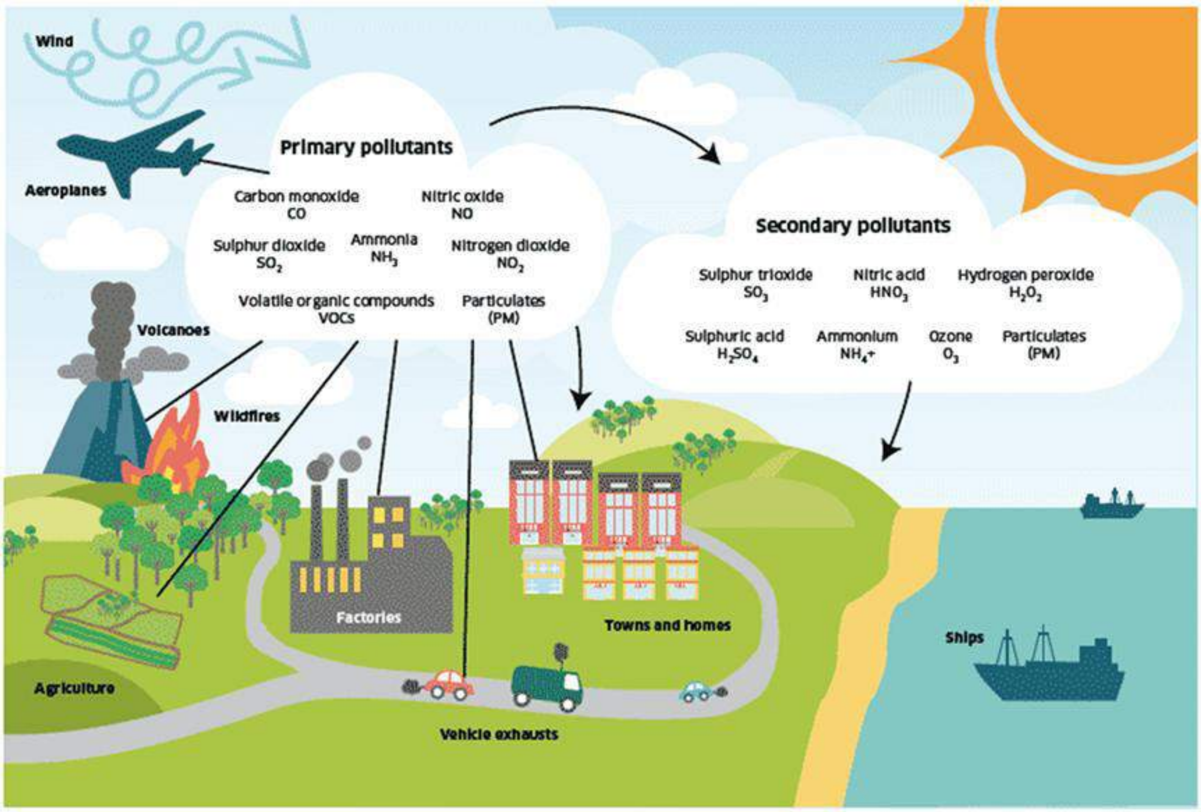


Fig. 1. Sources of air pollution
Source: Cleaner air for Scotland: the road to a healthier future, URL 2: https://www.gov.scot/publications/cleaner-air-scotland-road-healthier-future/pages/6/

Carbon monoxide (CO). Carbon monoxide is a colorless, odorless, and nonirritant toxic gas that is easily absorbed through the lungs. The amount of gas absorbed is dependent on the minute ventilation, the duration of exposure, and the relative concentrations of carbon monoxide and oxygen in the environment (Ernst & Zibrak, 1998). Carbon monoxide competes with oxygen for binding to hemoglobin. The affinity of hemoglobin for carbon monoxide is 200 to 250 times as great as its affinity for oxygen (Ernst & Zibrak, 1998). Carbon monoxide is a product of the incomplete combustion of hydrocarbons. The concentration of carbon monoxide in the atmosphere is usually less than 0.001% (Ernst & Zibrak, 1998). Carbon monoxide content in the air of less than 0.01% causes headaches and dizziness, and a content of 0.065 to 0.070% can cause death (Fig. 2) (Ugljikov monoksid, URL 3).

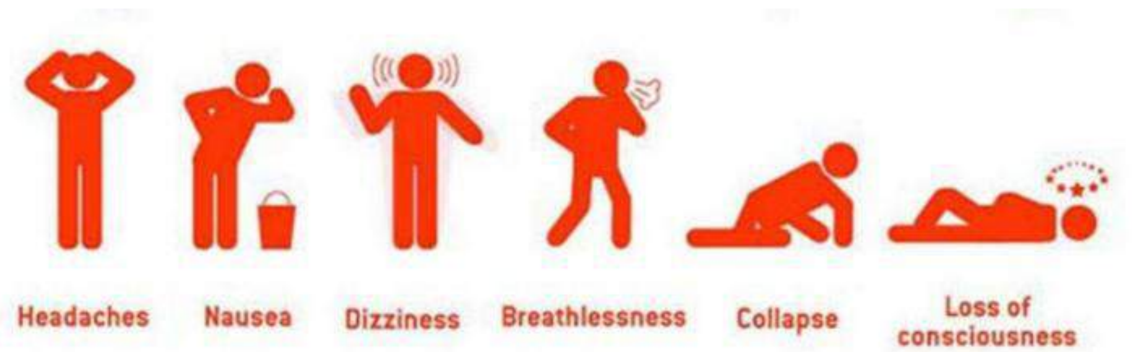


Fig. 2. Symptoms of carbon monoxide poisoning
Source: What Is Carbon Monoxide Poisoning, URL 4:
https://www.allweatherheatingandairconditioning.com/blog/what-is-carbon-monoxide-poisoning/

Study area. The Republic of Croatia is a country in Southeast Europe, covering 56,594 km^2, and its capital is Zagreb (Fig. 3). Geographical coordinates of endpoints: northernmost Žabnik, Sveti Martin na Muri municipality, 46° 33′ N and 16° 22′ E; the southernmost island of Galijula (Palagruža islands), 42° 23′ N and 16° 21′ E; the easternmost Ilok 45° 12′ N and 19° 27′ E; westernmost Bašanija (Cape Lako), 45° 29′ N and 13° 30′ E; the southernmost point on the mainland is Cape Oštra, Cavtat municipality, 42° 24′ N and 18° 32′ E (Hrvatska, URL 5).

Croatia is a predominantly lowland country. Lowlands (terrain below 200 m absolute altitude) occupy 53.4% of the territory, hills (200 to 500 m absolute altitude) 25.6% of the territory, and mountain and mountainous area (above 500 m absolute altitude) 21.0% of Croatia. The horseshoe shape of the territory indicates the importance of the Pannonian and coastal regions, interconnected mainly by the karst mountain region. The first of these regions covers a large part of the Peripannonian and a smaller part of the Pannonian area, and the second largest part of the eastern Adriatic area with almost all Adriatic islands. The predominantly karst mountain region of Gorski kotar and Lika, as the narrowest part of the mountainous area of Highland Croatia, connects the Peripanno-Pannonian and Adriatic areas (Hrvatska, URL 5).

Fig. 3. Topographic map of the Republic of Croatia
Source: Croatia, topographic map, URL 6: https://www.grida.no/resources/5316

SENTINEL-5P Mission. SENTINEL-5P, short for SENTINEL-5 Precursor, is a satellite mission launched on October 13, 2017 carrying the Tropospheric Monitoring Instrument (TROPOMI). The SENTINEL-5P mission represents the first in a series of atmospheric observing systems within Copernicus, which is the European Union's Earth observation programme (Kleipool et al, 2018) whose main purpose is monitoring the composition of the atmosphere. One major strength of the SENTINEL-5P mission is the global coverage of the TROPOMI instrument within only one day (Borsdorff et al., 2018) for use in monitoring and predicting air quality, climatic conditions, and ozone and ultraviolet radiation levels.

TROPOMI. The TROPOMI instrument is a space-borne, nadir-viewing, imaging spectrometer covering wavelength bands between the ultraviolet and the shortwave infrared. It consists of four spectrometers, each of which covers one part of the observed spectrum (TROPOMI Instrument, URL 7). It has a spectral resolution in the range of 0.25 to 0.54 nm and a minimum spatial resolution of 7 by 28 km. TROPOMI measures the levels of O3, NO2, SO2, bromate (BrO3-), formaldehyde (HCHO) and water vapor (H2O), CO and methane (CH4) (Veefkind et al., 2017) (Table 1.).

Table 1. Overview of TROPOMI spectral bands and their key features

<table>
<tr><th colspan="2">Spectral band</th><th>Spectral coverage [nm]</th><th>Aperture width [km]</th><th>Spectral resolution [nm]</th><th>Time resolution</th><th>Spatial resolution [km²]</th></tr>
<tr><td rowspan="2">ultraviolet</td><td>1</td><td rowspan="2">270-320</td><td rowspan="8">~2600</td><td rowspan="2">0.49</td><td rowspan="8">daily</td><td>7x28</td></tr>
<tr><td>2</td><td rowspan="5">7x3.5</td></tr>
<tr><td rowspan="2">visible</td><td>3</td><td rowspan="2">320-495</td><td rowspan="2">0.54</td></tr>
<tr><td>4</td></tr>
<tr><td rowspan="2">near infrared</td><td>5</td><td rowspan="2">675-775</td><td rowspan="2">0.38</td></tr>
<tr><td>6</td></tr>
<tr><td rowspan="2">shortwave infrared</td><td>7</td><td rowspan="2">2305-2385</td><td rowspan="2">0.25</td><td rowspan="2">7x7</td></tr>
<tr><td>8</td></tr>
</table>

Source: Veefkind et al., 2017

TROPOMI has a high radiometric accuracy to infer the carbon monoxide total column over dark vegetation surfaces with a precision of < 10% and has the capability to detect and monitor the air pollution from hotspots like larger cities and industrial regions (Borsdorff et al., 2018).

Downloading SENTINEL-5P data. Data collected within the SENTINEL-5P mission is freely accessible and can be downloaded free of charge through various web services. For the purposes of this paper, the data are downloaded from the Mundi web service (https://mundiwebservices.com/) solely for the simplicity and interactivity of the interface. SENTINEL-5P products are available as NetCDF files in two levels. Because total geolocated carbon monoxide columns are available as a second-level product (SENTINEL-5P L2), a second-level product overview was selected.

Available data are also classified by time, so there are NRT (near real time), OFFL (offline) and RPRO (reprocessed) data. NRT data are available within three hours of observation, cover only one spatial area, and remain available for one month. OFFL data are available within 5 days of observation and cover the full orbit (Sentinel-5P, URL 8).

The interface for displaying and downloading data is quite simple to operate and allows you to draw or mark the area for which you want to download data with a point, rectangle or polygon. It is also possible to set the time frame within which the data is to be downloaded. There is also the option to select some additional filters such as product type and processing method.

Firstly, the area of the territory of the Republic of Croatia is marked with a rectangle. A slightly wider area than the default one is drawn if a certain part of the boundary data is lost during processing. Data were downloaded for the period from January to September 2020 for every fifteenth day of the month, and the time frame for each individual file was selected accordingly. The product type is set to L2 CO which represents the carbon monoxide level data given as a second level product. Finally, the processing method is set to offline, as we want to download data from the archive that cover the full orbit of the satellite (Fig. 4).

Fig. 4. Downloading data from the Mundi web service
Source: own work

Georeferencing data. After downloading all the data, they were loaded into the QGIS3 software package in order to access their further processing. QGIS is an open source Geographic Information System (GIS) user under a GNU (General Public License) license. QGIS is the official project of the OSGeo (Open Source Geospatial Foundation) foundation. It runs on many operating systems, supports a number of vector, raster, database formats, and contains many functionalities (About QGIS, URL 9). The data were loaded as raster layers and an error was noticed in their coordinates (Fig. 5).

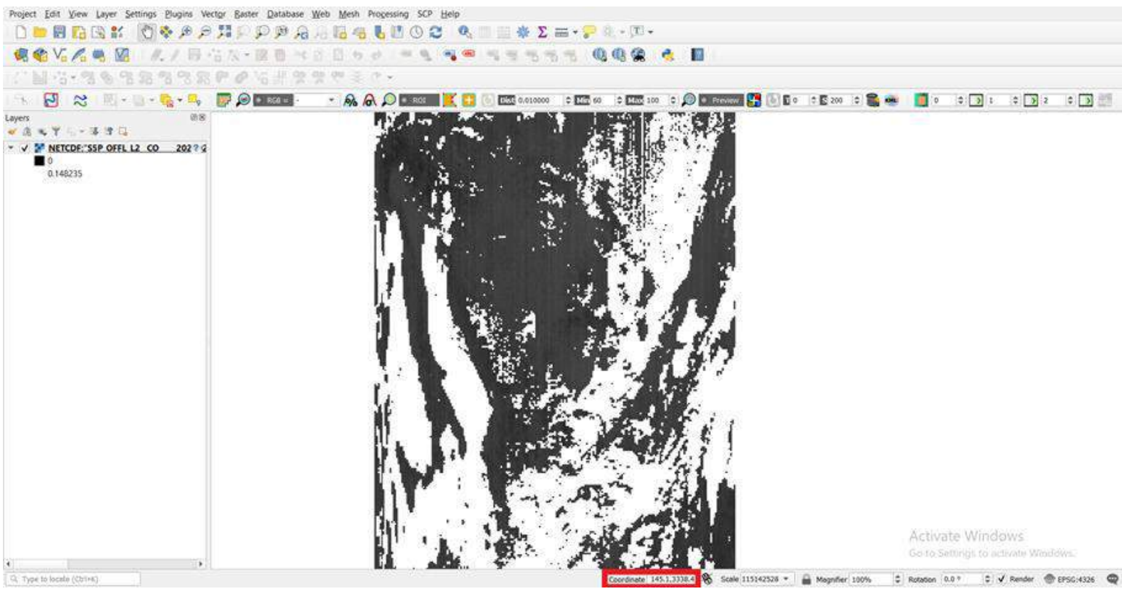


Fig. 5. Error in the coordinates of the downloaded data in QGIS
Source: own work

By loading the data into NASA's free software for viewing NetCDF files – Panoply, it was noticed that all data are properly georeferenced and displayed with the right coordinates corresponding to the system in which they were downloaded that is WGS84 (World Geodetic System 1984) coordinate system (Fig. 6).

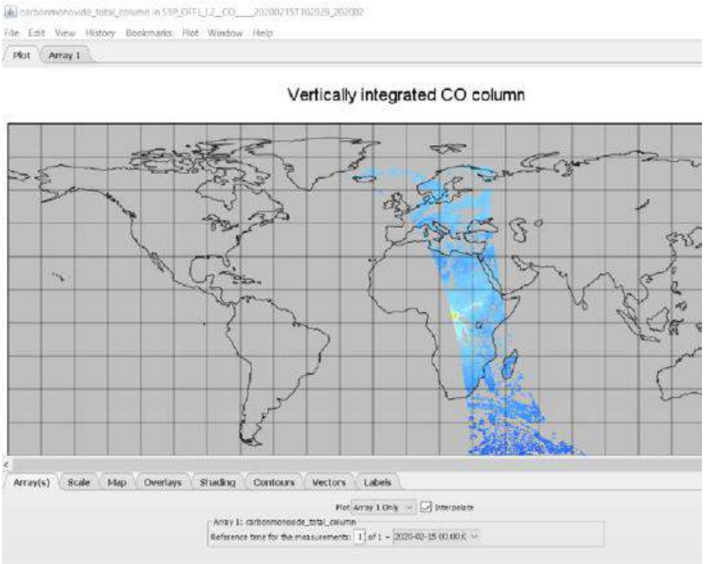


Fig. 6. Checking the georeferenced data in the Panoply software
Source: own work

To properly display the data in QGIS and access further processing, it was necessary to extract a column with the total level of carbon monoxide from each file via Command Prompt and link it to its true coordinates and translate it into raster TIF format. This procedure was performed using the commands shown in Figure 7.

```
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200115T095855_20200115T114025_11691_01_010302_20200119T021840.nc:PRODUCT/carbonmonoxide_total_column CO1501.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200215T102029_20200215T120159_12131_01_010302_20200218T121103.nc:PRODUCT/carbonmonoxide_total_column CO1502.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200315T112052_20200315T130222_12543_01_010302_20200318T130540.nc:PRODUCT/carbonmonoxide_total_column CO1503.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200415T114327_20200415T132458_12983_01_010302_20200417T012736.nc:PRODUCT/carbonmonoxide_total_column CO1504.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200515T104234_20200515T122405_13408_01_010302_20200517T002643.nc:PRODUCT/carbonmonoxide_total_column CO1505.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200615T110235_20200615T124404_13840_01_010302_20200617T005509.nc:PRODUCT/carbonmonoxide_total_column CO1506.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200715T113948_20200715T132118_14274_01_010302_20200722T214909.nc:PRODUCT/carbonmonoxide_total_column CO1507.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200815T101459_20200815T115629_14713_01_010302_20200818T074227.nc:PRODUCT/carbonmonoxide_total_column CO1508.tif
gdalwarp -geoloc NETCDF:S5P_OFFL_L2__CO_____20200915T103056_20200915T121226_15153_01_010302_20200917T001851.nc:PRODUCT/carbonmonoxide_total_column CO1509.tif
```

Fig. 7. Used commands in Command Prompt
Source: own work

The data were then reloaded into the QGIS and it was noticed that the coordinate error was successfully corrected (Fig. 8).

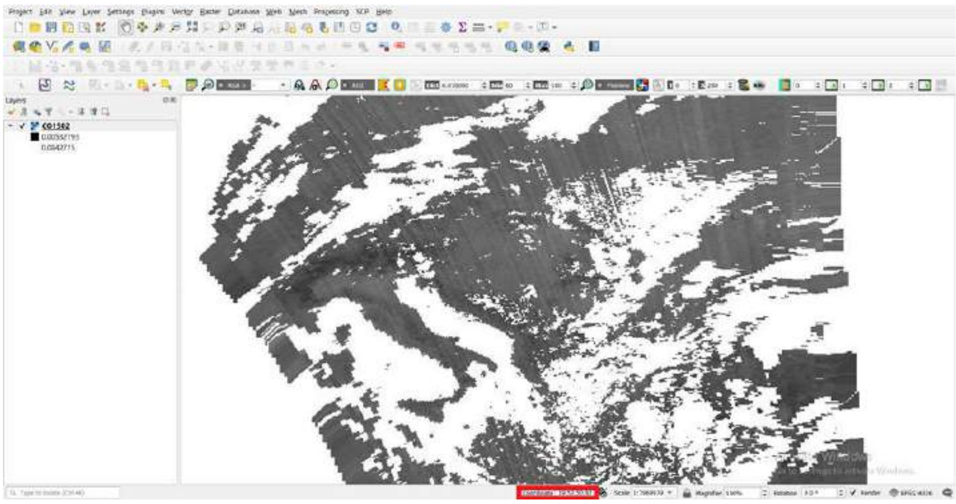


Fig. 8. Data with true coordinates in the WGS84
Source: own work

Downloading vector layers. Since the raster will be cut in the territory of the Republic of Croatia, a vector layer of administrative boundaries at a scale of 1:10 000 000 was downloaded from the Natural Earth service (https://www.naturalearthdata.com/downloads/). Vector layers of roads and settlements were also downloaded on the assumption that urban areas and roads are associated with higher levels of carbon monoxide.

Data processing. In order to access the processing, it is necessary to have all the raster and vector data in the same coordinate system. Since the basic geodetic coordinate system for the territory of the Republic of Croatia is HTRS96 (*Hrvatski terestrički referentni sustav 1996*), all data were reprojected by simply saving the layer in the desired system.

The first step in data processing is to extract the border of the Republic of Croatia from the layer of all administrative borders. This was done by selecting the border of Croatia and saving it in a separate layer, noting that only selected objects should be saved. Then, with the spatial operation *Intersection*, all other vector layers were cut to the layer of the Croatian border to obtain only the data located on the territory of the Republic of Croatia. To cut the raster layer on the Croatian border layer, the *Clip raster by mask layer* operation was used.

Since the total levels of carbon monoxide for the territory of the Republic of Croatia in the observed time frame range between 0 and 0.06 mol m^{-2}, all raster layers were manually classified into six classes as shown in Figure 9.

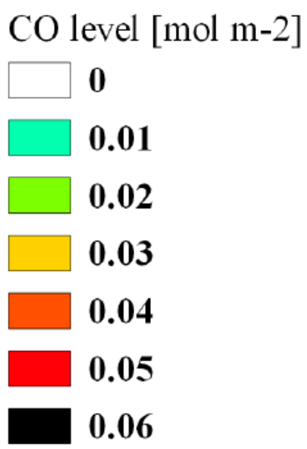


Fig. 9. Classification of raster layers
Source: own work

The *Fill nodata* algorithm was used to fill in some valueless areas by interpolation from edges. The values for the no-data regions are calculated by the surrounding pixel values using inverse distance weighting. After the interpolation a smoothing of the results takes place (Fill nodata, URL 10).

A comparison of one raster layer before and after the implementation of the mentioned algorithm is given in Figure 10.

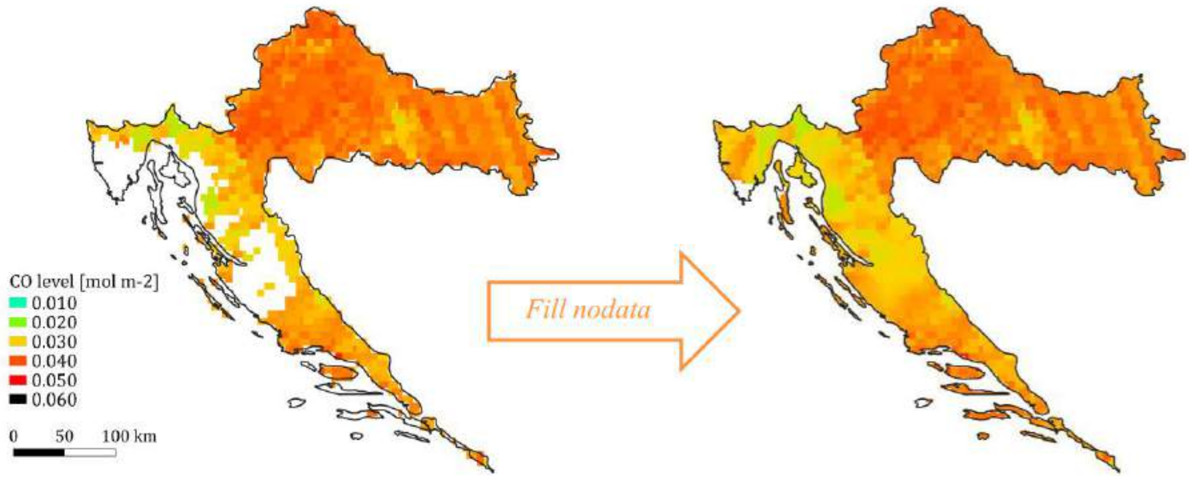


Fig. 10. Comparison of the raster layer before and after the use of *Fill nodata* algorithm
Source: own work

Results and discussion

Data quality control and unit of measurement. The quality of the TROPOMI CO data is related to the variable *qa_value* for each image and it is recommended using data for which the values of the mentioned variable are higher than 0.5 (Table 2) (Landgraf et al., 2020).

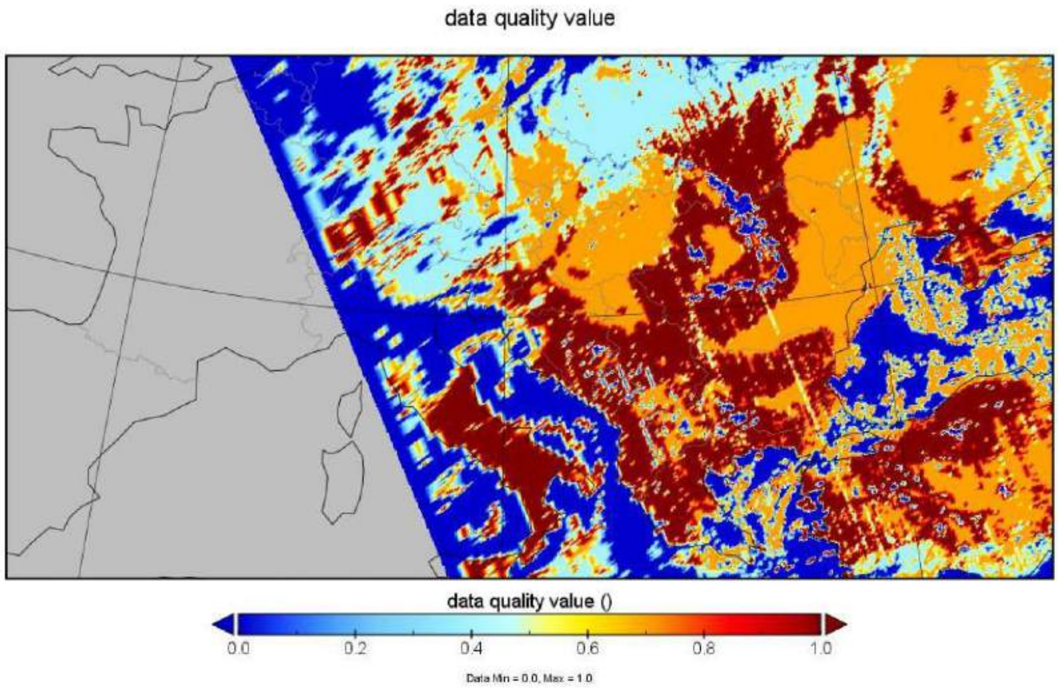
Table 2. qa_value parameter definition

qa_value	Remark
1.0	clear sky and clear-sky like observations
0.7	mid-levels cloud
0.4	high clouds, experimental data set
0.0	corrupted or defective data

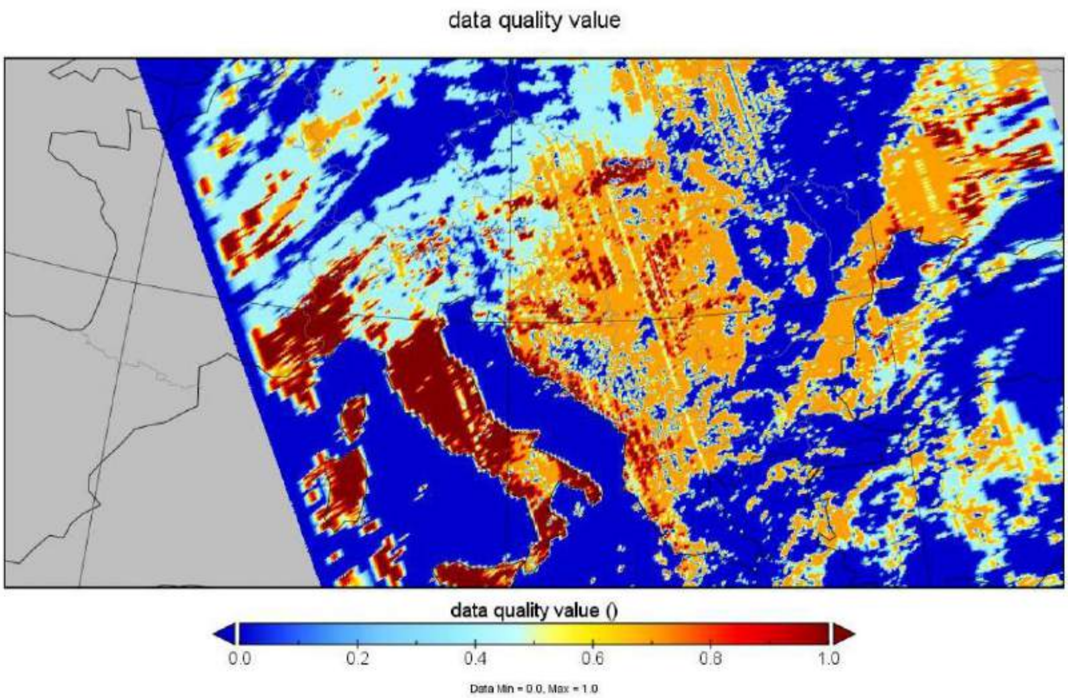
Source: Landgraf et al., 2020

With the help of Panoply software, you can visualize each downloaded image and see the quality of the data used in preparing this paper (Fig. 11).

15.01.


data quality value
data quality value ()
0.0
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.02.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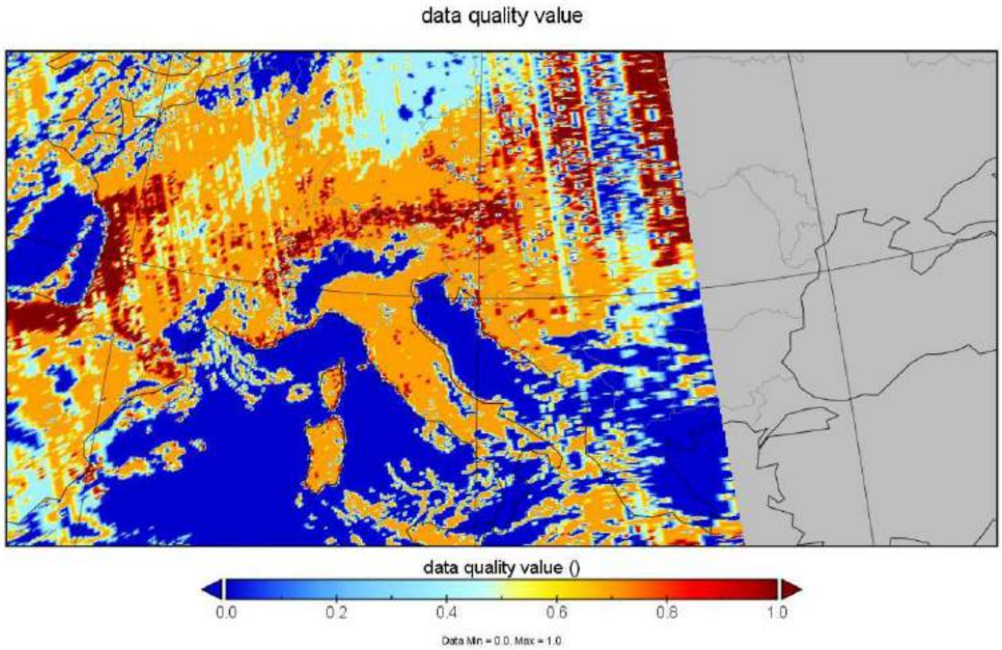
data quality value ()
0.0
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.03.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data quality value ()
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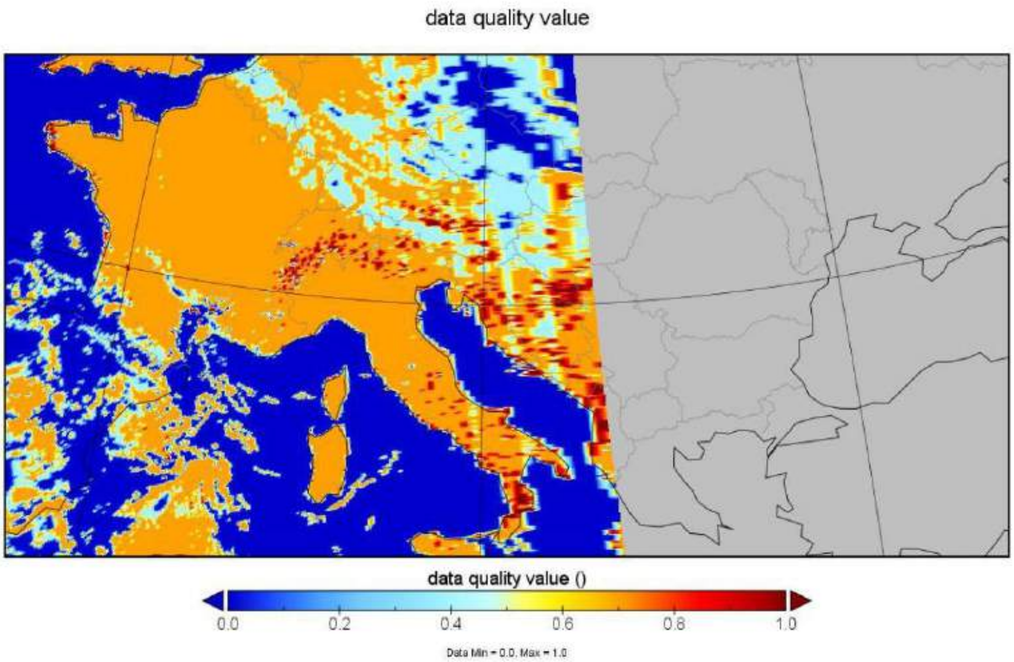
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.04.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data quality value ()
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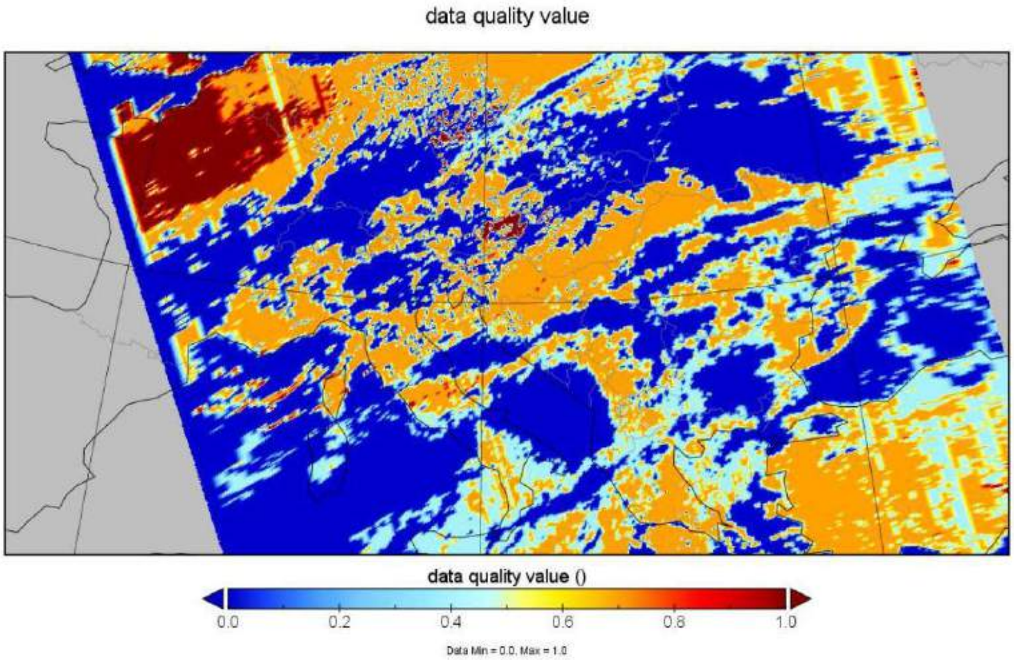
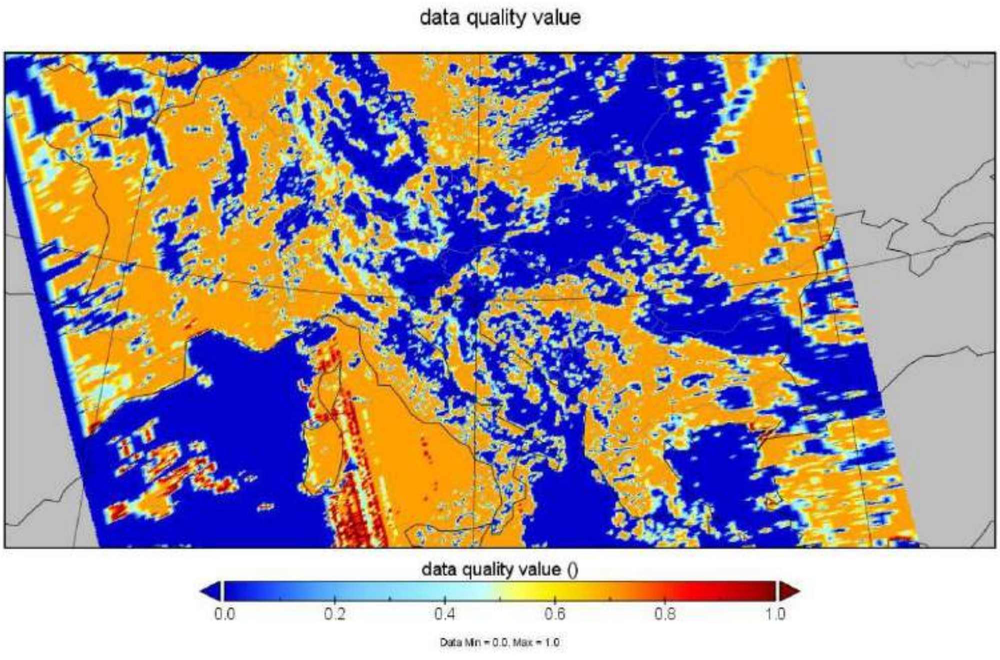
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.05.


data quality value
data quality value ()
0.0
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.06.


data quality value
data quality value ()
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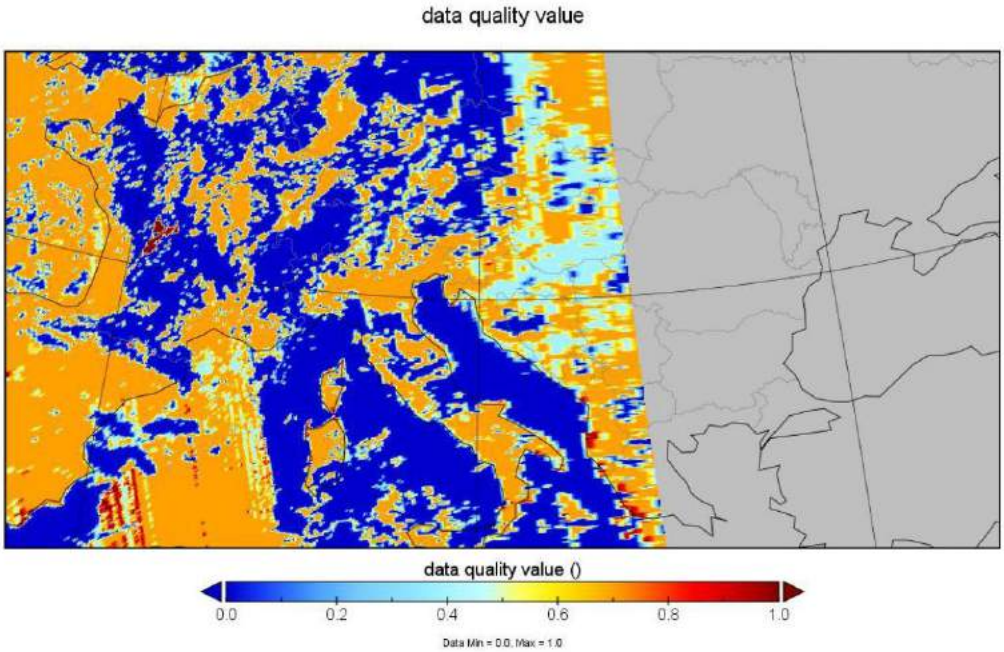
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.07.


data quality value
data quality value ()
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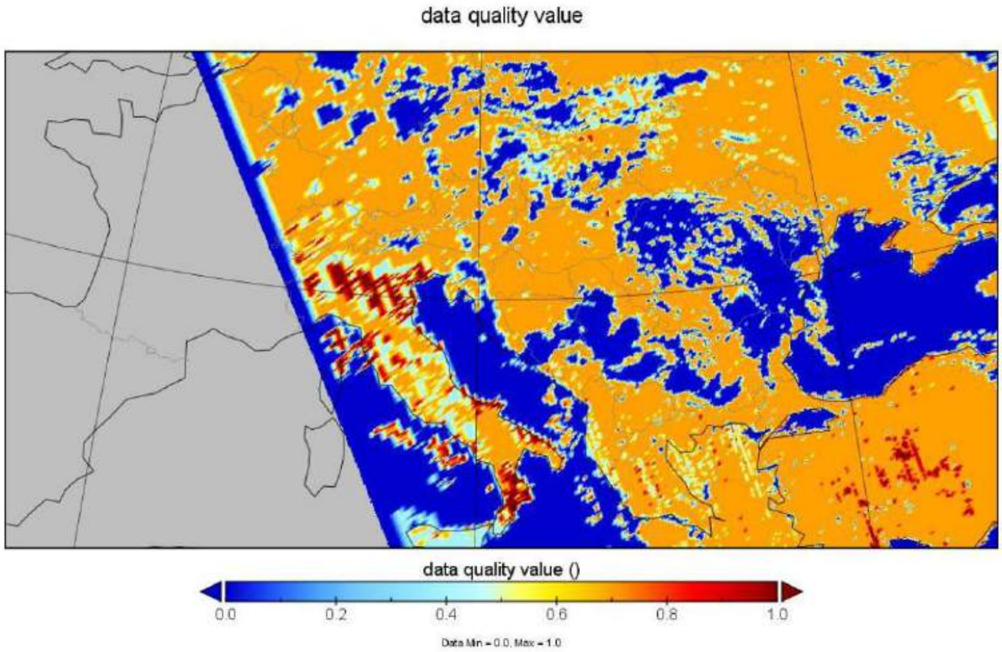
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

15.08.


data quality value
data quality value ()
0.0
0.2
0.4
0.6
0.8
1.0
Data Min = 0.0, Max = 1.0

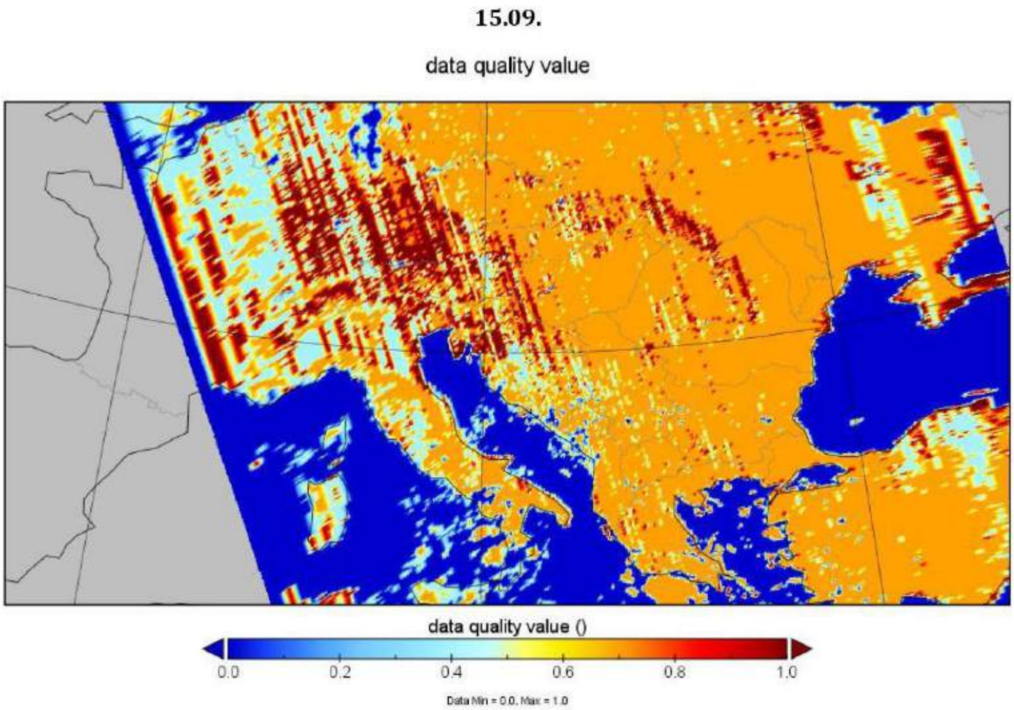


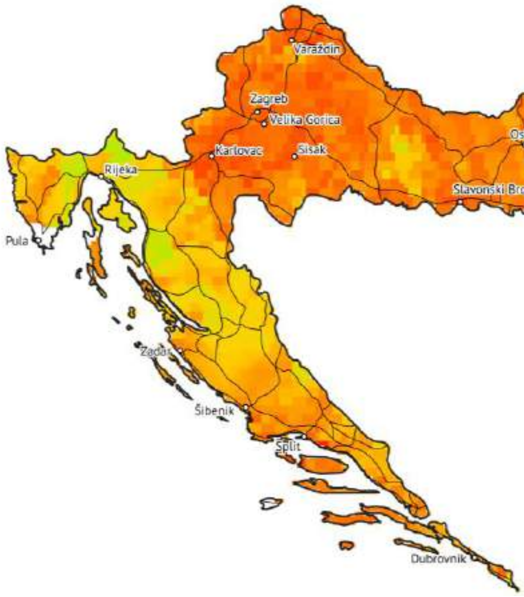
Fig. 11. Visualization of the *qa_value* parameter
Source: own work

It can be noticed that the used data are more than satisfactory for each individual image. The images from May and June show some damaged or incorrect data that were thrown out in the processing, and these parts were filled in the already mentioned way using the *Fill nodata* algorithm.

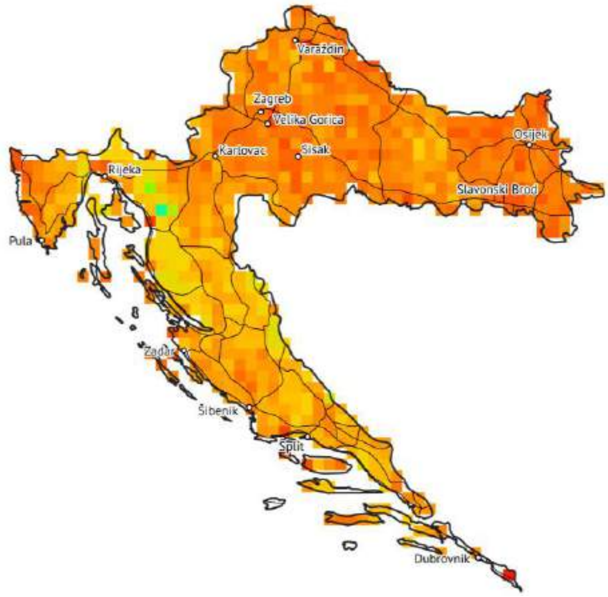
The unit of measurement in which the data are given is mol m^{-2} which represents the number of units of atoms per surface.

Analysis of result. Finally, Figure 12. shows the total levels of carbon monoxide in the territory of the Republic of Croatia from January to September 2020 for every fifteenth day of the month.

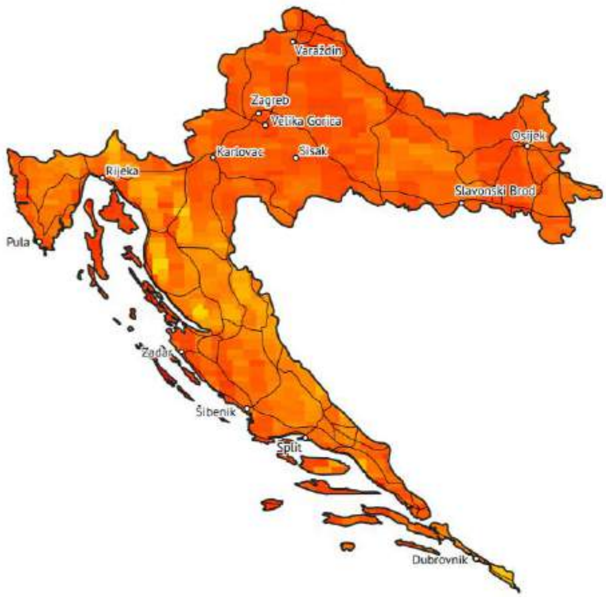
15. 01.



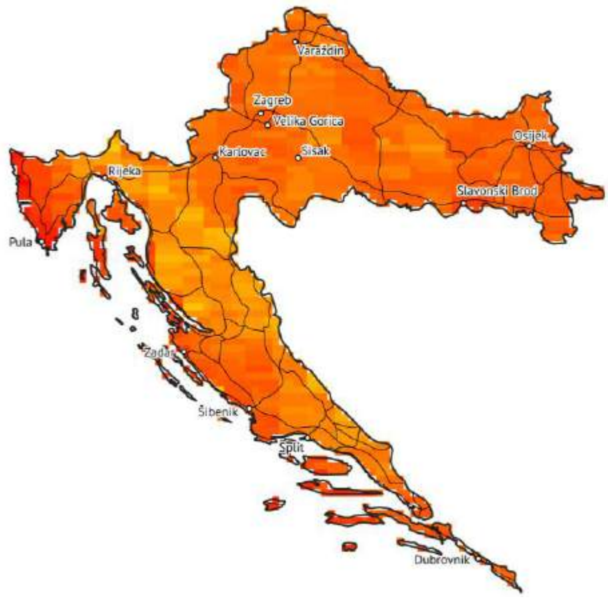
15. 02.

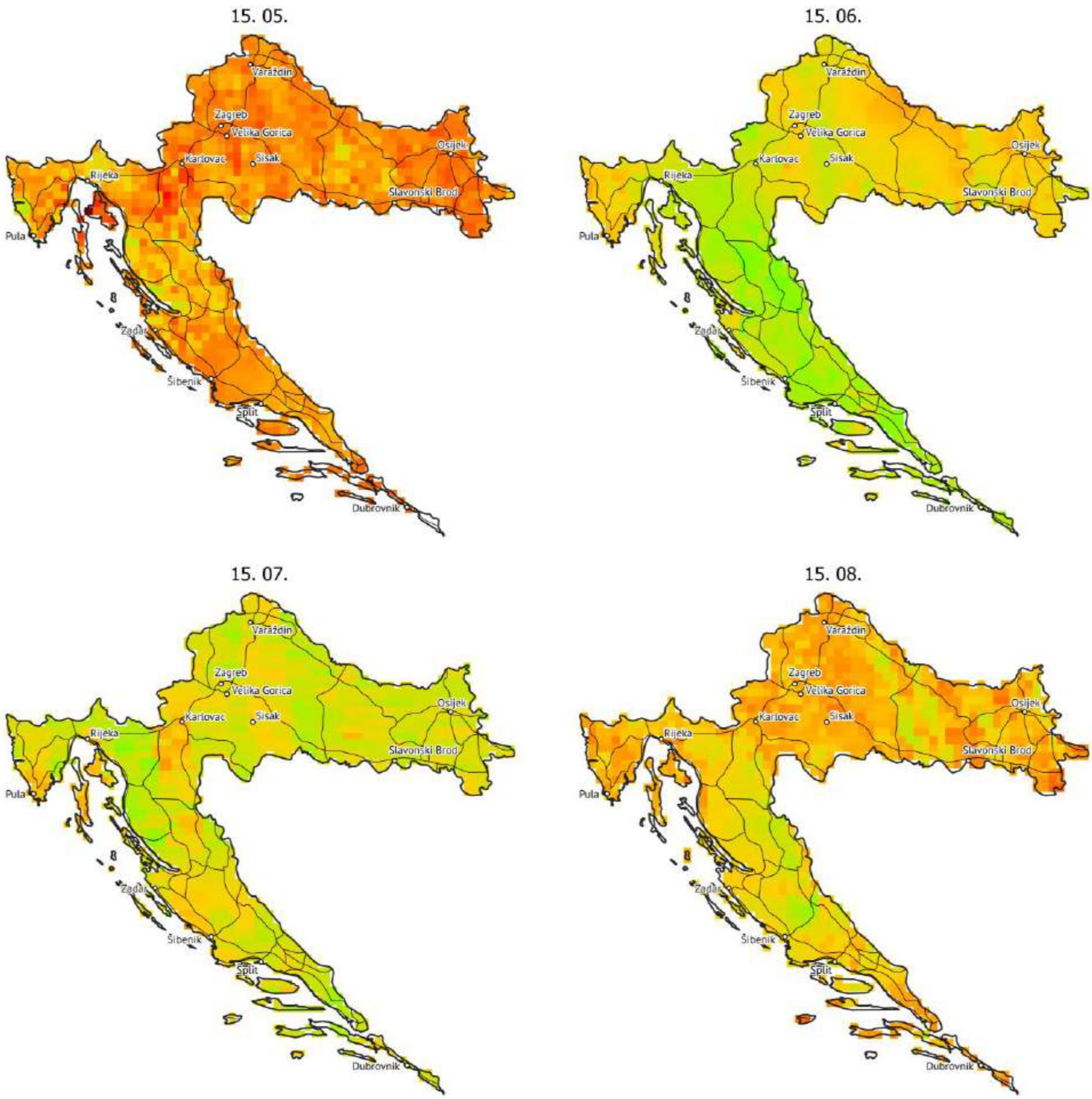


15. 03.



15. 04.




15. 05.
Varaždin
Zagreb
Velika Gorica
Osijek
Karlovac
Sisak
Rijeka
Slavonski Brod
Pula
Zadar
Šibenik
Split
Dubrovnik
15. 06.
Varaždin
Zagreb
Velika Gorica
Osijek
Karlovac
Sisak
Rijeka
Slavonski Brod
Pula
Zadar
Šibenik
Split
Dubrovnik
15. 07.
Varaždin
Zagreb
Velika Gorica
Osijek
Karlovac
Sisak
Rijeka
Slavonski Brod
Pula
Zadar
Šibenik
Split
Dubrovnik
15. 08.
Varaždin
Zagreb
Velika Gorica
Osijek
Karlovac
Sisak
Rijeka
Slavonski Brod
Pula
Zadar
Šibenik
Split
Dubrovnik

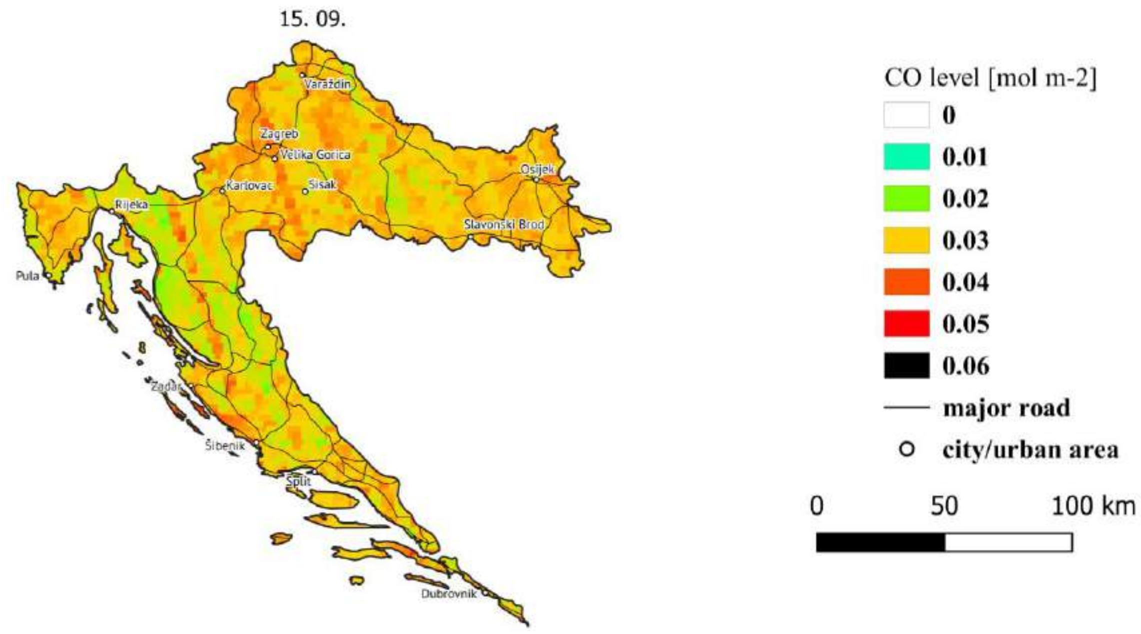


Fig. 12. Total levels of carbon monoxide in the territory of the Republic of Croatia (15.01. – 15.09.2020)
Source: own work

In Figure 12 is visible that urban areas are more likely to have a higher level of CO and that the areas of major roads are also more polluted. However, what turned out to be interesting was the drastic change in June and July, when there was a sudden clearing of the air, and in August and September, the level of CO slowly began to rise again. It is also interesting that the two months with the highest level of CO were March and April when the lockdown measures due to the coronavirus pandemic were the most severe.

Figure 13 gives us insight into CO levels in the five biggest Croatian cities for the observed period. We can notice that all cities follow a similar trend which begins with a small drop in the first two months followed by a rise in March and April, then dropping again starting from May and slowly rising that occurred towards the end. The maximum value of 0.041 mol m^{-2} was measured on April 15th in Zadar and the minimum of 0.025 mol m^{-2} on June 15th in Split. The comparison between population and average CO pollution for the same five cities is shown in Figure 14. Based on these five cities, there is a positive correlation coefficient of 0.71 between population and average CO level, which shows a moderate to good correlation between those two variables.

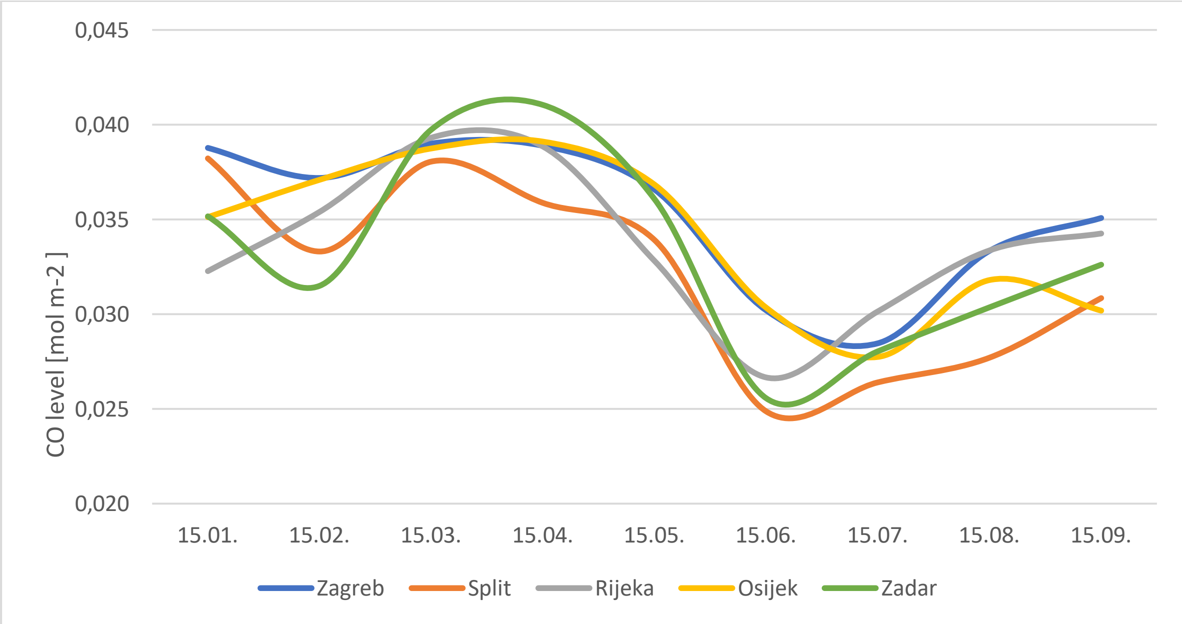


Fig. 13. CO level over five biggest cities
Source: own work

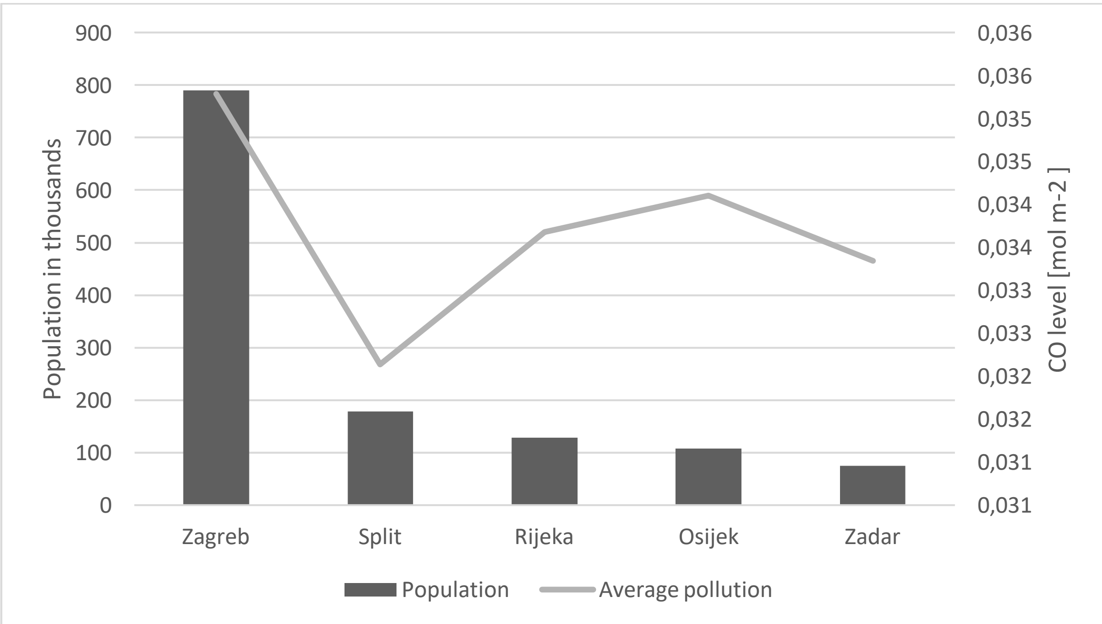


Fig. 14. Comparison between population and average pollution
Source: CO level data, own work; Population data by Croatian Bureau for Statistics, Stanovništvo u najvećim gradovima i općinama, Popis 2011., URL 11

Throughout the observed period, the geographical region that stands out as the most unpolluted is the region Highland Croatia (Fig. 15), which is in support of several studies that have investigated the relationship between altitude and air quality, and have reported that air pollution declines with height (Kaplan & Avdan, 2020).

Fig. 15. Geographical regions of the Republic of Croatia
Source: Contemporary regions, URL 12

Conclusion

This paper presents the level of carbon monoxide in the territory of the Republic of Croatia from the data observed by the TROPOMI instrument of the satellite mission SENTINEL-5P for the period from January to September 2020 for every fifteenth day of the month. Carbon monoxide as one of the primary air pollutants has a great influence in determining air quality, so its monitoring is of great importance for global health. The results of this study showed that urban and major road areas are more exposed to higher levels of CO. The link was noticed also between the level of pollution and altitude, therefore lower areas are more polluted than the higher ones. March and April stand out as the two months with the highest level of CO, even though at that time lockdown measures were the most severe due to the coronavirus pandemic. A sharp decrease in CO levels was noticed between May and June.

The research confirmed the hypothesis that urban areas and areas of major roads are more polluted with carbon monoxide. However, the study partially refuted the hypothesis that the lockdown due to the coronavirus pandemic had a reduction in carbon monoxide pollution, as the observed reduction in CO levels occurred two months after the lockdown period and their link cannot be seen.

This paper gives general insight on the total level of carbon monoxide over the territory of the Republic of Croatia for the observed period, but in order to get a complete picture of air pollution, it is necessary to take into account all other air pollutants that are omitted in this paper.

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