International Journal of Engineering and Geosciences (IJEG),
Vol; 5, Issue; 3, pp. 130-137, October, 2020,

International Journal of Engineering and Geosciences (IJEG),
Vol; 5, Issue; 3, pp. 130-137, October, 2020, ISSN 2548-0960, Turkey,
DOI: 10.26833/ijeg.644089

SPACE-BORNE AIR POLLUTION OBSERVATION FROM SENTINEL-5P TROPOMI: RELATIONSHIP BETWEEN POLLUTANTS, GEOGRAPHICAL AND DEMOGRAPHIC DATA

Gordana Kaplan [1]*, Zehra Yigit Avdan[2]

[1] Earth and Space Institute, Eskisehir Technical University, Eskisehir/Turkey;
(gkaplan@eskisehir.edu.tr) **ORCID 0000-0001-7522-9924**
[2] Department of Environmental Engineering, Eskisehir Technical University, Eskisehir/Turkey;
(zyigit@eskisehir.edu.tr); **ORCID 0000-0001-7445-3393**

*Corresponding Author, Received: 07/11/2019, Accepted: 11/01/2020

ABSTRACT: This study presents an analysis of the mean atmospheric column nitrogen dioxide (NO_2) and carbon monoxide (CO) over the Republic of North Macedonia during a six-month period. Measurements of NO_2 and CO obtained from the recently launched Sentinel-5 Precursor spacecraft with TROPOspheric Monitoring Instrument (Sentinel-5P TROPOMI) have been used. The aim of this study was to use relatively high-resolution satellite data for local air quality/air pollution monitoring and to investigate the relation of the pollutants with geographical and demographical data of the study area. For that purpose, along with CO and NO_2 data from TROPOMI, population statistics, digital elevation model and vegetation cover have been used for geo-spatial and statistical analyses. The findings show significantly high CO and NO_2 values in several parts of the study area, especially high CO values in the Vardar and Polog Valleys, and high NO_2 values in the densely populated cities. According to the analyses, there is high positive correlation between the NO_2 and the population statistics ($r = 0.78$; $R^2 = 0.61$) and high negative correlation ($r = -0.9$; $R^2 = 0.80$) between the altitude and the CO values of the study area. The overall results of this study confirmed the capability of Sentinel-5P TROPOMI data to be used in monitoring the air quality and air pollution over local areas.

Keywords: *Remote Sensing, Air pollution, Air quality, Population, Digital Terrain Model, Sentinel-5 TROPOMI.*

1. INTRODUCTION

With the rapid increase of the World`s population rises the problem of air pollution. One of the main causes of air pollution are urbanization, energy consumption, transportation, and motorization. Also, population growth and exposure to air pollutants have a negative impact on the quality of the environment and human health (Mayer 1999, Kampa and Castanas 2008, Hou et al. 2019). The World Health Organization (WHO) has identified air pollution as the single largest environmental health risk in the World (Organization 2016). Together with climate change, air pollution is one of the most serious threats to global health (Campbell-Lendrum and Prüss-Ustün 2019). It has been estimated that approximately four million people die every year as a result of exposure to air pollution in 2016, ambient air pollution has contributed to 7.6% of all deaths Worldwide (Organization 2016).

The biggest air pollutants encountered in our daily life are particulate matter (PM), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and carbon dioxide (CO_2) (Chen et al. 2007). High concentrations of O_3, PM, and NO_2 near the Earth's surface can cause serious health problems, such as pulmonary and cardiovascular diseases (Brunekreef and Holgate 2002), and recognition is growing of the combined health effects of multiple pollutants (Dominici et al. 2010).

NO_2 is one of the largest components of urban air pollution and a precursor to ground-level O_3, PM, and acid rain (Bechle et al. 2013). The major source of NO_2 is the burning of fossil fuels such as coal, oil and gas. According to the European Environment Agency 2018 Air Quality report, more than 60% of the nitrogen dioxide in European cities comes from motor vehicle exhaust. Other sources of NO_2 are petrol and metal refining, electricity generation from coal-fired power stations, other manufacturing industries and food processing.

CO is a product of incomplete combustion as encountered in the operation of vehicles, heating, coal power generation, and biomass burning (Godish et al. 2014). Approximately 40% of CO comes from natural sources like volcanic eruptions, emission of natural gases, degradation of vegetation and animals, and forest fires (Varma et al. 2009), and 60% comes from fossil fuel consumption, garbage disposal, tobacco smoke, and charcoal fires (Vreman et al. 2000). Although tropospheric CO is not regarded as a health concern outdoors, recent studies show a possible link between exposure to urban CO concentrations and cardiac problems (Andre et al. 2010). Satellite observations of tropospheric NO_2 have been conducted since 1995 (Burrows et al. 1999) with the Global Ozone Monitoring Experiment (GOME) satellite instrument, designed to observe the several gases in the Earth`s stratosphere and troposphere.

For a reliable prediction and decision-making to mitigate the impact of air pollutants, continuous and accurate monitoring of the air quality is necessary (Hou, Wang et al. 2019). In comparison with conventional measurements, remote sensing techniques and Geo-Information Systems (Guo et al. 2019) are capable of providing complementary information for unmonitored areas (Theys et al. 2019) and for acquiring information about the Earth such as Land and Sea Surface Temperature (Khorrami et al. 2019, Nacef et al. 2016), vegetation cover, air quality and even predict and evaluate natural disaters such as fires (Comert et al. 2019). Satellite observation for air quality have been used for over four decades starting with the launch of the Total Ozone Monitoring Instrument (TOMS) in 1978, GOME in 1995 (Burrows et al. 1999), Ozone Monitoring Instrument (OMI) in 2004, and Sentinel-5 Precursor Tropospheric monitoring instrument (Sentinel-5P TROPOMI) in 2017. These satellite instruments are designed to observe the several gases in the Earth`s stratosphere and troposphere. For example, Jabeen et al. (Jabeen and Khokhar 2019) used low-spatial resolution OMI satellite data for monitoring the atmospheric burdens of SO_2 over Pakistan over a time period of 2005–2016, while Hou et al. (Hou et al. 2019) used OMI satellite data for investigating the temporal and spatial dynamics of NO_2 over China. Similar, Oner et al. (Oner and Kaynak 2016) evaluated the NO_x emissions from available inventories using satellite NO_2 retrievals from OMI over Turkey. Deferring from the other air-quality observation satellite instruments, TROPOMI has a relatively high spatial resolution that is necessary for air quality applications (Abida et al. 2016). Since the launch of Sentinel-5p, several studies have shown the success of the TROPOMI instrument. Thus, Kaplan et al. (Kaplan et al. 2019), used TROPOMI data for monitoring the NO_2 over Turkey, Theys et al. (Theys et al. 2019) investigated volcanic SO_2, and Borsdorff et al. (Borsdorff et al. 2018) presented the first results of measuring CO with TROPOMI over China. Statistical analyses of the global comparison between TROPOMI and ground-based measurements show small percentage difference (Garane et al. 2019). This study investigates the relationship between air pollutants, geographical and demographical data using high-resolution space-borne data retrieved from the TROPOMI sensor over a six-month period over the Republic of North Macedonia. Using high-resolution Sentinel-5p imagery, the main objectives of this study are:

- Estimating the NO_2 and CO amount over the Republic of North Macedonia;
- Determining the relationship between the demographic data and air pollutants;
- Determining the relationship between geographical data and air pollutants.

2. DATA AND METHODS

2.1 Study Area

The Republic of North Macedonia (41.6086° N, 21.7453° E) is a landlocked country within the Balkan Peninsula in Southeast Europe (Figure 1), with a total area of 25.713 km^2. The countries geography consists of mountains, valleys, and rivers, defined by a central valley formed by the Vardar river framed by mountain ranges with sixteen mountains higher than 2,000 meters above sea level.

(IJEG),

International Journal of Engineering and Geosciences

Vol; 5, Issue; 3, pp. 130-137, October, 2020,

Figure 1. Study Area; Republic of North Macedonia

Based on the latest United Nations estimates, Macedonia has 2.086.815 inhabitants. The city of Skopje, formed on the riverbed of Vardar, is the capital with more than 500.000 of 2.08 million inhabitants. North Macedonia has a transitional Mediterranean to continental climate.

In the past few years, the air quality in the country is a cause of serious concern as the limit values set for the protection of human health are significantly exceeded. According to the Macedonian Air Quality Assessment Report for 2005-2015, air pollution is on high level in the largest urban settlements, especially in the city of Skopje and Tetovo, where the NO_2 and CO have exceeded the limit values of 40 µm/m^3 for NO2 at annual, and 10 µm/m^3 at daily period. As one of the main air polluters are considered to be household heating, population density, transportation, industry, and urbanization. The national air quality monitoring network includes 17 stations in different parts of the country measuring SO_2, CO, NO_2, O_3 and PM. According to the Air quality in Europe - 2018 report (Agency 2018), the annual limit value of air pollutants in 2016 has been above the limited values.

2.1 Data and Methods

TROPOMI is a space-borne spectrometer covering wavelength bands between the ultraviolet and the shortwave infrared, and it is the single payload of the Sentinel-5p spacecraft launched 13th October 2017 into the low earth orbit funded jointly by the Netherlands Space Office and the European Space Agency (ESA). The data has open access and it can be downloaded from the ESA Copernicus Open Access Hub (https://scihub.copernicus.eu/). The instrument is designed to obtain data for air quality and climate observations (Voors, de Vries et al. 2017). The instrument operates in a push-broom configuration (non-scanning), with a swath width of approximately 2600 km on the Earth's surface which makes daily global coverage in combination with good spatial resolution possible. No additional pre-processing is required before using the data.

Using spectral bands from the ultraviolet, visible and near-infrared wavelength range, TROPOMI measures O_3, NO_2, SO_2, bromate (BrO_3^-), formaldehyde (HCHO) and water vapor (H_2O) tropospheric columns from the ultraviolet, visible and near-infrared wavelength, and CO and methane (CH_4) tropospheric columns are measured from the short-wave infrared wavelength range (Veefkind, Kleipool et al. 2017) (Table 1).

Table 1. Summary of the TROPOMI spectral bands and their key features (Veefkind, Kleipool et al. 2017)

Band		Spectral coverage [nm]	Swath width [km]	Spectral resolution [nm]	Temporal resolution	Spatial sampling [km^2]
UV	1	270 – 320	~2600	0.49	Daily	7x28
	2					7x3.5
VIS	3	320 – 495		0.54		
	4					
NIR	5	675 – 775		0.38		
	6					
SWIR	7	2305 – 2385		0.25		7x7
	8					

In comparison with the other existing air quality observing space-borne instruments, TROPOMI's much finer spatial resolution promises to improve substantially of the information content. TROPOMI is the first imaging spectrometer ever to deliver global data with a moderate spatial resolution and a continuous spectral sampling of the red and NIR spectral regions (the so-called vegetation red-edge), which are also covered by GOME-2 but with a much coarser spatial resolution. (Guanter et al. 2015).

With the theoretical fact that there is a high relation between the altitude and air pollution density (Müezzinoğlu 1987), several studies have investigated the relationship between altitude and air quality, and have reported that air pollution declines with height (Ji et al. 2018). However, there is insufficient evidence to support significantly increased ecological effects and dispersion change at high altitudes.

Taking into consideration the advantages of the TROPOMI instrument, this paper investigates the relationship between air pollutants, geographical and demographical data using high-resolution space-borne data over a six-month period over the Republic of North Macedonia. The mean value of the NO_2 and CO collected from July 2018 to January 2019 were compared with the geographical and demographic data (Figure 2) from the study area. Thus, a satellite retrieved digital terrain model (DTM) and a vegetation cover map, , were used for a statistical relationship with the air pollutants (Figure 3).

A NDVI from MODIS with an approximate spatial resolution of 1 km was used in this study. In order to be able to compare the data, the NDVI resolution has been decreased to TROPOMI`s resolution. Same was the case for the 90 m DTM from the satellite ASTER.

The summary and maximum value of the air pollutants, CO and NO_2, were statistically calculated for thirty-four municipalities in North Macedonia, separately. Accordingly, the same calculations were made for geographical and vegetation data. Using geospatial analyses, the remote sensing data were linked to the demographical statistics and afterward, statistical analyses were performed.

In a campaign carried by the Finish Meteorological Institute and the Royal Netherlands Meteorological Institute during April-September 2018 (Ialongo et al. 2018), TROPOMI data were compared with ground-based observation in Helsinki. According to the findings, it was concluded that the differences between the total columns derived from the TROPOMI and Pandora instruments are on average less than 10 %.

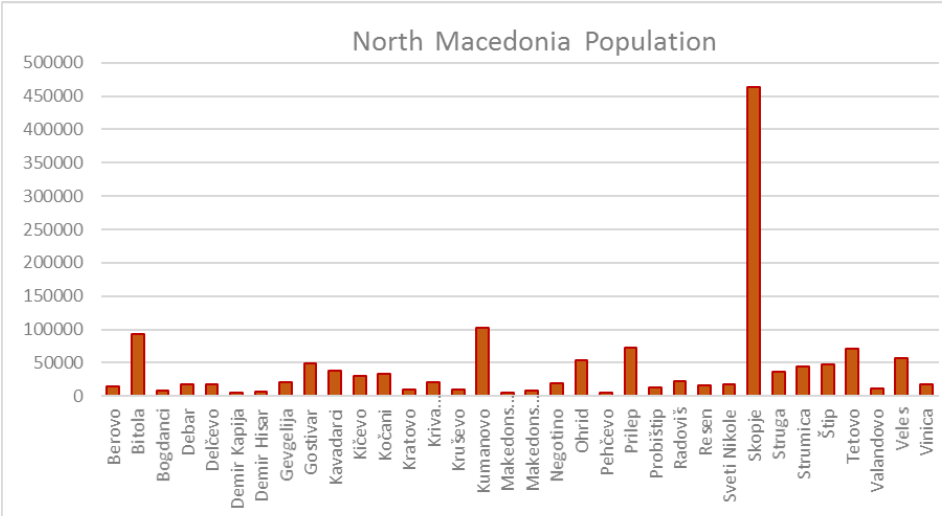

Figure 2. North Macedonia population

the

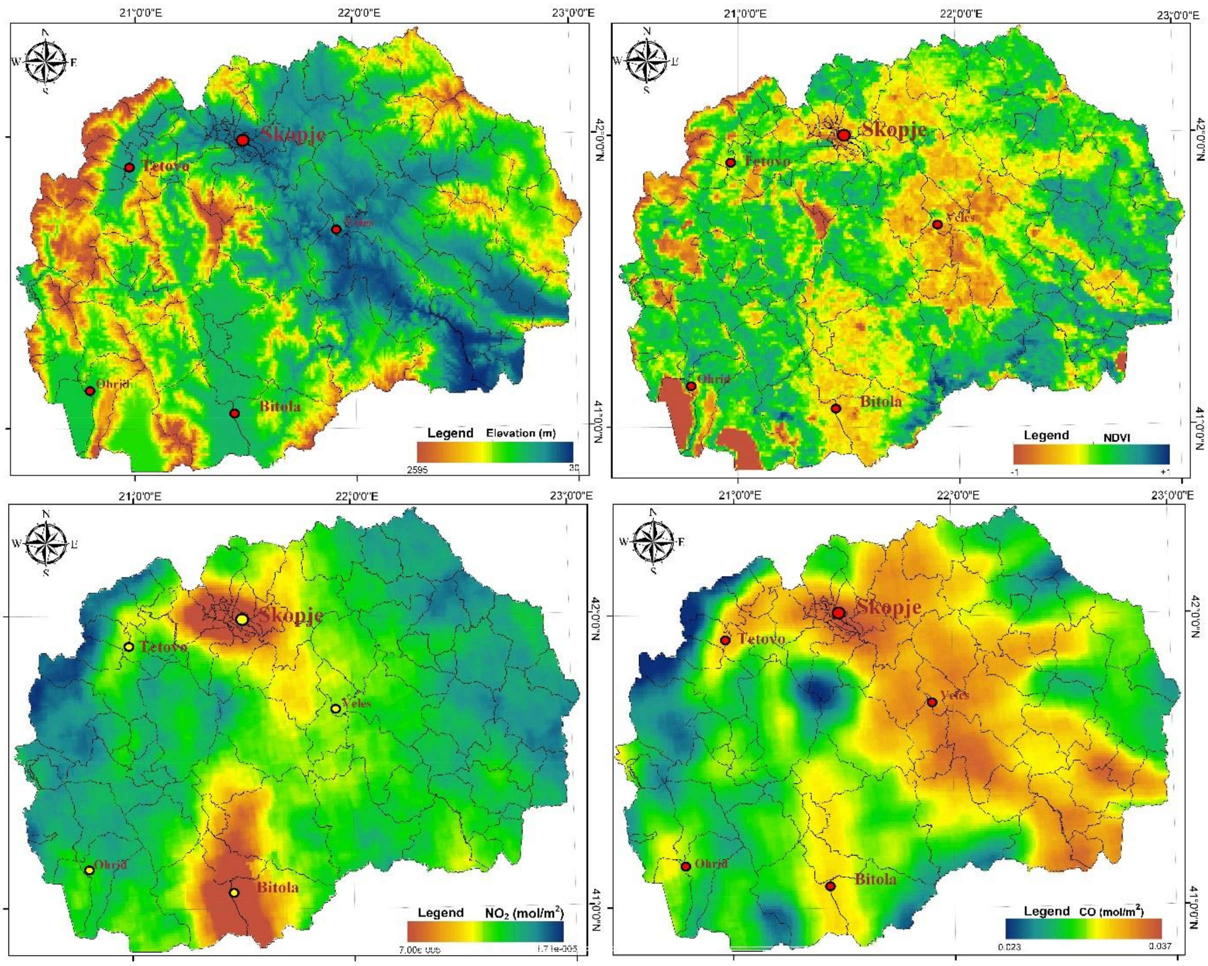

Figure 3. Remote Sensing data used in this study

3. RESULTS AND DISCUSSION

3.1 Overall results of CO and NO_2

The spatial distribution of tropospheric CO and over the Republic of North Macedonia during July 2018 – January 2019 are presented in Figure 4. The selected period is from summer, autumn and winter. Observing both visual (Figure 3) and statistical results of CO, it can be noticed that several regions have significantly higher values than others. Thus, high values can be noticed in the cities of Skopje, with highest value of 0.036 mol/km^2, Strumica, Negotino, Kavadarci, Gevgelija, Demir Kapija, and Veles, respectively. If seen geographically, it can be noticed that the highest CO values are set in the Vardar Valley. Other than that, high CO values can be also noticed in the Polog Valley, in the cities Prilep and Bitola, respectively.

Figure 5 shows the spatial distribution of tropospheric NO_2 over the Republic of North Macedonia from July 2018 – January 2019. Observing both visual (Figure 3) and statistical results of NO_2, it can be noticed that several regions have significantly higher values than others. Thus, high values can be noticed in the cities of Skopje, with highest value of $7.0*10^{-5}$ mol/km^2, Bitola $6.0*10^{-5}$ mol/km^2, Prilep $5.0*10^{-5}$ mol/km^2, Kumanovo 4.0*10-5 mol/km^2, respectively. It should be noticed that these are cities with highest population statistics.

3.2 Relationship Between Pollutants, Geographical and Demographical Data

Although the relationship between pollutants and other factors is generally known, further investigation is needed. Several studies have investigated the relationship between altitude and air quality, and have reported that air pollution declines with height (Ji et al. 2018). However, there is insufficient evidence to support significantly increased ecological effects at high altitudes. In order to mitigate air pollution and to increase air quality, firstly the biggest contributors and causes of air pollution need to be detected. In this study, the relation between several air pollutants, CO and NO_2, and demographical and geographical data have been statistically analyzed. For that purpose, coefficient of determination and correlation coefficients have been retrieved, and the results of the correlation between the NO_2 and the population statistics are presented in Figure 6 from where a high correlation between the population and both maximum value and summary of the NO2 can be noticed. Thus, it can be concluded that in more than 60% of the cases, the NO2 value will increase if the population increases and vice versa (Figure 6). These results are expected, as the major source of NO_2 is the burning of fossil fuels such as coal, oil and gas.

Figure 4. Mean tropospheric CO obtained from TROPOMI over North Macedonia from July 2018 to January 2019

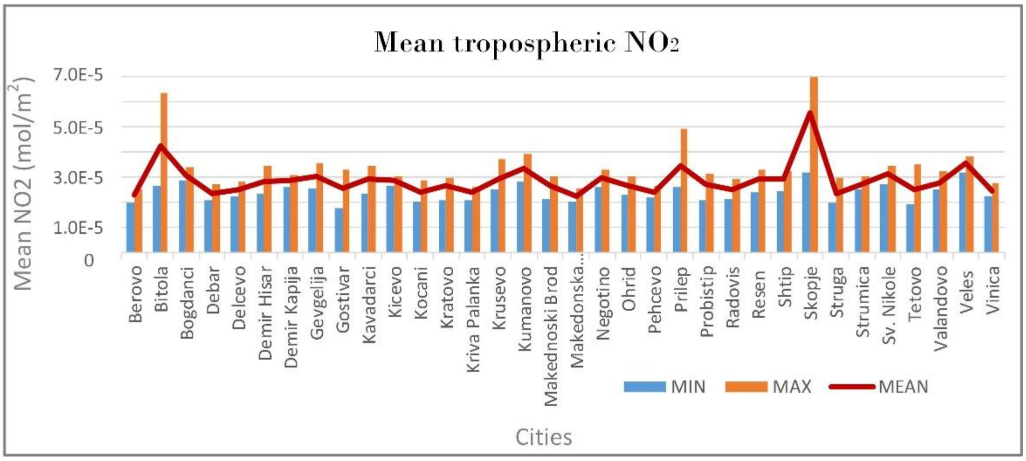

Figure 5. Mean tropospheric NO2 obtained from TROPOMI over North Macedonia from July 2018 to January 2019

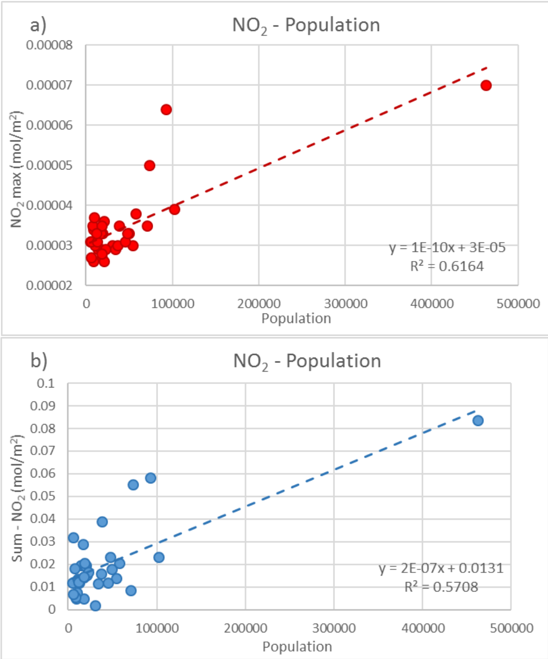

Figure 6. Mean values of tropospheric NO_2 obtained from TROPOMI over North Macedonia from July 2018 to January 2019 and statistical correlation with; a) maximum NO2 value; b) summary of NO_2

Although no significant relation could be found between the CO and the population statistics, the results showed that CO values are highly correlated with the elevation of the area. This can be also seen in Figure 3 where high CO values are noted along Vardar Valley followed by high values in the Polog valley. Thus, the correlation coefficient between the CO and the DTM shows high negative correlation ($r = -0.9$; $R^2 = 0.8$), meaning that 80% of the times, as the altitude rises, the CO value will decrease. Also, an analysis between the two air pollutants was made and the results showed a medium positive correlation ($r = 0.51$) between CO and NO_2. The correlation values between the air pollutants, geographical and demographical data can be seen in Figure 7.

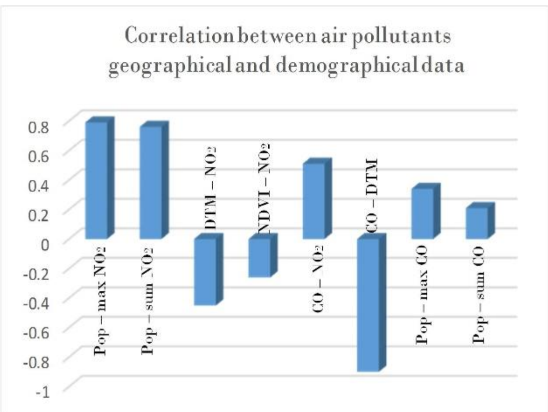

Figure 7. Correlation coefficients between air pollutants obtained from TROPOMI and geographical and demographical data

4. CONCLUSION

In this study, the relation between air pollutants, CO and NO_2 remotely sensed data retrieved from the Sentinel-5P TROPOMI instrument over the Republic of North Macedonia during the period July 2018 – January 2019, and geographical and demographical data has been investigated. In comparison with the other existing air quality observing space-borne instruments, with TROPOMI's much finer spatial resolution, in this study detailed investigation of the air quality in every municipality was made. Furthermore, using remote sensing, geo-spatial analyses and statistical analyses, the relation between the North Macedonia`s population statistics, altitude values extracted from a DTM, vegetation cover, and mean values over a six-month period of CO and NO_2 have been made. The results from this study can be summarized as follows:

1) Both visual and statistical results of CO indicate that several regions have higher values than others. Significantly high values can be noticed in the Vardar and Polog Valley;

2) From the NO_2 observation, high values can be noticed in the cities with highest population; Skopje, with a highest value of 7.0*10-5 mol/km², Bitola, Prilep, Kumanovo, respectively;

3) The coefficient of determination and correlation coefficients indicates high correlation between the NO_2 and the population statistics ($r = 0.78$; $R^2 = 0.61$);

4) The results showed high negative correlation ($r = -0.9$; $R^2 = 0.8$) between the altitude of the study area and the CO values.

The overall results of this study confirm the capability of Sentinel-5P TROPOMI data to be used in monitoring the air quality and air pollution over local areas. In this study, analyses were made separately for thirty-four municipalities. Monitoring the air quality with ground measurements can be challenging and insufficient as there is limited number of air-quality monitoring stations. With TROPOMI data, air quality information can be obtained daily with a relatively high spatial resolution. Compared with the Macedonian Air Quality Assessment Report for 2005-2015, the results are with good correlation, as the report also indicates that air pollution is on high level in the largest urban settlements, especially in the city of Skopje and Tetovo, where the NO_2 and CO have exceeded the limit values of 40 µm/m3 for NO2 at annual and 10 µm/m3 at daily period.

For future studies, we recommend investigating the seasonal variation of the pollutants observed with the TROPOMI instrument, exploring other pollutants, validating the results with ground measurements, and evaluating other factors such as wind direction, building density or other factors that may contribute to air pollution.

REFERENCES

Abida, R., L. El Amraoui, P. Ricaud, W. Lahoz, H. Eskes, A. Segers, L. Curier, J. de Haan, A. Nijhuis and D. Schuettemeyer (2016). "Impact of Spaceborne Carbon Monoxide Observations from the S-5P platform on Tropospheric Composition Analyses and Forecasts." Atmospheric Chemistry and Physics 2016 (2): 1-1.

Agency, E. E. (2018). "Air quality in Europe — 2018 report." Available at: https://www.eea.europa.eu › air-quality-in-europe-2018. Access date: 10.11.2019

Andre, L., J. Boissière, C. Reboul, R. Perrier, S. Zalvidea, G. Meyer, J. Thireau, S. Tanguy, P. Bideaux and M. Hayot (2010). "Carbon monoxide pollution promotes cardiac remodeling and ventricular arrhythmia in healthy rats." American journal of respiratory and critical care medicine 181(6): 587-595.

Bechle, M. J., D. B. Millet and J. D. Marshall (2013). "Remote sensing of exposure to NO2: Satellite versus ground-based measurement in a large urban area." Atmospheric Environment 69: 345-353.

Borsdorff, T., J. Aan de Brugh, H. Hu, I. Aben, O. Hasekamp and J. Landgraf (2018). "Measuring carbon monoxide with TROPOMI: First results and a comparison with ECMWF‐IFS analysis data." Geophysical Research Letters 45(6): 2826-2832.

Brunekreef, B. and S. T. Holgate (2002). "Air pollution and health." The lancet 360(9341): 1233-1242.

Burrows, J. P., M. Weber, M. Buchwitz, V. Rozanov, A. Ladstätter-Weißenmayer, A. Richter, R. DeBeek, R. Hoogen, K. Bramstedt and K.-U. Eichmann (1999). "The global ozone monitoring experiment (GOME): Mission concept and first scientific results." Journal of the Atmospheric Sciences 56(2): 151-175.

Campbell-Lendrum, D. and A. Prüss-Ustün (2019). "Climate change, air pollution and noncommunicable diseases." Bulletin of the World Health Organization 97(2): 160.

Chen, T.-M., W. G. Kuschner, J. Gokhale and S. Shofer (2007). "Outdoor air pollution: nitrogen dioxide, sulfur dioxide, and carbon monoxide health effects." The American journal of the medical sciences 333(4): 249-256.

Çömert, Resul, DİLEK KÜÇÜK, and Uğur Avdan. "OBJECT BASED BURNED AREA MAPPING WITH RANDOM FOREST ALGORITHM." International Journal of Engineering and Geosciences 4.2: (2019) 78-87.

Dominici, F., R. D. Peng, C. D. Barr and M. L. Bell (2010). "Protecting human health from air pollution: shifting from a single-pollutant to a multi-pollutant approach." Epidemiology (Cambridge, Mass.) 21(2): 187.

Garane, K., M.-E. Koukouli, T. Verhoelst, V. Fioletov, C. Lerot, K.-P. Heue, A. Bais, D. Balis, A. Bazureau and A. Dehn (2019). "TROPOMI/S5ptotal ozone column data: global ground-based validation & consistency with other satellite missions."

Godish, T., W. T. Davis and J. S. Fu (2014). Air quality, CRC Press.

Guanter, L., I. Aben, P. Tol, J. Krijger, A. Hollstein, P. Köhler, A. Damm, J. Joiner, C. Frankenberg and J. Landgraf (2015). "Potential of the TROPOspheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5 Precursor for the monitoring of terrestrial chlorophyll fluorescence." Atmospheric Measurement Techniques 8(3): 1337-1352.

Guo, L., J. Luo, M. Yuan, Y. Huang, H. Shen and T. Li (2019). "The influence of urban planning factors on PM2. 5 pollution exposure and implications: A case study in China based on remote sensing, LBS, and GIS data." Science of The Total Environment 659: 1585-1596.

Hou, Y., L. Wang, Y. Zhou, S. Wang, W. Liu and J. Zhu (2019). "Analysis of the tropospheric column nitrogen dioxide over China based on satellite observations during 2008–2017." Atmospheric Pollution Research 10(2): 651-655.

Ialongo, I., H. Virta, H. Eskes, J. Hovila and J. Douros (2018). "Comparison of TROPOMI/Sentinel 5 Precursor NO2 observations with ground-based measurements in Helsinki."

Jabeen, Z. and M. F. Khokhar (2019). "Extended database of SO2 column densities over Pakistan by exploiting satellite observations." Atmospheric Pollution Research 10(3): 997-1003.

Ji, H., S. Chen, Y. Zhang, H. Chen, P. Guo and P. Zhao (2018). "Comparison of air quality at different altitudes from multi-platform measurements in Beijing." Atmospheric Chemistry and Physics 18(14): 10645-10653.

Kampa, M. and E. Castanas (2008). "Human health effects of air pollution." Environmental pollution 151(2): 362-367.

Kaplan, G., Z. Y. Avdan and U. Avdan (2019). Spaceborne Nitrogen Dioxide Observations from the Sentinel-5P TROPOMI over Turkey. Multidisciplinary Digital Publishing Institute Proceedings.
Mayer, H. (1999). "Air pollution in cities." Atmospheric environment 33(24-25): 4029-4037.

Khorrami, Behnam, et al. "Land surface temperature anomalies in response to changes in forest cover." International Journal of Engineering and Geosciences 4.3 (2019): 149-156.

Müezzinoğlu, A. (1987). "Air Pollution and Quality, in Turkish " Dokuz Eylül Üniversitesi Mühendislik Mimarlık Fakültesi Ders Notu MM/ÇEV-87 EY 127.

Nacef, Lamri, et al. "Variability and decadal evolution of temperature and salinity in the mediterranean sea surface." International Journal of Engineering and Geosciences 1.1 (2016): 20-29.

Oner, E. and B. Kaynak (2016). "Evaluation of NOx emissions for Turkey using satellite and ground-based observations." Atmospheric Pollution Research 7(3): 419-430.

Organization, W. H. (2016). "Ambient air pollution: A global assessment of exposure and burden of disease." Available at: https://www.who.int › phe › publications › air-pollution-global-assessment Access date: 05.12.2019

Theys, N., P. Hedelt, I. De Smedt, C. Lerot, H. Yu, J. Vlietinck, M. Pedergnana, S. Arellano, B. Galle and D. Fernandez (2019). "Global monitoring of volcanic SO 2 degassing with unprecedented resolution from TROPOMI onboard Sentinel-5 Precursor." Scientific reports 9(1): 2643.

Varma, D. R., S. Mulay and S. Chemtob (2009). Carbon monoxide: from public health risk to painless killer. Handbook of toxicology of chemical warfare agents, Elsevier: 271-292.

Veefkind, J. P., Q. Kleipool, A. Ludewig, D. Stein-Zweers, I. Aben, J. De Vries, D. G. Loyola, H. Nett, A. Richter and M. Van Roozendael (2017). Early Results from TROPOMI on the Copernicus Sentinel 5 Precursor. AGU Fall Meeting Abstracts.

Voors, R., J. de Vries, I. S. Bhatti, D. Lobb, T. Wood, N. van der Valk, I. Aben and P. Veefkind (2017). TROPOMI, the Sentinel 5 Precursor instrument for air quality and climate observations: status of the current design. International Conference on Space Optics—ICSO 2012, International Society for Optics and Photonics.

Vreman, H. J., R. J. Wong and D. K. Stevenson (2000). "Carbon monoxide in breath, blood, and other tissues." Carbon monoxide toxicity: 19-60.