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Spatiotemporal patterns of atmospheric carbon monoxide over the Crimean Peninsula and the Black Sea: Sentinel-5P/TROPOMI data (2019—2024)

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The spatiotemporal distribution of the annual average of atmospheric CO column densities based on TROPOMI data from the Sentinel-5P satellite over the Crimean Peninsula and the Black Sea for 2019—2024 was analyzed. The average annual value over the Crimean Peninsula was $(3.2—3.6)\cdot10^{-2}$ mol/m^2, while over the surface of the Black Sea, it was $(3.0—3.7)\cdot10^{-2}$ mol/m^2, and in coastal seawater — $(3.7—4.2)\cdot10^{-2}$ mol/m^2. Spatial differences in the CO concentration may be associated with the characteristics of atmospheric processes (photochemical processes and atmospheric circulation), microbial oxidation, gas hydrate processes in the sea, and anthropogenic activity.

Key words: carbon monoxide, atmosphere, Sentinel-5P satellite, TROPOMI.

Introduction. Carbon monoxide (CO) is a significant atmospheric trace gas. Approximately 40 % of its emissions originate from natural sources and 60 %, from anthropogenic activities [Holloway et al., 2000; IPCC, 2021]. Global annual emissions of CO are estimated [Conte et al., 2019; Cordero et al., 2019; Zuo et al., 1998; Holloway et al., 2000] at ~$2.5\cdot10^3$ Tg CO/yr, with 30 % (~$0.75\cdot10^3$ Tg CO/yr) from biomass burning, 30 % (~$0.76\cdot10^3$ Tg CO/yr) from methane oxidation, 27 % (~$0.68\cdot10^3$ Tg CO/yr) from the

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oxidation of biogenic hydrocarbons, and approximately 12 % (~$0.3 \cdot 10^3$ Tg CO/yr) from fossil fuel combustion. The average concentration of CO in the atmosphere is about 90 ppbv, corresponding to an atmospheric burden of approximately $0.4 \cdot 10^3$ Tg CO. The primary sink for CO in the atmosphere is its reaction with hydroxide (OH), which destroys it. The sensitivity of CO to the OH field varies both spatially and seasonally. A 30 % increase in OH concentration results in CO reduction ranging from 4 % to 23 %, with lower sensitivities near emission regions where advection is a strong local sink. The atmospheric lifetime of CO ranges from approximately 10 days in summer over continental regions to over a year at the poles during winter, where lifetime is defined as the turnover time in the troposphere due to reactions with OH. The lifetime of CO in the troposphere averages around two months. Methane (CH_4) oxidation is the only source of CO across all atmospheric, contributing a total of $0.76 \cdot 10^3$ Tg CO/yr [Zuo et al., 1998; Holloway et al., 2000]. The reaction of methane with the hydroxyl radical produces CO as a byproduct. Therefore, this CO source depends on the distribution of both OH and CH_4 in the atmosphere. Climate conditions can influence the concentration of carbon monoxide in the atmosphere and its degassing from the ocean [IPCC, 2021]. Precipitation and air humidity influence the oxidation processes of CO in the atmosphere and the rate of removal with precipitation, while the reaction with oxygen leads to the formation of CO_2. Climate conditions also impact biological processes, such as the activity of microorganisms in soil and aquatic ecosystems, which can affect the carbon cycle and the level of CO in the atmosphere. Temperature affects fuel combustion processes and their quantity, and in cold conditions, CO emissions increase. While from arid soil, CO is released directly into the atmosphere.In the arid conditions of Crimea [Boychenko et al., 2022; Maidanovych, Khlobystov, 2023], it can create local maxima in gas concentration.

This study analyzed the spatiotemporal distribution of annual average carbon monoxide (CO) column densities over the Black Sea and the Crimean Peninsula during 2019—2024, based on data from the TROPOMI instrument aboard the Sentinel-5P satellite.

Methods and materials. The annual average carbon monoxide (CO) column densities (10^{-2} mol/m^2) were derived from the TROPOMI instrument aboard the Sentinel-5P satellite. Daily global coverage with a high spatial resolution of 7×7 km^2 was aggregated into monthly and yearly averages within grid nodes and administrative boundaries of the Black Sea and the Crimean Peninsula during 2019—2024. Data processing utilized specialized cloud-based tools, including the Google Earth Engine platform, a powerful resource for geospatial analysis and visualization [Earth…, 2023]. Maps were generated using remote sensing data provided by ESA [Gorelick et al., 2017].

Study Region: The Black Sea is an inland continental sea connected via the Bosphorus Strait to the Sea of Marmara and onward via the Dardanelles Strait to the Aegean Sea and the Mediterranean Sea. The latter is connected to the Atlantic Ocean through the Gibraltar Strait and to the Indian Ocean through the Suez Canal, the Red Sea, and the Babel-Mandeb Strait. The Crimean Peninsula is located between the northern part of the Black Sea and the western part of the Sea of Azov in the southern region of Ukraine.

Results. ***Assessment of the average annual atmospheric CO column density from the Sentinel-5P/TROPOMI instrument over the Crimean Peninsula (2019—2024).*** Analysis of imagery extracted from Sentinel-5P for 2019—2024 reveals that the average annual column density of CO was $(3.2—3.4) \cdot 10^{-2}$ mol/m^2 over the Crimean Peninsula (Fig. 1). The minimum CO content, approximately $(2.7 \pm 0.2) \cdot 10^{-2}$ mol/m^2, is typically observed in the mountainous regions of Crimea. This can be attributed to the local climate, as the Crimean Mountains receive about 900—1200 mm of precipitation annually, which facilitates the removal of CO from the atmosphere through precipitation. Additionally, the relatively low impact of anthropogenic factors contributes to this reduction

[Maidanovych, Khlobystov, 2023]. The maximum CO content is found in coastal areas and at the junction with the mainland, reaching $(3.6\pm0.2)\cdot10^{-2}$ mol/m^2. This elevated concentration is associated with active anthropogenic activities such as urban development, industrial operations, commercial activities, resort infrastructure, and military ranges. Furthermore, biological processes typical for marine ecosystems, arid climatic conditions, and atmospheric oxidation contribute to increased CO levels. Note that, in 2022, the annual average of CO column densities dropped to approximately $(2.9\pm0.2)\cdot10^{-2}$ mol/m^2, primarily due to a decrease in industrial and agricultural production, reduced tourist flows, and a decline in the presence of enemy troops, which had moved further south into Ukraine. The seasonal variation of the CO column density over the Crimean Pen-

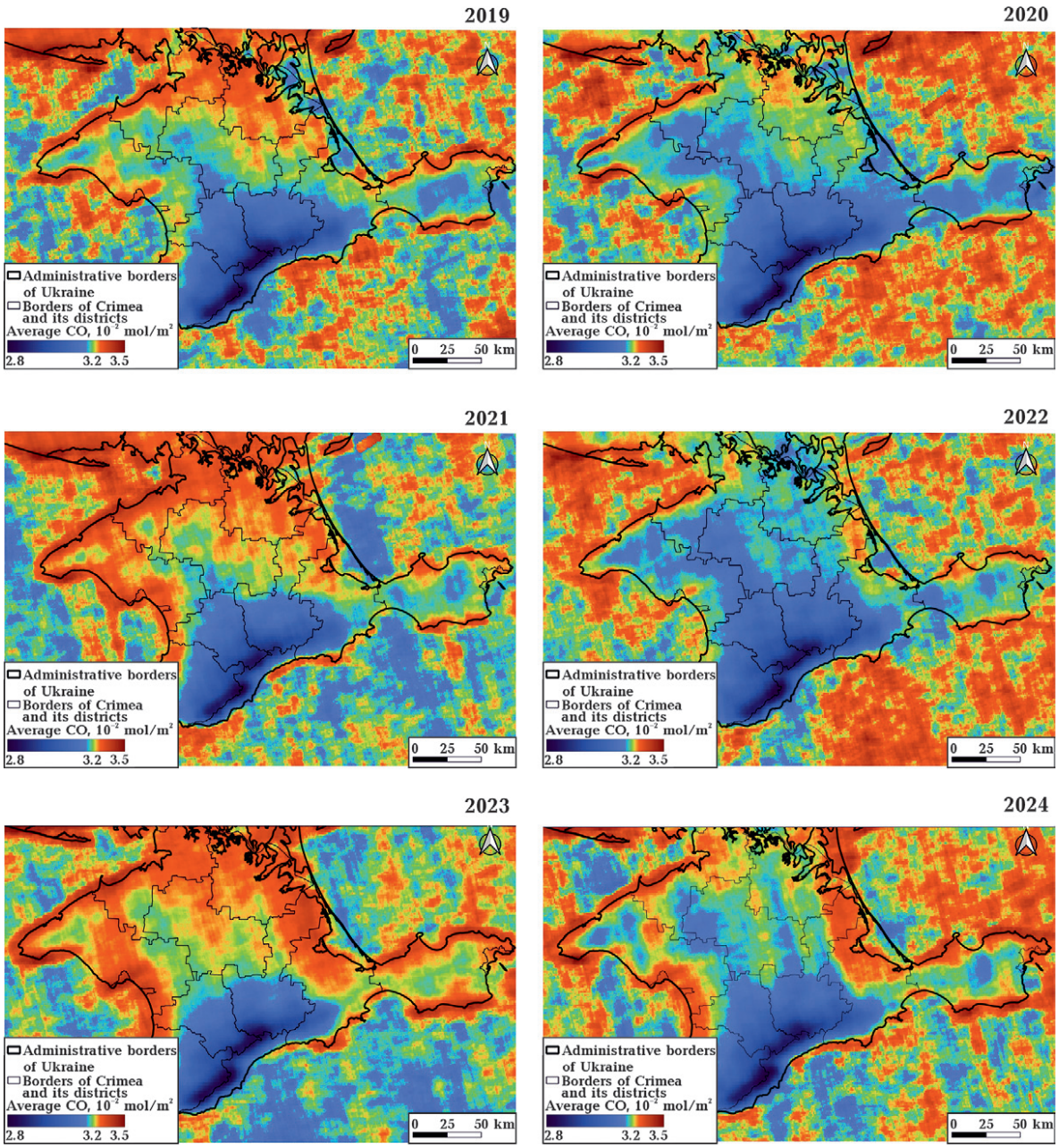

Fig. 1. Average annual atmospheric CO column density (10^{-2} mol/m^2) from the Sentinel-5P/TROPOMI instrument over the Crimean Peninsula (Ukraine) in 2019—2024.

insula does not exhibit pronounced fluctuations throughout the year [Maidanovych, Khlobystov, 2023].

Assessment of the average annual atmospheric CO column density from the Sentinel-5P/TROPOMI instrument over the Black Sea (2019—2024). Carbon monoxide in surface sea waters is produced predominantly by photochemical processes, oxidized by microorganisms, and out gassed to the atmosphere. The photoproduction rate of carbon monoxide was found to be well correlated to the concentration of dissolved organic carbon in coastal and open ocean surface waters [Zuo et al., 1998; Conte et al., 2019]. The reaction between CH_4 and the OH leads to the formation of CO [Holloway et al., 2000]. As a result, the CO source is influenced by the distribution of both OH and CH_4 in the atmosphere, which can also be released from

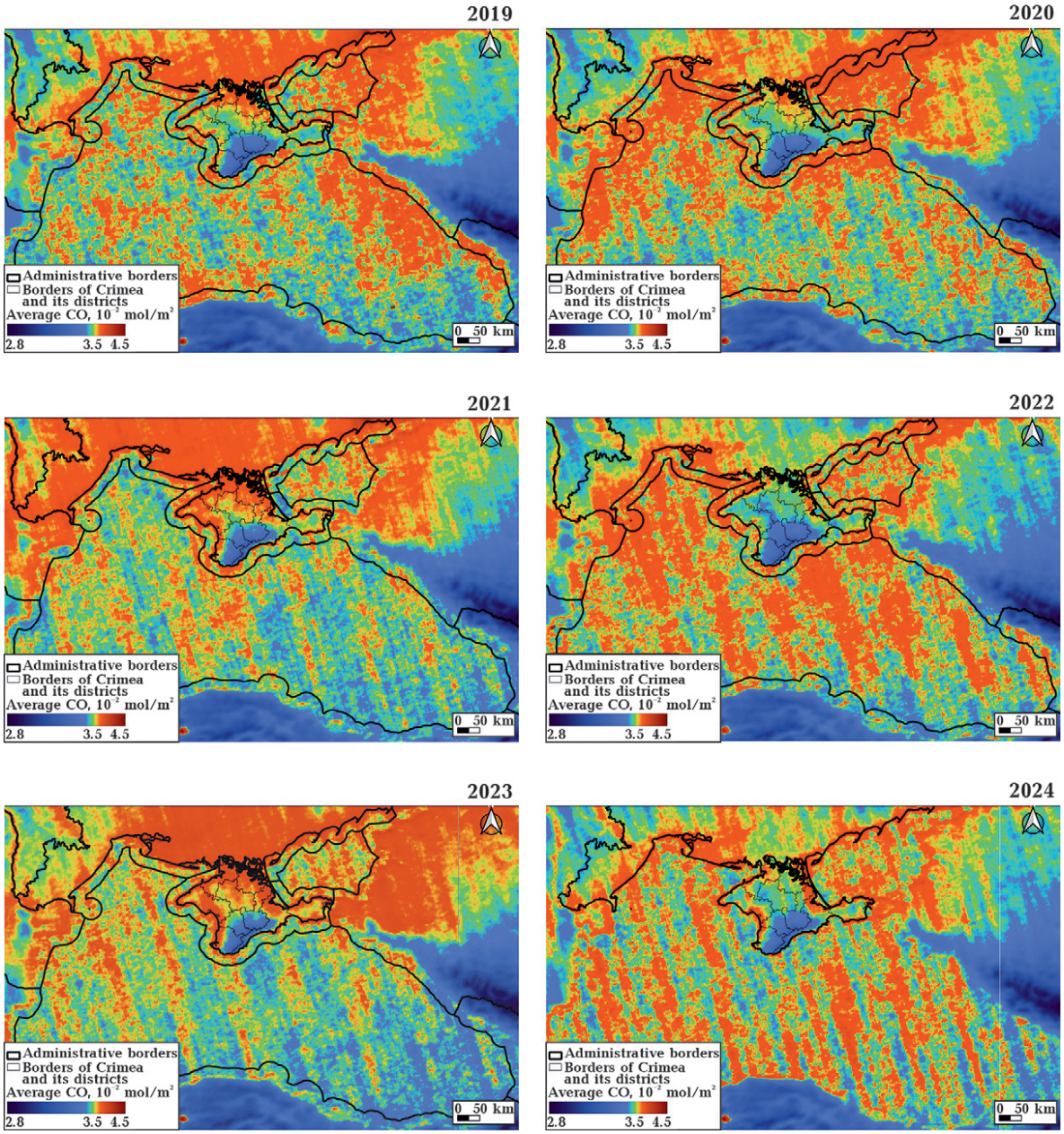

Fig. 2. Average annual atmospheric CO column density (10^{-2} mol/m^2) from the Sentinel-5P/TROPOMI instrument over the Black Sea in 2019—2024.

deep-sea waters, including during the decomposition of gas hydrates. The Black Sea region is an oil and gas-bearing area with an extensive network of deep faults and active hydrocarbon degassing, which may affect the distribution of CO concentration in the atmospheric air column under climate change conditions.

Analysis of imagery extracted from Sentinel-5P for 2019—2024 reveals that the average of the total CO column concentration over the surface open sea water was (3.1—3.5)·10^{-2} mol/m^2. The minimum values of the total CO column concentration fluctuated within the range of (2.0—2.2)·10^{-2} mol/m^2 (with the lowest value in 2022), while the maximum values ranged (3.3—3.8)·10^{-2} mol/m^2 (with the highest value in 2023) (Fig. 2).

An increase in average annual atmospheric CO column density over the Black Sea was observed in 2022 and 2024, potentially linked to the peculiarities of atmospheric processes such as photochemical reactions and atmospheric circulation, as well as microbial oxidation, gas hydrate processes in the sea, and anthropogenic activity.

Conclusions. The analysis of the spatio-temporal distribution of atmospheric carbon monoxide (CO) based on the Sentinel-5P/TROPOMI instrument over the Crimean Peninsula and the Black Sea for 2019—2024 reveals that the average annual atmospheric CO column density over the Crimean Peninsula was (3.4±0.2)·10^{-2} mol/m^2. The average CO concentration overthe surface open Black Sea seawater ranged (3.1— 3.7)×$\times 10^{-2}$ mol/m^2 over coastal seawater, it ranged (3.7—4.2)·10^{-2} mol/m^2.

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Просторово-часовий розподіл атмосферного оксиду вуглецю над Кримським півостровом та Чорним морем: дані Sentinel-5P/TROPOMI (2019—2024)

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Аналіз просторово-часового розподілу оксиду вуглецю (CO) у стовпі атмосферного повітря на основі даних TROPOMI зі супутника Sentinel-5P над Кримським півостровом і Чорним морем за 2019—2024 рр. показав, що його середньорічні значення над Кримським півостровом становили $(3.4\pm0.2)\cdot10^{-2}$ моль/м^2, водночас над поверхнею Чорного моря коливалися в межах $(3.0—3.7)\cdot10^{-2}$ моль/м^2, а у прибережній морській воді — $(3.7—4.2)\cdot10^{-2}$ моль/м^2. Просторові відмінності у вмісті CO в атмосфері можуть бути пов'язані з особливостями атмосферних процесів (фотохімічні процеси та атмосферна циркуляція), процесами окислення мікроорганізмів, процесами в морі та антропогенною діяльністю.

Ключові слова: оксид вуглецю, атмосфера, супутник Sentinel-5P, TROPOMI.