The Relationship between Air Pollution and Sea Surface Temperature Anomalies in the Northern Adriatic Sea

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Abstract: Air pollution emissions are recognised as a significant climate driver contributing to global warming and its multiple impacts. A key consequence is sea-level rise, which is largely driven by increased air and sea temperatures. This study examines trends and spatial correlations of sea surface temperature (SST) and air pollutants in the Northern Adriatic Sea from 2019 to 2022 using publicly available multi-satellite data. The Advanced Very-High-Resolution Radiometer (AVHRR) data were used to calculate SST anomalies, while TROPOspheric Monitoring Instrument (TROPOMI) and the Copernicus Atmospheric Monitoring Service (CAMS) data provided insights into air pollution. Trend analysis revealed a significant increase in SST of about 0.6 °C/yr. Spatial correlation analysis revealed strong positive correlations between SST anomalies and air pollutants in the Rijeka Bay. These results highlight the intertwined nature of air pollution and SST anomalies influenced by climate change and anthropogenic activities.

Keywords: sea surface temperature; Adriatic Sea; air pollution; climate change.

1 Introduction

In the recent years, the natural balance of the Earth's climate system has mainly been disrupted by the excessive accumulation of human-induced greenhouse gases, contributing to the increased mean temperature of the Earth. Covering about three quarters of the Earth's surface, the world's oceans are storing an estimated 91 percent of the excess heat energy trapped in the Earth's climate system by greenhouse gases (NOAA 2024). Accumulation of the heat, which is going faster in the upper layers of the ocean than in the bottom layers, is causing the thermal expansion of the ocean, which is, together with ice-mass loss, one of the main contributors of the sea level rise (Cazenave and Cozannet 2014). Therefore, Global Climate Observing System (GCOS) defines SST as one of the essential climate variables (ECV), since sea surface is a boundary between the ocean and the atmosphere. Thus, SST plays a key role in regulating climate, responds to its natural variability and human-driven climate changes (Pisano et al. 2020).

Human-driven climate change, which has been mostly caused by the excessive burning of fossil fuels over the past 150 years, has drastically changed the air quality. Key air pollutants with large impacts on public health (Lave and Seskin 2013) and the environment (Saurabh Sonwani and Vandana Maurya 2019) are, among others, surface ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and particulate matter (PM). Increase in temperature can lead to degraded air quality and extreme pollution events (Fiore et al. 2015).

To date, several studies have assessed the SST variations in the Adriatic Sea (Pisano et al. 2020, Bonacci et al. 2021, García-Monteiro et al. 2022) to investigate long-term and seasonal variability, as well as the impact of the air pollutants from nearby ports in the Adriatic Sea on the air quality (Vilke et al. 2022, Mei et al. 2023), but none of them has addressed dependence of air pollution on SST.

Thus, this is the first study to undertake the investigation of the connection between the air pollution variability and the SST in the Northern Adriatic Sea which is chosen as the area of interest because it is directly connected to a European hotspot for air pollution, the Po Valley (Lonati and Riva 2021). In addition, the largest ports of the Adriatic Sea are in its northern part: Trieste (Italy), Venice (Italy), Koper (Slovenia) and Rijeka (Croatia). This also contributes to the increased levels of air pollution, since the port transport sector increases pollutant emissions (Vilke et al. 2022, Owusu-Mfum et al. 2023). Therefore, the main objective of this study is to perform the long-term analysis of SST, SST anomalies and different air pollutants (CO, NO_2, surface O_3, PM_{10} and dust), as well as their spatial and temporal variability to determine the possible dependency between the two variables.

2 Materials and methods

2.1 Study area

The Northern Adriatic Sea includes the coastal regions of north-eastern Italy, western Slovenia, and western Croatia. Italy's longest river, the Po, flows into the Adriatic Sea near Venice. Its valley, surrounded by the Alps to the north and the Apennines to the south, acts as a natural basin, creating a microclimate that often traps pollutants. This, in combination with the high density of people, agriculture, traffic and industry often result in high levels of air pollutants (Lonati and Riva 2021).

2.2 Used datasets

The National Oceanic and Atmospheric Administration's (NOAA) AVHRR instrument provides SST data with high spatial (4 km) and temporal (twice a day) resolution. Sentinel-5P is the first Copernicus mission with the primary objective of monitoring the Earth's atmosphere. It is equipped with the TROPOMI spectrometer providing atmospheric measurements related to air quality daily. CAMS is dedicated to providing numerous global and regional information on air quality. SST and TROPOMI data were collected by the Google Earth Engine (GEE), while CAMS data was downloaded from CAMS Atmosphere Data Store. A short description of each analyzed pollutant is given in Table 1.

2.3 Methodology

The best quality daily SST data were downloaded for the period 1982-2022. Data from 1982-2015 were used to calculate mean monthly SST reference values. SST values from 2019 to 2022 are then subtracted from the reference SST to obtain SST anomalies. Used TROPOMI data are L3 offline data from GEE already pre-processed for quality, covering the period from 2019 to 2022. AVHRR and TROPOMI data have been resampled to match the spatial resolution of CAMS data by averaging within pixels. CAMS data are derived from European air quality forecasts, validated against in situ observations, and cover the period from the end of June 2020 to 2022. All values in the dataset outside the three medians of the mean absolute deviation (MAD) were defined as outliers and removed. Monthly mean values were calculated to plot time-series graphs, providing insights into long-term trends and seasonal patterns. The Pearson correlation coefficient of each pollutant with SST anomalies was calculated with a significance level of $p < 0.05$ for all 10 km pixels in the study area. In addition, the Inverse Distance Weighting (IDW) spatial interpolation was used to fill-in the missing values and obtain a continuous correlation maps.

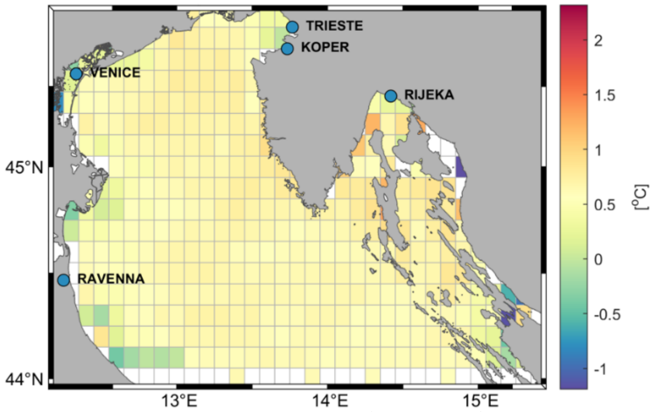

Figure 1. Average SST anomalies (2019-2022) over the study area. Blue dots represent cities with largest ports in the study area.

3.1 Time-series plots

Time-series graphs of monthly SST, SST anomalies and selected air pollutants are shown in Figure 2, together with their trend lines.

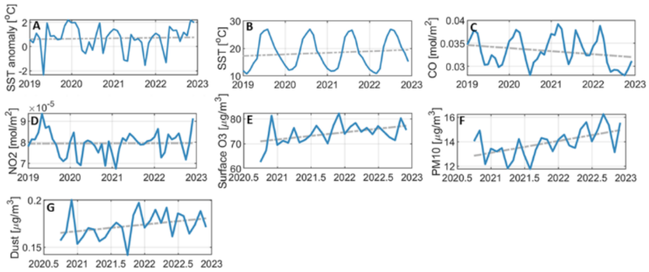

Figure 2. Time series of: a) SST anomaly, b) SST, c) CO, d) NO2, e) surface O3, f) PM10, g) dust in the study area.

Table 1. Air pollutants analyzed in this study.

N.	Pollutant	Description	Source	Temporal resolution	Spatial resolution	Units
1	CO	Total vertical column of CO	TROPOMI	daily	1.132 km	mol/m^2
2	NO_2	Total vertical column of NO_2	TROPOMI	daily	1.132 km	mol/m^2
3	Dust	Fraction in PM_{10}	CAMS	hourly	10 km	µg/m^3
4	Surface O_3	O_3 concentration at ground level	CAMS	hourly	10 km	µg/m^3
5	PM_{10}	Concentration of PM smaller than 10 micrometres in diameter	CAMS	hourly	10 km	µg/m^3

3 Results

Mean SST anomalies over the observed period are shown in Figure 1.

3.2 Spatial correlation plots

The relationship between air pollutants and SST anomalies is shown in Figure 3 expressed as the Pearson correlation coefficient for each pixel in the study area.

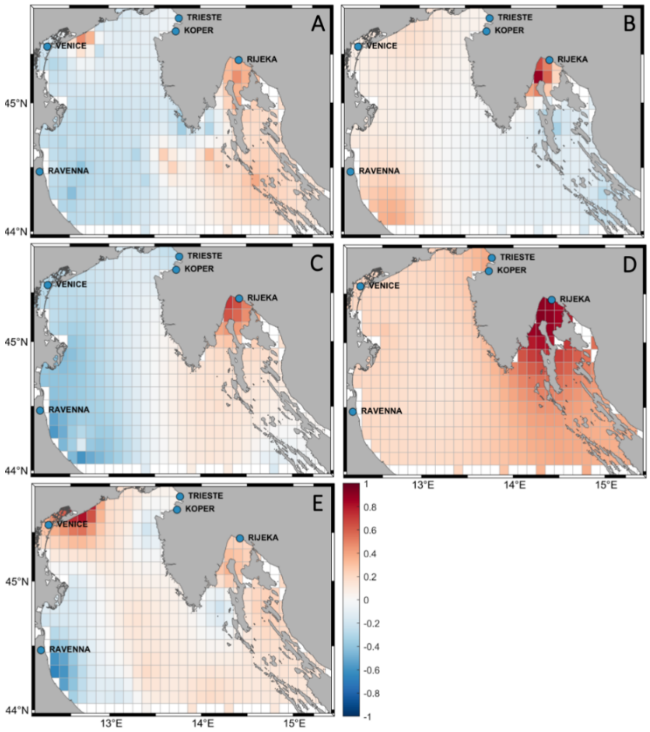

Figure 3. Pearson correlation coefficients ($p < 0.05$) with SST anomalies of: a) CO, b) NO_2, c) surface O_3, d) PM_{10} and e) dust over the study area.

4 Discussion and summary

4.1 Trend analysis

Time-series graphs from 2019 to 2022 for SST and TROPOMI variables, and from June 2020 to 2022 for CAMS variables, shown in Figure 2, provide insight into their trends and seasonal patterns. The SST in the study area has a strong regular seasonal pattern with an increasing trend of about 0.6 °C/yr, while García-Monteiro et al. (2022) estimated the average annual increase of SST in the entire Adriatic Sea from 2003 to 2019 to be about 0.1 °C/yr. The observed SST anomalies in our study also have a specific seasonality, where negative anomalies are observed in spring or autumn months, while the strongest positive anomalies are observed in winter and summer months. On the other hand, TROPOMI gives us an insight into the CO and NO_2 trends in our study area, and while CO has a strong negative trend in the observed period, the NO_2 trend remains the same over the years. There is a significant decrease in NO_2 levels in 2020, which may be related to the COVID-19 lockdown at that time, as reported in other studies (Tonion and Pirotti 2022). CAMS data for surface O_3, PM_{10} and dust show strong positive trends for all three pollutants, indicating that air pollution is a growing challenge in the Northern Adriatic Sea.

4.2 Spatial correlation analysis

Correlation maps between air pollutants and SST anomalies in the study area (Figure 3) provide information about their change on a spatial scale. CO shows medium positive correlations around the urban areas of Venice and Rijeka, and low positive correlations along the east coast and islands. On the other hand, NO_2 shows strong positive correlations in the Rijeka Bay. Marine traffic, including shipping and cruise ships, is reported as a source of NO_2 in port cities and coastal areas (Owusu-Mfum et al. 2023). Ground level O_3 is also an increasing pollutant in coastal urban areas (Pan et al. 2017), and increased concentration of O_3 is strongly connected with increase in SST in the Rijeka Bay, while negative correlations are distributed along the west coast. Another important pollutant in coastal areas, as reported by Owusu-Mfum et al. (2023), is PM_{10}, which has only positive correlations with SST anomalies in the study area. Again, the strongest correlations are observed in the Rijeka Bay. Although dust pollution is related to PM_{10}, it has a different relationship with SST anomalies in our study area, where the highest positive correlations are found around Venice, while stronger negative correlations are found in the urban area south of Ravenna, like O_3. Strong connection between increased levels of air pollutants and increase in SST can be explained by the fact that the Rijeka Bay is a semi-enclosed coastal area, where sea currents are west-northwest (WNW) directed (Domian et al. 2005).

This study set out to examine trends and spatial relationships between the change in SST and levels of different air pollutants in the North Adriatic Sea. Based on the presented results, it is found that the strongest correlation between SST anomalies and air pollution is found in the Rijeka Bay, because of its specific location. However, future studies should investigate non-linear correlations between SST anomalies and air pollution, and put a greater focus on other influencing variables which can have impact on observed parameters in this study (e.g. sea currents or wind patterns). Policy makers should use these findings to develop strategies to reduce air pollution and address climate change impacts in the region.

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