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Airborne pollen, wildfires, and Saharan dust control atmospheric carbohydrates and shape their biogeochemical impacts in northern Mediterranean

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Abstract. Carbohydrates are ubiquitous, water-soluble organic compounds that serve as tracers of atmospheric organic matter sources, participate in cloud chemical processes, and, once deposited to surface waters, provide readily bioavailable carbon that can stimulate microbial activity and affect marine biogeochemistry. The Mediterranean Sea, influenced by variable natural and anthropogenic inputs, is a key region for assessing how emission sources affect atmospheric organic matter composition and fluxes. Here, we studied the impact of three key sources, pollen episodes, Saharan dust intrusions, and biomass burning, on atmospheric carbohydrate concentrations, deposition pathways (dry, wet, and total), and their effects on northern Mediterranean coastal waters. Carbohydrate composition varied seasonally, reflecting shifts in local emissions, long-range transport, and meteorological conditions, with wet deposition as the dominant removal pathway. Spring pollen episodes were the dominant source of primary sugars, while summer sugar alcohols indicated minor fungal contributions. Biomass burning, including residential heating and wildfires, produced the highest anhydrosugars levels and significantly increased total dissolved carbohydrates. In contrast, Saharan dust contributed insignificant organic carbon fractions and had limited impact on carbohydrate deposition. Event-based analysis showed that pollen and dust episodes increased surface dissolved organic carbon by 0.2–0.7%, whereas biomass burning induced short-term increases of up to 5%. Although overall atmospheric contributions to marine dissolved organic carbon pool were modest, the high fraction of labile carbohydrates indicated that episodic deposition events delivered important pulses of bioavailable carbon. These findings emphasize the need to resolve short-term atmosphere-ocean interactions to better understand coastal carbon cycling and its broader environmental implications.

1 Introduction

The atmosphere is a complex mixture of gases, aerosols, and particulate matter, encompassing a wide range of chemical constituents, including organic matter. According to the International Energy Agency, global carbon flux into the atmosphere reached 36,800 Tg C yr^{-1} in 2022, with organic carbon accounting for 30% of total emissions (Wang et al., 2019). Organic

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carbon is commonly divided into water-soluble organic carbon (WSOC) and water-insoluble fractions, with WSOC typically representing 10%–80% of total organic carbon (Hegde & Kawamura, 2012; Du et al., 2014). Atmospheric deposition constitutes a major pathway by which this organic matter is transferred to terrestrial and aquatic ecosystems. Organic compounds are removed from the atmosphere via dry and wet deposition processes (Iavorivska et al., 2016; Xie et al., 2022), thereby influencing regional carbon cycling, and altering terrestrial and marine biogeochemistry (Yan & Kim, 2012; Iavorivska et al., 2017; Decina et al., 2018). In the Mediterranean Sea, organic carbon deposition via wet and dry processes is estimated at 10–20 × 10^{10} mol C yr^{-1} (Copin-Montégut, 1993). As ocean stratification intensifies under global warming, the relative importance of atmospheric inputs to surface waters is expected to increase (Kanakidou et al., 2012), underscoring the need for more accurate quantification of atmospheric organic matter deposition.

Among organic constituents, carbohydrates are biologically important, water-soluble compounds ubiquitous across all major Earth system compartments. They dominate primary production in the biosphere (Field et al., 1998) and are key components of organic matter in the hydrosphere (Benner et al., 1992), lithosphere (Hedges et al., 2000), pedosphere (Oades, 1984), and atmosphere (Theodosi et al., 2018). In the atmosphere, carbohydrates originate from both natural and anthropogenic sources, including primary biogenic emissions (e.g., pollen, vegetation, fungal spores, soil resuspension, and mineral dust) (Bauer et al., 2008; Fu et al., 2012a) and human activities such as industrial processes, agriculture, and biomass burning (Fraser and Lakshmanan, 2000; Sopčić et al., 2025a). Due to their abundance and source specificity, carbohydrates serve as effective molecular tracers for identifying sources and transport pathways of atmospheric organic matter (Medeiros et al., 2006a; Sopčić et al., 2025a, 2025b).

Atmospheric carbohydrates are typically classified into three main groups: (i) anhydrosugars, formed during pyrolysis of cellulose and hemicellulose, and widely used as tracers of biomass burning (Theodosi et al., 2018; Milinković et al., 2021; Sopčić et al., 2025a); (ii) sugar alcohols, primarily derived from fungal spores and soil dust, commonly used as tracers of fungal biomass (Simoneit et al., 2004; Bauer et al., 2008); and (iii) primary saccharides, continuously emitted from biological particles such as pollen, plant debris, algae, and biologically active soil, serving as tracers of vegetation and soil-derived material (Fu et al., 2012a; Xiao et al., 2018).

In addition to their role as source-specific tracers, atmospheric carbohydrates influence cloud microphysical processes across both liquid and ice phases. Their high solubility and abundance in bioaerosols enhance cloud condensation nuclei activity via hygroscopic growth, while polysaccharide components can also contribute to ice nucleation as both ice-forming and ice-binding agents in mixed-phase clouds (Dreischmeier et al., 2017; Hartmann et al., 2025). These processes link carbohydrate-rich organic matter to cloud development, radiative effects, and precipitation pathways, highlighting their importance for understanding coupled atmospheric chemistry, climate, and biogeochemical cycling.

When deposited into surface waters, carbohydrates represent a readily bioavailable source of carbon and energy that can stimulate microbial activity and productivity (Seitzinger & Sanders, 1999; Iavorivska et al., 2017). In coastal marine systems, atmospheric inputs of carbohydrates have been shown to significantly influence carbon cycling, with reported enhancements in winter primary productivity of up to 15-fold compared to summer conditions (Chen and Liu, 2024). Globally, wet deposition

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transfers approximately 306–580 Tg C yr^{-1} to the Earth's surface (Willey et al., 2000; Kanakidou et al., 2012), corresponding to nearly half of the annual carbon input delivered to the oceans by rivers (IPCC, 2014).

Atmospheric deposition is particularly important in the Mediterranean Sea, a semi-enclosed and highly oligotrophic basin that is especially sensitive to climate change and atmosphere-ocean interactions (Durrieu de Madron et al., 2011). In this region, atmospheric inputs of organic carbon can exceed riverine contributions, with estimates suggesting up to 9-fold higher inputs compared to the Rhône River (Sempéré et al., 2000). Furthermore, dry deposition alone may contribute nearly twice the carbohydrate input of major riverine sources (Theodosi et al., 2018). The region is continuously influenced by anthropogenic emissions from industrialized northern areas (Guerzoni and Chester, 2013) as well as by natural inputs such as Saharan dust, which episodically delivers nutrients and organic carbon (Vincent et al., 2016). Episodic dust intrusions can trigger bacterial blooms and enhance carbon mineralization (Pulido-Villena et al., 2008). Additionally, extensive Mediterranean vegetation represents a major seasonal source of airborne pollen rich in carbohydrates, lipids, and proteins. Primary bioaerosols, including pollen and plant fragments, can contribute 12–30% to the total organic carbon of atmospheric particulate matter (Womiloju et al., 2003; Jaenicke, 2005). Biomass burning, especially during hot and dry summers, is another dominant and recurrent source of atmospheric carbohydrates in the region (Turquety et al., 2013; Bowman et al., 2020). Atmospheric deposition has been shown to enhance dissolved organic carbon concentrations in surface Mediterranean waters and to support up to 25% of daily microbial carbon demand (Galletti et al., 2020).

Despite their ecological importance, data on atmospheric deposition of carbohydrates in the Mediterranean, particularly in coastal regions, remain limited. Most existing studies have focused on dry deposition processes and on episodic inputs associated with biomass burning or Saharan dust events, while comprehensive assessments across all deposition pathways, and/or biological emission sources, are lacking. For example, measurements in the eastern Mediterranean report annual dry deposition fluxes of carbohydrates of 9.19 mg C m^{-2} yr^{-1} (Theodosi et al., 2018). In addition, studies of wildfire events have shown pronounced short-term increases in anhydrosugar and WSOC concentrations (Sopčić et al., 2025a). However, relatively few studies have quantified carbohydrate deposition in wet or in total (dry + wet) deposition. This limitation is important as available data suggest that total atmospheric inputs of WSOC in Mediterranean may exceed riverine contributions by up to a factor of six (Galletti et al., 2020).

Moreover, while atmospheric carbohydrate measurements exist for the eastern and western Mediterranean (e.g., Theodosi et al., 2018; Santos et al., 2021), studies in the northern Mediterranean remain scarce. Importantly, no previous work has systematically examined the combined influence of key regional emission events, such as high-pollen episodes, Saharan dust intrusions, and biomass burning, on carbohydrate concentrations and deposition fluxes across all deposition pathways (dry, wet, and total). To address these gaps, this study presents the first comprehensive investigation of carbohydrates associated with the specified emissions in dry, wet, and total atmospheric deposition in the northern Mediterranean. Specifically, it aims to (i) characterize the seasonal variability of atmospheric carbohydrates across deposition pathways, (ii) identify their dominant sources and quantify deposition fluxes with particular emphasis on episodic events of high-pollen episodes, Saharan dust intrusions, and biomass burning events, and (iii) assess their potential biogeochemical impacts on coastal marine ecosystems.

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2 Materials and methods

2.1 Study area

Sampling was conducted at a rural site Martinska located on the eastern central Adriatic coast (43°74' N 15°88' E; Fig. 1). The Adriatic Sea, representing the northernmost part of the Mediterranean, is generally oligotrophic (Viličić, 2014) and therefore particularly sensitive to external inputs and environmental stressors. The sampling station is situated in a relatively remote area, surrounded by uninhabited land within a ~5 km radius to the west, northwest and, southwest. The nearest urban center, the town of Šibenik (~34,000 inhabitants), lies approximately ~2 km to the east. The region is characterized by intensive tourism and mariculture, with minimal influence from local industrial activities. However, it is periodically affected by long-range transport of Saharan dust. The surrounding landscape consists of extensive karst fields and Mediterranean vegetation, which act as a continuous source of atmospheric pollen, while mountainous terrain to the north and northeast further influences local meteorology. The climate is typically Mediterranean, with mild, wet winters and hot, dry summers, and is strongly influenced by northeasterly (bora) and southeasterly (sirocco) winds. These conditions contribute to a persistently high wildfire risk. Over the past 15 years, the Šibenik-Knin County has been among the most fire-affected regions along the Adriatic coast, particularly during summer (Šiljković and Mamut, 2016). In 2024, the National Firefighting Operations Centre reported 6,650 fires, including 3,825 vegetation fires, which burned a total of 26,807 hectares (National Firefighting Operations Centre, 2024). This represents a 21% increase in wildfire occurrence and a 411% increase in burned area compared to the previous year (European Forest Fire Information System, 2024; N1 Zagreb Hina N1, 2024).

Figure 1: Map of the region and location of the sampling site. Map made by using QGIS (http://qgis.osgeo.org).

2.2 Sample collection and processing

Atmospheric sampling was carried out during a field campaign from 21 March to 29 September 2024, covering thus two seasons, spring and summer, when airborne pollen, Saharan dust intrusions, and wildfires typically reach their peak intensity and frequency.

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Samples of atmospheric aerosols with aerodynamic diameter ≤ 10 µm (PM_{10}) were collected for 48 h each on quartz fiber filters (Pallflex Tissuquartz 2500QAT-UP, Pall Life Sciences, USA; diameter 47mm) using the low-volume sampler (PNS 18T-DM-3.1, Comde-Derenda, Germany) mounted on the roof of the measuring station (~5 m a. g. l.; flow rate 2.3 $m^3 h^{-1}$). Prior to exposure, filters were pre-combusted at 450 °C for 4 h. A total of 94 samples were collected, covering the whole field campaign period. After sampling, the filter samples were placed in Petri dishes and stored at -20 °C until analysis. For quality control purpose, along with each sample batch, field blank filter was taken and processed in the same way as collected samples.

Wet deposition samples were collected on an event basis using a custom automatic rainwater sampler installed at ~2 m a. g. l. at the sampling station. The sampler was activated by a precipitation sensor, which opened the lid only during rainfall to prevent dry deposition. Rainwater was directed through a pre-cleaned funnel (10% HCl; Merck, Germany; 27 cm diameter) into a polycarbonate carboy (Nalgene; Thermo Fisher Scientific, USA) housed within the sampler. After each rainfall event, the collection bottle was replaced, and the sample was filtered within 1 h of collection. Events with volume insufficient for analysis and/or with a delay of ≥2 days between rainfall and collection were excluded. In total, 8 wet deposition samples were obtained during the study period. Operational blanks were collected prior to each sampling event.

Total deposition was collected using a Bergerhoff collector (~5 m a. g. l.) composed of a metal stand, a bottle holder with bird guard, and an HDPE collecting bottle (89 mm diameter). A total of 30 total deposition samples were collected at ~1-week interval.

Wet and total deposition samples were filtered through pre-washed 0.45 µm syringe filters (Sartorius, Germany) to remove the insoluble fraction. Total deposition samples collected during dry periods were first dissolved in a known volume of ultrapure Milli-Q water prior to filtration. The filtrate volume was recorded, and aliquots were separated and preserved for targeted analyses. The samples aiming for dissolved organic carbon (DOC) analysis were preserved with $HgCl_2$ (final concentration 10 mg L^{-1}) and stored in the dark at 4 °C until analysis.

2.3 Sample analysis

2.3.1 PM_{10} mass

The PM_{10} mass was determined gravimetrically using a microbalance (205 Delta Range/A, Mettler Toledo, USA) according to the EN 12341:2023 standard, by weighing filters before and after sampling. Prior to each weighing, PM_{10} filters were conditioned for 24 h (72 h in total) at 20.0 ± 0.5 °C and relative humidity of 47.7 ± 1.0%.

2.3.2 Water-soluble organic carbon

WSOC in PM_{10} samples was quantified in two aliquots of filter extracts. Filter portions (2.54 cm^2) were extracted in 21 mL of ultrapure Milli-Q water, sonicated for 3 min, and stored for 24 h at 4 °C. The extracts were filtered (0.7 µm, Whatman GF/F, UK; pressure < 5 psi), and WSOC in the aliquots, along with DOC in the filtrates of wet and total deposition samples, was analyzed according to EN 1484:2002 in a laboratory accredited under EN ISO/IEC 17025:2017. Quantification was performed

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by high-temperature catalytic oxidation at 680 °C using a TOC-V_{CPH} 5000 analyzer (Shimadzu, Japan) equipped with a platinum-silica catalyst and a non-dispersive infrared CO_2 detector. The method detection limit was 0.068 mg C L^{-1}. For consistency, DOC is hereafter referred to as WSOC (i.e., measured DOC = WSOC).

2.3.3 Dissolved carbohydrates

Total dissolved carbohydrates (DTCHO) were determined in wet and total deposition samples spectrophotometrically at 635 nm using a UV-1280 UV/VIS spectrophotometer (Shimadzu, Japan), following a slightly modified MBTH method (Johnson & Sieburth, 1977; Senior & Chevolot, 1991). Briefly, aliquots (5 mL) of filtered samples were acidified with 30% HCl (final concentration 1.7 mol L^{-1}) and hydrolyzed at 100 °C for 3.5 h. Hydrolysates were neutralized to pH 10–12 with NaOH (10 mol L^{-1}), reduced with KBH_4, and subsequently treated with HIO_4, $NaAsO_2$, and HCl, followed by reaction with MBTH and $FeCl_3$. The resulting colored solutions were incubated at 18 °C for 3.5 h and measured immediately afterwards. For total dissolved monosaccharides (DMCHO) determination, the hydrolysis step was omitted. The concentration of total dissolved polysaccharides (DPCHO) was calculated as a difference of DTCHO and DMCHO. Concentrations are expressed as carbon equivalents using dextran calibration standard (Dextran 5000; Sigma Aldrich, USA). The method detection limit was 30 µg C L^{-1}.

2.3.4 Carbohydrate biomarkers

Three different classes of atmospheric biomarker carbohydrate compounds (anhydrosugars, primary sugars, and sugar alcohols) were analyzed in PM_{10}, wet, and total deposition samples using high-performance anion-exchange chromatography with pulsed amperometric detection (HPAEC-PAD). The detailed analytical procedure is described in Sopčić et al. (2025b). Briefly, PM_{10} samples were prepared by extracting a portion of a quartz filter (4.91 cm^2) in 2 mL of ultrapure water (18.2 MΩ cm^2, Smart2Pure3 UF/UV, Thermo Scientific Barnstead GenPure) in an ultrasonic bath for 45 min at 30 ± 5 °C. Wet and total deposition samples (20–30 mL) were first lyophilized to concentrate the material while preventing carbohydrate loss or thermal degradation. The dried residues were then redissolved in 4 mL of ultrapure water, manually mixed, and sonicated under the same conditions as PM_{10} samples. All extracts were subsequently centrifuged for 10 min at 3000 rpm, transferred to polypropylene vials, and analyzed using an ICS-6000 (Thermo Fisher Scientific, USA). The effectiveness of sample preparation across all three matrices was verified by analyzing model samples with known concentrations of the target carbohydrates, which underwent identical preparation and analysis procedures. Recoveries determined for a total of 8 samples from each matrix ranged from 87% to 106%.

The target carbohydrates (anhydrosugars = levoglucosan, galactosan, mannosan; primary sugars = fructose, galactose, glucose, mannose, saccharose; sugar alcohols = xylitol, arabitol, erythritol, sorbitol, mannitol) were separated on a Dionex CarboPac MA1 analytical column (250 × 4 mm) using NaOH as the eluent, with a gold working electrode and a standard quadruple potential waveform employed for detection. Two separate approaches were used to achieve optimal separation of the analytes. An isocratic method with a mobile phase concentration of 500 mmol L^{-1} NaOH was used to analyze sugar alcohols and primary

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sugars, including xylitol, arabitol, erythritol, mannitol, galactose, glucose, levoglucosan, fructose, and saccharose. A gradient method, with the mobile phase concentration increasing from 280 mmol L^{-1} to 450 mmol L^{-1} NaOH, was applied for the determination of anhydrosugars and additional monosaccharides, specifically galactosan, mannose, mannosan, and sorbitol. Limits of detection (LOD) of analytes determined in PM_{10} samples were 0.4, 2.3, 0.1, 0.1, 0.6, 1.1, 1.7, 4.6, 0.9, 1.7, 1.7, 16.7, and 25.4 ng m^{-3} and in wet and total deposition samples 3.7, 20.8, 1.1, 17.3, 55.0, 10.7, 15.4, 62.9, 8.2, 15.4, 15.9, 153.0, and 232.8 ng mL^{-1} for xylitol, arabitol, erythritol, sorbitol, mannitol, mannose, glucose, levoglucosan, mannosan, galactose, galactosan, fructose, and saccharose, respectively. In PM_{10}, more than 65% of measurements were below LOD for xylitol, mannosan, galactosan, mannose, galactose, fructose, and saccharose. A similar absence of these carbohydrates in PM_{10} was also reported by Sopčić et al. (2025b) during a year-long study conducted at a rural background station in Plitvice Lakes, Croatia. In wet deposition, this threshold was exceeded for levoglucosan, xylitol, erythritol, mannosan, galactosan, mannose, galactose, fructose, and saccharose, whereas in total deposition it was observed for levoglucosan, mannosan, galactosan, mannose, galactose, fructose, and saccharose. These compounds were therefore excluded from further analysis and discussion.

2.4 Meteorological conditions

Real-time meteorological data, including daily average air temperature, relative humidity, precipitation (Fig. S1), and wind speed and direction (Fig. S2) were obtained from the nearby Šibenik station of the Croatian Meteorological and Hydrological Service. Daily mean ambient temperatures ranged from 9.6 °C to 32.1 °C (22.9 ± 5.6 °C), showing a distinct seasonal pattern with a relatively cooler spring (19.0 ± 4.2 °C) and a warm summer (26.5 ± 4.1 °C). Precipitation varied throughout the study period, alternating between dry and wet periods, and increased notably toward the end of summer. Relative humidity (RH) ranged from 30 to 88%, while average wind speeds were comparable between the two seasons (3.2 ± 1.9 m s^{-1} in spring and 3.1 ± 1.7 m s^{-1} in summer). Wind direction patterns reflected the regional regime, dominated by strong bora winds from the coastal mountains and frequent southerly winds from the open sea.

2.5 Air masses source region classification

The NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) (Stein et al., 2015), driven by meteorological data from the Global Data Assimilation System (GDAS; 1°, global, 2006–present), was used to reconstruct the history of air-mass trajectories. Backward trajectories were calculated over 72-h intervals at a 24-h resolution, representing 3 characteristic points within each 48-h sampling period (beginning, middle, and end of sampling for each PM sample). Each plot represents an ensemble of 3 single backward trajectories arriving at the sampling site at 5 m a. g. l.

Based on the prevailing direction of the trajectories and their relative residence time, two general source sectors were defined: (a) continental (CONT) - air masses predominantly residing over continental Europe (Fig. S3a), and (b) marine (MAR) - air masses predominantly residing over the open Adriatic Sea and/or Mediterranean Sea (Fig. S3b). Samples not clearly attributable to either sector were classified as “undetermined” (mixed) cases, representing 32% of the dataset, and excluded

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from further discussion. This classification approach was applied to ensure an unambiguous assessment of the influence of contrasting long-range source regions on the composition of atmospheric deposition.

2.6 Identification of specific atmospheric events

During the sampling campaign, three types of region characteristic atmospheric events were considered: high airborne pollen events, Saharan dust intrusions, and open-fire biomass burning episodes.

High airborne pollen events were characterized using airborne pollen concentrations determined within the national monitoring network and provided for Šibenik area by the Institute of Public Health of Šibenik-Knin County. Pollen was classified into three categories: trees, grasses, and weeds (Fig. S4), and total daily concentrations were calculated as the sum of all categories. Days with total concentrations exceeding 1000 grains m^{-3} were classified as high-pollen events.

Saharan dust intrusions were identified using HYSPLIT back-trajectory analysis in combination with satellite observations and atmospheric transport models. MODIS imagery, NASA Earth Observatory reports, ESA data, Copernicus Atmosphere Monitoring Service (CAMS) analyses, and EUMETSAT case studies were used to confirm the long-range Saharan dust transport into Europe, including Croatia, during several episodes in 2024 (NASA Earth Observatory, 2024; NASA MODIS, 2024; EUMETSAT, 2024; ESA, 2024; CAMS, 2024) (Fig. S5a and b).

Biomass burning events in Šibenik-Knin County were identified using combination of official records from the Šibenik Fire Department (https://www.jvp-sibenik.hr/), the Fire Association of Šibenik-Knin County (https://www.vatrogastvo-sibenik-knin.hr/), and the Croatian Firefighting Association (https://hvz.gov.hr/) with the MODIS Terra and Aqua satellite imagery (Fig. S6). For each fire event, information was collected on the type of intervention (e.g., number of vehicles, aerial support), duration, affected area, and vegetation type. During the study period, several intense and/or prolonged wildfires were recorded, affecting grasslands, Mediterranean shrub, oak forests, pine, cypress, and olive groves, particularly during summer.

Based on these datasets and the PM_{10} mass measurements, the following event periods were defined: high-pollen episodes (22–30 March, 1–17 April, 7–9 May, and 11–13 May 2024), Saharan dust intrusions (30 March–1 April, 29 April–3 May, 15–23 May, 7–13 June, and 19–23 June 2024), and intensive biomass burning events (23–25 June, 29 June–1 July, 7–13 July, 29 July–4 August, 6–8 August, 10 August–9 September, and 17–23 September 2024) (Fig. 2).

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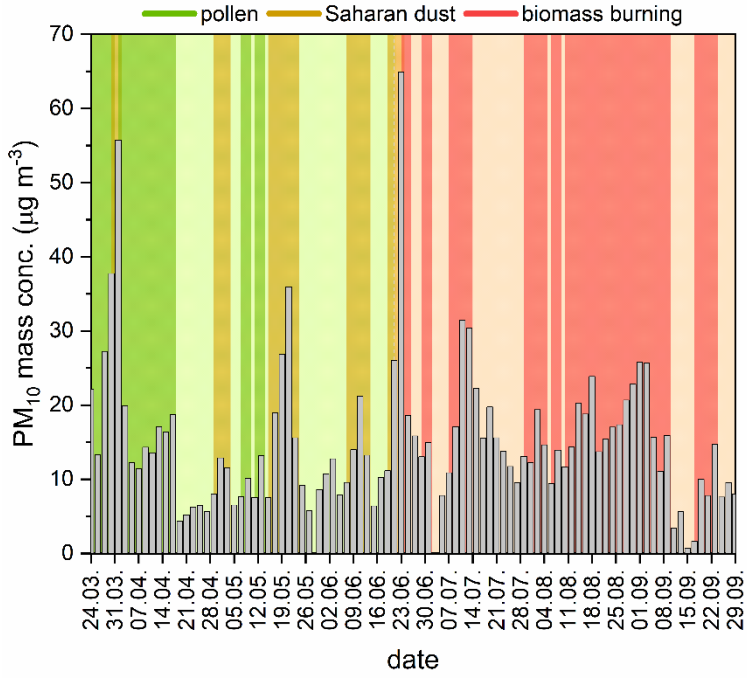

Figure 2: Periods with specific atmospheric events at the coastal central Adriatic site between March and September 2024: high-pollen episodes (> 1000 grains m-3) marked in green, Saharan dust intrusions in yellow, and intensive BB episodes in red. Temporal variability of PM10 mass concentrations is shown on the left y-axis (grey boxes).

2.7 Calculation of deposition fluxes

Wet (F_w) and total (F_t) deposition fluxes were calculated as:

$$F_{w,t} = \frac{C \times V}{A \times P} \quad (1)$$

where C is the concentration of the parameter in the wet or total deposition sample (µg L^{-1}), V is the collected rainwater or rinse solution volume (L), A is the funnel or vessel area (m^2), and P is the sampling duration for each sample (day).

Dry deposition fluxes (F_d) were estimated as:

$$F_d = C_d \times V_d \quad (2)$$

Here, C_d is the concentration of water-soluble parameters in PM_{10} (µg m^{-3}), and V_d is the deposition velocity (m s^{-1}). It is well known that there are no widely accepted values for deposition velocities and uncertainty in the used values can be as high as 100%. However, numerous studies have shown that sugar alcohols and primary sugars are predominantly associated with coarse particles, whereas anhydrosugars are mainly present in the fine fraction (Tsai et al., 2015; Bhattarai et al., 2019; Samaké et al., 2019b). Based on kinetic model calculations, deposition velocities in marine environments are typically assumed to be 2 cm s^{-1} for coarse and 0.1 cm s^{-1} for fine particles (Theodosi et al., 2018; H.-Y. Chen & Huang, 2021). These values have been widely applied in flux estimations (Mariraj Mohan, 2016; Theodosi et al., 2018; Xie et al., 2022) and are supported by

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measurements at the Finokalia station (Crete, Greece), where size-segregated sampling of nutrients and trace metals confirmed that 2 cm s^{-1} (coarse) and 0.1 cm s^{-1} (fine) provide reliable estimates for this type of region (Kouvarakis et al., 2000; Theodosi et al., 2010). Furthermore, since WSOC is mainly distributed in the fine fraction, with an approximate fine-to-coarse ratio of 70:30 (Koulouri et al., 2008; Bougiatioti et al., 2013), its V_d was estimated as a weighted average:

$$V_{d,WSOC} = f_{fine} \times V_{d,fine} + f_{coarse} \times V_{d,coarse} \quad (3)$$

where f_{fine} and f_{coarse} are the WSOC fractions in fine and coarse particles, and $V_{d,fine}$ and $V_{d,coarse}$ are the respective deposition velocities. This calculation yields V_d for WSOC of 0.67 cm s^{-1}, which is comparable with values reported in previous studies (Theodosi et al., 2018; Wu et al., 2018; Xie et al., 2022).

2.8 Data analysis

Data normality was assessed using the Shapiro-Wilk test. As some datasets showed deviations from normality, all data were log-transformed to improve distributional symmetry and homoscedasticity. For log-transformation and subsequent statistical analyses, values below LOD were set to 1/2 of the LOD. All statistical analyses were performed on log-transformed data at a 95% confidence level ($p < 0.05$), unless stated otherwise.

Welch's T-test was applied to compare seasonal datasets as well as background versus deposition events. Pearson correlation was used to assess relationships among measured parameters, while principal component analysis (PCA) was conducted to examine parameter associations with respect to seasons. Samples influenced by deposition events were excluded from background statistics and analyzed separately. Averages are reported as mean ± 1 standard deviation.

Wind roses and bivariate polar plots of mean PM_{10} parameter concentrations under different wind conditions were generated using the Openair R package (Carslaw & Ropkins, 2012; Carslaw & Beevers, 2013).

3 Results and discussion

3.1 Atmospheric carbohydrates composition and seasonal variability

A summary of overall and seasonal mean concentrations of the measured parameters in atmospheric samples is presented in Table 1. The carbohydrate results are presented in terms of the following groupings. For PM_{10}: [anhydrosugars] = [levoglucosan]; [primary sugars] = [glucose]; [sugar alcohols] = [erythritol] + [arabitol] + [mannitol] + [sorbitol]. For wet deposition: [primary sugars] = [glucose]; [sugar alcohols] = [arabitol] + [mannitol] + [sorbitol]. For total deposition: [primary sugars] = [glucose]; [sugar alcohols] = [xylitol] + [erythritol] + [arabitol] + [mannitol] + [sorbitol]. Across all matrices, total monosaccharide biomarkers (Total MB) in the collected samples were calculated as the sum of [primary sugars], [sugar alcohols], and [anhydrosugars].

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Table 1. Overall and seasonal mean concentrations ± standard deviation (N = number of samples) of relevant parameters measured in PM_{10}, wet, and total deposition at the coastal central Adriatic site between March and September 2024. Statistically significant differences among seasons where N ≥ 3 are marked with * ($p < 0.05$) and ** ($p < 0.01$).

PM_{10}	**Sampling period**	**Spring**	**Summer**
Mass (μg m^{-3})	15.2 ± 9.7 (N = 94)	14.6 ± 9.8 (N = 45)	15.8 ± 9.6 (N = 49)
WSOC (μg C m^{-3})	1.34 ± 0.85 (N = 94)	0.90 ± 0.50** (N = 45)	1.75 ± 0.90** (N = 49)
Anhydrosugars (ng m^{-3})	17.4 ± 17.5 (N = 35)	17.1 ± 9.5 (N = 19)	17.7 ± 23.8 (N = 16)
Primary sugars (ng m^{-3})	14.2 ± 16.1 (N = 85)	17.4 ± 21.1** (N = 36)	11.9 ± 10.6** (N = 49)
Sugar alcohols (ng m^{-3})	17.9 ± 18.8 (N = 93)	10.9 ± 8.2** (N = 44)	24.1 ± 23.0** (N = 49)
Total MB (ng m^{-3})	37.4 ± 33.6 (N = 93)	32.6 ± 29.7* (N = 44)	41.8 ± 36.2* (N = 49)
WET DEPOSITION	**Sampling period**	**Spring**	**Summer**
WSOC (μg C L^{-1})	1436.29 ± 1171.52 (N = 8)	898.48 ± 275.64 (N = 3)	1758.98 ± 1368.46 (N = 5)
DMCHO (μg C L^{-1})	143.4 ± 104.7 (N = 8)	112.1 ± 73.3 (N = 3)	162.3 ± 115.6 (N = 5)
DPCHO (μg C L^{-1})	705.4 ± 1013.0 (N = 8)	171.6 ± 44.7 (N = 3)	1025.7 ± 1169.2 (N = 5)
DTCHO (μg C L^{-1})	848.9 ± 1099.8 (N = 8)	283.7 ± 116.0 (N = 3)	1188.0 ± 1273.0 (N = 5)
Primary sugars (μg L^{-1})	49.8 ± 36.8 (N = 5)	-	47.1 ± 40.7 (N = 4)
Sugar alcohols (μg L^{-1})	17.3 ± 17.6 (N = 6)	14.0 ± 10.6 (N = 2)	19.0 ± 20.0 (N = 4)
Total MB (μg L^{-1})	58.8 ± 54.9 (N = 6)	44.2 ± 40.8 (N = 2)	66.1 ± 59.4 (N = 4)
TOTAL DEPOSITION	**Sampling period**	**Spring**	**Summer**
WSOC (μg C L^{-1})	1495.20 ± 1112.40 (N = 30)	1590.39 ± 1411.61 (N = 15)	1400.01 ± 681.25 (N = 15)
DMCHO (μg C L^{-1})	171.1 ± 147.1 (N = 30)	208.0 ± 181.5 (N = 15)	134.3 ± 87.2 (N = 15)
DPCHO (μg C L^{-1})	373.9 ± 292.2 (N = 30)	414.8 ± 374.6 (N = 15)	333.0 ± 164.7 (N = 15)
DTCHO (μg C L^{-1})	545.1 ± 412.5 (N = 30)	622.8 ± 531.2 (N = 15)	467.3 ± 214.4 (N = 15)
Primary sugars (μg L^{-1})	47.2 ± 36.6 (N = 22)	51.7 ± 29.0 (N = 10)	43.4 ± 41.5 (N = 12)
Sugar alcohols (μg L^{-1})	32.0 ± 37.6 (N = 25)	23.0 ± 21.0 (N = 11)	39.0 ± 45.4 (N = 14)
Total MB (μg L^{-1})	73.5 ± 68.4 (N = 25)	70.0 ± 48.3 (N = 11)	76.2 ± 80.7 (N = 14)

The PM_{10} mass concentration measured over the entire sampling period averaged 15.2 ± 9.7 μg m^{-3}, with insignificant seasonal variability, although slightly higher levels were observed in summer compared to spring (Fig. 2; Table 1). A similar trend of increased PM_{10} mass during summer was also observed in a previous study conducted in the same area (Milinković et al., 2022), although, compared to the same study, the average PM_{10} mass reported here is lower. Moreover, the average PM_{10} mass measured in this study is lower than values reported for other Mediterranean coastal urban and suburban areas (27.0 ± 13.7 μg m^{-3} Galindo et al., 2020; 27.9 ± 17.0 μg m^{-3} Clemente et al., 2023; 21.9 μg m^{-3} Chatoutsidou et al., 2025; 28.2 ± 14.7 μg m^{-3} Tobarra et al., 2025), but comparable to that observed at rural background sites (14.9 μg m^{-3} Castagna et al., 2021; 14 ± 10 μg m^{-3} Sopčić et al., 2025a). As a significant PM_{10} component (9.4 ± 3.9%), WSOC exhibited a clear seasonal increase, with nearly doubling from spring (0.90 ± 0.50 μg C m^{-3}) to summer (1.75 ± 0.90 μg C m^{-3}). This could be related to enhanced biogenic activity during the warmer months (D'Angelo et al., 2025; Garg et al., 2025; Thoma et al., 2025), as well as with increased emissions during intense summer regional wildfires (Jakovljević et al., 2021; Sopčić et al., 2025a), and increased

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maritime and land traffic emissions during the tourist season (Jakovljević et al., 2021; Milinković et al., 2021; Dufresne et al., 2025). Among monosaccharide biomarkers, sugar alcohols and primary sugars showed the strongest seasonality, with sugar alcohols levels nearly doubling from spring (10.9 ± 8.2 ng m^{-3}) to summer (24.1 ± 23.0 ng m^{-3}), a trend consistent with that observed in other studies (Verma et al., 2018; Haque et al., 2022; Sopčić et al., 2025b). In contrast, anhydrosugars showed no clear seasonal trend, suggesting comparable contributions from different seasonal sources. Overall, Total MB were moderately higher during summer (41.8 ± 36.2 ng m^{-3}) compared to spring (32.6 ± 29.7 ng m^{-3}), indicating enhanced summer sources of the total measured biomarkers.

In wet deposition, WSOC concentrations also increased from spring (898.48 ± 275.64 µg C L^{-1}) to summer (1758.98 ± 1368.46 µg C L^{-1}), although the difference was not statistically significant, likely due to the limited number of samples. This trend is consistent with that observed for PM_{10} and indicates effective removal of increased atmospheric organic matter via precipitation (Mullaugh et al., 2014; Santos et al., 2021). DTCHO and its components, DMCHO and DPCHO, similarly increased in summer, with DPCHO comprising more than 60% of DTCHO in both seasons. The elevated summer WSOC and DTCHO concentrations correspond to those observed in PM_{10}. The contribution of DTCHO to WSOC ranged from ~31% in spring to ~49% in summer, suggesting a stronger influence of carbohydrates on wet deposition composition during summer. Primary sugars and sugar alcohols showed pronounced seasonal differences, while no anhydrosugars were detected in any wet deposition samples. Total MB levels, however, remained similar across seasons, implying shifts in dominant sources rather than changes in overall loading.

Total deposition exhibited a different seasonal pattern. In contrast to its individual components, WSOC, DTCHO, DMCHO, and DPCHO were all higher in spring than in summer, highlighting the influence of intense spring precipitation events on total deposition chemistry. Individual monosaccharide biomarker groups again showed substantial seasonal variability, whereas Total MB showed limited seasonal variation with comparable concentrations in summer (76.2 ± 80.7 µg L^{-1}) and spring (70.0 ± 48.3 µg L^{-1}). However, the limited number of samples may reduce the robustness of this interpretation.

Although generally significant only in PM_{10}, these results demonstrate seasonal differences in atmospheric carbohydrates, and organic matter in general, with wet deposition further amplifying these differences through efficient scavenging. The strong seasonal variation among individual groups of monosaccharide biomarkers, combined with the absence of a significant seasonal trend in their total amounts, suggests shifts in the dominant sources between seasons that maintain their atmospheric levels. The opposite trend observed in total deposition relative to its individual components, with elevated concentrations of most measured organic matter constituents during spring, suggests a strong influence of individual intense spring precipitation events, as well as short but strong spring source processes, on total deposition chemistry. These findings underscore the strong influence of meteorological conditions and dominant seasonal sources on atmospheric organic matter composition, as well as the importance of wet deposition as a removal mechanism for atmospheric carbohydrates, consistent with studies in Portugal and North Carolina (Mullaugh et al., 2014; Santos et al., 2021).

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3.2 Atmospheric carbohydrates source identification and contribution

To identify the potential sources of observed atmospheric WSOC in the central Adriatic area, WSOC concentrations in PM_{10} samples were analyzed according to the contribution of contrasting CONT and MAR air-mass sectors. Back-trajectory analysis indicated contributions from both continental and marine aerosols, although with differing magnitudes. In both seasons, air masses arriving from the CONT sector were associated with significantly higher WSOC concentrations than those from the MAR sector (Fig. 3a). Consequently, air masses arriving from the CONT sector can be considered a stronger source of atmospheric organic matter in the coastal central Adriatic area than those from the southern MAR sector, particularly during summer (Fig. 3b).

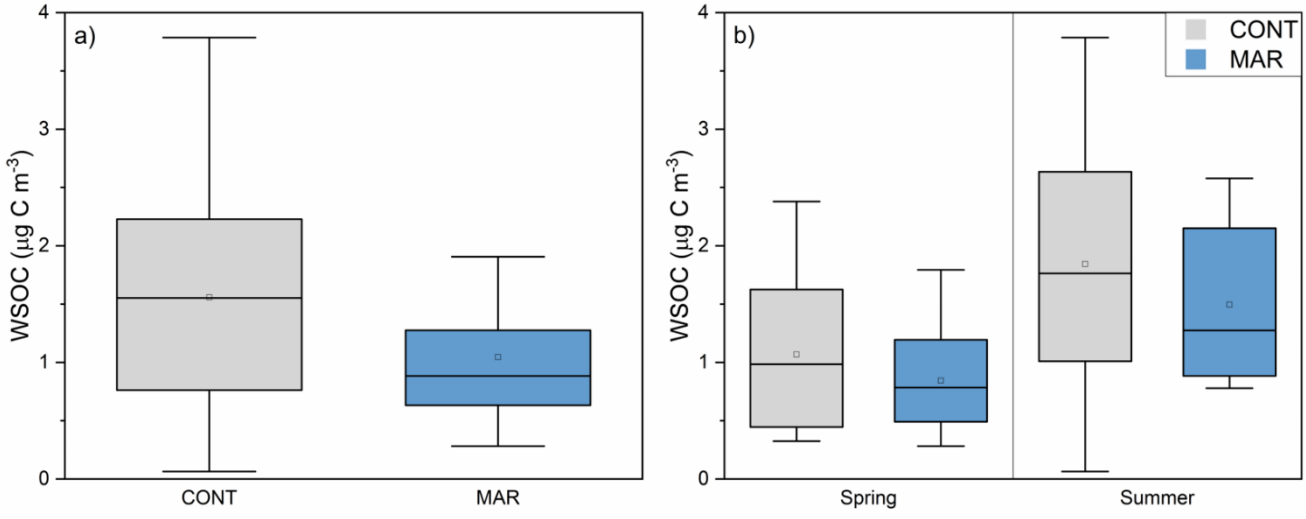

Figure 3: Contribution of contrasting continental (CONT) and marine (MAR) air-mass sectors to WSOC concentrations measured at the central Adriatic coastal site over the entire study period (a) and during different seasons (b). The box edges show the 25th to 75th percentile range, the vertical line shows the 50th percentile, while the whiskers indicate the 5th to 95th percentile range. The squares indicate the mean.

Atmospheric synoptic weather parameters significantly influence the transport, dispersion, and concentration of air constituents across different regions, with various parameters affecting these processes to varying degrees. Wind direction and speed, turbulence, and atmospheric stability, however, have been shown to exert the strongest impact on PM_{10} dispersion (Demuzere et al., 2009; Lai et al., 2023). Indeed, over the study period, WSOC concentrations in PM_{10} measured here showed a statistically significant inverse relationship with increasing wind speed, although the correlation strength was weak (r = -0.348, p < 0.01, N = 94; Fig. S7). This indicated enhanced dilution and reduced accumulation under more ventilated conditions. Seasonal bivariate polar plot analysis further showed that the highest WSOC concentrations occurred under low wind speeds and stable atmospheric conditions (Fig. 4), highlighting the dominant role of local sources in controlling atmospheric WSOC levels at the coastal central Adriatic site, particularly during summer. Elevated WSOC concentrations observed at moderate wind speeds additionally suggest a measurable contribution from more distant continental sources, pointing to the combined

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influence of both local/regional and distant emissions, consistent with earlier findings for black carbon in the same area (Cvitešić Kušan et al., 2020; Milinković et al., 2021).

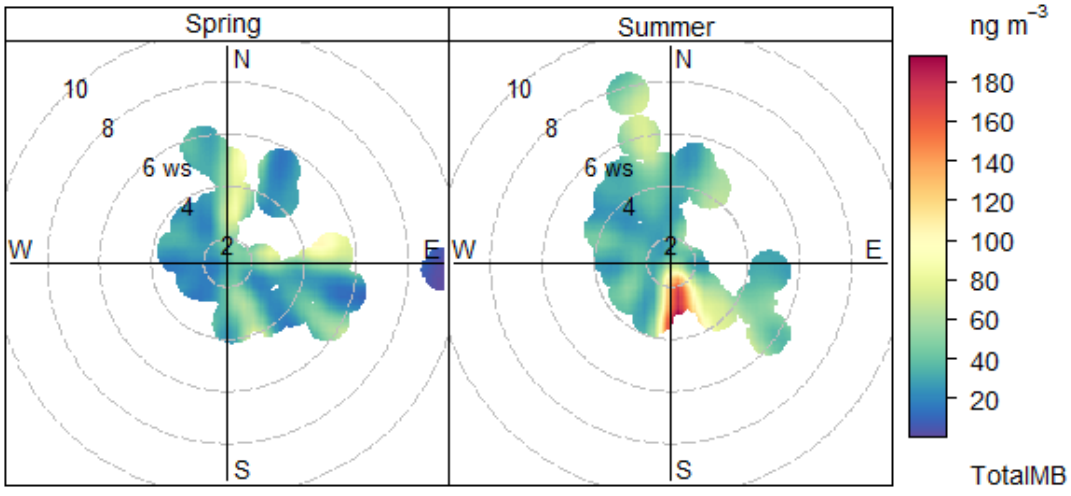

Figure 4: Seasonal bivariate polar plots of mean WSOC concentrations in PM_{10} at the central Adriatic coastal site in spring and summer. The color scale indicates the mean concentration levels. The wind speed (ws) intervals are in m s^{-1}.

A more detailed, monthly analysis of the Total MB composition of atmospheric WSOC, accounting for wind direction and speed (Fig. 5) provides further insight into seasonal source characteristics. The highest Total MB concentrations occurred under low wind speeds and stable atmospheric conditions, particularly in March and August. These findings indicate that spring local/regional continental sources exert the strongest influence on atmospheric carbohydrates in March, while summer sources dominate in August. A strong influence of local emission sources on atmospheric carbohydrate concentrations has also been observed in other studies (Mullaugh et al., 2014; Santos et al., 2021).

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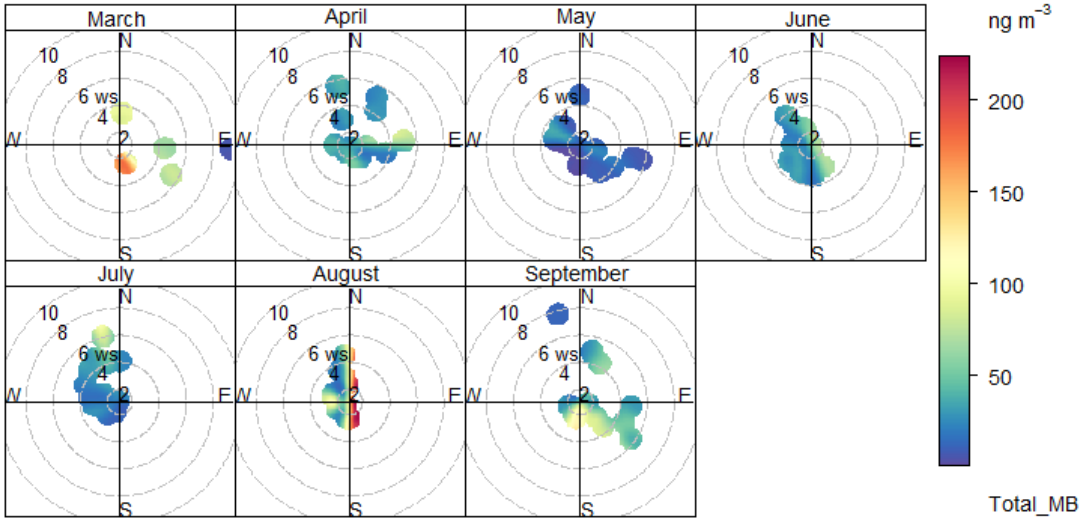

Figure 5: Monthly bivariate polar plots of total monosaccharide biomarker (Total MB) concentrations in PM_{10} at the central Adriatic coastal site. Color scale indicates mean concentration levels. Wind speed (ws) intervals are in m s^{-1}.

To gain further insight into seasonal variability and potential dominant sources, PCA was performed on the PM_{10} dataset, as substantially fewer samples were available for wet and total deposition. Principal components (PCs) with eigenvalues greater than 1 were calculated, and their contributions to total variance were evaluated. The first two PCs explained 54.40% of the total variance (Fig. 6), indicating that these two PCs capture the main structure of the dataset, with PC1 accounting for 35.82% and PC2 for 18.58%. PC1 clearly separated spring and summer samples along the horizontal axis, indicating that seasonality was the dominant source of variability in the dataset. Primary sugars, sugar alcohols, and Total MB during spring clustered on the positive side of PC1, indicating strong correlations and tightly grouped and similar behavior among these compounds. In contrast, summer variables were positioned on the negative side of PC1, reflecting a distinct seasonal shift in PM_{10} chemical composition. PC2 further resolved variability by differentiating key chemical fractions within the summer period. PM_{10} mass, WSOC, and anhydrosugars in summer showed relatively strong positive loadings on PC2, indicating a common source or atmospheric process. The association between WSOC and PM_{10} mass further indicated that variations in organic carbon content were closely linked to overall particulate load during summer. The PCA results highlight a pronounced seasonal contrast in PM_{10} chemical composition at the coastal central Adriatic site.

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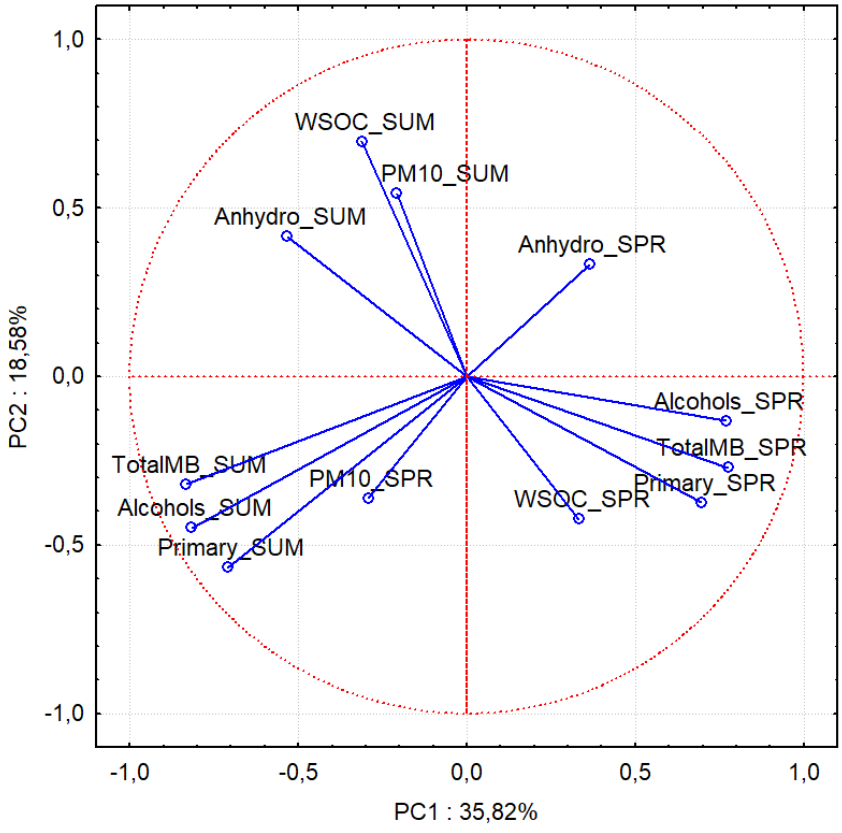

Figure 6: Principal component analysis (PCA) loading plots for the first two principal components derived from the PM_{10} dataset collected during spring (SPR) and summer (SUM) 2024 sampling campaign at the coastal central Adriatic. The variables included were: PM_{10} mass (PM10), water soluble organic carbon (WSOC), primary sugars (Primary), sugar alcohols (Alcohols), anhydrosugars (Anhydro), and total monosaccharide biomarkers (TotalMB).

We further investigated seasonal and matrix-dependent variations of atmospheric carbohydrates in the coastal central Adriatic by assessing the influence of identified specific local and regional sources, including high airborne pollen episodes and bio mass burning events, together with long-range Saharan dust intrusions, on their concentrations and composition (Table 2). To this end, parameters measured across all three matrices during these events (Sect. 2.6.) were analyzed by event type and compared with background conditions. Background conditions were defined by excluding all measurements obtained during deposition events from the overall dataset. In addition, PM_{10} samples collected on rainy days were excluded from the background analysis, as precipitation scavenges atmospheric particles and therefore such samples do not represent true background conditions.

Table 2. Mean concentrations ± standard deviation (N = number of samples) of parameters measured in PM_{10}, wet, and total deposition at the coastal central Adriatic site during specific atmospheric events between March and September 2024. No wet deposition samples were collected during the pollen episodes. Statistically significant differences between background and each specific event where $N \geq 3$ are marked with * ($p < 0.05$) and ** ($p < 0.01$).

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PM_{10}	Background	Pollen	Saharan dust	Biomass burning
Mass (µg m^{-3})	9.7 ± 4.4 (N = 36)	17.7 ± 7.1** (N = 14)	27.4 ± 17.2** (N = 11)	19.3 ± 5.2** (N = 22)
WSOC (µg C m^{-3})	0.96 ± 0.59 (N = 36)	1.28 ± 0.49* (N = 14)	1.02 ± 0.58 (N = 11)	2.47 ± 0.65** (N = 22)
Anhydrosugars (ng m^{-3})	12.6 ± 4.2 (N = 7)	20.5 ± 10.8** (N = 11)	-	20.0 ± 25.8** (N = 13)
Primary sugars (ng m^{-3})	8.9 ± 6.0 (N = 32)	30.8 ± 28.4** (N = 14)	7.6 ± 5.1 (N = 6)	9.5 ± 6.5* (N = 22)
Sugar alcohols (ng m^{-3})	13.3 ± 9.5 (N = 36)	11.8 ± 4.3 (N = 14)	9.1 ± 6.1 (N = 10)	21.2 ± 14.6** (N = 22)
Total MB (ng m^{-3})	23.6 ± 14.9 (N = 36)	58.8 ± 36.1** (N = 14)	14.8 ± 11.4 (N = 10)	42.5 ± 29.1** (N = 22)
WET DEPOSITION	**Background**	**Pollen**	**Saharan dust**	**Biomass burning**
WSOC (µg C L^{-1})	738.45 ± 189.27 (N = 3)	-	910.00 ± 337.00 (N = 2)	2485.00 ± 1333.01 (N = 3)
DMCHO (µg C L^{-1})	88.3 ± 49.5 (N = 3)	-	132.5 ± 82.5 (N = 2)	205.9 ± 123.4 (N = 3)
DPCHO (µg C L^{-1})	88.7 ± 60.2 (N = 3)	-	172.5 ± 54.7 (N = 2)	1677.5 ± 1102.8* (N = 3)
DTCHO (µg C L^{-1})	177.0 ± 54.3 (N = 3)	-	305.0 ± 137.2 (N = 2)	1833.3 ± 1221.1 (N = 3)
Primary sugars (µg L^{-1})	-	-	-	60.0 ± 39.4 (N = 3)
Sugar alcohols (µg L^{-1})	8.9 ± 5.5 (N = 2)	-	-	20.6 ± 22.9 (N = 3)
Total MB (µg L^{-1})	13.2 ± 9.8 (N = 2)	-	-	80.5 ± 62.3 (N = 3)
TOTAL DEPOSITION	**Background**	**Pollen**	**Saharan dust**	**Biomass burning**
WSOC (mg C L^{-1})	903.88 ± 408.83 (N = 7)	1567.41 ± 1050.68 (N = 5)	1331.50 ± 430.07 (N = 4)	1592.95 ± 725.20* (N = 11)
DMCHO (µg C L^{-1})	83.8 ± 48.1 (N = 7)	231.9 ± 200.2 (N = 5)	215.9 ± 57.3** (N = 4)	149.2 ± 74.4 (N = 11)
DPCHO (µg C L^{-1})	205.2 ± 82.6 (N = 7)	482.8 ± 327.2 (N = 5)	228.1 ± 67.8 (N = 4)	448.3 ± 271.5* (N = 11)
DTCHO (µg C L^{-1})	289.0 ± 89.4 (N = 7)	714.7 ± 526.3 (N = 5)	444.0 ± 100.3 (N = 4)	597.5 ± 307.1* (N = 11)
Primary sugars (µg L^{-1})	21.1 ± 8.8 (N = 4)	66.3 ± 27.0* (N = 3)	33.04 ± 14.47 (N = 3)	51.1 ± 45.0 (N = 9)
Sugar alcohols (µg L^{-1})	33.0 ± 44.0 (N = 5)	34.2 ± 21.5 (N = 3)	8.09 ± 2.07 (N = 3)	39.3 ± 42.9 (N = 11)
Total MB (µg L-1)	49.9 ± 46.6 (N = 5)	100.5 ± 47.4 (N = 3)	41.13 ± 15.90 (N = 3)	81.1 ± 86.2 (N = 11)

3.2.1 High-pollen episodes

During the spring period (March–May) 2024, intense pollen episodes were recorded in the study area, with total daily airborne pollen concentrations exceeding 4000 grains m^{-3}, particularly in March (Fig. S4). The occurrence of elevated pollen concentrations under low wind speed conditions (Fig. S8) indicates that local Mediterranean vegetation was the dominant source of airborne pollen and, consequently, a potential major contributor to local atmospheric carbohydrates. According to Mullaugh et al. (2014), carbohydrates can contribute with 10–35% to the dissolved organic carbon in rain during periods of high pollen.

Therefore, beyond the increase in PM_{10} mass, such high airborne pollen loads statistically significantly increased WSOC and Total MB concentrations in both PM_{10} and total deposition samples relative to background conditions, primarily driven by an increase in primary sugars (Table 2). Compared to background levels, primary sugars and Total MB increased by 247% and 149% in PM_{10}, respectively, and by 214% and 101% in total deposition. In addition, elevated airborne pollen concentrations also enhanced DMCHO and DPCHO levels in total deposition samples, resulting in a 147% increase in DTCHO relative to background conditions, although these changes were not statistically significant. Pearson correlation analysis of PM_{10} parameters revealed strong positive relationships between total airborne pollen and carbohydrate components ($r > 0.881$; Table

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3), with the strongest correlation observed for glucose ($r = 0.912$, $p < 0.01$, N = 14; Table 3), a common monosaccharide found in pollen (Pacini et al., 2006; de Weger et al., 2024). Although glucose is mainly emitted from terrestrial plant fruits, pollen, and developing leaves, and typically exhibits elevated concentrations in spring (Fu et al., 2012a; Santos et al., 2021; Haque et al., 2022), it has also been proposed, together with trehalose, as a molecular tracer of surface soil resuspension due to its presence in soil biota (Nirmalkar et al., 2015; Mu et al., 2021; Z. Wang et al., 2021). However, primary sugars such as glucose are associated with coarse particles and are predominantly released into atmospheric aerosols through direct emissions from primary biogenic sources, such as plant material, pollen grains, and microorganisms, whereas primary sugars in fine particles are mainly linked to soil resuspension, dust, and biomass burning (Khan et al., 2021; Wang et al., 2021). Given that monosaccharides, such as glucose, are predominantly found in the coarse fraction of particulate matter (Tsai et al., 2015; Samaké et al., 2019b; Clemente et al., 2024), that agricultural activities are neither characteristic nor frequent in the vicinity of the sampling site, and the strong correlations observed between total pollen and glucose or primary sugars ($r = 0.912$, $p < 0.01$, N = 14; Table 3), as well as Total MB concentrations ($r = 0.881$, $p < 0.01$, N = 14; Table 3), these results confirmed pollen as the dominant source of the measured atmospheric carbohydrates during the observed events. This is further supported by Fu et al. (2012a), who reported that springtime atmospheric aerosol carbohydrates, including glucose, are commonly associated with emissions from blooming pollen.

Table 3. Pearson correlation matrix for parameters measured in PM_{10} during pollen episodes in 2024 at the central Adriatic coastal site. Values represent *r*-values (N = 14). Statistically significant regressions are marked with ** ($p < 0.01$).

Parameter	PM_{10}	WSOC	Glucose	Total MB	Total Pollen
PM_{10}	1.000				
WSOC	0.169	1.000			
Glucose	0.488	0.381	1.000		
Total MB	0.386	0.408	0.949**	1.000	
Total pollen	0.418	0.529	0.912**	0.881**	1.000

Atmospheric glucose may also, under certain conditions, be influenced by marine emissions, particularly in coastal and marine environments. Sea spray aerosol production is a recognized pathway for the transfer of organic matter, including carbohydrates, from the ocean to the atmosphere (Hasenecz et al., 2020; Rocchi et al., 2024). However, this marine-derived organic fraction is generally dominated by complex polysaccharides and other high-molecular-weight compounds, rather than free low-molecular-weight monosaccharides such as glucose. This distinction is supported by Zeppenfeld et al. (2021), who reported substantial differences between monosaccharide compositions in atmospheric aerosols and those in seawater over the Western Antarctic Peninsula. Consequently, even in coastal environments influenced by marine emissions, atmospheric glucose is more plausibly attributed to terrestrial biogenic sources than to direct oceanic emission (e.g., Santos et al., 2021). Although marine contributions may increase under conditions of enhanced sea spray generation, such as high wind speeds and wave activity (Zeppenfeld et al., 2021), no such influence was evident in the present study. PM_{10} glucose concentrations showed no

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statistically significant relationship with wind speed ($r = 0.050$, $p > 0.05$, N = 94), indicating that wind-driven marine emissions did not control its variability. The predominantly terrestrial origin of glucose observed in the present study is further supported by the dominance of continental air masses over marine ones during the sampling period (CONT 40% vs. MAR 28%). Additional evidence is provided by Clemente et al. (2024), who report that nearly 70% of glucose in particulate matter is associated with particles larger than 1 μm, consistent with primary contributions from plant debris and soil material. In parallel, the enrichment of mannitol in the coarse fraction (Clemente et al., 2024), supports primary biogenic emissions as its origin, as mannitol is commonly attributed to fungal spores (Carvalho et al., 2003). Weak but statistically significant positive correlation observed between mannitol and glucose in this study ($r = 0.373$, $p < 0.01$, N = 94) therefore suggests their shared terrestrial origin, reflecting enhanced emissions from continental biogenic sources. Very strong and significant positive correlation between total pollen counts and PM_{10} glucose concentrations ($r = 0.912$, $p < 0.01$, N = 94) further reinforces this interpretation.

3.2.2 Saharan dust intrusions

Relative to background conditions, in PM_{10} samples only particulate mass increased by 183% during the 2024 Saharan dust intrusions (Table 2), while WSOC did not statistically significantly increase in any of the matrices. DTCHO and their fractions, DMCHO and DPCHO, in both wet and total deposition were moderately higher than under background conditions, although the limited number of collected samples may affect the robustness of this interpretation, especially as only DMCHO levels in total deposition were statistically significantly different than in background samples. Conversely, in both PM_{10} and total deposition, concentrations of all monosaccharide groups and Total MB were not significantly different comparing dust intrusion periods and background (Table 2). In wet deposition, monosaccharide biomarkers were detected in only one of the two samples collected during dust intrusions. These results, in addition to further supporting the efficient scavenging of carbohydrates by wet deposition processes, indicate that Saharan dust intrusions over the central Adriatic coastal region led to elevated PM_{10} concentrations, with no significant contribution to atmospheric organic matter, including carbohydrate, levels (Appendix S1). The absence of monosaccharide biomarkers, despite the presence of dissolved carbohydrates, suggests inputs of other carbohydrate compounds not covered by the biomarker analysis and/or not characteristic of the known sources investigated in this study.

This interpretation is consistent with findings from Lampedusa, where Saharan dust-associated organic matter was shown to be predominantly derived from local/regional natural sources, particularly sea spray, while Saharan dust acted primarily as a carrier phase rather than a dominant source of organic matter (Galletti et al., 2020). This study further demonstrated that the organic load associated with dust is highly variable. Similarly, our results suggest that, although Saharan dust events substantially enhance particulate load, they do not necessarily translate into increased concentrations of atmospheric carbohydrate biomarkers, reinforcing the idea that observed organic matter is likely dominated by natural background sources and that dust primarily modulates particulate transport rather than directly contributing substantial carbohydrate-derived organic loads.

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3.2.3 Biomass burning

During 2024 biomass burning events (Fig. 2), all measured parameters across the three matrices increased significantly relative to background levels (Table 2). The most pronounced increases were observed in wet deposition, where WSOC rose by 236%, Total MB by 510%, and DTCHO by 936%, representing the largest increases observed across all matrices. However, these differences were not statistically significant, likely due to the limited number of samples. In PM_{10} during biomass burning events, anhydrosugar concentrations increased by 59% compared to background levels, whereas in wet and total deposition samples, these compounds were undetectable. Such elevated atmospheric carbohydrate levels, particularly anhydrosugars, indicate biomass burning as their significant source in the central Adriatic region.

Monthly bivariate polar plot analysis of anhydrosugar concentrations in PM_{10} revealed two periods of elevated concentrations (Fig. 7), with slightly higher values in the warmer months (July–August) than in cooler months (March–April). Both spring and summer relationship with wind speed and direction suggest a dominant influence of regional and more distant, continental sources of atmospheric anhydrosugars.

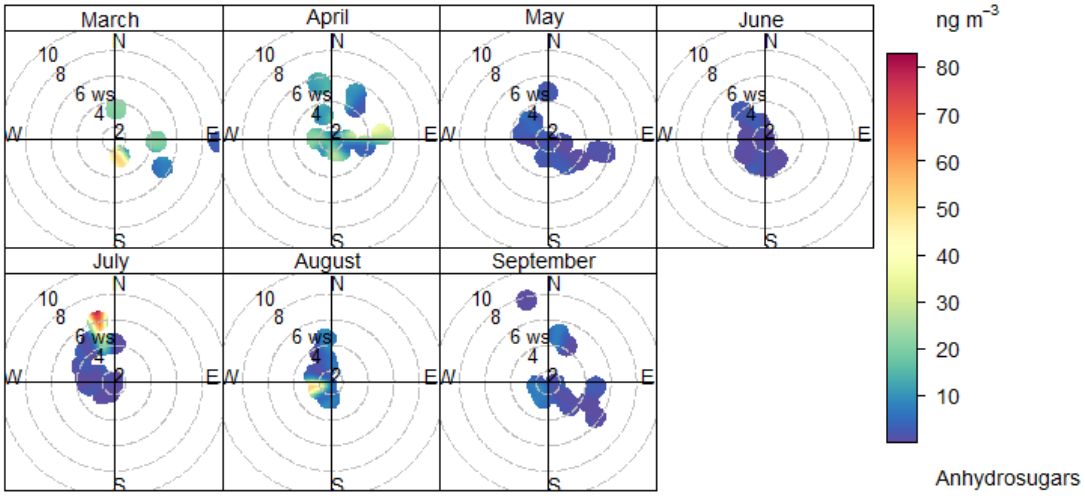

Figure 7: Monthly bivariate polar plots of anhydrosugars concentrations in PM_{10} at the central Adriatic coastal site. Color scale indicates mean concentration levels. Wind speed (ws) intervals are in m s^{-1}.

Spring anhydrosugar concentrations were significantly negatively correlated with air temperature (r = -0.632, p < 0.01, N = 45; Fig. 8), indicating that anhydrosugar concentrations increased as air temperature decreased, confirming residential wood burning as a dominant source during colder months, such as March and April. This is consistent with previous observations of negative temperature dependence in the biomass burning fraction of black carbon in the same area (r = -0.33), which peaks in the cold season due to increased local, regional, and long-range continental emissions from residential wood heating (Milinković et al., 2021). This also explains elevated anhydrosugar concentrations observed during pollen episodes in cooler spring months (Table 2; Appendix S1).

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In contrast, summer concentrations showed statistically insignificant correlation with temperature (r = 0.084, p > 0.05; N = 49; Fig. 8), suggesting sources other than domestic heating. Using MODIS Terra and Aqua satellite imagery together with archival records from firefighting services, elevated anhydrosugar concentrations in PM_{10} were associated with forest wildfires occurring during summer 2024 (Fig. 2.; Fig. S6). The highest anhydrosugar concentrations (> 80 ng m^{-3}; Figs. 7 and 8) coincided with the 29 July–4 August wildfire (Fig. S6), also observed in other regional studies (Sopčić et al., 2025a). High temperatures, low relative humidity, and strong winds, typical summer conditions in the central coastal Adriatic (Šegota and Filipčić, 2003), pravailed during the 29 July–4 August wildfire episode, creating conditions favorable for wildfire occurrence. These conditions are often associated with air stagnation, which limits pollutant dispersion and degrades air quality (Barriopedro et al., 2023; Zhang et al., 2024; Sopčić et al., 2025a), further amplifying the impact of forest wildfires on atmospheric chemical composition. Consequently, higher anhydrosugar concentrations observed during warmer months indicate that summer wildfires in the central Adriatic governed atmospheric carbohydrates levels.

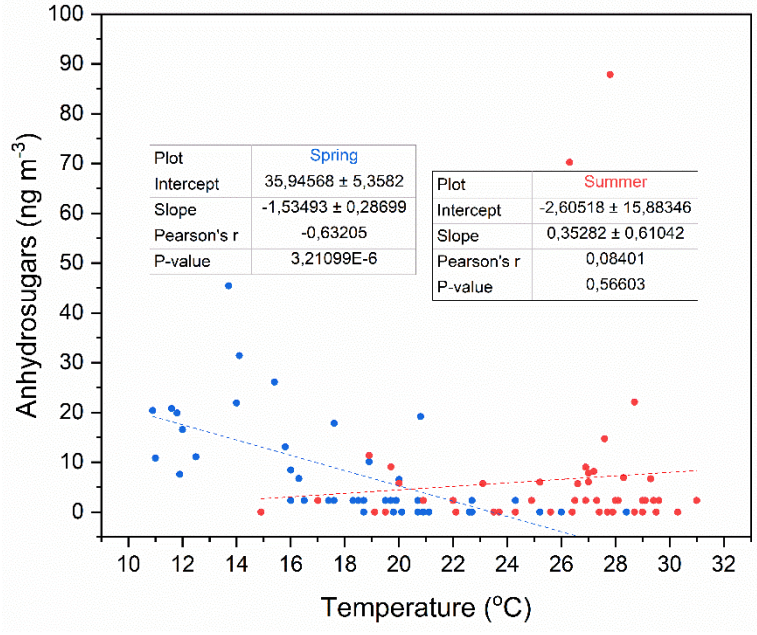

Figure 8: Correlation analysis of spring and summer time anhydrosugars concentrations in PM_{10} and air temperature during the 2024 sampling campaign at the coastal central Adriatic site. Pearson correlation results are embedded within the figure.

Overall, atmospheric anhydrosugar levels and carbohydrate composition in the central coastal Adriatic are influenced not only by pollen episodes, but also by residential wood burning during the colder months and forest wildfires in the warmer months (Appendix S1), highlighting both the continuous impact of biomass burning and the diversity of episodic emission sources in the study area.

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3.2.4 Other (biogenic) sources

In addition to the previously identified sources, monosaccharide biomarker analysis revealed an additional dominant source of atmospheric carbohydrates at the coastal central Adriatic site. Sugar alcohols exhibited strong seasonal variability in PM_{10}, with statistically significantly higher concentrations in summer than in spring (by 121%; Table 1, Fig. 9). Similar summertime enhancements of sugar alcohols in aerosols and rainwater samples have been reported in previous studies (Verma et al., 2018; Haque et al., 2022; Sopčić et al., 2025b). Analysis of PM_{10} sugar alcohol concentrations in relation to wind parameters strongly indicated that summer sugar alcohols predominantly originated from local sources (Fig. 9).

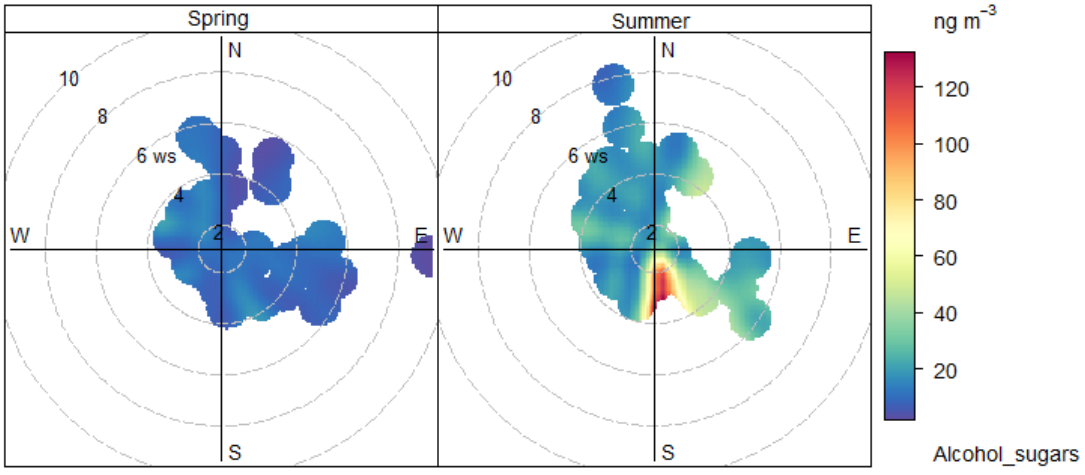

Figure 9: Seasonal bivariate polar plots of mean sugar alcohols concentrations in PM_{10} at the central Adriatic coastal site in spring and summer 2024. Color scale indicates mean concentration levels. Wind speed (ws) intervals are in m s^{-1}.

Sugar alcohols are reduced saccharides primarily formed through plant biological activity and microbial metabolism and are predominantly associated with biogenic organic aerosol sources (Pietrogrande et al., 2014; Theodosi et al., 2018). Among them, arabitol and mannitol are widely used as biomarkers of fungal biomass, as they are produced by fungi and bacteria during the degradation of natural organic matter (Amato et al., 2024; Samaké et al., 2019a). In addition, these compounds are recognized as primary photosynthetic products in mature leaves and have been associated with increased inputs of vegetation detritus during spring bloom events (Pashynska et al., 2002; Burshtein et al., 2011). However, elevated concentrations of sugar alcohols in PM_{10} observed during the summer months indicate that vegetation was not their dominant source. Mannitol and trehalose function as stress-induced fungal metabolites, with production enhanced under low soil moisture conditions typical of summer (Medeiros et al., 2006b). Consistently, substantially higher summer concentrations of trehalose, mannitol, and arabitol compared to winter and spring are attributed to intensified fungal activity under heat and drought stress (Jia et al., 2010; Verma et al., 2018). Furthermore, the positive correlation between enhanced summer sugar alcohol concentrations and air temperature indicates that fungal spore activity is strongly regulated by air temperature (Zhu et al., 2015). Therefore, the sugar alcohols observed during summer at the investigated site point to fungal activity as their dominant source.

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Moreover, mannitol and arabitol have occasionally been detected in aerosols influenced by biomass burning plumes, especially on synoptic scales (Medeiros & Simoneit, 2008; Fu et al., 2012b; Yang et al., 2012). However, the absence of positive, statistically significant correlation between sugar alcohols and anhydrosugars during wildfire events at the coastal central Adriatic site (r = -0.091, p > 0.05, N = 22) suggests that biomass burning was not a significant source of sugar alcohols in this region.

3.3 Deposition fluxes

To assess the influence of specific atmospheric events, i.e., sources, on deposition fluxes, concentrations of the measured parameters in PM_{10}, wet, and total deposition samples were converted into dry, wet, and total deposition fluxes, respectively, and compared with background conditions (Table 4).

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Table 4. Mean values ± standard deviation (number of samples in brackets) of calculated deposition fluxes for parameters measured in dry, wet, and total deposition at the coastal central Adriatic site during specific atmospheric events between March and September 2024. No wet deposition samples were collected during the pollen episodes. Statistically significant differences between background and each specific event where N ≥ 3 are marked with * ($p < 0.05$) and ** ($p < 0.01$).

DRY DEPOSITION	**Background**	**Pollen**	**Saharan dust**	**Biomass burning**
WSOC (μg C m^{-2} d^{-1})	558 ± 339 (N = 36)	743 ± 283* (N = 14)	588 ± 338 (N = 11)	1428 ± 378** (N = 22)
Anhydrosugars (μg m^{-2} d^{-1})	1 ± 0 (N = 7)	2 ± 1** (N = 11)	-	2 ± 2** (N = 13)
Primary sugars (μg m^{-2} d^{-1})	15 ± 10 (N = 32)	53 ± 49** (N = 14)	13 ± 9 (N = 6)	16 ± 11* (N = 22)
Sugar alcohols (μg m^{-2} d^{-1})	23 ± 16 (N = 36)	20 ± 7 (N = 14)	16 ± 10 (N = 10)	37 ± 25** (N = 22)
Total MB (μg m^{-2} d^{-1})	37 ± 26 (N = 36)	75 ± 47** (N = 14)	25 ± 18 (N = 10)	54 ± 36* (N = 22)
WET DEPOSITION	**Background**	**Pollen**	**Saharan dust**	**Biomass burning**
WSOC (μg C m^{-2} d^{-1})	14357 ± 7376 (N = 3)	-	-	49627 ± 29486 (N = 3)
DMCHO (μg C m^{-2} d^{-1})	1662 ± 958 (N = 3)	-	-	3771 ± 1640 (N = 3)
DPCHO (μg C m^{-2} d^{-1})	1881 ± 1822 (N = 3)	-	-	32990 ± 22809* (N = 3)
DTCHO (μg C m^{-2} d^{-1})	3543 ± 2132 (N = 3)	-	-	36760 ± 24438 (N = 3)
Primary sugars (μg m^{-2} d^{-1})	-	-	-	1015 ± 280** (N = 3)
Sugar alcohols (μg m^{-2} d^{-1})	170 ± 81 (N = 2)	-	-	290 ± 225 (N = 3)
Total MB (μg m^{-2} d^{-1})	246 ± 157 (N = 2)	-	-	1305 ± 493* (N = 3)
TOTAL DEPOSITION	**Background**	**Pollen**	**Saharan dust**	**Biomass burning**
WSOC (μg C m^{-2} d^{-1})	4376 ± 2305 (N = 5)	4977 ± 1951 (N = 3)	6397 ± 2841 (N = 4)	6916 ± 3511 (N = 11)
DMCHO (μg C m^{-2} d^{-1})	359 ± 227 (N = 5)	643 ± 376 (N = 3)	1014 ± 346** (N = 4)	639 ± 337 (N = 11)
DPCHO (μg C m^{-2} d^{-1})	929 ± 429 (N = 5)	1553 ± 743 (N = 3)	1000 ± 180 (N = 4)	1974 ± 1321 (N = 11)
DTCHO (μg C m^{-2} d^{-1})	1288 ± 454 (N = 5)	2196 ± 1117 (N = 3)	2014 ± 384 (N = 4)	2614 ± 1516 (N = 11)
Primary sugars (μg m^{-2} d^{-1})	85 ± 30 (N = 4)	252 ± 139 (N = 3)	144 ± 49 (N = 3)	202 ± 180 (N = 9)
Sugar alcohols (μg m^{-2} d^{-1})	152 ± 216 (N = 5)	127 ± 97 (N = 3)	37 ± 2 (N = 3)	157 ± 167 (N = 11)
Total MB (μg m^{-2} d^{-1})	220 ± 231 (N = 5)	379 ± 231 (N = 3)	180 ± 48 (N = 3)	323 ± 340 (N = 11)

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The average background dry deposition flux of WSOC in this study (558 ± 339 μg C m^{-2} d^{-1}; Table 4) was comparable to measurements from a remote coastal eastern Mediterranean site (480 μg C m^{-2} d^{-1}; Theodosi et al., 2018). However, it was lower than the annual average reported for coastal waters near Yangma Island (790 ± 470 μg C m^{-2} d^{-1}; Xie et al., 2022) and substantially lower than values observed in the Yellow Sea (1500 ± 1180 μg C m^{-2} d^{-1}) and East China Sea (3570 ± 1540 μg C m^{-2} d^{-1}) during dust storm seasons (Bao et al., 2017). Background dry deposition fluxes of individual carbohydrate groups (primary sugars: 15 ± 10 μg C m^{-2} d^{-1}, sugar alcohols: 23 ± 16 μg C m^{-2} d^{-1}, anhydrosugars: 1 ± 0 μg C m^{-2} d^{-1}; Table 4) somewhat differed from those reported at the remote coastal eastern Mediterranean site (primary sugars: 21 μg C m^{-2} d^{-1}, sugar alcohols: 4 μg C m^{-2} d^{-1}, anhydrosugars: 1 μg C m^{-2} d^{-1}; Theodosi et al., 2018). Wet deposition fluxes exceeded dry deposition by one to two orders of magnitude, indicating that precipitation was the dominant removal pathway for atmospheric organic matter. As a result, total deposition fluxes reflected the combined influence of emission strength and wet scavenging efficiency. The average background total deposition flux of WSOC measured here (4376 ± 2305 μg C m^{-2} d^{-1}; Table 4) was comparable to values reported for Lampedusa, a remote central Mediterranean site (~3970 μg C m^{-2} d^{-1}; Galletti et al., 2020), and for the Cap Ferrat peninsula in southern France (~4240 μg C m^{-2} d^{-1}; Pulido-Villena et al., 2008). It was higher than fluxes reported for the northwestern Mediterranean (~1940 μg C m^{-2} d^{-1}; Djaoudi et al., 2018) but lower than those measured in three western Mediterranean lakes (~5040 μg C m^{-2} d^{-1} in 2005; de Vicente et al., 2012). Against this background, episodic events, particularly biomass burning and pollen episodes, produced, in some cases intense, increases in deposition fluxes of atmospheric organic matter and its components.

Pollen episodes primarily enhanced the deposition of biogenic material, especially through dry deposition. During these events, dry deposition fluxes of primary sugars statistically significantly increased three- to four-fold relative to background values, while Total MB fluxes more than doubled. Although not statistically significant, total deposition fluxes of DTCHO and its components, DMCHO and DPCHO, increased by nearly twofold compared with background conditions. In contrast, both dry and total deposition fluxes of sugar alcohols decreased. This pattern indicates that high-pollen episodes predominantly enhanced the dry deposition of primary sugars. No wet deposition samples were collected during pollen episodes, leaving the role of precipitation in the removal of pollen derived organic matter to be addressed in future research.

Biomass burning events produced the largest overall increases in organic matter deposition, particularly via wet deposition. Wet deposition fluxes of WSOC were three- to four- fold higher than background values, while DTCHO fluxes increased by more than an order of magnitude, indicating highly efficient precipitation-mediated scavenging. However, these differences were not statistically significant, likely due to the limited number of samples available. Total deposition fluxes during these events reflected both enhanced emissions and effective wet removal. Biomass burning episodes are also known to increase wet deposition of nutrients, especially nitrate, underscoring their potential biogeochemical impact (Milinković et al., 2022).

Saharan dust intrusions exhibited a distinct pattern. Total deposition fluxes of WSOC and DTCHO were insignificantly slightly elevated, whereas primary sugars, sugar alcohols, and Total MB fluxes were generally comparable to or lower than background levels. This indicates a limited contribution of biogenic carbohydrates during dust intrusions, with deposition dominated by mineral dust and other, unspecified carbohydrate components. Similarly, Djaoudi et al. (2018) observed that the minimum

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atmospheric fluxes of soluble organic carbon, nitrogen, and phosphorus coincided with the Saharan event in April 2016, indicating that atmospheric fluxes with a desert signature are typically depleted in soluble organic matter. Although no wet deposition samples were collected during the Saharan dust intrusion in this study, which typically drives dust deposition to the Mediterranean Sea, previous work has shown that dry deposition can also represent a substantial, or even the main pathway, for the input of DOC and other chemical species to the Mediterranean (Morales-Baquero et al., 2013; Galletti et al., 2020). Biomass burning episodes generated the largest increases in both dry and wet deposition fluxes, particularly for WSOC and DTCHO (including DMCHO and DPCHO), highlighting their role as major sources of atmospheric carbohydrates and organic matter in general. Pollen episodes predominantly enhanced the deposition of primary sugars, whereas Saharan dust intrusions had limited impact on carbohydrate fluxes. These findings underscore the importance of considering event-specific atmospheric transport pathways and emission sources when assessing organic matter and carbohydrate deposition in coastal Mediterranean environments and indicate that episodic events can represent a significant fraction of the seasonal input of organic carbon and carbohydrates to the surface environment, with potential implications for nutrient supply and coastal biogeochemical processes.

3.4 Biogeochemical significance

Atmospheric deposition of dissolved organic matter provides episodic inputs of bioavailable carbon to surface waters in receiving marine environments. To evaluate the potential impact of organic matter and carbohydrates introduced during high-pollen episodes, Saharan dust intrusions, and biomass burning events on the adjacent Adriatic Sea, we estimated event-based increases in surface layer DOC concentrations resulting from total deposition of WSOC and DTCHO. Given the high wet deposition fluxes observed during biomass burning events and generally important role of precipitation in scavenging atmospheric organic matter (e.g., Djaoudi et al., 2018), we quantified the specific contribution of wet deposition to bioavailable DOC. During high-pollen and Saharan dust episodes, no wet deposition samples were collected, therefore, the potential contribution of wet deposition during these events could not be assessed. All calculations were made assuming instantaneous mixing within the upper 1 m of the water column and are expressed relative to the average ambient DOC concentration (1.007 ± 0.099 mg L^{-1}; Furdek Turk et al., 2024).

Table 5. Mean ± standard deviation of daily event based increases in surface layer bioavailable carbon concentrations (ΔC) in the Adriatic Sea during pollen (POLL), Saharan dust (SD), and biomass burning (BB) episodes, derived from wet and total atmospheric deposition of WSOC and DTCHO, expressed as absolute values (μg L^{-1} d^{-1}) and relative changes (% d^{-1}) with respect to the average ambient DOC concentration (1.007 ± 0.099 mg L^{-1}), assuming instantaneous mixing within the upper 1 m of the water column.

Wet deposition	ΔC (μg L^{-1} d^{-1})	DOC (% d^{-1})
$WSOC_{BB}$	50 ± 29	5 ± 30
$DTCHO_{BB}$	37 ± 24	4 ± 25

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Total deposition	ΔC (μg L^{-1} d^{-1})	DOC (% d^{-1})
$WSOC_{POLL}$	5 ± 2	<1
$WSOC_{SD}$	6 ± 3	1 ± 3
$WSOC_{BB}$	7 ± 4	1 ± 4
$DTCHO_{POLL}$	2 ± 1	<1
$DTCHO_{SD}$	2 ± 0	<1
$DTCHO_{BB}$	3 ± 2	<1

Event based calculations show that daily total deposition of WSOC and DTCHO during all events generally increased surface layer DOC concentrations by 2–7 μg L^{-1} d^{-1}, corresponding to 0.2–0.7% of the average ambient DOC pool (Table 5). Among total deposition, biomass burning and Saharan dust events increased DOC slightly more than high-pollen episodes, reflecting their generally higher WSOC inputs. DTCHO constituted a substantial fraction of the deposited WSOC in both wet and total deposition. During total deposition, DTCHO accounted for approximately 30–40% of the WSOC derived carbon input, with somewhat higher proportions during pollen episodes (44%), and lower fractions during biomass burning (38%) and dust events (31%). Although absolute DOC increases from total deposition inputs are smaller relative to the ambient pool, the consistently high DTCHO fraction indicates that a significant share of the deposited carbon is in carbohydrate, chemically labile form and may therefore be readily bioavailable. In contrast, daily wet deposition during biomass burning events generated substantially larger pulses, reaching up to 50 μg L^{-1} d^{-1}, or 5% of the ambient DOC. In wet deposition during biomass burning events, DTCHO contributed 74% of the WSOC derived increase, indicating that most of the wet deposited organic carbon is present in carbohydrate form.

While total deposition represents a smaller but more continuous contribution across emission sources, wet deposition during biomass burning events can deliver short but comparatively large pulses of such labile carbon, that may stimulate microbial activity and induce transient biogeochemical responses in the surface layer. Overall, atmospheric deposition delivers episodic inputs of bioavailable carbon to the surface waters of the Adriatic Sea, with effects that depend strongly on event intensity and deposition mode. While the long-term contribution to the Adriatic carbon pool is modest, these episodic inputs may still exert localized and short-term biogeochemical effects.

4 Conclusions

This study provides the first integrated characterization of atmospheric carbohydrates across dry, wet and total deposition pathways at a coastal northern Mediterranean (central Adriatic) site, including the assessment of key regional atmospheric sources, including high-pollen episodes, Saharan dust intrusions, and biomass burning events. By combining source-specific molecular biomarkers, deposition flux calculations, and event-based analyses, the study identified the major sources influencing atmospheric carbohydrates, quantified their transfer to the coastal environment, and evaluated their potential significance for atmosphere–ocean carbon cycling in the Adriatic Sea.

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Atmospheric carbohydrate concentrations displayed pronounced variability driven by clear seasonal shifts in dominant sources. Mean PM_{10} concentration was 15.2 ± 9.7 μg m^{-3}, with WSOC representing 9.4 ± 3.9% of particulate mass and increasing from 0.90 ± 0.50 μg C m^{-3} in spring to 1.75 ± 0.90 μg C m^{-3} in summer. Total MB showed a moderate seasonal increase from 32.6 ± 29.7 ng m^{-3} in spring to 41.8 ± 36.2 ng m^{-3} in summer, while individual biomarker groups revealed distinct seasonal source signatures. Wet deposition was the dominant removal pathway, with background WSOC and Total MB deposition fluxes of 14357 ± 7376 and 246 ± 157 μg C m^{-2} d^{-1}, respectively, exceeding dry deposition fluxes (558 ± 339 and 37 ± 26 μg C m^{-2} d^{-1}, respectively) by one to two orders of magnitude. The average background total WSOC deposition flux of 4376 ± 2305 μg C m^{-2} d^{-1} was comparable to values reported for other Mediterranean coastal environments, indicating that atmospheric deposition represents a continuous pathway for the transfer of organic carbon to surface waters.

Spring high-pollen episodes represented a major previously underestimated source of atmospheric carbohydrates. During periods with airborne pollen concentrations exceeding 4000 grains m^{-3}, primary sugars and Total MB increased by 247% and 149% in PM_{10}, respectively, and by 214% and 101% in total deposition relative to background conditions. The strong correlations between airborne pollen and PM_{10} glucose (r = 0.912, p < 0.01, N = 14) and Total MB (r = 0.881, p < 0.01, N = 14) supported airborne pollen as a major contributor during these events. Biomass burning represented the strongest episodic source of atmospheric carbohydrate enrichment and deposition. Residential wood burning during colder months and regional wildfires during summer substantially increased atmospheric organic carbon and carbohydrate concentrations across all atmospheric matrices. The largest impact was observed in wet deposition, where biomass burning events increased WSOC by 236%, Total MB by 510%, and DTCHO by 936% compared with background conditions. Enhanced anhydrosugar concentrations in PM_{10} (+59%) further supported biomass burning as a major source of atmospheric carbohydrates. In contrast, Saharan dust intrusions primarily increased particulate mass (+183%) without significantly increasing atmospheric carbohydrate concentrations or deposition fluxes, indicating that Saharan dust, although important for mineral aerosol transport, had limited direct influence on carbohydrate deposition. Increased summer sugar alcohols concentrations (+121% in PM_{10}) further indicate an additional, although comparatively smaller, contribution from fungal emissions under warm Mediterranean conditions.

During episodic emissions events, total daily atmospheric deposition of DTCHO and WSOC increased Adriatic Sea surface-layer DOC concentrations by approximately 2–7 μg L^{-1} d^{-1}, corresponding to 0.2–0.7% of the ambient DOC pool. Importantly, DTCHO accounted for approximately 30–40% of deposited WSOC, demonstrating that a substantial fraction of atmospheric organic carbon reaches surface waters in potentially bioavailable carbohydrate forms. During biomass burning events, wet deposition of WSOC produced substantially larger short-term inputs, increasing surface DOC concentrations by up to 50 μg L^{-1} d^{-1} (approximately 5% of the ambient DOC pool), with DTCHO accounting for 74% of this contribution. Although atmospheric deposition represents a relatively small contribution of the long-term coastal DOC reservoir, these episodic inputs may trigger transient increases in microbial carbon availability and influence short-term coastal biogeochemical processes.

Overall, this study demonstrates that atmospheric carbohydrate deposition in the coastal Mediterranean is shaped by the combined influence of background emission sources, intense episodic local and regional events, atmospheric transport, and

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prevailing meteorological conditions. Background atmospheric carbohydrate composition reflects contributions from multiple sources, including biogenic emissions such as vegetation- and fungal-derived inputs, as well as diffuse anthropogenic contributions. In contrast, episodic events, particularly high-pollen emissions and wildfire episodes, produce short-term increases in atmospheric carbohydrate concentrations and deposition, disproportionately enhancing inputs of chemically labile organic carbon to coastal waters. These episodic events therefore represent important mechanisms linking terrestrial ecosystems, atmospheric organic matter cycling, and marine biogeochemistry. The contrasting impacts of Saharan dust intrusions further emphasize that emission sources characteristics, transport pathways and atmospheric organic matter composition are important factors influencing atmosphere-ocean carbon transfer.

Compared with previous studies from Mediterranean and other coastal environments, this work advances current understanding by quantifying the relative importance of different atmospheric sources contributing to carbohydrate deposition rather than only characterizing atmospheric concentrations. Although pollen, biomass burning, fungal emissions, and desert dust have previously been recognized as important contributors to atmospheric organic matter, their respective contributions to carbohydrate deposition remain largely unresolved, with the contribution of airborne pollen being particularly poorly constrained in Mediterranean coastal environments. The present study provides the first quantitative assessment of the contribution of pollen events to atmospheric carbohydrate deposition in a Mediterranean coastal environment, demonstrating that high-pollen episodes can represent a major source of atmospheric carbohydrates. By integrating dry, wet, and total deposition pathways with event-based assessment of multiple characteristic Mediterranean contributors, including pollen, biomass burning, fungal emissions, and Saharan dust, this study provides new insight into the processes governing organic carbon transfer between terrestrial ecosystems, the atmosphere, and coastal marine environments.

Despite limitations related to the single-site seasonal sampling period, limited wet deposition observations during individual events, and the inability of biomarker-based source apportionment to fully resolve overlapping emission sources, the integration of source-specific characteristics, event-based observations of organic matter and biomarker concentration patterns, and deposition fluxes provides strong support for the identified dominant source influences. Future studies expanding observations across multiple seasons, years, and Mediterranean regions, while integrating complementary source apportionment approaches, could further refine atmospheric carbohydrate budgets and improve understanding of their response to climate-driven changes.

Under future climate scenarios characterized by increasing temperatures, more frequent droughts, enhanced pollen production (Ziska & Caulfield, 2000; Ziska et al., 2019), altered precipitation regimes, and more frequent and intense wildfires, both the magnitude and chemical composition of atmospheric organic matter deposition are likely to change. This is particularly relevant for Mediterranean ecosystems, where shifts in wildfire activity and terrestrial biological cycles may alter the timing, intensity, and biogeochemical significance of atmospheric organic carbon inputs to coastal waters. Incorporating these event-driven atmospheric processes into regional atmosphere-ocean carbon budgets will therefore improve assessments of coastal ecosystem functioning, organic carbon cycling, and climate-biosphere feedbacks in the Mediterranean, and other coastal marine environments.

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Data availability

The data that support the findings of this study are openly available at: https://doi.org/10.5281/zenodo.19794244.

Author contributions

Andrea Milinković performed conceptualization, formal analysis, methodology, data curation, visualization, writing - original draft. Suzana Sopčić contributed formal analysis, performed data curation and handled validation. Dora Crmarić contributed methodology. Slađana Strmečki performed methodology and led validation, funding acquisition, project administration, and supervision. All authors contributed to draft review and editing, and approved the final publication.

Competing interests

The authors declare that they have no conflict of interest.

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References

Amato, F., van Drooge, B. L., Jaffrezo, J.-L., Favez, O., Colombi, C., Cuccia, E., Reche, C., Ippolito, F., Ridolfo, S., and Lara, R.: Aerosol source apportionment uncertainty linked to the choice of input chemical components, Environ. Int., 184, 108441, https://doi.org/10.1016/j.envint.2024.108441, 2024.

Bao, H., Niggemann, J., Luo, L., Dittmar, T., and Kao, S.-J.: Aerosols as a source of dissolved black carbon to the ocean, Nat. Commun., 8, 510, https://doi.org/10.1038/s41467-017-00437-3, 2017.

Barriopedro, D., García–Herrera, R., Ordóñez, C., Miralles, D., and Salcedo–Sanz, S.: Heat Waves: A Growing Threat to Society and the Environment, Eos (Washington. DC)., 104, https://doi.org/10.1029/2023EO235012, 2023.

Bauer, H., Claeys, M., Vermeylen, R., Schueller, E., Weinke, G., Berger, A., and Puxbaum, H.: Arabitol and mannitol as tracers for the quantification of airborne fungal spores, Atmos. Environ., 42, 588–593, https://doi.org/10.1016/j.atmosenv.2007.10.013, 2008.

Benner, R., Pakulski, J. D., McCarthy, M., Hedges, J. I., and Hatcher, P. G.: Bulk Chemical Characteristics of Dissolved Organic Matter in the Ocean, Science (1979)., 255, 1561–1564, https://doi.org/10.1126/science.255.5051.1561, 1992.

Bhattarai, H., Saikawa, E., Wan, X., Zhu, H., Ram, K., Gao, S., Kang, S., Zhang, Q., Zhang, Y., Wu, G., Wang, X., Kawamura, K., Fu, P., and Cong, Z.: Levoglucosan as a tracer of biomass burning: Recent progress and perspectives, Atmos. Res., 220, 20–33, https://doi.org/10.1016/j.atmosres.2019.01.004, 2019.

Bougiatioti, A., Zarmpas, P., Koulouri, E., Antoniou, M., Theodosi, C., Kouvarakis, G., Saarikoski, S., Mäkelä, T., Hillamo, R., and Mihalopoulos, N.: Organic, elemental and water-soluble organic carbon in size segregated aerosols, in the marine boundary layer of the Eastern Mediterranean, Atmos. Environ., 64, 251–262, https://doi.org/10.1016/j.atmosenv.2012.09.071, 2013.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., van der Werf, G. R., and Flannigan, M.: Vegetation fires in the Anthropocene, Nat. Rev. Earth Environ., 1, 500–515, https://doi.org/10.1038/s43017-020-0085-3, 2020.

Burshtein, N., Lang-Yona, N., and Rudich, Y.: Ergosterol, arabitol and mannitol as tracers for biogenic aerosols in the eastern Mediterranean, Atmos. Chem. Phys., 11, 829–839, https://doi.org/10.5194/acp-11-829-2011, 2011.

Carslaw, D. C. and Beevers, S. D.: Characterising and understanding emission sources using bivariate polar plots and k-means clustering, Environmental modelling & software, 40, 325–329, https://doi.org/10.1016/j.envsoft.2012.09.005, 2013.

Carslaw, D. C. and Ropkins, K.: Openair—an R package for air quality data analysis, Environmental Modelling & Software, 27, 52–61, https://doi.org/10.1016/j.envsoft.2011.09.008, 2012.

Carvalho, A., Pio, C., and Santos, C.: Water-soluble hydroxylated organic compounds in German and Finnish aerosols, Atmos. Environ., 37, 1775–1783, https://doi.org/10.1016/S1352-2310(03)00066-9, 2003.

Castagna, J., Senatore, A., Bencardino, M., and Mendicino, G.: Concurrent Influence of Different Natural Sources on the Particulate Matter in the Central Mediterranean Region during a Wildfire Season, Atmosphere (Basel)., 12, 144, https://doi.org/10.3390/atmos12020144, 2021.

Chatoutsidou, S. E., Bali, A., and Lazaridis, M.: PM10 mass concentration characteristics in a coastal mediterranean site: a yearly study of seasonality and sources with short term elemental analysis, Air Qual. Atmos. Health, 18, 2317–2332, https://doi.org/10.1007/s11869-025-01763-y, 2025.

Chen, H.-Y. and Huang, S.-Z.: Composition and supply of inorganic and organic nitrogen species in dry and wet atmospheric deposition: Use of organic nitrogen composition to calculate the Ocean's external nitrogen flux from the atmosphere, Cont. Shelf Res., 213, 104316, https://doi.org/10.1016/j.csr.2020.104316, 2021.

Chen, H. Y. and Liu, T. W.: Composition and Biogeochemical Effects of Carbohydrates in Aerosols in Coastal Environment, J. Mar. Sci. Eng., 12, https://doi.org/10.3390/jmse12101834, 2024.

Clemente, Á., Galindo, N., Nicolás, J. F., Crespo, J., Pastor, C., and Yubero, E.: Local versus Regional Contributions to PM10 Levels in the Western Mediterranean, Aerosol Air Qual. Res., 23, 230218, https://doi.org/10.4209/aaqr.230218, 2023.

Clemente, Á., Yubero, E., Nicolás, J. F., Crespo, J., and Galindo, N.: Organic tracers in fine and coarse aerosols at an urban Mediterranean site: contribution of biomass burning and biogenic emissions, Environmental Science and Pollution Research, 31, 25216–25226, https://doi.org/10.1007/s11356-024-32789-x, 2024.

Copernicus Atmosphere Monitoring Service (CAMS): Copernicus Saharan dust strongly affects air quality in the Eastern Mediterranean, 2024. Retrieved from https://atmosphere.copernicus.eu/copernicus-saharan-dust-strongly-affects-air-quality-eastern-mediterranean.

Copin-Montégut, C.: Alkalinity and carbon budgets in the Mediterranean Sea, Global Biogeochem. Cycles, 7, 915–925, https://doi.org/10.1029/93GB01826, 1993.

Cvitešić Kušan, A., Kroflič, A., Grgić, I., Ciglenečki, I., and Frka, S.: Chemical characterization of fine aerosols in respect to water-soluble ions at the eastern Middle Adriatic coast, Environmental Science and Pollution Research, 27, 10249–10264, https://doi.org/10.1007/s11356-020-07617-7, 2020.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

D'Angelo, L., Ungeheuer, F., Ma, J., Ferrero, L., Colombi, C., Cuccia, E., Dal Santo, U., Biffi, B., and Vogel, A. L.: Contrasting organic aerosol molecular composition between the urban and agricultural environment of the Po Valley, https://doi.org/10.5194/egusphere-2025-5522, 19 November 2025.

Decina, S. M., Templer, P. H., and Hutyra, L. R.: Atmospheric Inputs of Nitrogen, Carbon, and Phosphorus across an Urban Area: Unaccounted Fluxes and Canopy Influences, Earths Future, 6, 134–148, https://doi.org/10.1002/2017EF000653, 2018.

Demuzere, M., Trigo, R. M., Vila-Guerau de Arellano, J., and van Lipzig, N. P. M.: The impact of weather and atmospheric circulation on O 3 and PM 10 levels at a rural mid-latitude site, Atmos. Chem. Phys., 9, 2695–2714, https://doi.org/10.5194/acp-9-2695-2009, 2009.

Djaoudi, K., Van Wambeke, F., Barani, A., Hélias-Nunige, S., Sempéré, R., and Pulido-Villena, E.: Atmospheric fluxes of soluble organic C, N, and P to the Mediterranean Sea: Potential biogeochemical implications in the surface layer, Prog. Oceanogr., 163, 59–69, https://doi.org/10.1016/j.pocean.2017.07.008, 2018.

Dreischmeier, K., Budke, C., Wiehemeier, L., Kottke, T., and Koop, T.: Boreal pollen contain ice-nucleating as well as ice-binding 'antifreeze' polysaccharides, Sci. Rep., 7, 41890, https://doi.org/10.1038/srep41890, 2017.

Dufresne, M., Salameh, T., Leonardis, T., Gille, G., Armengaud, A., and Sauvage, S.: Volatile organic compound sources and impacts in an urban Mediterranean area (Marseille, France), Atmos. Chem. Phys., 25, 5977–5999, https://doi.org/10.5194/acp-25-5977-2025, 2025.

Durrieu de Madron, X., Guieu, C., Sempéré, R., Conan, P., Cossa, D., D'Ortenzio, F., Estournel, C., Gazeau, F., Rabouille, C., Stemmann, L., Bonnet, S., Diaz, F., Koubbi, P., Radakovitch, O., Babin, M., Baklouti, M., Bancon-Montigny, C., Belviso, S., Bensoussan, N., Bonsang, B., Bouloubassi, I., Brunet, C., Cadiou, J.-F., Carlotti, F., Chami, M., Charmasson, S., Charrière, B., Dachs, J., Doxaran, D., Dutay, J.-C., Elbaz-Poulichet, F., Eléaume, M., Eyrolles, F., Fernandez, C., Fowler, S., Francour, P., Gaertner, J. C., Galzin, R., Gasparini, S., Ghiglione, J.-F., Gonzalez, J.-L., Goyet, C., Guidi, L., Guizien, K., Heimbürger, L.-E., Jacquet, S. H. M., Jeffrey, W. H., Joux, F., Le Hir, P., Leblanc, K., Lefèvre, D., Lejeusne, C., Lemé, R., Loÿe-Pilot, M.-D., Mallet, M., Méjanelle, L., Mélin, F., Mellon, C., Mérigot, B., Merle, P.-L., Migon, C., Miller, W. L., Mortier, L., Mostajir, B., Mousseau, L., Moutin, T., Para, J., Pérez, T., Petrenko, A., Poggiale, J.-C., Prieur, L., Pujo-Pay, M., Pulido-Villena, Raimbault, P., Rees, A. P., Ridame, C., Rontani, J.-F., Ruiz Pino, D., Sicre, M. A., Taillandier, V., Tamburini, C., Tanaka, T., Taupier-Letage, I., Tedetti, M., Testor, P., Thébault, H., Thouvenin, B., Touratier, F., Tronczynski, J., Ulses, C., Van Wambeke, F., Vantrepotte, V., Vaz, S., and Verney, R.: Marine ecosystems' responses to climatic and anthropogenic forcings in the Mediterranean, Prog. Oceanogr., 91, 97–166, https://doi.org/10.1016/j.pocean.2011.02.003, 2011.

Du, Z., He, K., Cheng, Y., Duan, F., Ma, Y., Liu, J., Zhang, X., Zheng, M., and Weber, R.: A yearlong study of water-soluble organic carbon in Beijing II: Light absorption properties, Atmos. Environ., 89, 235–241, https://doi.org/10.1016/j.atmosenv.2014.02.022, 2014.

EUMETSAT: Dust events in the Mediterranean in early 2024, 2024. Retrieved from https://user.eumetsat.int/resources/case-studies/dust-events-in-the-mediterranean-in-early-2024.

European Forest Fire Information System: Annual Statistics for Croatia, 2024.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

European Space Agency (ESA): Saharan dust plume, 2024. Retrieved from https://www.esa.int/ESA_Multimedia/Images/2024/04/Saharan_dust_plume.

Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P.: Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components, Science (1979)., 281, 237–240, https://doi.org/10.1126/science.281.5374.237, 1998.

Fraser, M. P. and Lakshmanan, K.: Using Levoglucosan as a Molecular Marker for the Long-Range Transport of Biomass Combustion Aerosols, Environ. Sci. Technol., 34, 4560–4564, https://doi.org/10.1021/es991229l, 2000.

Fu, P., Kawamura, K., Kobayashi, M., and Simoneit, B. R. T.: Seasonal variations of sugars in atmospheric particulate matter from Gosan, Jeju Island: Significant contributions of airborne pollen and Asian dust in spring, Atmos. Environ., 55, 234–239, https://doi.org/10.1016/j.atmosenv.2012.02.061, 2012a.

Fu, P. Q., Kawamura, K., Chen, J., Li, J., Sun, Y. L., Liu, Y., Tachibana, E., Aggarwal, S. G., Okuzawa, K., and Tanimoto, H.: Diurnal variations of organic molecular tracers and stable carbon isotopic composition in atmospheric aerosols over Mt. Tai in the North China Plain: an influence of biomass burning, Atmos. Chem. Phys., 12, 8359–8375, https://doi.org/10.5194/acp-12-8359-2012, 2012b.

Furdek Turk, M., Vrana, I., Milačič, R., Ščančar, J., Dautović, J., Ciglenečki, I., and Mikac, N.: Spatial and temporal distribution of tributyltin in the coastal environment of the Croatian Adriatic (2016-2023): TBT remains a cause for concern, Front. Mar. Sci., 11, https://doi.org/10.3389/fmars.2024.1422057, 2024.

Galindo, N., Yubero, E., Clemente, Á., Nicolás, J. F., Varea, M., and Crespo, J.: PM events and changes in the chemical composition of urban aerosols: A case study in the western Mediterranean, Chemosphere, 244, 125520, https://doi.org/10.1016/j.chemosphere.2019.125520, 2020.

Galletti, Y., Becagli, S., Di Sarra, A., Gonnelli, M., Pulido-Villena, E., M. Sferlazzo, D., Traversi, R., Vestri, S., and Santinelli, C.: Atmospheric deposition of organic matter at a remote site in the central Mediterranean Sea: Implications for the marine ecosystem, Biogeosciences, 17, 3669–3684, https://doi.org/10.5194/bg-17-3669-2020, 2020.

Garg, A., Desservettaz, M., Christodoulou, A., Christoudias, T., Kanawade, V. P., Savvides, C., Vrekoussis, M., Naqui, S., Jokinen, T., Byron, J., Williams, J., Mihalopoulos, N., Liakakou, E., Sciare, J., and Bourtsoukidis, E.: Heat and continental transport shape the variability of volatile organic compounds in the Eastern Mediterranean: Insights from multi-year observations and regional modeling, https://doi.org/10.5194/egusphere-2025-5124, 6 November 2025.

Guerzoni, S. and Chester, R.: The impact of desert dust across the Mediterranean, Springer Science & Business Media, 2013.

Haque, Md. M., Zhang, Y., Bikkina, S., Lee, M., and Kawamura, K.: Regional heterogeneities in the emission of airborne primary sugar compounds and biogenic secondary organic aerosols in the East Asian outflow: evidence for coal combustion as a source of levoglucosan, Atmos. Chem. Phys., 22, 1373–1393, https://doi.org/10.5194/acp-22-1373-2022, 2022.

Hartmann, S., Schrödner, R., Hassett, B. T., Hartmann, M., van Pinxteren, M., Fomba, K. W., Stratmann, F., Herrmann, H., Pöhlker, M., and Zeppenfeld, S.: Polysaccharides─Important Constituents of Ice-Nucleating Particles of Marine Origin, Environ. Sci. Technol., 59, 5098–5108, https://doi.org/10.1021/acs.est.4c08014, 2025.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

Hasenecz, E. S., Jayarathne, T., Pendergraft, M. A., Santander, M. V., Mayer, K. J., Sauer, J., Lee, C., Gibson, W. S., Kruse, S. M., Malfatti, F., Prather, K. A., and Stone, E. A.: Marine Bacteria Affect Saccharide Enrichment in Sea Spray Aerosol during a Phytoplankton Bloom, ACS Earth Space Chem., 4, 1638–1649, https://doi.org/10.1021/acsearthspacechem.0c00167, 2020.

Hedges, J. I., Eglinton, G., Hatcher, P. G., Kirchman, D. L., Arnosti, C., Derenne, S., Evershed, R. P., Kögel-Knabner, I., de Leeuw, J. W., Littke, R., Michaelis, W., and Rullkötter, J.: The molecularly-uncharacterized component of nonliving organic matter in natural environments, Org. Geochem., 31, 945–958, https://doi.org/10.1016/S0146-6380(00)00096-6, 2000.

Hegde, P. and Kawamura, K.: Seasonal variations of water-soluble organic carbon, dicarboxylic acids, ketocarboxylic acids, and α-dicarbonyls in Central Himalayan aerosols, Atmos. Chem. Phys., 12, 6645–6665, https://doi.org/10.5194/acp-12-6645-2012, 2012.

Iavorivska, L., Boyer, E. W., and DeWalle, D. R.: Atmospheric deposition of organic carbon via precipitation, Atmos. Environ., 146, 153–163, https://doi.org/10.1016/j.atmosenv.2016.06.006, 2016.

Iavorivska, L., Boyer, E. W., and Grimm, J. W.: Wet atmospheric deposition of organic carbon: An underreported source of carbon to watersheds in the northeastern United States, Journal of Geophysical Research: Atmospheres, 122, 3104–3115, https://doi.org/10.1002/2016JD026027, 2017.

IPCC: Climate change: mitigation of climate change, in: Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change, 2014.

Jaenicke, R.: Abundance of Cellular Material and Proteins in the Atmosphere, Science (1979)., 308, 73–73, https://doi.org/10.1126/science.1106335, 2005.

Jakovljević, I., Šimić, I., Mendaš, G., Sever Štrukil, Z., Žužul, S., Gluščić, V., Godec, R., Pehnec, G., Bešlić, I., Milinković, A., Bakija Alempijević, S., Šala, M., Ogrizek, M., and Frka, S.: Pollution levels and deposition processes of airborne organic pollutants over the central Adriatic area: Temporal variabilities and source identification, Mar. Pollut. Bull., 172, 112873, https://doi.org/10.1016/j.marpolbul.2021.112873, 2021.

Johnson, K. M. and Sieburth, J. M.: Dissolved carbohydrates in seawater. I, A precise spectrophotometric analysis for monosaccharides, Mar. Chem., 5, 1–13, https://doi.org/10.1016/0304-4203(77)90011-1, 1977.

Kanakidou, M., Duce, R. A., Prospero, J. M., Baker, A. R., Benitez-Nelson, C., Dentener, F. J., Hunter, K. A., Liss, P. S., Mahowald, N., Okin, G. S., Sarin, M., Tsigaridis, K., Uematsu, M., Zamora, L. M., and Zhu, T.: Atmospheric fluxes of organic N and P to the global ocean, Global Biogeochem. Cycles, 26, https://doi.org/10.1029/2011GB004277, 2012.

Khan, J. Z., Sun, L., Tian, Y., Dai, Q., Hu, T., and Feng, Y.: Size Distribution of Ambient Particulate Matter and Its Constituent Chemical Species Involving Saccharides During Early Summer in a Chinese Megacity, Front. Environ. Sci., 9, https://doi.org/10.3389/fenvs.2021.659329, 2021.

Koulouri, E., Saarikoski, S., Theodosi, C., Markaki, Z., Gerasopoulos, E., Kouvarakis, G., Mäkelä, T., Hillamo, R., and Mihalopoulos, N.: Chemical composition and sources of fine and coarse aerosol particles in the Eastern Mediterranean, Atmos. Environ., 42, 6542–6550, https://doi.org/10.1016/j.atmosenv.2008.04.010, 2008.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

Kouvarakis, G., Tsigaridis, K., Kanakidou, M., and Mihalopoulos, N.: Temporal variations of surface regional background ozone over Crete Island in the southeast Mediterranean, Journal of Geophysical Research: Atmospheres, 105, 4399–4407, https://doi.org/10.1029/1999JD900984, 2000.

Lai, H.-C., Dai, Y.-T., Mkasimongwa, S. W., Hsiao, M.-C., and Lai, L.-W.: The Impact of Atmospheric Synoptic Weather Condition and Long-Range Transportation of Air Mass on Extreme PM10 Concentration Events, Atmosphere (Basel)., 14, 406, https://doi.org/10.3390/atmos14020406, 2023.

Mariraj Mohan, S.: An overview of particulate dry deposition: measuring methods, deposition velocity and controlling factors, International journal of environmental science and technology, 13, 387–402, https://doi.org/10.1007/s13762-015-0898-7, 2016.

Medeiros, P. M. and Simoneit, B. R. T.: Source profiles of organic compounds emitted upon combustion of green vegetation from temperate climate forests, Environ. Sci. Technol., 42, 8310–8316, https://doi.org/10.1021/es801533b, 2008.

Medeiros, P. M., Conte, M. H., Weber, J. C., and Simoneit, B. R. T.: Sugars as source indicators of biogenic organic carbon in aerosols collected above the Howland Experimental Forest, Maine, Atmos. Environ., 40, 1694–1705, https://doi.org/10.1016/j.atmosenv.2005.11.001, 2006a.

Medeiros, P. M., Fernandes, M. F., Dick, R. P., and Simoneit, B. R. T.: Seasonal variations in sugar contents and microbial community in a ryegrass soil, Chemosphere, 65, 832–839, https://doi.org/10.1016/j.chemosphere.2006.03.025, 2006b.

Milinković, A., Gregorič, A., Grgičin, V. D., Vidič, S., Penezić, A., Kušan, A. C., Alempijević, S. B., Kasper-Giebl, A., and Frka, S.: Variability of black carbon aerosol concentrations and sources at a Mediterranean coastal region, Atmos. Pollut. Res., 12, 101221, https://doi.org/10.1016/j.apr.2021.101221, 2021.

Milinković, A., Penezić, A., Kušan, A. C., Gluščić, V., Žužul, S., Skejić, S., Šantić, D., Godec, R., Pehnec, G., Omanović, D., Engel, A., and Frka, S.: Variabilities of biochemical properties of the sea surface microlayer: Insights to the atmospheric deposition impacts, Science of the Total Environment, 838, https://doi.org/10.1016/j.scitotenv.2022.156440, 2022.

Morales-Baquero, R., Pulido-Villena, E., and Reche, I.: Chemical signature of Saharan dust on dry and wet atmospheric deposition in the south-western Mediterranean region, Tellus B: Chemical and Physical Meteorology, 65, 18720, https://doi.org/10.3402/tellusb.v65i0.18720, 2013.

Mu, L., Li, X., Li, Y., Liu, X., Bai, H., Li, X., and Liu, T.: Molecular Distribution, Seasonal Variations, and Sources of Typical Polar Organics in PM 2.5 from Jinzhong, China, ACS Earth Space Chem., 5, 663–675, https://doi.org/10.1021/acsearthspacechem.0c00350, 2021.

Mullaugh, K. M., Byrd, J. N., Avery, G. B., Mead, R. N., Willey, J. D., and Kieber, R. J.: Characterization of carbohydrates in rainwater from the Southeastern North Carolina, Chemosphere, 107, 51–57, https://doi.org/10.1016/j.chemosphere.2014.03.014, 2014.

N1 Zagreb Hina N1: Croatia records 21% increase in wildfires in 2024, 2024.

NASA Earth Observatory: Desert dust envelops Portugal and Spain, 2024. Retrieved from https://earthobservatory.nasa.gov/images/152604/desert-dust-envelops-portugal-and-spain.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

NASA MODIS: Saharan dust cloud over Europe, 2024. Retrieved from https://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2024-03-28.

National Firefighting Operations Centre: National Firefighting Operations Centre Report, 2024.

Nirmalkar, J., Deb, M. K., Deshmukh, D. K., Tsai, Y. I., and Verma, S. K.: Molecular markers in ambient aerosol in the Mahanadi Riverside Basin of eastern central India during winter, Environmental Science and Pollution Research, 22, 1220–1231, https://doi.org/10.1007/s11356-014-3416-4, 2015.

Oades, J. M.: Soil organic matter and structural stability: mechanisms and implications for management, Plant Soil, 76, 319–337, https://doi.org/10.1007/BF02205590, 1984.

Pacini, E., Guarnieri, M., and Nepi, M.: Pollen carbohydrates and water content during development, presentation, and dispersal: a short review, Protoplasma, 228, 73–77, https://doi.org/10.1007/s00709-006-0169-z, 2006.

Pashynska, V., Vermeylen, R., Vas, G., Maenhaut, W., and Claeys, M.: Development of a gas chromatographic/ion trap mass spectrometric method for the determination of levoglucosan and saccharidic compounds in atmospheric aerosols. Application to urban aerosols, Journal of Mass Spectrometry, 37, 1249–1257, https://doi.org/10.1002/jms.391, 2002.

Pietrogrande, M. C., Bacco, D., Visentin, M., Ferrari, S., and Casali, P.: Polar organic marker compounds in atmospheric aerosol in the Po Valley during the Supersito campaigns — Part 2: Seasonal variations of sugars, Atmos. Environ., 97, 215–225, https://doi.org/10.1016/j.atmosenv.2014.07.056, 2014.

Pulido-Villena, E., Wagener, T., and Guieu, C.: Bacterial response to dust pulses in the western Mediterranean: Implications for carbon cycling in the oligotropic ocean, Global Biogeochem. Cycles, 22, https://doi.org/10.1029/2007GB003091, 2008.

Rocchi, A., von Jackowski, A., Welti, A., Li, G., Kanji, Z. A., Povazhnyy, V., Engel, A., Schmale, J., Nenes, A., Berdalet, E., Simó, R., and Dall'Osto, M.: Glucose Enhances Salinity-Driven Sea Spray Aerosol Production in Eastern Arctic Waters, Environ. Sci. Technol., 58, 8748–8759, https://doi.org/10.1021/acs.est.4c02826, 2024.

Samaké, A., Jaffrezo, J.-L., Favez, O., Weber, S., Jacob, V., Albinet, A., Riffault, V., Perdrix, E., Waked, A., and Golly, B.: Polyols and glucose particulate species as tracers of primary biogenic organic aerosols at 28 French sites, Atmos. Chem. Phys., 19, 3357–3374, https://doi.org/10.5194/acp-19-3357-2019, 2019a.

Samaké, A., Jaffrezo, J.-L., Favez, O., Weber, S., Jacob, V., Canete, T., Albinet, A., Charron, A., Riffault, V., Perdrix, E., Waked, A., Golly, B., Salameh, D., Chevrier, F., Oliveira, D. M., Besombes, J.-L., Martins, J. M. F., Bonnaire, N., Conil, S., Guillaud, G., Mesbah, B., Rocq, B., Robic, P.-Y., Hulin, A., Le Meur, S., Descheemaecker, M., Chretien, E., Marchand, N., and Uzu, G.: Arabitol, mannitol, and glucose as tracers of primary biogenic organic aerosol: the influence of environmental factors on ambient air concentrations and spatial distribution over France, Atmos. Chem. Phys., 19, 11013–11030, https://doi.org/10.5194/acp-19-11013-2019, 2019b.

Santos, P. S. M., Santos, G. T. A. D., Cachada, A., Patinha, C., Coimbra, M. A., Coelho, E., and Duarte, A. C.: Sources of carbohydrates on bulk deposition in South-Western of Europe, Chemosphere, 263, https://doi.org/10.1016/j.chemosphere.2020.127982, 2021.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

Šegota, T. and Filipčić, A.: Köppenova podjela klima i hrvatsko nazivlje, Geoadria, 8, 17–37, https://doi.org/10.15291/geoadria.93, 2003.

Seitzinger, S. P. and Sanders, R. W.: Atmospheric inputs of dissolved organic nitrogen stimulate estuarine bacteria and phytoplankton, Limnol. Oceanogr., 44, 721–730, https://doi.org/10.4319/lo.1999.44.3.0721, 1999.

Sempéré, R., Charrière, B., Van Wambeke, F., and Cauwet, G.: Carbon inputs of the Rhône River to the Mediterranean Sea: Biogeochemical implications, Global Biogeochem. Cycles, 14, 669–681, https://doi.org/10.1029/1999GB900069, 2000.

Senior, W. and Chevolot, L.: Studies of dissolved carbohydrates (or carbohydrate-like substances) in an estuarine environment, Mar. Chem., 32, 19–35, https://doi.org/10.1016/0304-4203(91)90023-P, 1991.

Šiljković, Ž. and Mamut, M.: Forest fires in Dalmatia, Bulletin of Geography. Socio-economic Series, 117–130, https://doi.org/10.1515/bog-2016-0019, 2016.

Simoneit, B. R. T., Elias, V. O., Kobayashi, M., Kawamura, K., Rushdi, A. I., Medeiros, P. M., Rogge, W. F., and Didyk, B. M.: Sugars - Dominant water-soluble organic compounds in soils and characterization as tracers in atmospheric participate matter, Environ. Sci. Technol., 38, 5939–5949, https://doi.org/10.1021/es0403099, 2004.

Sopčić, S., Godec, R., Prskalo, H., and Pehnec, G.: Impact of a Summer Wildfire Episode on Air Quality in a Rural Area Near the Adriatic Coast, Fire, 8, https://doi.org/10.3390/fire8080299, 2025a.

Sopčić, S., Jakovljević, I., Štrukil, Z. S., and Bešlić, I.: Source identification of carbohydrates and polycyclic aromatic hydrocarbons in a rural area near the Plitvice Lakes National Park, Croatia, Atmos. Environ., 345, https://doi.org/10.1016/j.atmosenv.2025.121050, 2025b.

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., and Ngan, F.: NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System, Bull. Am. Meteorol. Soc., 96, 2059–2077, https://doi.org/10.1175/BAMS-D-14-00110.1, 2015.

Theodosi, C., Markaki, Z., Tselepides, A., and Mihalopoulos, N.: The significance of atmospheric inputs of soluble and particulate major and trace metals to the eastern Mediterranean seawater, Mar. Chem., 120, 154–163, https://doi.org/10.1016/j.marchem.2010.02.003, 2010.

Theodosi, C., Panagiotopoulos, C., Nouara, A., Zarmpas, P., Nicolaou, P., Violaki, K., Kanakidou, M., Sempéré, R., and Mihalopoulos, N.: Sugars in atmospheric aerosols over the Eastern Mediterranean, Prog. Oceanogr., 163, 70–81, https://doi.org/10.1016/j.pocean.2017.09.001, 2018.

Thoma, M., Bachmeier, F., Knauf, K., David, J., Simon, M., and Vogel, A. L.: Seasonal analysis of organic aerosol composition resolves anthropogenic and biogenic sources at a rural background station in central Europe, Environmental Science: Atmospheres, 5, 703–713, https://doi.org/10.1039/D4EA00163J, 2025.

Tobarra, D., Yubero, E., and Carratala, A.: Trends of anthropogenic sources in a Southeastern Mediterranean coastal site over five years, Atmos. Environ., 355, 121279, https://doi.org/10.1016/j.atmosenv.2025.121279, 2025.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

Tsai, Y. I., Sopajaree, K., Kuo, S.-C., and Hsin, T.-Y.: Chemical Composition and Size-Fractionated Origins of Aerosols over a Remote Coastal Site in Southern Taiwan, Aerosol Air Qual. Res., 15, 2549–2570, https://doi.org/10.4209/aaqr.2015.09.0566, 2015.

Turquety, S., Menut, L., Bessagnet, B., Anav, A., Viovy, N., Maignan, F., and Wooster, M.: APIFLAME v1.0: high resolution fire emission model and application to the Euro-Mediterranean region, https://doi.org/10.5194/gmdd-6-5489-2013, 6 November 2013.

Verma, S. K., Kawamura, K., Chen, J., and Fu, P.: Thirteen years of observations on primary sugars and sugar alcohols over remote Chichijima Island in the western North Pacific, Atmos. Chem. Phys., 18, 81–101, https://doi.org/10.5194/acp-18-81-2018, 2018.

de Vicente, I., Ortega-Retuerta, E., Morales-Baquero, R., and Reche, I.: Contribution of dust inputs to dissolved organic carbon and water transparency in Mediterranean reservoirs, Biogeosciences, 9, 5049–5060, https://doi.org/10.5194/bg-9-5049-2012, 2012.

Viličić, D.: Specific oceanological characteristics of the Croatian part of the Adriatic, Hrvatske vode, 22, 297–314, 2014.

Vincent, J., Laurent, B., Losno, R., Bon Nguyen, E., Roullet, P., Sauvage, S., Chevaillier, S., Coddeville, P., Ouboulmane, N., di Sarra, A. G., Tovar-Sánchez, A., Sferlazzo, D., Massanet, A., Triquet, S., Morales Baquero, R., Fornier, M., Coursier, C., Desboeufs, K., Dulac, F., and Bergametti, G.: Variability of mineral dust deposition in the western Mediterranean basin and south-east of France, Atmos. Chem. Phys., 16, 8749–8766, https://doi.org/10.5194/acp-16-8749-2016, 2016.

Wang, F., Lang, Y., Liu, C.-Q., Qin, Y., Yu, N., and Wang, B.: Flux of organic carbon burial and carbon emission from a large reservoir: implications for the cleanliness assessment of hydropower, Sci. Bull. (Beijing)., 64, 603–611, https://doi.org/10.1016/j.scib.2019.03.034, 2019.

Wang, Z., Wu, D., Li, Z., Shang, X., Li, Q., Li, X., Chen, R., Kan, H., Ouyang, H., Tang, X., and Chen, J.: Measurement report: Saccharide composition in atmospheric fine particulate matter during spring at the remote sites of southwest China and estimates of source contributions, Atmos. Chem. Phys., 21, 12227–12241, https://doi.org/10.5194/acp-21-12227-2021, 2021.

de Weger, L. A., Verbeek, C., Markey, E., O'Connor, D. J., and Gosling, W. D.: Greater difference between airborne and flower pollen chemistry, than between pollen collected across a pollution gradient in the Netherlands, Science of The Total Environment, 934, 172963, https://doi.org/10.1016/j.scitotenv.2024.172963, 2024.

Willey, J. D., Kieber, R. J., Eyman, M. S., and Avery, G. B.: Rainwater dissolved organic carbon: Concentrations and global flux, Global Biogeochem. Cycles, 14, 139–148, https://doi.org/10.1029/1999GB900036, 2000.

Womiloju, T. O., Miller, J. D., Mayer, P. M., and Brook, J. R.: Methods to determine the biological composition of particulate matter collected from outdoor air, Atmos. Environ., 37, 4335–4344, https://doi.org/10.1016/S1352-2310(03)00577-6, 2003.

Wu, Y., Liu, J., Zhai, J., Cong, L., Wang, Y., Ma, W., Zhang, Z., and Li, C.: Comparison of dry and wet deposition of particulate matter in near-surface waters during summer, PLoS One, 13, https://doi.org/10.1371/journal.pone.0199241, 2018.

Xiao, M., Wang, Q., Qin, X., Yu, G., and Deng, C.: Composition, Sources, and Distribution of PM2.5 Saccharides in a Coastal Urban Site of China, Atmosphere (Basel)., 9, 274, https://doi.org/10.3390/atmos9070274, 2018.

https://doi.org/10.5194/egusphere-2026-3179
Preprint. Discussion started: 15 July 2026

Xie, L., Gao, X., Liu, Y., Yang, B., Lv, X., Zhao, J., and Xing, Q.: Atmospheric dry deposition of water-soluble organic matter: An underestimated carbon source to the coastal waters in North China, Science of the Total Environment, 818, https://doi.org/10.1016/j.scitotenv.2021.151772, 2022.

Yan, G. and Kim, G.: Dissolved organic carbon in the precipitation of Seoul, Korea: Implications for global wet depositional flux of fossil-fuel derived organic carbon, Atmos. Environ., 59, 117–124, https://doi.org/10.1016/j.atmosenv.2012.05.044, 2012.

Yang, Y., Chan, C., Tao, J., Lin, M., Engling, G., Zhang, Z., Zhang, T., and Su, L.: Observation of elevated fungal tracers due to biomass burning in the Sichuan Basin at Chengdu City, China, Science of the total environment, 431, 68–77, https://doi.org/10.1016/j.scitotenv.2012.05.033, 2012.

Zeppenfeld, S., van Pinxteren, M., van Pinxteren, D., Wex, H., Berdalet, E., Vaqué, D., Dall'Osto, M., and Herrmann, H.: Aerosol Marine Primary Carbohydrates and Atmospheric Transformation in the Western Antarctic Peninsula, ACS Earth Space Chem., 5, 1032–1047, https://doi.org/10.1021/acsearthspacechem.0c00351, 2021.

Zhang, Z., Xu, W., Zeng, S., Liu, Y., Liu, T., Zhang, Y., Du, A., Li, Y., Zhang, N., Wang, J., Aruffo, E., Han, P., Li, J., Wang, Z., and Sun, Y.: Secondary Organic Aerosol Formation from Ambient Air in Summer in Urban Beijing: Contribution of S/IVOCs and Impacts of Heat Waves, Environ. Sci. Technol. Lett., 11, 738–745, https://doi.org/10.1021/acs.estlett.4c00415, 2024.

Zhu, C., Kawamura, K., and Kunwar, B.: Organic tracers of primary biological aerosol particles at subtropical Okinawa Island in the western North Pacific Rim, Journal of Geophysical Research: Atmospheres, 120, 5504–5523, https://doi.org/10.1002/2015JD023611, 2015.

Ziska, L. H. and Caulfield, F. A.: Rising CO 2 and pollen production of common ragweed (Ambrosia artemisiifolia L.), a known allergy-inducing species: implications for public health., Aust. J. Plant Physiol., 27, 893–898, https://doi.org/10.1071/PP00032, 2000.

Ziska, L. H., Makra, L., Harry, S. K., Bruffaerts, N., Hendrickx, M., Coates, F., Saarto, A., Thibaudon, M., Oliver, G., and Damialis, A.: Temperature-related changes in airborne allergenic pollen abundance and seasonality across the northern hemisphere: a retrospective data analysis, Lancet Planet. Health, 3, e124–e131, https://doi.org/10.1016/S2542-5196(19)30015-4, 2019.