Source apportionment of black carbon from fossil fuel and biomass burning at an urban site in North Africa (Kenitra, Morocco)

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Abstract

In an urban area of Kenitra, Morocco, the apportionment of black carbon (BC) sources into fossil fuel (BCff) and biomass burning (BCwb) using the Aethalometer model has been conducted. This study investigates the temporal trends of BCff and BCwb contributions to the total BC concentrations. The analysis unveils distinct diurnal, weekly, and seasonal patterns in BCff and BCwb concentrations, providing insights into the origins and dynamics of BC pollution. Source apportionment results revealed that the relative contribution of fossil fuels to total black carbon concentrations was more pronounced during winter and summer. In contrast, the contribution of biomass burning exhibited variability across different seasons. Fossil fuel has higher seasonal contributions (ranging from 90.1% in winter to 93.8% in autumn) than biomass burning (ranging from 6.2% in autumn to 9.9% in winter) to the total BC concentrations. This seasonal variation highlights the complex interplay between meteorological conditions and emission sources. Diurnally, BCff peaks during traffic rush hours (human-induced morning and evening homecoming traffic), while biomass-burning-derived BC (BCwb) peaks at nighttime, particularly in winter, reaching values as high as 13% of total BC concentration. Nighttime BC concentration, on average, surpasses daytime levels, suggesting the stronger influence of meteorological conditions than emissions. These variations in BCff and BCwb levels provide compelling evidence of their local origins, primarily from vehicle emissions, socioeconomic activities, and industry-related combustion in the study area. This study underscores also a significant link between biomass and fossil fuel-derived black carbon emissions, with their levels being affected by meteorological conditions such as wind, temperature, and pressure. Lastly, these findings underline the critical importance of considering temporal variations in BC pollution in the development of effective air quality management strategies.
Keywords: Black carbon, Source apportionment, Fossil fuel, Biomass burning, Temporal variation.
Black carbon (BC) is a type of air pollution known to be detrimental to both the environment and human health and primarily originates from the incomplete combustion of biomass and fossil fuels (Bounakhla et al., 2022). BC absorbs sunlight, contributing significantly to global warming by reducing the amount of energy reflected in space. Understanding the sources of BC is crucial for developing effective air pollution management strategies (Allen, 2014; Kompalli et al., 2014). Urban areas, particularly in North Africa, often experience high BC concentrations due to factors such as heavy traffic and biomass burning for waste incineration, industrial activities, and transportation (Bachmann, 2009). Investigating the origins of BC in North African cities is therefore crucial.

Source apportionment is a method used to determine the contribution of different sources to air pollution levels. By measuring BC concentrations and employing statistical models, researchers can identify the sources responsible. The use of a seven-wavelength Aethalometer facilitates source apportionment for BC, distinguishing between BC from fossil fuel combustion ($BC_{ff}$) and biomass burning ($BC_{wb}$) based on their absorption characteristics (Mousavi et al., 2019; Sandradewi et al., 2008). $BC_{ff}$ results from the incomplete combustion of fossil fuels like coal, oil, and gasoline, while $BC_{wb}$ is produced during the burning of biomass, such as wood and agricultural waste. The relative contributions of $BC_{ff}$ and $BC_{wb}$ vary depending on factors such as region and season (Deng et al., 2020). Maritz et al. (2015) suggested that for a better understanding of $BC_{ff}$ and $BC_{wb}$ origins and
how they affect the total mass concentration of BC, it is crucial to analyze their seasonal and diurnal variations.

Carbonaceous aerosols, a significant portion of air pollution in Moroccan cities, originate from various sources throughout the year. Traffic emissions, fuel combustion for energy, and biomass burning are major local contributors, while long-range transport from other regions also plays a role (Benchrif et al., 2022, 2024; Deabji et al., 2024; Otmani et al., 2022). Studies across Morocco reveal this diverse fingerprint. In Tetouan, northern Morocco, (Benchrif et al., 2018, 2022, 2024) identified local carbonaceous species as key drivers of seasonal variations in fine and total aerosols. Central Morocco shows a dominance of fossil fuel combustion as the primary source, based on the high OC-to-EC ratio reported by Deabji et al. (2024). However, they acknowledge the potential influence of biomass burning. Furthermore, in Salé, northwest Morocco, reflects a similar trend. Otmani et al. (2022) found fossil fuel-related component BC_{ff} as the prevailing source of BC throughout their monitoring period, with a strong correlation between black carbon and the traffic tracer, nitrogen dioxide (NO₂). Beyond urban areas, a field investigation at a remote high-altitude Moroccan site highlights the influence of regional and even trans-regional transport of pollutants on aerosol composition (Deabji et al., 2021). Studies in Algeria (Merabet et al., 2019) linked black carbon levels (BC_{ff} and BC_{wb}) to traffic, wildfires, and the southern Algerian oil industry. Their study also points to the influence of cultural events, pollution episodes, and long-range transport
from Europe on black carbon concentrations and source contributions. Looking beyond Morocco, studies in Mediterranean cities underscore the importance of considering biomass burning as a key source of BC (Costabile et al., 2017; Titos et al., 2017). In Athens, for instance, recent studies argued that the fossil fuel-related component dominated throughout the year, with BC from wood burning accounting for a significant portion of the total BC during winter nights (Kaskaoutis et al., 2020; Liakakou et al., 2020).

This study aims to go into further detail on the source apportionment of BC and investigate the origins and contributions of BC\textsubscript{ff} and BC\textsubscript{wb} to total BC concentrations in Kenitra City, Morocco. Our earlier studies (Bounakhla et al., 2022, 2023) were performed to understand the long-term concentration variability of BC mass concentration, and employed state-of-the-art technologies to assess how meteorological parameters influence BC concentrations. They had already referred to the significant impact of traffic-related sources, meteorological conditions, and long-range aerosol transport on the temporal variability of BC. The current study goes beyond the simple measurement of total BC concentrations. It meticulously probes into the discrete contribution of fossil fuel and biomass on the total BC concentrations. By employing the Aethalometer source apportionment model and harnessing data of high time resolution (at 5-minute intervals), we attain an unprecedented degree of discernment regarding these origins. This granularity allows us to uncover nuanced diurnal, weekly, and seasonal patterns that were not previously explored. The high
temporal resolution data used in this study also enables the detection of rapid changes and episodic pollution events.

2 MATERIALS AND METHODS

In this study, we estimated the contributions of different sources of black carbon (BC) emissions in an urban area of Kenitra City, Morocco, (Fig. 1) using data from a seven-wavelength (370, 470, 520, 590, 660, 880, and 950 nm) Aethalometer (Model AE-31, Magee Scientific, USA). The carbonaceous aerosol measurements were carried out at a time resolution of 5 min from mid-July 2020 to mid-February 2021. The measurement site (Lat: 34.234194; Lon: -6.614889) is located in the Atlantic region, which is characterized by its coastal climate with high humidity and moderate temperatures. The site is situated in an urban area, surrounded by a mix of residential, commercial, and industrial zones. The measurement site is strategically placed between three major traffic roads that link different parts of the city and beyond. Further details of the instrument and measurement procedure are described in Bounakhla et al. (2022).

To calculate the contributions of wood burning (BC$_{wb}$) and fossil fuel combustion (BC$_{ff}$) to BC emissions, the Aethalometer model was used based on the method developed by (Sandradewi et al. 2008). The BC$_{ff}$ and BC$_{wb}$ mass concentrations were obtained as expressed in Eqs. (1), (2), and (3). $\sigma_{abs}(\lambda)$ is defined as the measured optical absorption coefficient at the wavelength $\lambda$. AAE$_{ff}$ and AAE$_{wb}$ are parameters assumed a priori representing the Absorption Ångström Exponent (AAE)
for the fossil fuel and wood-burning combustion sources, respectively. BB% is the biomass burning percentage.

\[
BB(\%) = \frac{\sigma_{abs}(470 \text{ nm}) - \sigma_{abs}(950 \text{ nm}) x (\frac{470}{950})^{-AAE_{ff}}}{\sigma_{abs}(950 \text{ nm}) x (1 - (\frac{470}{950})^{-AAE_{wb}} x (\frac{470}{950})^{-AAE_{ff}})} \tag{1}
\]

\[
BC_{wb} = BB \times BC \tag{2}
\]

\[
BC_{ff} = (1 - BB) \times BC \tag{3}
\]

The robustness of the Aethlometer model relies on choosing appropriate Absorption Ångström Exponents for both fossil fuel (AAEff) and wood burning (AAEwb). Selecting the right AAE for the specific sampling site is crucial because even for the same type of emission source, the AAE can vary depending on the specific fuel subtypes and combustion conditions (Li et al., 2021). However, a minimum AAE value of 0.9 is considered for calculations using the two-component Aethalometer model, as observed during fog episodes in New Delhi (Attri et al., 2016). Typically, AAEff and AAEwb are determined by comparing the contributions of BCff and BCwb with other techniques (e.g., organic tracers, carbon-14), which help in distinguishing between these two sources of BC.

This study employed a sensitivity analysis to identify the most suitable AAE values that yield realistic BC source contributions. The analysis methodology followed the approaches outlined by Harrison et al. (2013) and Titos et al. (2017). A preliminary sensitivity test was conducted using a wide range of AAE values for both AAEwb and AAEff, including the spectrum reported in prior literature. However, further investigation is required to refine the selection of the Ångström...
coefficient, which will be addressed in a future publication. Previous studies suggest that $\text{AAE}_{\text{ff}}$ values have been observed in the range of 0.9–1.1 (Kumar et al., 2019), while $\text{AAE}_{\text{wb}}$ values ranging from 1.1 to 2.2 have been reported by Sandradewi et al. (2008) and Attri et al. (2016). For our sampling site, we utilized $\text{AAE}_{\text{wb}} = 1.9$ and $\text{AAE}_{\text{ff}} = 0.9$. This selection was achieved by comparing the daily trends of fine $\text{BC}_{\text{ff}}$ and $\text{BC}_{\text{wb}}$ with various $\text{AAE}_{\text{wb}}$ values and selecting the combination that produced the most realistic patterns.

Fig. 1. Position of the Black Carbon measurement site in Kenitra (indicated by the red square) situated in the Atlantic region (upper right panel), far from the city center of Kenitra (upper left panel), positioned amidst three major traffic roads (bottom right panel) and situated within an urban area (bottom left panel). Note the different scales of the maps (Bounakhla et al., 2022).
During the observation period, 48-hour air mass isentropic back trajectories at an altitude of 500 meters above ground level over Tetouan were computed, with four trajectories per day calculated every 6 hours, aiming to analyze the long-term transport of aerosols. These air mass trajectories were retrieved from the GDAS current 7-day archive (ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1/, accessed in October 2021), and HYSPLIT™ (Version 5.0) software was utilized for air mass backward trajectory analyses, as detailed in our previous study by Bounakhla et al. (2022). The clustering of air mass back trajectories was employed to explore the primary three-dimensional transport pathways. Additionally, statistical methods involving back trajectories combined with Black Carbon (BC) concentration, known as the Concentration Weighted Trajectory (CWT) model (Hsu et al., 2003), were utilized to provide insights into the source locations and predominant transport pathways for BC$_{ff}$ and BC$_{wb}$, contributing to the degradation of air quality in Kenitra, Morocco. In this approach, each grid cell is assigned a weighted concentration, calculated by averaging sample concentrations associated with trajectories that crossed that specific grid cell, as outlined by Hsu et al. (2003). Further details of the CWT model were elucidated by previous studies (Deng et al., 2020; Liu et al., 2003; Polissar et al., 2001).

3 RESULTS AND DISCUSSION

3.1 Overview of BC, BC$_{ff}$, and BC$_{wb}$ mass concentrations
This study presents novel findings on Black Carbon (BC) concentrations with a notably high temporal resolution in an urban area of Kenitra, Morocco. Table 1 outlines data on BC, BC_{ff}, and BC_{wb} mass concentrations from diverse locations. The table provides comprehensive information regarding the location type, duration of study, methodologies employed for measurement, and corresponding concentration values. For our study period, on average BC_{ff} represents approximately 91% of total BC in PM_{2.5}, suggesting that the main BC pollution in Kenitra originated from fossil fuel (Merabet et al., 2019). BC concentration and contributions from fossil fuel, and wood burning at our urban site are low compared to typical average values from other urban/suburban areas. The mean (± standard deviation of 5-min values) BC mass concentration was 0.90 ± 0.80 µg m^{-3}. The mean concentrations from fossil fuels (BC_{ff}) and wood burning (BC_{wb}) were 0.81 ± 0.74 µg m^{-3}, and 0.08 ± 0.11 µg m^{-3}, respectively. The mean percentage of biomass burning (BB) was 9.58 ± 8.41%, and 5 minute values of BB ranged from 0.1% (indicative of predominantly fossil fuel sources) to 99.2% (reflecting predominance of wood burning). These detailed findings confirm that BC pollution in Kenitra predominantly arises from fossil fuel combustion activities. This conclusion is in line with corroborative evidence suggesting a strong association between BC emissions and local anthropogenic activities (Bounakhla et al., 2022, 2023).

As to the levels of BC and its two principal components (BC_{ff} and BC_{wb}), the annual mean recorded in our study was notably lower compared to findings from a prior investigation by
Mousavi et al. (2019) conducted in urban Milan, Italy, where concentrations were reported at 1.92 ± 0.35 µg m⁻³ for BC, 1.38 ± 0.10 µg m⁻³ for BCₚ, and 0.55 ± 0.09 µg m⁻³ for BCₚ. Similarly, in suburban Bareggio, Italy, Mousavi et al. (2019) reported higher concentrations of BC (2.76 ± 0.57 µg m⁻³), BCₚ (1.33 ± 0.13 µg m⁻³), and BCₚ (1.43 ± 0.34 µg m⁻³). In a study conducted in suburban Athens, Greece, Diapouli et al. (2017) observed concentrations of 2.0 ± 0.9 µg m⁻³ for BC, 1.7 ± 0.7 µg m⁻³ for BCₚ, and 0.3 ± 0.4 µg m⁻³ for BCₚ, suggesting elevated levels. These elevated concentrations in European cities could be attributed partially to prevailing meteorological conditions and human activities, particularly the combustion of fossil fuels and increased wood burning for residential heating, as reported in other European regions. In contrast, Merabet et al. (2019) reported comparable levels of BC, BCₚ, and BCₚ in a suburban background in Algiers, Algeria, with values of 1.11 ± 2.03 µg m⁻³ for BC, 1.06 ± 2.00 µg m⁻³ for BCₚ, and 0.05 ± 0.26 µg m⁻³ for BCₚ concentrations.

Table 1. BC, BCₚ, and BCₚ values (in µg m⁻³) recorded in Kenitra, Morocco compared to those reported in other locations. The table is ordered according to BC mass concentration.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of location</th>
<th>Study period</th>
<th>Measurement techniques/methods</th>
<th>BC mass concentration range, µg m⁻³</th>
<th>BCₚ mass concentration range, µg m⁻³</th>
<th>BCₚ mass concentration range, µg m⁻³</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiamen, China</td>
<td>Urban</td>
<td>January–December 2014</td>
<td>7-wavelength Aethalometer (AE31) with a PM₂.₅ cut-off inlet worked at a flow rate of 5 L min⁻¹</td>
<td>4.27 ± 1.87</td>
<td>2.93 ± 1.44</td>
<td>1.34 ± 0.54</td>
<td>(Deng et al., 2020)</td>
</tr>
<tr>
<td>Location</td>
<td>Type</td>
<td>Collection Period</td>
<td>Methodology</td>
<td>Concentration (± Standard Deviation)</td>
<td>Reference</td>
<td></td>
<td></td>
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<tr>
<td>Dehradun (north-west Himalayas)</td>
<td>Semi-Urban</td>
<td>Jan 2011 to Dec 2017</td>
<td>7-wavelength (370, 470, 520, 590, 660, 880 and 950 nm) Aethalometer (AE42)</td>
<td>3.85 ± 1.16  2.54  1.31</td>
<td>(Kant et al., 2020)</td>
<td></td>
<td></td>
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<tr>
<td>Bareggio, Italy</td>
<td>Suburban</td>
<td>July–August 2017, September–October 2017,</td>
<td>7-wavelength Aethalometer (AE31), with a measurement time-resolution of 2</td>
<td>2.76 ± 0.57  1.33 ± 0.13  1.43 ± 0.34</td>
<td>(Mousavi et al., 2019)</td>
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<tr>
<td></td>
<td></td>
<td>and January–March 2018</td>
<td>min and flow rate of 5 L min⁻¹</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Athens, Greece</td>
<td>Suburban</td>
<td>March 2013 to February 2014</td>
<td>7-wavelength Aethalometer (AE31).</td>
<td>2.0 ± 0.9  1.7 ± 0.7  0.3 ± 0.4</td>
<td>(Diapouli et al., 2017)</td>
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<tr>
<td>Milan, Italy</td>
<td>Metropolitan</td>
<td>July–August 2017, September–October 2017,</td>
<td>2 single-wavelength Aethalometers (AE51), with a time resolution of 5</td>
<td>1.92 ± 0.35  1.38 ± 0.10  0.55 ± 0.09</td>
<td>(Mousavi et al., 2019)</td>
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<tr>
<td></td>
<td></td>
<td>and January–March 2018</td>
<td>min and a flow rate of 0.05 L min⁻¹</td>
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<tr>
<td>Klang Valley, Malaysia</td>
<td>Suburban</td>
<td>1 January to 31 May 2020</td>
<td>7-wavelength Aethalometer (AE-33) with a flow rate of 5 L min⁻¹</td>
<td>1.90 ± 0.70  1.52 ± 0.32  0.38 ± 0.06</td>
<td>(Ezani et al., 2021)</td>
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<tr>
<td>Helsinki, Finland</td>
<td>Urban</td>
<td>Oct 2015 to May 2017</td>
<td>7-wavelength Aethalometer (AE33), with a measurement time-resolution of 1</td>
<td>1.69 ± 1.52  1.57 ± 1.48  0.14 ± 0.21</td>
<td>(Helin et al., 2018)</td>
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<td>min and flow rate of 5 L min⁻¹</td>
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<tr>
<td>Algiers, Algeria</td>
<td>Suburban</td>
<td>1 June 2014 to 31 May 2015</td>
<td>7-wavelength Aethalometer (AE33), with a measurement time-resolution of 1</td>
<td>1.11 ± 2.03  1.06 ± 2.00  0.05 ± 0.26</td>
<td>(Merabet et al., 2019)</td>
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<td></td>
<td>Background</td>
<td></td>
<td>min and flow rate of 5 L min⁻¹</td>
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<tr>
<td>Kenitra, Morocco</td>
<td>Urban</td>
<td>July 2020 to February 2021</td>
<td>7-wavelength Aethalometer (AE31) with a PM2.5 inlet and a flow rate of 5 L</td>
<td>0.90 ± 0.80  0.81 ± 0.74  0.08 ± 0.01</td>
<td>This work</td>
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<tr>
<td></td>
<td></td>
<td>min⁻¹</td>
<td></td>
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<td></td>
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<tr>
<td>Helsinki, Finland</td>
<td>Suburban</td>
<td>Dec 2015 to Dec 2016</td>
<td>7-wavelength Aethalometer (AE33), with a measurement time-resolution of 1</td>
<td>0.88 ± 1.5  0.489 ± 0.77  0.39 ± 0.8</td>
<td>(Helin et al., 2018)</td>
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<tr>
<td></td>
<td></td>
<td>min and flow rate of 5 L min⁻¹</td>
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</tr>
<tr>
<td>Central Taiwan</td>
<td>Rural</td>
<td>January 1st to December 31st, 2019</td>
<td>Multi-angle absorption photometer (MAAP) with PM10 inlet.</td>
<td>0.79 ± 0.64  0.71 ± 0.57  0.08 ± 0.19</td>
<td>(Cheng et al., 2022)</td>
<td></td>
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</tr>
</tbody>
</table>

### 3.2 Temporal Variation of BC from Fossil Fuel and Wood Burning

#### 3.2.1 Seasonal variation of BC<sub>ff</sub> and BC<sub>wb</sub> levels

This section presents the Aethalometer-model-resolved average concentrations of BC<sub>ff</sub> and BC<sub>wb</sub> across different seasons, as outlined in Table 2. The seasonal changes of the BC<sub>ff</sub> concentrations
were significantly higher during the winter (1.18 ± 1.07 µg m⁻³) and autumn (0.95 ± 0.67 µg m⁻³),
representing, respectively, a 45% and 17% increase compared to the overall period average (0.82
± 0.74 µg m⁻³). In contrast, BC_{ff} concentrations were lower during summer (0.68 ± 0.54 µg m⁻³,
16% decrease). A similar tendency was observed for BC_{wb} concentrations, with peak values
recorded during winter (0.12 ± 0.16 µg m⁻³, 47% higher), and lowest values in summer (0.07 ±
0.09 µg m⁻³, 13% lower) and autumn (0.05 ± 0.04 µg m⁻³, 37% lower). These seasonal variations
could be attributed, at least in part, to changing local meteorological conditions, variations in
human activities, and the intensity of widespread sources (Chauhan et al., 2024). For instance, the
higher contribution of fossil fuels during winter could be linked to more stable meteorological
conditions (see Table 2), as indicated by the high relative humidity (87%) and stable boundary
layer (around 950 m), inhibiting the dispersion and transportation of BC aerosols. Additionally,
increased fossil fuel consumption for activities such as traffic, power plants, and industrial
processes during winter contributes to elevated BC_{ff} levels. Furthermore, Spearman’s correlation
coefficient analysis revealed a significant correlation between BC_{ff} and total BC concentrations (r
= 0.9, p-value < 0.01), with BC_{ff} accounting for approximately 91% of total BC in PM_{2.5}. This
suggests that variations in BC_{ff} closely align with overall BC concentrations, consistent with
findings from previous studies (Bounakhla et al., 2022), indicating road traffic as a major source
of BC_{ff} near the monitoring site. Furthermore, as depicted in Fig. 2, long-range atmospheric
transport events could potentially lead to increased BCff concentrations, contingent upon the trajectory heights and pathways of air masses. The outcomes derived from the Concentration-Weighted Trajectory (CWT) model analysis indicate that BCff levels are impacted by air masses originating from populated regions within Morocco and the Atlantic, as well as those originating from the Iberian region and the Strait of Gibraltar.

Fig. 2. Weighted Average Concentrations of BCff during the entire sampling period in Kenitra. The red areas represent the main potential source areas affecting BCff concentrations. Scales are in ng m$^{-3}$. 
As for $\text{BC}_{\text{wb}}$ levels, Kenitra City is likely exposed to minor black carbon emissions associated with various biomass-burning sources, including traditional public bathhouses (hammams), agricultural waste burning, and forest fires. According to Sibley & Sibley (2015), traditional hammams consume significant amounts of wood for space and water heating, estimated to be between one and two tons per day. In addition, operations at hammams tend to peak during the winter months due to higher clientele, with the average daily number of bathers significantly increasing from around forty during the hot season to several hundred during the cold season (Sibley & Sibley, 2015). Moreover, the agricultural burning activities, emissions of wood combustion in hammams (two hammams within a radius of 1 km of the sampling site), forest fires in northern Morocco, waste incineration, and reduced effectiveness of rainfall in cleansing the atmosphere contribute as combined factors to changes in $\text{BC}_{\text{wb}}$ concentrations observed in the Kenitra region.

Additional evidence from emission inventories can further elucidate the relationship between the sources of black carbon ($\text{BC}_{\text{wb}}$ and $\text{BC}_{\text{fr}}$) identified in this study. For instance, the International Energy Agency (IEA) offers comprehensive analyses of Morocco's energy policies, highlighting the substantial contribution of fossil fuels to urban pollution, particularly from the transportation and industrial sectors (IEA, 2019). Furthermore, reports from the Global Green Growth Institute (GGGI) on Morocco's emission reduction strategies shed light on the seasonal variability of
biomass burning emissions, influenced by agricultural practices and residential heating (GGGI, 2021). Additionally, the Mediterranean Atmospheric Emission Inventory (MEAEI) provides regional emission data, underscoring the impact of local traffic and industrial activities on BC emissions (MEAEI, 2018).

**Table 2.** Descriptive statistics (mean, standard deviation (sd), minimum [Min], and maximum [Max] concentrations) of 5-minute BC, BCff (fossil fuel BC), BCwb (wood burning BC), and BB (biomass burning percentage) measured from mid-July 2020 to mid-February 2021 at an urban location in Kenitra. Absorption Ångström Exponents used for the applied Aethalometer source apportionment model are AAEwb = 1.9 and AAEff = 0.9. Summary data are subdivided into three seasons over Kenitra city. N stands for the number of total datasets used.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Entire period</th>
<th>Winter</th>
<th>Autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>N for BCff and BCwb datasets used</td>
<td>11434</td>
<td>2730</td>
<td>649</td>
<td>8055</td>
</tr>
<tr>
<td>BC (µg m⁻³)</td>
<td>0.90 ± 0.80 [6.70 - 0.0]</td>
<td>1.30 ± 1.17 [6.70 - 0.0]</td>
<td>1.01 ± 0.70 [4.21 - 0.0]</td>
<td>0.75 ± 0.58 [6.50 - 0.09]</td>
</tr>
<tr>
<td>BCff (µg m⁻³)</td>
<td>0.81 ± 0.74 [6.57 - 0.0]</td>
<td>1.18 ± 1.07 [6.57 - 0.0]</td>
<td>0.95 ± 0.67 [4.20 - 0.0]</td>
<td>0.68 ± 0.54 [6.34 - 0.0]</td>
</tr>
<tr>
<td>BCwb (µg m⁻³)</td>
<td>0.08 ± 0.11 [1.70 - 0.0]</td>
<td>0.12 ± 0.16 [1.63 - 0.0]</td>
<td>0.05 ± 0.05 [0.59 - 0.0]</td>
<td>0.07 ± 0.09 [1.70 - 0.0]</td>
</tr>
<tr>
<td>BB (%)</td>
<td>9.58 ± 8.41 [99.15 - 0.0]</td>
<td>9.76 ± 8.49 [99.15 - 0.0]</td>
<td>6.20 ± 5.80 [63.85 - 0.05]</td>
<td>9.86 ± 8.55 [97.14 - 0.0]</td>
</tr>
<tr>
<td>Daily Ratio of hourly BCff</td>
<td>1.19</td>
<td>1.54</td>
<td>1.35</td>
<td>0.99</td>
</tr>
<tr>
<td>Daily Ratio of hourly BCwb</td>
<td>1.16</td>
<td>1.74</td>
<td>1.07</td>
<td>0.92</td>
</tr>
<tr>
<td>N for meteorological parameters</td>
<td>781</td>
<td>144</td>
<td>325</td>
<td>312</td>
</tr>
<tr>
<td>RH (%)</td>
<td>79 [100 - 0]</td>
<td>87 [100 - 0]</td>
<td>79 [100 - 0]</td>
<td>76 [100 - 0]</td>
</tr>
<tr>
<td>WS (m s⁻¹)</td>
<td>2.9 [15.4 - 0.0]</td>
<td>2.7 [9.8 - 0.0]</td>
<td>2.7 [15.4 - 0.0]</td>
<td>3.3 [9.8 - 0.0]</td>
</tr>
<tr>
<td>Sunrise time (a.m., local time)</td>
<td>n.a</td>
<td>08:27</td>
<td>07:34</td>
<td>06:42</td>
</tr>
<tr>
<td>Sunset time (p.m., local time)</td>
<td>n.a</td>
<td>06:33</td>
<td>06:53</td>
<td>08:17</td>
</tr>
</tbody>
</table>
3.2.2 Monthly variation of BC_{ff} and BC_{wb} levels

The monthly variations of BC_{ff} and BC_{wb} concentrations are depicted in Fig. 3. The monthly mean BC_{ff} concentration increased from August to November and then decreased in January and February. November witnessed the peak BC_{ff} concentration (1.09 ± 0.74 µg m^{-3}), while August recorded the lowest (0.56 ± 0.51 µg m^{-3}). These significant variations in BC_{ff} mass concentration can be attributed to various influential factors, including shifts in socioeconomic activities, levels of precipitation and relative humidity, changes in synoptic wind patterns, fluctuations in temperature, and changes in the intensity of aerosol sources. For instance, the decline in BC_{ff} concentration observed in August is likely attributable to reduced vehicle emissions, particularly from diesel trucks, during the summer holiday period. This observation aligns with the patterns identified in both the seasonal and diurnal BC_{ff} data (Fig. 5). However, the increase in BC_{ff} levels since the beginning of autumn can be attributed to the heightened socioeconomic activity that typically begins after the summer holidays, resulting in the resumption of more regular industrial and transportation schedules (Merabet et al., 2019).
Fig. 3: Monthly distribution of BC_r (upper panel) and BC wb (bottom panel) in (ng m^{-3}). The five-number summary visualized by the boxplot includes, respectively, the minimum, the first quartile (25^{th} percentile), the median, the third quartile (75^{th} percentile), and the maximum. Due to some technical issue in the Aethalometer, monthly data from December were excluded.

During the warmer months, beginning in July, BC wb contributions to BC levels exhibited a decline. The monthly BC wb concentration showed an increase from August to September, followed by a decrease in October and November, subsequently rising again from November onwards at this location. The mean concentration in July, at 0.07 ± 0.07 µg m^{-3}, indicates a reduction in biomass burning activities, typical during warmer months when there is decreased demand for such activities. This trend continues into August, with the mean concentration further decreasing to 0.06
± 0.09 µg m$^{-3}$, supporting the reduction in biomass burning during the summer season. With the transition to autumn in September, BC$_{wb}$ concentrations begin to rise, with the average value increasing to 0.08 ± 0.11 µg m$^{-3}$. This uptick suggests an increased utilization of biomass burning for incineration purposes. However, the highest BC$_{wb}$ mean concentration, observed in November at 0.09 ± 0.05 µg m$^{-3}$, could potentially be linked to air masses originating from Europe, carrying a high load of BC$_{wb}$ due to domestic heating emissions. Wildfires represent another significant biomass-burning source that could impact BC$_{wb}$ concentrations. As illustrated in Fig. 4, the long-range influence of BC$_{wb}$ appears to be potentially more pronounced in July compared to August, based on the trajectory heights and pathways of air masses, as indicated by the concentration-weighted trajectory (CWT) model analysis. However, since August 1, 2020, numerous wildfires have been recorded, destroying several hectares of vegetation. These wildfires occurred in various locations across Morocco, including the Haouz al Mellaliyin forest in M’diq, the Akesmaz forest near Chefchaouen in northern Morocco, the Tighmert oasis near Guelmim in southern Morocco, and forests in the province of Al Haouz near Marrakech (Mebtoul, 2020; Serbouti et al., 2022). Despite these incidents, it seems unlikely that they significantly contributed to the biomass burning levels in the Kenitra region.
Fig. 4. Weighted Average Concentrations of BC$_{wb}$ during sampling periods in Kenitra. The red areas represent the main potential source areas affecting BC$_{wb}$ concentrations. Scales are in ng m$^{-3}$.

3.3 Impact of Diurnal Trend Changes on BC$_{ff}$ and BC$_{wb}$ Concentrations

The diurnal cycles of hourly averaged BC$_{ff}$ and BC$_{wb}$ concentrations across the entire period, as well as during summer, autumn, and winter seasons, are illustrated in Fig. 5. A distinct and significant diurnal variation in both BC$_{ff}$ and BC$_{wb}$ concentrations was evident throughout the day, exhibiting clear differences between seasons. While the diurnal profile of BC$_{ff}$ displayed a bimodal pattern, characterized by peaks in human-induced morning and evening rush hour traffic, the diurnal profile of BC$_{wb}$ showed an increase towards the nocturnal and early morning periods. The shape and trend of the diurnal variation of BC concentration are consistent with the findings of Merabet et al. (2019) in suburban Algiers, Algeria, and Liakakou et al. (2020) in an urban background area of Athens, Greece.

Throughout the day, there is a consistent rise in BC$_{ff}$ concentration, leading to distinct peaks between 6 and 9 a.m. local time (LT) shortly after sunrise. This is followed by a gradual decline to
lower concentrations around midday (11 a.m. – 5 p.m.) and then another increase, reaching peak values in the evening around 9 p.m. after sunset. During the morning hours, maximum hourly BCff concentrations were approximately 1.24 µg m\(^{-3}\) at 7 a.m., 1.36 µg m\(^{-3}\) at 8 a.m., and 1.39 µg m\(^{-3}\) at 10 a.m. In the evening, peak concentrations were around 0.85 µg m\(^{-3}\) at 9 p.m., 1.42 µg m\(^{-3}\) at 11 p.m., and 1.78 µg m\(^{-3}\) at 10 p.m., during summer, autumn, and winter, respectively. For BCwb, the diurnal profile averaged during summer exhibited a relatively flat pattern, characterized by a sharp morning peak centered around 6–9 a.m., followed by a decline to minimum values by approximately 3–4 p.m. Subsequently, there was a gradual ascent, culminating in a broader evening peak around 9 p.m. The average hourly BCwb concentration during summer was 0.071 µg m\(^{-3}\), ranging from 0.039 to 0.13 µg m\(^{-3}\). Overall, BCwb levels remained relatively consistent until midnight. During winter, the diurnal profile displayed a pre-dawn minimum around 5 a.m., followed by a wide morning peak from 9 a.m. to 3 p.m. Additionally, a second peak, relatively more pronounced, was observed around 6 p.m. BCwb concentrations continued to increase during nighttime until 11 p.m., with the maximum mean concentration reaching nearly 0.25 µg m\(^{-3}\).

One of the notable findings in this investigation is the average ratio between nighttime (7 p.m to 6 a.m.) and daytime (7 a.m. to 6 p.m.) concentrations of BCff and BCwb, calculated over the entire study period, which exceeded unity, measuring 1.19 and 1.16, respectively, as presented in Table 1. On a seasonal basis, the daily ratio of hourly BCff was determined to be 1.54, 1.35, and 0.99.
during the winter, autumn, and summer seasons, respectively. This suggests a relatively stronger influence of meteorological conditions between seasons than emission sources during nighttime compared to daytime. A noteworthy observation is that, for the majority of the time, the contribution of fossil fuel to BC concentrations is lower in the morning compared to the evening hours. However, this characteristic is less pronounced for the contribution of biomass burning during summer, where BC_{wb} concentrations in the evening are lower than those in the morning (daily ratio = 0.92).

The increased contribution of BC_{wb} to total BC levels, particularly during the winter months, can be attributed to increased emissions from biomass-burning activities, including those associated with traditional bathhouse operations and industrial sectors. Nevertheless, the greater proportion of fossil fuel combustion in BC concentrations may be linked to temperature inversions, leading to the accumulation of primary pollutants associated with BC, alongside other critical factors (Chauhan et al., 2024). These variations in BC_{ff} and BC_{wb} levels suggest that daily variations in BC concentrations are heavily influenced by both local emissions and meteorological factors (Tiwari et al., 2013). Previous studies (Chauhan et al., 2024; Doumbia et al., 2012) emphasize the substantial contribution of local sources primarily due to commuter traffic, as well as to the fumigation effect within the boundary layer, which brings evening aerosols near the surface from the nocturnal residual boundary layer shortly after sunrise, further impacting BC concentrations.
3.4 Weekly changes in BC_{ff} and BC_{wb} concentrations

As shown in Fig. 6, the collected dataset reveals distinct patterns in weekly changes of BC_{ff} and BC_{wb} concentrations, with varying levels observed depending on the day of the week. To investigate potential variations in BC_{ff} and BC_{wb} concentrations throughout the week, a one-way ANOVA test was employed across the entire dataset. This analysis revealed a statistically significant difference in concentrations between days (p-value < 0.001), suggesting a clear pattern.
However, the distinction between weekdays and weekends was less pronounced, indicating a moderate level of significance. In simpler terms, our findings demonstrate that BC_{ff} and BC_{wb} concentrations fluctuated measurably depending on the day of the week. For instance, Mondays exhibited the highest average BC concentrations, with BC_{wb} reaching 0.09 µg m^{-3} and BC_{ff} at 1.09 µg m^{-3}, while Sundays showed the lowest BC_{wb} content at 0.07 µg m^{-3} and Saturdays the lowest BC_{ff} concentration at 0.83 µg m^{-3}. This intriguing trend suggests a potential correlation between the onset of the work week and increased BC emissions, likely influenced by heightened industrial and vehicular activities. Conversely, weekends saw a noticeable decrease in BC levels, possibly due to reduced anthropogenic activity. The lowest BC_{wb} and BC_{ff} levels were recorded on Thursdays and Fridays, respectively, while both experiencing peak concentrations on Thursdays at 0.76 µg m^{-3} for BC_{wb} and 2.89 µg m^{-3} for BC_{ff}. These findings underscore the complex interplay of factors such as traffic patterns, weather conditions, and industrial operations influencing BC_{wb} and BC_{ff} dynamics in the studied area.

Moreover, our dataset covers three distinct seasons — autumn, summer, and winter — each analyzed across various days of the week. In autumn, BC_{wb} displayed dynamic patterns, with the lowest levels observed on Mondays (approximately 0.10 µg m^{-3}) and the highest on Fridays (around 2.47 µg m^{-3}), indicating substantial variability. Conversely, BC_{ff} showed a different trend, peaking on Tuesdays with an average concentration of approximately 1.02 µg m^{-3} and reaching its lowest
point on Thursdays. Transitioning to the summer season, $BC_{wb}$ levels remained relatively consistent throughout the week, with Mondays recording the lowest values and Wednesdays the highest, averaging around 0.75 $\mu g \, m^{-3}$. In contrast, $BC_{ff}$ exhibited more variability, with Thursdays exhibiting the highest levels (approximately 1.23 $\mu g \, m^{-3}$) and Mondays the lowest. Finally, during winter, $BC_{wb}$ levels remained stable, with Mondays and Sundays reporting the lowest and highest concentrations, respectively, at approximately 1.19 $\mu g \, m^{-3}$. Conversely, $BC_{ff}$ displayed pronounced variations, with Thursdays showing the highest levels (around 1.56 $\mu g \, m^{-3}$) and Tuesdays recording the lowest concentrations. Winter consistently displayed the highest $BC_{ff}$ levels across all days of the week.

Furthermore, it is important to note that BC measurements were conducted during the COVID-19 curfew imposed by the government, starting on June 11, 2020, and continuing until the end of the sampling period. A detailed timeline of the mobility restrictions and relaxation measures implemented in Kenitra city during the Coronavirus pandemic is outlined in our previous paper (Bounakhla et al., 2022). This latter highlighted that the observed low BC levels were likely a result of the nationwide curfew (ranging from 7 p.m. to 5 a.m. or 9 p.m. to 6 a.m.) enforced by authorities during the sampling period. During this time, most activities occurred during the daytime, which impacted Kenitra's air quality significantly and altered the city's usual rhythm. Consequently, the absence of distinct weekend/weekday effects can be attributed to the prolonged nighttime curfew.
in Kenitra. A recent study in urban Delhi, India (Goel et al., 2021) suggested that extended periods of lockdown relaxation led to an increasing trend in contributions of BC_{fr} and BC_{wb} to BC levels, driven by heightened anthropogenic activities and agricultural waste burning, respectively.
Fig. 6. Weekly variation of BC_{ff} (upper panel), and BC_{wb} (lower panel) concentrations averaged for weekdays throughout the entire sampling period.

3.5 Relationship between BC_{ff}, BC_{wb}, and Meteorological Factors

Correlation analysis, as shown in Fig. 7, indicated that BC_{wb} and BC_{ff} have a moderate positive correlation (r = 0.59, p-value < 0.01), suggesting that trends between such black carbon emission categories are most probably very often the same. For instance, where there is a rise in BC_{wb} levels, BC_{ff} is likely to also increase, and where there is a decrease in BC_{wb} levels, BC_{ff} would be similarly observed. This may indicate a forcing or influencing common factor by which BC_{ff} and BC_{wb} were concurrently affected, such as likely originating from general sources or a common general ambient pollution level. Wind speed and BC_{wb} levels have a weak negative correlation (r = -0.25, p-value < 0.01). Therefore, it can be said that higher wind speed brings about a low decrease in BC_{wb} levels. This would be due to strong winds picking up BC particles and taking them much further, such that the BC_{ff} would be highly diluted and show a much stronger moderately negative correlation (r = -0.52, p-value < 0.01) with wind speed than BC_{wb}. This further implies that BC_{ff} concentrations were lower with increased wind speeds, pointing toward an important dispersion or dilution of these particulates under windy conditions. The weak negative correlation between BC_{wb} and temperature (r = -0.27, p-value < 0.01) indicates that BC_{wb} values are slightly lower under warm conditions. Such behavior can be well explained considering atmospheric dynamics. As temperatures rise, there is increased vertical mixing, which leads to dilution of the surface BC.
concentration. Moderately negative correlation with temperature; its value ($r = -0.42$, p-value < 0.01) for BC$_{ff}$ is larger compared to BC$_{wb}$. This points to a greater possibility of BC$_{ff}$ being more sensitive to temperature change, as it will have a sharp decline in the BC$_{ff}$ value at high temperatures. Changes in BC sources or increased vertical mixing during warm periods could be the cause of this.

Fig. 7. Spearman correlation coefficient between meteorological variables (specifically wind speed (ws), wind direction (wd), temperature (temp), atmospheric pressure (pres), relative humidity (RH), and boundary layer height (PBLH)) and BC$_{ff}$ and BC$_{wb}$. Correlations with statistical significance exceeding the 95% confidence level are denoted by bold color.
Atmospheric pressure shows a weak positive relationship \((r = 0.30, \text{p-value} < 0.01)\) with BC\(_{wb}\); that is, there is very little increase or none at all in BC\(_{wb}\) levels with a higher pressure. Over any high-pressure area, there always exists a stable atmospheric condition. This might prevent the dispersion of black carbon particles in the first place. Compared to atmospheric pressure, BC\(_{ff}\) has a moderately positive correlation \((r = 0.50, \text{p-value} < 0.01)\) which is stronger than BC\(_{wb}\). This would mean that with an increase in pressure, there will be steadier atmospheric conditions with less spread, hence increasing BC\(_{ff}\). Relative humidity does not exhibit a strong correlation with BC levels. The correlation is so weak that it likely has negligible influence. This characteristic is evident in both BC\(_{wb}\) and BC\(_{ff}\) \((r = 0.05; r = -0.01, \text{respectively})\). In BC\(_{wb}\) and BC\(_{ff}\), the relation to planetary boundary layer height is weak \((r = 0.13 \text{ and } 0.04, \text{p-value} < 0.01, \text{respectively})\). This indicates that PBLH is not directly significant to these emissions levels of black carbon. PBLH influenced the spatial domain of the pollutant concentration, while it had rather limited influence on the concentrations of BC\(_{wb}\) and BC\(_{ff}\). In contrast, recent studies (Adasme et al., 2022; Christodoulou et al., 2022) have highlighted the significant influence of PBLH on local concentrations of BC\(_{ff}\) and BC\(_{wb}\). Adasme et al. (2022) propose that a shallower PBLH might restrict vertical diffusion, causing BC\(_{ff}\) and BC\(_{wb}\) to accumulate at lower altitudes within the boundary layer, potentially exacerbating local pollution. Christodoulou et al. (2022) add another
layer of complexity, suggesting that nighttime stability in PBLH can impact the dispersion of pollutants like BC$_{wb}$ and other aerosols, leading to their buildup in the lower atmosphere.

4

CONCLUSIONS

In this study, source apportionment of Black Carbon (BC) in an urban area in Kenitra, Morocco was investigated, focusing on the temporal variations of the main sources (fossil fuel and biomass burning) contributing to BC levels over the years 2020–2021. Utilizing the Aethalometer source apportionment model, we gained insights into the seasonal, weekly, and diurnal patterns of BC pollution, providing a valuable understanding of its origins and dynamics. Our findings highlight the significant contribution of fossil fuel (BC$_{ff}$) to BC pollution throughout the year, with heightened seasonal contributions observed in winter and autumn. While lower BC$_{ff}$ concentrations occur in summer due to aerosol dispersion driven by high wind speeds, higher BC$_{ff}$ concentrations are observed in winter due to factors such as a shallow boundary layer, long-range transport, and local traffic emissions. Conversely, biomass burning exhibits slight variability across seasons, with generally lower contributions, ranging on average from a low of 0.05 µg m$^{-3}$ in autumn to a high of 0.12 µg m$^{-3}$ in winter. The diurnal variation of BC$_{ff}$ to total BC concentrations revealed peaks during traffic rush hours, reflecting human–induced morning and evening traffic patterns. The diurnal cycle of each season is closely linked to source activities and local meteorological conditions, such as boundary layer height, which influences BC$_{ff}$ concentrations during morning
Biomass–burning–originated BC (BC_{wb}) demonstrated nighttime peaks, particularly in winter, reaching up to 13% of total BC concentration. This notable contribution of BC_{wb} is likely associated with emissions from industry–related combustion and traditional bathhouses. The study highlights a moderate positive correlation between black carbon emissions from biomass combustion and fossil fuel combustion, suggesting that they often vary in tandem due to potentially shared sources or common environmental influences. Variations in wind speed and temperature demonstrate distinct impacts on BC concentrations, with wind speed inversely affecting BC levels and higher temperatures promoting vertical mixing, thus diluting BC presence. A weak to moderate positive correlation between atmospheric pressure and BC_{wb} and BC_{ff}, respectively, indicates a stabilizing effect on BC concentrations under high–pressure conditions. The minimal influence of relative humidity and planetary boundary layer height on BC emissions points to the complex interplay of various factors in determining black carbon levels in the atmosphere.

Overall, this study offers valuable insights into the dynamics of BC pollution, its sources, and behavior within the urban region of Kenitra. These findings emphasize the significance of accounting for temporal variations in formulating efficient strategies for managing air quality.
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