The influence of meteorological conditions and atmospheric circulation types on PM_{10} levels in western Turkey

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Abstract High levels of atmospheric pollutants have been frequently measured in Turkey during the last decade. Specifically, the occurrence of these high particulate matter concentrations is often related to either local-scale conditions or regional-scale transport. In order to better understand the atmospheric factors that trigger poor air quality, further research investigating the relationship between air pollution and meteorological variables or atmospheric circulation patterns is needed. In this study, the influence of synoptic-scale weather types on PM_{10} levels over the Aegean region of Turkey is investigated for the period 2008–2015. First of all, hourly PM_{10} concentrations of 13 air quality stations are respectively converted to daily, seasonal, and regional averages. The seasonal variability of PM_{10} values in the region indicates that high particulate matter concentrations are registered in winter, fall, spring, and summer months with mean values at 90.6 (± 38.3 standard deviation), 66.9 (± 28.3), 61.6 (± 23.4), and 54.1 (± 12.8) $\mu g\ m^{-3}$, respectively. In regard to the synoptic-scale approach, eight directional and two vorticity types of the Lamb weather type (LWT) method are used in the analysis. Based on the results, poor air quality conditions are observed in all seasons during active southeasterly (SE, interaction between a low pressure over Italy and a high pressure over the Caspian Sea) circulation types (CTs). In winter, mainly easterly (E), SE, southerly (S), and anticyclonic (A) weather patterns result in above normal PM_{10} concentrations. In addition to these four CTs, southwesterly (SW) types also cause higher PM_{10} values in the spring season. During summer, SE, SW, westerly (W), and cyclonic (C) CTs are associated with above-normal PM_{10} values. During fall, obvious higher PM_{10} concentrations are found during SE, S, and A types.

Keywords Aegean · Circulation types · Lamb weather type · Turkey · PM_{10}

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Introduction

Long-range transport of pollutants as well as their physical and chemical transformations is strongly dependent

on meteorological conditions (Andersson et al. 2007). To understand the influence of atmospheric conditions on the transport of pollutants, circulation-to-environment approach is used by classifying or clustering synoptic-scale maps, prior to seeking links with the local-scale environment (Yarnal 1993). As a result of this approach, synoptic climatological classification methods became popular in evaluating the impact of climate upon a variety of environmental problems such as air quality. It is shown in these methods that, while various air masses cause high frequency of serious pollution events, others are almost always related to much better air quality (Cheng and Lam 2000). So far, numerous researches indicating the impacts of weather and climate on O_3 (Dayan and Levy 2002; Demuzere et al. 2009; Shan et al. 2009; Demuzere and van Lipzig 2010; Lesniok et al. 2010; Zhang et al. 2012; Russo et al. 2014; Otero et al. 2016), PM_{10} (Buchanan et al. 2002; Dayan and Levy 2004; Demuzere and van Lipzig 2010; Lesniok et al. 2010; Stefan et al. 2010; Zhang et al. 2012; Russo et al. 2014; Fortelli et al. 2016), NO_x (Cheng and Lam 2000; Zhang et al. 2012; Pope et al. 2014; Russo et al. 2014; Grundstrom et al. 2015), and SO_x (Cheng and Lam 2000; Oanh et al. 2005) levels were done for different parts of the globe.

In terms of the dust source areas, Sahara is known as the main aeolian dust region in the world, which is responsible for half of the mineral dust emissions globally (Zender et al. 2004). Due to the significant deposition rate of Saharan dust in the Mediterranean (3–14 g/m^2 per year) especially with the largest value in the eastern parts (Prospero 1996), the Eastern Mediterranean (EM) basin is shown as an important dust transport route from the source region. According to the previous dust particle studies investigated for the EM basin, prevailing air masses bringing natural dust particles and local meteorological conditions such as wet or dry depositions were studied in detail (e.g., Papayannis et al. 2005, 2008; Katragkou et al. 2009; Kassomenos et al. 2011; Nastos 2012; Gaetani and Pasqui 2014; Gkikas et al. 2015; Paschalidou et al. 2015).

Due to the geographical closeness to the Sahara dust source region and the crossing routes of the air masses, Turkey is mainly influenced by natural particulate matters at different times. To understand the atmospheric mechanism that brings suspended dust particles, numerous researches were done for the specific or the whole part of the country by especially focusing on synoptic maps, WRF models, and air mass trajectories (e.g.,

Karaca et al. 2009; Koçak et al. 2011; Kabatas et al. 2014; Baltaci 2017; Kabatas et al. 2018).

Differently from the aforementioned studies related to Turkey, any quantitative synoptic climatological procedure based on PM_{10} was not studied in detail. With the construction of synoptic-PM_{10} work, possible prediction of particulate matter concentrations can be achieved through predicting the arrival of weather categories that are most typically associated with high air pollution concentrations. To overcome this deficiency, the main goal of this paper is to understand the synoptic climatology of particulate matter in western Turkey. For this reason, we applied the objective version of Lamb weather type (LWT) method to Aegean Region (western Turkey) to relate air quality with circulation types by using daily PM_{10} values from 13 air quality stations in the region.

In "Data and methodology," descriptions of air quality data and the used methods are explained. Results of the relationship between synoptic air masses and PM_{10} concentration levels are presented in "Results and discussion." The last part, "Summary and conclusions" is devoted to the summary and conclusions.

Data and methodology

Air quality data

According to the European Union's Air Quality Standard (EU AQS), the limit values for PM_{10} are 40 µg m^{-3} for the annual averaged concentrations and 50 µg m^{-3} for the 24-h averaged concentrations, a value which must not be exceeded more than 35 times in a calendar year (EU, 1999, 2008).

In our study, the air quality data were obtained from the National Air Quality and Monitoring Network database (NAQMS, http://www.havaizleme.gov.tr/Services/AirQuality). PM_{10} is monitored in the NAQMS network using a standard beta gauge method with automatic online monitors. Detailed explanation of the method of data collection for PM_{10} can be found in a Twinning Interim Quarterly Report (TIQR 2010: no. 01 TR/07/IB/EN/02). Hourly measurements of PM_{10} are selected from 13 stations in Aegean Region (western Turkey in Fig. 1) for the period 2008–2015. Hourly observations are converted to daily values for each station. For regional approach, averages of daily mean
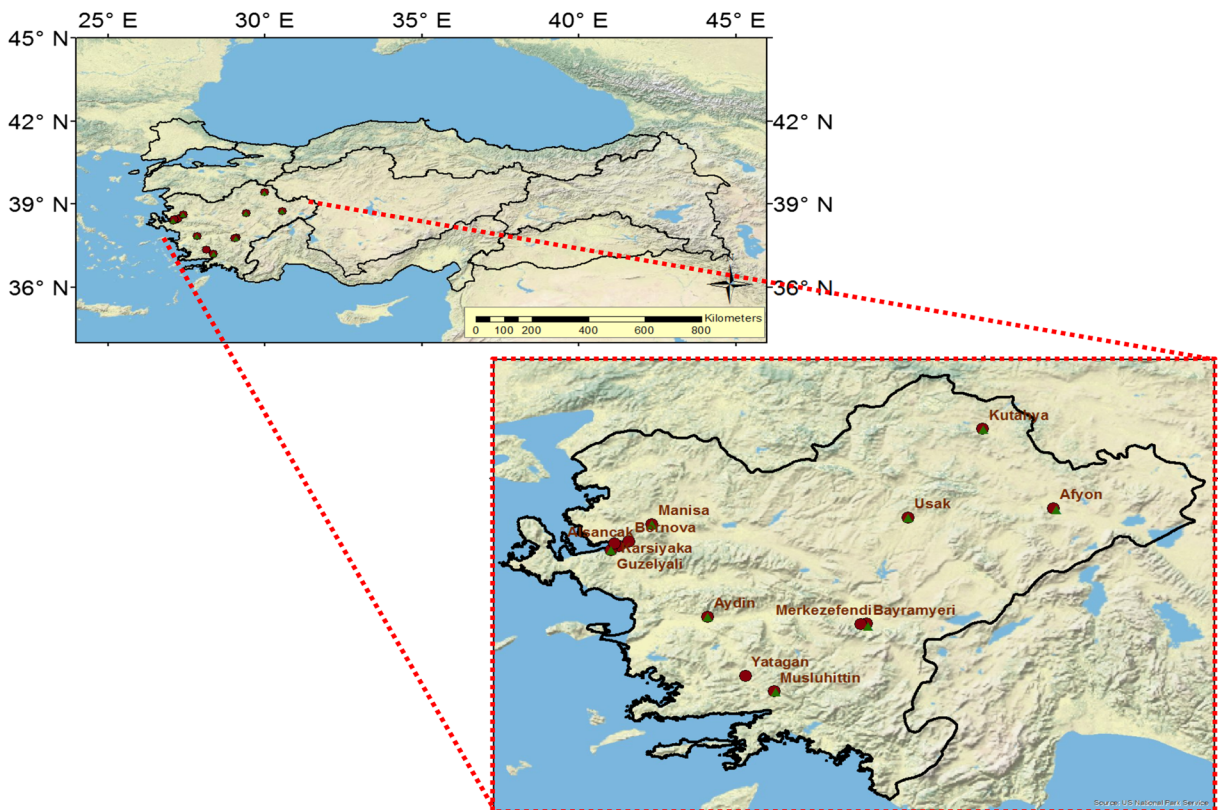
Fig. 1 Distribution of 13 of air quality stations (brown points) and 8 meteorological stations (green triangles) in the Aegean region. The outset shows the borders of the Aegean along with the other six geographic regions in Turkey

PM_{10} values associated with 13 stations are used in the study.

Lamb weather type

In order to find atmospheric CTs causing poor and better air quality conditions, we used the objective version of Lamb weather type. This method is firstly used for the British Isles as subjective classification by focusing on synoptic charts (Lamb 1972). Later, using daily grid-point mean sea level pressure data, the automated version of LWT classified CTs into 27 different categories. These categories include 8 directional (north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), northwest NW)), 3 pure (cyclonic (C), anticyclonic (A), unclassified (U), and 16 hybrid types. The hybrid types are a combination of the pure and directional types which the first letter represents the pure type, and the rest represents the directional type (CN, CNE, CE, CSE, CS, CSW, CW, CNW, AN, ANE, AE, ASE, AS, ASW, AW, ANW) (Jones et al. 1993). In this

study, by using daily mean sea level pressure data from NCEP/NCAR Reanalysis (Kalnay et al. 1996) for the period 2008–2015, we adapted LWT from the Marmara region (Baltacı et al. 2015, 2017; Akkoyunlu et al. 2019) to the Turkish Aegean region by using the same grid resolution and different grid locations and constants of the formulas.

Results and discussion

Variation of PM_{10} levels and their relationship with meteorological variables

On monthly basis, highest PM_{10} concentrations are found in the region during December, January, and November months, respectively (Fig. 2a). In these months, daily mean PM_{10} values reach to 100 $\mu g\ m^{-3}$ levels, which is almost two times higher than the EU daily limits. It is known that local emissions play a significant role in having excessive particulate matter
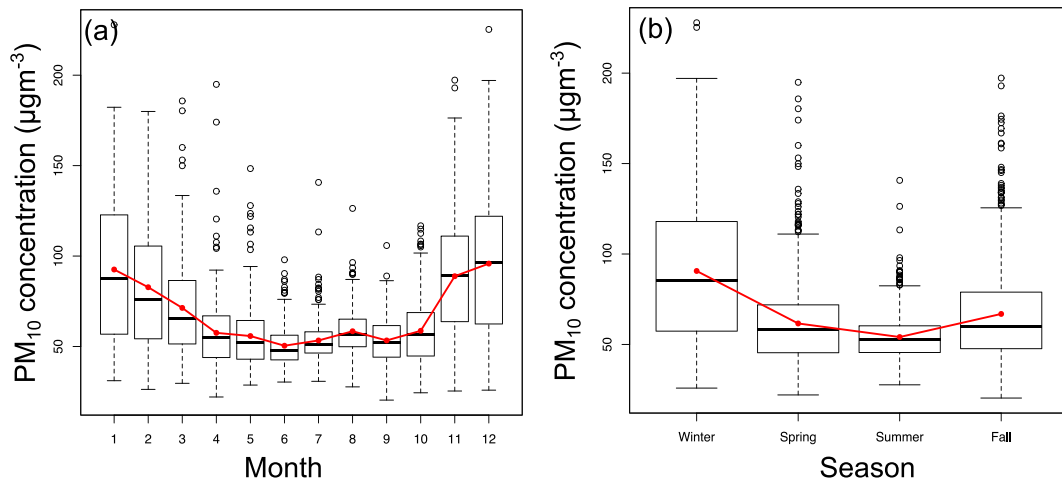
Fig. 2 (a) Monthly and (b) seasonal distribution of PM_{10} concentration values in the Aegean region for the period 2008–2015. The boxes present the median, the first and third quartiles, while whiskers and dots present the minimum and maximum value and possible outliers respectively. Red lines indicate the mean monthly and seasonal PM_{10} values, respectively

concentrations in winter times (e.g., Kassomenos et al. 2014). These local pollution emissions occur mainly caused by transportation (i.e., private cars, public transportation, aircrafts, ships, heavy diesel trucks), industrial emissions, and residential heating. Except winter and fall months, daily PM_{10} values decrease and the lowest values are found during summer months. Besides, the PM_{10} data are still exceeding the threshold limits. On seasonal basis, the average PM_{10} values are calculated as 90.6, 66.9, 61.6, and 54.1 μg m^{-3}, in winter, fall, spring, and summer seasons, respectively (Fig. 2b).

Preceding studies revealed that several meteorological variables such as air temperature, wind speed and direction, relative humidity, precipitation, cloud cover, dew point temperature, and mixing layer height can be relevant to characterize air pollution (Hooybergs et al. 2005; Demuzere et al. 2009; Pearce et al. 2011). In our study, we used daily mean temperature and daily total precipitation values as primary meteorological variables from the eight meteorological stations in the Aegean region (green triangles in Fig. 1) to better understand the influence of local meteorological conditions on particulate matter concentrations. Temperature and precipitation data belonging to these eight meteorological stations were converted to regional averages to represent the Aegean region of Turkey. As it was shown in Fig. 3a, the regional average of monthly mean temperature ranges from 5 °C in January to 26 °C in August. When the lowest temperature records are found in January, the highest monthly precipitation amounts are measured as 125 mm. Some authors explained the winter

precipitation mechanism of the region with the impacts of the negative phase of the North Atlantic Oscillation (NAO) (e.g., Türkeş and Erlat, 2003). During this phase, the storms pass through the Mediterranean Sea by moving in the west-east direction and bring moist air and transfer it as precipitation to the Turkish Aegean region. For the daily extreme precipitations (R10, daily total precipitation values greater than 10 mm), Baltaci et al. (Baltacı et al. 2018) found that the influence of the Atlantic Oscillation (AO) on R10 is more obvious than the other circulation indices such as North Atlantic Oscillation (NAO), East Atlantic/Western Russia (EA/WR), East Atlantic (EA), and Scandinavian (SCA). Although removal mechanism of the precipitation decreases PM_{10} values, we observed higher PM_{10} concentration levels in this season. One reason can be explained by the loadings of local sources such as residential heating and traffic and industrial emissions. In addition, the studied region generally suffered from the insufficient water supply due to having low amounts of precipitation in the summer months. Extending of the summer Asian low to the inner parts of Turkey prevents coming of mid-latitude cyclones, which bring precipitation to the region. Hence, warm days and nights are more frequently observed in the region because of the influence of the Asian low. To investigate the impacts of regional-scale meteorological conditions on particulate matters, we correlated regional temperature and precipitation data with PM_{10} concentration values (Fig. 3b). During the summer months (July and August), statistically significant positive relations were found between
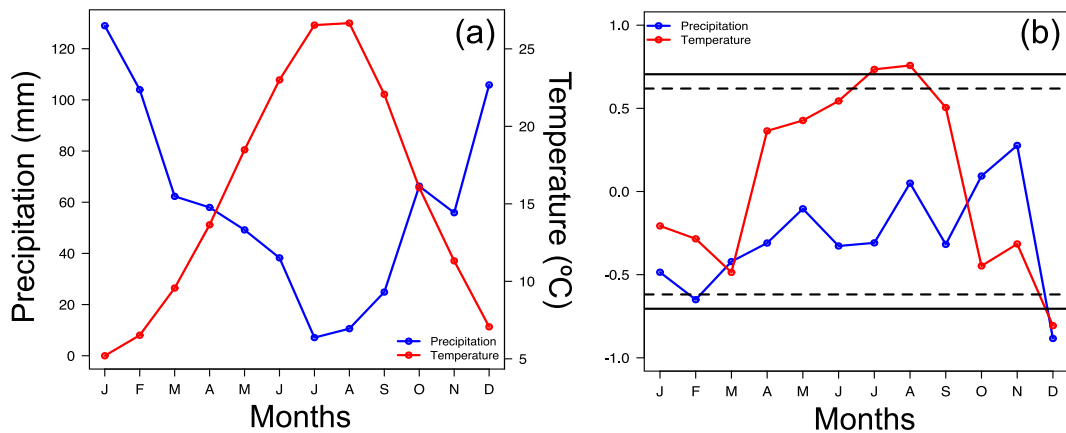
Fig. 3 (a) Monthly variation of precipitation and temperature distribution over the region. (b) Correlation coefficients between meteorological variables (i.e., precipitation and temperature) and PM10 concentration values for each month in the Aegean.

Statistically significant correlation values at the 99% and 95% levels are the ones which are greater than the absolute values denoted by the solid and dashed lines, respectively

regional mean monthly air temperature and the PM_{10} values. This relationship implies that high daily PM_{10} values are found if the region has high daily temperature records. On the other hand, a statistically significant negative correlation was found between regional mean temperature and PM_{10} in December. In terms of precipitation, statistically significant negative relations with PM_{10} were found during February and December. During this wet deposition, atmospheric pollutants are transported to the ground in the form of rain or snow and thus, the removal mechanism of precipitation (e.g., Baltaci 2017) plays a significant role for low concentration levels of PM_{10}. Also, it can be concluded that, when the region gets above-normal daily precipitation amounts because of the large-scale mode of the NAO, the region can experience below-normal PM_{10} values. If we have dry winters and proper synoptic patterns, which transfer natural dust particles, similar to that of winter 2008 (e.g., Kabatas et al. 2018), this condition may cause air pollution and high concentration levels of PM_{10} over the region. As a result, the transferring of natural dust particles especially in spring months (Moulin et al. 1998) can be shifted to the winter or summer months due to the extreme dry (warm) winters (summers).

Atmospheric circulation types over the Aegean region of Turkey

We mainly calculated the seasonal frequencies of atmospheric CTs over the Aegean region of Turkey as percentages for the period 2008–2015. During the winter,

the most frequently shown four atmospheric CTs are mainly C (19%), E (15%), A (9%), and SW (8%), respectively (Fig. 4a). Half of all CTs generally come from these four CTs to the region. In the spring, A, W, E, and C types are more prominent and represent almost 48% of all CTs in the region (Fig. 4b). A and W types are often seen in the spring months compared with other seasons. In summer, NE, E, and C types represent 54% of all patterns and NE is found as the most frequently shown circulation type when compared with the other seasons (Fig. 4c). In fall months, E, NE, C, and A types are observed as the most dominant circulations over the region, respectively (Fig. 4d).

To relate CTs with PM_{10} concentrations in the region, first, we extracted the composites of mean sea level pressure data for each CT for the period 2008–2015 (Fig. 5). Hence, we gain insight about the positions of the low- and high-pressure centers (LPC and HPC, respectively), which cause pure and vorticity CTs at each CT. According to main results, N types occur as a result of the interactions between HPC over the continental Europe and LPC over the Middle East. As shown in Fig. 4, the region is not influenced by N cases during all seasons. Owing to the movement of HPC from western Europe to the Balkan Peninsula, N types turn to the NE circulation and NE is more active in the region during the summer, fall, and spring months, respectively. NE brings more moist and cool air from the Sea of Marmara and prevents excessive heating of the region. Also, high wind speeds occur in the region due to the strong pressure gradient force. Easterly movement of this HPC from 20° E to 25° E longitudes concludes with
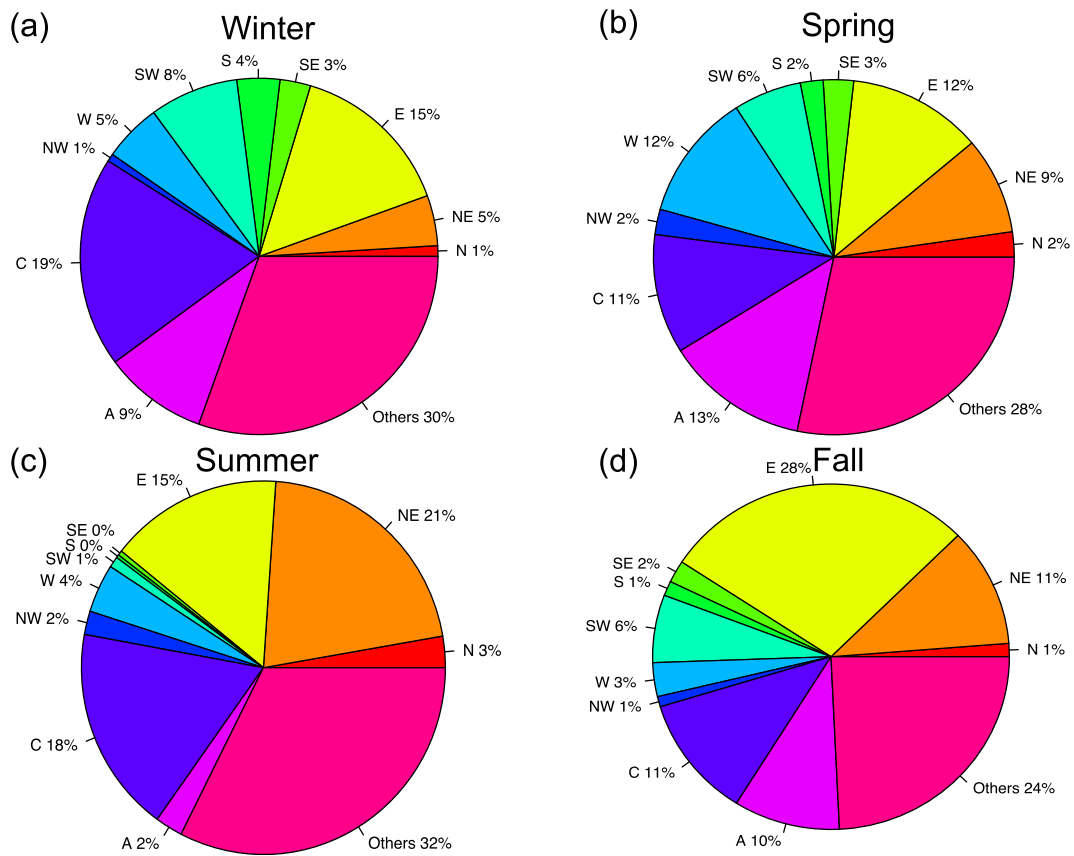
Fig. 4 Seasonal mean percentage frequencies of CTs occurring in Aegean for the period 2008–2015

E types, and dry terrestrial air from Central Anatolia is transferred to the region especially in the fall months. In southerly components of the CTs (i.e., SE, S, and SW), the positions of the LPC over Italy and HPC over the Caspian Sea determine the atmospheric types that affect the Turkish Aegean region. These three CTs are more influential during the winter months due to their highest seasonal frequencies. Location of the LPC over the Black Sea with 1008-hPa core leads to W and NW types. It is shown LPC and HPC over the Aegean region during C and A types, respectively.

Relationship between atmospheric CTs and PM_{10}

In regard to circulation-to-environment approach, we mainly analyzed the changes of PM_{10} concentrations for each CT. It was shown from Fig. 6a that E, SE, S, and A types cause above-normal daily PM_{10} values during the winter months. The region is more influenced by the poor air quality (PAQ) conditions when the flows especially come from the Sahara (i.e., SE and S types).

As a result of this during long-range transport of suspended dust particles, PM_{10} values are measured as high as 120 µg m^{-3} on daily average and exceed 100 µg m^{-3} in all active SE and S atmospheric types. When an anticyclone is active in the region, especially after SE and S days, particulate matters do not move from the Aegean region of Turkey to the surrounding areas due to the subsidence. Hence, daily PM_{10} values range from 110 to 140 µg m^{-3} with 125 µg m^{-3} average. On the other hand, we have better air quality conditions during the active NE and C types. In NE, air flows with high wind speeds pass over the Sea of Marmara and transfer more moist and warmer air to the region. The relatively drier and cooler local air masses meet with new moist and warmer air in the region, which results in below-normal daily PM_{10} values. If the cyclone is settled over the Aegean region, high amounts of daily precipitation and the convergence mechanism of the synoptic system clean the air above the region and the investigated region generally experiences better air quality conditions. Although high daily particles are transferred from

Fig. 5 Long-term mean of daily mean sea level pressure (MSLP) composites of eight main directional and two vorticity CTs during the period from 2008 to 2015. The brown rectangle indicates the Aegean region. H and L mark the high and low-pressure centers, respectively
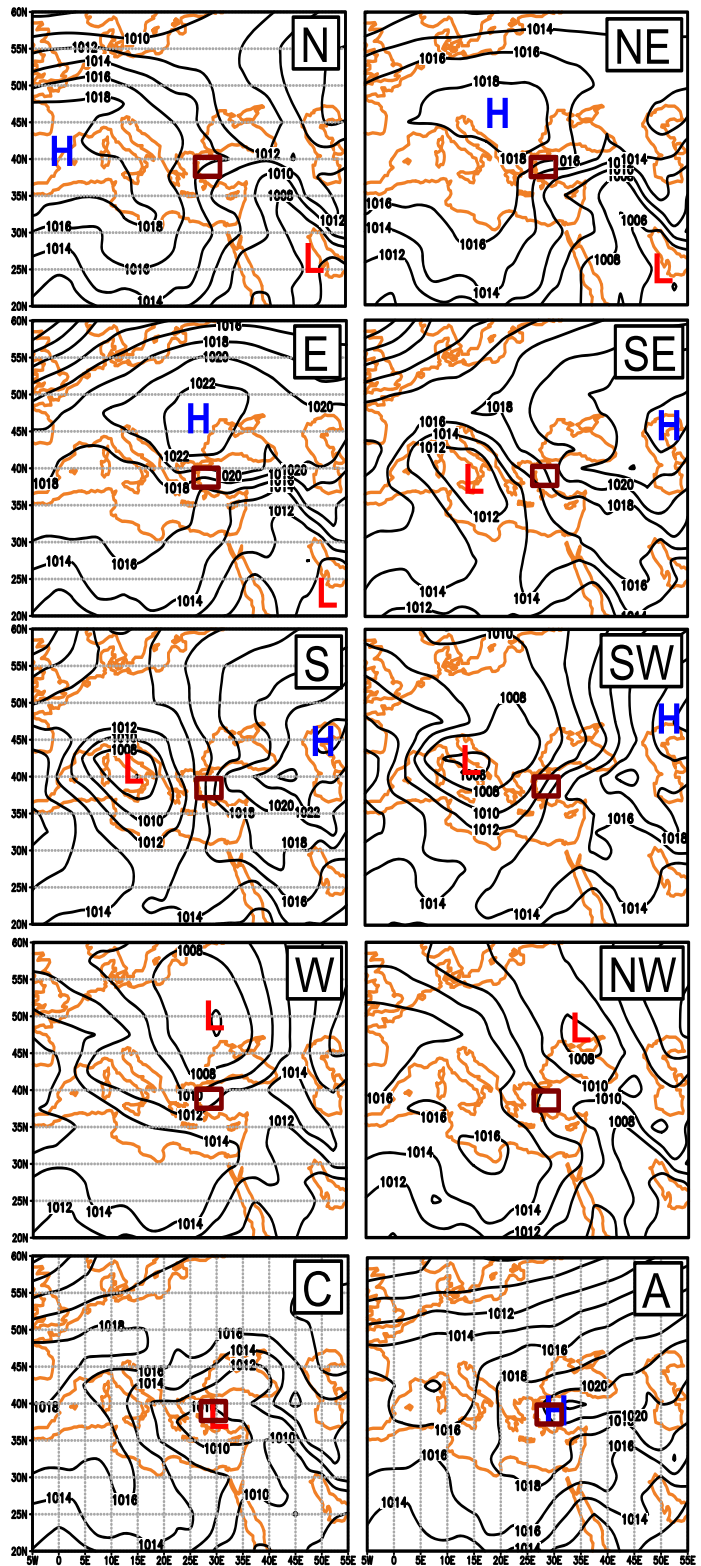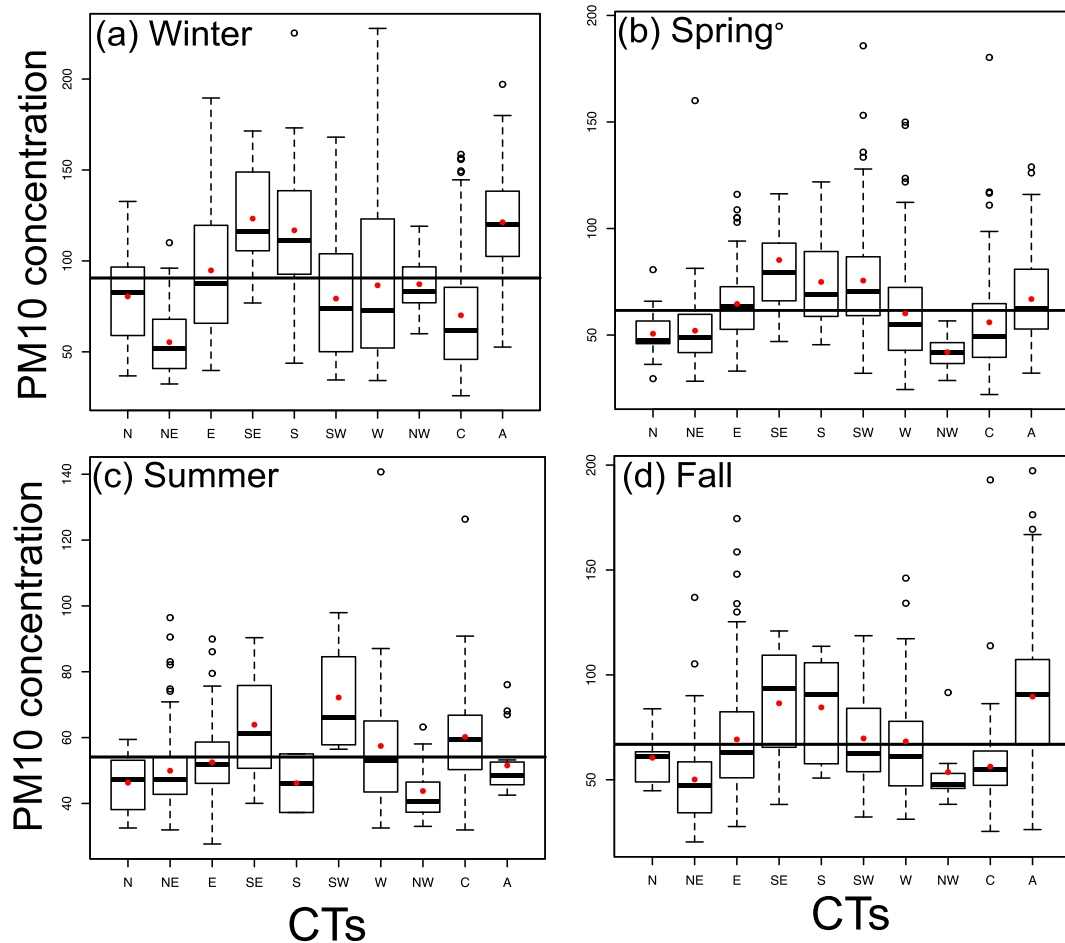
Fig. 6 Box-whisker plots with the concentration of PM_{10} according to the Lamb weather type classes for (a) winter, (b) spring, (c) summer, and (d) fall seasons over the period 2008–2015. The box and whiskers present the median, the first and third quartiles, the minimum and maximum value and possible outliers. Horizontal lines indicate the seasonal mean PM_{10} values of Aegean region for each season. The red dots are the mean PM_{10} values of Aegean region for each season. The red dots are the mean PM_{10} values during each CT. The CTs are the same as in Fig. 3

Northern Africa, the region does not experience high daily PM_{10} concentrations during the SW types. In this type, dusty air particles gain more moisture when passing over the Mediterranean Sea and because of the land-sea interactions, the sea-effect precipitation mechanism generally occurs in the region, which decreases daily PM_{10} concentration below-normal values. In some dry winters for the western Turkey such as in 2008, it was found that the spring dust–season period (MAM) may be extended to late winter or early summer months (FMAMJ).

In addition to PAQ CTs in winter (i.e., E, SE, S, A), the region also suffers from high daily PM_{10} values during the active SW cases in spring (Fig. 6b). Southerly components of these CTs generally bring Saharan dust

to the region, and almost 11% of all spring days result with above-normal PM_{10} values. Differently from the winter months, dry days under these three CTs make the region more polluted owing to having a high particulate matter concentration in these transition months. Due to obvious dust loadings in the spring months, many authors have focused on the synoptic conditions that cause high PM_{10} concentration especially for the western part of Turkey (e.g., Baltaci 2017; Kabatas et al. 2018).

Although minimum daily PM_{10} concentration values are seen in summer; the days with SE, SW, W, and C types generally cause above-normal PM_{10} values in all summer days. From these four CTs, daily EU PM_{10} threshold level exceeded during active all days with SE and SW types (Fig. 6c). During fall, daily mean

PM_{10} concentrations exceed 50 μg m^{-3} in the region as a consequence of the influence of SE, S, and A patterns. On the other side, NE and C types balance poor weather conditions by bringing fresh air (Fig. 6d).

Temporal behavior of PAQ CTs

In order to better understand the interannual variation of PM_{10} concentration associated with PAQ CTs, we extracted total numbers of PAQ CTs for each season, which are explained in "Relationship between atmospheric CTs and PM10," and their contribution to PM_{10} levels for each year (Fig. 7). In winter, the contribution of PAQ CTs on PM_{10} levels is higher than the normals in each year. Additionally, although year 2008 is shown as the highest mean PM_{10} concentration level, the contribution of PAQ CTs on PM_{10} levels is more meaningful in 2011 due to highest frequencies of SE, S, and A types in this year

(Fig. 7a). During spring, if we have more PAQ CTs above 40 days, it is easily shown above-normal PM_{10} records over the region similar to that of years 2009 and 2011 (Fig. 7b). In terms of the summer season, the dominant PAQ CT is cyclonic atmospheric type in each year and if the number of this CT exceeds 10 days in the season, we are getting more daily PM_{10} concentration in the Aegean part of Turkey (Fig. 7c). During fall, PAQ CTs mainly cause higher PM_{10} than normal values in each year and we have more SE, S, and A types in year 2010 (Fig. 7d).

Summary and conclusions

In this paper, after analyzing the monthly and seasonal variations of PM_{10} values for Aegean region (W Turkey) and investigating the influence of local-scale
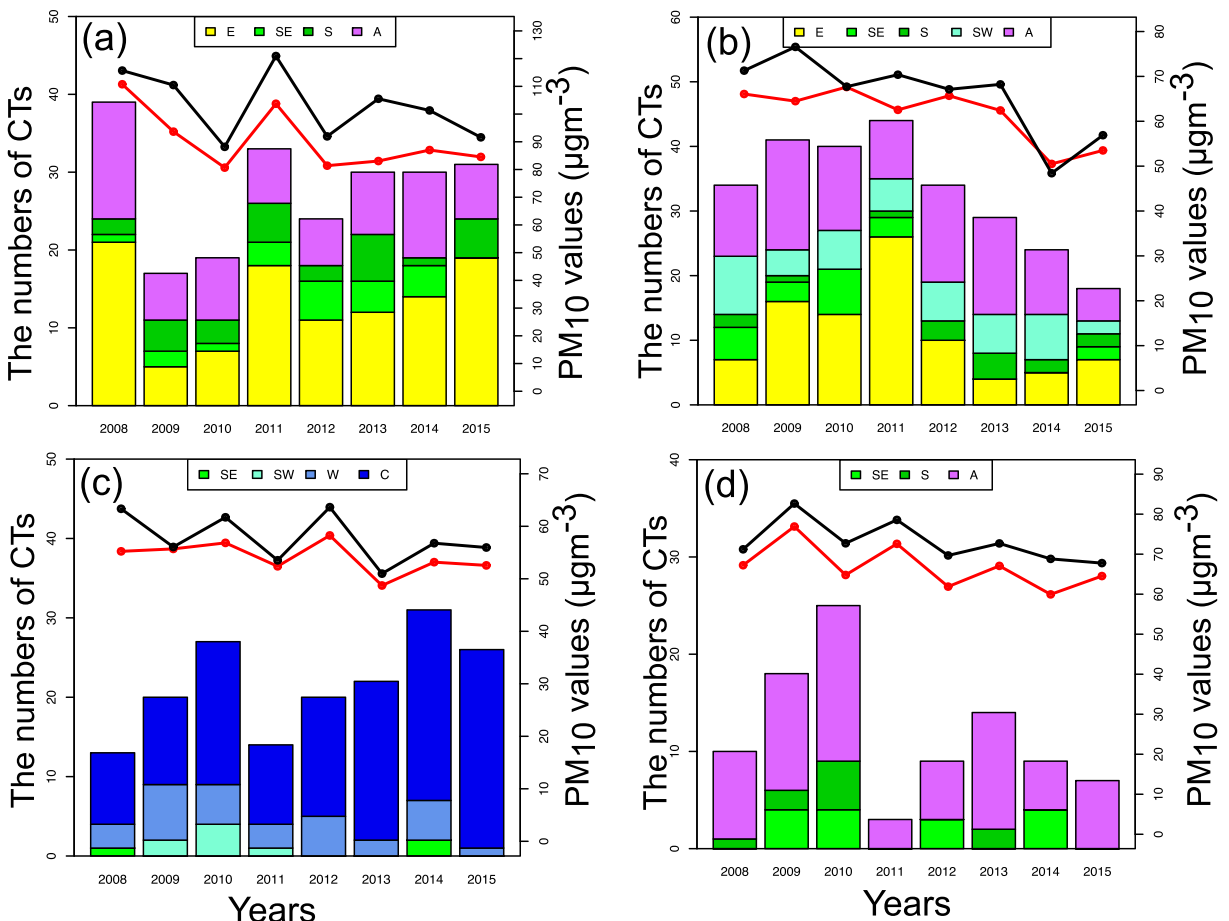

Fig. 7 Temporal variation of the numbers of the PAQ CTs and their contribution to annual PM_{10} values (black lines) for (a) winter, (b) spring, (c) summer, and (d) fall seasons. The red lines indicate the annual mean PM_{10} values from 2008 to 2015

meteorological factors on particulate matter concentrations, we then investigated the impacts of large-scale atmospheric patterns to these particle concentrations. For this circulation-to-environment approach, we firstly classified the atmospheric CTs that influence the Aegean region of Turkey by using Lamb weather type (LWT) methodology on daily mean NCEP/NCAR reanalysis sea level pressure data. Then, we investigated the long-term seasonal relationship between these CTs and PM_{10} variations for the region for the period of 2008–2015. We have utilized station PM_{10} and meteorological data from the Turkish Aegean region, supplied by the Turkish National Air Quality Monitoring Network and the Turkish State Meteorological Service. The main results are as follows.

The region is mainly influenced by the high PM_{10} concentrations during December, January, and November, respectively. On seasonal basis, daily mean high PM_{10} amounts are mainly found during the winter, fall, spring, and summer months with the mean values of 90.6 ($\pm$ 38.3 standard deviation), 66.9 ($\pm$ 28.3), 61.6 ($\pm$ 23.4), and 54.1 ($\pm$ 12.8) $\mu g\,m^{-3}$, respectively. According to the results related to the regional-scale meteorological conditions, a statistically significant negative relation between precipitation and PM_{10} is more obvious during February and December. This implies that, if we expect daily precipitation over the whole regional domain, this atmospheric mechanism causes wet deposition and decreases the daily mean PM_{10} concentrations to the below-normals. In addition, statistically significant positive correlations between temperature and particle matters during the summer months explain the impacts of dry and warm air conditions on the suspended air particles.

According to the regional-scale transport of dust particles, the region has above-normal daily mean PM_{10} values under the influence of SE atmospheric types in all seasons. Despite the less frequent occurrence of this CT during all seasons, the interactions between the LPC over Italy and the HPC over the Caspian Sea cause high dust loadings from Northern Africa to the Aegean region of Turkey in a very short time. In addition to this CT, the E and A types are also important for the region to result in poor air quality during the winter months due to their high incidence rates. During spring, we have shown high particle concentrations in the region as a result of the active southerly components of the CTs (i.e., SE, S, and SW), E and A types. Differently from the winter months, insufficient precipitation from the Mediterranean Sea to the Aegean region of Turkey

during these CTs makes this season important to be shown as dust particle transport from Sahara. In summer, many daily characteristics of SE, SW, and C atmospheric CTs (more than 75% of all these types) cause above-normal particle matter concentrations in the region. While cyclonic atmospheric conditions in winter cause cleaner air in the region than usual due to the precipitation, this CT reduces air quality conditions during summer. The main reason of this mechanism is found as dry deposition processes under this synoptic condition. The penetration of the dry summer Asiatic monsoon to the inner parts of Turkey concludes with high daily temperature records and longer dry spells. During fall, SE, S, and A cases are the dominant patterns that cause poor air quality conditions over the region. Owing to have more common, the A types are more important in this season due to its highest frequencies and all days with anticyclonic types cause above-normal PM10 conditions and exceed the daily PM10 threshold levels.

These results are mainly important for air quality forecasting, and the occurrence of atmospheric CTs associated with high concentrations of atmospheric pollutants can be used as a alert signal to take precautions especially for health problems.

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