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Long-range aerosol transport from Europe to Istanbul, Turkey

T. Kindap[a,c,*], A. Unal[b], S.-H. Chen[c], Y. Hu[b], M.T. Odman[b], M. Karaca[a,d]

[a]*Eurasia Institute of Earth Sciences, Istanbul Technical University, 34469, Turkey*
[b]*School of Civil and Environmental Engineering, Georgia Institute of Technology, USA*
[c]*Department of Land, Air, and Water Resources, University of California, Davis, CA 95616, USA*
[d]*Faculty of Mining, Istanbul Technical University, 34469, Turkey*

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Abstract

Northern and western parts of Turkey frequently experience air pollution episodes. Transport of air pollutants from Europe to these regions has not been studied sufficiently. This study aims to identify and analyze the contribution of long-range aerosol transport to air pollution in the city of Istanbul. Istanbul is the largest urban settlement in Northwestern Turkey, with more than 12 million inhabitants in the metropolitan area.

The methodology developed for the study as well as the results obtained are presented here. Meteorological modeling provided the wind fields that were first used in a trajectory analysis and then, along with other meteorological data, input to an advanced air quality model. Backward trajectories suggested that when the prevailing wind direction is westerly or northwesterly, such as in the case of the episode studied here, a significant fraction of the pollutants emitted from Europe may be transported to and deposited in Turkey. An emission processing module was developed to prepare the emission inputs required by the air quality modeling system. The long-range aerosol transport simulations demonstrated and quantified the source/receptor relationships between Europe and Turkey. For the selected episode, it has been found through model simulations that the responses of Istanbul background PM10 levels to the emissions of individual European countries can range from 0.5 to 13%. The response of Istanbul background PM10 concentrations can be as much as 26% according to the sensitivity analysis results, when anthropogenic emissions throughout Europe are changed by 50%. This result suggests that trans-boundary sources may be responsible for as much as half of the background PM10 in Istanbul.

Keywords: Air pollution; Trans-boundary aerosol transport; Emission processing; PM10

1. Introduction

Long-range transport of air pollutants has generally been studied in Europe under the framework of the European Monitoring and Evaluation Program (EMEP). As the results of these studies show, long-range trans-boundary transport is responsible for a significant fraction of the particulate matter (PM) pollution in European cities as well as in rural areas (EMEP-WMO, 1999). Anthropogenic sources of PM are abundant in Europe because of the heavy industrial activity, the high volumes of traffic and the urbanization of many countries (EMEP/CCC-Report, 1999). Recently, there has been extensive research and several regulations have been issued on

*Corresponding author. Eurasia Institute of Earth Sciences, Istanbul Technical University, Ayazaga Campus, Istanbul, Turkey. Fax: +90 212 2856210.
E-mail address: kindap@itu.edu.tr (T. Kindap).

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PM pollution mainly because of severe public health risks, as well as visibility reduction and damages to sensitive ecosystems in Europe (EPA, 1996; WHO, 1996). On the other hand, more detailed information on chemical and physical properties of aerosols is still needed in order to understand and correctly predict long-range trans-boundary transport of aerosols, their deposition, and their effects on human health (EMEP Report 4/2003).

PM levels, compositions, and physical and thermodynamic properties generally vary with geographic location and seasons (Alpert and Hopke, 1981; Finlayson-Pitts and Pitts, 1986; Seinfeild and Pandis, 1998). Van der Zee et al. (1998) have found that PM10 (PM with aerodynamic diameter less than 10 μm) levels differ by as much as 20% between urban and non-urban areas in Northwestern Europe. Hoek et al. (1997) showed that the difference in PM10 concentrations within countries across Europe appears to be considerably higher than the difference between urban and rural sites. This can be attributed to continuous emissions from a densely populated continent, small weather variability between the measurement sites, and the importance of long-range transport.

Long-range transport of PM has been studied intensively in Southern Scandinavia (e.g., Pakkanen et al., 1996). Air masses originating from the British Isles, Central and Eastern Europe were mainly responsible for the long-range transport of PM to Scandinavia. Lelieveld et al. (2002) have shown that long-range CO transport from both Western and Eastern Europe, mostly from fossil fuel use, constitutes 60–80% of the boundary-layer CO over the Mediterranean. Hacisalihoglu et al. (1992) showed that during a field experiment near the Black Sea, 70% of the mean concentrations of various pollutants have originated from Western and Central Europe. Sciare et al. (2003) found significant aerosol contribution of anthropogenic emissions from Central Europe to the Mediterranean region.

Sometimes unexpected poor air quality is observed in Western and Northwestern Turkey, and these high pollutant levels are suspected to be caused by transport from other countries. Because of the wide range of sources involved, it is very difficult to determine the origins of PM pollution episodes in Northwestern Turkey. However, it has become clear in recent years that the most severe PM episodes are accompanied by westerly winds (Tayanç, et al., 1998). When the flow east of the Carpathian Mountains is channeled over the Black Sea, the Marmara Sea, or the Aegean Sea, Northwestern Turkey is exposed to long-range transport originating from European countries. For example, poor air quality was observed between 5 January and 12 January 2002 in Istanbul. Istanbul is the largest urban center in Northwestern Turkey, with more than 12 million inhabitants in the metropolitan area. According to the observations from monitoring sites operated by the Istanbul Metropolitan Municipality, hourly PM10 levels were in excess of 300 $\mu g\,m^{-3}$ at several locations throughout

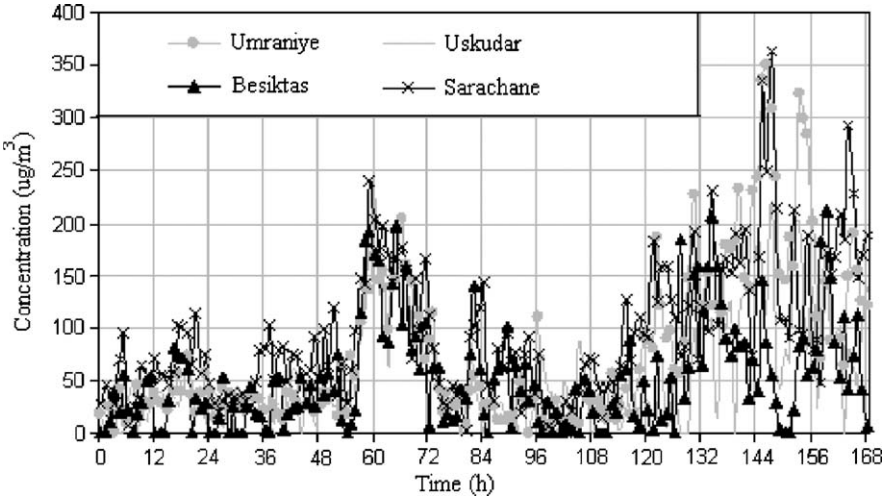


Fig. 1. Time series of measured PM10 concentration at Umraniye, Uskudar, Besiktas, and Sarachane observation stations in Istanbul from 00 UTC 5 January to 00 UTC 12 January 2002. While Umraniye is in an industrial area, Uskudar, Besiktas and Sarachane are roadside stations in urban areas. They are all affected by traffic emissions.

the city on 11 January 2002 (Fig. 1). The winds were predominantly westerly during this period suggesting that long-range transport from Europe might have played an essential role in elevating ambient PM levels of Istanbul.

The objective of this paper is to assess the long-range aerosol transport and provide some quantitative information about the source-receptor relationships between emission throughout Europe and Turkey. Measurements of PM in Turkey did not exist until recently and their possible influence by long-range transport from Europe has not been discussed in the literature. The existing PM10 observations are very limited and they are only for the city of Istanbul. Considering the present knowledge about the long-range aerosol transport for Turkey, which is very limited, this paper aims to fill a gap in our knowledge by investigating the origins of PM, which is the essential information needed for the design of effective emission control strategies.

2. Modeling system

A regional-scale air quality modeling system is adopted in this study, and it consists of three main components: a meteorological model, an emissions processor, and a chemistry/transport model. The meteorological model is the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5; Grell et al., 1994). An emission processing module is developed for this study. The chemistry/transport model is the US/EPA Community Multiscale Air Quality Modeling System (CMAQ; Byun and Ching, 1999). Each model is briefly introduced in the following sections.

2.1. Meteorological model

MM5 is a mesoscale atmospheric model and has been widely used to generate meteorological data for calculations in air pollution studies. Here, a single domain with a horizontal resolution of 50 km is used, and there are 137, 116, 37 grid intervals in the east–west, north–south, and vertical directions, respectively. The chosen model physics options are the RRTM (rapid radiative transfer model) radiation scheme, Kain–Fritsch cumulus parameterization, medium range forecast (MRF) boundary layer parameterization, and simple ice microphysics scheme.

2.2. Emissions processor

The air quality model requires input of speciated emissions values for each grid box over the entire domain at each model time step. When this study was being conducted one of the best available emission inventory for Europe was the 2001 EMEP inventory (2002 emissions became available later) where emissions data are available as annual totals for each European country. For the purpose of air quality modeling the emissions inventory data must be processed to produce gridded, speciated, temporally and vertically distributed values. Here, an emissions processor was developed to carry out these functions. Note that the processing of biogenic emissions was different than the processing of anthropogenic sources since there was no readily available emissions inventory for biogenic emissions.

Anthropogenic emissions impact almost every region on the surface of the earth. Even over central Atlantic and Pacific Oceans, significant contributions to the chemistry from anthropogenic emissions are often observed (e.g., Parrish et al., 1993; Dickerson et al., 1995). Here, we use the gridded European continental anthropogenic emissions inventory (UNECE/EMEP activity data and emission database). This database provides emissions for 10 anthropogenic source sectors at 50-km horizontal resolution over a map produced by polar stereographic projection. The grid used in the air quality model also has a 50-km resolution however it lies on a map produced by a Lambert conformal projection. Therefore, the emissions were mapped from the emissions grid to the air quality model grid. The emission totals are conserved during this gridding operation. Note that at present, a large fraction of the EMEP/CORINAIR (CO-oRdination d'Information Environnementale) emissions inventory is filled with expert information from the main source categories of energy, transport, agriculture, production and processes.

The inventory includes annual anthropogenic emissions of SO_x, NO_x, NH_3, VOCs and PM. In order to be used as input to air quality models total VOC, SO_x and NO_x emissions provided in the inventory must be speciated. We used the source sector specific VOC speciation profile obtained from the United Kingdom speciation given in Photochemical Oxidants Review Group (1993) and SO_x and NO_x speciation provided by EMEP (EMEP/CORINAIR) and USEPA-SMOKE (MCNC,

2000). After speciating the annual emissions (for each grid in our modeling domain) we distributed them temporally to meet the requirements of the air quality model. To do this we utilized the methodology used in MCNC (Microelectronics Center of North Carolina) SMOKE (sparse matrix operator kernel emissions) model. In this method temporal allocation factors for monthly, weekly, weekdays–weekend diurnal variations are determined. Then annual emission data are multiplied with these factors. It should be noted that, source specific temporal factors from United States are used here since no publicly available data for European sectors were found. It is possible that there might be differences between European and American source sectors in terms of temporal allocation.

Finally we vertically distributed the gridded, speciated and temporally distributed emissions. For this we utilized sector specific vertical distributions. These distributions have been based upon plume-rise calculations performed for emission sources considered to be typical for different emission categories, under a range of stability conditions (EMEP Report 1/2003).

In Europe, biogenic and natural emissions can be important. For example, European forest emissions are only a small part of the global total, but even on an annual basis they are significant in the European NMVOC inventory (Simpson et al., 1999). In this study, NMVOC emissions from all types of vegetation have been considered. Currently, biogenic emission data are not available in EMEP gridded emissions inventory. In order to assess biogenic emissions, certain input information is needed. Among the most important parameters are temperature and radiation, which are directly affecting the emission behavior. In addition, detailed information about the distribution and the density of plants, including specific species, is required. For these reasons, a separate methodology is utilized here for biogenic emissions. This method is similar to that in the Biogenic Emissions Inventory System (BEIS3; Vukovich & Pierce, 2002), and includes land use data and estimation of hourly emissions taking into account the meteorological data (e.g., temperature and solar radiation) and speciation. For the processing of biogenic emissions, the biogenic land use files for emission processor are obtained from MM5 land use data for Europe. These data were provided by the US Geological Survey (USGS) including 24 different categories for land-use and vegetation. Methodology developed by Guenther (1996) is utilized for calculation of biogenic emissions along with the revised algorithms and improvements of Simpson et al. (1999). In our study, the spatial domain is the entire Europe with parts of Asia, Africa and the Atlantic Ocean with a resolution of 5 min. It is well known that the uncertainties in the determination of biogenic emissions, especially with such coarse resolution, are very large. The daily total isoprene emissions calculated by the emissions processor for Turkey is approximately 600 mg for a winter episode. Finally, biogenic emissions are merged with the already processed anthropogenic emissions and, together, they are input to the air quality model.

2.3. Air quality model

The PM10 size distribution in CMAQ is represented by the superposition of three lognormal modes: the nucleation and accumulation modes for particles under the diameter of 2.5 μm (PM2.5) and a coarse mode. PM2.5 consists of sulfate, nitrate, ammonium, elemental carbon, organic carbon and soil components; the coarse mode includes sea-salt and dust. The aerosol dynamical processes considered include primary emissions, new particle formation by nucleation, particle growth, coagulation, evaporation/condensation, dry deposition and scavenging by clouds. Chemical reactions form secondary PM such as sulfate, nitrate, ammonium and organic compounds.

The CMAQ horizontal grid size is also set to 50 km with 132 cells along the east–west direction and 111 cells in the north–south direction covering all of Europe. There are 20 layers in the vertical direction; these layers are identical to those used in MM5 simulations. Because of the insufficient observational data, the initial and boundary conditions are set to background concentrations starting from 00:00 UTC 5 January 2002 for the entire simulation. The same initial and boundary conditions are used in the changed emissions simulations conducted to analyze sensitivities.

3. Model simulations

We ran MM5 to generate meteorological data and the emissions processor to generate emission data. Then these data were input to CMAQ which, in turn, performed pollutant transport and chemical

transformation, to simulate a winter episode in Europe. The National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) data (with 2.5° by 2.5° resolution) were used for MM5 boundary and initial conditions. The model integrated seven days starting from 0000 UTC 5 January 2002. To reduce the error due to time interpolation in the air quality model, hourly data were produced for use in CMAQ. The emissions processor was configured as described above and a base case simulation was performed with CMAQ using the emissions inputs produced by the emissions processor. To understand where pollutants might be coming from, we used MM5 results to calculate backward trajectories. Air trajectories ending in Istanbul were tracked backward towards their origin starting from the times when peak values of PM10 occurred in Istanbul (i.e., 7 January and 10 January 2002; Fig. 1). To further prove our hypothesis that pollutants might propagate from other metropolitan areas and industrial centers in Europe and enhance background levels of PM10 in Istanbul during high-pollution episodes, we conducted a series of CMAQ model runs where we targeted the impact of emissions from specific source areas. In each simulation, we increased or reduced emissions of individual countries and sub-regions by 50%. This approach allows for the quantifications of transport from specific sources to the receptor area of interest (Odman et al., 2002). It enables us to determine the response of Istanbul PM10 to 50% increase/decrease in anthropogenic emissions from specified country/region (Table 1).

4. Results and discussions

4.1. Meteorological model results

An air quality model uses meteorological data, such as winds, moisture, and temperature, to calculate transport, mixing, and chemical reactions. Therefore, the accuracy of meteorological model outputs strongly affects the performance of air quality simulations. Fig. 2 shows observed and MM5 simulated 10-m winds and 2-m temperatures at Gokceada and Malkara meteorological stations, which are located 220 km southwest and 160 km west of Istanbul, respectively. Comparison shows that simulated winds are in agreement with observations at Gokceada station during the simulation period except on 7 January when winds are relatively calm. For Malkara, the wind direction is about 30°–60° off and the largest differences from observations occur again on 7 January. Compared to simulated winds, simulated 2-m temperatures are in better agreement with observations. MM5 is able to catch the trend of temperature changes, including diurnal cycles, except on 7 January. In general, 2-m temperatures at Gokceada station are better simulated than at Malkara. With the exception of 7 January, the results of the MM5 simulation are in good agreement with observations.

Fig. 3 shows model simulation results and The European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis at 1200 UTC 10 January 2002. Compared with ECMWF reanalysis, MM5 reproduces reasonably well the horizontal distribution of the sea level pressure, temperature

Table 1
Simulated Istanbul PM10 response to 50% change in anthropogenic emissions during 5–12 January 2002. Sensitivity analysis results give quantitative information about the impact of each country or the entire region to Istanbul

Country	Total emission[a] (2001)	Istanbul PM10 response to 50% increase		Istanbul PM10 response to 50% decrease	
	(Gg)	Ave (%)	Max (%)	Ave (%)	Max (%)
Bulgaria	2016	2	7	−2	8
Romania	4566	4	13	−4	−13
Poland	7104	1.5	7	−1.6	−9
Ukraine	5703	1.5	8	−1.8	−10
Russia	20,066	0.5	8	−0.5	−7
Region[b]		12	24	−9	−26
Region[b] and Turkey		45	50	−46	−50

[a]Total emissions, according to EMEP data base, of CO, NH_3, NO_x, SO_x, NMVOC and PM.

[b]Region includes Greece, Bulgaria, Romania, Poland, Ukraine, Russia, Hungary, Slovakia, Moldova, Belarus, Lithuania, Latvia and Estonia.

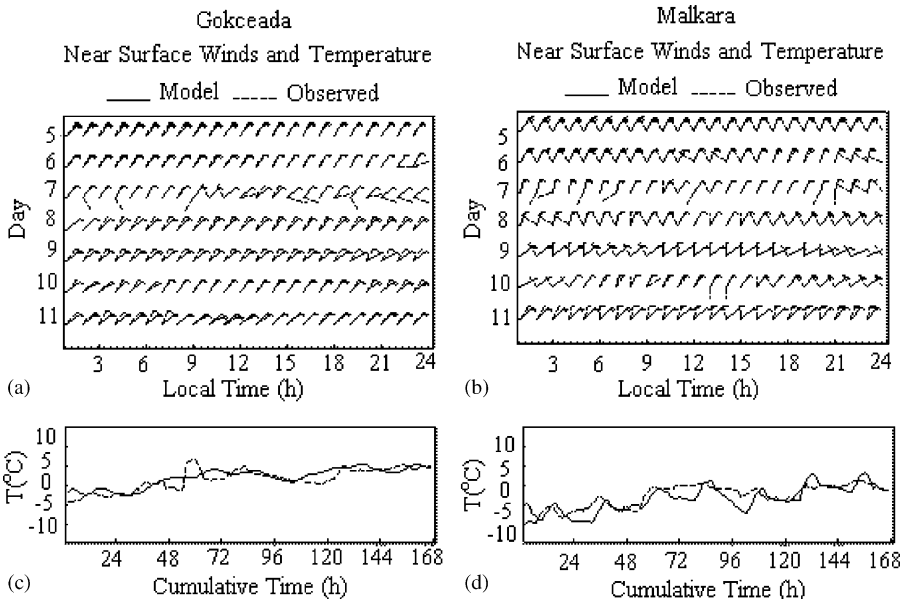


Fig. 2. Observed (dashed lines) and MM5 simulated (solid lines) 10-m winds (a full barb equals 10 knots and a half barb equals 5 knots) and 2-m temperatures (°C) for (a) Gokceada and (b) Malkara meteorology stations from 00 UTC 5 January to 00 UTC 12 January 2002.

and winds at 850 mb, and geopotential heights and horizontal winds at 500 mb. However, there are some minor discrepancies. Model simulated 850 mb temperature is slightly warmer than ECMWF reanalysis over central Europe and cooler over the ocean and west coastal Europe. The simulated 500 mb cyclonic circulations over northeast Europe are weaker than those of the analysis. Although the model used coarse resolution to match the resolution of the emission inventory (50 km), the meteorological model is capable of producing realistic meteorological data which is essential for any air quality model application.

4.2. Backward trajectory results

Fig. 4a shows 36-h backward trajectories ending at Istanbul on 0000 UTC 8 January, which roughly corresponds to the first peak in Fig. 1. Fig. 4b shows 48-h backward trajectories from 0000 UTC 11 January 2002, which corresponds to the second peak in Fig. 1. Starting from the ground level in the vicinity of Istanbul, backward trajectories had less than a 1-km height at the end of each simulation. These trajectories indicate the possibility of long-range transport from west, northwest, and north of Europe to Turkey. This result supports our hypothesis that long-range transport from north and northwest of Turkey may play an important role in the high pollution episodes experienced in Istanbul during the month of January 2002.

4.3. Air quality model results

Model simulated PM10 concentration are compared with those measured at four stations in Istanbul (Fig. 5). Note that while the trend is captured reasonably well there is more than an order of magnitude difference between the simulated and observed concentrations. Comparisons of modeled PM10 to observations at two stations in Athens, Greece also showed large differences in magnitude. The primary reason for the large underestimation here is most likely coarse grid resolution. The first model layer above the ground is 92 m and the horizontal resolution is 50 km. This coarse resolution can substantially dilute the concentration of pollutants. On the other hand, all the stations in Fig. 5 are in areas of high PM10 concentrations and concentration gradients. Sarachane, Besiktas and Uskudar stations are in densely populated urban areas and the Umraniye station is in an industrial area. In addition, they are all roadside stations affected by traffic emissions. Therefore the measurements are not representative of even the PM10 levels surrounding the stations and they should certainly not be compared to the simulated concentrations, which represent averages

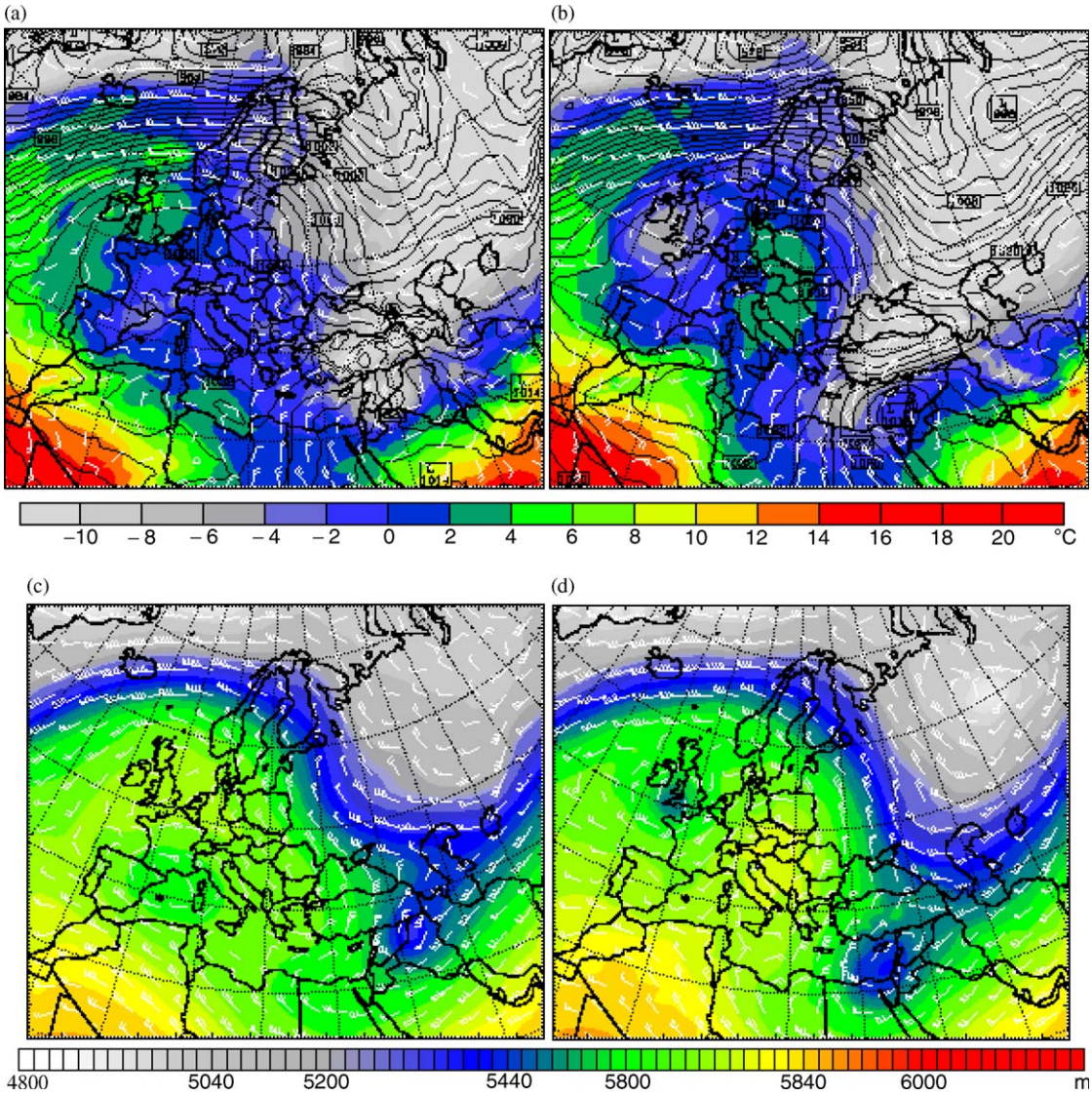
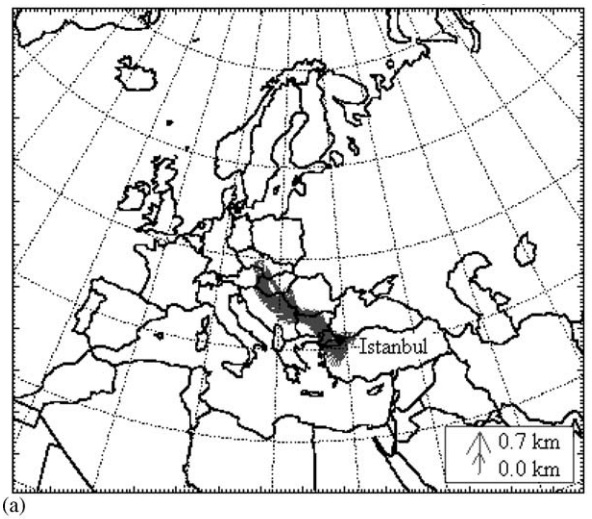
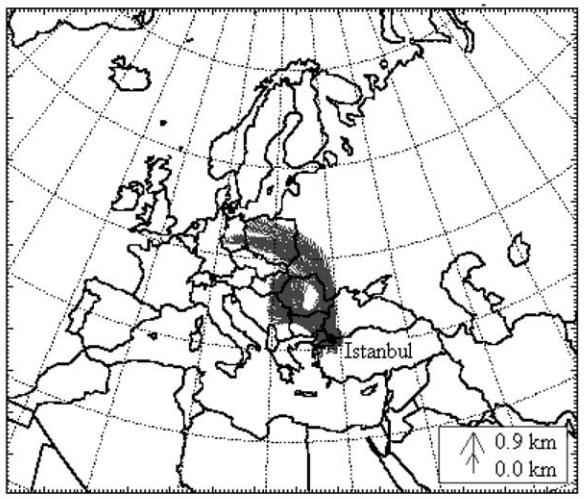


Fig. 3. MM5 model simulated sea level pressure, 850 mb temperature and horizontal wind vector in panel (a) and ECMWF analysis in panel (b). MM5 model simulated 500 mb geopotential height and horizontal wind vector in panel (c) and ECMWF analysis in panel (d).

for the $50 \times 50\,km^2$ area covered by a grid cell. The simulated concentrations are more representative of the background PM10 concentrations. Another reason for the order-of-magnitude difference between the observed and simulated concentrations may be the lack of treatment for resuspended dust in the CMAQ model. In reality, resuspended dust may be a significant contributor to Istanbul's PM10 levels. The discrepancies may also be due to the deficiencies in EMEP emission data. The annual emission inventory data are based on data reported from the European countries, and these data are filled with experts' estimates when they are incomplete or inconsistent. Such interpretations may introduce errors. Furthermore, biogenic emissions are absent in EMEP database. In addition, the use of 2001 emission data (instead of 2002 data, which were not available) in combination with a January 2002 meteorological episode resulted in added uncertainty when comparing the CMAQ model results to monitoring data. Note that speciation for PM10 is still not available in EMEP datasets therefore we cannot compare modeled PM10 components to observations. For the most part, CMAQ correctly reproduces the trends in observed PM10 values for Istanbul. For example, the model



(a)



(b)

Fig. 4. Two sets of model-generated backward trajectories starting at the ground level in the vicinity of Istanbul: (a) 36-h backward trajectories starting at 0000 UTC 8 January 2002 and (b) 48-h backward trajectories starting at 0000 UTC 11 January 2002. The boxes which are on the right corner in each panel indicate the initial and final heights of the trajectories. All trajectories are within 1-km altitude.

is able to catch the relatively high-pollution episodes on 7 January and 10 January.

4.4. Sensitivity analysis results

The backward trajectory analysis has shown the possible sources of PM10 transported to Turkey. To simulate the background PM10 response to local and transported emissions, we have re-run CMAQ with changed anthropogenic emission data. Note that we are speaking of a simulated response and not an actual response here. First, a change of 50% was applied to regional anthropogenic emissions to see the contribution of transport. Here, what we refer to as the "region" includes Bulgaria, Romania, Poland, Ukraine, Russia, Hungary, Slovakia, Moldova, Belarus, Lithuania, Latvia and Estonia. Then, in addition to the emissions of the aforementioned region, anthropogenic emissions from Turkey were also changed by 50% so that the difference of this case from the previous one can tell the response of Istanbul background PM10 concentrations to local emissions. Finally, anthropogenic emissions of major contributors to PM10 in the Istanbul area (Romania, Bulgaria, Poland, Ukraine and Russia) were also changed individually to further examine transport on an individual country basis. Table 1 shows the difference in PM10 concentrations between the increased or decreased emissions run and the base case run. This difference is the response of Istanbul PM10 levels to the change in emissions. Note that the biogenic emissions are the same in all simulations.

The results show that the largest and most consistent response during the simulation period (Fig. 6a) occurred when, among the countries, emissions originating from Romania were changed. Dark gray background color in Fig. 6 shows differences in terms of the PM10 levels in Istanbul between the base-case and the case of 50% increased emissions. During the simulation period, increased emissions from Romania augmented the PM10 concentrations in Istanbul by as much as 13%. The average increase for the entire simulation is 4%. As for the 50% emission reduction scenario, the same levels of change have been observed as a decrease (Table 1). Emissions of Bulgaria were also observed to create a consistent response in Istanbul PM10 (Fig. 6b). The maximum response of Istanbul PM10 to a 50% increase in emissions from Bulgaria is an increase of 7%. The simulation average response is 2%. Similar results can be seen in Fig. 6c for Poland, but not as much as Romania. During the simulation period, changing the emissions of Poland by 50% could yield as much as 7% increase and 9% decrease in Istanbul PM10 levels. The same increase and reduction scenarios were performed for Ukraine emissions. Maximum impact was observed to be 8% increase or 10% decrease. While the average impact of increased Ukraine emissions to Istanbul PM10 was a 1.5% increase, 1.8% decrease was observed for the reduction

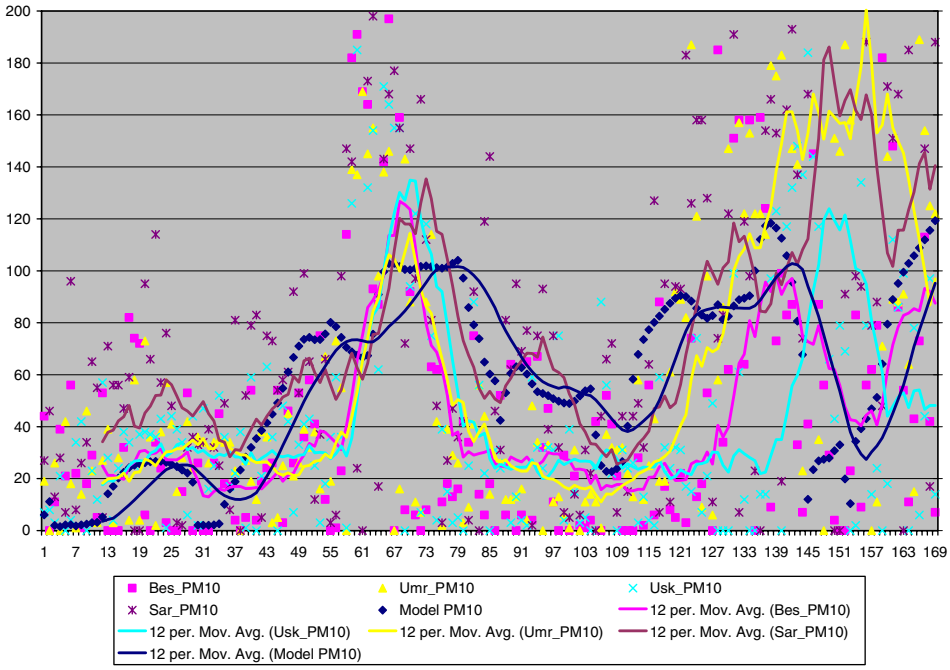


Fig. 5. Observed PM10 concentrations (left axis) at Besiktas (■), Umraniye (▲), Uskudar (×) and Sarachane (∗) and model simulated concentrations (right axis) for the $50 \times 50\,km^2$ Istanbul cell (♦) and 12-h trend lines of all concentrations from 00 UTC 5 January to 00 UTC 12 January 2002.

scenario. In contrast to Romania, Bulgaria and Poland, the response to Ukraine emissions was not continuous and became significant in discrete time periods (Fig. 6d). Russia has the biggest emission potential in Europe. It has approximately 1129 Gg annual total PM10 emissions (UNECE/EMEP). Total value of Russian emissions is bigger than the total emissions of Bulgaria, Romania, Poland and Ukraine combined (Table 1). However, when all of its anthropogenic emissions were changed by 50%, the impact of Russian emissions to the PM10 levels in Istanbul did not exceed plus or minus 8%. Furthermore, these effects could only be observed for a short time period during the late hours of 8 January (Fig. 6e).

Both observations and results of base-case CMAQ model have demonstrated two different instances of poor air quality over Istanbul. The first one was observed on 7 January and the second one was observed on 10 January. During the first high pollution period, sensitivity analysis attributed a PM10 response of 2% to Ukraine, 4% to Bulgaria, 7% to Poland and 10% to Romania emissions (namely, to a 50% change in those emissions). As for the second high pollution period, the response of Istanbul PM10 is 1% to Ukraine and Russia, 3% to Poland, 7% to Bulgaria and 13% to Romania anthropogenic emissions. Factors such as total annual emissions, dominant transport modes and distances traveled determine the relative impacts. Bulgaria has the smallest total emission among these countries but its contributions are quite significant. Romania's annual total emissions are approximately twice as large as those of Bulgaria, but they are still small when compared to Poland or Russian emissions (Table 1). Clearly, the proximity of Bulgaria or Romania helps the transport of significant amounts of aerosols to North-western Turkey and Istanbul. On the other hand, since the emission potential also bears significance, the impact of Ukraine and Poland aerosol transport also become important in spite of the far distances. It is worth noting that, besides country locations and potential emissions, dominant atmospheric dynamics play a significant role in determining ambient air quality in Istanbul. While Russia has the biggest potential emissions and is at close proximity to Northern Turkey, Russian emissions influenced Istanbul PM10 only for a short period. Similarly, Greece is very close to the area but its impact was negligible during the simulation period, therefore it was not shown.

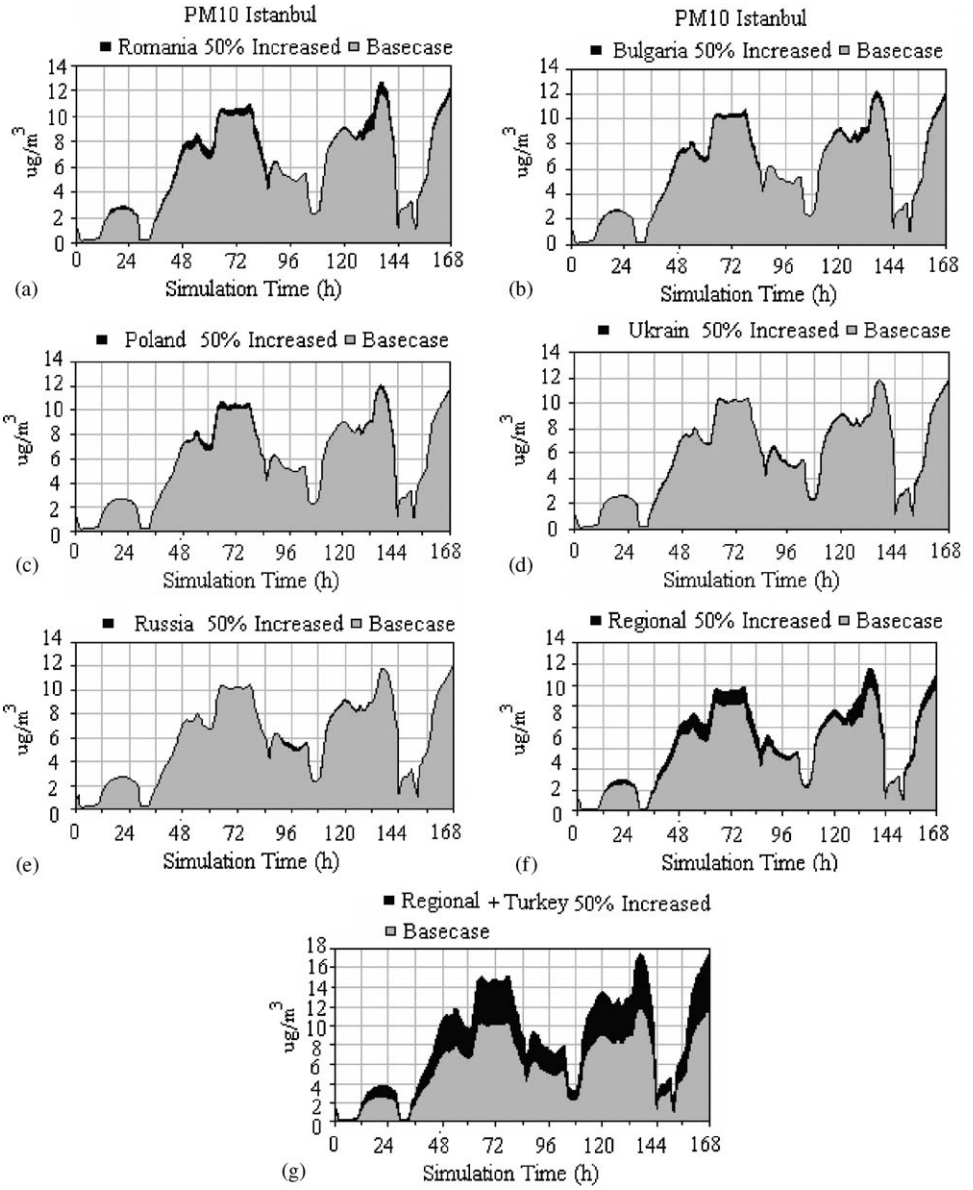


Fig. 6. Evolution of simulated PM10 concentration in Istanbul, Turkey. The frames are experiments with an increase of 50% anthropogenic emission for: (a) Romania, (b) Bulgaria, (c) Poland, (d) Ukraine, (e) Russia, (f) the "Religion" and (g) the Region plus Turkey. The light gray area indicates the PM10 result from the base case and the dark gray area indicates the difference of each experiment from base case.

Regional sensitivity analyses were also carried out for the same period which covered the entire Eastern Europe. Besides Romania, Bulgaria, Poland, Ukraine and Russia; Hungary, Slovakia, Moldova, Belarus, Lithuania, Latvia and Estonia were added for regional analyses (Fig. 6f). First, a continuous response of Istanbul PM10 attracted our attention. Naturally, the quantity of the response changed from time to time but, 12% average increase and 9% average decrease were observed over Istanbul as a result of 50% increase and decrease in regional emissions. The results of the analyses could reach up to 24% increase and 26% decrease of PM10 for the Istanbul grid cell during the simulations. The maximum increase occurred between 10:00 and 13:00 on 7 January (58–61 h in Fig. 6f) and at 13:00 on 10 January (133 h in Fig. 6f). Finally, in addition to those from Eastern

Europe, emissions from Turkey have also been taken into consideration (Fig. 6g). Turkey, with its large population and industrial activities, is a big source for its own air pollution. Annual emissions of PM10 from Turkey are estimated to be 420 Gg (UNECE/EMEP). Combined with transport from Europe to Northern and western Turkey, national emissions might create inevitable poor air quality from time to time. When Turkish and Eastern European emissions were changed by 50% the average increase and decrease observed during the simulation were 45% and 46%, respectively (Fig. 6g). About 90% of PM10 estimates in Istanbul are associated with primary emissions (crustal material and other PM10 such as road dust). Only 10% of PM10 is secondary and is associated with sulfate formation from SO_2 emissions through reaction with the OH radical both in gas and aqueous phases. This leads to the apparent linear behavior of PM10 in response to changes in emissions.

5. Conclusions

In this study, we investigated the trans-boundary particulate matter transport from Eastern European countries to Turkey. This type of study had never been carried out before for Turkey. In addition to difficulties involved with setting and running atmospheric models in a new region, emission modeling alone has been the most challenging task. A new emission processing module has been developed for this study.

At the beginning of the study, trans-boundary pollution was hypothesized to be an important problem for Northwestern Turkey. The study demonstrated that the impact of Eastern European emissions to PM10 concentrations in Istanbul may be significant under certain meteorological conditions. First, trajectory analysis showed that episodes with relatively high concentrations of PM10 in Istanbul are accompanied by northwesterly winds indicating the effects of especially Eastern European countries. Then, sensitivity analysis showed that, during the simulation period, aerosol transport from Europe to Northern and Western Turkey is seen all the time when the region is considered as a whole. Although this transport accounts for a small percentage of Istanbul PM10 levels on average, at times it can constitute about one quarter of Istanbul's PM pollution during the simulated period. As a result, when air pollution of the Northern or Western Turkey is evaluated, the contribution of long-range transport from Europe must be kept in mind.

Together with the back-trajectory study and the sensitivity analysis, origins, and quantities of the PM10 impacts were investigated. Furthermore, assuming linear response, the contribution of each country/region can be estimated as two times the response to 50% emission changes modeled in this study. As a result, one can say that the contribution of these countries can be responsible for as much as half of the Istanbul background PM10 levels under certain meteorological conditions.

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