Exploring the applicability of future air quality predictions based on synoptic system forecasts

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Abstract

For a given emissions inventory, the general levels of air pollutants and the spatial distribution of their concentrations are determined by the physiochemical state of the atmosphere. Apart from the the trivial seasonal and daily cycles, most of the variability is associated with the atmospheric synoptic scale. A simple methodology for assessing future levels of air pollutants' concentrations based on synoptic forecasts is presented. At short time scales the methodology is comparable and slightly better than persistence and seasonal forecasts at categorical classification of pollution levels. It's utility is shown for air quality studies at the long time scale of a changing climate scenario, where seasonality and persistence cannot be used. It is demonstrated that the air quality variability due to changes in the pollution emissions can be expected to be much larger than that associated with the effects of climatic changes.
Capsule: Air quality in a changing climate scenario can be studied using air pollution predictions based on synoptic system forecasts.

Keywords: Air quality management, Climate change, Synoptic classification

1. Introduction

Numerous chemicals introduced into the atmosphere by natural and anthropogenic sources have harmful effects on living organisms and may damage different aspects of the environment through various processes on many time scales (Seinfeld and Pandis, 1998). The adverse effects of air pollutants on human health are well known (e.g., World Health Organization, 2006; Pope et al., 1995; Schwartz and Dockery, 1992) and short term prediction of their concentrations is important in cases where they may reach deleterious levels. Long term predictions of air quality are important for better management of the air resources and for estimations of their possible long term impacts on the public's health and on the environment (Vallero, 2007).

Ambient air quality is closely linked to the prevailing weather conditions (Seinfeld and Pandis, 1998). Most of the meteorological variables depend to a large extent on the dominating atmospheric configuration at the synoptic scale and thus the synoptic patterns are associated with the quality of the air (Ganor et al., 2010; Chen et al., 2008; Cheng et al., 2007a; Tanner and

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Law, 2002; Triantafyllou, 2001). The link between the prevailing meteorology and the quality of the air is at many levels. At the small spatial scales, the wind's direction determines where local emissions will go. The local wind speed and the nature of the atmospheric stratification determine a pollutant's dispersion around the main advection axis. Local sun radiation intensity (function of cloud cover), temperature and humidity determine the rates of chemical reactions and transformations affecting the emissions. Large scale atmospheric flows dictate transboundary transport of pollutants, with their composition usually strongly affected by aging processes (Vallero, 2007). Al these meteorological conditions depend to a large extent on the type of synoptic system dominating a region and thus, the synoptic systems provide very useful information for predicting the air quality. The effects of local factors like topography, urbanisation and sea breeze cannot be neglected though, and they are superimposed on the synoptic scale conditions (Tanner and Law, 2002; Triantafyllou, 2001). The synoptic system dominating a region at a certain time is usually defined using the regional pressure and temperature fields, which are described by data observations (Pearce et al., 2011; Cheng et al., 2007a; Alpert et al., 2004). For that purpose, point–wise data can be processed and classified by a completely automated mathematical scheme (Pearce et al., 2011; Cheng et al. , 2007a), or by a manual or semi–automatic procedure based on a training set of spatial maps classified by experts (Alpert et al., 2004).

Due to the complexity of the processes governing air quality, air pollution prediction is a tough challenge. The difficulties lie in the complication of atmospheric photochemistry and the uncertainties due to the inaccuracies in emission inventories, in addition to the uncertainties associated with the forecast of the atmospheric state. Even the state of the art of chemical transport models require integration of data observations in order to achieve reasonable outputs for short term predictions (Carmichael et al., 2008). Moreover, use of chemical transport models becomes computationally prohibitive for studies at the very long time scales.

This study presents a very simple alternative methodology for assessing future air pollutant levels, based on forecasted synoptic systems. The use of photochemical model is obviated but the trade off may be a reduced accuracy. The method does compare well with the simple seasonal and persistence forecasts benchmark methods for short term predictions. However, unlike these benchmarks it can be utilised for studying the long term impacts of climatic changes on future air quality, based on existing climate model outputs.

2. Data

A 16 years database (1991-2006) of daily classification to synoptic systems of the 12:00 UTC eastern Mediterranean NCEP data was developed and provided by Alpert et al. (2004). A corresponding database for 1950-2099 was also provided based on the ECHAM4/OPYC3 global climate model output (Roeckner et al., 1996, Chou et al., 2006). The ECHAM4/OPYC3 is a coupled ocean–atmosphere model. Its control run until 1990 was based on the observed CO_2 and other greenhouse gasses emissions. Since 1990, the model was run according to input adapted from the IPCC Special Report on Emissions Scenarios scenario B2, where dynamics of technological changes continue along the historical trends (IPCC, 2007). The synoptic system classification is based on a semi–objective classification of geopotential height, temperature and the horizontal wind components at the the 1000 hPa level. Alpert et al. (2004) defined 19 synoptic systems characteristic to the eastern Mediterranean, which can be lumped into six groups. The systems names and their group affiliations are given in Table 1.

The air quality data were observed by the air quality monitoring networks in the Haifa, Gush Dan and the southern coast areas of Israel (Fig. 1). The network in Haifa consists of 20 stations.

Deployment of the monitoring network commenced during 1985 but the number of stations has stabilised only since 2002. This study considers the 2002-2006 data of SO_2, NO_2, O_3, and PM_{10} for most of the stations, and the 1997-2006 data for the Nave Shaanan station, which has longer records for all the pollutants. The Gush Dan network consists of 22 stations. Monitoring started in this region in the mid 1990s and the 1995-2006 data of SO_2, NO_2, O_3, and $PM_{2.5}$ are used in this study. The southern Israeli coast is covered by a network of 24 stations. The 2000-2006 data of SO_2, NO_2, O_3, and $PM_{2.5}$ are used in this study. Every monitoring station usually observes only a subset of the pollutants. Many of the stations also observe at least one of the following meteorological variables: wind speed and direction, temperature, relative humidity and pressure. The observed data in all cases are half–hourly mean values. This work considers the daily 12:00 UTC air pollution data so that they are compatible with the 12:00 UTC synoptic systems classification.

3. Methods

Consider a set of classifications of the atmospheric states in a region to synoptic system types, carried out for a certain characterising period. Using this set and the corresponding observed air quality data, synoptic pollution coefficients P_{ij} can be calculated for each pollutant at any monitoring location in the region as follows,

$$P_{ij} = \frac{1}{N_j} \sum_{k=1}^{N_j} C_{ik}, \tag{1}$$

where C_{ik} is the sample of the pollutant's observed concentrations at the N_j time points when one of the $i = 1, \ldots, M$ recognised synoptic systems appeared in a calendarian month j during the characterising period. In principle, a coefficient for each system could be produced for the whole characterising period (i.e., one coefficient for each system) but the refinement to monthly resolution is usually very beneficial. The pollution coefficients can also be characterised by a different statistic of the sample of C_{ik}, e.g. using its median instead of the mean. In this study the classification to the $M = 19$ eastern Mediterranean synoptic system of Alpert et al. (2004) is used, based on the daily 12:00 UTC NCEP data. A similar classification process can be carried out for the output of a numerical weather prediction (NWP) model at its native resolution or at any other lower resolution. Such a classification can be also carried out for a climate model output that was run for periods in the past for which air pollution observations exist. Due to the dominance of the daily cycle in pollutant concentrations variability, in all cases the air pollution concentrations C_{ik} should be the ones observed at hours corresponding to the time of the day for which the synoptic classification is produced (i.e., if the classifications are for 12:00 UTC, C_{ik} should be air pollution data observed at 12:00 UTC or some statistic of the observed data around this hour). It must also be emphasised that P_{ij} pertains to the specific location of the air pollutant observations. That way the local conditions that impact the air pollution levels (e.g., topography, emission sources, etc.) are taken into account.

Each pollutant is thus characterised at each monitoring location by an Mx12 matrix of coefficients for each time of the day for which forecasts are desired. Forecasts for the pollutant's concentrations at a given time point can be produced by assigning it a value from the relevant matrix of pollution coefficients, given the synoptic system forecasted for this time point and the calendarian month in which it falls. In the case of an NWP, the air quality forecast are for the selected hours of the day during the forecasting horizon of the NWP. In the case of a climate model, air quality forecasts can be produced for the full forecasting period of the model. Clearly, in the case of a climate model the air quality at the specific time points is of no importance. However, statistics of the pollutant concentrations during long climate model forecast periods (say, years or decades) can be calculated and studied. Changes in the frequency of appearance of the synoptic systems captured by the model will manifest themselves as variations in the air pollutant concentrations. Assuming current emissions or any emissions trend in the forecasting model, this may provide some hints regarding the future air quality variations in the monitoring location.

The lower and upper uncertainty level in the air pollution forecasts can be expressed as,

$$P_{ij} - \alpha(P_{ij} - P_{ij}^{min}), \tag{2}$$

and

$$P_{ij} + \beta(P_{ij}^{max} - P_{ij}), \tag{3}$$

where P_{ij}^{min} and P_{ij}^{max} are the minimum and maximum of the sample C_{ik}, respectively, and α and β are coefficients in the range [0 1] that can be selected according to the desired confidence level. Alternatively, low and high percentile values of the set C_{ik} can serve as the lower and upper limits of the prediction. The most suitable statistics to define the system coefficients and their limits may vary between pollutants and regions. They can be determined by a cross–validation process in which the level of risk is set in advance by the selection of the α and β parameters or the values of the limiting percentiles. For this study, we used the mean value (defined in eq. 1) as a system coefficient, and low and high percentiles for uncertainties. It must be noted that these uncertainty calculations assume an air pollution emission scenario similar to the one during the characterising period. The unknown future variations in the pollution emissions are not accounted for in this work and the possible implications are discussed later.

The process described above of forecasting a pollutant's concentration and its uncertainty range, based on the synoptic system classification, can be carried out for a few monitoring stations in a region. This step involves very little additional work and costs, and it results in spatial maps of the forecasted pollution levels and their uncertainties.

4. Results

4.1. Air pollution characteristics of the synoptic systems

Alpert et al (2004) discuss in length the meteorological characteristics associated with the synoptic systems experienced in the eastern Mediterranean. Figure 2 shows the characteristic air pollution concentrations associated with the different synoptic systems, calculated for station Tachana Merkazit in Tel Aviv. The mean, and the 10% and 90% percentiles of the concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$ are presented. As mentioned in the Methods section, it is beneficial to calculate these characteristic concentrations, or pollution coefficients, separately for each calendarian months but for brevity's sake, only the full year coefficients are shown here. In some cases there are clear differences between the pollution coefficients of the different synoptic systems and between the system groups. For example, the SO_2 concentrations associated with systems 1-3, the Red Sea Troughs, are much higher than those of systems 4-6 of the Persian Trough group. However, the range between the 10th and 90th percentile values can be very wide and there is some overlap between the ranges of all four pollutants, for almost all the systems.

Each synoptic system is associated with a certain typical wind direction that determines the main axis of air pollution dispersion and thus, to a certain extent, its spatial concentration pattern.

(The levels of the concentrations are mainly determined by the typical wind speed, atmospheric stratification conditions and the atmospheric chemistry rates.) Figure 3 shows maps of the spatial patterns of the mean SO_2 concentrations in the Haifa bay area for a representative system from each of the six synoptic system groups. The representative systems were selected as the most prevalent in their corresponding groups. The only significant SO_2 sources in the region are the oil refinery and the power plant, located at its centre (see Fig. 3). When the region is dominated by the Persian Trough and the High to the West systems, the typical winds are from the northwest. As a result, the mean SO_2 concentrations during these systems (Figs. 3a and 3b, respectively) are highest southeast of the SO_2 sources. The High to the North and the Sharav Low systems (Figs. 3c and 3d, respectively) are usually associated with easterly winds. When these systems dominate the eastern Mediterranean, Haifa stations that observe high SO_2 concentration are mostly to the west of the SO_2 sources. The Cyprus Low to the North and the Red Sea Trough with an Eastern Axis are cyclonic systems that result in wind in the general westerly direction (varying according to its stage). The SO_2 spatial pattern associated with them (Figs. 3e and 3f) is of high values east of the sources and low values west of them. The conditions typical to each system have impact on the spatial distributions of all the other pollutants as well but as these pollutants have many local and scattered sources (e.g. traffic), the differences between the associated spatial patterns are not as clear.

4.2. Short term air pollution prediction

An example of a short term air quality prediction by the proposed method is shown in Fig. 4. In each of the plots the 12:00 $PM_{2.5}$ true concentrations in station Tachana Merkazit in Tel Aviv during 1 December 2005 to 28 February 2006 are shown along with the method's predictions and their specified uncertainties. The predictions in this case are based on the mean values of the concentration samples for each synoptic system (eq. 1). The uncertainty limits shown in Figs. 4a, 4b and 4c span the 5-95, 10-90 and 25-75 percentiles for each synoptic system, respectively. Naturally, as the uncertainty limits narrow they include less of the real values within their bounds. Eighty five, 75 and 55 out of the 88 valid real data shown in Figs. 4a, 4b and 4c, respectively, are within the uncertainty bounds. The large uncertainties shown in Fig. 4 imply that the prediction skills of the proposed method cannot be expected to be very high. It is important therefore to verify that the predictions are comparable to those achieved by common benchmarks.

The two benchmark methods we consider are the seasonal and persistence forecast methods. The seasonal forecast assigns the pollutant concentration prediction at a certain day to be the mean value of the air pollution concentration sample observed at its calendarian day during all the years in the study period. Due to the relatively small number of years in the available time series (and thus a small number of time points to calculate each calendarian mean), our calculation included data of the relevant calendarian day and its adjacent six days (e.g., the calendarian mean of 15 January at 12:00 was calculated using the time points on January 12-18 at 12:00 in all the years in the study period). A second benchmark, may be the simplest one, is the persistence forecast. This method assigns as the forecasted pollution concentration the observed concentration in some previous day, according to the desired forecast lag time. In spite of its simplicity, persistence has a very strong prediction power and was found more powerful predictor of air pollution than any meteorological variable by Lam and Cheng (1998).

Figure 5 provides a comparison between the performance of the proposed method and the two benchmarks. As a performance measure we use the Success Rate (SR), defined as the number of times, out of the total number of predictions, that the forecast is within the correct categorical level of the concentration range of the pollutant. We define for this purpose the Low, Medium and High SR levels to be delimited by the tertiles of the concentration ranges of each pollutant in each station. The SR is thus the ratio between the number of times that a forecasting scheme predicts a value within the correct concentration range to the total number of predictions. Values of the SR fall within zero (complete failure) and one (complete success). The comparison in Fig. 5 is for the SO_2, NO_2, O_3 and $PM_{2.5}$ daily 12:00 concentrations in the Gush Dan stations. For a more comprehensive review of the proposed method's performance compared to the benchmarks, Table 2 provides the number of stations for which the method achieved the highest SR in each of the monitoring networks along the Israeli coast. Table 2 also provides the corresponding number of times that the proposed method achieved the highest Pearson correlation coefficient. Examining Fig. 5 and Table 2, it can be concluded that the proposed method have a small, but clear advantage, compared to the benchmarks, especially in the NO_2 and $PM_{2.5}$ forecasts. It is interesting to note that the additional information that the synoptic system forecast provide does result in some advantage compared to the simpler methods. However, given the additional efforts it requires, the advantage of the proposed method seems marginal for the short term predictions and adopting this method for routine air quality forecasts might not be warranted.

4.3. Application for future climate air quality assessment

Figure 6 shows the predicted annual mean anomalies (residuals after subtracting the mean) of concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$ for the years 1997-2099, based on synoptic system classification of the ECHAM4/OPYC3 model output and the pollution coefficients calculated for stations Nave Shaanan in Haifa and Tachana Merkazit in Tel Aviv. Using anomalies of the concentrations enables plotting the two forecasts on the same scale (there are significant differences in the mean pollution levels between the two stations) and better appreciation of the magnitude of the long term variability. The annual variability is relatively small, with an amplitude of about 1 $\mu g/m^3$ for all the pollutant series. The amplitude of the variations in the SO_2 in Nave Shaanan is much larger than that in Tachana Merkazit. The location of Nave Shaanan is very close to the local SO_2 sources (see Fig. 3), and being situated on a mountain slope at the elevation of the stacks leads to large variations in the SO_2 concentrations during different synoptic systems. Commensurate amplitudes of the annual variations in the two stations exist for all the other pollutants.

The correlation between the two forecasts are 0.77, 0.44, 0.40 and 0.85 for SO_2, NO_2, O_3 and $PM_{2.5}$, respectively. The $PM_{2.5}$ levels in Israel are dominated by transboundary transport of sulphates and nitrates from eastern Europe, and by dust particles from the surrounding deserts (Erel et al., 2007). The spatial variability of $PM_{2.5}$ and the associated variability in the $PM_{2.5}$ pollution coefficients are thus small and result in similar long term $PM_{2.5}$ forecast in the two stations. Most of the SO_2 in Israel is due to large industrial plants, emitting quite constantly 24 hours a day. The temporal variations in the SO_2 concentrations are therefore mainly due to the variability in the meteorological conditions which are characteristic to different synoptic systems. Thus, the correlation between the SO_2 forecasts for the two locations is also relatively high. The lower correlation between the forecasts of NO_2 and O_3 is probably due to the fact that the concentrations of these two pollutants depend mainly on the NO_x and VOCs emissions of the local traffic. Variations in the traffic emissions as a result of changes in the traffic patterns and volumes, the weekly cycle, due to holidays, etc. are clearly not related to the dominating synoptic system. This results in differences between the NO_2 and O_3 pollution coefficients calculated for different stations for each synoptic system, and to different temporal variability patterns in the long term forecasts.

An example of the possible importance of long term forecasts is given in Fig. 7. The figure shows the 1997-2099 anomalies of the yearly $PM_{2.5}$ concentrations in Haifa, considering only days which were assigned synoptic system belonging to one of two special groups. One group includes systems 4, 5, 6 and 8, which transport to Israel $PM_{2.5}$, mainly sulphates and nitrates, from eastern Europe. The second group consists of systems 2, 12, 13, 18 and 19, which transport to Israel mineral dust from northern Africa. The shown values are the anomalies from the annual means, with the means calculated taking only the concentration values during days when the mentioned synoptic system groups were present (other days assigned zero value). No clear trend is noted in the levels of the dust–related PM during the 103 years period. However, the levels of $PM_{2.5}$ transported from eastern Europe is increasing with a linear trend that results in additional 2 $\mu g/m^3$ during this period. Given that eastern Europe transport is a major contributor to the $PM_{2.5}$ burden in Israel (Asaf et al., 2008; Erel et al., 2007), this is an important and interesting finding, suggesting that local control measures to reduce PM emissions may not be sufficient to abate the future $PM_{2.5}$ in Israel.

5. Discussion and conclusions

This study proposes a very simple method for assessing the future air quality in a location for which historical air pollution records and a corresponding set of classifications of the weather to synoptic systems are available. The method was shown to be comparable, and slightly better than the seasonal and one–day–lag persistence forecasts in a three air pollution networks along the Israeli Mediterranean coast. By its nature, persistence cannot be used for long term air quality forecasts and seasonal forecasting is not useful for studies which consider possible climatological changes. Given an output of a climate model for the region, the method proposed by this work enables studying future air quality in a changing climate scenario. The climate change effect is incorporated in the variations in the frequency of the appearance of the various synoptic patterns. This assessment can serve as an alternative to the more complicated and expensive approach of using chemical transport air pollution schemes driven by climate models (Jacob and Winner, 2009). However, a major drawback of the proposed approach is its use of constant pollutant coefficients. Moreover, the accuracy of our assessment depends to a large degree on the ability of the climate model to produce synoptic systems similar to the real ones, and with frequencies which are similar to the observed ones.

The accuracy of the proposed method is a concern in its application for forecasting long term trends in the air quality. However, a much larger concern is the caveat hidden in the assumption of current air pollution emission levels while calculating the pollution coefficients. The last few decades have seen variations in air pollution emissions in the developed world (happily, mainly decreasing trends) whose impact on the air quality probably dwarfs the possible variations due to different prevalence of the synoptic systems in the future. For example, SO_2 levels in Haifa, Israel, were reduced by more than an order of magnitude in the last 20 years and are expected to drop to almost zero level once the local power plant and refineries switchover from use of fuel oil to natural gas. VOC levels in most developed countries experienced a similar drop (Dollard et al., 2007) and will probably be further reduced with the on–going improvements in private vehicle emission controls. The introduction of electric cars will bring about a decrease in both VOCs and NO_x emissions and thus also in the O_3 levels. The increased use of non–combustive energy production sources and better emission controls on industrial plants will result in a decrease in PM, NO_x and O_3.

Figure 8 shows a comparison between the real annual average 1997-2006 concentrations of SO_2, NO_2, O_3 and $PM_{2.5}$ in Nave Shaanan, Haifa, and the hindcasting by the proposed method. The synoptic system pollution coefficients were calculated using the data during the whole observation period and are thus providing information on that period's mean levels. This results in hindcasts for these pollutants which are almost nonvariant in time, in contrast to the very significant trends in the local SO_2, NO_2 and O_3 levels. The sources of $PM_{2.5}$ in Haifa, much of it desert dust and transported sulphates and nitrates from eastern Europe, have not significantly changed during 1997-2006. However, even for this pollutant the hindcast is not close to the real record, probably due to insufficient accuracy in capturing the yearly variations in the synoptic system occurrence by the climate model. Cheng et al. (2007b) assumed three different scenarios of air pollution emissions in their assessment of climatic impact on air quality however, there is no guarantee that any of these scenarios will materialise. Future air pollutants emissions are an unknown but given the examples shown in Fig. 8, it is very probable that their variations will have a larger impact on future air pollution levels compared to the relatively small variations expected due to any reasonable variations in the occurrence of synoptic systems in a changing world climate.

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Table 1: A list of the synoptic systems, their synoptic system group affiliations and the seasons in which they are most frequent. The synoptic systems definitions and the group affiliation follow Alpert et al. (2004).

System No.	System Name	Group	Season
1	Red Sea Trough with the Eastern axis	Read Sea Trough	Autumn/Winter
2	Red Sea Trough with the Western axis	Read Sea Trough	Autumn/Winter
3	Red Sea Trough with the Central axis	Read Sea Trough	Autumn/Winter
4	Persian Trough (Weak)	Persian Trough	Summer
5	Persian Trough (Medium)	Persian Trough	Summer
6	Persian Trough (Deep)	Persian Trough	Summer
7	High to the East	Siberian High	Winter
8	High to the West	Subtropical High	Spring/Summer
9	High to the North	Siberian High	Winter
10	High over Israel (Central)	Siberian High	Winter
11	Low to the East (Deep)	Cyprus Low	Winter
12	Cyprus Low to the South (Deep)	Cyprus Low	Winter
13	Cyprus Low to the South (Shallow)	Cyprus Low	Winter
14	Cyprus Low to the North (Deep)	Cyprus Low	Winter
15	Cyprus Low to the North (Shallow)	Cyprus Low	Winter
16	Cold Low to the West	Cyprus Low	Winter
17	Low to the East (Shallow)	Cyprus Low	Winter
18	Sharav Low to the West	Sharav Low	Spring
19	Sharav Low over Israel (Central)	Sharav Low	Spring

Table 2: The number of times the synoptic classification method performed best compared to the two benchmark forecasting methods in three of the air pollution networks along the Israeli coast. The performance is tested for four common pollutants and is measured by the success rate of forecasting the correct categorical level (Low/Medium/High) of the pollution, and by the correlation coefficient between the true and predicted concentration values. The numbers in parentheses are the numbers of monitors of the pollutant in the network.

	SO_2	NO_2	O_3	PM[a]
Success rate				
Haifa	3 (20)	7 (10)	7 (9)	9 (9)
Gush Dan	0 (18)	17 (18)	6 (10)	8 (8)
South coast	7 (24)	17 (22)	13 (17)	7 (9)
Correlation				
Haifa	17 (20)	9 (10)	6 (9)	7 (9)
Gush Dan	10 (18)	16 (18)	10 (10)	7 (8)
South coast	24 (24)	22 (22)	7 (17)	9 (9)

[a] PM_{10} in Haifa and $PM_{2.5}$ in Gush Dan and the southern coast.

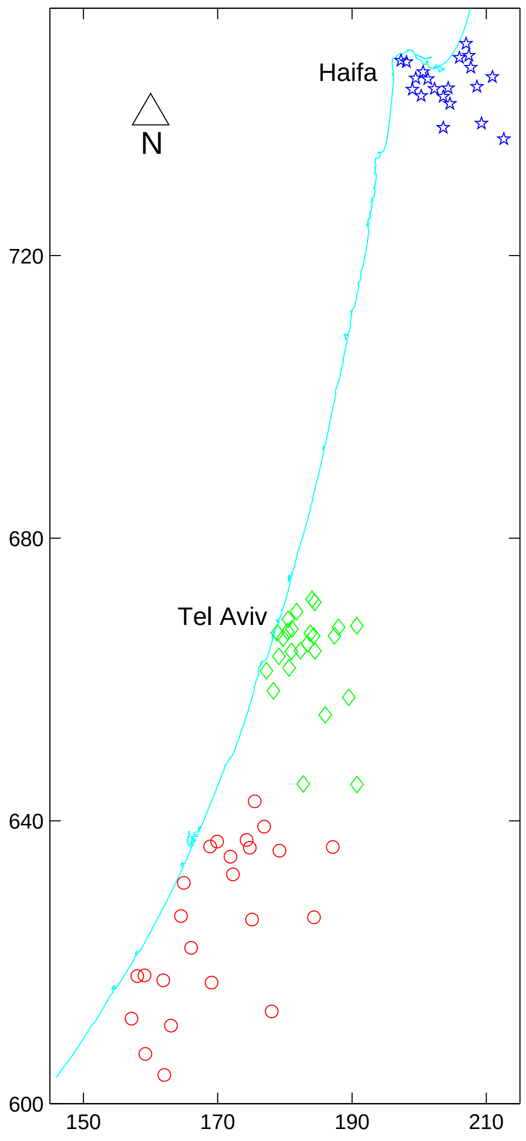

Figure 1: A map showing the location of the monitoring stations. Stations in Haifa are marked with pentagrams, station in Gush Dan are marked by diamonds and station in the southern coast are marked by circles. The coordinates are in kilometres in the New Israel Grid system.

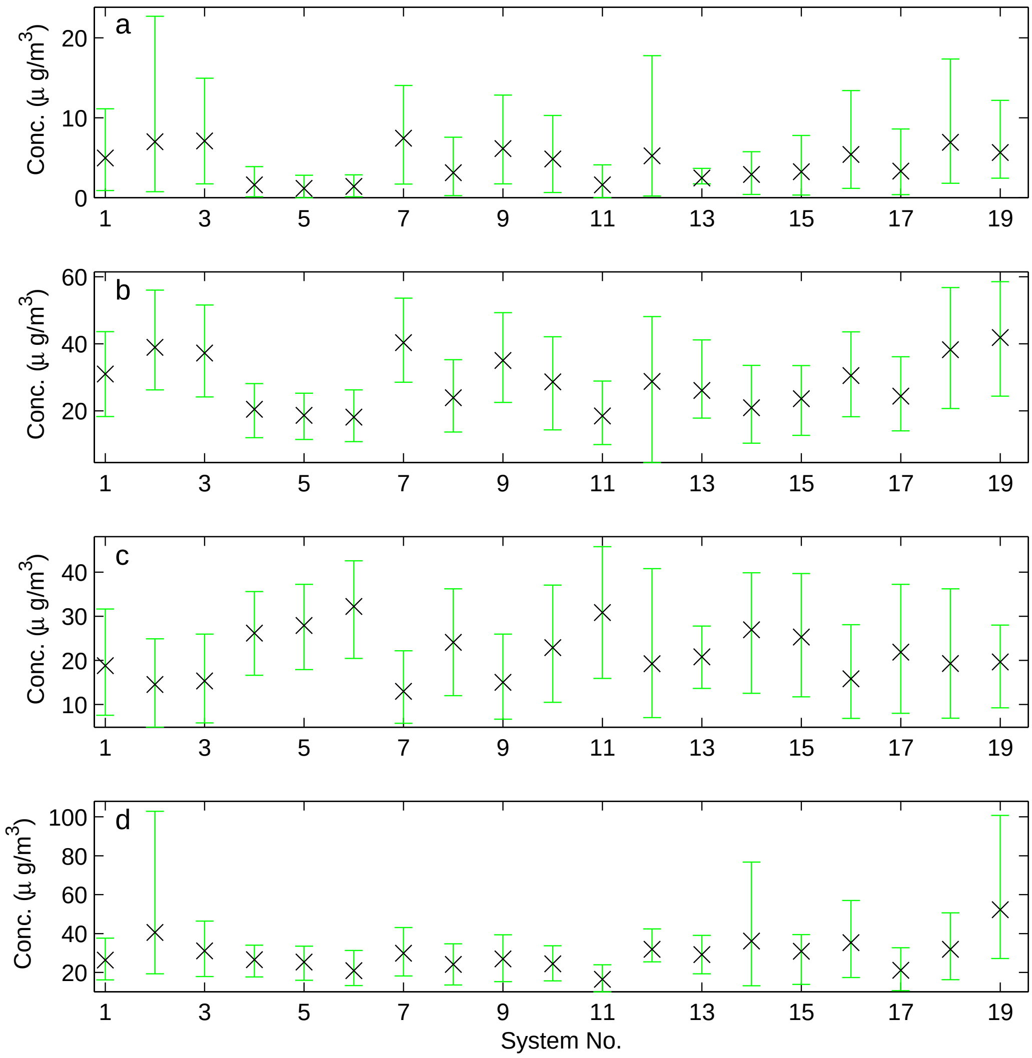

Figure 2: The annual mean and the 10% and 90% percentiles of the pollutant concentrations for each of the eastern Mediterranean synoptic systems in station Tachana Merkazit in Tel Aviv, Israel. (a) SO_2 (b) NO_2 (c) O_3 (d) $PM_{2.5}$.

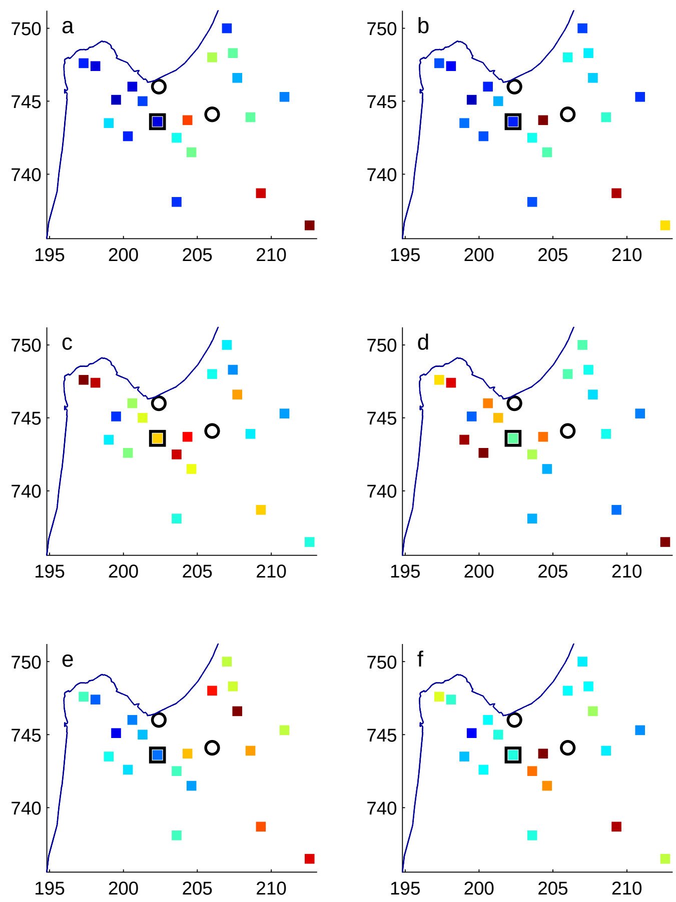

Figure 3: Maps of the spatial distribution of the mean 2002-2006 SO_2 concentration values in the Haifa region during the most prevalent system in each of the six synoptic system groups. The colour coded concentrations are normalised such that their range is zero to one (deep blue to cyan to red to brown, respectively). The continuous blue line is the shoreline. The two circles denote the locations of the oil refinery and the power plant which are the major SO_2 sources in the region. Station Nave Shaanan is marked with a thick black frame. (a) Persian Trough (Weak), (b) High to the West, (c) High to the North, (d) Sharav Low over Israel (Central), (e) Cyprus Low to the North (Shallow), and (f) Red Sea Trough with an Eastern axis.

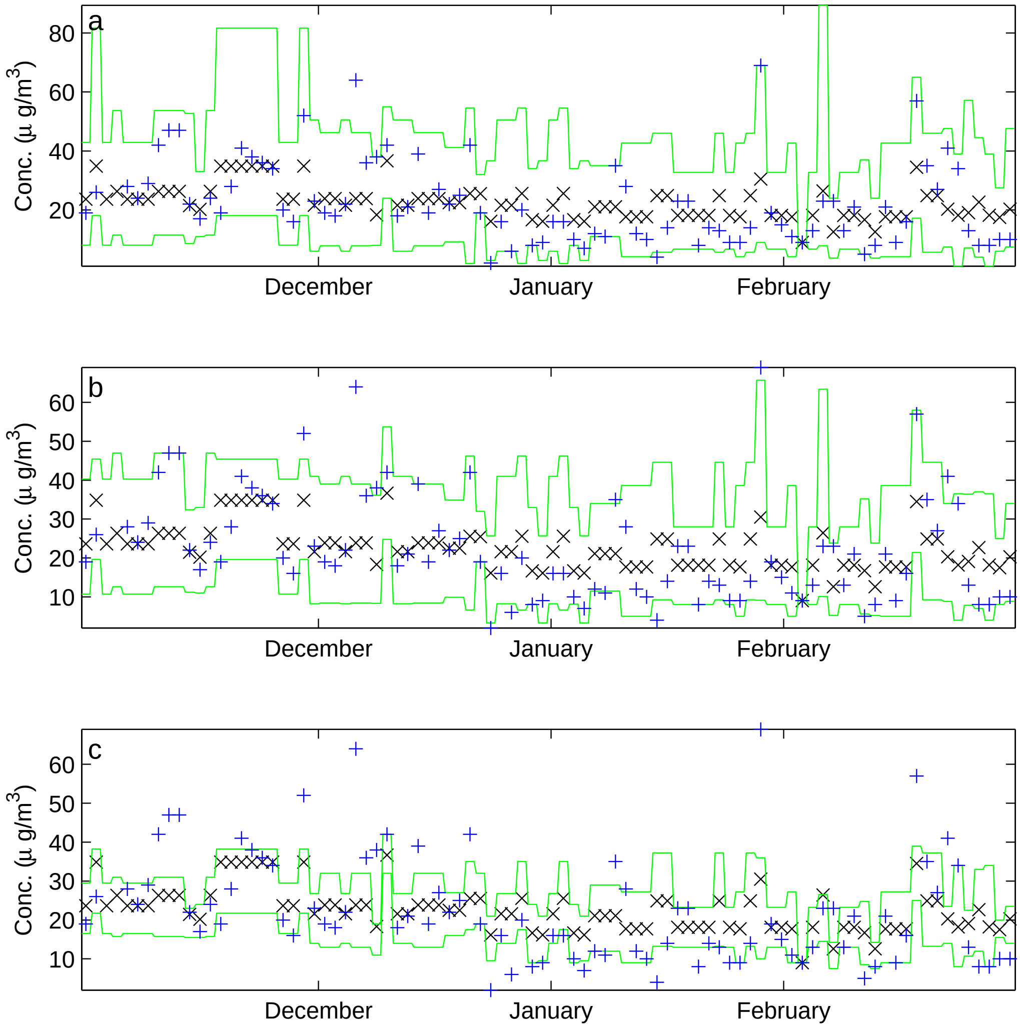

Figure 4: Daily prediction of $PM_{2.5}$ concentrations in Tachana Merkazit station, Tel Aviv, during winter 2005/2006 and their uncertainties. True values are denoted by a +, the predictions by an x and the uncertainties are denoted by the solid line envelope. (a) Uncertainties are the 5th and 95th percentile values. (b) Uncertainties are the 10th and the 90th percentile values. (c) Uncertainties are the 25th and the 75th percentile values. The uncertainty envelope includes 85, 75 and 55 of the 88 true valid values in (a), (b) and (c), respectively.

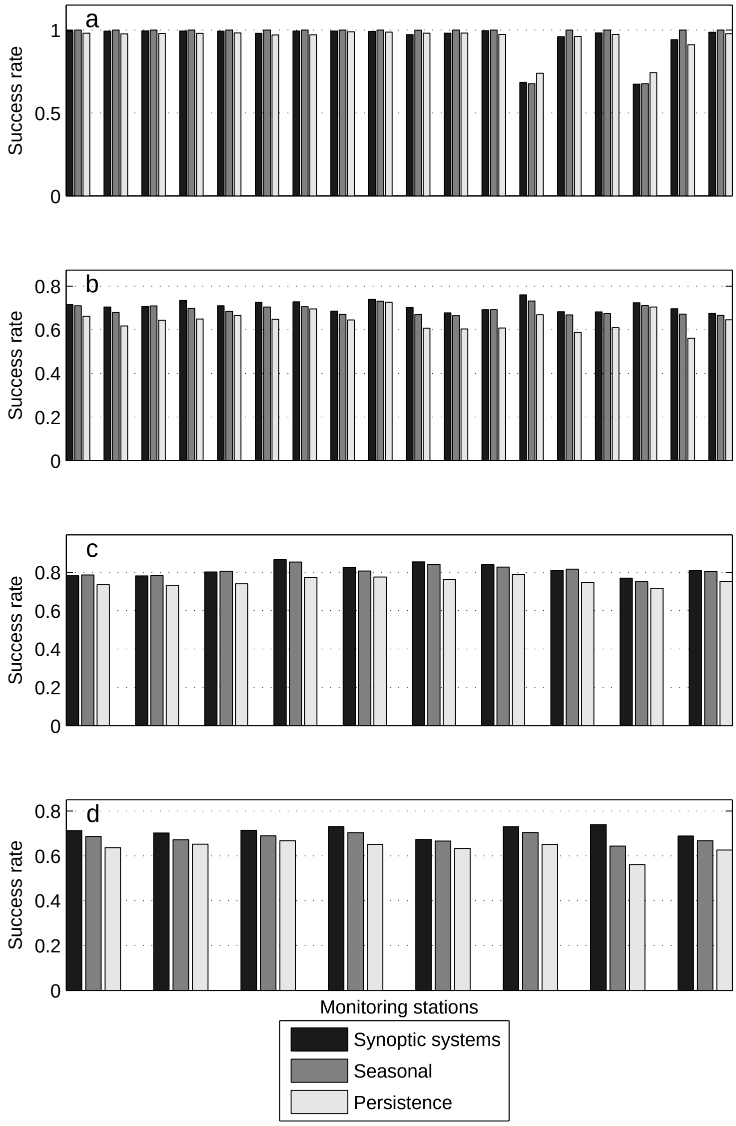

Figure 5: The success rate at predicting the correct categorical level (Low/Medium/High) of the true daily 12:00 pollution concentration by the synoptic system forecast, seasonal forecast and persistence with one day lag. The observations are from the stations in the Gush Dan network during the study period 1995-2006. (a) SO_2, (b) NO_2, (c) O_3, (d) $PM_{2.5}$.

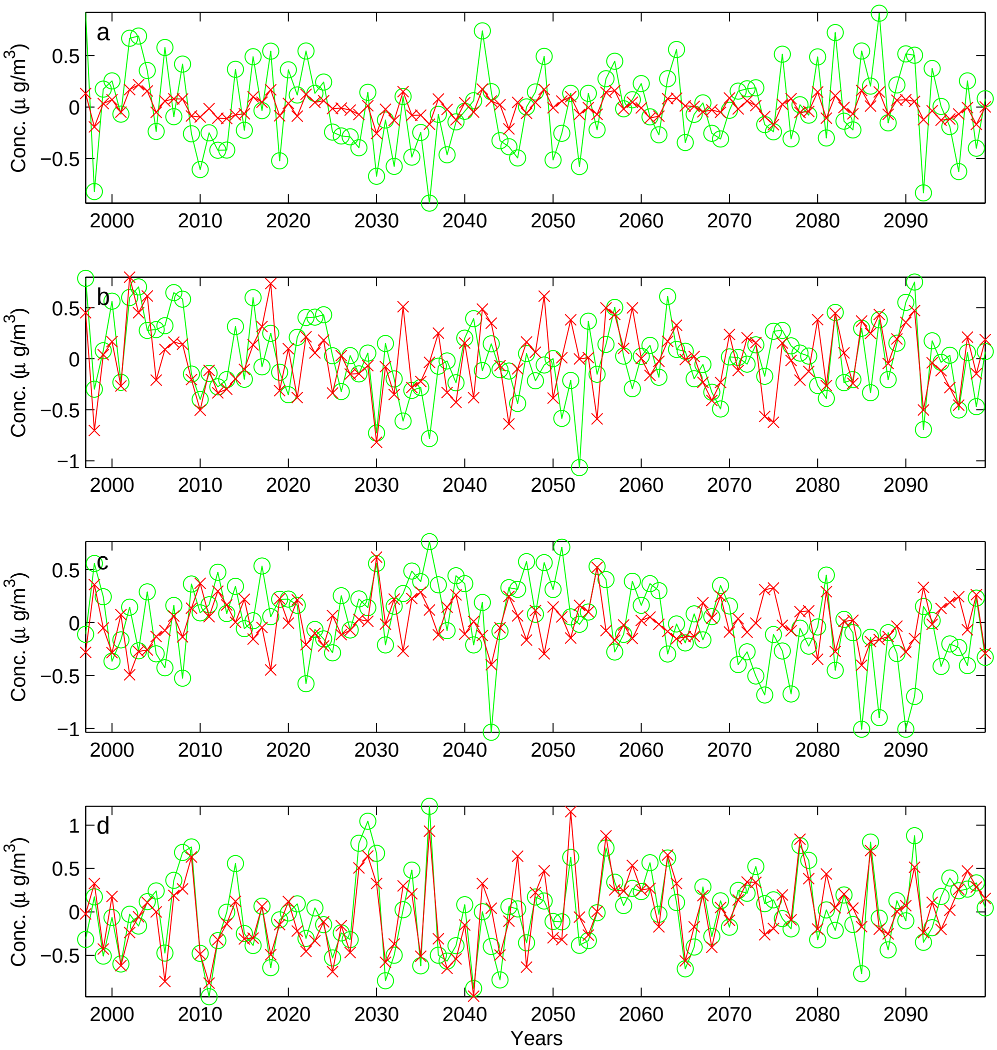

Figure 6: The anomalies of the yearly pollutant concentrations, predicted based on the climate model's daily forecast of synoptic systems and the pollution coefficients from stations Nave Shaanan in Haifa (circles) and Tachana Merkazit in Tel Aviv (x-marks). (a) SO_2, (b) NO_2, (c) O_3, (d) $PM_{2.5}$.

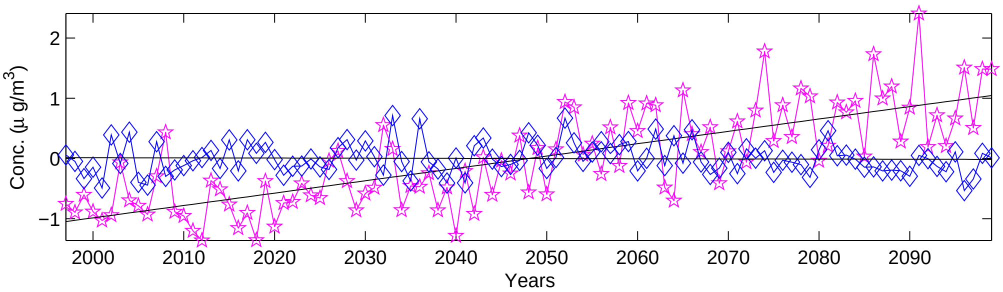

Figure 7: The anomalies of the yearly $PM_{2.5}$ concentrations, considering only days which were assigned synoptic system belonging to one of two groups. The shown values are the anomalies from the annual means, with the means calculated taking only the concentration values during days when the mentioned synoptic systems groups were present. The pentagrams denote the mean annual values due to synoptic systems transporting $PM_{2.5}$ to the eastern Mediterranean from eastern Europe (systems 4, 5, 6 and 8). The diamonds mark values due to synoptic systems transporting mineral dust from northern Africa (systems 2, 12, 13, 18 and 19). The solid lines are linear regression lines fitted to the two curves.

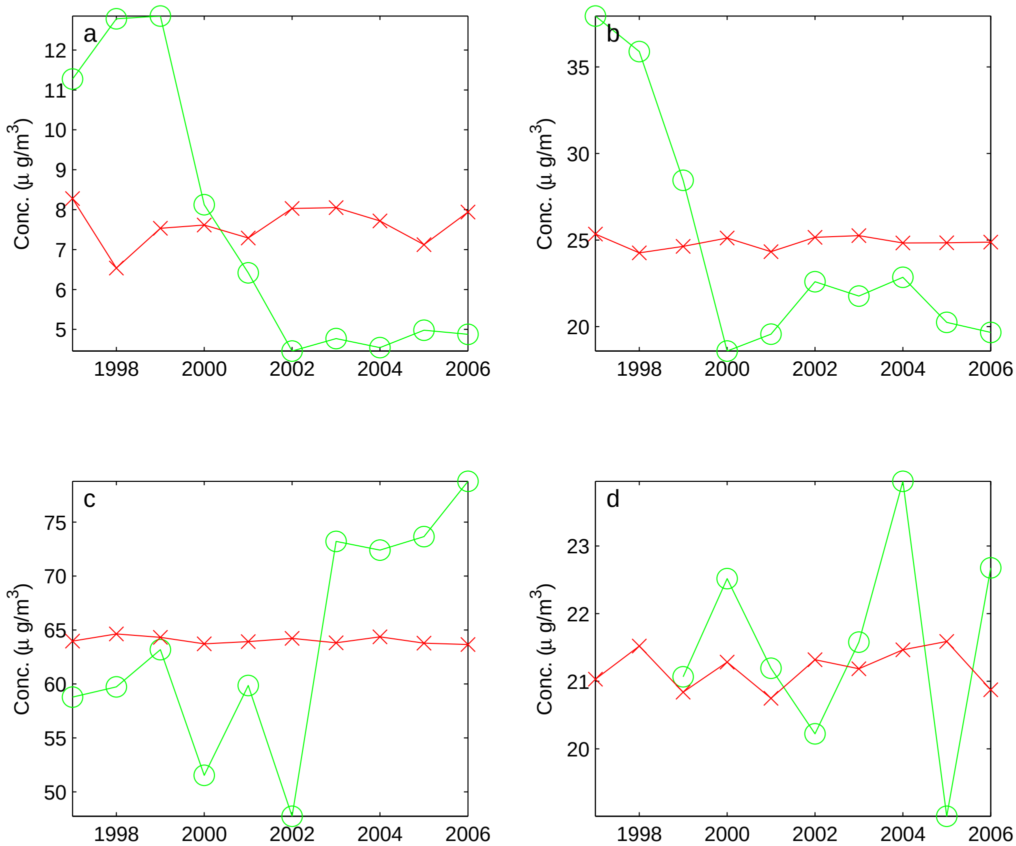

Figure 8: The real 1997-2006 annual mean pollution concentrations in Haifa, Israel (circles) and the corresponding hindcasting estimates (x-marks) by the synoptic classification method. (a) SO_2, (b) NO_2, (c) O_3, (d) $PM_{2.5}$.