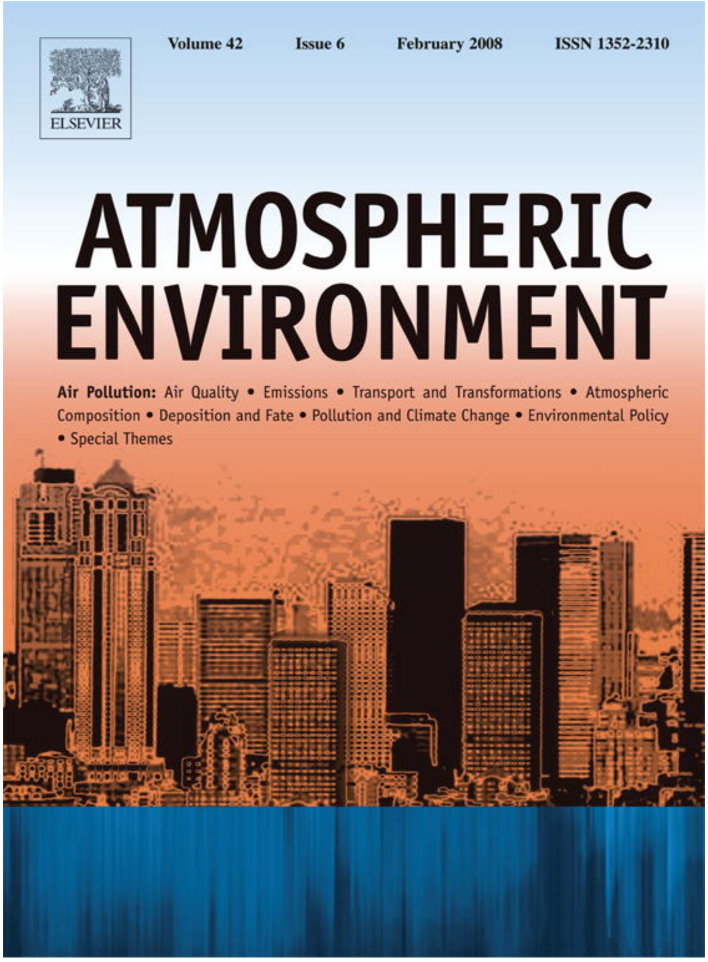
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Quality and performance of a PM10 daily forecasting model ☆

Ernst Stadlober[a,*], Siegfried Hörmann[b], Brigitte Pfeiler[a]

[a]*Institute of Statistics, Graz University of Technology, Steyrergasse 17/IV, 8010 Graz, Austria*
[b]*Department of Mathematics, University of Utah, 155 South 1400 East, JWB 233, Salt Lake City, UT 841120090, USA*

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Abstract

Particularly in the cold season unfavorable dissemination conditions of the ambient air lead to higher-than-average PM10 concentrations in parts of the western Alpe-Adria-Region, covering the provinces South Tyrol, Carinthia and Styria. Therefore, EU pollution standards cannot be met in the cold season and partial traffic regulation measures are taken in Bolzano, Klagenfurt and Graz, the three capitals in this region. Decision making for these regulations may be based on the average PM10 concentration of the next day provided that reliable forecasts of these values can be offered. In the present paper we show how multiple linear regression models combining information of the present day with meteorological forecasts of the next day can help forecasting daily PM10 concentrations for sites located in the three cities. Special emphasis is given to an appropriate selection of the regressor variables readily available as measured values, factors or meteorological forecasts suitable in operational mode. To reflect the quality of the forecast properly, we define a quality function where prediction errors near the threshold PM10 of $50\,\mu g\,m^{-3}$ are assumed to be more severe than errors in regions that are either far below or above the threshold. Since December 2004, the forecasts are used as a monitoring and information tool in Graz. Our daily forecasts have been carried out in cooperation with the meteorologists from the ZAMG Styria (Styrian meteorological office). The investigations in terms of the quality function and according possible decision rules show that our prediction models may support future decisions concerning possible traffic restrictions not only in Graz, but also in Bolzano and Klagenfurt.

Keywords: Forecasting PM10; Multiple linear regression; Meteorology; Quality function

1. Introduction

Particularly during the winter season, the basin areas of the Alps (including the cities of Graz, Klagenfurt and Bolzano) are exposed to weather conditions such as stationary temperature inversions, a low amount of precipitation and low wind velocities. These special weather conditions cause an extensive load of particulate matter (PM) in ambient air. The issue of PM/fine dust has recently caught remarkable attention and is still a very present and explosive topic in science and politics. The PM10 (particles with an aerodynamic diameter $<10\,\mu m$) concentration is measured in units of $\mu g\,m^{-3}$. According to the EU framework directive 1999/30/EC (European Community, 1999) the limit

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*Corresponding author. Tel.: +43 316 873 6478; fax: +43 316 873 6977.
E-mail address: e.stadlober@tugraz.at (E. Stadlober).
URL: http://www.stat.tugraz.at (E. Stadlober).

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value for the daily PM10 average is $50\,\mu g\,m^{-3}$ and must not be exceeded on more than 35 days of the year (valid for the years 2005–2009); a reduction to 7 days in 2010 is envisaged. Additionally, the annual PM10 average must not exceed the limit of $40\,\mu g\,m^{-3}$ ($20\,\mu g\,m^{-3}$ starting with 2010). However, at the test point GT1 in Graz (near the pedestrian zone in the center of the city) we observed in the period 2003–2006 between 90 (2004) and 137 (2003) exceedances of the daily PM10 limit and registered high annual averages between 41 and $49\,\mu g\,m^{-3}$. The physical and chemical composition of the particles is very complex. There are natural sources like pollen or crushing and grinding rocks and soil (primary particles). Contrarily, there are particles which arise from aerially pollutants (secondary particles). Anthropogenic particles are produced by traffic, domestic fuel and industry. They may be directly exhausted by burning processes or arise from mechanical abrasion of tyres, brakes, tarmac, etc. The coarse particles (PM10 –2.5) are composed of smoke, dirt and dust, the fine particles (PM2.5) are rather toxic organic compounds or heavy metals. Estimates about the proportion of the PM polluters differ widely and have to be related to the specific environment (urban, rural, seaside, etc.). For further information on aerosol source analysis in urban and rural areas of Austria we refer to the Aquella project http://www.iac.tuwien.ac.at/environ/aquella.html, which is still in progress.

Negative health effects caused by PM have been analyzed in many epidemiological and toxicological studies. An extensive general review can be found in Pope III and Dockery (2006). A description of the Austrian study AUPHEP is given in Hauck et al. (2004), while Schwarze et al. (2006) is an excellent review including 210 references of studies carried out in different regions throughout the world. In general, fine particles (PM2.5) are more likely to be toxic since they often consist of heavy metals and carcinogenic organic compounds. Furthermore, they are inhaled into the trachea and the respiratory system in general. In Klagenfurt and Bolzano where measurements for PM2.5 are available, it can be observed that the ratio PM2.5/PM10 is relatively constant. Hence investigations on PM10 in this region allow to draw some conclusions on finer PM fractions as well. In Bolzano about 40% of PM10 belong to the fine fraction, while the percentage in Klagenfurt is approximately twice as high. In contrast to the rare PM1 and PM2.5 data sources, extensive data on PM10 were available in all three cities. Furthermore, since the EU limits refer to PM10 we based our research on this specific measure.

Due to the negative health effects caused by PM10, policy had to react (and take drastic measures) against the PM problem. In the winter season 2006/2007, the cities of Bolzano, Graz and Klagenfurt as well as the respective Provinces were forced to take further action against high PM10 concentrations of the ambient air. In general, traffic regulations become effective if the limit values are exceeded for several days and if a reduction on the day in question is ‘‘unlikely’’. For the appropriate authorities it is necessary to base singular decisions on reliable forecasting models for daily PM10 concentrations. The objective of the present paper is to deliver PM10 forecasting models for the specific sites and to illustrate their practical applicability as a decision making tool for possible traffic restrictions. As the traffic regulations mentioned above regard the period between October and March, we based our models on that specific time of year. Better dissemination conditions for the ambient air during spring and summer lead to considerably lower PM10 concentrations and thus, there is no urgent need for action in that warm season of the year. The investigations were made within the framework of the EU-Life-project KAPA GS (Klagenfurts Anti PM10 Action Programme in cooperation with Graz and South-Tyrol: project duration from 1 July 2004 to 30 September 2007).

Our models are based on multiple linear regression which we found to be the most convenient method. Other typical approaches for PM prediction are neuronal networks (cf. Pérez and Reyes, 2002; Hooyberghs et al., 2005), discriminant analysis (cf. Silva et al., 2001) or Kalman filtering (cf. van der Wal and Jansen, 1999). The demand for our model was simplicity, practical feasibility and sufficient accuracy. Simplicity is guaranteed by the linear structure of the model. To obtain practical feasibility, it is vital to perform a careful choice of parameters. Meteorological parameters, for example, have to be forecasted individually (type-B parameters) in operational mode and thus it has to be assured that this additional uncertainty will not prevail. Hence, the precision of the prediction for a specific day will to some extent depend on the quality of the singular weather forecasts. Our empirical studies showed that temperature inversion, precipitation and wind velocity play an important role at all three sites. After consulting the ZAMG (Styrian meteorologic office) we decided to include variables which are representative for these impact factors and can also be forecasted with sufficient precision. In order to guarantee sufficient accuracy, we included all relevant parameters available or measured at the time when the forecasts were generated (type-A parameters), e.g. the PM10 24 h moving average.

In contrast to many theoretical studies, we are able to present the performance of the model in operational mode. During a three-year trial period in Graz we made PM10 forecasts available at the web site of our project (http://www.feinstaubfrei.at). For the generation of the predictions we used meteorological forecasts from ZAMG Styria where the meteorologists provided us with analyzed simulation data by the systems ECMWF and Aladin. We observed that PM10 forecasts for several days do not loose much quality if the type-B parameters were known. However, we found that forecasts of two or more days in advance will become unreliable in practise.

By virtue of the high dispersion of PM10 data and our specific requirements we found that commonly used measures do not reveal the quality of the forecasts with respect to our needs. A forecast of $15\,\mu g\,m^{-3}$ for an observation of $30\,\mu g\,m^{-3}$, for example, yields a 100% relative error, though both the observation and the prediction are clearly below the limit value. On the other hand we observe peaks with values $>150\,\mu g\,m^{-3}$. Typically, the model under-estimates jerky leaps and in this case a prediction of $110\,\mu g\,m^{-3}$ (say) is not bad, even though the absolute error is high; the forecast value still indicates alert status. Concerning decision making for traffic restrictions, we have to concentrate on avoiding errors leading to unjustified measures. In order to incorporate these specific requirements we used—besides standard measures like correlation or mean squared error—a quality function assigning a meaningful rating to each pair of observation and forecast value.

In the next section we describe the sites, databases and input parameters. Section 3 contains the methodology of our study and quality issues are discussed in Section 4. Results of test runs are analyzed in Section 5 and in the final section we summarize our findings and express our conclusions.

2. Data and parameter selection

2.1. Sites and database

Our investigations took place of sites within the cities of Bolzano, Klagenfurt and Graz. The three cities are located in basin areas south of the main Alpine crest and show similar climatical characteristics. Rain clouds from the Atlantic are kept away by the Alps implying low precipitation and low wind velocities during the cold period. Furthermore, stationary temperature inversions frequently occur at that time of year (due to the basin location). Some key data, listed in Tables 1 and 2, illustrate

Table 1
Percentage of PM10 levels observed within different meteorological scenarios for the test point GT1, where O–D covers the period 1 October to 31 December and J–M the period 1 January to 31 March

Precipitation	$\Delta_{temp}>0$								$\Delta_{temp}\leqslant 0$							
	Wind speed > median				Wind speed ≤ median				Wind speed > median				Wind speed ≤ median			
	Yes		No		Yes		No		Yes		No		Yes		No	
Month	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M
Low	63.0	40.6	36.0	14.7	32.4	19.5	14.0	–	25.0	25.0	4.0	–	20.0	–	2.4	–
Moderate	28.3	35.9	47.7	41.0	44.1	31.7	39.0	31.9	37.5	–	44.0	10.7	26.7	10.0	18.1	5.0
High	2.2	20.3	14.0	33.3	19.1	39.0	36.0	38.3	37.5	50.0	40.0	32.1	40.0	40.0	50.6	26.3
Very high	6.5	3.1	2.3	9.6	4.4	7.3	10.0	14.9	–	25.0	12.0	39.3	13.3	20.0	18.1	25.0
Alert	–	–	–	1.3	–	2.4	1.0	14.9	–	–	–	17.9	–	30.0	10.8	43.8
# observed	46	64	86	156	68	41	100	47	8	4	25	28	15	10	83	80
PM10 ($\mu g\,m^{-3}$)	31.9	38.5	36.9	50.2	39.6	48.4	50.0	67.8	43.0	54.4	51.6	77.5	52.0	94.4	67.2	96.4

The last row shows the average PM10 concentration within these groups. Here "low" $\triangleq$ PM10 $\leqslant 30$, "moderate" $\triangleq$ PM10 $\in (30,50]$, "high" $\triangleq$ PM10 $\in (50,75]$, "very high" $\triangleq$ PM10 $\in (75,100]$ and "alert" $\triangleq$ PM10 >100.

Table 2
The analogue of Table 1 for the test point KT1

Precipitation	$\Delta_{temp} > 0$								$\Delta_{temp} \leqslant 0$							
	Wind > median				Wind ⩽ median				Wind > median				Wind ⩽ median			
	Yes		No		Yes		No		Yes		No		Yes		No	
Month	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M	O–D	J–M
Low	62.5	26.1	18.4	11.6	21.9	7.7	7.9	5.3	–	–	20.0	–	12.5	–	2.9	–
Moderate	37.5	52.2	63.3	34.8	56.3	38.5	55.3	21.1	100	100	20.0	–	37.5	50.0	20.0	3.8
High	–	17.4	16.3	43.5	18.8	38.5	34.2	52.6	–	–	60.0	76.0	37.5	25.0	34.3	28.3
Very high	–	4.3	2.0	8.7	3.1	15.4	2.6	13.2	–	–	–	20.0	12.5	25.0	34.3	34.0
Alert	–	–	–	1.4	–	–	–	7.9	–	–	–	4.0	–	–	8.6	34.0
# observed	16	23	49	69	32	13	38	38	1	2	5	25	8	4	35	53
PM10 ($\mu g\,m^{-3}$)	25.0	42.4	39.3	53.4	41.9	54.7	45.3	63.7	45.9	39.3	49.0	69.7	51.7	56.1	70.9	87.8

Here inversion is the temperature difference between KT1 and KRE.

the situation at the specific sites of Graz and Klagenfurt.

Bolzano with nearly 100k residents is the capital of the north Italian province of South Tyrol. The city center is situated at about 260 m above sea level and is surrounded by mountains and several side valleys. Due to higher wind velocities there was more circulation of air than in Klagenfurt and Graz. PM10 data were available from three test points (BT1, BT2 and BT3) located in the urban traffic area. Whereas meteorological and additional pollution parameters (NO_2, SO_2, O_3) were observed at two further test points (BT4 and BRE). For our investigations we concentrated on the site BT1 ("Hadriansplatz" in city center) with data collected from 1 January 2001 to 31 March 2006 and recorded as half hour averages with only a few missing values.

At this site the daily PM10 limit was exceeded on 43 (2005) to 97 (2003) days of the year, mostly during the winter months (January–March and October–December) with 32 (2005) to 57 (2003) exceedances, only rarely (3–11 times) during the summer months (April–September), except in 2003 with 40 exceedances. This was obviously related to temporary local effects (nearby road work, hence heavy traffic of busses, etc.). Except in 2003 the annual averages were below the EU-limit ($29-34\,\mu g\,m^{-3}$).

Klagenfurt, the capital of the Austrian region Carinthia, has more than 90k residents. It is located in the east of the lake Wörthersee in the so-called Klagenfurt basin, 450 m above sea level where the mountains surrounding the city have up to 1000 m. The data situation is much more inhomogeneous and less complete than in Bolzano or Graz. From the three permanent test points we concentrated on the site Völkermarkterstraße (KT1) having the most complete database. It is situated in a traffic area and provide daily averages of PM10 and some meteorological data from ZAMG Klagenfurt for the period between 1 January 2003 and 31 March 2005. Göriach (KRE) is a meteorological test point with an altitude of about 840 m.

At KT1 the daily PM10 limit was exceeded on 58 (2002) to 80 (2004) days of the year, with only a few exceedances during the summer months. The annual average from 2001 to 2004 was between 35 and $38\,\mu g\,m^{-3}$.

Graz has approximately 250k residents and is the capital of the Austrian region Styria. It is situated in the north of the Grazer basin at 350 m above sea level. The crests of the mountains bordering at the north are about 400 m higher. The permanent PM10 monitoring network in Graz is made up of six test points of which three are located in traffic areas (GT1, GT2 and GT3), two in residential areas (GR1 and GR2) and one in the surrounding green belt (GG1). In addition to PM10, the test points provide other pollution and meteorological data on the basis of half hour averages. From the test point Kalkleiten (GRE) which is situated close to Graz 710 m above sea level we obtained temperature data. The first PM10 measurements were recorded on 1 July 2000 (GT3, Don Bosco), the last test point went on stream 1 July 2003 (GG1, Platte). For the current study we took into account measurements from GT1 (Graz center, near pedestrian zones) until

31 March 2007. During the operational mode of our forecasting model (starting on 18 October 2005) the ZAMG Styria delivered us daily meteorological forecasts.

For the years 2003–2006 we observed 90–137 exceedances of the daily limit value per year; on the average 83% during the winter months (83 (2004) to 106 (2003)) and 17% during the summer season (7 (2004) to 31 (2003)). In contrast to Bolzano and Klagenfurt the annual average was continually above the EU-limit of $40\,\mu g\,m^{-3}$ ($41–48\,\mu g\,m^{-3}$).

2.2. The input variables

In the sequel we give a concise discussion on the input variables that proved suitable for our regression and forecasting models. The investigations are based on daily averages and are designed for the cold season, i.e. the period from October 1 to March 31. During that period occur 83% of the yearly exceedances ($PM10 > 50\,\mu g\,m^{-3}$), e.g. in GT1 the average PM10 in the cold period is $\approx 55\,\mu g\,m^{-3}$, in contrast to the warm period with a significantly lower average of $34\,\mu g\,m^{-3}$. A more detailed analysis for Graz can be found in Hörmann et al. (2005). Temperature inversion has the most significant impact on the PM10 concentration in Klagenfurt and Graz. In order to measure temperature inversion for Graz we define

$$\Delta_{temp} = temp(GT1) - temp(GRE).$$

If the daily average Δ_{temp} is negative, we refer to this as an inversion day. In Klagenfurt, Δ_{temp} is defined by the temperature difference KT1 to KRE. GRE and KRE are suitable reference points to determine a low mixing layer height, since both test points are situated 300–400 m above ground level. Unfortunately, a corresponding test point is not available for Bolzano. The mountain site BRE (1750 m) is no significant value for this purpose. In the cold period, the daily average of Δ_{temp} in Klagenfurt and Graz is negative to a level of 27–30%. In case of $\Delta_{temp} \geqslant 0$ (no inversion day) at GT1 and KT1, the average PM10 load during the winter is nearly $50\,\mu g\,m^{-3}$, and it is about $80\,\mu g\,m^{-3}$ if $\Delta_{temp} < 0$. Obviously, the emergence of wind and precipitation leads to reduced PM10 concentrations. Especially in Bolzano the average wind speed is considerably higher than at the other two sites and here it has the strongest impact among the meteorological variables available. Other variables such as humidity and wind direction were not included in the model. The reason is twofold. First of all, our investigations showed that they can improve the models only marginally since most of their effects on PM10 are already absorbed by the other meteorological parameters. Secondly, the meteorological variables considered so far are related to the day of the prediction because they have an instantaneous effect on PM10. This has the disadvantage that they can be obtained only as forecasted values in operational mode. To get a useful model we are forced to include only those variables which can be forecasted with sufficient precision by meteorologists.

An important variable for our prediction models is the so-called lag value of PM10. Since in praxis the predictions for day $d+1$ should stand by at a certain time (in Graz at 12.00) of day d, we will include the PM10 24 h moving average from 12.00 on day $d-1$ to 12.00 on day d. For Klagenfurt, where the PM10 is only available in form of daily averages from 00.00 to 24.00 we used the estimate $(PM10_d + PM10_{d-1})/2$ instead.

The human impact is reflected to some extent by weekday/weekend differences of PM10. Fig. 1 shows that there is a significant reduction on Sun- and Holidays in the three cities. It is very likely that this effect arises from the reduced traffic load. In order to model this effect we included two dummy variables indicating Saturday as well as Sun- and Holiday. Recently, Lonati et al. (2006) studied the

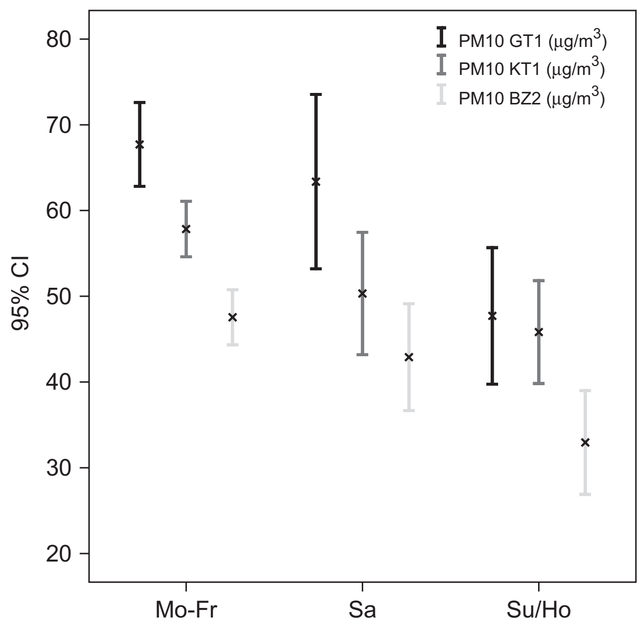

Fig. 1. There is a significant reduction of PM10 on Sundays and Holidays.

weekend effect for PM10 and PM2.5 emissions from traffic sources in the city of Milano. They found that traffic emissions appear responsible for about 50% of the PM10 concentration levels in the urban area.

An additional human impact factor is domestic fuel. Obviously, during frosty periods there is more demand on heating and thus we might estimate the influence of domestic heating partially via air temperature. It turns out that air temperature plays a major role in Klagenfurt and Graz, whereas it is negligible in Bolzano. Since there is a very high correlation between the temperature on proximate days, it suffices to include the lag value computed as the temperature 24 h moving average from 12.00 on day $d-1$ to 12.00 on day d.

A further remarkable observation is that under constant meteorological conditions the PM10 values become considerably higher in course of the winter period (Tables 1 and 2). This effect is visible at all three sites, especially in March when the PM10 concentration usually declines. One possible explanation for this phenomenon might be that the defilement of deposited road grit is increasing during the winter season. Our partners in KAPA GS from the Institute for Internal Combustion Engines and Thermodynamics at Graz University of Technology compared the ratios of the measured increment PM/NO_x with the ratios of calculated exhaust emissions of road traffic for the site KT1 in Klagenfurt. They found increasing ratios of measured increments in course of the winter period indicating growing contributions of non-exhaust emissions of PM10 (see Sturm, 2006). To model this observed effect we included dummy variables for January, February and March.

3. Methodology

3.1. Multiple linear regression

Our goal is to model the daily PM10 averages by a linear model which will be the basis for our forecasting models. The regression models are conceived for the dependent variable $\sqrt{\mathrm{PM10}}$. A square root transformation is necessary to assure a constant error variance and to avoid a violation of the model assumptions. It should be noted that the standard transformation used in this context is rather the log-transformation (see e.g. Lonati et al., 2006). However, in our case the model diagnostics showed better properties for the square root transformation: The coefficient of determination R^2 was usually slightly higher and the distribution of the residuals exhibited the structure of normal errors.

Model assumption: Let $z^{(i)}$ $(i = 1, 2, \ldots, m)$ be a pool of input variables and let $z_d^{(i)}$ be their value on day d. Then we assume that the following linear model for $\sqrt{\mathrm{PM10}}$ holds:

$$\sqrt{\mathrm{PM10}}_d = \beta_0 + \sum_{i=1}^{m} \beta_i z_d^{(i)} + \varepsilon_d \quad \text{where } \varepsilon_d \overset{\text{iid}}{\sim} N(0, \sigma^2).$$

Table 3 lists the input variables we found suitable for our investigations. For each site they are chosen via a stepwise regression procedure from a given candidate set of input variables. In the forward step

Table 3
Variables that were included in the regressions

Variables z_d	Type	Description	Available at
pm_lag	Metric	PM10 24 h moving average from 12.00 to 12.00 of day $d-1$	12.00 day $d-1$
temp_lag	Metric	$\mathrm{sign}(\mathrm{temp}_{12}) \cdot \sqrt{\mathrm{temp}_{12}}$, where temp_{12} is the temperature 24 h moving average from 12.00 to 12.00 of day $d-1$	12.00 day $d-1$
sat	0/1	$I\{\text{day } d = \text{Saturday}\}$	
sun	0/1	$I\{\text{day } d = \text{Sunday/holiday}\}$	
feb	0/1	$I\{\text{month} = \text{February}\}$	
march	0/1	$I\{\text{month} = \text{March}\}$	
wind	Metric	Average wind speed of day d	24.00 day d
prec	0/1	$I\{\text{there is precipitation on day } d\}$	24.00 day d
Δ_{temp}	Metric	Average temperature difference to reference test point on day d	24.00 day d

Here $I\{A\} = 1$ if A is true otherwise $I\{A\} = 0$.

Table 4
The table shows the order (r) of the inclusion of the variables z and the standardized Beta coefficients

Variables z	GT1		KT1		BT1	
	r	Beta	r	Beta	r	Beta
pm_lag	2	0.313	1	0.420	2	0.347
Δ_{temp}	1	−0.342	2	−0.234	8	−0.119
sun	4	−0.239	4	−0.218	3	−0.239
temp_lag	3	−0.192	3	−0.240	6	−0.104
wind	6	−0.243	7	−0.097	1	−0.525
prec	5	−0.164	5	−0.175	4	−0.155
march	7	0.192	8	0.107	5	0.237
sat	8	−0.145	6	−0.141	7	−0.130
feb	9	0.080	x	x	9	0.088
Corr. R^2	0.629		0.701		0.548	
Std. dev.	1.09		0.91		1.11	
Valid cases	858		378		811	

For these computations all available data of the cold periods were included.

the candidate variable with the highest partial F-value larger than a given threshold is included in the model. In the backward step a variable is removed from the model when its influence becomes negligible (low partial F-value), because of the variable entered in the forward step. The procedure ends when the forward step leads to no further improvement or the backward step indicates no further removal. Table 3 lists the input variables which remained in the model. One important advantage of this simple linear approach is that the parameters and results can still be interpreted conveniently. In contrast to other very complex models with numerous input parameters and/or functional relations covered by a black box mechanism, such a linear model is still transparent for the user.

It is important to note that variables may not be included even if they have a significant impact on PM10 in a one-dimensional examination. This will happen if the information covered by this parameter is contained in other variables which have already been included. Table 4 lists in which order the stepwise procedure included the regression variables, and also gives the standardized Beta coefficients describing the impact of each variable. The (theoretical) quality of the models is quite good, especially in Klagenfurt. However, the strong impact of the PM10 lag value for this site has to be put down to the estimated variable pm_lag (see Section 2.2). Temperature inversion Δ_{temp}, most important in Graz and second most important in Klagenfurt, is less important in Bolzano and entered there as one of the last variables. We are sure that in Bolzano a suitable reference test point for inversion would change the situation and improve the model. If we remove the parameter Δ_{temp} in Graz and Bolzano, e.g. we have a fairly resembling order in the inclusion of the variables z, and the corrected R^2, adjusted for the number of input parameters, is of the same order in both models.

4. The forecasting models

The multiple linear regression models obtained by means of the procedure described in Section 3.1, are now used as the basis for the forecasting models. As a first step we used historical data to compute the estimates $\hat{\beta}_i$ for the linear model. This can be done with any standard statistics package (we employed SPSS 14.0) and yields an estimate for $\sqrt{\text{PM10}}$. The simplest way to get an estimate for PM10 is to take the square of the predicted $\sqrt{\text{PM10}}$. The resulting bias is negligible for our purposes (and therefore will not be considered). Clearly, in operational mode the (observed) variables $z_d^{(8)} \triangleq \text{wind}$, $z_d^{(9)} \triangleq \text{prec}$ and $z_d^{(10)} \triangleq \Delta_{\text{temp}}$ for the day d of the prediction are not available and hence we replace them with their meteorological forecasts $\hat{z}_d^{(8)}$, $\hat{z}_d^{(9)}$ and $\hat{z}_d^{(10)}$, respectively. The PM10 forecast f_d for day d is given by the formula

$$f_d = \left(\hat{\beta}_0 + \sum_{i=1}^{7} \hat{\beta}_i z_i^{(d)} + \sum_{j=8}^{10} \hat{\beta}_j \hat{z}_j^{(d)}\right)^2.$$

As we will show in Section 7.1, the forecasts for prec, wind and Δ_{temp} caused some difficulties in Graz. For this reason we propose to omit variables with a rather weak effect on PM10, i.e. wind in Klagenfurt and Δ_{temp} in Bolzano. The quality of the corresponding models remains merely unchanged, the corrected R^2 decreases slightly to 0.696 in Klagenfurt and to 0.541 in Bolzano. It is likely that the additional error introduced by the weather forecasts will undo the marginal improvement these parameters contribute to the theoretical model. Due to the simple character of our models, the implementation step is extremely easy and the application in operational mode involves no numerical costs.

Forecasts for more than one day ahead are also desirable and can be realized easily by an iterative method. Assume that we want to forecast PM10 of day $d+n$, $n \geqslant 1$. Besides the values for $z_{d+n}^{(8)}$, $z_{d+n}^{(9)}$ and $z_{d+n}^{(10)}$ we now also have to estimate lag_pm

$\triangleq z_{d+n}^{(1)}$ and lag_temp $\triangleq z_{d+n}^{(2)}$ for day $d+n$. While $\hat{z}_{d+n}^{(2)}$ will be a meteorological forecast, we set

$$\hat{z}_{d+n}^{(1)} := f_{d+n-1},$$

where f_{d+n-1} is the forecast for day $d+n-1$. Now if we assume inductively that the PM10 forecast f_{d+n-1} for day $d+n-1$ already exists, we have

$$f_{d+n} = \left(\hat{\beta}_0 + \sum_{i=3}^{7} \hat{\beta}_i z_{d+n}^{(i)} + \sum_{j \in \{1,2,8,9,10\}} \hat{\beta}_j \hat{z}_{d+n}^{(j)}\right)^2.$$

It is not very surprising that the forecasts for more than one day ahead remain rather accurate when we assume knowledge of the exact meteorology of day $d, \ldots, d+n$. However, this is rather unrealistic in practise. As we will discuss in Section 8, even one day forecasts of the meteorological input variables wind, prec and Δ_{temp} may produce errors which considerably deteriorate the quality of the resulting PM10 forecasts. Consequently, our experience indicates that corresponding forecasts for more than one day will become unreliable in operational mode.

5. Quality of forecasting

5.1. Quality function

To measure the quality of our forecasts we need a reasonable rating system different from usual measures as e.g. the absolute error which is large if the forecast is $120\,\mu g\,m^{-3}$ and the observation is $170\,\mu g\,m^{-3}$. However, this forecast value will indicate a right decision when partial traffic regulation measures are taken whenever PM10 > certain limit (e.g. $50\,\mu g\,m^{-3}$). Contrarily, if the prediction is $55\,\mu g\,m^{-3}$ and the observation is $40\,\mu g\,m^{-3}$ a traffic regulation may not be justified and the relatively small error would cause undesirable consequences. Still, to rate only in terms of good or bad if both, forecast and observation, are above/below a certain limit is unsatisfactory. For this reason we define a quality function $Q : \mathbb{R}_+^2 \to [0,1]$ which assigns a value to each pair ($O =$ observation, $F =$ forecast) in $[0,1]$. Values close to 1 signify very good forecasts, whereas small values near to zero indicate low quality. Based

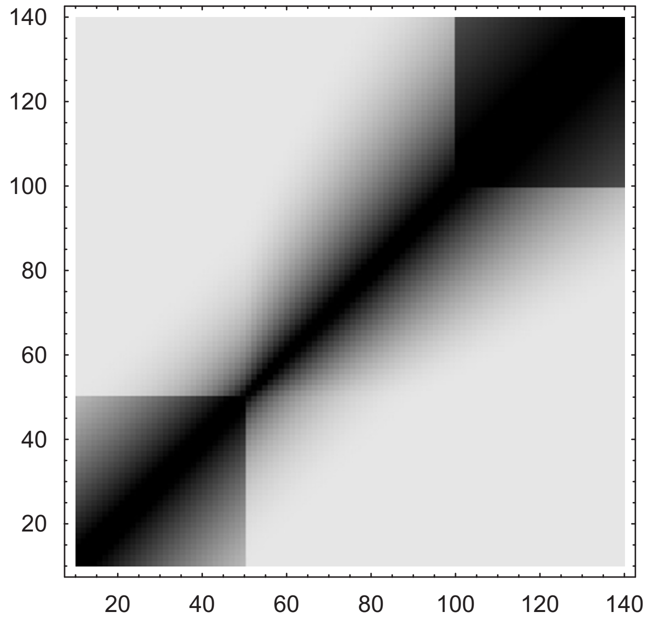

Fig. 2. Contour plot of the quality function Q. The darker the region in which (O,F) falls, the better the rating for the forecast.

on the outcome of $Q(O,F)$ we assign grades: $Q(O,F) \geqslant 0.8 \triangleq$ "excellent", $Q(O,F) \in [0.6, 0.8) \triangleq$ "good", $Q(O,F) \in [0.4, 0.6) \triangleq$ "satisfactory", $Q(O,F) \in [0.2, 0.4) \triangleq$ "bad", $Q(O,F) \in [0, 0.2) \triangleq$ "very bad". Since the function Q displays subjective criteria for the quality of the forecasts its applicability is limited to our special problem. Fig. 2 shows a contour plot of Q. Points (O,F) appearing in the dark area express good forecasts, whereas points (O,F) visible in the bright area indicate bad forecasts. The constellations $(O,F) \leqslant (50,50)$ (all-clear) or $(O,F) \geqslant (100,100)$ (alert) as well as $|O-F|$ "small" will get good rates. However, the strongest penalties are assigned to the events

$$\{O < 50, F > 50\} \quad \text{and} \quad \{O > 50, F < 50\}.$$

The function Q is given by the relation

$$Q(O,F) = 1 - \min\left\{\frac{a \cdot |O-F|}{D}, 1\right\},$$

where

$$D = 1 + \tfrac{1}{2}\sqrt{|O-50| + |F-50| + b \cdot I_{\{O \leqslant 50, F \leqslant 50\}} + c \cdot I_{\{O \geqslant 100, F \geqslant 100\}}}$$

which includes the indicator function I_E defined as follows: $I_E = 1$ if condition E is fulfilled, and $I_E = 0$ otherwise.

Our special choice of the parameters was $a = 10^{-1}$, $b = 10^2$, $c = 10^3$ to obtain rigorous

Table 5
Some special combinations of (O, F) and the corresponding grades (1, excellent; 5, very bad)

O	22	50	55	70	20	51	99	50	100
F	55	60	40	90	25	45	120	45	120
Quality	5	4	3	3	1	2	2	1	1

resulting rates. Table 5 shows the corresponding rating of some special configurations.

From the definition of $Q(O, F)$ it is clear that there are jumps near the thresholds ($O = 50, F = 50$) and ($O = 100, F = 100$). Let us consider two pairs of examples: $Q(45, 50)(= Q(50, 45)) = 0.92$ (“excellent”), $Q(45, 51)(= Q(51, 45)) = 0.74$ (“good”); $Q(120, 100)(= Q(100, 120)) = 0.89$ (“excellent”), $Q(120, 99)(= Q(99, 120)) = 0.68$ (“good”). This indicates a stronger penalty when the observation is below $50\,\mu g\,m^{-3}$ (above $100\,\mu g\,m^{-3}$) and the forecast is above $50\,\mu g\,m^{-3}$ (below $100\,\mu g\,m^{-3}$). Of course, the suggested definition of $Q(O, F)$ is one specific choice among others; e.g. it might be possible to define functions $Q(O, F)$ asymmetric in the arguments giving higher penalty when $O > F$. However, our proposal $Q(O, F)$ has been tested for three winter seasons in Graz and proved to be a suitable measure for the intended application.

6. Theoretical performance

The investigations below are based on all available data for the cold periods at the sites BT1, KT1 and GT1. To check the theoretical performance of our models, we computed the coefficient estimates $\hat{\beta}_i$ by excluding the last cold period available, which shall be our test period. Then we calculated the daily PM10 predictions of the test period with these estimated coefficients. Instead of the forecasted $\hat{z}_d^{(i)}$ $(i = 8, 9, 10)$ we used the measured values $z_d^{(i)}$, referred to as “exact” meteorological forecasts. This procedure is necessary in order to assure that the models are robust against different meteorological characteristics in the particular years. The selection of the last available period as test period is arbitrary (but natural), and additional investigations showed that the basic findings remain unchanged if we exclude any other period in between. By entering the observed meteorological values as exact meteorological forecasts we can measure the “theoretical” quality of our models. In Section 8 we test the reliability in operational mode, by inserting the daily meteorological forecasts instead.

The theoretical performance of the models is very promising. The forecasts 2005/2006 for Klagenfurt (15 October to 31 December 2005, 2 January to 31 March 2006) and Bolzano (1 October 2005 to 31 March 2006) were rated as “excellent”, “good” or “satisfactory” in 87% (Klagenfurt) and 86% (Bolzano) of the cases (see Fig. 3). In Graz the predictions for the test period 2006/2007 (1 October to 31 December 2006, 3 January to 31 March 2007) are assigned to the first three categories at a level of 94.5% (see Fig. 3).

7. Test run

7.1. Meteorological forecasts

In Graz, the daily meteorological forecasts delivered by the ZAMG Styria started on 15 December 2004 and includes the variables wind, Δ_{temp} and prec. The first winter period 2004/2005 was used as pilot study to test the performance of the model with actual weather forecasts. The quantitative forecast of the wind velocities was a particularly difficult task for the meteorologists. At the beginning of the test run the scale was systematically too high. The reason for this was that the test point providing wind data is situated in an area densely covered with buildings. Therefore, the overall wind speed at this site in Graz has a different order of magnitude than the other locations of the city. We overcame this obstacle by requiring a qualitative rating in four categories, from 1 = “low wind speed” to 4 = “high wind speed”. The mean values of the wind data ranging within two neighbored quartiles are then used as quantitative forecasts. The qualitative forecast “low”, for example, is replaced by the mean of the wind data below the 25% percentile. Still, wind velocity poses some problems and the forecasts are involved with a relatively large error.

The forecast for precipitation is required only qualitatively in terms of “yes” or “no”. During the registered period on nearly 30% of the days we observed prec > 0, but usually the amount of precipitation was rather low. The forecast “no precipitation” was correct to a level of 86%, but from the remaining 14% half of the observations showed a very short duration of precipitation below 2 h. On the other hand, the forecast “precipitation”

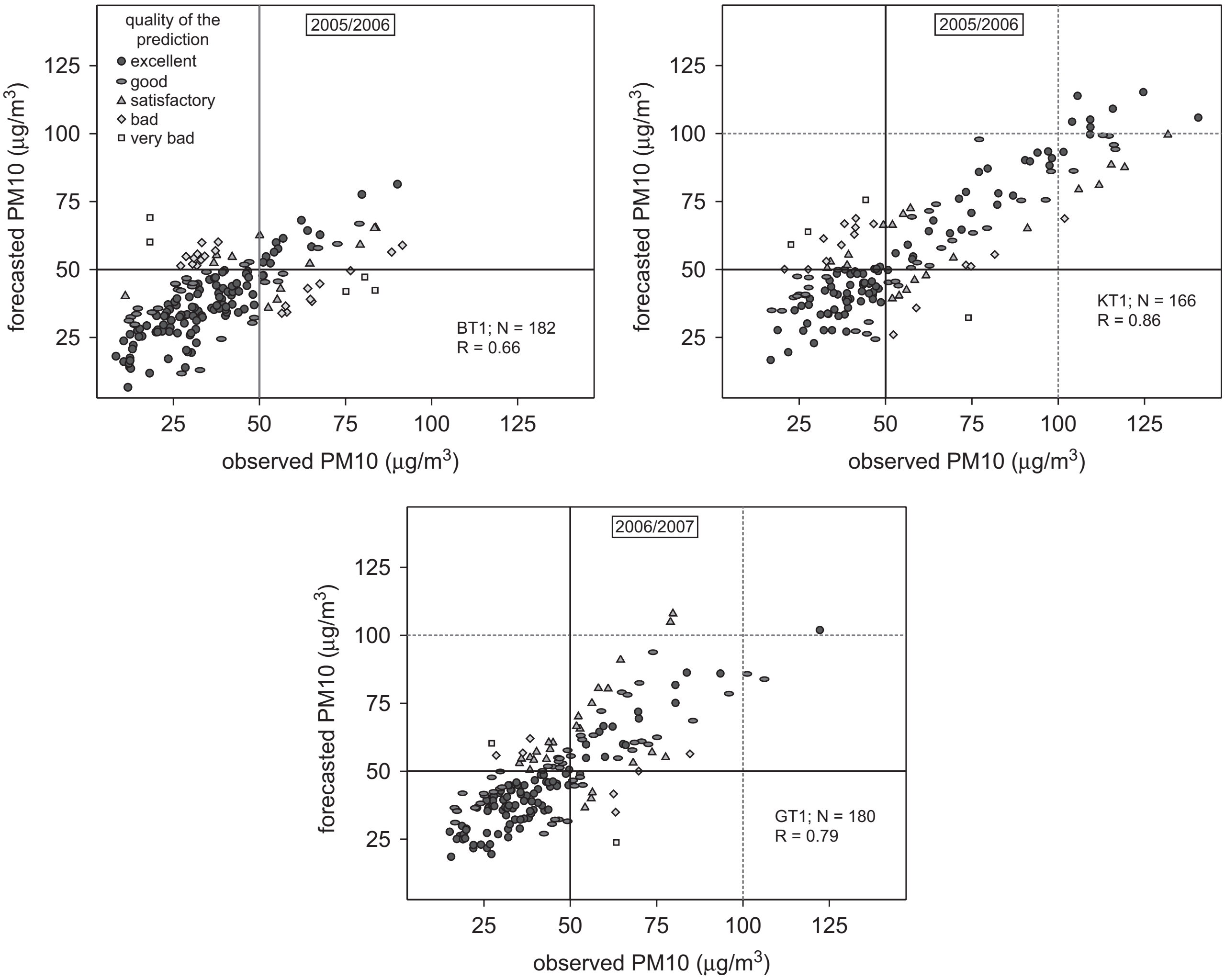

Fig. 3. Plots of observed against forecasted PM10 for the locations BT1 (top left), KT1 (top right) and GT1 (bottom).

was in agreement with the actual observation in 68% of the cases.

To our surprise the precision of the forecasts for Δ_{temp} was relatively good in the first winter period 2004/2005. The differences between observed and forecasted Δ_{temp} were symmetrically scattered around 0 and more than 50% were within the band of $\pm 1\,^{\circ}\text{C}$. In the two subsequent periods the interquartile range shifted to $(-0.28, 1.96)$ (2005/2006) and $(-0.37, 2.15)$ (2006/2007) signifying that there was a systematic trend to under-estimate Δ_{temp}.

8. Quality in operational mode

During our three test periods in Graz (15 December 2004 to 31 March 2005; 17 October 2005 to 31 March 2006; 2 November 2006 to 31 March 2007) we fed our linear models with the meteorological forecasts of wind, prec and Δ_{temp}. Before each season the parameters of the models were estimated anew from the updated data. As a matter of fact replacing the observed by the forecasted values causes an additional error and the question is how reliable the model remains. Fig. 4 compares the observed and forecasted PM10 for the period 17 October 2005 to 31 March 2006.

The fraction of forecasts which are ranked as "excellent", "good" or "satisfactory" decreases from 82% (exact forecasts) to 76% (meteorological forecasts). It is noticeable that low PM10 values are over-estimated relatively often while high PM10 values are frequently under-estimated. Whenever the alert status ($>100\,\mu\text{g}\,\text{m}^{-3}$) had been reached by the observation, the forecasted value exceeded at least the limit value $50\,\mu\text{g}\,\text{m}^{-3}$.

The loss of accuracy due to errors in the meteorological forecasts becomes more apparent in 2006/2007 when we compare Fig. 5 and the bottom panel of Fig. 3. The latter shows the quality

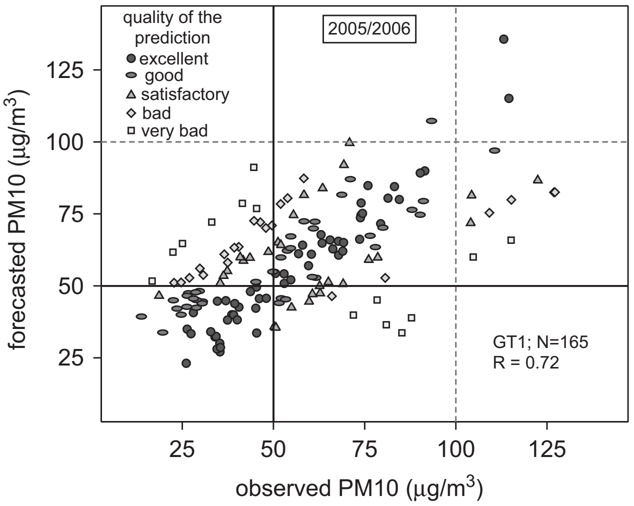

Fig. 4. Observed against forecasted PM10 for the winter period 2005/2006 in GT1.

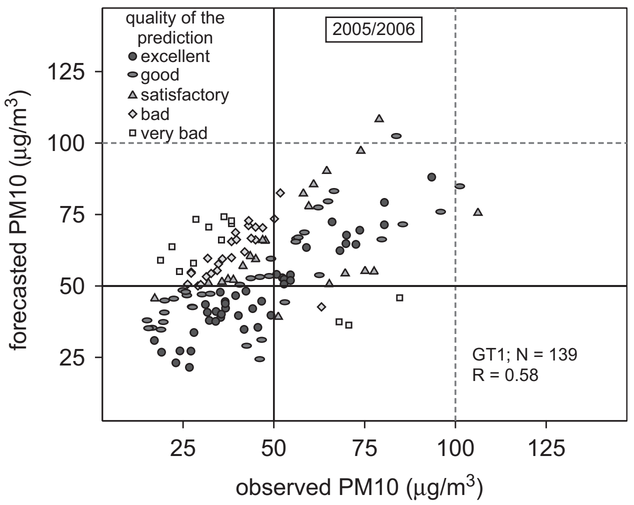

Fig. 5. Observed against forecasted PM10 for the winter period 2006/2007 in GT1.

under the assumption of exact meteorological forecasts, whereas Fig. 5 was prepared with meteorological forecasts from 2 November to 31 December 2006, 3 January to 31 March 2007 (9 days with persistent forecasts are excluded).

Here, only 73% of the PM10 forecasts were ranked in the categories "excellent", "good" and "satisfactory" (in comparison to 97% under the assumption of exact meteorological forecasts). There are at least two reasons for this lower rating. First, there was a greater proportion of under-estimated wind velocities compared to the season before. To overcome this problem in future we suggested the meteorologists to deliver six instead of four categories of wind speed. Secondly, the atypically mild winter season provided rather low PM10 concentrations near to the limit value $50\,\mu g\,m^{-3}$ where even small forecasting errors may result in a bad rating, because of the strong penalties.

Although the forecasting quality seems to be considerably lower in the practical scenario, we still think that the precision is sufficient in connection with intended traffic regulations. As a rule of thumb we propose to impose a traffic ban if the forecast is $>75\,\mu g\,m^{-3}$. As a measure of quality we define the *fraction of realized forecasted exceedances*

$$\mathrm{FRF}_{50|75} = \frac{\mathrm{no.(observation} > 50|\mathrm{prediction} > 75)}{\mathrm{no.(prediction} > 75)}.$$

As can be observed from Figs. 4 and 5, the corresponding values are $39/45 = 0.87$ (2005/2006) and $16/17 = 0.94$ (2006/2007), i.e. provided that the forecast exceeds $75\,\mu g\,m^{-3}$, then the observation exceeds at least the threshold $50\,\mu g\,m^{-3}$ with probability $\geqslant 0.87$.

As a complementary measure we can also define the *fraction of correctly forecasted exceedances* as

$$\mathrm{FCF}_{50|75} = \frac{\mathrm{no.(prediction} > 50|\mathrm{observation} > 75)}{\mathrm{no.(observation} > 75)}.$$

Here, we get the values $34/40 = 0.85$ (2005/2006) and $15/15 = 1.0$ (2006/2007), i.e. provided that the observation exceeds $75\,\mu g\,m^{-3}$, then the forecast exceeds at least the threshold $50\,\mu g\,m^{-3}$ with probability $\geqslant 0.85$.

9. Summary and conclusion

We show that PM10 forecasting models based on linear regression for Bolzano, Klagenfurt and Graz provide suitable results. Due to the simple and transparent character of the model we find that more complicated black box approaches are not necessary in this case. The input variables are selected in order to represent both meteorological and anthropogenic parameters. In general, we lay special emphasis on the practical performance and the treatability of the model. For the operational mode it is necessary that the variables are easily available and that both implementation and servicing for users are uncomplicated. The theoretical performance of the models is good. With respect to our quality function 86% (Bolzano, 2005/2006) to 97% (Graz 2006/2007) of the forecasts are assigned to the first three categories. In the practical test runs covering nearly three seasons in Graz, we observed that the necessary meteorological forecasts entail considerably more uncertainty. This is reflected by the fact that now only 73% (2005/2006) to 76% (2006/2007) of the forecasts are at least "satisfactory". However, the performance is very promising after all and there is still space for improvement by additional adaptations. Apart from being a monitoring tool we think that our model might also serve as a suitable and objective base for decision making traffic regulation measures.

References

European Community, 1999. Council Directive 1999/39/EC of 22 April 1999 regulating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air. Official Journal of the European Communities L163, 0041–0060.

Hauck, H., Berner, A., Frischer, T., Gomiscek, B., Kundi, M., Neuberger, M., Puxbaum, H., Preining, O., AUPHEP-Team, 2004. AUPHEP—Austrian project on health effects of particulates—general overview. Atmospheric Environment 38, 3905–3915.

Hooyberghs, J., Mensink, C., Dumont, G., Fierens, F., Brasseur, O., 2005. A neuronal network forecast for daily average PM10 concentrations in Belgium. Atmospheric Environment 39, 3279–3289.

Hörmann, S., Pfeiler, B., Stadlober, E., 2005. Analysis and prediction of particulate matter PM10 for the winter season in Graz. Austrian Journal of Statistics 34, 307–326.

Lonati, G., Giugliano, M., Cernuschi, S., 2006. The role of traffic emissions from weekends' and weekdays' fine PM data in Milan. Atmospheric Environment 40, 5998–6011.

Pérez, P., Reyes, J., 2002. Prediction of maximum of 24-h average of PM10 concentrations 30 h in advance in Santiago, Chile. Atmospheric Environment 36, 4555–4561.

Pope III, C., Dockery, D., 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air and Waste Management Association 56, 709–742.

Schwarze, P., Øvrevik, J., Låg, M., Refsnes, M., Nafstad, P., Hetland, R., Dybing, E., 2006. Particulate matter properties and health effects: consistency of epidemiological and toxicological studies. Human and Experimental Toxicology 25, 559–579.

Silva, C., Pérez, P., Trier, A., 2001. Statistical modelling and prediction of atmospheric pollution by particulate material: two nonparametric approaches. Environmetrics 12, 147–159.

Sturm, P., 2006. Analyse und Modellierung der Feinstaubbelastung in Klagenfurt. Technical Report I-24, Institut für Verbrennungskraftmaschinen und Thermodynamik.

van der Wal, J., Jansen, L., 1999. Analysis of spatial and temporal variations of PM10 concentrations in the Netherlands using Kalman filtering. Atmospheric Environment 34, 3675–3687.