A New Transport Index for Predicting Episodes of Extreme Air Pollution

PIET TERMONIA AND ALFRED QUINET

Royal Meteorological Institute of Belgium, Brussels, Belgium

(Manuscript received 6 May 2003, in final form 27 October 2003)

ABSTRACT

A new index that characterizes a typical length of horizontal and vertical transport is proposed to predict meteorological conditions that are unfavorable for the dispersion of air pollution. This index can be easily computed from the model output of a mesoscale NWP model and can be easily interpreted by a forecaster. It is shown that, for situations of low wind speed and stable atmosphere when atmospheric transport is weak, this index is sufficient to make reliable predictions of peaks of extreme concentrations of some pollutants whose concentrations are predominantly determined by a constant emission. The relation between this index computed from the output of the Aire Limitée Adaption Dynamique Développement International (ALADIN) NWP model and the extreme concentrations of the pollutant nitrogen dioxide (NO_2) during winter in the Brussels, Belgium, capital area is discussed in detail. Although the concentrations of NO_2 are also determined by chemical reaction of nitric oxide with ozone, the fact is used that, for strong pollution events during typical meteorological winter situations in Brussels (having low background concentrations of ozone), the high concentrations of NO_2 are mostly determined by direct NO_2 emission. It is also shown that by the same method some extreme concentrations of particulate matter with diameter <10 μm (PM_{10}) can be predicted to some extent.

1. Introduction

There is a growing interest from urban policy makers in monitoring and forecasting episodes of increased concentrations of pollutants. On a European level, several norms have been established to assess and to manage the air quality in the member states of the European Union (EU). For the four pollutants sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter with diameter of less than 10 μm (PM_{10}), and lead (Pb), EU directives are currently applied.

It is known well that meteorological processes have an important influence on the observed concentrations of air pollutants. In the case of situations with low wind speed and stable atmosphere, dispersion of airborne pollution becomes very weak and pollutants tend to accumulate in the stagnant air. For some pollutants, this case can cause a clear peak in the measured concentrations.

For the pollutants NO_2 and PM_{10}, some episodes occurred in the past in the Brussels, Belgium, capital area, where stable and low-wind meteorological situations were directly responsible for the exceedance of some of the EU norms. Moreover, the European Daughter Directive 1999/30/EC (European Community 1999, 41–60) imposes stronger restrictions on the occurrence of high concentrations of PM_{10} from 2005 onward. It is believed by the Brussels Institute for Management of the Environment (2000, hereinafter BIME 2000) that it will be difficult to meet those future standards if no control measures are undertaken.

An important cause of the pollution in the Brussels capital area is car traffic. In 1997, the total emission of nitrogen oxides was estimated to be 8227 Mg of which 4777 Mg came from traffic (BIME 2000). One of the objectives of BIME is to reduce traffic in Brussels on days when unfavorable meteorological conditions occur. For this goal, reliable weather forecasts are needed.

This article presents some tests of an index that gives a measure of the transport of nonreactive pollutants in stable atmospheric conditions. For those pollutants whose emission can be pragmatically considered constant (e.g., car traffic) and whose concentrations are not strongly dependent on chemical reactions, this index turns out to be useful for predicting extreme peaks of pollution that are potentially dangerous for exceeding health norms.

Today, problems of air pollution are tackled by specialized pollution-oriented forecast systems using urban-scale dispersion and chemical-reaction models; see Brandt et al. (2001) for an example. However, because meteorological conditions are the most determinant factor in the cases of interest in this paper, the proposed index is first tested in a model that is most suited for looking at meteorological effects: a numerical weather prediction (NWP) model, in particular, the mesoscale Aire Limitée Adaption Dynamique Développement In-

Corresponding author address: Piet Termonia, Royal Meteorological Institute of Belgium, Ringlaan 3, B-1180 Brussels, Belgium.
E-mail: piet.termonia@oma.be

ternational (ALADIN) model.[1] Such models provide the necessary input for the more specialized pollution models. Moreover, we believe that, besides the chemical-reaction model output, a simple index taking into account only meteorological conditions may be useful for briefing decision makers who do not have a good knowledge of the atmospheric sciences.

Various turbulence diffusion schemes exist in the literature to estimate the dispersion of pollutants. They are usually applied to estimate the concentrations across a plume of pollution emitted from a point source. These schemes are built around some predefined classes of the dispersive properties of the atmosphere. The classes are based upon some parameters that are expressed in terms of meteorological quantities. The most commonly known of them is the so-called Pasquill system; see Pasquill (1961) for the original classification system. The transport index proposed in the current paper is similar to the index used in the so-called Bultynck–Malet scheme (Bultynck and Malet 1972), which was an old Pasquill-type system. In contrast to this old index, the newly proposed index is easy to interpret physically.

2. The transport index

a. The index and its relation to pollution peaks

A characteristic length scale l can be calculated from the wind speed $\overline{u}$ and the Brunt–Väisälä frequency ν,

$$l = \overline{u}/\nu, \tag{1}$$

where

$$\nu = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}} \tag{2}$$

reflects the stability of the atmosphere, where z is height, g is gravity, and θ is the potential temperature. The smaller l will be found for a smaller $\overline{u}$ (weak horizontal transport) and a more stable atmosphere (weak vertical transport). In fact, this relation implies that when l reaches the lowest observed values one can be sure that both the wind is weak and the atmosphere is very stable. This index is only defined for a stable atmosphere.

The interpretation of this transport index is easy in the case of a nonreactive pollutant suspended in the air. If such a particle undergoes a perturbation in stable atmospheric conditions, it will start oscillating. This vertical oscillation will be superposed on the horizontal advection by the wind $\overline{u}$:

$$z = H\sin(\nu t) \quad \text{and} \quad x = \overline{u}t, \tag{3}$$

where x and z are the horizontal and the vertical coordinate, respectively, H is the amplitude of the oscillation, and t is time. The resulting movement of the particle is a sinusoidal wave, $\sin(2\pi x/\lambda)$ whose wavelength λ depends on the transport index l by $\lambda = 2\pi l$. This transport index is a measure for the absence of transport in the atmosphere. A nonreactive pollutant will not be dispersed if this index is small. Indeed, in that case the particle will stay oscillating in the same place.

This index has been studied and tested during three consecutive winters from December 1999 until February 2003 in the Brussels capital area and gave satisfactory results for predicting extreme peaks of air pollution. This section discusses a pollution episode in January 2001 in detail. In section 2b, extreme air pollution episodes will be defined based on exceedance of threshold values for certain pollutants. Precise conditions for l will be established to assess whether meteorological situations are favorable for such episodes. A systematic validation, based on these criteria, will then be presented.

Of the nitrogen oxides, only NO_2 is considered to be a pollutant. Although the concentrations of NO_2 are determined by chemical reactions of nitric oxide with ozone, the fact is used that for pollution events during typical meteorological winter situations (having low background concentrations of ozone), the high concentrations of NO_2 during strong pollution peaks are mostly determined by direct NO_2 emission. Moreover, because NO_2 is not particularly soluble in water, only in very small amounts is it removed from the air by precipitation. This article investigates to what extent extreme peaks of NO_2 concentrations can be predicted by considering it as a nonreactive pollutant, neglecting precipitation, and using the index l only, based on the assumption that it is released with constant emission.

European Directive 85/580/EEC (European Community 1985, p. 36) determined a guide value of 135 μg m^{-3} for the 98th percentile of the hourly values of the concentrations of NO_2, measured during the calendar year, for improving health protection and for long-term protection of the environment. In the more recent Daughter Directive 1999/30/EC (European Community 1999, 41–60), this guide value is not present anymore. There is only a limit value of 200 μg m^{-3} for the hourly values that can be exceeded only 18 times per year. Because the latter is exceeded only rarely in the Brussels capital area, the old guide value is considered as a reference value in this work.

In January of 2001, NO_2 was measured in nine stations in the Brussels area by BIME. Figure 1 shows the hourly concentrations of NO_2 from 3 to 23 January 2001, in six locations in the Brussels area: Ukkel, Kunst-Wet, Vismarkt, St.-Jans-Molenbeek, St.-Agatha-Berchem, and Haren. The dashed horizontal line on these plots indicates the hourly guide value of 135 μg m^{-3}. It can be seen that this value was exceeded several times during 17 and 18 January. In fact, during this episode the hourly guide value was exceeded at all nine stations. It was also exceeded during the morning on 19 January at the stations in Haren, St.-Agatha-Berchem, and Vismarkt.

[1] ALADIN is the acronym for the limited-area high-resolution model of Météo-France and partners (see ALADIN International Team Members 1997).

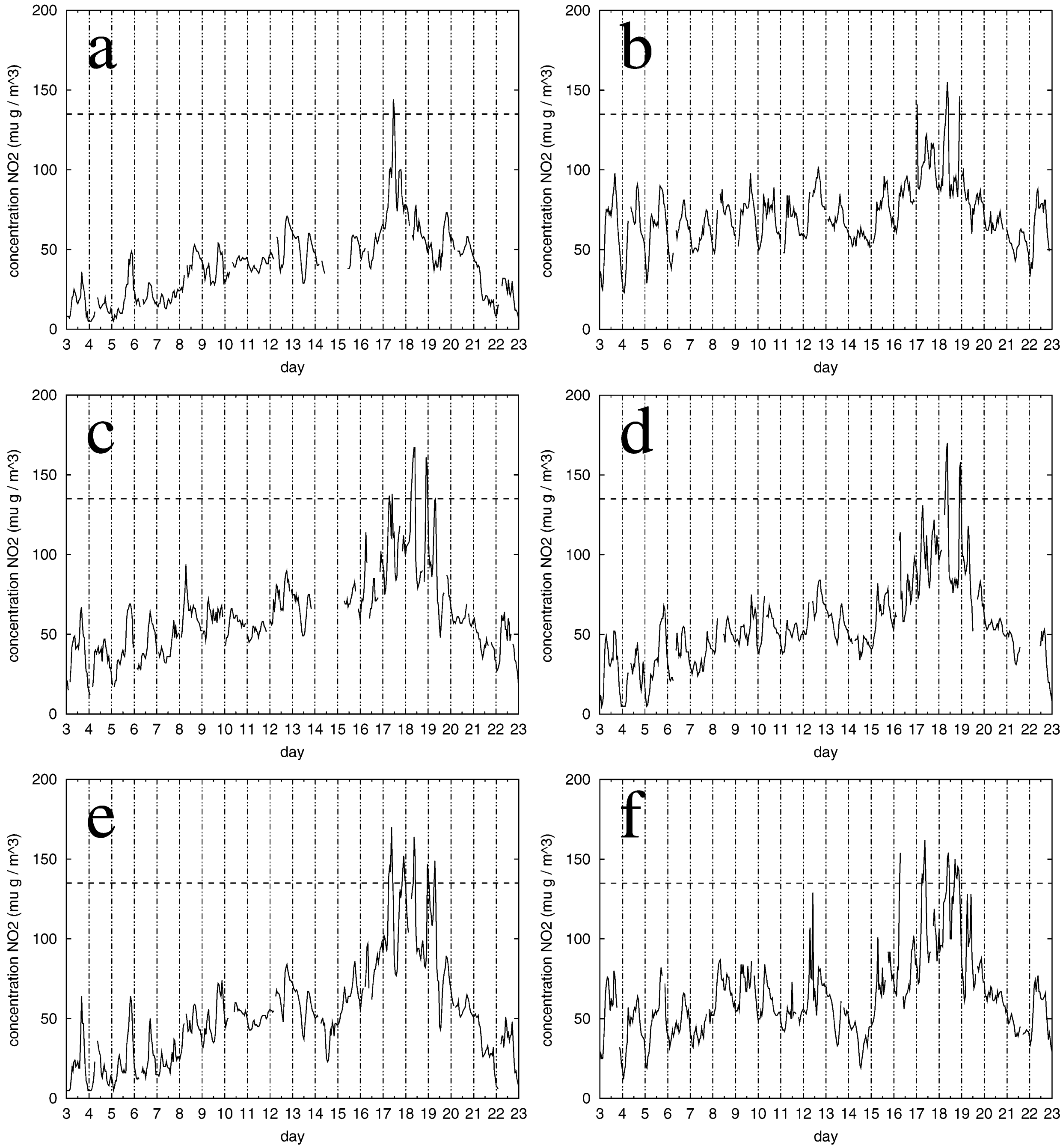

FIG. 1. The hourly values of the NO_2 concentrations (μg m^{-3}) in Jan 2001 for the stations (a) Ukkel, (b) Kunst-Wet, (c) Vismarkt, (d) St.-Jans-Molenbeek, (e) St.-Agatha-Berchem, and (f) Haren as measured by BIME. The EU guide value of 135 μg m^{-3} for the 98th percentile of the hourly values measured during the calendar year (Directive 85/580/EEC) is indicated by the dashed line.

For PM_{10} the mechanism is less clear than for NO_2. Although in urban areas road transport is believed to be a major source of emission of PM_{10}, the final concentrations are equally well determined by resuspension of road particles [see Lenschow et al. (2001) and Harrison et al. (2001) for studies carried out in Berlin, Germany, and London, England, respectively]. So the transport index is expected to be insufficient if other phenomena such as, for example, the absence of resuspension because of the humidity of the roads (Hien et al. 2002) are not taken into account. However, because a substantial influence of the wind and the temperature profiles on PM_{10} concentrations has been observed, its relation to the transport index is also briefly discussed.

The European Daughter Directive 1999/30/EC (European Community 1999, 41–60) determines a guide

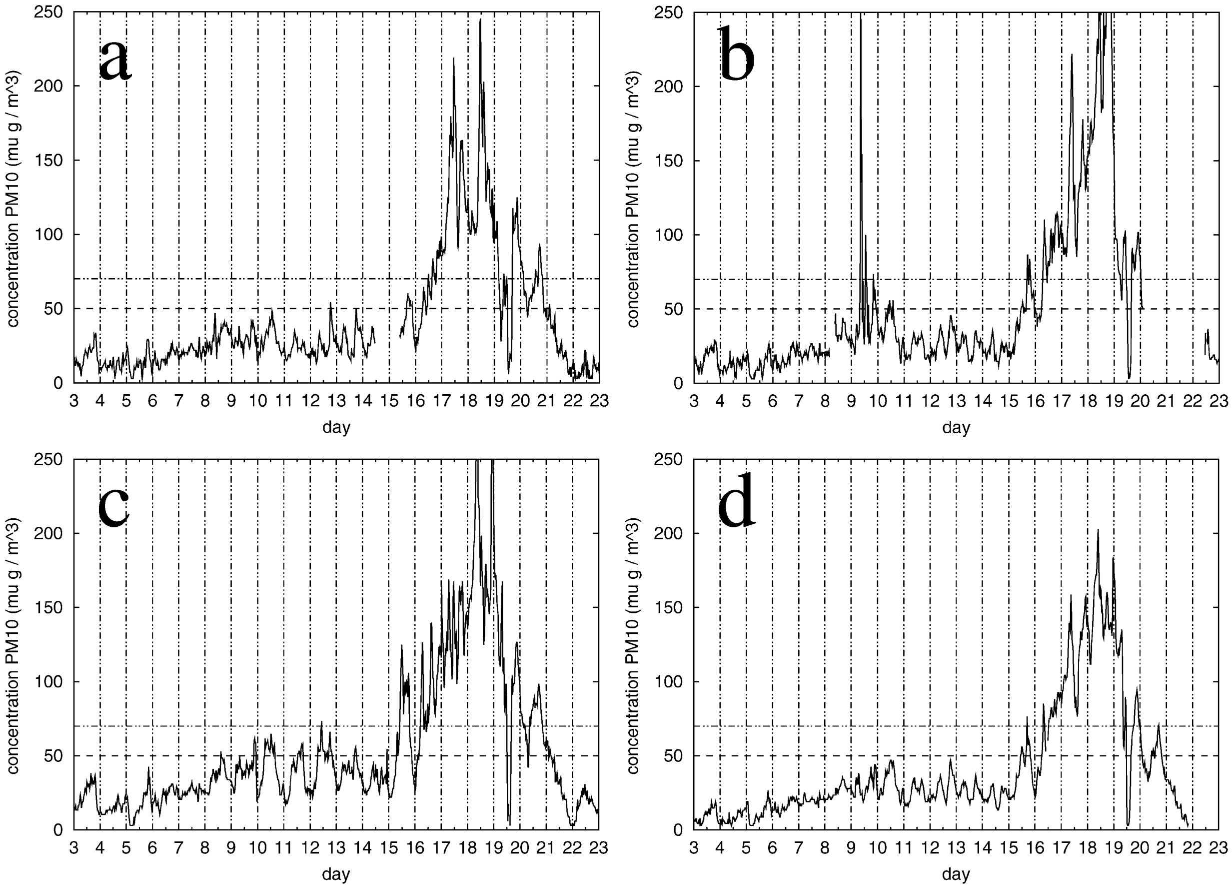

FIG. 2. The half-hourly values of the PM_{10} concentrations (μg m^{-3}) in Jan 2001 for the stations (a) Ukkel, (b) Neder-over-Heembeek, (c) St.-Jans-Molenbeek, and (d) St.-Agatha-Berchem, as measured by BIME. The EU guide value of 50 μg m^{-3} for the daily values (Daughter Directive 1999/30/EC) is indicated by the dashed line, together with the maximum allowed value of 70 μg m^{-3} by the 40% tolerance.

value for the daily averaged PM_{10} concentrations of 50 μg m^{-3}, with an allowed tolerance of 40% in 2001 and, hence, a maximum value of 70 μg m^{-3}. For January of 2001, measurements of PM_{10} were available in six stations in the Brussels area. For 17 and 18 January the value of 70 μg m^{-3} was exceeded at all stations. Figure 2 shows the half-hourly concentrations of PM_{10} as measured by BIME in the four locations of Ukkel, Neder-over-Heembeek, St.-Jans-Molenbeek, and St.-Agatha-Berchem. The European norms were satisfied for SO_2 and Pb in the Brussels area in 2001 (BIME 2000), and so their concentrations are not considered here.

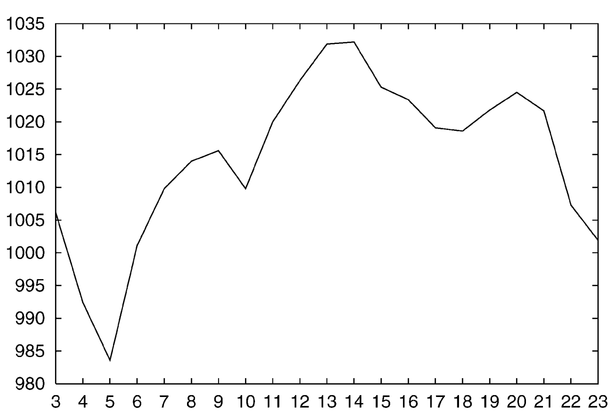

FIG. 3. Mean sea level pressure observed in Ukkel from 3 to 23 Jan 2001 (hPa).

Figure 3 shows the mean sea level pressure observed from 3 to 23 January 2001, in Ukkel. From this figure it can be verified that the pollution episode is associated with high mean sea level pressure, indicating the presence of an anticyclone. Note that the peak itself occurred at the end of a period with negative pressure tendency. In fact, from the 1200 UTC radio soundings launched by the Royal Meteorological Institute of Belgium (RMI) in Ukkel, it was verified that for each day of the period from 10 to 17 January, a clearly delineated inversion was present. These inversions were dynamically generated by a large-scale subsidence. This situation coincided with a drop of the wind speed, which reached its minimum on 17 and 19 January, as can be seen from Fig. 4. The combination of the low wind speed and the presence of the subsidence inversion coincided with the observed peaks in the measured concentrations seen in

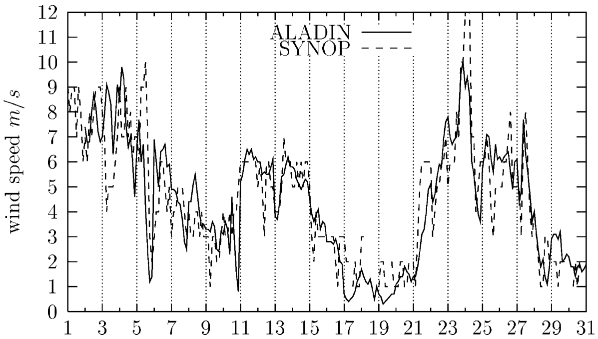

FIG. 4. The observed (SYNOP) and forecast (ALADIN) 10-m wind speed (in the 0–24-h forecast range) for Jan 2001 in Ukkel (Brussels) ($m\ s^{-1}$).

Figs. 1 and 2. The pollution episode observed in these figures occurred during low wind speed and stable meteorological conditions and, hence, low transport index.

The index l was evaluated from the model output of the ALADIN high-resolution model. ALADIN is a limited-area model run operationally 2 times per day at RMI at a resolution of 7 km to make forecasts up to 48 h. Figure 5 shows plots of the output from the ALADIN model of the transport length l as a function of the forecast range and altitude (with respect to sea level) of the ALADIN grid point nearest the station in Ukkel. Because of the spatial model resolution, this output is representative for the meteorological conditions in the six stations of BIME in the Brussels capital area mentioned above. The output is given for six 48-h forecast runs based on the 0000 UTC analyses of 3, 14, 16, 18, 20, and 22 January 2001. These days include the pollution episode discussed above.

Figure 5a illustrates the transport length l of a 48-h ALADIN forecast, based on the analysis at 0000 UTC 3 January 2001. These transport length values are representative for conditions that are dispersive enough to keep the concentrations of the pollutants low (see Figs. 1 and 2).

Figure 5b shows the forecast of l for 14 and 15 January. A shallow layer in which $l < 100$ m during the night between 14 and 15 January can be noticed on the plot. This layer is not deep enough to trap a large amount of pollutants. The situation is, therefore, not considered to be unfavorable for the dispersion of nonreactive pollutants. Note that such a layer was not present in the forecast for 3 and 4 January in Fig. 5a.

Figure 5c shows the forecast of the transport length, starting at 0000 UTC 16 January 2001. It can be seen that there is a layer close to the surface in which l is smaller than 100 m. This layer starts to grow at 1500 UTC until its top exceeds the height of 100 m. The white areas at the surface indicate unstable conditions ($\partial\theta/\partial z < 0$), where l is not defined. The whole phenomenon takes place over a time scale of about 24 h (from the start of the growth of the layer until its disappearance), causing an accumulation of the emitted pollutants. The situation during the night between 16 and 17 January is considered to be unfavorable for the dispersion of nonreactive pollutants. In Fig. 1, it can be seen that the value of 135 $\mu g\ m^{-3}$ was exceeded at all six stations during the morning of 17 January.

Figure 5d shows the forecast of the transport index l for 18 and 19 January. It can be seen that there is a thick layer in which $l < 100$ m. Hence, also for these days the situation is considered to be unfavorable for the dispersion of nonreactive pollutants. On 18 January the value 135 $\mu g\ m^{-3}$ was exceeded at five of the six stations. During the morning of 19 January, this value was exceeded at three of the six stations (there was a maximum of 159 $\mu g\ m^{-3}$ during the hour between 0000 and 0100 UTC).

Figure 5e shows the forecast of l based on the 0000 UTC analysis of 20 January. The layer with $l < 100$ m is disappearing. For the forecast for 22 and 23 January in Fig. 5f, the typical situation in which no layer of $l < 100$ m exists is found again.

So the situation was unfavorable for the dispersion of nonreactive pollutants during the night between 16 and 17 January and on 18 and 19 January. Figure 2 shows that the value of 70 $\mu g\ m^{-3}$ for PM_{10} was exceeded for this period, although there were no peaks on 19 January. Even if the relation is less clear, as in the case of NO_2, it shows that meteorological conditions played a major part in determining the final concentrations.

Note from the concentrations in Fig. 1 for NO_2 that the air quality was better on 19 January 2001 than on 18 January 2001, whereas Fig. 5d suggests the opposite. However, this result is due to forecast errors in the 24–48-h forecast range of the forecast based on the 0000 UTC analysis of 18 January 2001. This error can be seen in the 0–24-h forecast range (where the model has a higher forecast skill) on the 0000 UTC forecast on 19 January 2001 in Fig. 6, where the layer of $l < 100$ m disappears after 1200 UTC.

Figure 7 shows the ALADIN output of the mean sea level pressure and the 10-m wind at 0600 UTC 17 January 2001, at 30-h forecast time, well inside the period of the unfavorable conditions on Fig. 5c. The situation is clearly anticyclonic. The pressure over Belgium and the surrounding areas is quasi uniform (1021 hPa). There is a region with calm winds (less than 0.5 $m\ s^{-1}$) that includes Brussels in the north.

b. An objective validation

The proposed index was objectively validated by comparing the output of the 0000 UTC runs of the ALADIN model with the measured concentrations of NO_2 for the three consecutive winters [December–January–February (DJF)] 2000/01, 2001/02, and 2002/03, constituting data for 9 months in total. To keep the validation as coherent as possible, the same version of the ALADIN model was used for all of the forecasts.

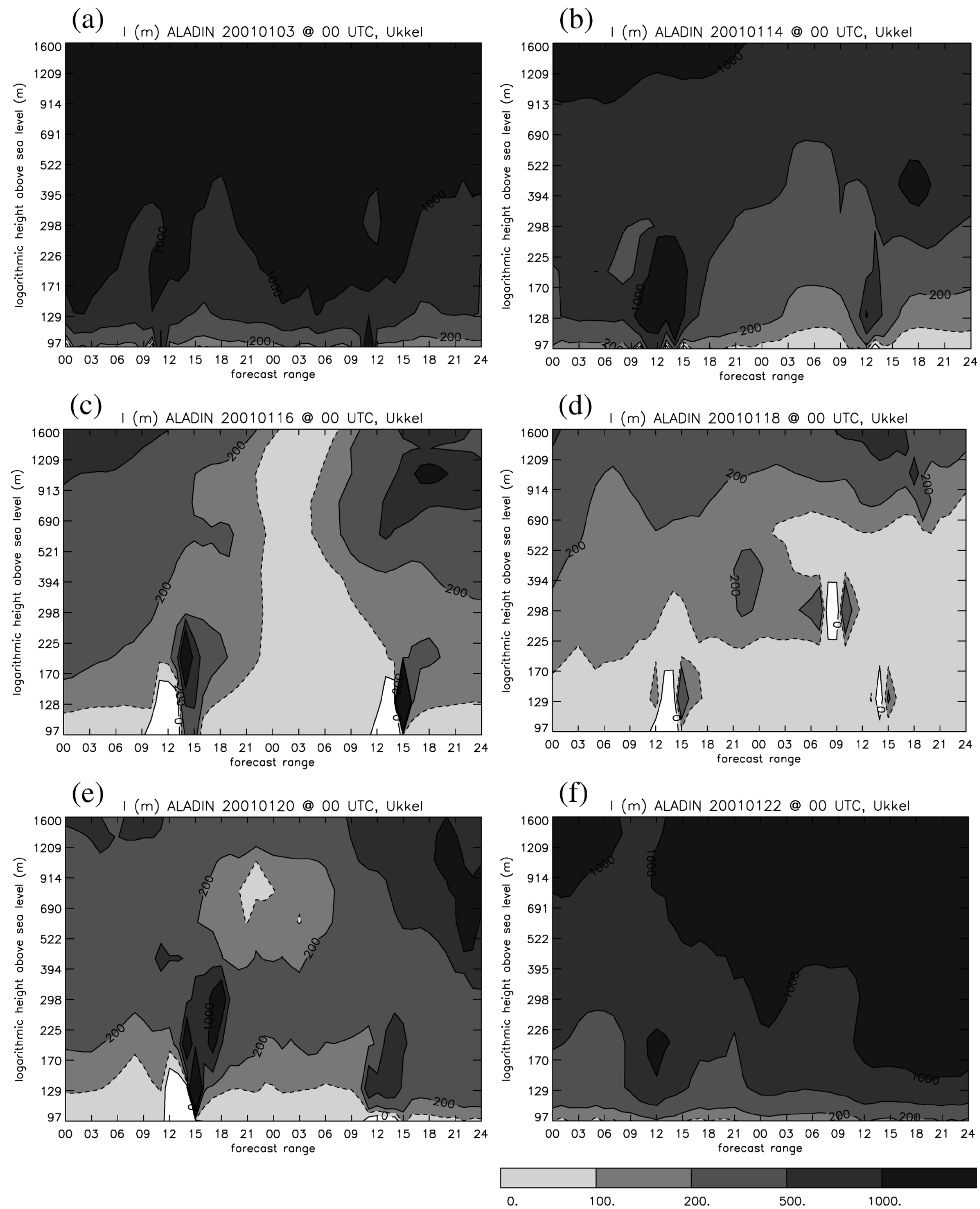

FIG. 5. Plots of the transport length l of the ALADIN forecast for the runs based on the analyses at 0000 UTC (a) 3, (b) 14, (c) 16, (d) 18, (e) 20, and (f) 22 Jan 2001. During the pollution episode on (c) 17 and (d) 18 and 19 Jan there is a layer in which $l < 100$ m in the lowest few hundred meters of the atmosphere. The white areas indicate unstable parts of the atmosphere where the Brunt–Väisälä frequency is not defined.

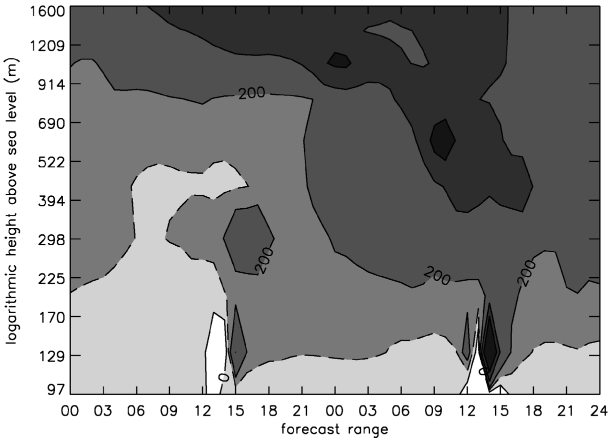

FIG. 6. Plot of the transport length l (m) of the ALADIN forecast for Ukkel for the run based on the analysis at 0000 UTC 19 Jan 2001. In contrast to the forecast of the previous day (see Fig. 5d). The layer with $l < 100$ m in the lowest few hundred meters of the atmosphere disappears after the 12-h forecast range. Scale is same as in Fig. 5.

TABLE 1. Dates on which the hourly value of 135 μg m^{-3} was exceeded for at least four out of the six stations Ukkel, Kunst-Wet, Vismarkt, St.-Jans-Molenbeek, St.-Agatha-Berchem, and Haren during the three winters (DJF) 2000/01, 2001/02, and 2002/03. On 9 Jan 2002, no data were available for the station Haren.

Date	No. stations
17 Jan 2001	5/6
18 Jan 2001	5/6
15 Feb 2001	5/6
9 Jan 2002	4/5
20–21 Feb 2003	4/6

A pollution peak was called extreme when the hourly value of 135 μg m^{-3} for NO_2 is exceeded in at least four of the following six measurement stations of BIME: Ukkel, Kunst-Wet, Vismarkt, St.-Jans-Molenbeek, St.-Agatha-Berchem, and Haren. These are the same stations as in Fig. 1. With this definition, exceedance was found on 5 days during these three winters, listed in Table 1.

From the discussion about January of 2001 above, criteria for forecast conditions that are unfavorable for

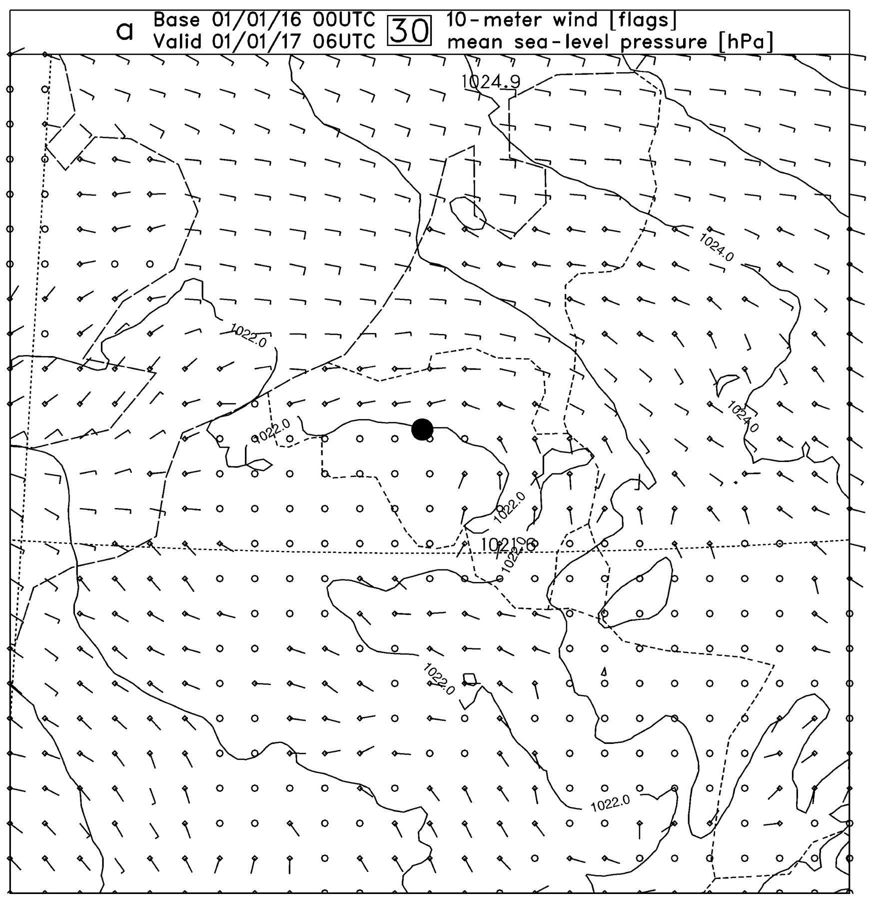

FIG. 7. The ALADIN output of the mean sea level pressure and the 10-m wind at 0600 UTC 17 Jan 2001. There is a large area of calm wind (less than 0.5 m s^{-1}), covering the north of France and Belgium (borders are indicated in dashed lines), including Brussels (indicated by the black dot) in the north.

TABLE 2. Dates on which a surface layer with $l < 100$ m was present with a depth of at least 100 m for a time span of 12 h or more, in the 0000 UTC ALADIN runs during the three winters (DFJ) 2000/01, 2001/02, and 2002/03. For some days, this layer was not present in all subsequent model runs covering this time span, indicating forecast inaccuracies. Those runs are presented in the lower part of the table.

Date	Comments on the forecast
16–17 Jan 2001 night	Layer became deeper than 500 m
18 Jan 2001	—
19 Jan 2001 morning	—
15 Feb 2001	Layer became deeper than 500 m
20–21 Feb 2003 night	Layer became deeper than 500 m
19 Jan 2001 afternoon	Conditions satisfied in the run on the 18th, layer disappeared in the run on the 19th
6–7 Jan 2002 night	Conditions satisfied in the run on the 6th, layer *not* deep enough in the 0–12-h range of the run on the 7th
8–9 Jan 2002 night	Conditions satisfied in the run on the 9th, layer *not* deep enough in the 0–12-h range of the run on the 9th
10 Jan 2003 afternoon	Layer in the 30–48-h range of the run on the 9th, time span *too short* in the run on the 10th

the dispersion of nonreactive pollutants were established as follows: There exists a layer at the surface for a time span on the order of 24 h, where $l < 100$ m. During these 24 h there should be an uninterrupted span of 12 h or more in which the layer is deeper than 100 m. In such layers, there may appear instabilities near the surface because of heating during the day. These instabilities can be ignored if they are covered from above with a layer of $l < 100$ m, preventing the escape of the pollutants upward. These conditions will be shortly called *unfavorable* henceforth. Note that using radiosounding profiles instead of model output is useless for the validation of the index because such profiles are usually available with time intervals of 12 or 24 h, which does not suffice to check the conditions for the accumulation of the pollutants.

For the same three winters from December 2000 until February 2003, it was checked as to on which days these criteria were satisfied in the forecast time evolution of the profiles of l, as exemplified in Fig. 5. The resulting days are listed in Table 2. In those cases in which l showed substantial differences in the 24–48-h forecast range with the 0–24-h forecast range of the subsequent day, the 0–24-h range was taken, assuming that it has a higher forecast skill. To get an idea of the predictability of the events, the days for which the conditions were only unfavorable in the first of the two forecasts are added to the lower part of Table 2, together with a comment on the forecast quality.

In comparing Table 2 with Table 1, it can be seen that in those forecast unfavorable conditions for which there is a priori no indication of a forecast error (upper part of Table 2), an extreme peak is found in Table 1, except during the morning of 19 January 2001, as discussed above. In this latter case there was exceedance in only three stations. Nevertheless, this can be seen as a tail of the episode that started in the evening of 16 January (see Fig. 1).

On 9 January 2002 there was exceedance in four of five stations as indicated in Table 1. The 24–48-h range of the 0000 UTC forecast run on 8 January was unfavorable to cause this peak. However, in the 0–24-h range of the 0000 UTC forecast on 9 January the layer with $l < 100$ m was shallower than 100 m. With the assumption that the latter is more reliable, it is concluded that this peak was not forecast well. It is interesting to note that there was no peak in Ukkel, which is explained by the fact that Ukkel is located higher than the other stations and is expected to have a layer of $l < 100$ m that is shallower than at the other stations, probably not deep enough to trap the pollutants.[2]

From the presented data it can be concluded that when the layer of $l < 100$ m becomes deep (deeper than 100 m) and the forecast is reliable, one may with very good confidence expect an extreme pollution peak in Brussels.

For operational purposes, the 24–48-h forecast range is used. The lower part of Table 2 shows that applying the objective criterion to the model output in this forecast range sometimes leads to false alerts, because of the forecast errors (but not because of the use of the index l). However, for the operational use of the ALADIN model output it was observed that in the cases in which the layer extends up to elevations higher than 500 m during winter (DJF) on a working day there is, based on the analysis of these 3-yr data, no doubt that a peak of extreme pollution will occur.

To discuss the most recent pollution peak, Fig. 8 shows the transport index l of the forecast of 20 February 2003. Table 3 shows the measured concentrations for 21 January 2003. The EU guide value of 135 μg m^{-3} for NO_2 was exceeded at seven out of the nine stations, except at St.-Agatha-Berchem and Ukkel where it was 130 and 134 μg m^{-3}, respectively. The EU guide value of 60 μg m^{-3} for PM_{10} was exceeded at all stations for which measurements were taken (the tolerance for 2003 is 20%). The layer of critical length $l = 100$ m was established using the data for the winter (DJF) of 2000/01. The data for the winters of 2001/02 and 2002/

[2] In fact, the resolution of the model is too small to parameterize such orographic differences.

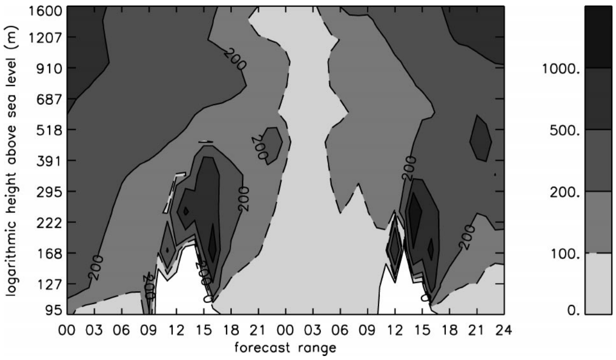

FIG. 8. Plot of the transport length (m) of the ALADIN forecast for Ukkel for the run based on the 0000 UTC analysis of 20 Feb 2003. A layer in which $l < 100$ m starts to grow from the surface in the lowest few hundred meters of the atmosphere, reaching an altitude of more than 1500 m. The white areas indicate unstable parts of the atmosphere for which the Brunt–Väisälä frequency is not defined.

TABLE 3. The maximal 1-h mean concentrations of NO_2 together with the time at which this maximum was measured, and the daily mean concentrations of PM_{10} on 21 Feb 2003 in nine different stations in the Brussels area. All concentrations are expressed in micrograms per cubic meter.

Station	NO_2 (μg m^{-3}) max 1-h mean	Time (LT)	PM_{10} (μg m^{-3}) daily mean
Brussels Kunst-Wet	164	1300	
Brussels Vismarkt	166	2300	
Elsene	220	0900	
Haren	187	1000	133
Neder-over-Heembeek	159	1100	99
St.-Agatha-Berchem	130	1300	78
St.-Jans-Molenbeek	170	2300	107
St.-Lambrechts-Woluwe	196	1000	84
Ukkel	134	1400	85

03 and, in particular, this recent peak should be considered as a nontrivial check.

During the three studied winters, some cases were found with low wind speeds but for which no extreme peaks of the type discussed above were observed. An example is 30 January 2001, on which the wind was weak (as can be seen on Fig. 4) but no strong persisting thermal inversion was present. This example confirms the need to take into account the stability for this kind of pollution event.

c. *Discussion*

The transport index l is closely related to the index used in the so-called Bultynck–Malet scheme (Bultynck and Malet 1972). This scheme defines seven stability classes based on estimates of the standard deviations of the crosswind and vertical distributions σ_y and σ_z of a bi-Gaussian model. It uses the following parameter:

$$\lambda = \log_{10}(10^6|S|), \tag{4}$$

where

$$S = (\partial\theta/\partial z)/\overline{u}^2. \tag{5}$$

The index S was used before by Högström (1964) to calculate σ_z, citing a rigorous theoretical treatment by Lettau (1952, 1959). In the existing diffusion schemes, this index was always calculated by taking the values of θ and $\overline{u}$ on fixed heights. For instance, in the Bultynck–Malet system $\overline{u}$ was taken at 69 m, and $\partial\theta/\partial z$ was calculated by taking the difference between 8 and 114 m. Today, $\overline{u}$ and $\partial\theta/\partial z$ can be computed on all model levels of a NWP model, as is done in Fig. 5.

The relation between the transport length l and S is

$$l = \left(\frac{\theta}{gS}\right)^{1/2}. \tag{6}$$

The value $\lambda \geq 2.75$ defined the first class E_1 in the Bultynck–Malet system, characterizing a very stable atmosphere. For potential temperature values of $\theta = 260, \ldots, 300$ K and critical value of $l = 100$ m, λ gets the values $\lambda = 3.4, \ldots, 3.5$, which correspond to an even stronger stability than the E_1 criterion in Bultynck and Malet (1972) for a very stable atmosphere. Figure 9 shows λ calculated from the forecast model output for the run based on the analysis at 0000 UTC 16 January 2001, to be compared with Fig. 5c. In comparing Fig. 9 with Fig. 5c, the presence of the low-l layer can be identified from the λ plot also by taking the critical value $\lambda = 3.5$. In fact, an investigation of the data for the three considered winters has shown that both l and λ can be used to predict the pollution peaks in Table 1.

Although the parameter λ gives the same results as the transport length l, its physical interpretation remains problematic; see, for instance, Lettau's derivation (1952, 1959) presented in the paper by Högström (1964).

3. Conclusions

A new transport index to identify meteorological conditions that are extremely unfavorable for the dispersion

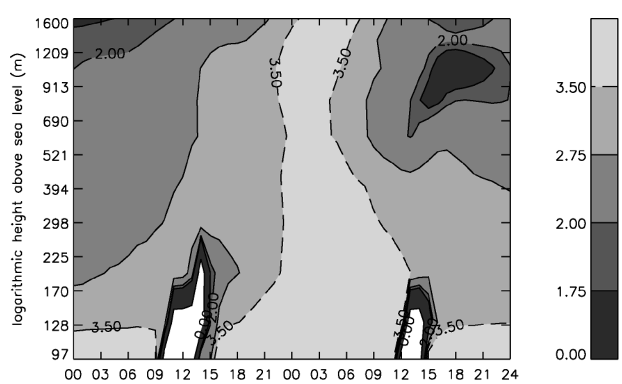

FIG. 9. The parameter λ of the Bultynck–Malet system for Ukkel for the ALADIN forecast for 16 and 17 Jan 2001, to be compared with the transport index in Fig. 5c.

of primary pollutants was introduced. It is based on the wind speed and the Brunt–Väisälä frequency.

It was discussed as to how extreme air pollution episodes of the pollutant NO_2 were predicted from the model output of the NWP model ALADIN during three consecutive winters in the Brussels capital area. Also, the concentrations of PM_{10} were discussed, but it was stressed that extra factors should be taken into account for this pollutant to obtain more reliable predictions. This investigation lies outside the scope of this article.

The index is related to an old index that was used in the past in diffusion schemes. It was shown that the meteorological conditions responsible for the discussed extreme pollution peaks can be identified from both indices. However, as compared with this old index, the new index has the advantage that it is easy to interpret physically. Furthermore, it is also now applied with a state-of-the-art NWP model. This application enhances its usefulness in an operational context, and it can thus easily be integrated in the forecaster's overview of the meteorological situation. This approach may also help in the assessment of the predicted concentrations of nonreactive pollutants by operational chemical transport models. This transport index is now operationally used at the Royal Meteorological Institute of Belgium.

Acknowledgments. We are much indebted to P. Vanderstraeten of BIME for providing us with the pollutant concentration data and for many useful discussions. We also benefited from useful discussions with O. Brasseur, C. Demuth, A. Derouane, and F. Fontaine. We thank three anonymous reviewers for carefully reading the manuscript. It was greatly improved by taking into account their numerous pertinent comments. This work was supported by the Belgian Federal Office for Scientific, Technical and Cultural Affairs (OSTC/DWTC/SSTC) and by the ALATNET training network. ALATNET is supported by the TMR/IHP Programme of the European Community, but the information provided here is the sole responsibility of the ALATNET team and does not reflect the European Community's opinion.

REFERENCES

ALADIN International Team Members, 1997: The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research. *WMO Bull.,* **46,** 317–324.

Brandt, J., J. H. Christensen, L. M. Frohn, F. Palmgren, R. Berkowicz, and Z. Zlatev, 2001: Operational air pollution forecasts from European to local scale. *Atmos. Environ.,* **35,** 91–98.

Brussels Institute for Management of the Environment, 2000: De luchtkwaliteit in het Brussels Hoofdstedelijk Gewest, Immissiemetingen 1997–1998–1999 (The air quality in the Brussels Capital Region, concentration measurements 1997–1998–1999). BIME Laboratory for Environmental Research, Tech. Rep., 153 pp. [Available in Dutch or French from BIME, Gulledelle 100, 1200 Brussels, Belgium.]

Bultynck, H., and L. Malet, 1972: Evaluation of atmospheric dilution factors for effluents diffused from an elevated continuous point source. *Tellus,* **24,** 455–472.

European Community, 1985: Council Directive 85/580/EEC of 20 December, amendment of Council Directive 85/203/EEC on air quality standards for nitrogen dioxide. Official Journal of the European Communities, No. L372.

——, 1999: Directive 1999/30/EC of the European Parliament and of the Council of 22 April 1999 relating to the limit values for SO_2, NO_2, and NO_x, particulate matter and lead in ambient air. Official Journal of the European Communities, No. L163.

Harrison, R. M., J. Yin, D. Mark, J. Stedman, R. S. Appleby, J. Booker, and S. Moorcroft, 2001: Studies of the coarse particle (2.5–10 μm) component in UK urban atmospheres. *Atmos. Environ.,* **35,** 3667–3679.

Hien, P. D., V. T. Bac, H. C. Tham, D. D. Nhan, and L. D. Vinh, 2002: Influence of meteorological conditions on $PM_{2.5}$ and $PM_{2.5–10}$ concentrations during the monsoon season in Hanoi, Vietnam. *Atmos. Environ.,* **36,** 3473–3484.

Högström, U., 1964: An experimental study on atmospheric diffusion. *Tellus,* **16,** 205–251.

Lenschow, P., H.-J. Abraham, K. Kutzner, M. Lutz, J.-D. Preuß, and W. Reichenbächer, 2001: Some ideas about sources of PM10. *Atmos. Environ.,* **35,** 23–33.

Lettau, H., 1952: The present position of selected turbulence problems in the atmospheric boundary layer. *Geophys. Res. Papers,* **19,** 49–95.

——, 1959: Wind profile, surface stress and geostrophic drag coefficients in the atmospheric surface layer. *Advances in Geophysics,* Vol. 6, 241–257.

Pasquill, F., 1961: The estimation of the dispersion of windborne material. *Meteor. Mag.,* **90,** 33–49.