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Meteorological evaluation of a severe air pollution episode in Helsinki on 27–29 December 1995

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This paper describes an evaluation and meteorological analysis of a severe air quality episode that occurred in the Helsinki Metropolitan Area during 27–29 December 1995. The pollutants originated predominantly from local sources. The episode was formed in anticyclonic high pressure conditions that lead to low wind speeds and the formation of an extremely strong ground-based radiation inversion. We utilised the 24 hourly forecasts of the Finnish version of the numerical weather forecasting model HIRLAM (High Resolution Limited Area Model, operational from 1999 to 2003). The HIRLAM model under-predicted both the inversion strengths (°C) and inversion temperature gradients ($^\circ C\ m^{-1}$), compared with the corresponding measured data. We also compared the temperature profiles predicted by HIRLAM with those predicted by the non-hydrostatic meteorological model MM5. The pollutant concentrations during the episode have been predicted using an urban dispersion modelling system, and evaluated against measured data.

Introduction

Air pollution episodes in and around cities can pose a serious hazard to human health. Under episodic conditions, concentrations of air pollutants can considerably exceed national and international standards and limit values (e.g., QUARG 1993 (alternatively, *see* http://www.aeat.com/netcen/airqual/reports/quarg/quarg_94.pdf), 1996 (alternatively, *see* http://www.aeat.com/netcen/airqual/reports/quarg/quarg_11.pdf)). Available information concerning European peak pollution episodes has been reviewed within the COST 715 action "Meteorology applied to Urban Air Pollution Problems" (e.g., Fisher *et al*. 2001) by Kukkonen (2001a; alternatively *see* http://cost.fmi.fi/statusreportprinted.pdf). The above mentioned review surveys the national situation in 13 countries; it can be utilised, e.g., by national or local authorities that are concerned with this problem.

The causes of air pollution episodes are complex and depend on various factors including emissions, meteorological parameters, topography, atmospheric chemical processes and solar radiation. The relative importance of such factors is dependent on the climatic characteristics, geographical region and the season of the year (e.g., Sokhi *et al*. 2002). For example, particulate matter episodes in many cities have been experienced in winter and spring times. Nitrogen dioxide episodes can occur both in winter and in summer, and ozone levels can be particularly high during summer periods.

Inversions, which lead to stagnant air, are particularly important in relation to episodes and these are in many cases responsible for very high levels of pollution (e.g., Piringer and Kukkonen 2002, alternatively *see* http://cost.fmi.fi/proceedingsotoulouse.pdf). In addition, regional and long-range transport of pollution can also lead to standards being exceeded, for example for fine particulate matter. Consequently, it is vital to understand the underlying processes on local, regional and continental scales that lead to air pollution episodes.

Watson and Chow (2002) analysed a wintertime $PM_{2.5}$ episode that occurred in California's San Joaquin Valley in January 2000. The episode lasted for approximately ten days. The influence of regionally and long-range transported $PM_{2.5}$ was substantial, as half or more of the urban fine particulate matter concentrations were present at surrounding non-urban locations. Primary particles accumulated during early morning and nighttime, decreasing when a shallow radiation inversion coupled to a valleywide air layer.

Liu and Chan (2002a, 2002b) analysed a two-day episode with increased concentrations of NO_x, RSP (Respirable Suspended Particulates) and SO_2 in Hong Kong in December 1999. They concluded that local vehicular and stationary emissions were mainly responsible for the increased concentrations. The stably stratified synoptic conditions combined with sea-land breezes over a complex topography were reported as the main meteorological factors affecting the concentrations.

Almbauer *et al*. (2000) investigated an episode in the city of Graz (Austria) that occurred from 10 to 13 January 1998. They used a mesoscale dispersion model to simulate local flow field and air quality during the episode, and compared the predicted concentrations of NO and NO_2 with the data from a local air quality monitoring network. They concluded that the increased NO and NO_2 concentrations were mainly originated from local traffic and domestic heating. The main meteorological factors were reported to be an anticyclonic weather situation, temperature inversions and local wind systems within a mountainous area.

Berge *et al*. (2002a) presented results from Numerical Weather Prediction (NWP) modeling in northern Europe during strong wintertime inversions, and discussed how realistic these simulations are. They utilised numerical results produced by two NWP models (HIRLAM and ECMWF, European Centre for Medium-Range Weather Forecasts), combined with the utilisation of the non-hydrostatic meteorological model MM5. These analyses also include numerical modeling of the same episode that is addressed here. We have included here a comparison of the vertical temperature profiles predicted by MM5 and HIRLAM, together with data measured at a mast of a height of 327 m.

The aim of this study is to help the national and local authorities by developing and evaluating methods for the forecasting of episodes. Emergency preparedness plans have been designed for several European cities, including Helsinki, in case of very severe episodes (e.g., Railo 1997). This paper is focused on analysing one specific historical episode in order to gain a better insight on the meteorological factors that influence the formation and evolution of wintertime NO_2 and particulate matter episodes. We also aimed to evaluate the validity of the routinely performed HIRLAM analyses for predicting the key meteorological variables in such cases.

Materials and methods

Experimental data

Meteorological data

We utilised meteorological data that were obtained at the sounding station of Jokioinen, at the radio tower of Kivenlahti, and at the synoptic stations of Helsinki–Vantaa airport and Isosaari.

The atmospheric sounding station of Jokioinen is located in southern Finland, at a distance of approximately 90 km northwest from Helsinki in a rural location, at a height of 104 m above the sea level (Fig. 1). The terrain surrounding the station consists of fairly flat fields and a few hills covered with forest; the height of the hills

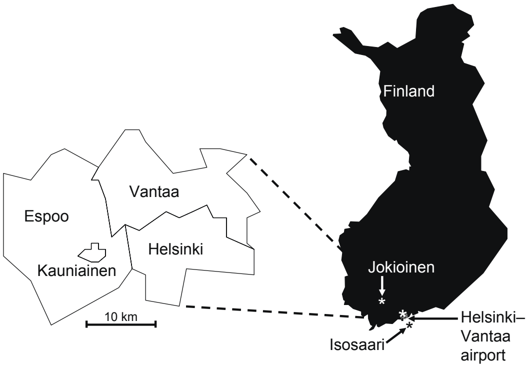

Fig. 1. The location of the meteorological sounding station of Jokioinen, and the meteorological stations at the Helsinki–Vantaa airport and at Isosaari.

is of the order of 20 m, as compared with the surrounding terrain (Tammelin 1991). The data contains measurements of the vertical profiles of atmospheric pressure, temperature, relative humidity, and wind direction and speed. The profiles are measured continuously twice a day, and the measured values are obtained from 50 to 80 height levels; the highest measuring altitude is approximately 22 km. The wind sensor is located at a height of 30 m from the ground surface.

The Kivenlahti mast is situated in the Helsinki Metropolitan Area (Fig. 2). The base of the Kivenlahti mast is at a height of 44 m above the sea level. The height of the mast is 327 m. The mast is situated at a distance of approximately 15 km to the west from the centre of Helsinki, and at a distance from the seashore of approximately from 5 to 8 km. The roughness length in the vicinity of the mast varies from 1.5 m to 3.0 m. The measurement instruments are located at nine levels, from 5 m to 327 m.

The data extracted from such measurements needs to be carefully evaluated in order to find out possible disturbances caused by the presence of the tower itself (e.g., Middleton 2002). For a more detailed description of the measurements and the site, and the evaluation of data quality, the reader is referred to Karppinen *et al.* (2002). The analysis of the wind speed measurement data demonstrated disturbances in one specific wind direction sector, approximately from 20° to 80°; for this sector, the anemometers are in the lee side of the structure. We utilised in this study only the temperature measurements; these are less sensitive to the presence of the mast, compared with the wind measurements.

Fig. 2. Location of the meteorological stations of Kivenlahti (radio tower), Helsinki–Vantaa airport and Isosaari within the Helsinki Metropolitan Area, comprising four cities (Helsinki, Espoo, Vantaa and Kauniainen). The air quality stations of Vallila and Töölö in central Helsinki, and Leppävaara and Luukki in Espoo have also been shown. The size of the depicted area is approximately 35 × 25 km^2. The areas with the highest proportion of buildings (*vs.* other forms of land use) have been presented with a grey shading.

The synoptic meteorological station at Helsinki–Vantaa airport is situated approximately at a distance of 15 km north of central Helsinki, and the station of Isosaari is located on an island that is situated approximately at a distance of 20 km south of central Helsinki (Fig. 2).

Air quality data

We analyzed air quality data from available urban air quality measurement stations in the whole of Finland during the episode. The stations have been described in detail by Kukkonen *et al.* (1999).

A more detailed analysis was performed regarding the concentration data measured at the urban air quality monitoring network stations in the Helsinki Metropolitan Area. In 1995, five permanently located and four mobile measurement stations (the latter ones are relocated each calendar year) were operated by the Helsinki Metropolitan Area Council. The pollutants measured were SO$_2$, NO and NO$_x$, CO, O$_3$, TSP and

PM_{10}. In addition, there was one urban meteorological measurement station. A more detailed description of the stations and the measurement programmes has been presented by Karppinen *et al.* (2000b) and Kousa *et al.* (2001). The terrain in the Helsinki Metropolitan Area is fairly flat; the height from the sea level varies from 0 to 114 m, with a mean height of 25.5 m.

We used measurement data from four air quality stations in the Helsinki Metropolitan Area. These include the urban traffic stations of Töölö and Vallila, the suburban station of Leppävaara and the urban background station of Luukki (Fig. 2). We present the hourly time-series of the data measured at two stations located in central Helsinki (Töölö and Vallila) in this paper.

The concentrations of oxides of nitrogen were measured with chemiluminescence methods (Environment AC30M/31M), the correct operation of which was checked daily. The concentrations of CO were measured with infrared absorption methods, (Environment CO10M/11M), and for the O_3, UV-absorption based method (Monitorlabs 8810) was used. The PM_{10} concentrations were measured with TEOM (Tapered Element Oscillating Microbalance, TEOM Series 1400/1400a). For a more detailed discussion of the quality control and quality assurance procedures, the reader is referred to Kousa *et al.* (2001), Kukkonen *et al.* (2001b) and Viidanoja *et al.* (2002).

The models

The numerical weather forecasting models

The numerical weather forecasting model HIRLAM serves as a basic tool for weather forecasts in several European countries (http://www.knmi.nl/hirlam/). We utilised in this study the Finnish operational HIRLAM version (e.g., Eerola 2000). It is a hydrostatic grid model that can be executed with two horizontal resolutions, 22 km and 44 km, for the synoptic and regional scale HIRLAM versions, respectively. The synoptic scale HIRLAM version 4.6.2 was used here in the numerical computations (resolution of 22 km); this version has been operational from November 1999 to March 2003. The larger computational domain covers Europe and the Northern Atlantic, and the smaller one Northern Europe, the British Isles, and part of continental Central Europe and Russia.

In both model versions, the number of horizontal grid points is 194 × 140, and there are 31 vertical grid levels. The boundary values for the larger domain are taken every six hours from the global ECMWF-model, and the smaller domain boundary values are taken from the larger domain every three hours.

The model output includes the following data for the standard pressure levels of 1000, 925, 850, 700, 500, 400, 300, 250, 100 and 70 hPa: wind, temperature, relative humidity, geopotential height and vertical velocity. The model also evaluates surface pressure and temperature, accumulated convective and stratiform precipitation and their intensities, sea surface temperature, ice coverage and albedo. The height of the lowest computational vertical level is 30 m, and additionally, the wind velocity at a height of 10 meters, temperature at a height of two meters and specific humidity at a height of two meters are interpolated, based on the values at the lowest vertical level and the surface values.

The non-hydrostatic meteorological MM5 model version 3 (Fifth Generation NCAR/Penn State Meso-Scale Modeling System) was used with a set-up of three nests with the horizontal resolution of 9, 3 and 1 km. The meteorological input data at the outer domain boundaries used for the simulations was obtained from the ECMWF model computations. For details of the model computations, the reader is referred to Berge *et al.* (2002b).

The meteorological pre-processing model

The meteorological pre-processing model MPP-FMI evaluates the turbulent heat and momentum fluxes in the atmospheric boundary layer from synoptic weather observations. The parameterization of the atmospheric boundary layer height is based on boundary layer scaling, utilizing meteorological sounding data (e.g., Karppinen *et al.* 2000a). This pre-processor has also been adapted to better allow for urban meteorological conditions (Karppinen *et al.* 2000c). The pre-processed meteorological data is based on a combination of the data from the synoptic stations at Helsinki–Vantaa airport and Isosaari.

The urban dispersion modelling system

For the evaluation of spatial distributions of NO_2 concentrations we applied a modelling system based on a combined application of the Urban Dispersion Modelling system UDM-FMI (Karppinen *et al*. 2000a) and the road network dispersion model CAR-FMI (Härkönen 2002) developed at the Finnish Meteorological Institute. In addition to the dispersion models, the modelling system includes the estimation of traffic flows, and emissions for stationary and vehicular sources, a meteorological pre-processing model, chemical transformation models and the statistical and graphical analysis of the computed times series of concentrations. The meteorological data used by the urban dispersion modelling system is obtained from the meteorological pre-processing model MPP-FMI.

An inherent limitation of the modelling system is quasi-stationarity, on a time scale of one hour. The dispersion models assume that pollutant concentrations can be treated as though these resulted from a time sequence of hourly steady states; this procedure does not take into account the temporal accumulation of the pollutants in the area. In case of very low wind speeds or calm conditions, this tends to cause an underprediction of the concentrations (Karppinen *et al*. 2001a).

Results

Evolution of the pollutant concentrations during the episode, and a comparison of the predicted concentrations with the measured data

Substantially increased pollutant concentrations were measured in several cities located in southern and western Finland, including Helsinki Metropolitan Area and five other cities (Turku, Tampere, Lahti, Lohja and Vaasa; Mäkelä *et al*. 1997). However, pollutant concentrations were not significantly high in cities situated in the eastern and northern parts of the country.

The concentrations of NO_2, PM_{10} and CO were substantially high during the episode at all of the urban and suburban air quality measurement stations in the Helsinki Metropolitan Area. As an example, the evolution of pollutant concentrations is presented for the measurement stations of Töölö and Vallila (Fig. 3). The concentrations of NO_2, CO, and PM_{10} started to increase on 27 December, and persisted at an increased level on 28 and 29 December, at both measurement stations. A similar temporal evolution of the concentrations of NO_2, CO, and PM_{10} was detected also in other urban and suburban measurement stations in the Helsinki Metropolitan Area (Mäkelä *et al*. 1997).

Due to the Christmas holidays the emissions from local traffic during the last week of December were actually lower, as compared with those during an average working week. There was a weekend on the 30 and 31 of December.

The measured concentrations can be compared with the currently applicable European Union limit values for the short-term concentrations of NO_2 and CO. The hourly EU limit value for NO_2 concentrations is 200 μg m^{-3}, allowing 18 exceedences per calendar year; this limit is required to be obtained at the latest in 2010. For CO, the corresponding eight-hourly gliding average EU limit value is 10 mg m^{-3}, to be obtained at the latest in 2005.

The numerical limit value of the NO_2 concentration was exceeded at all urban and suburban measurement stations in the Helsinki Metropolitan Area during the 28 and 29 of December. The highest hourly average concentration of NO_2 during the episode measured in the Helsinki Metropolitan area occurred at the station of Vallila, this value was 401 μg m^{-3} (at 21:00 on December 28). For instance, the limit value for concentration of NO_2 was exceeded during December 28 and 29 at the Töölö measurement station during a total of 25 hours.

The eight-hour EU limit value for CO was also exceeded during the episode at two measurement stations, at Leppävaara on the 29 December and at Töölö on the 28 December. The highest hourly average of CO measured in the Helsinki Metropolitan area during the episode

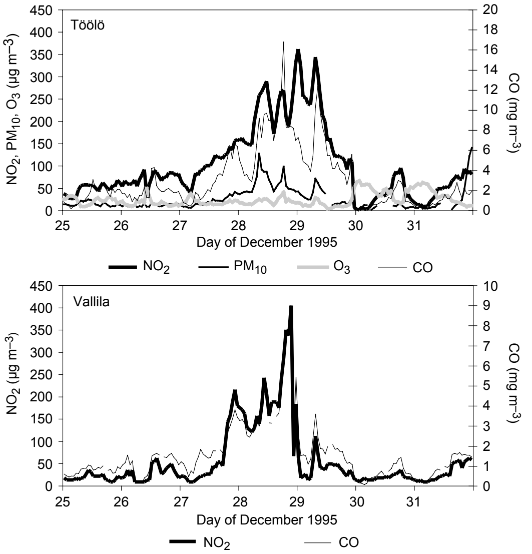

Fig. 3. The evolution of the NO_2, O_3, CO and PM_{10} concentrations in the course of the air pollution episode during 25–31 December 1995, at the stations at Töölö and Vallila.

was at the station of Töölö, 16.8 mg m^{-3} at 18:00 on 28 December.

For PM_{10} concentrations, the EU limit value is 50 μg m^{-3} over the averaging period of 24 hours (allowing 35 exceedings per year). The numerical limit value was exceeded at the station of Töölö on 28 December; the 24 hour average value was 58.6 μg m^{-3}. The highest hourly average PM_{10} concentration of 128 μg m^{-3} was measured on 28 December at 8:00 at the station of Töölö.

However, the limit values were not exceeded at the regional background station of Luukki; the fairly low levels of regional background concentrations refer to a mainly local origin of the pollutants. For example, a detailed computation shows that the measured NO_2 concentrations at the station of Luukki were on average 13% and 20% of the corresponding values at the stations of Töölö and Vallila, respectively, during the episode (from 27 to 29 December). During the 30 days preceding the episode, the corresponding average ratios of NO_2 concentrations at Luukki to those at Töölö and Vallila were actually higher, 23% and 32%, respectively.

The predicted concentrations of NO_2 in the Helsinki Metropolitan area on 28 December were calculated for 16:00 (this was the time of the highest measured concentrations during the episode) and 20:00 (Fig. 4). These results were computed using the urban dispersion modelling system of FMI; it should be noted that these are based on meteorological data produced by the meteorological pre-processing model MPP-FMI (not by the HIRLAM model).

Generally, during the initial stages of the episode, the predicted concentrations were close to the measured values or overpredictions, but at later times the concentrations were substantially underpredicted. For instance, the measured NO_2 concentration at the station of Töölö at 16:00 was 147 μg m^{-3}, while the corresponding predicted concentration at Töölö was in the range of 120–150 μg m^{-3}. The measured NO_2 concentration at the station of Vallila at this time was 110 μg m^{-3}, while the corresponding predicted concentration was slightly more than 200 μg m^{-3}. At 20:00 on 28 December, the measured NO_2 concentration at Töölö was 189 μg m^{-3}, while the predicted concentration was in the range of 120–150 μg m^{-3}; the measured concentration at Vallila was 347 μg m^{-3} and the predicted concentration was in the range of 120–150 μg m^{-3}. The underpredictions at the later stages were probably caused by the quasi-stationarity assumptions assumed in the dispersion models.

Evaluation of synoptic, meso- and microscale meteorological conditions

Synoptic meteorological conditions

According to the synoptic weather map for northern Europe on 28 December 1995, there was a widespread area of high pressure that extended from south-western Scandinavia to part of western Russia, and an area of low pressure prevailed northeast of Finland (Fig. 5). An anticyclonic high pressure region prevailed over southern Finland. This is qualitatively in agreement with the above mentioned observation of increased concentrations in several cities in southern and south-western parts of the country. Analysis of the preceding and consequent weather maps shows that a high atmospheric pressure prevailed in Helsinki during the whole duration of the episode (from 27 to 29 December).

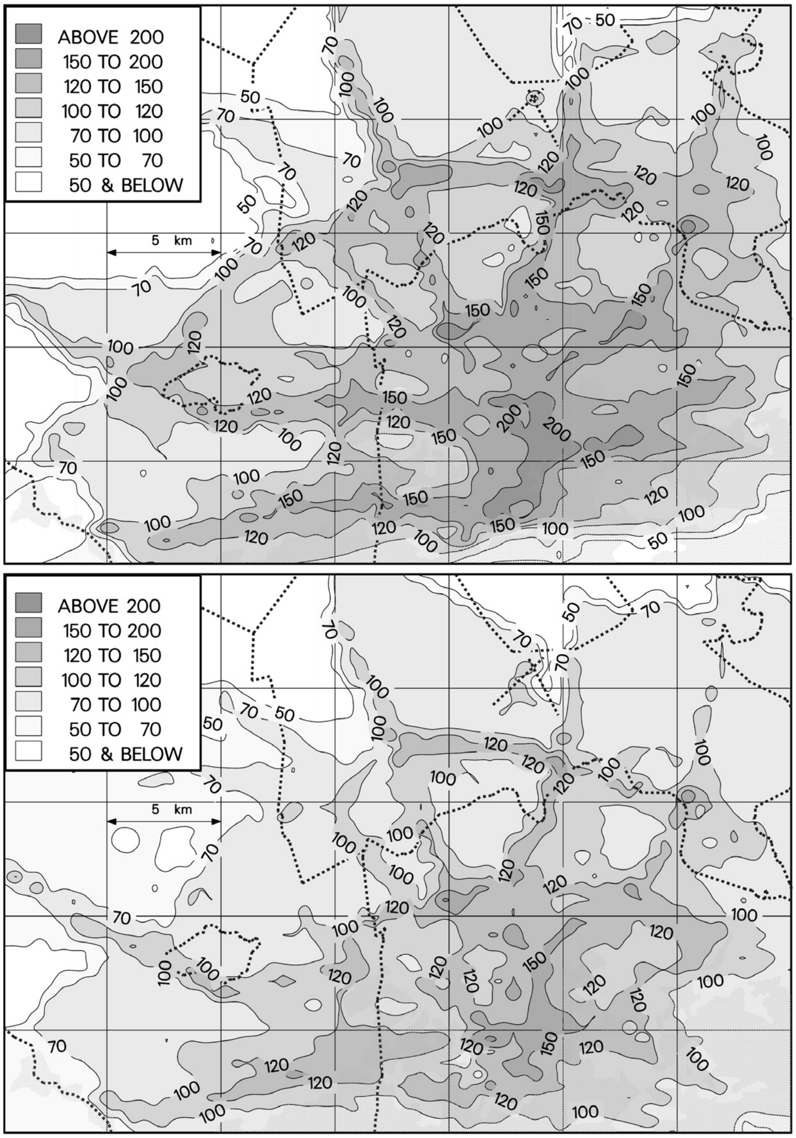

Fig. 4. The predicted spatial distributions of the hourly average concentrations of NO_2 ($\mu g\ m^{-3}$) on 28 December 1995 at 16:00 (upper panel) and 20:00 (lower panel).

An analysis of the horizontal wind fields predicted by the HIRLAM model shows that the air masses at the southern Finnish coast originated from the north-westerly direction in the Atlantic Ocean at the time of the episode (this can also be deduced based on the pressure isobars in Fig. 5, for a more limited area). This is in agreement with the corresponding computations by the MM5 model by Berge *et al*. (2002a). The HIRLAM results show that the air masses transported from the North Atlantic were cold and dry, and there was therefore no substantial formation of clouds. Dry conditions were favourable in terms of the formation of ground-based radiation inversions (as clouds reduce the transfer of heat from the ground surface by radiation).

Mesoscale meteorological conditions

The ground surface temperatures during the episode (from 27 to 29 December) at the station of Helsinki–Vantaa airport varied from –25 to –5 °C, and those at the station of Isosaari from –14 to –2 °C (Fig. 6). The temperatures in the sea area were substantially higher than those

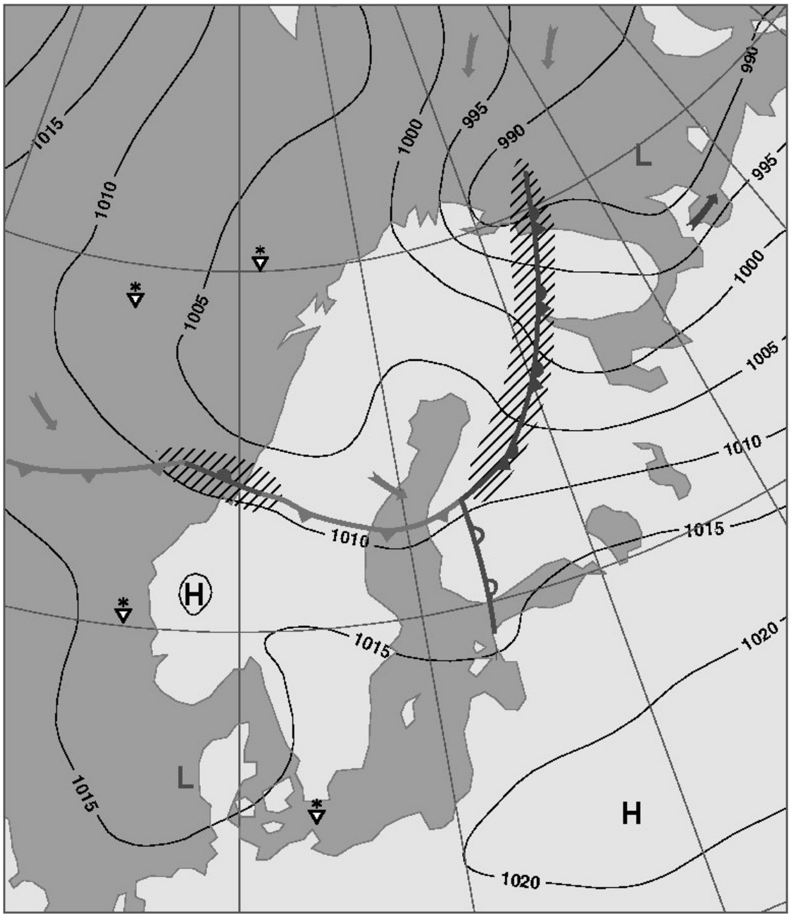

Fig. 5. The synoptic meteorological conditions in northern Europe on 28 December 00 UTC (Universal Time Coordinated), 1995, based on the analysis of the European Centre for Medium-Range Weather Forecasts. The curves show the atmospheric pressure at the ground level (hPa).

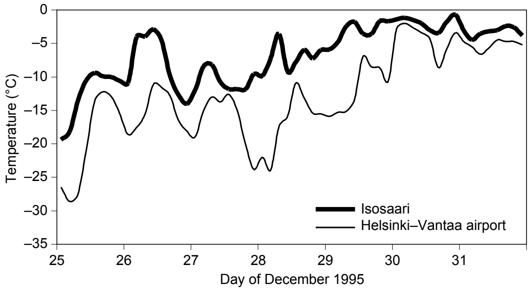

Fig. 6. The measured temperatures at a height of 2 m during the episode at the stations at Isosaari (an island in the Gulf of Finland) and Helsinki–Vantaa airport. The location of these stations is presented in Fig. 2.

over the mainland, due to the warming influence of the sea areas that are not covered with ice.

The evolution of the atmospheric pressure, the inverse Obukhov length (L^{-1}), and the wind speed and direction in the course of the episode are presented in Fig. 7. The values of pressure and L^{-1} were computed based on the data from the synoptic meteorological stations at Helsinki–Vantaa airport and Isosaari, using the meteorological pre-processing model MPP-FMI. The wind speed and direction have been measured at the mast of Kivenlahti at a height of 26 m.

The atmospheric pressure started to increase on 27 December, and remained at an elevated level until the end of the year. The atmospheric stability can be classified as stable or neutral during the whole period considered (i.e., $L^{-1} > 0$). The conditions for which $L^{-1} > 0.1$ m^{-1} can be classified as very stable. There were several periods of very stable atmospheric conditions; these follow a diurnal variation, in which the most stable conditions commonly occur at night. The most extended periods with a very stable stratification took place on 27–28 and 28–29 December.

In the early stages of the episode on 27–28 December, the wind speed measured at the mast of Kivenlahti at the height of 26 m was low or moderate, ranging from 1.0 to 3.2 m s^{-1}; on 29 December it increased substantially. The wind direction was predominantly westerly. These results are in agreement with the above mentioned HIRLAM analyses. Analysis of the observations at the station of Helsinki–Vantaa airport show that the sky was predominantly clear or mostly clear; although there was also some snowfall on 28 December.

The evolution of the measured concentrations can be qualitatively explained based on the variation of the above mentioned meteorological variables. The highest concentrations occurred from 27 to 29 December. This period lasted slightly longer than the most extended periods of extremely stable atmospheric stratification. During most of the period of increased concentrations, there were low or moderate wind speeds. Since the morning of 29 December, the wind speeds increased substantially, and the stability was predominantly neutral or slightly stable; these factors contributed to the decrease of pollutant concentrations.

There was snow cover over the land area in Finland during the episode; this also tends to increase the cooling of the ground surface. However, there was no widespread ice cover in the sea areas surrounding Helsinki at the time. The ice cover extended approximately to a distance of 11 km from the coastline of Helsinki (Finnish Institute of Marine Research 1995. Ice Chart N:o 29.12.1995.). The formation of a slight land–sea breeze would therefore be possible.

Measured and forecasted vertical temperature profiles

We have analysed the vertical temperature profiles at two locations: at a radio tower at Kivenlahti in the south-eastern part of the Helsinki Metropolitan Area, and at the sounding station of Jokioinen in southern Finland. These stations represent semi-urban (Kivenlahti) and rural environments (Jokioinen). Both profiles that were derived based on measured data and those forecasted for 24 hours by the HIRLAM model were considered (Fig. 8). We selected the 24-hour forecasts, as one of the main aims of this study was to evaluate the performance of the HIRLAM model in terms of operational air quality forecasts; these are commonly computed for the next day.

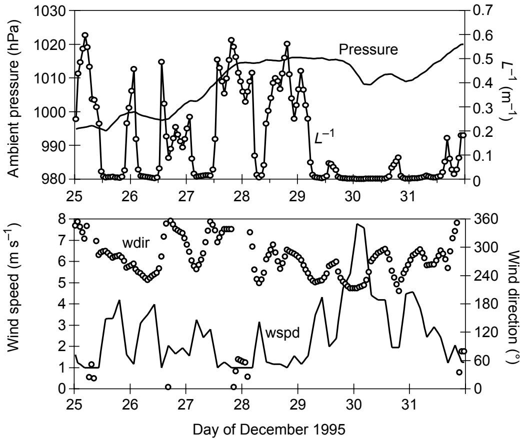

Fig. 7. The evolution of atmospheric pressure (upper panel, left-hand-side vertical axis) and inverse Obukhov length (L^{-1}: right-hand-side vertical axis), and wind speed (wspd: lower panel, left-hand-side vertical axis) and direction (wdir: right-hand-side vertical axis) at a height of 10 m in the course of the episode.

We selected simply the grid point of HIRLAM that was nearest to each of these stations. The grid points corresponding to the stations of Kivenlahti and Jokioinen were located approximately at a distance of 5 km south of the mast, and at a distance of 5 km west of the station, respectively. The lowest temperature measurement height in the Kivenlahti data was at 5.0 m, and the lowest forecasted temperature was predicted for the height of approximately 30 m.

The measured temperature profiles at 00 UTC at both Kivenlahti and Jokioinen show that there was an extremely strong ground-based temperature inversion on 28 December, and a fairly strong inversion also on 29 December, but the inversion had totally disappeared on 30 December. At 00 UTC on 28 December at Kivenlahti, the measured temperature increased 15 °C within the lowest 91 m of the atmosphere; at Jokioinen, the corresponding temperature increase was 18 °C within the lowest 120 m. Detailed examination of the diurnal variation of the measured inversion shows that the maximum vertical temperature gradient during the episode duration was

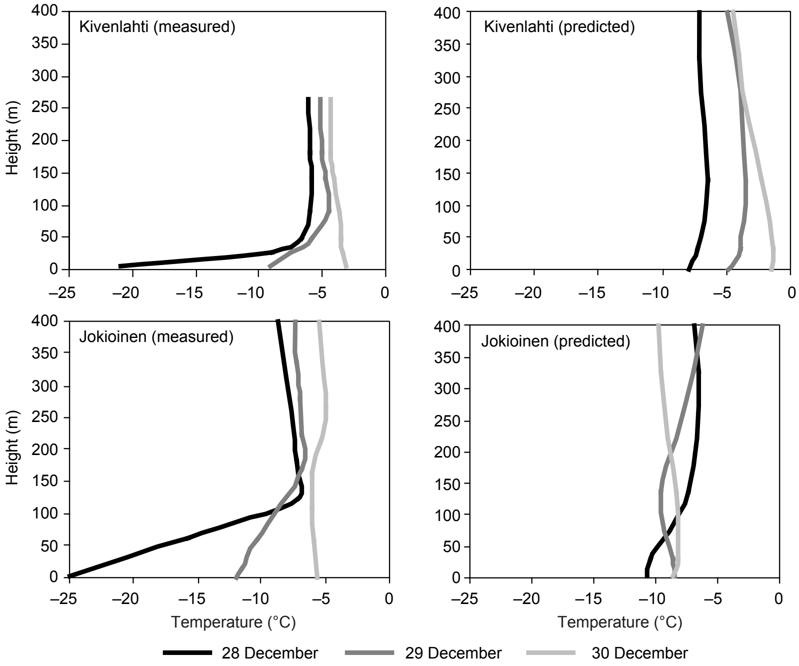

Fig. 8. The measured and 24 hourly forecasted temperature profiles at the Kivenlahti mast and at the sounding station of Jokioinen on 28–30 December 1995 at 00 UTC (heights from ground level). The predictions were computed with the Finnish version of the model HIRLAM, a version that was operational from 1999 to 2003 (4.6.2).

approximately 15 °C over the lowest 30 m of the atmosphere (Karppinen *et al.* 2002). An evaluation of inversion statistics shows that inversions of such a magnitude and duration are exceptional in southern Finland (Karppinen *et al.* 2001b).

At Kivenlahti on 28 and 29 December, the HIRLAM model predicted a temperature inversion of a couple of degrees. Although the HIRLAM model detects the inversion on these days, the model substantially underpredicts the inversion strengths (in °C), as compared with the corresponding measured data. At Jokioinen, the HIRLAM model predicts a moderate inversion on 28 December, but no inversion at all on 29 December.

The inversion strengths (°C) predicted by the HIRLAM model were substantially weaker or non-existent, as compared both with the corresponding values extracted from the mast data and the sounding data. The HIRLAM model also overpredicted surface temperatures and the height of the inversion layer. A detailed analysis shows that this under-prediction of inversions is related especially to an over-prediction of ground surface temperatures and near-surface wind velocities.

An overprediction of the inversion height (or the inability of the model to predict the existence of an inversion) would lead to an overestimation of the mixing height. In such a case, pollutant concentrations would be underestimated by any dispersion modelling system utilizing the meteorological data from the HIRLAM model.

According to previous evaluation studies of the HIRLAM model, its accuracy over land surfaces can be considered good; however, discrepancies from the observations can occur near the ground surface in cases of a stable boundary layer (e.g., Savijärvi and Kauhanen 2001). Pirazzini *et al.* (2002) found out that the HIRLAM model predicted too weak inversions in coastal and sea areas, probably caused by the treatments of surface albedo and temperatures. At Kivenlahti the nearest grid point represents partly a marine region, and thus, the results would be more inaccurate than on solid land regions.

The deviations of HIRLAM forecasts and data for the HIRLAM version utilized in this study are partly caused by deficiencies in the mathematical description of humidity and the state of the ground surface, e.g., the existence of snow cover. The deviations could partly also be caused by the finite grid resolution both vertically and horizontally (e.g., the horizontal resolution was 22 km).

Berge *et al.* (2002a) simulated this episode using the non-hydrostatic meteorological MM5

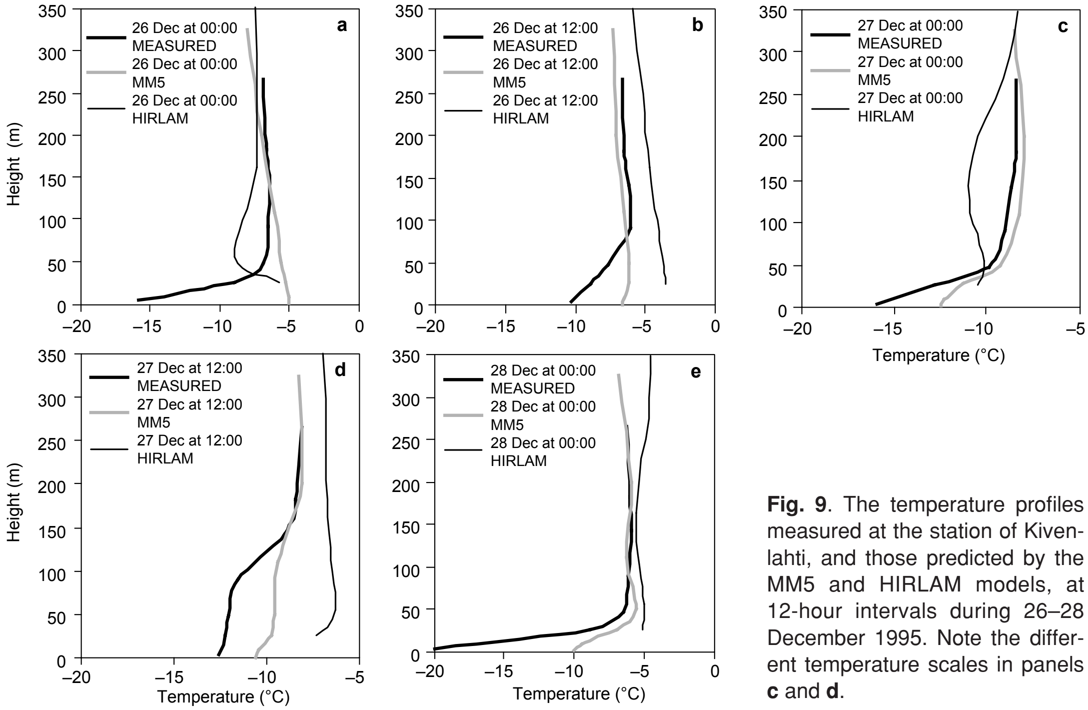

Fig. 9. The temperature profiles measured at the station of Kivenlahti, and those predicted by the MM5 and HIRLAM models, at 12-hour intervals during 26–28 December 1995. Note the different temperature scales in panels **c** and **d**.

model, with boundary data from the ECMWF model. The horizontal grid resolutions in the various nested MM5 simulations were 9, 3 and 1 km. The vertical temperature profiles at Kivenlahti measured during 26–27 December, and predicted with MM5 and HIRLAM are presented in Fig. 9. The MM5 model predicted the formation of inversions on December 27 and 28, but both the HIRLAM and MM5 models failed to predict the inversion on 26 December. Both models underpredicted the total inversion strengths (°C); these underpredictions were related to an overprediction of ground surface temperatures. Both models also in most cases underpredicted the inversion heights on 26 and 27 December. The MM5 model predicted the temperature profiles better than HIRLAM, although both models had problems especially in predicting the daytime temperature profiles.

Conclusions

In this work we studied an air pollution episode that occurred on 27–29 December 1995, in southern and western Finland. The episode was formed in a synoptic situation, during which cold and dry air was transported from the North Atlantic, in prevailing anticyclonic high pressure conditions. The measured ground level temperatures at the station of Helsinki–Vantaa airport varied from –25 to –5 °C during the episode. These conditions lead to low wind speeds and the formation of an extremely strong ground-based radiation inversion in the Helsinki Metropolitan Area; the mixing height available for the dispersion of pollutants was therefore exceptionally low. As a result, a severe air pollution episode was formed, in the course of which the concentrations of NO_2, PM_{10}, and CO were substantially high for a period of a few days at all the urban and suburban air quality monitoring stations in the Helsinki Metropolitan Area. The comparison of measured regional background concentrations with those measured at urban and suburban stations showed that the increased concentrations were predominantly originated from local sources.

According to the measured results at the Kivenlahti radio tower, the maximum temperature difference of the ground-based inversion was approximately 15 °C within the lowest 30 m of the atmosphere; this corresponds to an average temperature gradient of approximately 0.5 °C m^{-1}. The corresponding measured values at the station of Jokioinen showed an inversion of 18 °C within the lowest 120 m. An examination of the national climatological statistics shows that inversions of such a magnitude and duration are exceptional in southern Finland; the frequency of extremely strong inversions increases towards the northern parts of the country (Karppinen *et al*. 2001b). Inversions of such a temperature gradient have not been reported previously in any other urban areas in Europe (Piringer and Kukkonen 2002); this is caused by the specific boreal climatological characteristics.

Both the inversion strengths (°C) and the temperature gradients (°C m^{-1}) forecasted by the HIRLAM model were substantially lower, or non-existent, as compared both with the corresponding values extracted from the mast data and the sounding data. This under-prediction is related to an over-prediction of ground surface temperatures and near-surface wind velocities. These deviations of the HIRLAM forecasts and data are partly caused by deficiencies in the mathematical treatment of humidity and the state of the ground surface. The deviations can also partly be caused by the finite computational grid resolution, horizontally 22 km. Clearly, numerical weather forecasting models have originally been designed for meteorological predictions in a synoptic and meso-scale; instead of local scale predictions within the lowest atmospheric layers (e.g., Baklanov *et al*. 2002). The finer resolution, non-hydrostatic MM5 model predicted the temperature profiles better than HIRLAM, although both models had problems especially in predicting the daytime temperature profiles.

We also compared the pollutant concentrations predicted with an urban dispersion modelling system with those measured during the episode. During the initial stages of the episode, the dispersion modelling system either predicted the concentrations fairly well, or overpredicted the concentrations. In the latter stages, the model underpredicted the pollutant concentrations for both the monitoring sites considered. This is probably due to the quasi-stationarity assumptions of the modelling system, as this procedure does not take into account the accumulation in time of the pollutants in the area.

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