Convention on Long-range Transboundary Air Pollution

emep

Co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe

TECHNICAL REPORT
MSC-W 5/2004

Local and regional description of Particulate Matter in the Oslo area

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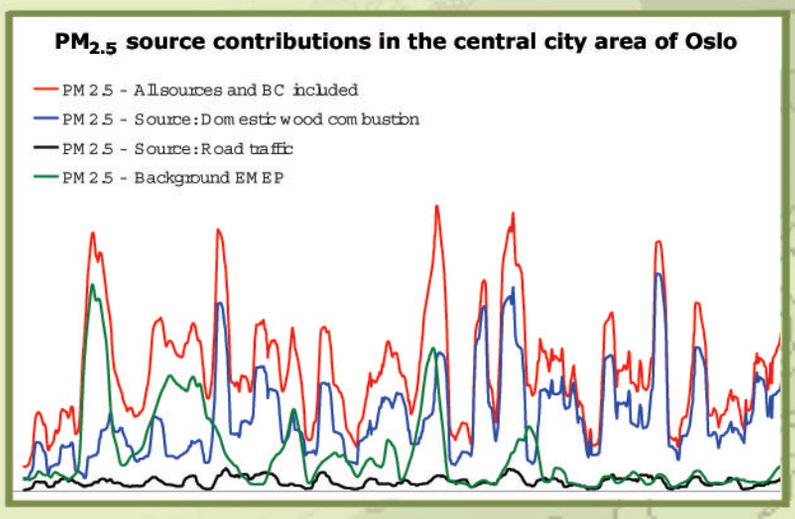

msc-w & NILU

EMEP Note 5/2004
Date: December 30, 2004

METEOROLOGISK INSTITUTT
Norwegian Meteorological Institute

Joint MSC-W & NILU Technical Report

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ISSN 0804-2446

Preface and acknowledgements

This report presents a study of the origin of particulate matter (PM) in Oslo and its surroundings. It identifies the influence of long-range transported PM pollution in the area and analyses the contribution of local urban sources.

It illustrates the capabilities of a flexible modelling system capable of describing air pollution transport at different scales. Since 2001, the Norwegian authorities have supported the development of a one-way nested modelling system that allows a coupled study of regional and local air pollution problems. In the developed system, the regional EMEP Unified Model has been coupled with the Norwegian urban scale model EPISODE developed at the Norwegian Institute for Air Research (NILU). To allow further analysis of local urban sources and trace local pollution levels, the Eulerian EPISODE model has been coupled with the AirQUIS-2003 emission inventory module.

The new nested modelling system is believed to be an important policy tool, able to support the design and follow the implementation of environmental policies in Norway. The co-operation between EMEP scientists and national researchers on air pollution can be used as an example by other countries under the Convention for Long-Range Transboundary Air Pollution interested in improving the modelling tools presently used for national pollution control and planning. The development of methods able to describe the influence of long-range transport in local/urban areas is especially relevant now with the entry into force of the Gothenburg Protocol and the on-going revision the National Ceilings-Directive under the European Commission's new Thematic Strategy on Air Pollution.

This work has been financed by the Norwegian Ministry of the Environment, the Norwegian Ministry of Fisheries and the Norwegian Pollution Control Authority.

EXECUTIVE SUMMARY

Particulate matter (PM) in the Oslo area has both a regional long-range transported contribution and a contribution from local sources. This report presents an initial attempt to identify the influence of the different sources of PM in the Oslo area with the help of a newly developed nested model system.

The average regional background $PM_{2.5}$ concentrations in Oslo calculated with the Unified EMEP model is estimated to be ~ 5 μg m^{-3}, for the period November – December 2003, which is also representative for averaged concentration of $PM_{2.5}$ for the rest of the year. The corresponding yearly averaged concentrations of PM_{10} are estimated to be somewhat higher ~5.6 μg m^{-3}, which indicates that the local influence of PM_{10} emissions in Oslo plays a small role in the determination of regional background PM concentrations. The calculated regional concentrations of PM_{10} and $PM_{2.5}$ are considered to represent the long-range transported component of urban background concentrations while the local contribution to PM concentrations inside the city area can not be represented with these estimates.

The modelled regional component of fine particulates in Oslo is composed of primary particulate matter (33%), secondary inorganic aerosols, namely, nitrates (29%), sulphates (19%), ammonium (15%) and a natural component from sea salt (4%). The regional long-range transported $PM_{2.5}$ concentrations levels can be viewed as a sum of a large number of smaller contributions from individual countries. The largest contribution is from Norwegian sources themselves, but these constitute only about 38% of the calculated $PM_{2.5}$ levels in Oslo. The remaining 62% originates in other European countries, especially Germany, Denmark, the United Kingdom and Sweden, but also other countries. More than 10 countries have contributions larger than 2% of the Oslo concentration levels.

An analysis of the relative importance of different emission sectors in the background regional levels in Oslo shows that these are dominated by emissions from agriculture, road traffic, incineration and waste. Not surprisingly, ammonia emissions from agriculture are the most important single sector source for background $PM_{2.5}$ in Oslo (35%), given the relevant role of ammonium in controlling the chemical transport of secondary organic aerosols.

Comparison with PM background observations done elsewhere shows that the modelled regional PM levels are underestimated, generally because wind blown dust sources and traffic-induced re-suspension are presently not included in the calculations and neither are the thermodynamic and chemical processes leading to the formation of secondary organic aerosols. For $PM_{2.5,}$ the underestimation of regional background levels is generally about 25-30%, and up to 40-50% for PM_{10} concentrations. The underestimation of PM_{10} is larger than for $PM_{2.5}$ because the missing re-suspension and wind blown sources are mostly contributing to the coarse particle fraction.

Inside the urban area, comparison with observations can not be done directly with the regional model results, because the distribution of local sources in the urban area is generally not well represented in a coarse regional grid. Especially in Oslo, the city area is effectively about ¼ of the regional grid size of 50x50km^2. An appropriate description of urban sources requires the use of nested models like the ones used in the present project, where the regional scale EMEP model is linked to the Norwegian local scale model EPISODE with a grid resolution of 1x1km^2 and EPISODE is further linked to an sub-grid line source model and a detailed

emission data base within an Air Quality Information System (AirQUIS). Such a detailed system is more capable of reproducing the observed PM levels inside the city area than a pure regional model, and facilitates the comparison of various source contributors to ambient particulate matter in Oslo.

The nested model simulation has been carried out for the period lasting from the 1st of November until the end of December 2003, i.e. during a period when it is to be expected that local sources can give high PM concentrations. On average for the two-month period, the estimated regional background contributes with about 30% to $PM_{2.5}$ and 20% to PM_{10} concentrations calculated in the central city area. We can expect the contribution from regional background sources to be higher in summer because dominant local sources (like domestic wood burning and use of studded tyres) are not contributing during that season. For the two-month simulation, however, the highest concentration peaks in Oslo are caused by local sources. The estimated PM levels reach up to 90 $\mu g\ m^{-3}$ for $PM_{2.5}$ and up to about 400 $\mu g\ m^{-3}$ for PM_{10} in Oslo. The results from this study also reveal that the various sources contribute differently depending both on location and on whether we consider $PM_{2.5}$ or PM_{10}. In areas with no local emissions, i.e. over the fjord or in the forests surrounding the city, the regional background will naturally dominate the concentration levels.

The estimated $PM_{2.5}$ levels in the central and western city area are dominated by emissions from domestic wood burning, being responsible for more than 60 % of the ground level concentrations in some grid cells. Road traffic is the second most important contributor to $PM_{2.5}$ concentrations in Oslo. However, for $PM_{10,}$ road traffic is the most dominant contributor followed by domestic wood burning as the second most important. This is especially the case in the areas along the main highways, where dense traffic in combination with high vehicular speed, leads to high concentrations of coarse particles due to traffic-induced re-suspension. Much higher relative contributions to the PM_{10} levels are also found from road traffic at individual receptor points close to the roads, higher than estimated from the grid cell values (which normally are interpreted as urban background values). In central and western city grid cells without direct contributions from the main road network, domestic wood burning typically dominate the estimated PM_{10} levels.

Regional $PM_{2.5}$ background concentrations can episodically increase to levels of more than 40 $\mu g\ m^{-3}$. This can happen when specific meteorological conditions cause plumes with high concentration levels to be transported from northern Europe towards Norway, as clearly demonstrated in the model results presented in Section 3 for the November 5 – 9 episode. The highest peaks caused by local sources need not, and in most cases will not, coincide with the highest peaks of regional origin. High concentration levels due to local sources typically appear under high-pressure conditions, with low wind speed and near surface temperature inversions, resulting in low mixing of the pollutant emissions. These conditions differ markedly from the cases when regional air masses with high concentration of pollutants are transported over large distances.

The results show that an accurate description of urban pollution and its sources requires the use of coupled model systems. Now that the coupled modelling system is operative, further refinements of these calculations and/or their extension to other Norwegian cities will be crucially dependent on the availability of fine resolution emission data.

SAMMENDRAG

Både regional langtransport og lokale kilder bidrar til svevestøv (partikulær masse, PM) i Oslolufta. Denne rapporten presenterer et første forsøk på å identifisere innflytelsen av de forskjellige kildene til svevestøvet i Oslo ved hjelp av et nyutviklet koblet modellsystem.

Den modellerte gjennomsnittskonsentrasjonen for det regionale bakgrunnsnivået av $PM_{2.5}$ i Oslo er beregnet ved bruk av "Unified-EMEP" modellen til å være omtrent 5 μg m^{-3}, for to-måneders perioden november – desember 2003. Dette er også en representativ verdi for den årlige gjennomsnittskonsentrasjonen for $PM_{2.5}$. Den tilsvarende årlige gjennomsnitts-konsentrasjonen for PM_{10} er anslått til å være bare litt høyere, ~ 5.6 μg m^{-3}, noe som indikerer at den lokale innflytelsen av PM_{10}-utslipp i Oslo spiller en liten rolle i beregningene av de regionale bakgrunnskonsentrasjonene av PM. De beregnede regionale konsentrasjonene av PM_{10} og $PM_{2.5}$ antas å representere det langtransporterte bidraget til konsentrasjonsnivåene i byområdet mens det lokale byskala bidraget ikke kan representeres med disse estimater.

De modellerte regionale finfraksjonspartiklene ($PM_{2.5}$) i Oslo består av primære partikler (33%), sekundære uorganiske aerosoler, d.v.s. nitrater (29%), sulfater (19%), ammonium (15%) og en naturlig forekommende komponent fra sjøsalt (4%). Konsentrasjonsnivåene av $PM_{2.5}$ forårsaket av regional langtransport kan betraktes som en sum av et stort antall av mindre bidrag fra ulike land. Det største bidraget er fra egne norske kilder, men disse utgjør bare omtrent 38 % av de beregnede $PM_{2.5}$ nivåene i Oslo. De resterende 62% er forårsaket av utslipp fra andre europeiske land, fortrinnsvis Tyskland, Danmark, England og Sverige, men også fra øvrige land. Mer enn 10 land bidrar med mer enn 2 % av konsentrasjonsnivåene i Oslo.

En analyse av den relative betydningen av ulike utslippsektorer for det regionale bakgrunnsnivået i Oslo, viser at de dominerende utslippene kommer fra landbruk, veitrafikk, forbrenning og avfallsbehandling. Det er ikke uventet at utslippet av ammoniakk fra landbruket er den viktigste enkeltkilden for langtransportert $PM_{2.5}$ i Oslo (35%). Dette skyldes den viktige rollen som ammonium spiller når det gjelder å kontrollere den kjemiske transporten av sekundære uorganiske aerosoler.

Sammenlikninger med regionale bakgrunnsobservasjoner av PM viser at de modellerte regionale PM nivåene underestimeres. Generelt skyldes dette at vind-oppvirvlet støv og trafikkindusert oppvirvling foreløpig ikke er inkludert i modellberegningene, ei heller de termodynamiske og kjemiske prosessene som leder til dannelse av sekundære organiske aerosoler. For $PM_{2.5}$, underestimerer modellen de observerte luftkonsentrasjoner med 25-30% og for PM_{10} er de modellerte regionale bakgrunnsnivåene vanligvis 40-50% lavere enn obsersasjonene. Underestimeringen er størst for PM_{10} siden det manglende bidraget fra oppvirvlet støv i første rekke består av grovfraksjonspartikler.

Innenfor urbane områder kan man ikke sammenlikne observasjoner direkte med modellerte regionale konsentrasjonsnivåer, siden fordelingen av lokale kilder i slike områder ikke er godt nok beskrevet i det grove regionale modellgitteret. Dette er spesielt tilfelle i Oslo der selve byområdet bare utgjør omtrent ¼ av den regionale gitterstørrelsen på 50 x 50 km^2. En passende beskrivelse av urbane kilder fordrer bruk av nestede modeller av den type som er anvendt i dette prosjektet. Vi har her nestet den regionale EMEP modellen sammen med den norske lokalskala-modellen EPISODE som har hatt en gitteroppløsning på 1x1km^2. Videre er EPISODE modellen koplet sammen med en sub-gitter linjekildemodell og en detaljert

utslippsdatabase innenfor et Luftkvalitetsystem (AirQUIS). Et slikt detaljert system er i stand til å reprodusere observerte nivåer av PM innenfor byområdet, og er derfor bedre egnet til å sammenlikne bidragene fra ulike kilder til den totale partikkelkonsentrasjonen i Oslolufta enn regionale modeller.

Simuleringene med det nestede modellsystemet er blitt utført for en to-måneders periode f.o.m. 1. november t.o.m 31. desember 2003, d.v.s. i en periode da det forventes at lokale kilder kan forårsake høye partikkelkonsentrasjoner. I gjennomsnitt for hele beregnings-perioden utgjør det estimerte regionale bidraget omtrent 30% og 20% av de estimerte nivåene av h.h.v $PM_{2.5}$ og PM_{10} i det sentrale byområdet. Vi kan gå ut fra at bidraget fra den regionale bakgrunnen er større om sommeren siden dominerende lokale kilder (f.eks. vedfyring og piggdekk) ikke bidrar i denne sesongen. I løpet av den benyttede beregningsperioden er det imidlertid de lokale kildene som forårsaker de høyeste konsentrasjonsverdiene. Nivåer opp mot 90 $\mu g\ m^{-3}$ ble beregnet for $PM_{2.5}$ og opp mot 400 $\mu g\ m^{-3}$ for PM_{10} innenfor byområdet. Resultatene fra denne studien viser også at de ulike kildene bidrar i forskjellig grad avhengig både av geografisk posisjon og av hvilke komponent ($PM_{2.5}$ eller PM_{10}) som betraktes. I områder uten lokale kilder, f.eks. over fjorden og over skogsområdene rundt byen, vil naturligvis det regionale bakgrunnsbidraget være dominerende.

De estimerte nivåene av $PM_{2.5}$ i det sentrale og vestlige byområdet er dominert av utslipp fra vedfyring, som er ansvarlig for mer enn 60% av konsentrasjonsnivåene i bakkenivå i enkelte gitterruter. Utslipp fra veitrafikk er den nest viktigste bidragsyteren til $PM_{2.5}$ konsentrasjoner i Oslo. For PM_{10} er imidlertid veitrafikken den mest dominerende bidragsyteren, fulgt av vedfyring som den nest viktigste. Dette er mest utpreget i områdene langs hovedveinettet gjennom byen, der stor trafikkmengde i kombinasjon med høy trafikkhastighet, fører til svært store konsentrasjoner av grovfraksjonspartikler forårsaket av trafikkindusert oppvirvling av veistøv. Mye større relativt bidrag til PM_{10} nivåer finner man også fra veitrafikken i enkeltstående reseptorpunkter nær hovedveier, enn de man estimerer i gitterrutene (som tolkes som gyldige for bybakgrunn). I gitter-ruter i det sentrale og vestre byområdet, som ikke får bidrag fra hovedveinettet, vil vedfyringen typisk også være den dominerende kilden for PM_{10}.

Regionale $PM_{2.5}$ bakgrunnskonsentrasjoner kan i episoder komme opp i nivåer på mer enn 40 $\mu g\ m^{-3}$. Dette kan skje når spesielle meteorologiske forhold fører forurensede luftmasser fra Nord-Europa mot Norge, en situasjon som er tydelig demonstrert i modellresultatene som er presentert i Kapittel 3 for episoden som forekom i perioden 5 – 9 November. De høyeste verdiene som forårsakes av lokale kilder trenger ikke, og vil som oftest heller ikke, sammen-falle med de regionale episodene. Høye konsentrasjonsnivåer p.g.a. lokale kilder vil typisk forekomme i høytrykksitusajoner, med lave vindstyrker og forekomst av bakkenære temperaturinversjoner, d.v.s. forhold som leder til liten grad av spredning av utslippene. Dette er meteorologiske forutsetninger som er klart forskjellige fra forholdene som er rådende når forurensede regionale luftmasser transporteres over store avstander.

Resultatene presentert i denne rapporten viser at en nøyaktig beskrivelse av luftforurensingen i byområder, og dens kilder, krever bruk av nestede (koblede) modellsystemer. Når et slikt system nå er operativt, vil ytterligere forbedringer av beregningene og/eller eventuell gjennomføring av slike beregninger i andre norske byer, være svært avhengige av at utslippsdata med tilstrekkelig fin oppløsning blir gjort tilgjengelige.

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1. Introduction

The harmful effects of air pollution on human health have raised a series of concerns in recent years and resulted in revisions of environmental protection actions. Long-term objectives for the protection of the environment include now the protection of human health as an end-point. Both the revision of the Gothenburg Protocol under the Convention of Long-range Transboundary Air Pollution and the new Thematic Strategy on Air Pollution from the European Commission consider now to include interim objectives for the protection of human health. This renewed focus on human health imposes further needs for accurate descriptions of air pollution levels in urban areas and improved understanding of their origin.

Of the traditional pollutants, ozone and particulate matter are particularly significant due to their documented harmful effects on human health. Exposure to PM in ambient air has been linked to a wide range of adverse health effects, from transient changes in the respiratory tract to increased risk of death from cardiovascular and respiratory diseases or lung cancer. For ozone, there is also compiled evidence on effects on asthma incidence, lung damage and inflammatory responses.

Both ozone and PM have a significant long-range transported component and a similarly relevant local contribution. Thus, traditional environmental protection actions focusing on either urban scale exposure analysis or long-range regional transport need now to be coupled in order to include the control of the relevant sources both from local and regional sources.

This implies that policies for the protection of the environment should be addressed not only at national level but also include requirements in urban areas where population is at risk. It also implies that the tools used up to now to support national pollution control and planning need to be further developed to describe the influence of long-range transport in urban areas.

Aware of the need for further development of the traditional air pollution modelling tools, the Norwegian authorities initiated a project in 2001 to allow the use a flexible modelling system capable of describing air pollution transport at different scales in their national policy planning. The resulting modelling system is based on the coupling and further development of two existing models: the regional scale EMEP Unified Eulerian model (EMEP, Report 1/2003, Berge and Jakobsen, 1998; Olendrzynski et al, 2000) developed by the Norwegian Meteorological Institute (met.no) and the urban scale EPISODE model (Grønskei et al., 1993; Walker et al., 1999; Slørdal et al., 2002, 2003) developed by the Norwegian Institute for Air Research (NILU).

In the first part of the project, these models were adapted to allow for independent simulations with variable model domains and grid resolutions (Wind et al., 2002). In the second part of the project (Wind et al., 2003), the models were developed further in order to allow for both self-nesting capabilities and for coupling between the two models. The flexibility of the modelling system allows now for applications in a wide range of scales: from local/urban, to regional and hemispheric scale.

Independently of the scale chosen for the simulations, the ability of the new modelling system to determine the origin of air pollution relies on the accuracy of meteorological and emission input data. In the first part of the project, refined emission data from the Norwegian fishing

fleet were used to produce updated estimates of their impact to acidification and eutrophication (Tarrasón and Wind, 2003). In the second part of the project, the coupling capabilities between the two models were illustrated in a simulation of ozone levels for a European city where both emission inventories and meteorological data were available at fine resolution to the modelling teams (Wind et al., 2003).

This final report of the project presents a study of the origin of particulate matter in Oslo. The study distinguishes the contribution of long-range transported particulate matter and the influence of local sources to PM levels. An initial comparison of local vs. long-range transported PM in Oslo is presented for the two months of November and December 2003. The period was selected to illustrate the importance of local sources during periods with high PM levels.

In order to perform this analysis two major improvements have been implemented in the modelling system. Firstly, particle deposition has been included in the EPISODE model. To achieve consistency with the deposition treatment in the EMEP model, this process has been implemented by use of the same parameterisation scheme as in the Unified EMEP model. This scheme is described in detail in EMEP - Report 1/2003. Secondly, to allow for the necessary detail in the local emission distribution, the self-nested EPISODE version has been incorporated in the Air Quality Management System, AirQUIS-2003 (AirQUIS, 2005; Slørdal et al., 2003; Laupsa et al., 2005). This system is implemented in Oslo, and contains a detailed emission database for the city. Within this system, sub grid line- and point source models can be applied as part of EPISODE, thereby allowing a more detailed description of the concentration distribution close to important sources. The EPISODE/AirQUIS system and the emission data applied within this study are presented in Chapter 2.

In Chapter 3, the sources of regional and local contributions to PM in Oslo are investigated. First, the long-range transported contribution is estimated for a full year with the regional EMEP Unified model. The calculations identify the largest contributions both by European countries and by emission activity sectors. Second, the contribution of local Oslo sources is identified through nesting the EMEP Unified model with the coupled AIRQUIS/EPISODE local scale model. The analysis of the contribution of the local sources is done only for a two-months winter period, when the local contribution is expected to be at its highest. Although the comparison is presently hampered by the lack of consistent emissions estimates at local and regional scales, the calculated PM Oslo levels are considered to be indicative of the observed PM levels and the estimation of the origin representative for winter months.

Conclusions and recommendations on how to improve the present estimates in the future are presented in Chapter 4. In particular, now that the modelling tools have been developed, it is extremely important for Norway to initiate the compilation of fine resolution emission inventories in order to support the policy assessment work at national and local level.

2. Emissions of Particulate Matter in Oslo

In this section we will describe the emission of particulate matter as represented in the two modelling systems. Particulate matter in Oslo is both due to local and to regional sources. In the regional EMEP model calculations, both precursor gaseous emissions of SO_2 , NO_X and NH_3 need to be considered as well as primary emissions of particulate matter in the fine ($PM_{2,5}$) and the coarse mode (PM coarse). For the small-scale calculations, the EPISODE model includes primary particles. These primary particles are considered inert in the model and their removal by dry and wet deposition is now implemented in EPISODE following the EMEP Unified model parameterisations.

2.1 Emissions applied in the regional scale EMEP model

The latest reported EMEP emissions set cover the year 2002. A detailed description of the definition and background of the emission data can be found in (Vestreng et al, 2004). For the purpose of this study the regional emission levels for 2002 can be considered as a sufficiently good approximation for the 2003 emission levels. Figure 2.1 gives an overall picture of the distribution of $PM_{2.5}$ emissions in Europe. The grid cell containing Oslo has a size of 50x50 km^2.

The emissions are divided in 11 SNAP sectors. An overview of the sector definition and the corresponding emission rates in the grid cell that includes Oslo is given in table 2.1. In the grid cell covering Oslo, 64.3% of $PM_{2.5}$ comes from sector 2, which includes domestic heating. Road transport (sector 7) represents also a large source of PM. Sector 9 (waste treatment disposal) is a relatively large source of $PM_{2.5}$, but since the emissions are released through high smokestacks they will have relatively less effect on the local pollution than for example road traffic.

The EMEP model calculates the rate of emissions of pollutants based on the total amount emitted per year. For $PM_{2.5}$ this total is 2577.94 tons/year in the grid cell containing Oslo, which is equivalent to an average of 32.7 ng m^{-2} s^{-1} [*]. Due to seasonal variations, the average emission rate of $PM_{2.5}$ for the period November to December (40.1 ng m^{-2} s^{-1}) is higher than the yearly average.

For PM_{10} the corresponding emission rate is 44.2 ng m^{-2} s^{-1} for the period November to December. PM_{coarse} is defined as the coarse part of PM_{10} i.e. PM_{coarse} = PM_{10} - $PM_{2.5}$; the averaged emissions of PM_{coarse} is 4.1 ng m^{-2} s^{-1} for the period November to December.

The total emission in a grid cell is weighted by a factor to represent time dependence. In figure 2.2 the time evolution of the $PM_{2.5}$ and PM_{coarse} emissions in the EMEP model are represented for the two months period from the 1st of November to the end of December 2003. This time factor has a seasonal variation, a weekly variation and a day/night variation. The time factor differs also according to sectors. The time factors are defined according to average climatological values, but do not take into account the instantaneous meteorological

[*] In order to facilitate comparison between emission rates covering different areas and time periods, the emission rates in this report are given in ng·m^{-2}·s^{-1}. A constant rate of 1 ng·m^{-2}·s^{-1} over the EMEP grid cell covering Oslo corresponds to a yearly emission of 78.84 tons.

conditions. This can be a source of discrepancy between the EMEP modelled and the actual emissions, since for example heating is very much temperature dependent.

Sector	**Description**	**$PM_{2.5}$ emissions**		**PM_{coarse} emissions**	
		$ng \cdot m^{-2} \cdot s^{-1}$	%	$ng \cdot m^{-2} \cdot s^{-1}$	%
Sector 1	Combustion in energy and transformation industries	0	0	0.0	0.1
Sector 2	Non-industrial combustion plants	25.8	64.3	1.1	25.9
Sector 3	Combustion in manufacturing industry	1.2	3.0	0.8	19.2
Sector 4	Production processes	0.4	1.1	0.6	14.4
Sector 5	Extraction & distribution of fossil fuels and geothermal energy	0	0	0	0
Sector 6	Solvent and other product use	0	0	0	0
Sector 7	Road transport	5.5	13.8	1.4	34.4
Sector 8	Other mobile sources and machinery	0.9	2.3	0.1	1.6
Sector 9	Waste treatment and disposal	6.2	15.4	0.0	0.4
Sector 10	Agriculture	0.1	0.2	0.2	3.9
Sector 11	Other sources and sinks	0	0	0	0
Total	All sources	40.1	100.0	4.1	100.0

Table 2.1: The table shows the average emission rates and relative contributions of PM for each SNAP sector in the period November to December in the EMEP grid cell containing Oslo.

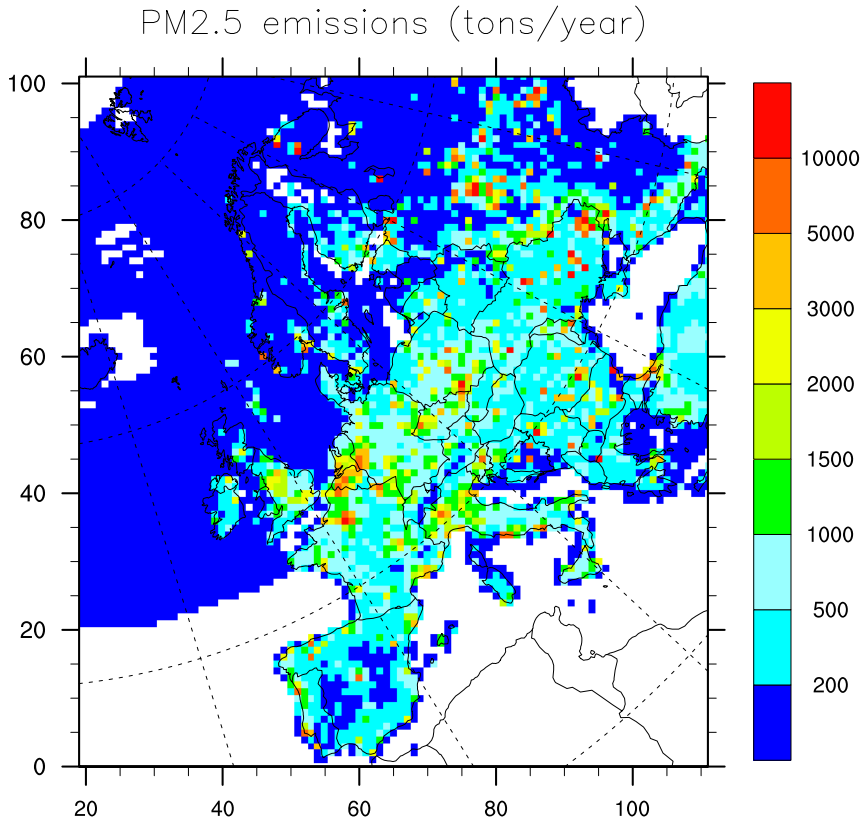

Figure 2.1: The average distribution of $PM_{2.5}$ emissions (in units of tons per year per grid cell) in the European region as defined in EMEP.

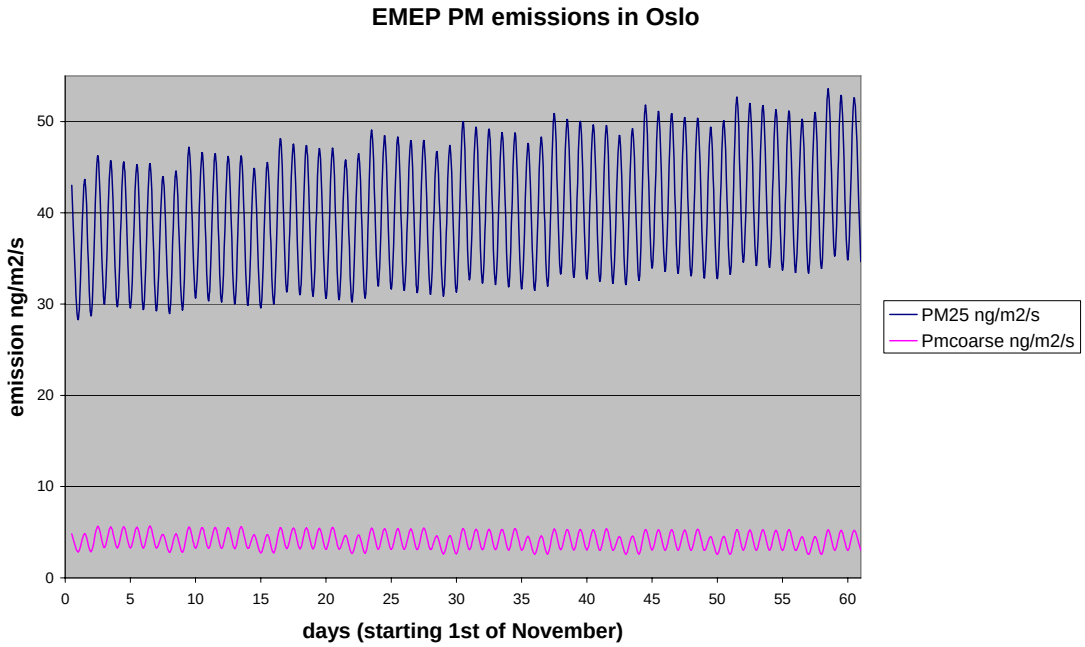

Figure 2.2: The time evolution of the PM emissions as defined in the EMEP model in the period November-December 2003. The emissions are lower during night and on Saturday and Sundays.

2.2 Emissions applied in the urban scale AirQUIS/EPISODE model system

For the Oslo area covered by EPISODE (18 x 22 km^2; see Figure 2.3), the emissions have been divided into two separate categories; i.e. area sources and line sources†, which are input to the Eulerian grid model and the sub grid line source model of EPISODE, respectively. EPISODE also contains a point source sub grid model, but since there are no important large point sources in Oslo, this sub grid model has not been applied in this work, and all of the emissions have either been treated as area- or line-sources. As part of the present work the EPISODE version with nesting capabilities has been incorporated into the Air Quality Information System, AirQUIS-2003, thereby allowing for use of the emission data-base within this system.

The Eulerian grid model within EPISODE is the same model that was used during the first part of this project, and is thoroughly described in the previous project reports (Wind et al., 2002 and 2003; Slørdal et al., 2003). EPISODE solves the time dependent advection/-diffusion equation on a 3 dimensional grid. Finite difference numerical methods are applied to integrate the solution forward in time. In the present simulations a grid resolution of 1 km^2 has been applied.

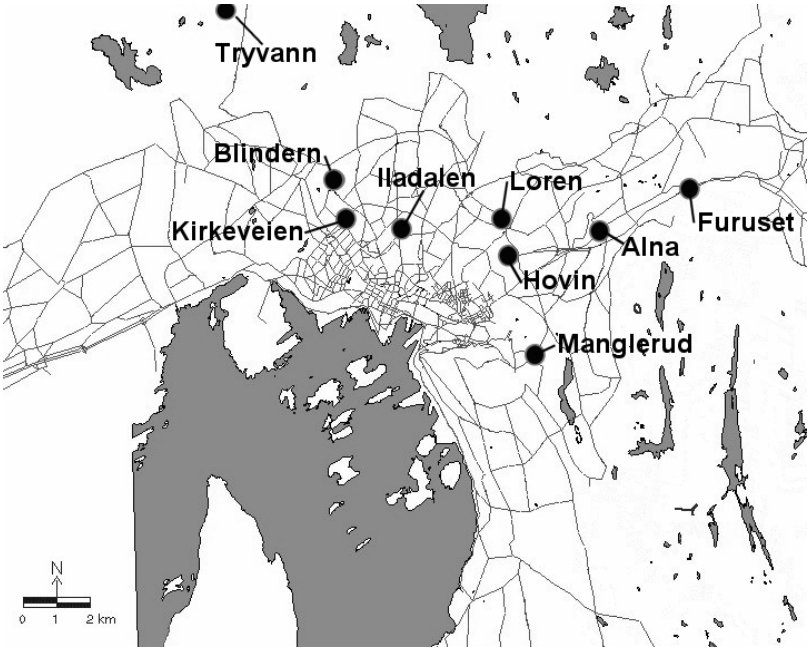

Figure 2.3: The 22x18 km^2 EPISODE model domain for Oslo. The applied road network (treated as line sources) is depicted as thin grey lines. In addition the positions of various meteorological and air quality measurement sites are shown as black circles with their names attached.

The sub-grid line source model is based on a standard integrated Gaussian model, HIWAY-2 (Petersen, 1980). This is a model that calculates concentration levels of pollutants, from road traffic at distances tens to hundreds of meters downwind of the road. Each lane of traffic is modelled as though it is a straight, continuous, finite length, line source with a uniform

† Area sources: Sources that are distributed in the grid system and specified as emissions in mass per area per time in each model grid cell. Line sources: Sources that are distributed along the applied road network and specified as emissions in mass per length unit of road per time.

emission rate. Air pollution concentrations are found by interpreting the line source as a finite sum of simple Gaussian point-source plumes, and the total line source contribution is then found by integrating numerically over the length of the line source (Slørdal et al., 2003).

The AirQUIS-2003 emission inventory module contains data such as fuel consumption, emission factors, physical description of stacks and processes, traffic load etc. Estimates of hourly emissions of the different air pollutants are calculated by application of an emission model. For the present Oslo application the emission data have been split into two separate categories. These are:

- **Line source emissions:** Include all emissions from road traffic, i.e. SNAP sector 7. In the calculations presented in this report only roads with annual daily traffic (ADT) above 3000 vehicles are included as line sources. The emissions from the roads with lower ADT are treated as ground level area sources.
- **Area source emissions:** Include both stationary sources that are too small to be regarded as point sources as well as road traffic emissions from roads with ADT below the given user defined limit. These emissions are distributed as hourly gridded emissions in a similar way as in the EMEP model.

The method applied to calculate the PM_{10} contribution from traffic-induced re-suspension, mainly consisting of PM_{coarse}, takes into account the effect of vehicle composition, traffic speed and, during the winter season, the percentage of vehicles with studded tyres, on each road segment. Since practically no particles are re-suspended when the roads are wet, hourly data on relative humidity and precipitation within the modelling area is used as input to the emission model. This source is contributing as line source emissions for line sources with ADT above the given limit, and as area source emissions for line sources with less traffic load.

The estimates for the line source emissions and the contribution from re-suspension are produced by NILU, whereas all other emission information are produced by Statistics Norway (SN).

By calculating hourly emissions from both line sources and area sources in Oslo for the period 1st of November – 31st of December 2003, and distributing the total emissions geographically within the applied model grid, the average $PM_{2.5}$ and PM_{10} emission intensity (in g/s) become as shown in Figure 2.4 and 2.5, respectively. The applied model grid is explicitly shown as grid squares in these plots. Since the area of each grid cell is 10^6 m^2 the values in these figures is converted to ng m^{-2} s^{-1} simply by multiplying by 1000.

The average emission intensity for the whole 22 x 18 km^2 model domain is 95 ng $m^{-2}s^{-1}$ $PM_{2.5}$ and 179 ng $m^{-2}s^{-1}$ PM_{10} (i.e. 84 ng $m^{-2}s^{-1}$ PM_{coarse}). However, large variability's are seen within the model domain for both components. The average emission intensity of $PM_{2.5}$ reaches a value as high as 701 ng m^{-2} s^{-1} in the central grid cell (10,12), i.e. the grid cell containing the Bogstadveien/Bislett area. Emissions from domestic wood-burning (part of SNAP sector 2), which is regarded as only emitting to the fine fraction, is the dominant source of $PM_{2.5}$ in this grid cell, and contribute to as much as 87.98 % of the average value for this particular period. Road traffic (mainly exhaust particles, with a small additional contribution from re-suspended particles) only contributes with 1.59 %, leaving 10.43 % to other

combustion sources like domestic heating by fossil fuel (rest of SNAP sector 2) and other mobile sources and machinery (SNAP sector 8).

For PM_{10} a maximum average emission intensity of 1299 ng m^{-2} s^{-1} is reached in the south-western grid cell (4,10), i.e. the grid cell covering the connection E18-Fornebu/Ring 3. In this grid cell road traffic (mainly contributing with re-suspended particles to the coarse fraction, PM_{coarse}, and exhaust particles to the fine fraction) is the dominant PM_{10} source contributing to 67.23 % of the emission intensity. Domestic wood burning is estimated to be responsible for as much as 31.69 % of the average emission intensity in this grid cell, resulting in only 1.08 % from other sources.

Note that the relative contribution of the various sources, given above as percentages, will not necessarily be reflected as similar percentages when considering contributions to ground level concentration levels. The main reason for this is that traffic sources are emitted at ground level, whereas emissions from wood burning are released above roof level. This means that the wood-burning emissions will be somewhat diluted before reaching ground level. This effect is taken into account in EPISODE by applying the sub grid line source model for the traffic emissions (thereby being able to model the high concentration levels observed close to the main roads), while the emissions from domestic wood-burning are included as area sources and therefore experience a certain amount of initial dilution depending on grid size. Consequently, when estimating the ground level particle concentrations, the relative importance of wood burning will systematically be less than indicated by the above emission contribution figures.

In Figure 2.6 and 2.7, time series of the estimated $PM_{2.5}$ and PM_{coarse} emissions in grid cell (10,12) and (4,10) are presented, respectively. Note that the PM_{10} emission is the sum of $PM_{2.5}$ and PM_{coarse}. The small contribution of coarse fraction particles (caused by re-suspension of road dust) in grid cell (10,12) is clearly demonstrated in Figure 2.6; while this source is the largest in grid cell (4.10), see Figure 2.7. Note also the strong increase in $PM_{2.5}$ emissions during the calculation period, reflecting the climatologically governed increase in wood consumption.

Since the area covered by EPISODE contains the largest emitters, it is to be expected that the average emission intensity per square meter generally will be larger than for the EMEP grid cell. In addition, not all the sources of PM are presently described in the Unified EMEP regional model. Important examples of sources that are not included are wind blown sources and traffic induced re-suspension of road dust. Different analysis have shown that these sources are the main contributors to PM_{coarse} during the winter and spring season in Oslo (Laupsa et al., 2005), and can therefore explain why the emissions of PM_{coarse} are much higher in the local model than in the regional model. This also illustrates the need of including re-suspension as a process in regional scale models.

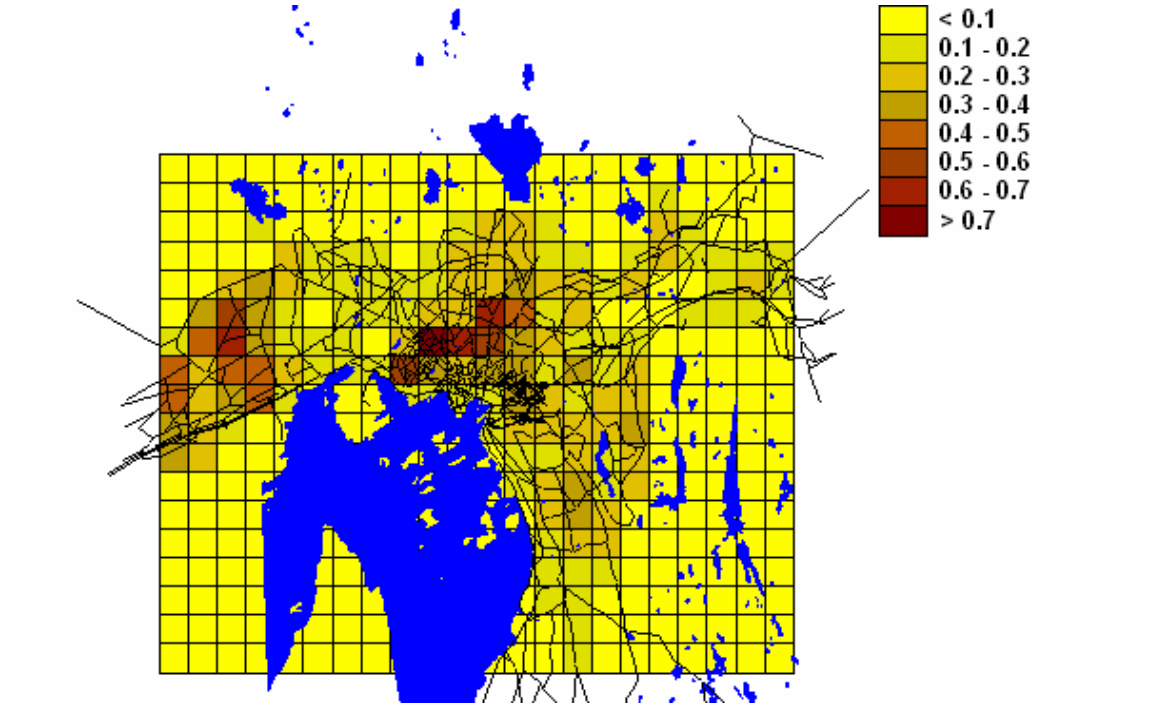

Figure 2.4: Average emission intensity of $PM_{2.5}$ in Oslo (g/s) for the two-month period November – December 2003. The highest value of 701 ng m^{-2} s^{-1} is found in grid cell (10,12), i.e. the grid cell covering the Bogstadveien/Bislett area. Summing over all cells the average emission intensity is 95 ng $m^{-2}s^{-1}$.

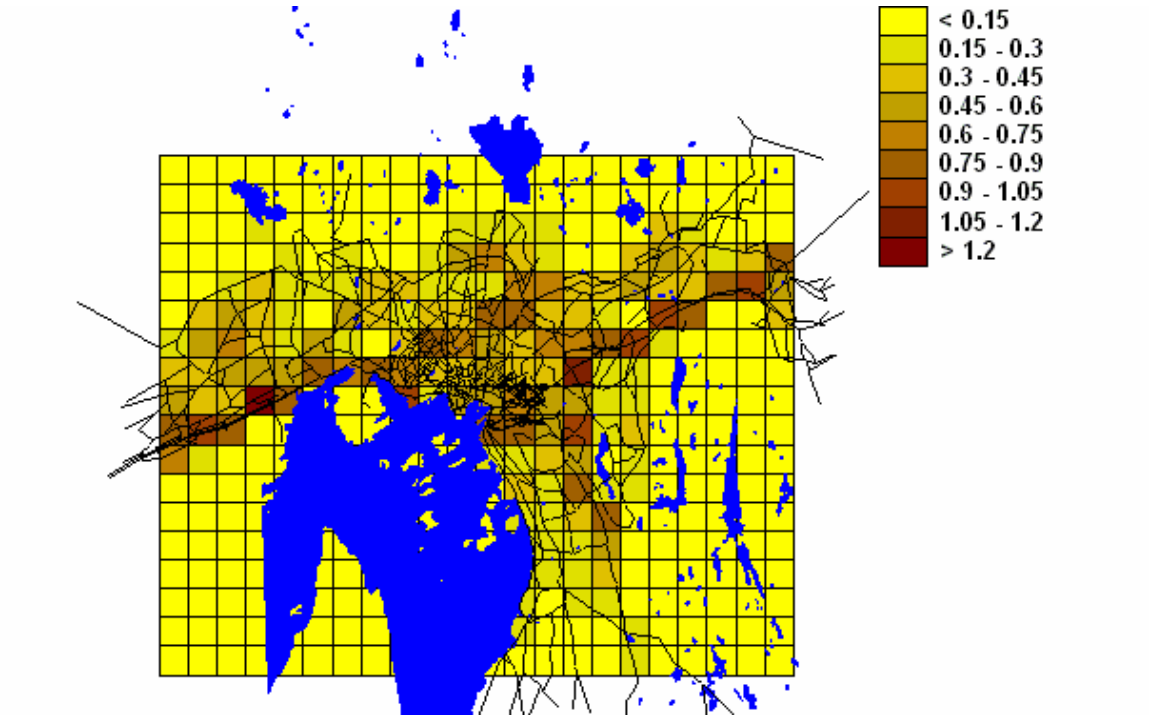

Figure 2.5: Average emission intensity of PM_{10} in Oslo (g/s) for two-month period November – December 2003. The highest value of 1299 ng m^{-2} s^{-1} is found in grid cell (4,10), i.e. the grid cell covering the connection E18-Fornebu/Ring 3. Summing over all cells the average emission intensity is 179 ng $m^{-2}s^{-1}$.

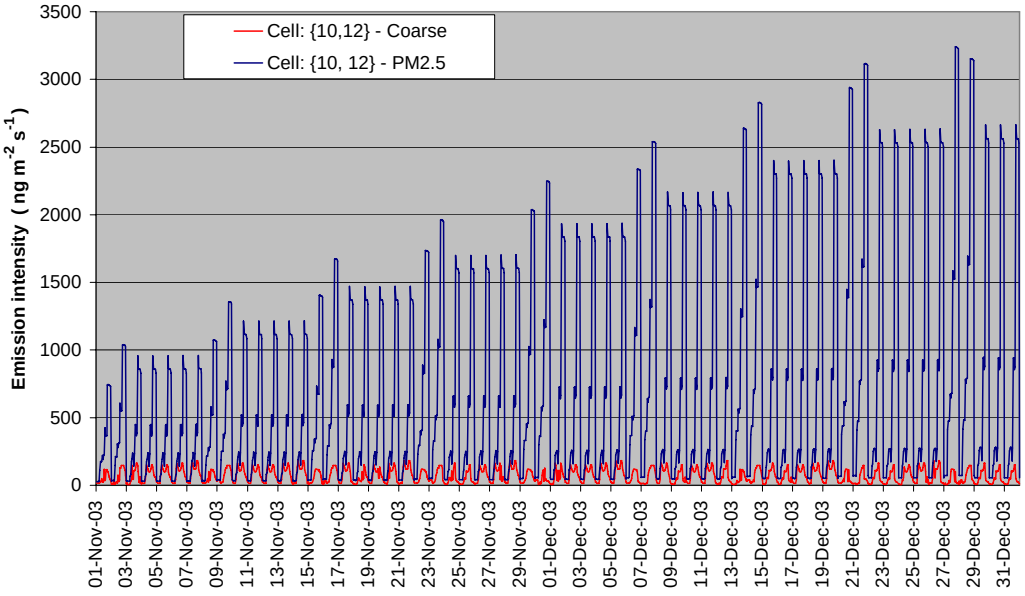

Figure 2.6: The hourly emission intensity of the fine ($PM_{2.5}$) and the coarse ($PM_{10} - PM_{2.5}$) particle fraction for the "wood-burning" dominated grid cell (10,12), covering the Bogstadveien/Bislett area.

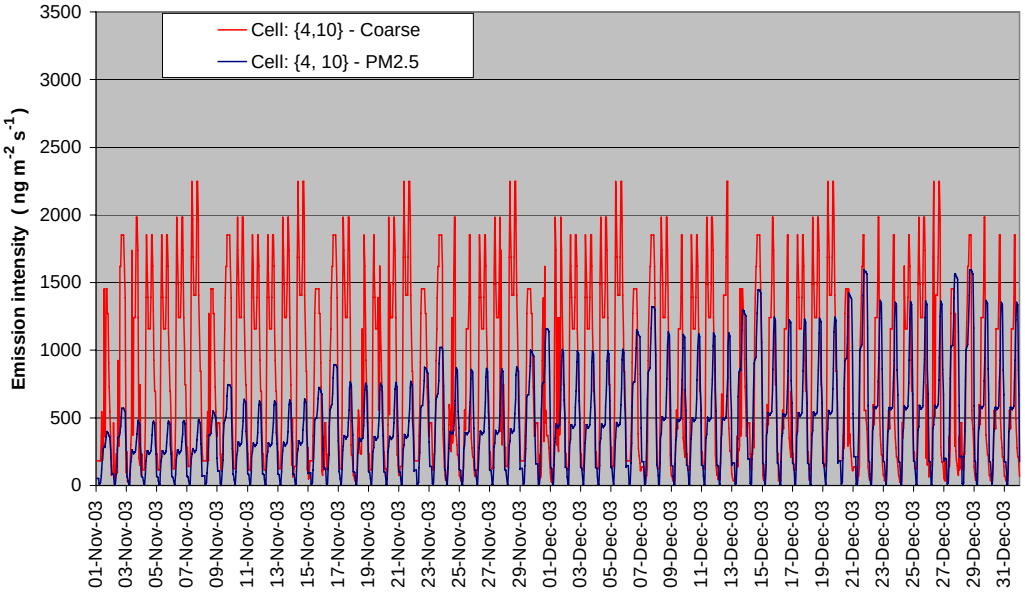

Figure 2.7: The hourly emission intensity of the fine ($PM_{2.5}$) and the coarse ($PM_{10} - PM_{2.5}$) particle fraction for the traffic dominated grid cell (4,10), i.e. the grid cell covering the connection E18-Fornebu/Ring 3.

3. Concentrations of Particulate Matter in Oslo

3.1 Regional contributions to $PM_{2.5}$ in Norway and in Oslo

In this section the background particulate matter in Oslo is analysed from a long-range transport perspective. The "Oslo area" is here defined as the EMEP grid cell comprising Oslo. The size of the grid cell is approximately 50x50km^2. The concentrations relate to yearly averaged concentrations. The data has been defined in the same way as in (Klein et al, 2004); it is based on year 2000 meteorology and CLE_2010 emissions scaled to 2002 emissions.

Since the PM_{coarse} is relatively less important in the context of long-range transport, we will mostly discuss the fine particulates ($PM_{2.5}$) in this section.

Figure 3.1 gives an overall picture of the average $PM_{2.5}$ concentrations in Europe. Norway lies outside the region of highest concentrations in Northern Europe, but under specific meteorological conditions, the "European plume" can be transported over the southern part of Norway. Although the values presented here are for November 2003, these are representative of the yearly averaged $PM_{2.5}$ levels over Oslo at the beginning of the 2000s.

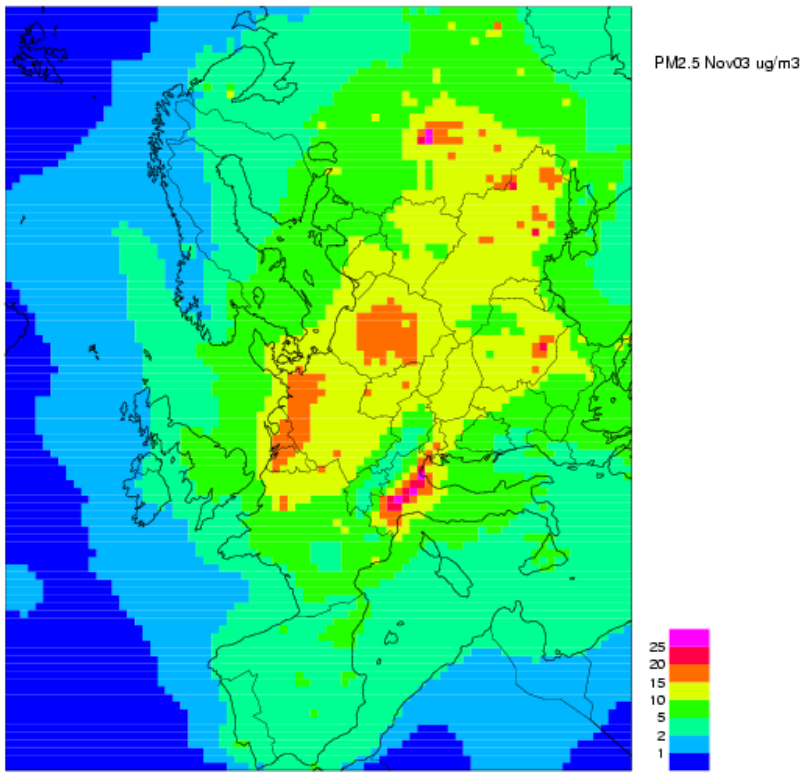

Figure 3.1: Average concentration of $PM_{2.5}$ in the European region in November 2003 (units: µg m^{-3}).

3.1.1 Country contributions to PM in Norway and in Oslo

The pie charts of figure 3.2 show the relative contributions of different countries to the concentrations of $PM_{2.5}$ in Norway and in Oslo.

The contributions of 44 different countries and 5 sea areas have been taken into account. The definition of the country codes is as follows: NO-Norway, DE-Germany, UK-United Kingdom, RU-Russian federation, DK-Denmark, PL-Poland, SE-Sweden, NOS-North Sea, FR-France, NL-Netherlands.

About 78 % of the $PM_{2.5}$ in Norway and 62 % of the $PM_{2.5}$ in the Oslo area have a source outside Norway.

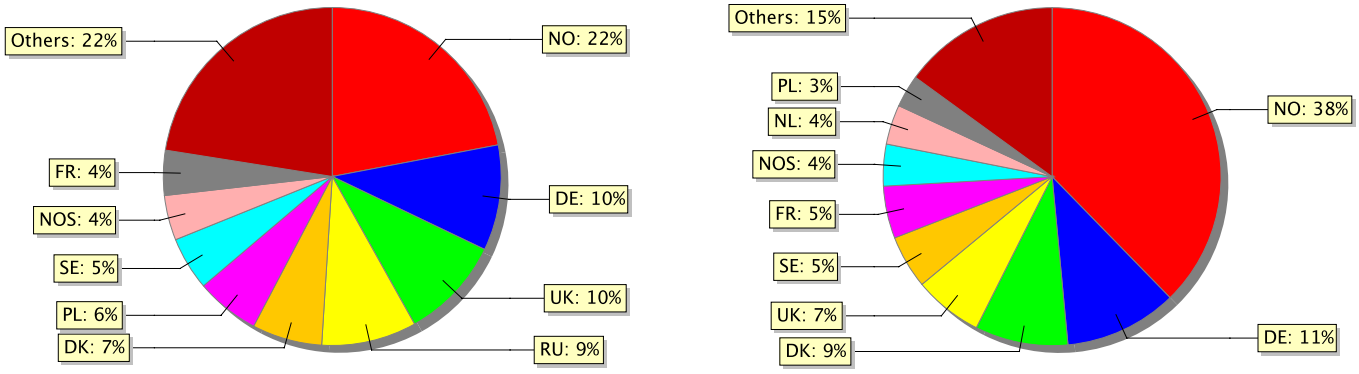

Figure 3.2: Relative contribution to $PM_{2.5}$ from most important countries to concentrations in Norway (left hand side figure) and Oslo (right hand side figure).

The differences between the pie charts for Oslo and Norway are simple to interpret in terms of location of the main pollutant sources. Most of the Norwegian emission sources are located in the southern part of the country; as a consequence Norway has a relatively larger responsibility for the $PM_{2.5}$ concentration in Oslo (38%) than on average in Norway (22%). Conversely Russia contributes 9% to the concentration in Norway but only 2% to $PM_{2.5}$ in Oslo. This can be interpreted by the fact that Russian $PM_{2.5}$ affects mostly the northern parts of Norway.

Norway itself is the largest single contributor, it accounts for about 38% of background $PM_{2.5}$ concentrations in Oslo; eight other countries have contribution ranging from 11% to 3% and still 15% of the total concentrations are the sum of contributions smaller than 3%.

A large number of countries contribute significantly to the pollution levels in Norway. The influence of these countries and the long-range transported particulates are essential for a correct description of the background concentrations in Norway.

3.1.2 Chemical origin of $PM_{2.5}$ in Oslo

Fine particulate matter ($PM_{2.5}$) in the EMEP model includes at present primary particles (PPM), sea salt (SS) and secondary inorganic aerosols (SIA). The secondary inorganic aerosols are composed of nitrate (NO_3^-), sulphate (SO_4^{2-}) and ammonium (NH_4^+) and are formed by condensation of gaseous precursors, namely from emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3).

The average chemical composition of $PM_{2.5}$ in Oslo is shown in the left hand side pie chart of figure 3.3. Fine particulate matter is divided into fine primary particulate matter ($PPM_{2.5}$), fine nitrate (NO_3), sulphate (SO_4), ammonium (NH_4) and fine sea salt (SS). Since sea salt is not of anthropogenic origin it has not be taken into account in the other pie charts of this section.

The primary component to particulate matter is considered to be inert and there is a direct proportionality between the amount emitted and the modelled concentrations. On the other hand, the secondary inorganic aerosols depend on the emissions in a non-linear way, and a change of for instance ammonium emissions will also affect the NO_3 and SO_4 concentrations.

The right hand side pie chart of figure 3.3 gives an indication of the chemical origin of the fine particulate matter. 34% of the $PM_{2.5}$ in Oslo is due to emissions of primary particulate matter, 24% is due to the emissions of ammonia, 23% to sulphur oxides, 17% to nitrogen oxides and 2% is due to emissions of non-methane volatile organic compounds (NMVOC). This means for example, that a 5% reduction of PPM by all countries will have the same effect in Oslo as a 10% reduction of NO_X (10·17 = 5·34).

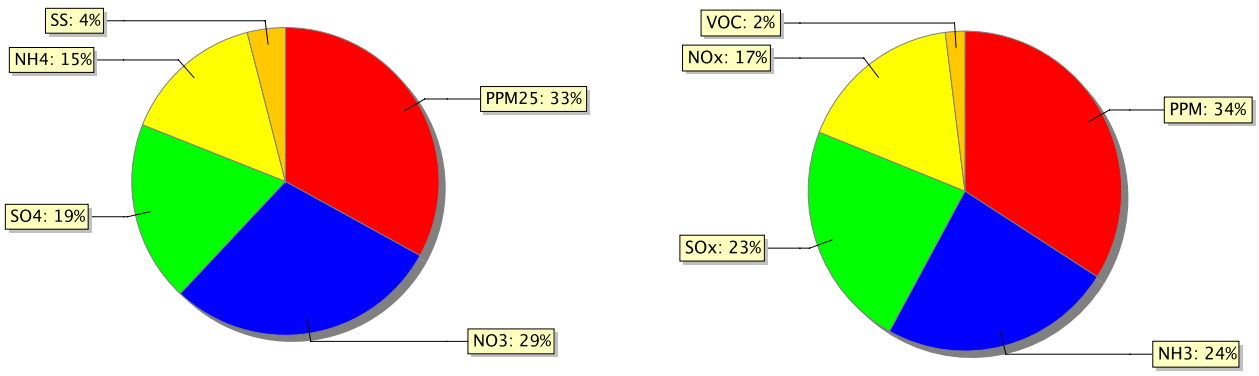

Figure 3.3: Chemical composition of $PM_{2.5}$ in Oslo (left hand side figure) and relative importance for $PM_{2.5}$ of different emission (right hand side figure).

Comparison with PM background observations in the EMEP network (EMEP 4/2003 and EMEP 4/2004) shows that the modelled regional PM levels are underestimated, generally because wind blown dust sources and re-suspension are presently not included in the calculations and neither are the thermodynamic and chemical processes leading to the formation of secondary organic aerosols. For $PM_{2.5}$, the underestimation of regional background levels is generally by 25-30%, and up to 40-50% for PM_{10} concentrations. The underestimation of PM_{10} is larger than for $PM_{2.5}$ because the missing re-suspension and wind blown sources are expected to be mostly emitted in the coarse fraction.

3.1.3 Influence of different European activity sectors in Oslo

In figure 3.4 we show the relative contributions to $PM_{2.5}$ of the different SNAP sectors to Norway and Oslo. Only the anthropogenic sources (sector 1 to 10) are included.

In this test the influence of only 28 European countries are taken into account: the 25 member countries of the European Union (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain, Sweden, United Kingdom, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia) and Norway, Switzerland and Iceland. In addition, for practical reasons, meteorology from year 2003 and projection of emissions for 2010 ("CLE_2010") have been used for this test. The relative contributions of different countries are different in this emission set and the fractions presented in figure 3.4 are therefore not directly comparable to the other results presented in this report. Still, they provide a useful overview of the relative importance of different activity sectors in the regional PM background levels over Oslo.

The sector 10 has the largest influence on the concentration levels of $PM_{2.5}$ in Norway and Oslo (41 % and 35 % respectively). Sector 10 includes emissions from agriculture and this large contribution can be traced back to ammonia emissions, which are transformed into ammonium nitrate (NH_4NO_3) and ammonium sulphate ($(NH_4)_2SO_4$). Ammonium controls the chemistry of both nitrate and sulphate and consequently it plays a significant role in the long-range transport of secondary inorganic aerosols. The results in figure 3.4 indicate once more the need for control strategies in agriculture related activities.

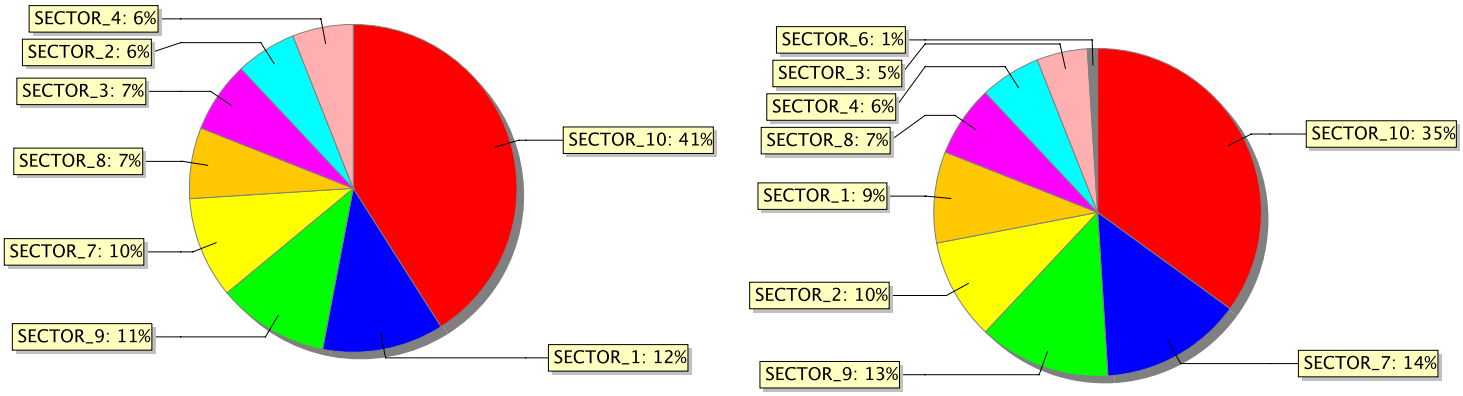

Figure 3.4: Relative contribution to $PM_{2.5}$ from 11 SNAP sectors to concentrations in Norway (left hand side figure) and Oslo (right hand side figure).

3.2 The influence of local Oslo sources

3.2.1 Nesting of the local grid into the EMEP regional grid

The EMEP model covers a large region with a coarse grid (50 km resolution), while the grid used by EPISODE has a high resolution (1 km) but covers an area that corresponds to less than ¼ of the size of one EMEP grid cell. In the simulations presented in this report, the 1 km resolution grid is nested directly into the EMEP grid. That means that the concentrations levels at the boundaries of the small grid are defined by the concentrations of the EMEP grid cell covering Oslo. A better approach would have been to include an intermediate region covering a large area around Oslo with an intermediate resolution (200km x 200km with 5 km resolution for example). However since no emission inventory is available at this intermediate resolution, it is difficult to improve the description of the region around Oslo.

The vertical levels of the EPISODE and EMEP model do not match. The middle of the lowest layer in the EMEP grid is at a height of about 46m, while EPISODE has the three lowest layers at 7, 21 and 49,5 meters. In order to define the values at the boundaries of the small grid in EPISODE, a vertical interpolation has to be performed. In previous work (Wind et al., 2003) this interpolation was done in after the model simulation. In this project the vertical profiles of the concentrations have been calculated directly inside the EMEP model at the height required by EPISODE. In this way it was possible to take into account the downward fluxes for the lowest levels.

3.2.2 Regional versus local contributions of PM in Oslo based on results from the EMEP model

In figure 3.5 and 3.6 the time evolution of the $PM_{2.5}$ and PM_{coarse} as calculated in the EMEP model are presented. For $PM_{2.5}$, the concentrations are varying over a large range of values, from almost no $PM_{2.5}$ to over 40 μg m^{-3}, depending on the particular meteorological conditions during that period, see figure 3.5. The PM_{coarse} never exceeds 3.5 μg m^{-3} in the EMEP regional model. The coarse part is much smaller than the fine contributions in the regional description, see figure 3.6.

The lower curve in figure 3.5 and 3.6 gives the concentrations obtained by putting all Norwegian emissions to zero. For the peak around the sixth day, the curves with and without Norwegian contributions are close to each other. This means that the air pollution in Oslo at that time is essentially due to long-range transported air pollution.

In figure 3.7 the $PM_{2.5}$ concentrations over Europe in the period 4th to 9th of November are shown. The evolution of the concentration levels support the interpretation of a plume with high concentrations moving from Northern Europe to the southern part of Norway.

On the other hand the peak around the 21st day is almost entirely removed when the Norwegian emissions are set to zero (in the $PM_{2.5}$ case). Local effects are therefore expected to be the most important in this case (see figure 3.8).

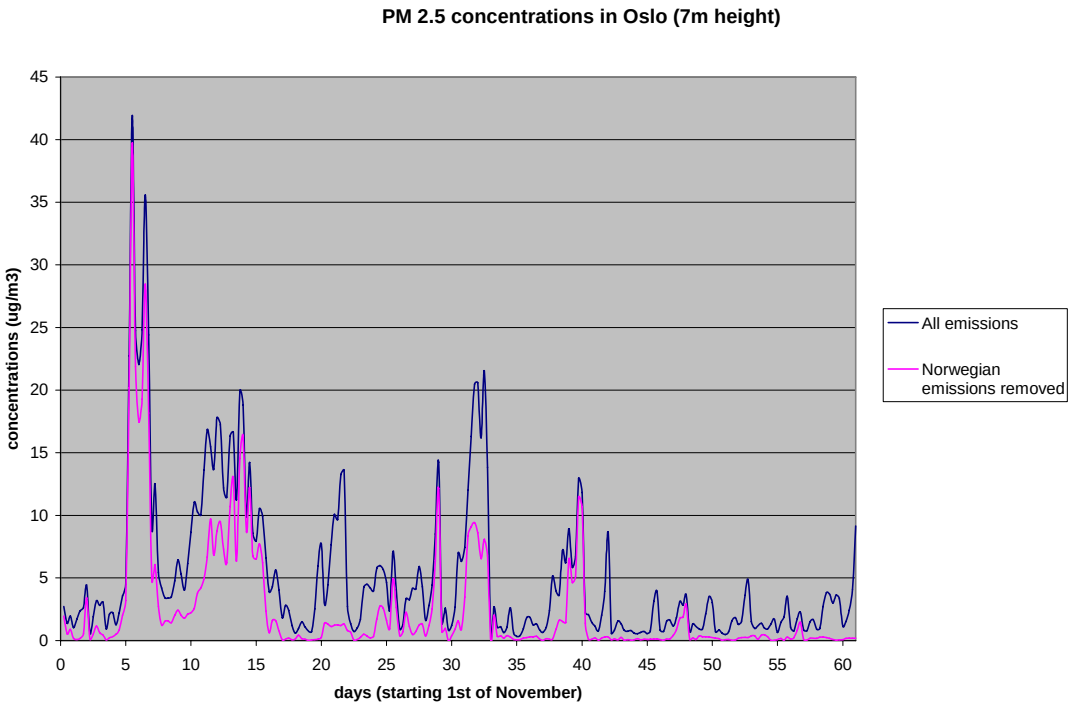

Figure 3.5: $PM_{2.5}$ concentrations in Oslo close to the ground (7 m height) as calculated in the EMEP model. The blue curve represents the actual concentrations, while the red curve show the concentrations obtained when all the Norwegian emissions are set to zero.

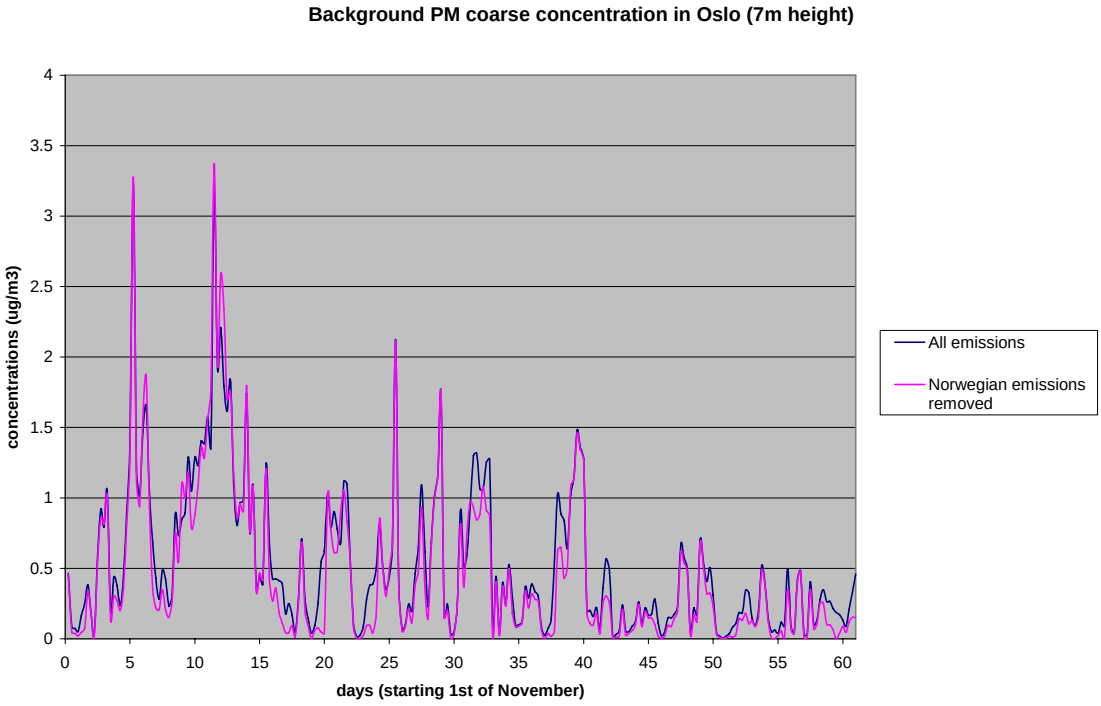

Figure 3.6: PM_{coarse} concentrations in Oslo close to the ground (7 m height) as calculated in the EMEP model. The blue curve represents the actual concentrations, while the red curve show the concentrations obtained when all the Norwegian emissions are set to zero.

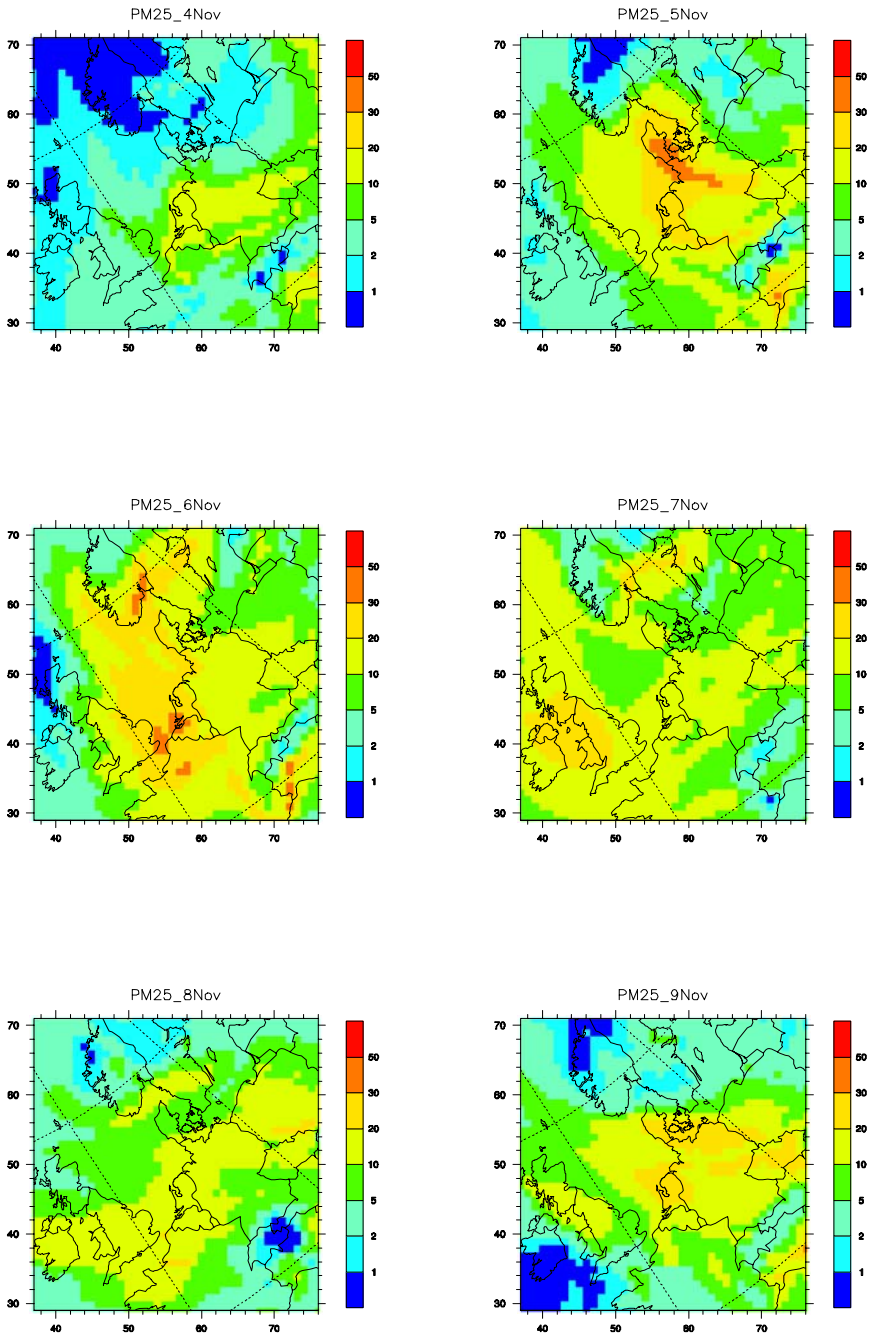

Figure 3.7: Average daily $PM_{2.5}$ concentrations in northern Europe in the period 4th to 9th of November. A plume of high concentrations is moving over the southern part of Norway.

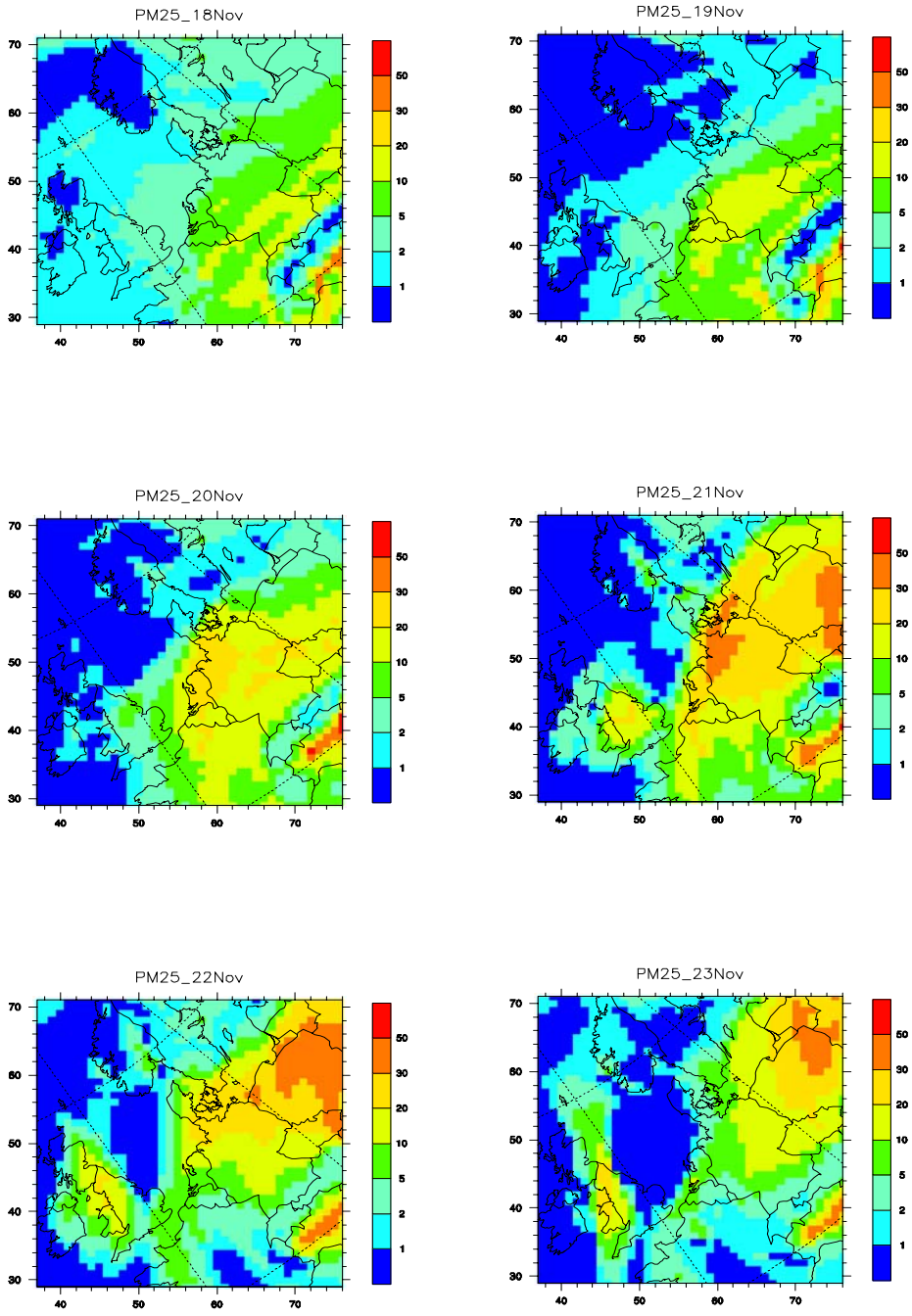

Figure 3.8: Average daily $PM_{2.5}$ concentrations in northern Europe in the period 18th to 25th of November. The increase around Oslo the 21st of November seems to have local origins, and is not long range transported.

3.2.3 Regional versus local contributions to Oslo based on the coupled EMEP and AirQUIS/EPISODE model system

3.2.3.1 PM_{10} simulations

The calculated average PM_{10} concentration field (given in $\mu g\ m^{-3}$) for the two-month period November – December 2003 is presented in Figure 3.9. The highest values of 35.9 $\mu g\ m^{-3}$ are found in the neighbouring grid cells (4,10) and (5,10), i.e. the grid cells covering the E18-Fornebu/Ring 3 connection and the Lysaker area. The regional background contributes to these grid cells with a value of about 3.9 $\mu g\ m^{-3}$, i.e. about 10.9 % of the maximum computed average values. The regional contribution in these cells are lower than the averaged lower layer EMEP value due to the vertical profile of the boundary values. This means that interior grid cells can be influenced by lower background contributions if vertical exchange processes are important.

During individual hours much higher concentration levels are computed. An example of such a field is shown in Figure 3.10. In this Figure the Eulerian grid concentration for the lowermost model layer, valid for hour 17 to 18 on the 8th of December 2003, is presented. Concentration levels reaching 200 $\mu g\ m^{-3}$ in grid cell (3,9) and 199 $\mu g\ m^{-3}$ in grid cell (4,10) are computed as grid cell averages for this particular hour. Note that at individual building points close to the main road system even higher concentration levels are estimated by the sub grid line source model. The regional background level estimated by the EMEP model for this hour is only about 5 $\mu g\ m^{-3}$, i.e. 2.5 % of the maximum hourly grid square average concentration of 200 $\mu g\ m^{-3}$.

Comparison with local PM_{10} observations

Below a comparison between measured and calculated PM_{10} levels are presented for three measurement sites within the model domain. The three sites are Iladalen (urban background station), Kirkeveien (central street station) and Løren (street station at Ring 3). The locations of these stations are depicted in Figure 2.3 in Section 2.2. For each of these stations time series of observed and AirQUIS/EPISODE calculated PM_{10} concentration values will be presented. In addition the lower layer EMEP model concentration value, i.e. the value that is applied as boundary condition in the lowermost AirQUIS/EPISODE layer, is presented.

It should be noted that the distinction between the urban station (Iladalen) and the street stations (Kirkeveien and Løren) in this context is that the urban value is estimated by the average grid value (average over the model grid cell covering the Iladalen site), while the street station values are calculated at the exact location of the measurement point and consist of the average grid value plus an additional contribution from the sub grid line source model. This means that the model predicted street station values always will be somewhat larger than the average grid value for the grid cell covering the site. Of the two selected street stations, Løren is influenced most strongly by the sub grid line source contribution since the traffic load and the vehicular speed is much higher at Ring 3 than at Kirkeveien.

In Figure 3.11 the time series for the three stations are presented as hourly values. In November the applied EMEP background values seems to form the baseline on which the observed concentrations fluctuate due to local sources. As mentioned in Section 3.2.2, the importance of the regional contribution is clearly demonstrated during the two-day period,

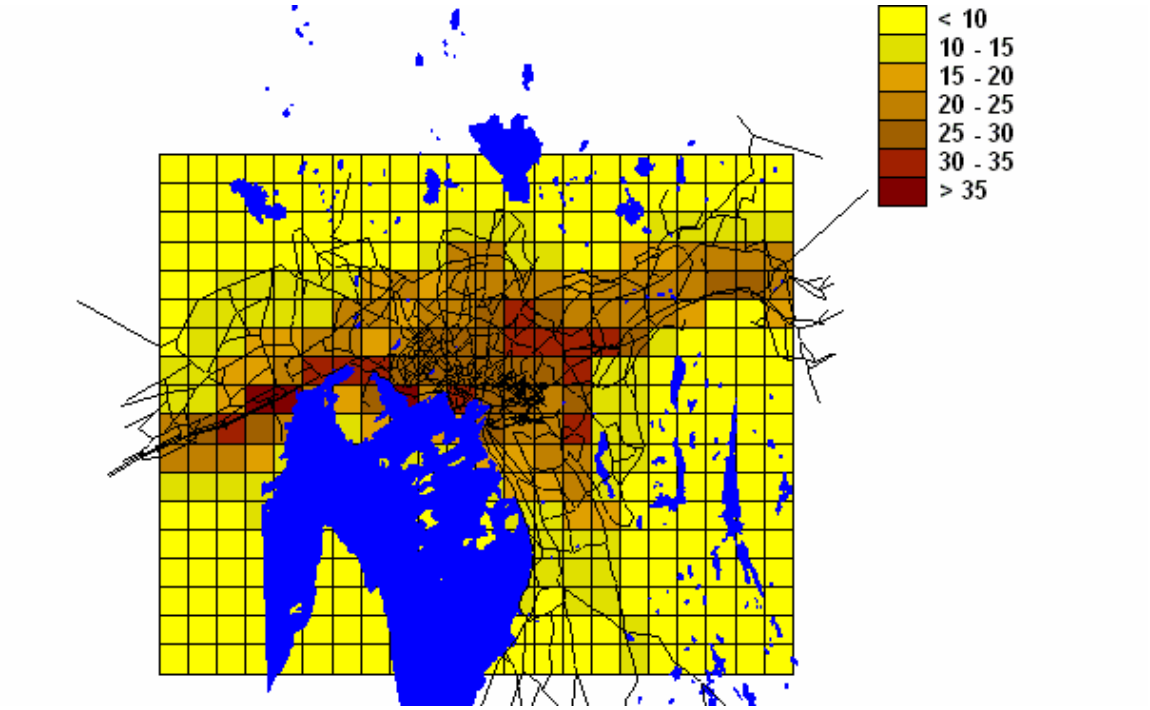

Figure 3.9: Average concentration of PM_{10} in Oslo ($\mu g\ m^{-3}$) for the two-month period November – December 2003.

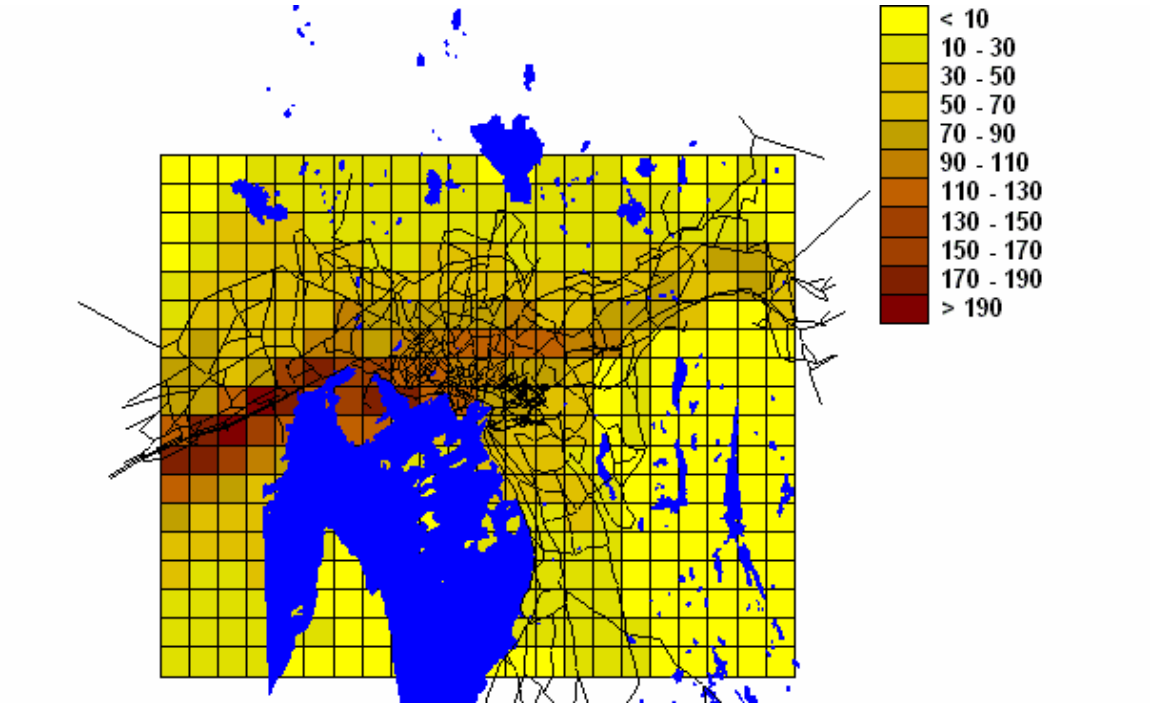

Figure 3.10: Example of hourly concentration field of PM_{10} ($\mu g\ m^{-3}$) valid for hour 17 to 18 on the 8th of December 2003.

6th – 8th November. However, during most of December the background values are extremely low, and are to a much lesser extent reflecting the minimum levels of the observed PM_{10} values. When comparing the AirQUIS/EPISODE calculated values with the observations, the degree of fit is quite variable. However, the model predicted values are reproducing the

general pattern of the observed time series, i.e. reaching similar maximum levels, showing similar variance in the time series and producing similar average values for the total two-month period. This is seen in the statistical figures for the three stations presented in Table 3.1 below.

In contrast the applied EMEP boundary values attain an average value of just 22 % and a standard deviation of 26 % of the corresponding values at the urban station (Iladalen). When the EMEP values are correlated with the hourly Iladalen data, a correlation coefficient of 0.15 is found (not shown in Table 3.1). The low values of the standard deviation and the correlation are to a large extent caused by the coarse EMEP resolution. If meteorological and emission input data had been available at intermediate spatial resolutions, i.e. between 50 km^2 and 1 km^2, the self-nested versions of the EMEP/EPISODE model system could have been utilized to produce boundary conditions with more detailed spatial and temporal resolution. However, it is difficult to quantify the amount of improvement that could be expected from such a nesting procedure, without actually performing test-simulations.

	EMEP BC	Iladalen		Kirkeveien		Løren	
		Calc.	Obs.	Calc.	Obs.	Calc.	Obs.
Average, Nov – Dec 2003 (μg m^{-3}):	5.6	27.3	25.9	30.4	32.3	42.4	42.5
Standard deviation from average (μg m^{-3}):	6.6	31.3	25.8	24.9	33.0	55.3	57.7
Correlation coefficient:		0.35		0.35		0.34	
Slope of linear regression line:		0.31		0.26		0.33	
Intercept of linear regression line (μg m^{-3}):		19.2		21.9		28.5	

Table 3.1: Statistical parameters for the comparison of the AirQUIS/EPISODE predicted hourly PM_{10} concentrations with the observations at the three measurement sites. The ground level EMEP estimated average and standard deviation are included as well.

Since the air quality guidelines on PM_{10} are related to daily averages, the time series given in Figure 3.11 are re-produced as running daily average values in Figure 3.12. Apart from the difference in time resolution, much of the same features are seen in Figure 3.12 as in Figure 3.11. The statistical comparison of the running daily averages is presented in Table 3.2. The correlation at Iladalen and Løren become significantly better when considering daily averages while the model correlate slightly less when compared to the daily observations at Kirkeveien. The standard deviation of the daily averaged EMEP boundary values drop slightly to 5.9 μg m^{-3}, and the correlation with the Iladalen measurements increase to 0.24 (not shown in Table 3.2).

	EMEP BC	Iladalen		Kirkeveien		Løren	
		Calc.	Obs.	Calc.	Obs.	Calc.	Obs.
Average, Nov – Dec 2003 (μg m^{-3}):	5.6	27.3	25.9	30.4	32.3	42.4	42.5
Standard deviation from average (μg m^{-3}):	5.9	11.4	14.5	11.6	21.6	23.9	34.1
Correlation coefficient:		0.47		0.33		0.46	
Slope of linear regression line:		0.37		0.18		0.32	
Intercept of linear regression line (μg m^{-3}):		18.0		24.9		29.1	

Table 3.2: Statistical parameters for the comparison of the AirQUIS/EPISODE predicted running daily average PM_{10} concentrations with observations at the three measurement sites. The ground level EMEP estimated average and standard deviation are included as well.

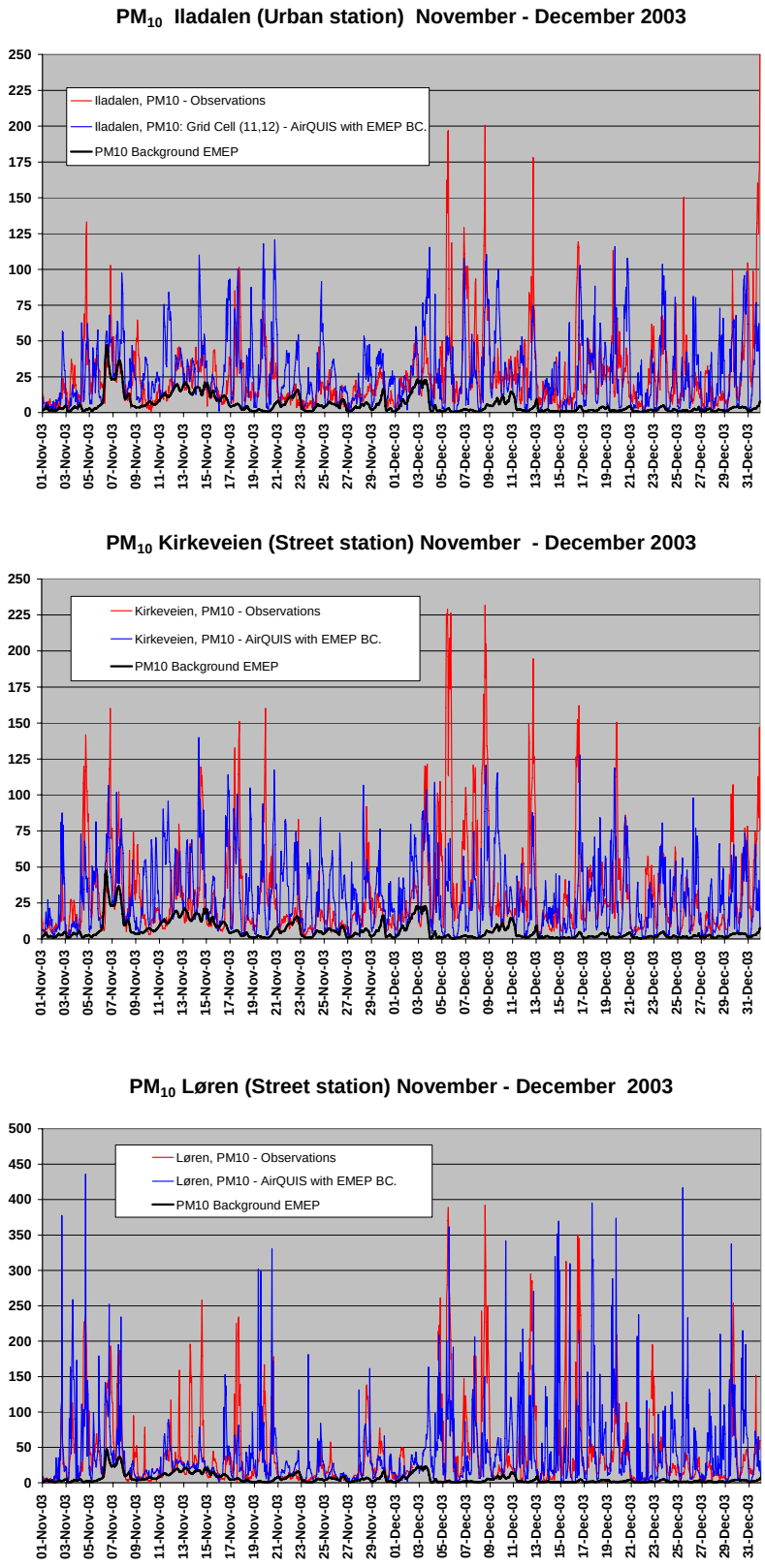

Figure 3.11: Hourly values of PM_{10} ($\mu g\ m^{-3}$) at the urban background station Iladalen, and the street stations Kirkeveien and Løren.

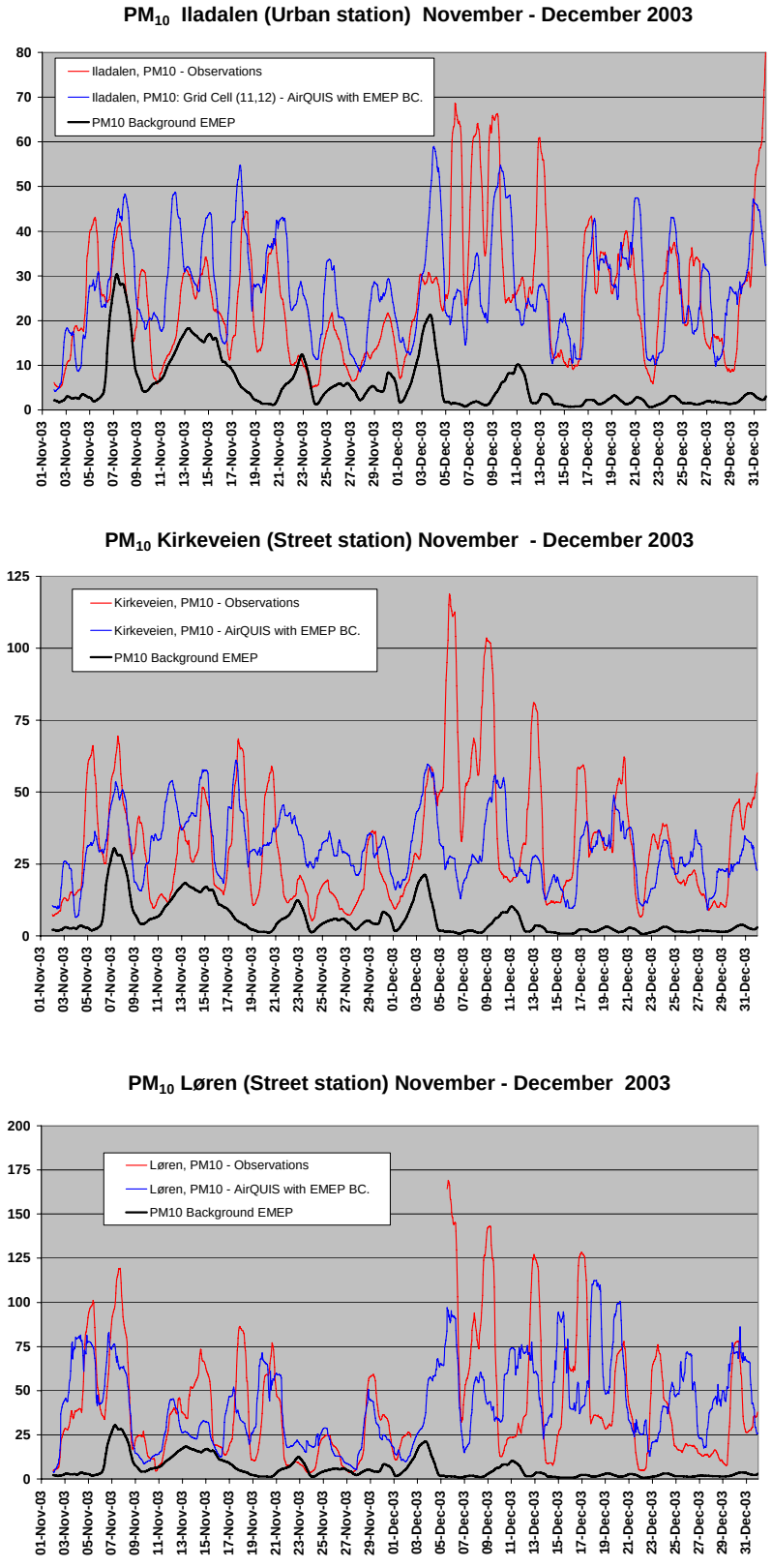

Figure 3.12: Daily running average of PM_{10} ($\mu g\ m^{-3}$) at the urban background station Iladalen, the urban/street station Kirkeveien and the street station Løren.

3.2.3.2 $PM_{2.5}$ simulations

The calculated average $PM_{2.5}$ concentration field (given in $\mu g\ m^{-3}$) for the two-month period November – December 2003 is presented in Figure 3.13. The highest values of 17.7 $\mu g\ m^{-3}$ are found in the central grid cells (10,12) and (11,12), i.e. the grid cells stretching eastward from Bogstadveien towards Alexander Kiellands Plass. The regional background contributes to this field with a constant value of about 5 $\mu g\ m^{-3}$, i.e. about 28 % of the maximum computed grid average values.

An example of an hourly computed $PM_{2.5}$ field is shown in Figure 3.14. In this Figure the Eulerian grid concentration for the lowermost model layer, valid for hour 21 to 22 on the 30th of December 2003, is presented. Concentration levels up to 91.4 $\mu g\ m^{-3}$, in (10,11), is computed as grid cell averages for this particular hour. The regional background level estimated by the EMEP model for this hour is as low as about 2 $\mu g\ m^{-3}$.

Comparison with local $PM_{2.5}$ observations

A comparison between measured and calculated hourly $PM_{2.5}$ levels are presented for the two street stations, Kirkeveien and Løren, in Figure 3.15 below. Unfortunately, no urban background measurement data were available during the November – December 2003 period.

The EMEP calculated particle levels for the Oslo grid cell is mainly in the fine fraction, and consequently the EMEP boundary values contribute more to the calculated $PM_{2.5}$ levels than was the case for PM_{10}; see Figure 3.11. Again this is most clearly demonstrated during the month of November. During this month the boundary values even become higher than the measured street level concentrations. This is particularly the case during the regionally dominated episode from the 5th to the 9th of November, and indicates that the regional contribution is somewhat overestimated during this period.

Another feature seen from Figure 3.15 is that the general variation of the observed $PM_{2.5}$ signal is reproduced by the AirQUIS/EPISODE model, even though it seems like the model has a tendency to overestimate the maximum hourly values, especially at Kirkeveien. The parameters showing the statistical relationships between the calculated and observed values in Figure 3.15 are presented below in Table 3.3. As expected the statistical measures are somewhat better for $PM_{2.5}$ than for PM_{10}, (see Table 3.1). This is due to the difficulties in estimating correctly the contribution of coarse particles from traffic-induced re-suspension. As seen in Table 3.3, the applied EMEP boundary values now attain an average value of about 1/3, and a standard deviation of 55 – 60 % of the corresponding measured values at the two stations.

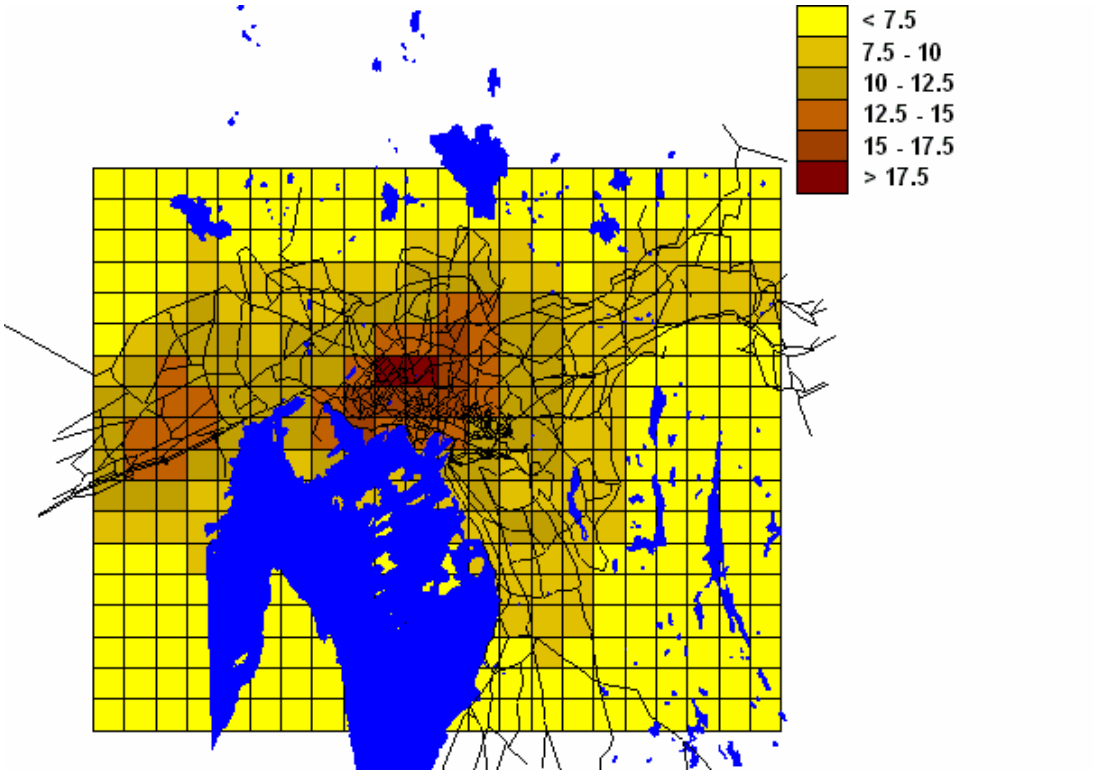

Figure 3.13: Average concentration of $PM_{2.5}$ in Oslo (μg m^{-3}) for the two-month period November – December 2003.

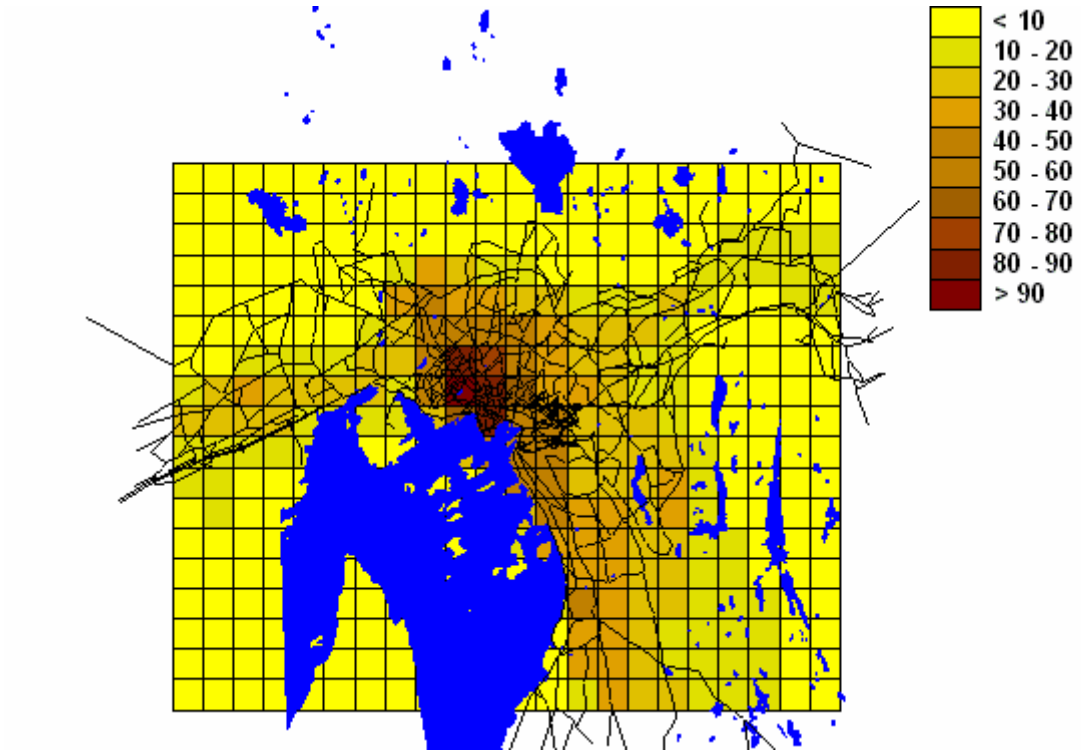

Figure 3.14: Example of hourly concentration field of $PM_{2.5}$ (μg m^{-3}) valid for hour 21 to 22 on the 30th of December 2003.

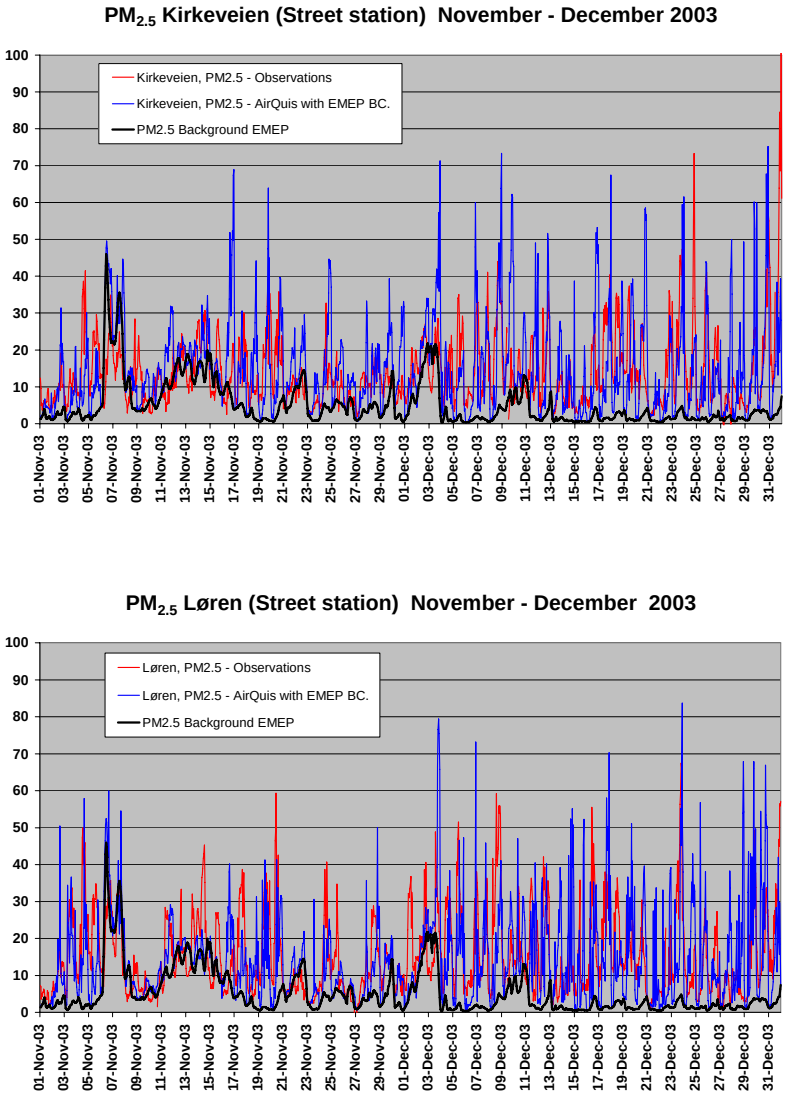

Figure 3.15: Hourly values of $PM_{2.5}$ (µg m^{-3}) at the urban/street station Kirkeveien and the street station Løren.

	EMEP BC	Kirkeveien		Løren	
		Calc.	Obs.	Calc.	Obs.
Average, Nov – Dec 2003 (µg m^{-3}):	5.1	15.0	14.1	14.4	15.4
Standard deviation from average (µg m^{-3}):	6.2	12.7	10.2	12.5	11.3
Correlation coefficient:		0.40		0.41	
Slope of linear regression line:		0.50		0.46	
Intercept of linear regression line (µg m^{-3}):		8.0		7.4	

Table 3.3: Statistical parameters for the comparison of the AirQUIS/EPISODE predicted hourly $PM_{2.5}$ concentrations with the observations at the two measurement sites. The ground level EMEP estimated average and standard deviation are included as well.

Similar to the time series of PM_{10}, the $PM_{2.5}$ time series given in Figure 3.15 are also re-produced as running daily averages in Figure 3.16. The corresponding statistical parameters are presented in Table 3.4.

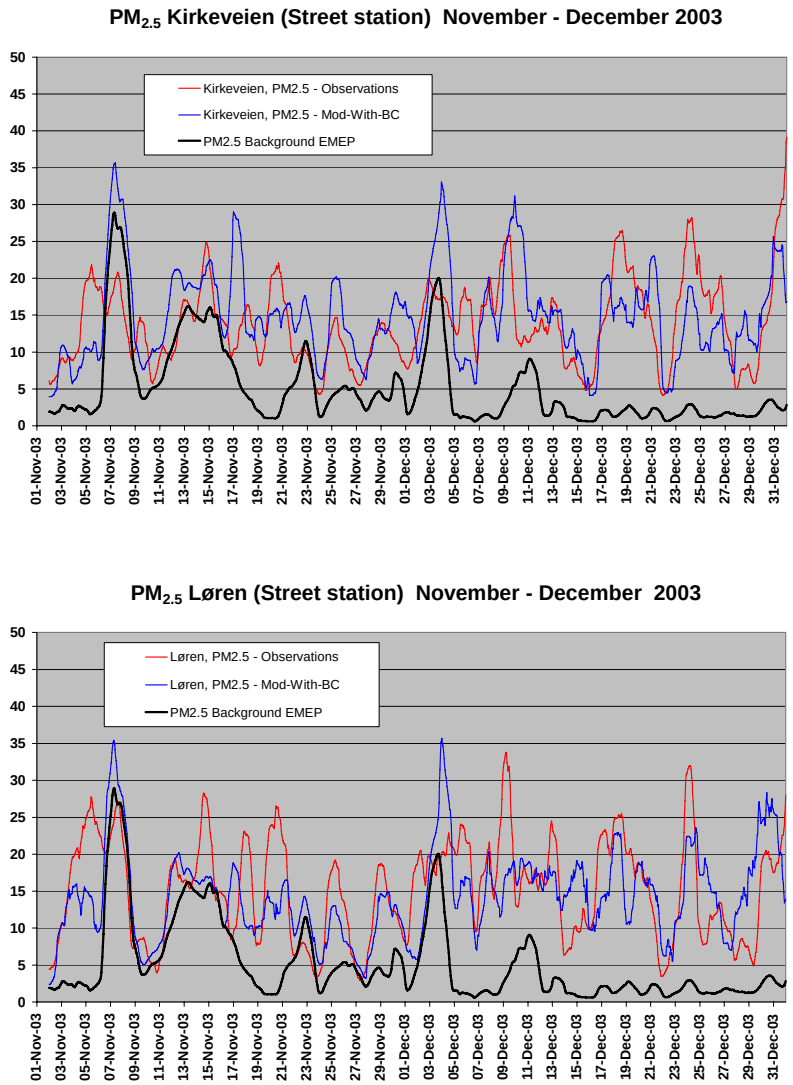

Figure 3.16: Daily running average of $PM_{2.5}$ (µg m^{-3}) at the urban/street station Kirkeveien and the street station Løren.

	EMEP BC	Kirkeveien		Løren	
		Calc.	Obs.	Calc.	Obs.
Average, Nov – Dec 2003 (µg m^{-3}):	5.1	15.0	14.1	14.4	15.4
Standard deviation from average (µg m^{-3}):	5.5	6.2	5.7	5.9	6.8
Correlation coefficient:		0.45		0.54	
Slope of linear regression line:		0.49		0.47	
Intercept of linear regression line (µg m^{-3}):		8.2		7.3	

Table 3.4: Statistical parameters for the comparison of the AirQUIS/EPISODE predicted running daily averaged $PM_{2.5}$ concentrations with the observations at the two measurement sites. The ground level EMEP estimated average and standard deviation are included as well.

At both stations the correlation of the AirQUIS/EPISODE results improve significantly when considering daily averages, reaching as high as 0.54 at Løren. As seen in Table 3.4 the standard deviation of the daily averaged EMEP boundary values drop slightly from 6.2 to 5.5 $\mu g\ m^{-3}$, and compares then rather well with the time variability of the measured daily averages at the measurement stations.

Even though there are some deviations, the above validation material clearly demonstrates that the AIRQUIS/EPISODE model is able to reproduce the observed particle concentration levels fairly well in Oslo. The importance of an accurate estimate of the regional contribution is also illustrated. Without applying these estimates as boundary conditions, several periods will be severely underestimated by the modelling system.

Since road traffic and domestic wood burning is considered to be the two most important local particle sources in Oslo, their contribution to the calculated PM_{10} and $PM_{2.5}$ concentration levels are discussed further in Section 3.2.3.3 and 3.2.3.4.

3.2.3.3 The influence of local emissions on ambient PM_{10} concentrations

When only emissions from road traffic (exhaust particles and traffic induced re-suspension) are included, the AirQUIS/EPISODE model system calculates an average PM_{10} concentration field (in $\mu g\ m^{-3}$) as shown in Figure 3.17. This contour-plot should be compared with Figure 3.9, in which all sources and the EMEP boundary values are included. In Figure 3.17 the maximum value of 26.3 $\mu g\ m^{-3}$ is found in grid cell (5,10), i.e. the grid cell covering the Lysaker area. This grid cell, together with the neighbouring grid cell (4,10), i.e. the E18 Fornebu/Ring 3 connection, also reached the highest value in Figure 3.9 (35.9 $\mu g\ m^{-3}$), and the traffic sources thus contribute with as much as 73.2 % of the total average PM_{10} concentration in this area. In grid cell (4,10), which is the grid cell with the highest total PM_{10} emissions (see discussion of Figure 3.9), an average PM_{10} value of 23.7 $\mu g\ m^{-3}$ is computed from road traffic. This amounts to 66.0 % of the total concentration estimate.

The contribution from domestic wood burning to the average PM_{10} concentration is shown in Figure 3.18. This source produces values of 6.1 $\mu g\ m^{-3}$ in grid cell (5,10) and 8.5 $\mu g\ m^{-3}$ in grid cell (4,10). These numbers amounts to 17 % and 23.7 % of the total PM_{10} concentrations estimated for these grid cells, respectively. Insignificant contributions are found from other sources, leading to a 10 % contribution from the regional background to the average PM_{10} concentration in these two grid cells.

Based on the material in Figure 3.17 and 3.18, a similar source contribution analysis can be done for the central grid cell (10,12), i.e. the grid cell containing the Bogstadveien/Bislett area. As shown in Section 2.2 this is the grid cell with the largest $PM_{2.5}$ emissions. The analysis show that of the total average PM_{10} value of 25.3 $\mu g\ m^{-3}$, 10.7 $\mu g\ m^{-3}$ (42.3 %) comes from domestic wood burning, 10.5 $\mu g\ m^{-3}$ (41.5 %) comes from road traffic and 3.9 $\mu g\ m^{-3}$ (15.4 %) is attributed to the EMEP values applied at the model boundaries. This leaves just 0.8 % for other sources in this particular grid cell.

In Figure 3.19 the source contributions to the running daily average PM_{10} concentrations are shown as time series for the grid cells (4,10) and (10,12). From these time series, the dominating influence of traffic emissions in grid cell (4.10) is clearly evident. In the central grid cell (10,12) wood-burning and road traffic are contributing more equally. It is also interesting to note that the relative source contribution varies substantially throughout the simulation period. When interpreting these results one should keep in mind that it is the grid values that are presented in Figure 3.19. In the vicinity of the main road system, where the sub grid line source is applied, higher particle concentrations are computed, and in these areas the traffic contributions therefore become more dominant. To illustrate this the road traffic contribution to the running daily average PM_{10} concentrations at the measurement street station Løren and in the grid cell (14,13), which contain the Løren site, are shown in Figure 3.20. As seen from this figure the traffic contribution is at times substantially higher at the Løren receptor point than indicated by the grid value. The corresponding effect on the average source contribution are shown in Figure 3.21, where the percentage of the total calculated concentration from the various sources are shown as pie-charts for both the Løren receptor point and for grid cell (14,13). The contribution from road traffic is increasing from 63.5 % to 78.0 %, with a corresponding decrease in the other sources.

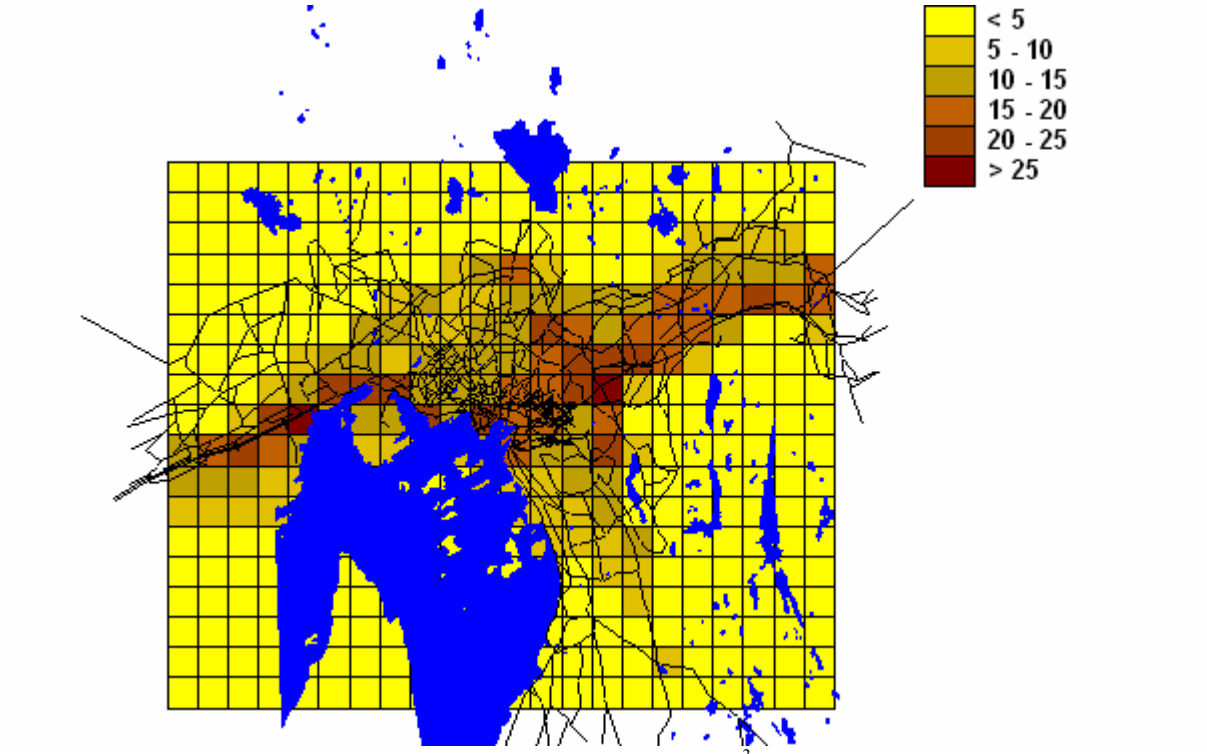

Figure 3.17: Average concentration of PM_{10} in Oslo (µg m^{-3}) for the two-month period November – December 2003, when only road traffic sources are included. No boundary values are applied

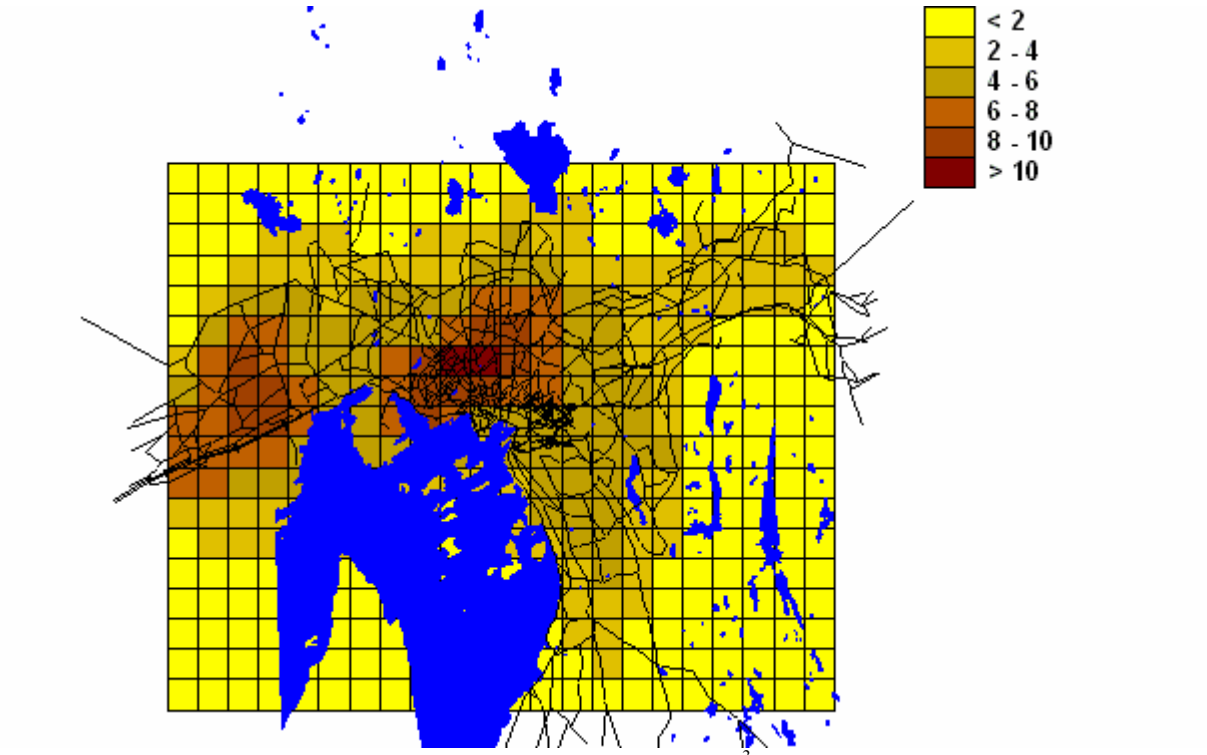

Figure 3.18: Average concentration of PM_{10} in Oslo (µg m^{-3}) for the two-month period November – December 2003, when only domestic wood burning sources are included. No boundary values are applied

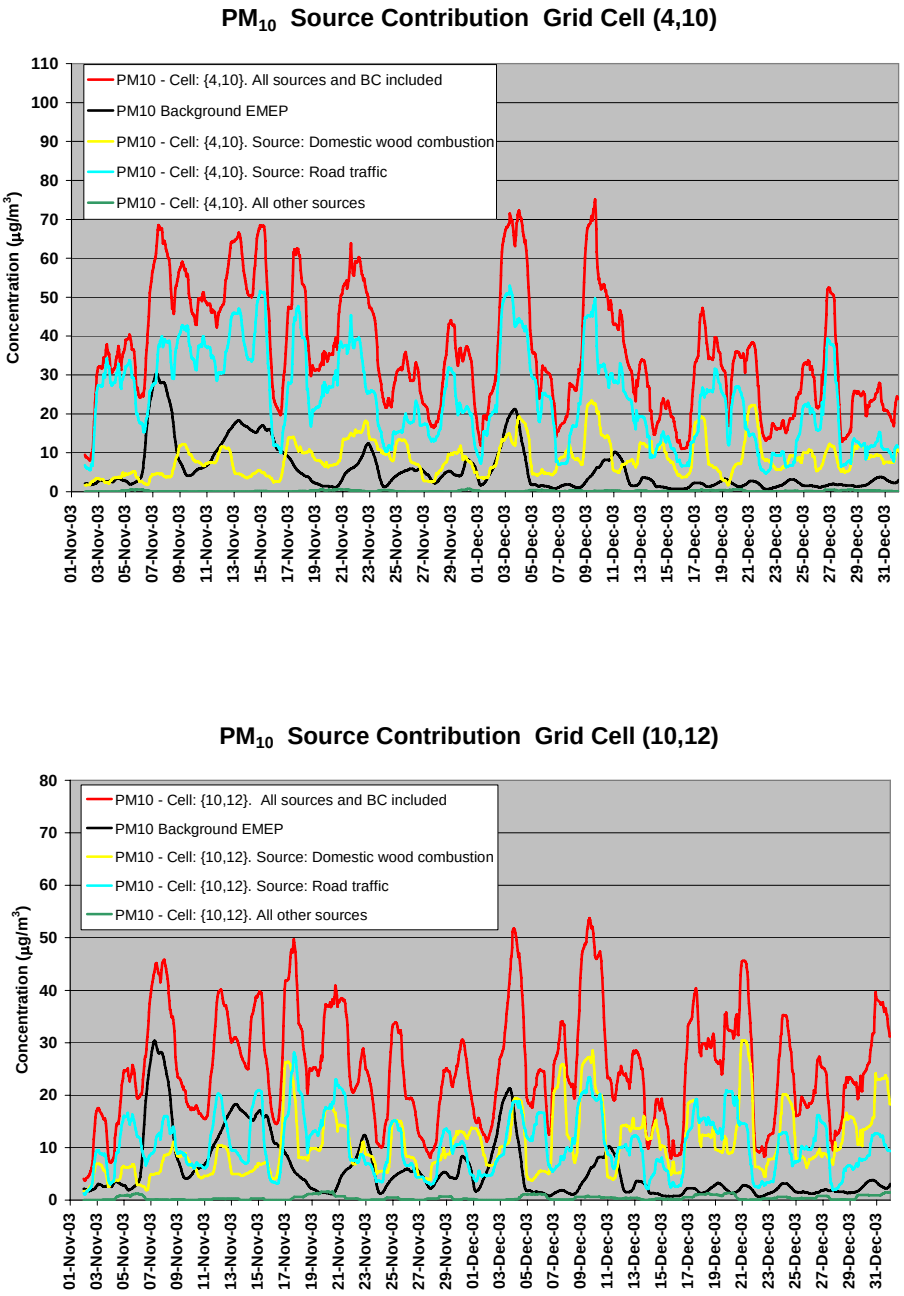

Figure 3.19: Source contributions to the estimated daily running average of PM_{10} (in µg m^{-3}) in grid cell (4,10), i.e. the E18 Fornebu/Ring 3 connection, and in grid cell (10,12), i.e. the Bogstadveien/Bislett area.

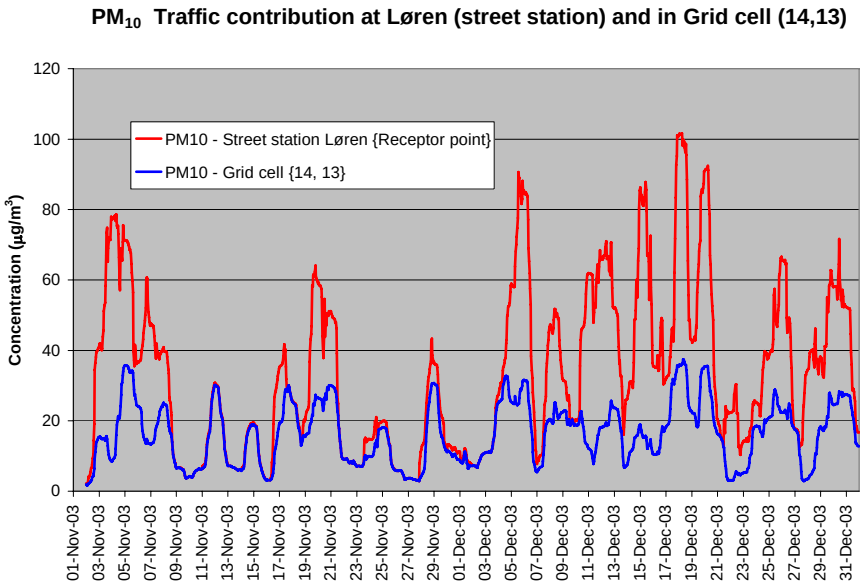

Figure 3.20: Traffic contributions to the estimated daily running average of PM_{10} (in µg m^{-3}) at the street station Løren and in grid cell (14,13), i.e. the grid cell containing the Løren receptor point.

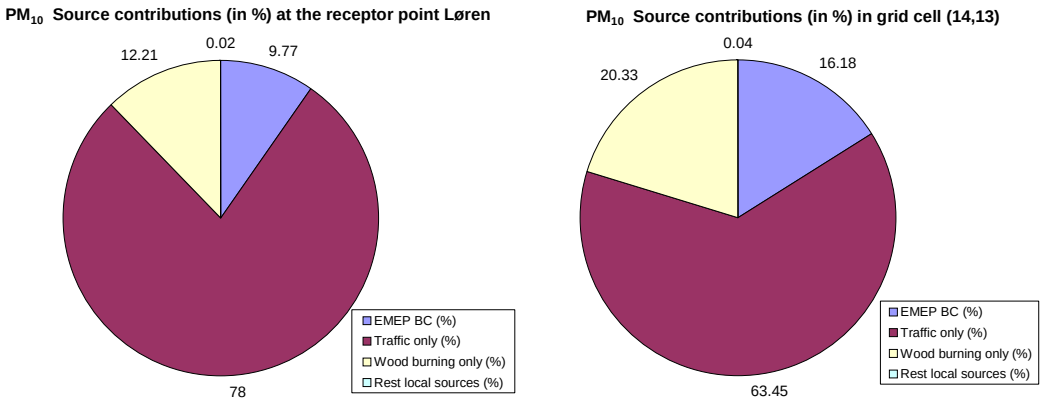

Figure 3.21: Source contributions to the average computed PM_{10} concentration (in %) at the street station Løren and in grid cell (14,13), i.e. the grid cell containing the Løren receptor point.

3.2.3.4 The influence of local emissions on ambient $PM_{2.5}$ concentrations

The average $PM_{2.5}$ concentration field computed by the AirQUIS/EPISODE when only road traffic emissions (mainly exhaust particles, and a small contribution from traffic induced re-suspension) are included, is presented in Figure 3.22. Similarly, the average $PM_{2.5}$ field when only including emissions from wood burning are shown in Figure 3.23. These contour-plots should be compared with Figure 3.13, in which all sources and the EMEP boundary values are included.

The maximum values in Figure 3.22 are found in grid cell (10,12), i.e. the Bjørvika/-Gamlebyen area, with an average value of 2.8 $\mu g\ m^{-3}$. The exhaust emissions are relatively high in this area because of the heavy traffic load. Nevertheless, on average the regional background contributes more to the total average $PM_{2.5}$ concentration in this area (3.8 $\mu g\ m^{-3}$). The total $PM_{2.5}$ concentration computed in this grid cell was 13.7 $\mu g\ m^{-3}$ (see Figure 3.13) indicating that road traffic only contributes with about 20 %, and that 30 % is attributable to the regional background. The two other large contributors are traffic activity in the harbour area (28%) and emissions from wood combustion (42 %). Note that the PM_{10} levels do not reach its maximum in this grid cell since traffic induced re-suspension is limited by the rather low vehicle speed.

In grid cell (4,10), i.e. in the grid cell where the highest PM_{10} concentrations are found, the road traffic contribution to the average $PM_{2.5}$ concentration is only 1.6 $\mu g\ m^{-3}$, less than half of the regional contribution. The total average $PM_{2.5}$ value in this grid cell is 14.9 $\mu g\ m^{-3}$, of which 10.7 % is from road traffic, 57.7 % is from wood burning, and 26.8 % are from the EMEP boundary contribution, leaving 4.8 % to other sources.

When only emissions from domestic wood burning are included, the highest average $PM_{2.5}$ level (10.8 $\mu g\ m^{-3}$) is computed in grid cell (10,12), i.e. in the Bogstadveien/Bislett area, see Figure 3.23. As shown in Figure 3.13, this is also the grid cell where the highest $PM_{2.5}$ value is computed when all sources and the EMEP boundary values are included, i.e. 17.7 $\mu g\ m^{-3}$. Thus, in this grid cell wood burning is responsible for as much as 61.0 % of the total $PM_{2.5}$ values. The regional EMEP background contribute quite substantially with 21.2 %, while road traffic contribute with only 0.8 %, thereby leaving as much as 17 % to other combustion sources.

In Figure 3.24 the source contributions to the running daily average $PM_{2.5}$ concentrations are shown as time series for the selected grid cells (4,10) and (10,12). The small effect of the road traffic on the fine particle fraction is the most surprising result found in these plots. Even in the densely trafficated area covered by grid cell (4.10) the road traffic is of rather little importance. As for PM_{10}, however, it must be stressed that the traffic influence on $PM_{2.5}$ levels is more pronounced close to the main road network. Using again the Løren site and the surrounding grid cell (14,13) as illustrative example, Figure 3.25 show the increased traffic influence on daily averages of $PM_{2.5}$ in the vicinity of the Ring 3 in this particular example. In Figure 3.26 this issue is further illustrated by pie charts showing the source contribution to the average $PM_{2.5}$ concentration both at the Løren receptor point and in grid cell (14,13). The contribution from road traffic is almost doubled from 16.1 % to 30.2 %, with a substantial decrease in the relative contribution from the other sources.

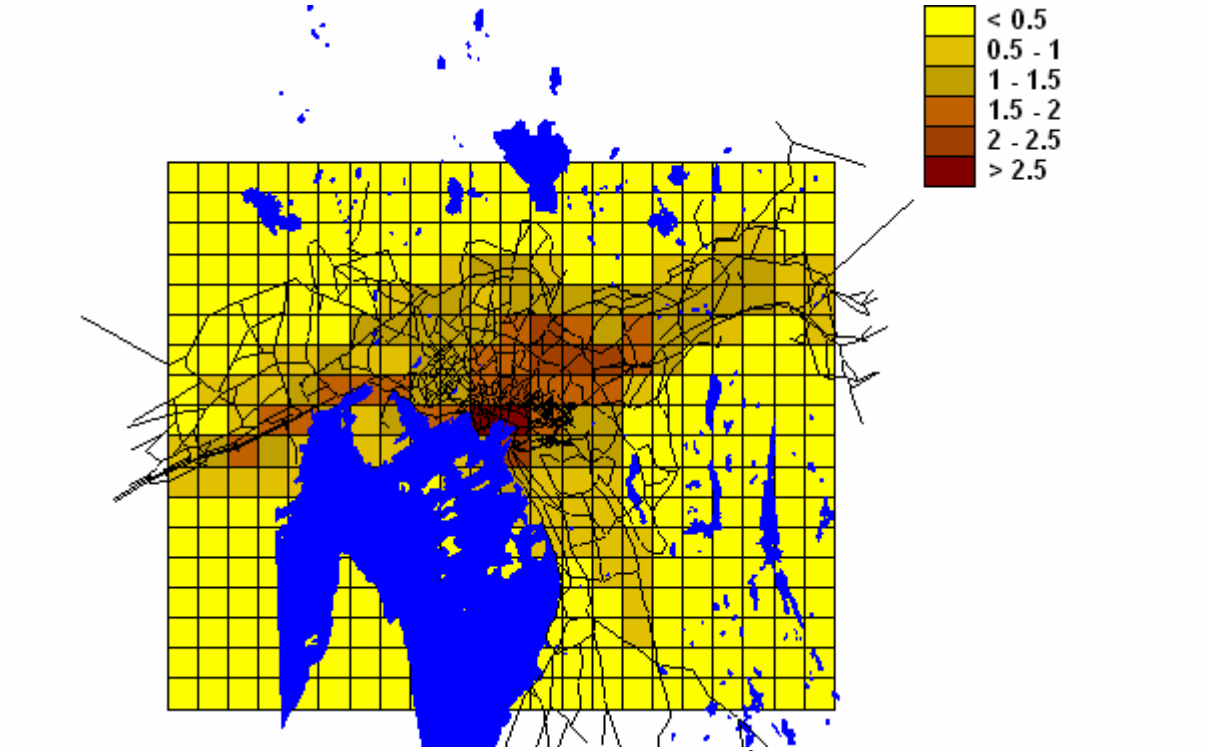

Figure 3.22: Average concentration of $PM_{2.5}$ in Oslo ($\mu g\ m^{-3}$) for the two-month period November – December 2003, when only road traffic sources are included. No boundary values are applied.

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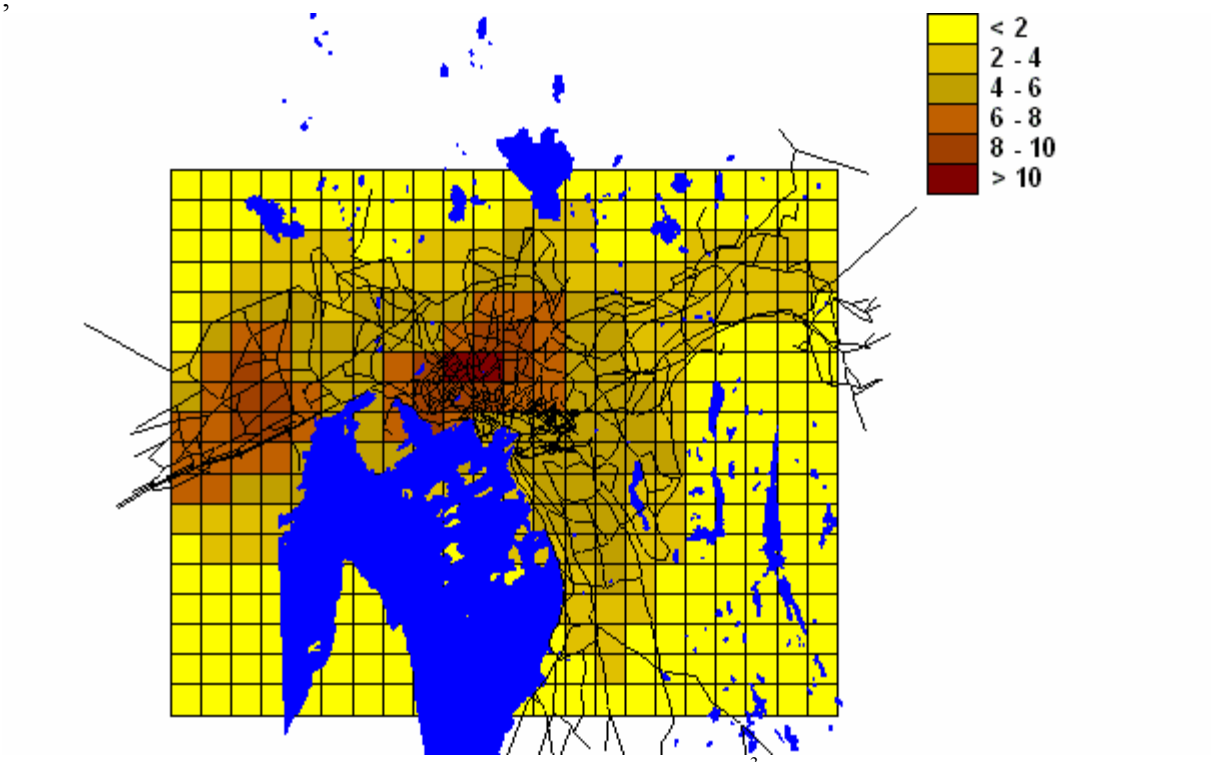

Figure 3.23: Average concentration of $PM_{2.5}$ in Oslo ($\mu g\ m^{-3}$) for the two-month period November – December 2003, when only domestic wood burning sources are included. No boundary values are applied.

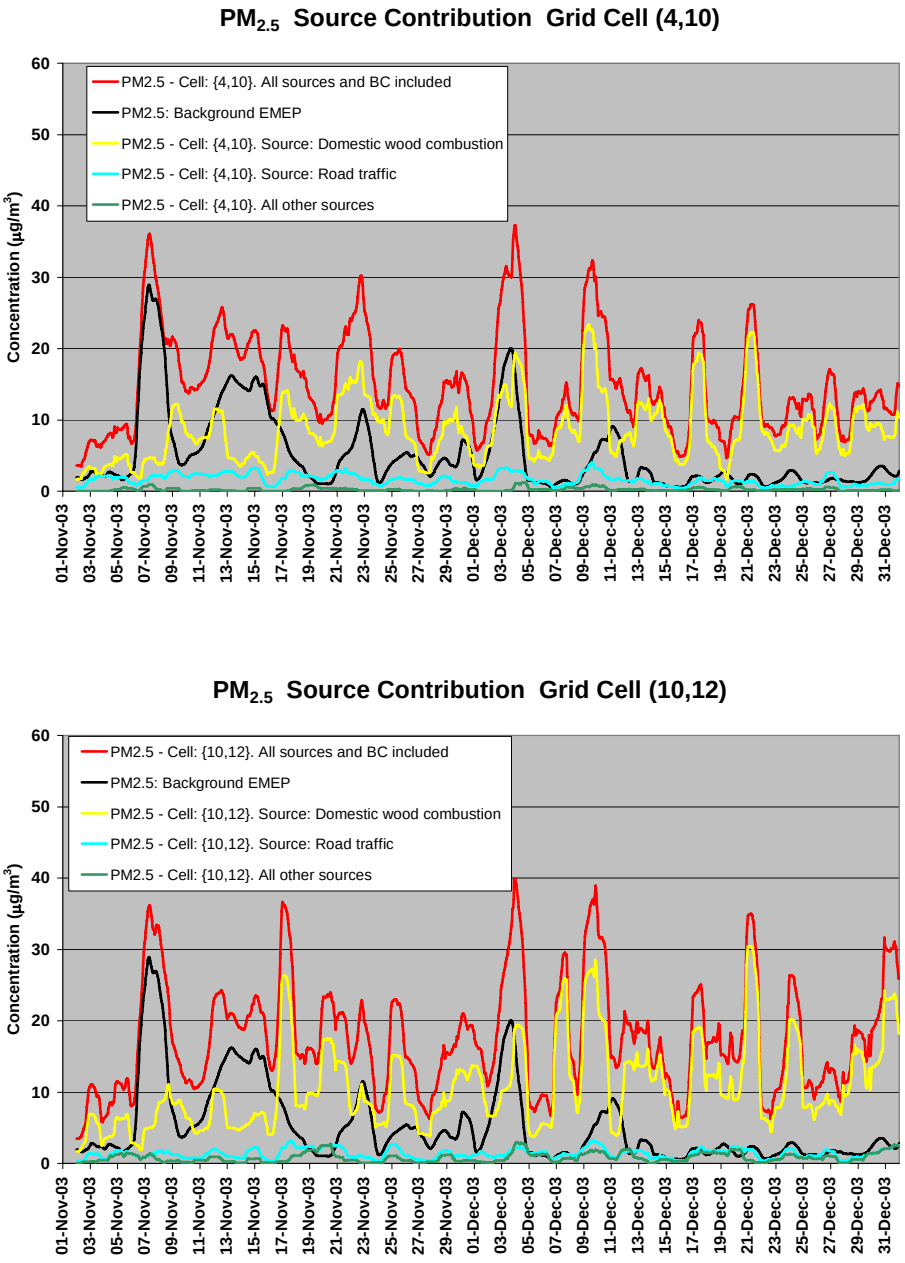

Figure 3.24: Source contributions to the estimated daily running average of $PM_{2.5}$ (in µg m^{-3}) in grid cell (4,10), i.e. the E18 Fornebu/Ring 3 connection, and in grid cell (10,12), i.e. the Bogstadveien/Bislett area.

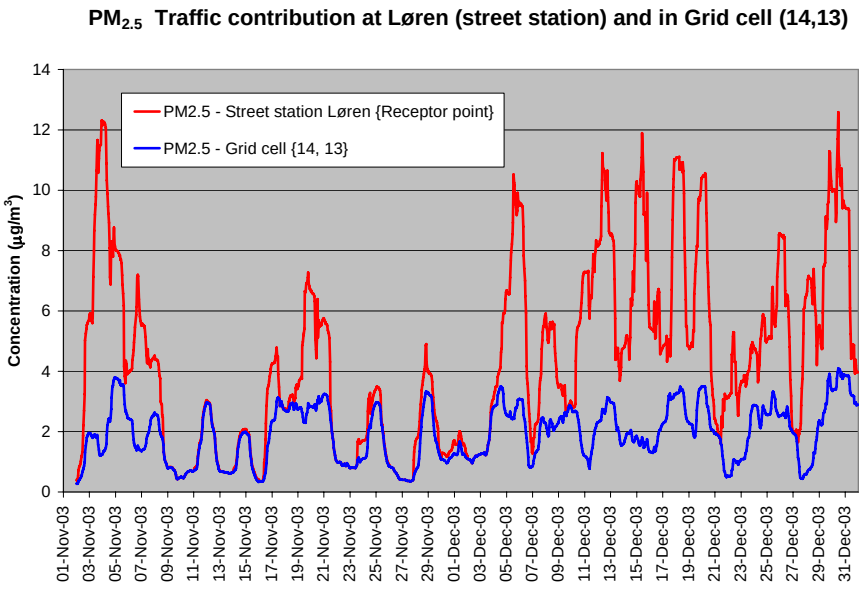

Figure 3.25: Traffic contributions to the estimated daily running average of $PM_{2.5}$ (in µg m^{-3}) at the street station Løren and in grid cell (14,13), i.e. the grid cell containing the Løren receptor point.

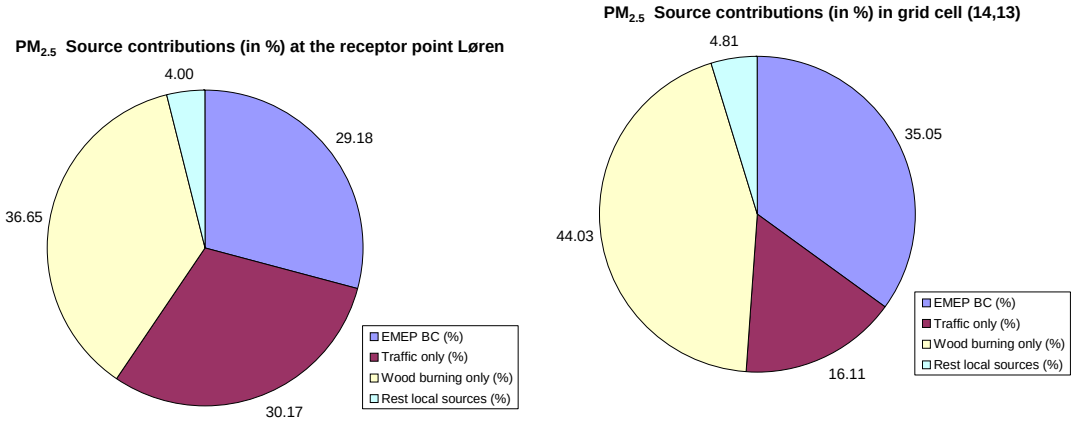

Figure 3.26: Source contributions to the average computed $PM_{2.5}$ concentration (in %) at the street station Løren and in grid cell (14,13), i.e. the grid cell containing the Løren receptor point.

4. Conclusions and recommendations

In this report the results from a detailed study of the various source contributors to ambient particulate matter in Oslo have been presented. Special emphasis has been put on the comparison of the estimated regional (or long-range transport) contribution and the contribution from local sources within the Oslo city area.

On the regional scale the $PM_{2.5}$ concentrations levels can be viewed as a sum of a large number of smaller contributions from individual countries. More than 10 countries have contributions larger than 2% to background PM concentrations in Oslo. Norway is, as expected, the largest single contributor country (38%). The fine particulates are composed of primary particulate matter (33%), nitrates (29%), sulphates (19%), ammonium (15%) and sea salt (4%). An analysis of the relative importance of different emission sectors shows that agriculture is the most important source for background $PM_{2.5}$ in Oslo (35%). Agriculture is a large emitter of NH_3, which can condensate into particles ($(NH_4)_xSO_4$ and NH_4NO_3). These particles can be transported over long distances and are therefore relatively important in areas far from the main sources.

The average regional background $PM_{2.5}$ concentrations in Oslo is ~ 5 μg m^{-3} for the period November-December 2003 and corresponds to about 30% of the concentrations observed within the Oslo city area. However, the background concentration levels can episodically increase to levels of more than 40 μg m^{-3}. This can happen when specific meteorological conditions causes plumes with high concentration levels to be transported from northern Europe towards Norway. This is clearly demonstrated in the model results presented in Section 3 for the November 5 – 9 episode. To properly model the observed concentration levels within Oslo during these episodes, application of high quality data from regional models like the EMEP model at the fine scale model boundaries is of vital importance.

During winter and spring high levels of coarse particles (PM_{coarse} = PM_{10} - $PM_{2.5}$) are observed in Oslo. The source of these large particles is mainly traffic- and wind-induced re-suspension of surface particles. Since the present version of the Unified EMEP model does not include re-suspension and wind blown dust, this model will necessarily underestimate the background contribution to the high observed PM_{10} levels in Oslo.

In order to compare the regional background contribution to PM levels in Oslo with the observed concentrations inside the city, the use of nested models is required. This is because the distribution of local sources in the urban area is generally not well represented in a coarse regional grid. Especially in Oslo, the city area is effectively about ¼ of the regional grid size of 50x50km^2. This, together with the lack of re-suspension, explain the difficulties of the regional model to reproduce the observed PM-values in Oslo. The inconsistency in primary emissions of PM in the Oslo area between the regional and the urban estimates is a relevant caveat in the results, as is the lack of fine resolution emission data in the vicinity of the Oslo region. The availability of such data would facilitate the implementation of the nesting system and a more correct identification of the relative importance of regional vs. local sources.

The results from the two-month simulation performed in this study, lasting from the 1st of November until the end of December 2003, show that the highest concentration peaks in Oslo are caused by local sources. The urban scale model system applied in this study,

AirQUIS/EPISODE, takes into account the most important local sources and is therefore, in combination with a grid resolution of 1 x 1 km^2 and application of a sub-grid line source model, able to reproduce the high observed particle levels (reaching about 90 $\mu g\ m^{-3}$ for $PM_{2.5}$ and about 400 $\mu g\ m^{-3}$ for PM_{10}) in Oslo during the simulation period. The results from this study reveal that the various sources contribute differently depending both on location and on whether we consider $PM_{2.5}$ or PM_{10}. In areas with no local emissions, i.e. over the fjord or in the forests surrounding the city, the regional background will naturally dominate the concentration levels.

The estimated $PM_{2.5}$ levels in the central and western city area are dominated by emissions from domestic wood burning, being responsible for more than 60 % of the ground level concentrations in some grid cells. Road traffic is the second most important contributor to $PM_{2.5}$ concentrations in Oslo. One should note that the relative influence of this source is stronger close to the main road network than on the urban (or model grid) scale, see end of Section 3. The regional contribution is quite substantial when considering the average $PM_{2.5}$ levels, contributing about 30 % even in central grid cells with large local emissions.

For PM_{10} road traffic is the most dominant contributor followed by domestic wood burning. This is especially the case in the areas along the main highways, where dense traffic in combination with high vehicular speed, leads to huge concentrations of coarse particles due to traffic-induced re-suspension. Much higher relative contributions to the PM_{10} levels are also found from road traffic at individual receptor points close to the roads, higher than those estimated from the grid cell values (which normally are interpreted as urban background values). In central and western city grid cells without direct contributions from the main road network, domestic wood burning typically dominate the estimated PM_{10} levels. The regional background contributes less to PM_{10} than to $PM_{2.5}$, and is typically responsible for less than 20 % of the average PM_{10} concentration in urban grid cells.

The highest peaks caused by local sources need not, and in most cases will not, coincide with the highest peaks of regional origin. High concentration levels due to local sources typically appear under high-pressure conditions, with low wind speed and near surface temperature inversions, resulting in low mixing of the pollutant emissions. These conditions differ markedly from the cases when regional air masses with high concentration of pollutants are transported over large distances.

The regional background and the urban pollution of local origin are two different and complementary descriptions of the total air pollution. The regional background model will capture episodes of long-range transported pollutants and thereby contribute significantly to the urban air pollution, especially during regularly occurring episodes with elevated regional contributions. However, during periods in which local sources are dominant, large variability in concentration levels are observed over small distances, and consequently the background concentrations give a poor representation of the actual air pollution levels within the urban area. Therefore, in order to treat both conditions, the regional model needs to be coupled by an urban scale model, which is able to take into account these local scale effects.

The present estimate probably underestimates the contribution of long-range transported PM to the observed Oslo levels because the regional background concentrations are acknowledged to be underestimated and because the simulations are made for a period when the local contribution is expected to be at its maximum. Still, this study provides a valid first estimate of the relative contribution of different sources to Oslo PM levels.

This study has only given preliminary answers to important questions. One important limitation of the simulations performed in this project is the lack of emission inventory at the intermediate resolution (~5 km) around Oslo that would allow a more accurate identification of the relative importance of regional vs. local sources. Extension to other cities is also hampered by the lack of fine resolution emission data.

It would also be interesting to perform this type of simulations for a full year in order to identify the seasonal variations in the local contribution to episodes. The generalisation of these initial results needs to be evaluated over several years, in order to give statistical information about the frequency of different meteorological situations that lead to high levels of air pollution.

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