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An integrated model for evaluating the emissions, atmospheric dispersion and risks caused by ambient air fine particulate matter - KOPRA

Jaakko Kukkonen

FINE

SYKE

KTL

ytv

STADIA
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Nordic Envicon

LT Consult

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Partners and collaborators of KOPRA

- **Partners**
  - Finnish Meteorological Institute
  - Finnish Environment Institute
  - National Public Health Institute
  - Nordic Envicon
  - Helsinki Metropolitan Area Council
  - Helsingin Polytechnic - Stadia
- **Collaborators**
  - Harvard University
  - Delft Technical University
  - University of Helsinki
- **Duration**

  2002 - 2005

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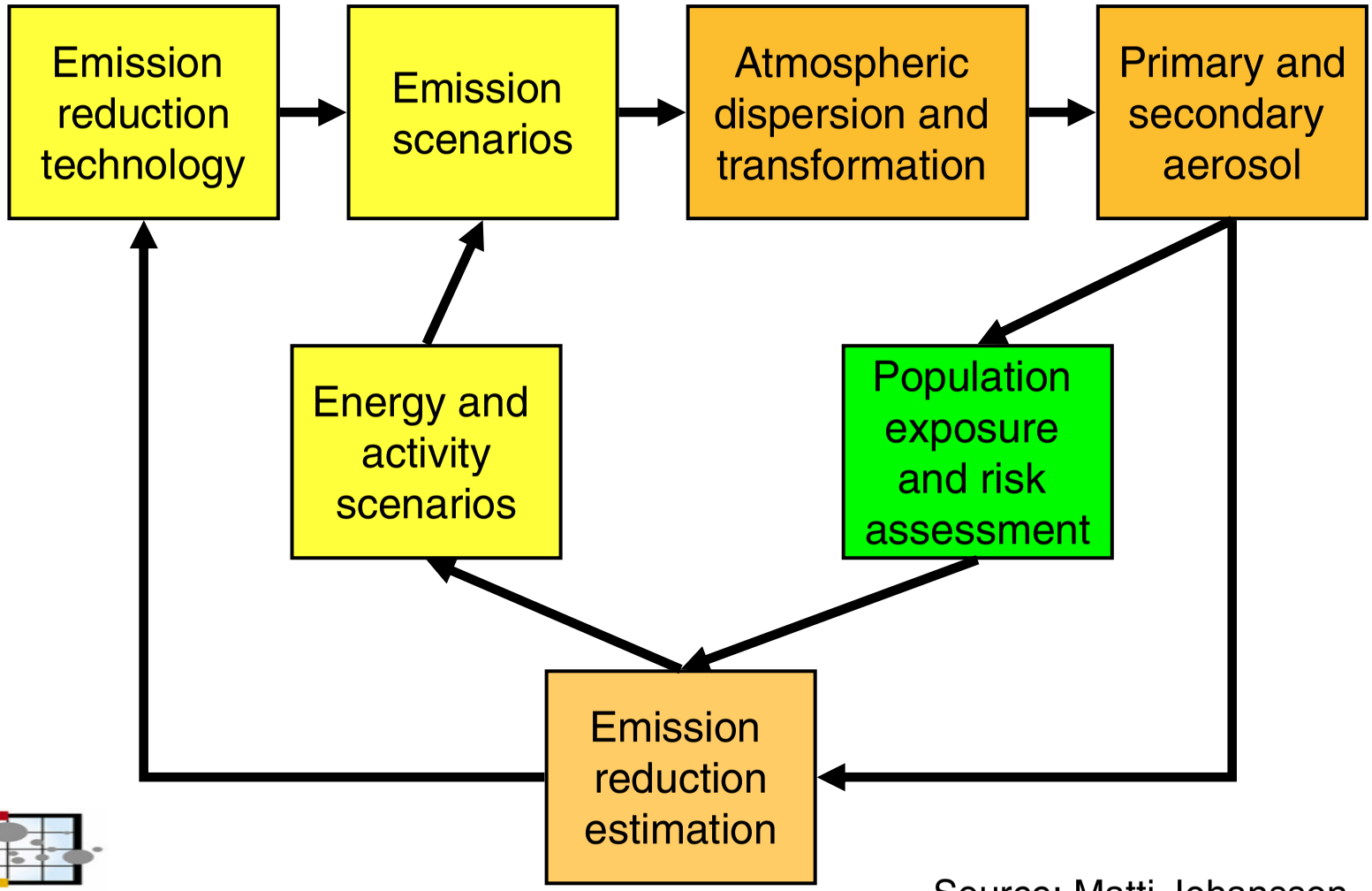
The processes evaluated in KOPRA



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Source: Matti Johansson, SYKE

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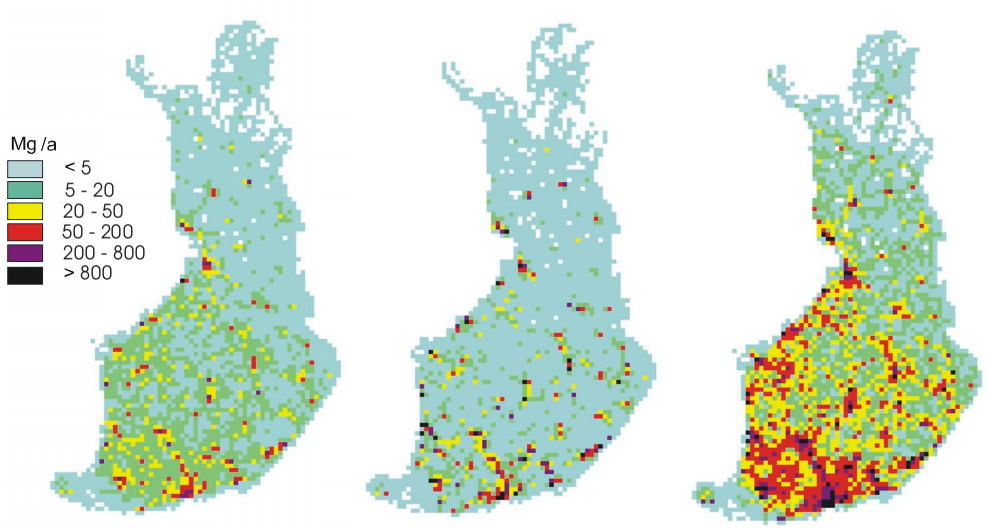
Finnish Regional Emission Scenario (FRES) model

- Anthropogenic emissions 1990, 2000, 2010, 2020 (several activity scenarios)
- Comprehensive and congruent calculation for primary PM and precursors
  - TSP, PM10 - 2.5 - 1 - 0.1, chemical composition in size classes
  - SO_2, NO_x, NH_3, NMVOC
- Abatement technologies and costs
- Aggregation: 8 main sectors, over 100 sub sectors
- Large point sources (approx.250), area emissions ($1 \times 1km^2$)
- Several emission heights



$PM_{2.5}$ SO_2 NO_x

www.environment.fi/syke/pm-modeling

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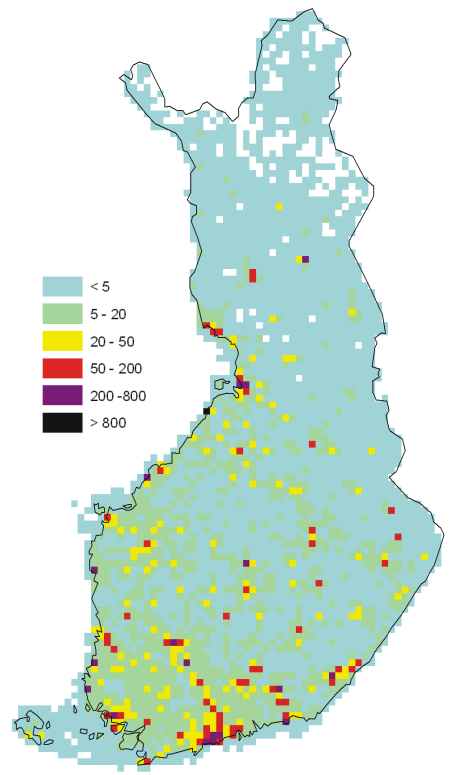
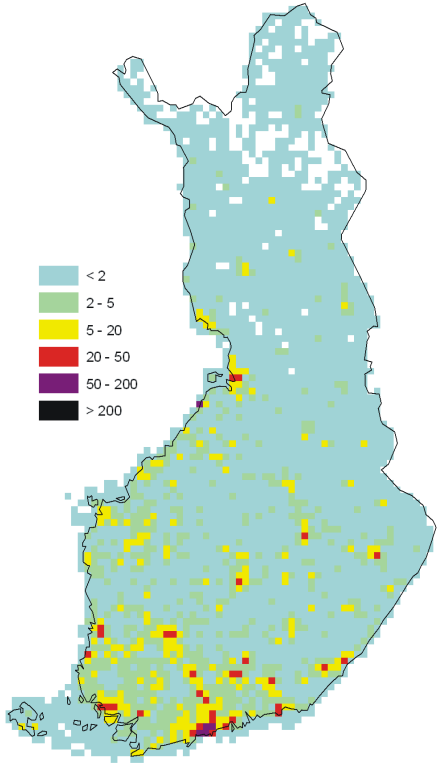
Finnish emissions in 2000

Primary particulate matter (PM) (Mg/a)

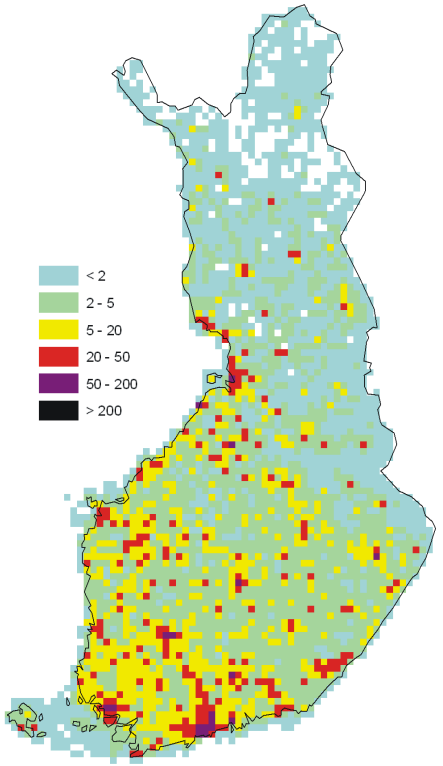
at 1 x 1 km^2 level, presented at 10 x 10 km^2 grid



PM2.5



Black carbon in PM2.5



Organic carbon in PM2.5

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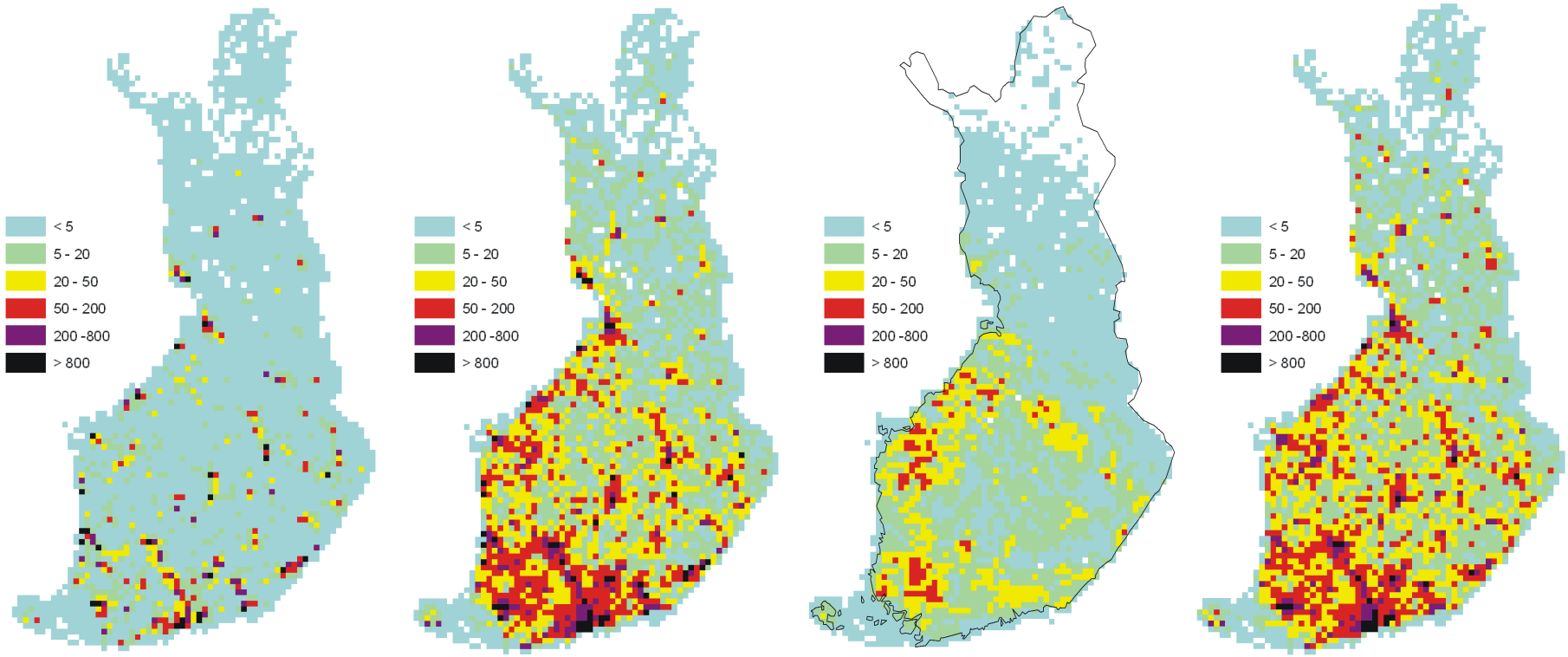
Finnish emissions in 2000

Gaseous pollutants (Mg/a)

at 1 x 1 km^2 level, presented at 10 x 10 km^2 grid



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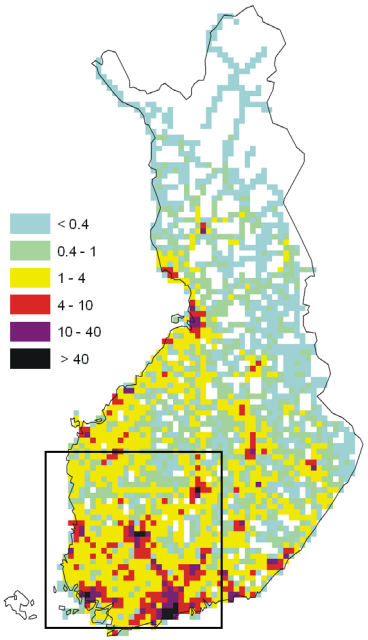
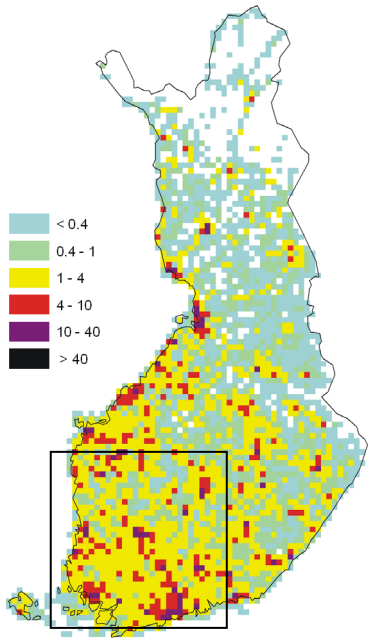
Finnish emissions in 2000

Primary PM2.5 by sectors (Mg/a)

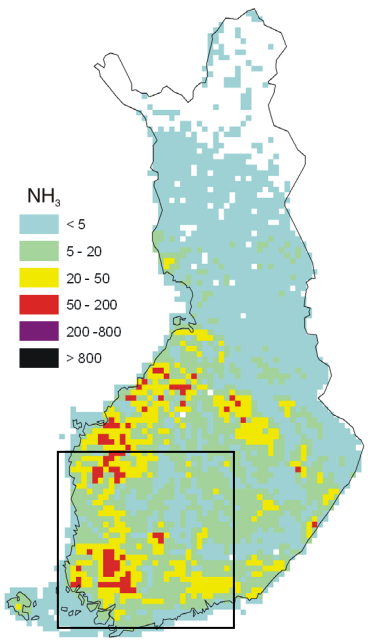
at 1 x 1 km^2 level, presented at 10 x 10 km^2 grid



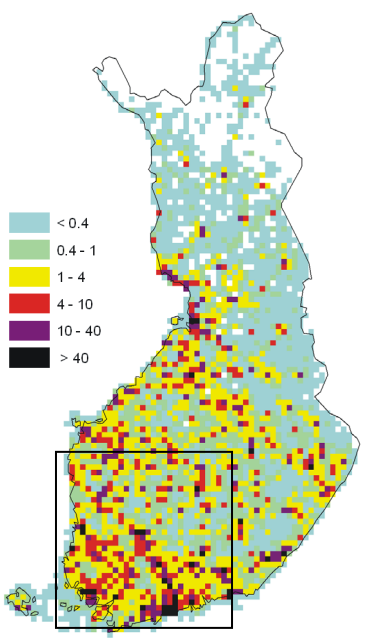
Road traffic



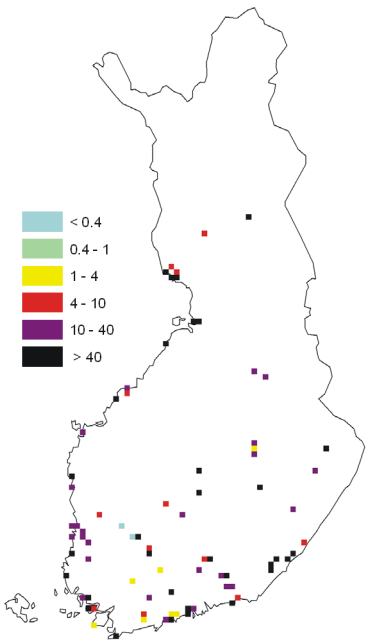
Residential combustion



Agriculture (NH_3)



Other area sources



Point sources

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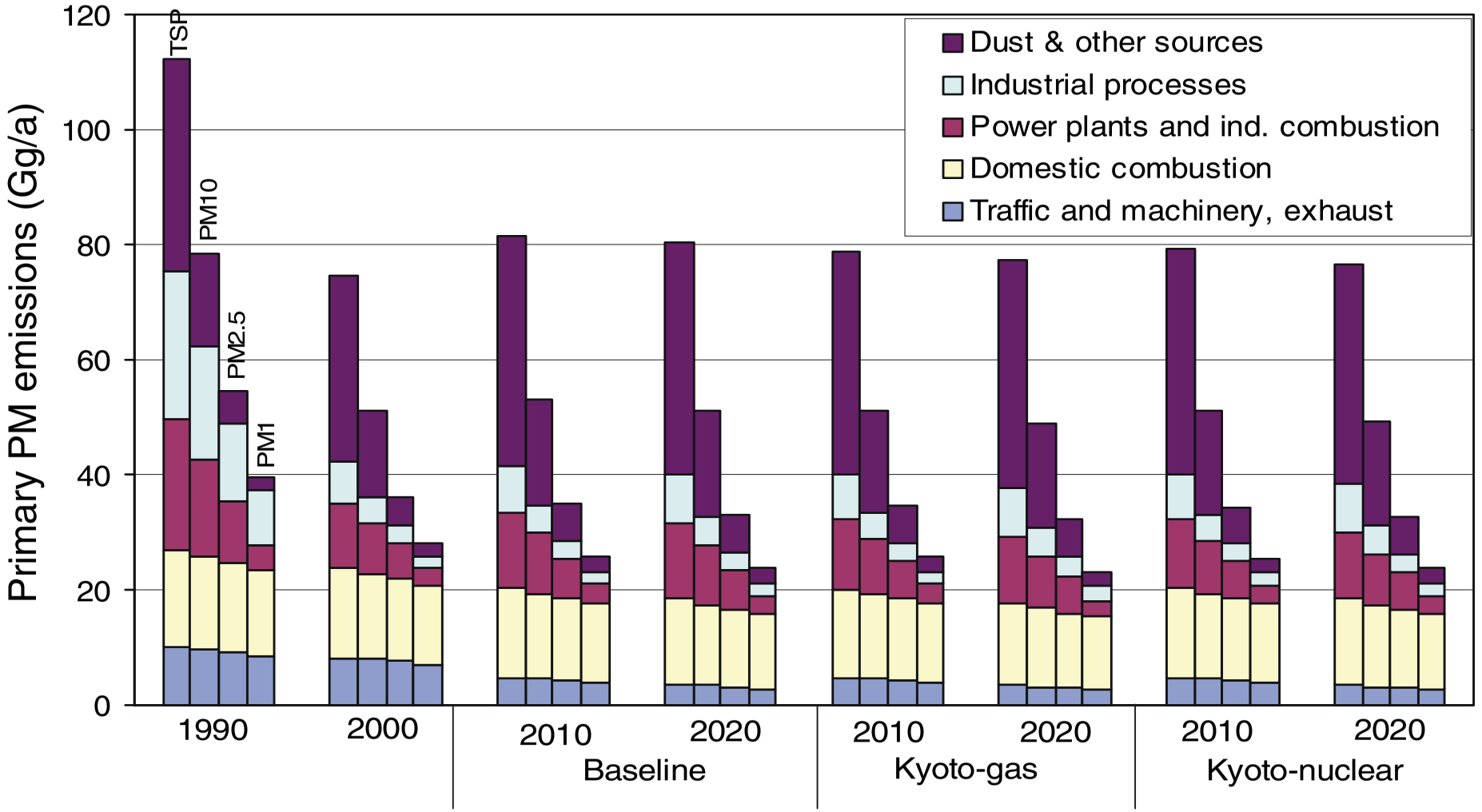
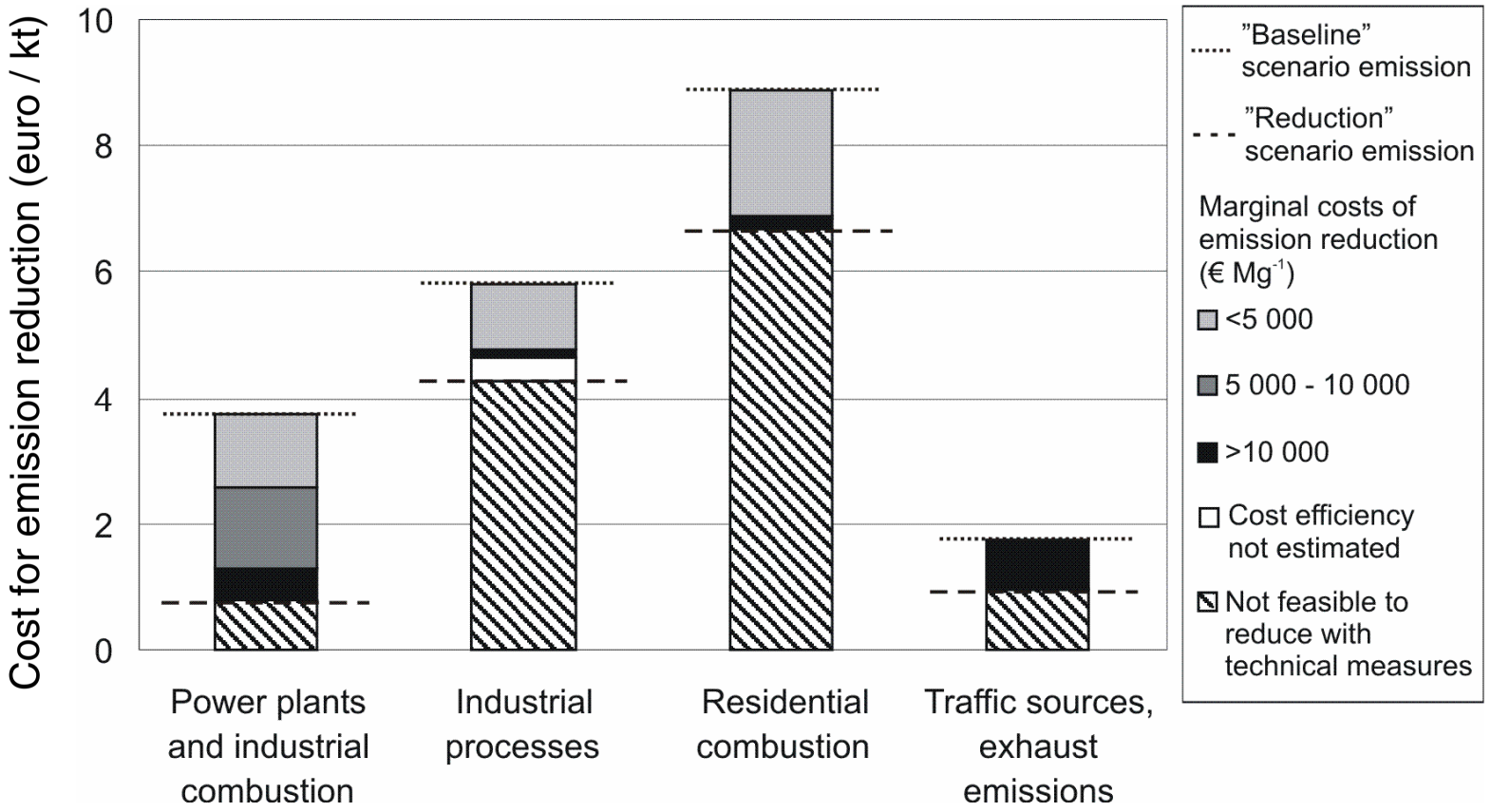
Environmental Impact Assessment of the Climate Strategy 2001



Cost-efficiency for $PM_{2.5}$ emission reductions in 2020



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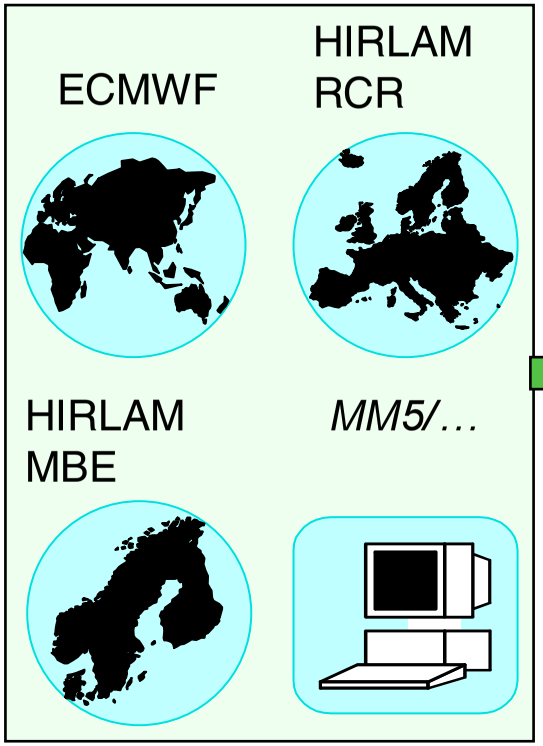
Modelling system - FMI

Weather prediction models



Dispersion models - long-range, regional

- SILAM
  LRT, meso,
  radioactivity
- HILATAR
  LRT, meso
- MATCH (SMHI)
  LRT, meso

Aerosol process models

MONO32 (U Helsinki, Stadia)
UHMA (U Helsinki, FMI)

Dispersion and effects models – urban, local

- CAR-FMI, roadside
- UDM-FMI, urban
- OSPM (NERI), street canyon
- BUOYANT
  fires
- ESCAPE,
  chemical accidents
- EXPAND (FMI, YTV)
  population exposure

SILAM modelling system

- **Lagrangian Monte-Carlo random-walk dispersion model**
- **Components and features:**
  - iterative high-precision advection algorithm
  - random-walk diffusion
    - well-mixed boundary layer
    - fixed-term diffusion in free troposphere
  - point, area and nuclear bomb source terms
  - forward and adjoint dispersion dynamics
  - extensive meteorological pre-processor
- **Evaluation**
  - European Tracer Experiment ETEX (both forward and adjoint)
  - Chernobyl accident
  - Multi-annual re-analysis of air quality over Europe (within FINE-KOPRA)

Sofiev M, P. Siljamo, I. Valkama, M. Ilvonen and J. Kukkonen, 2006. A dispersion modelling system SILAM and its evaluation against ETEX data. Atmos. Environ. 40 (2006) 674–685.

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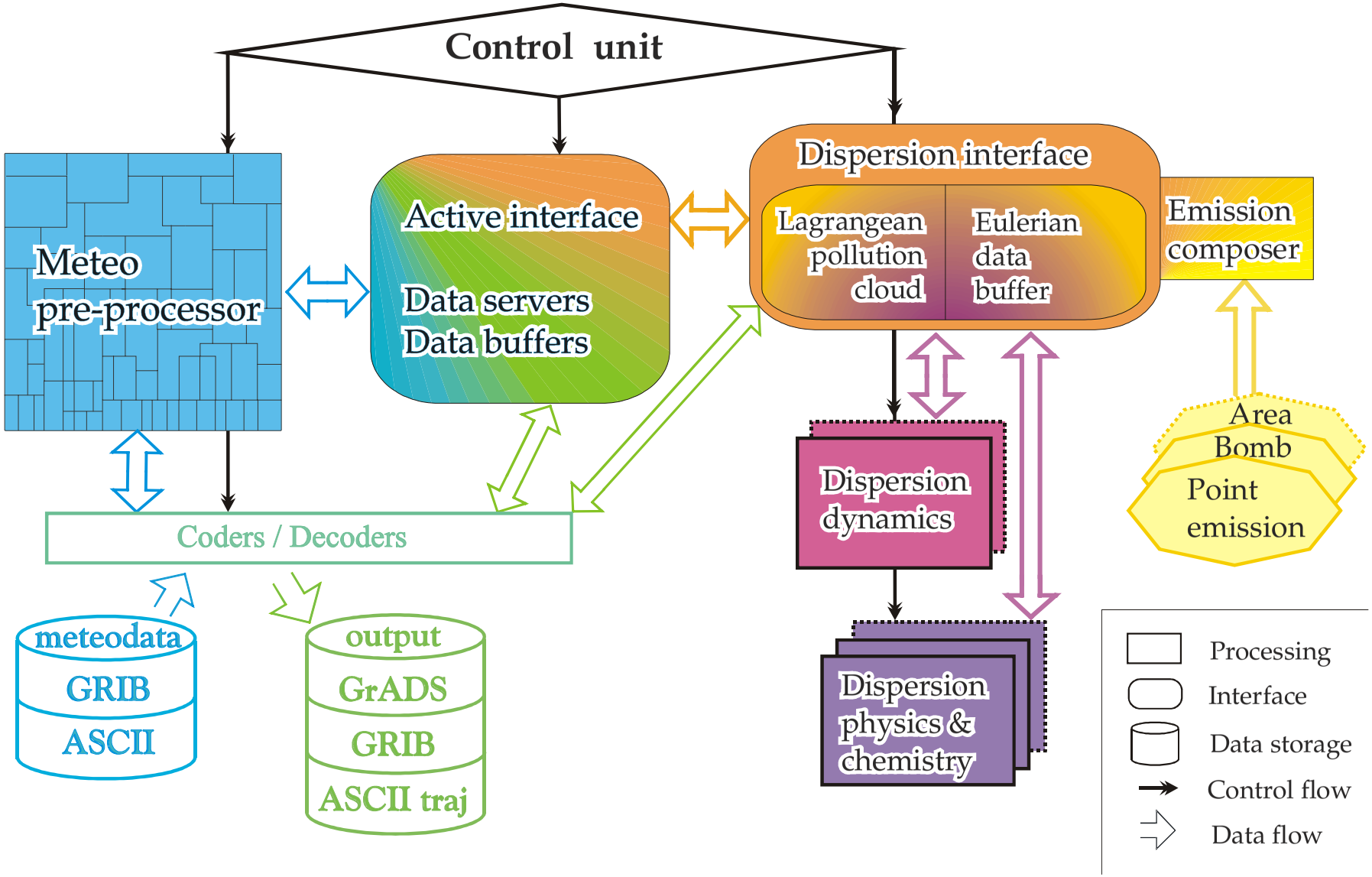

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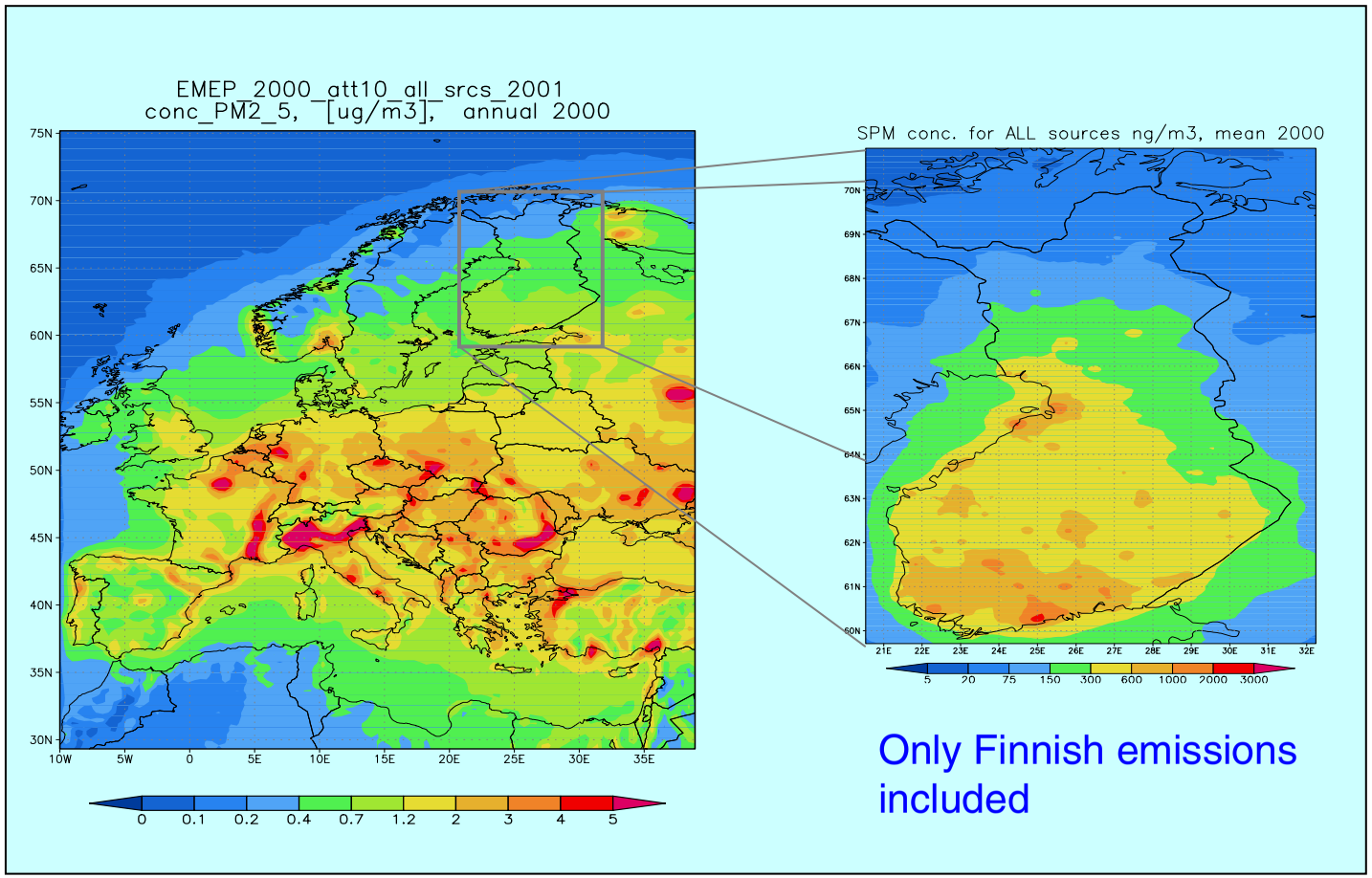
Concentrations of primary fine particles ($PM_{2.5}$) in Europe in 2000

- Models: HIRLAM 6 + SILAM
- Emissions: EMEP 2000, nationally SYKE
- Resolution 30 km for Europe and 5 km for Finland
- Scales up to 5 and 3 µg/m^3 (Europe and Finland)



Only Finnish emissions included

Lähde:
M.Sofiev

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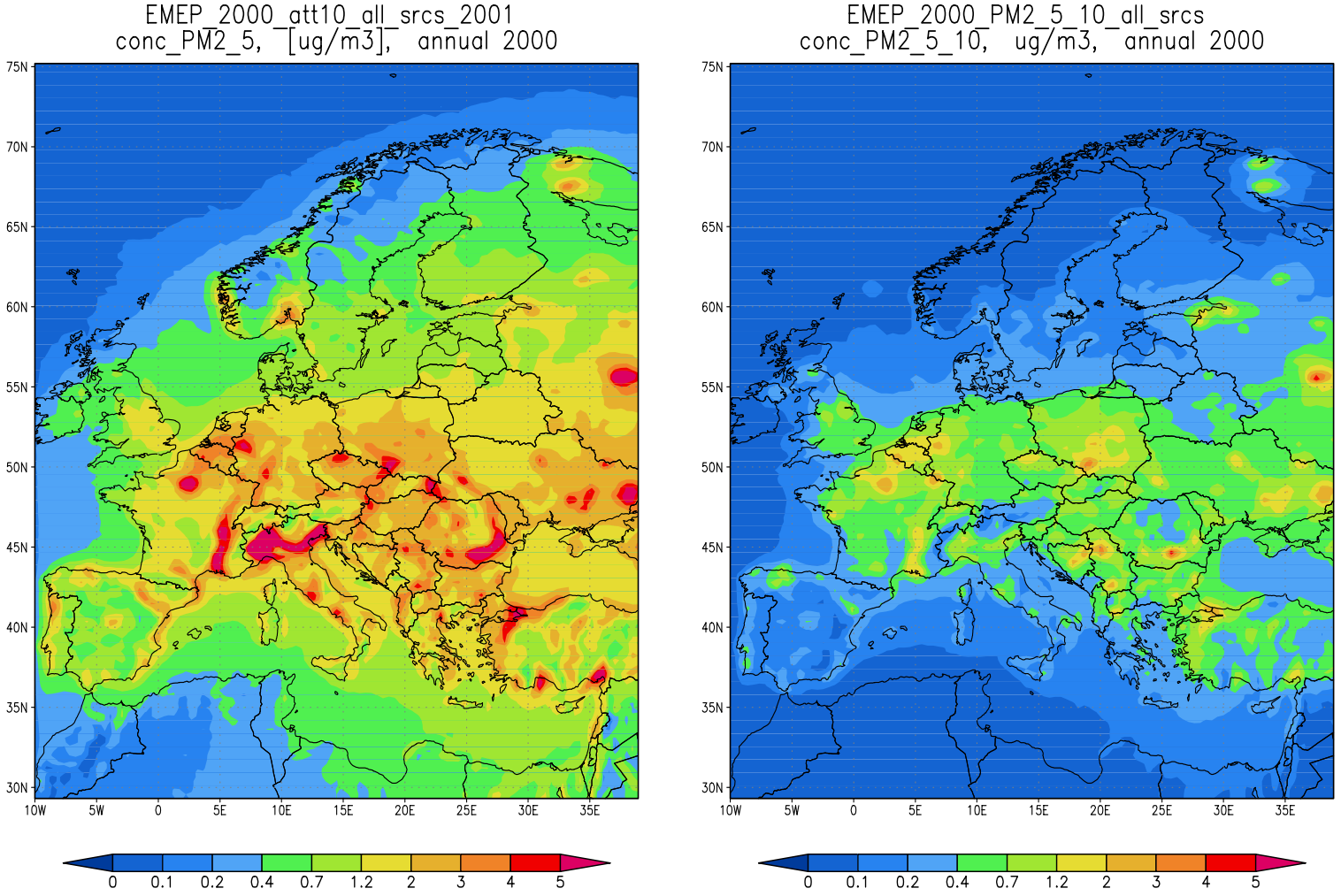
SILAM predictions for primary $PM_{2.5}$ (left) and $PM_{2.5-10}$ (right), in 2000 (mg/m3)



Predicted sulphate concentrations in 2000

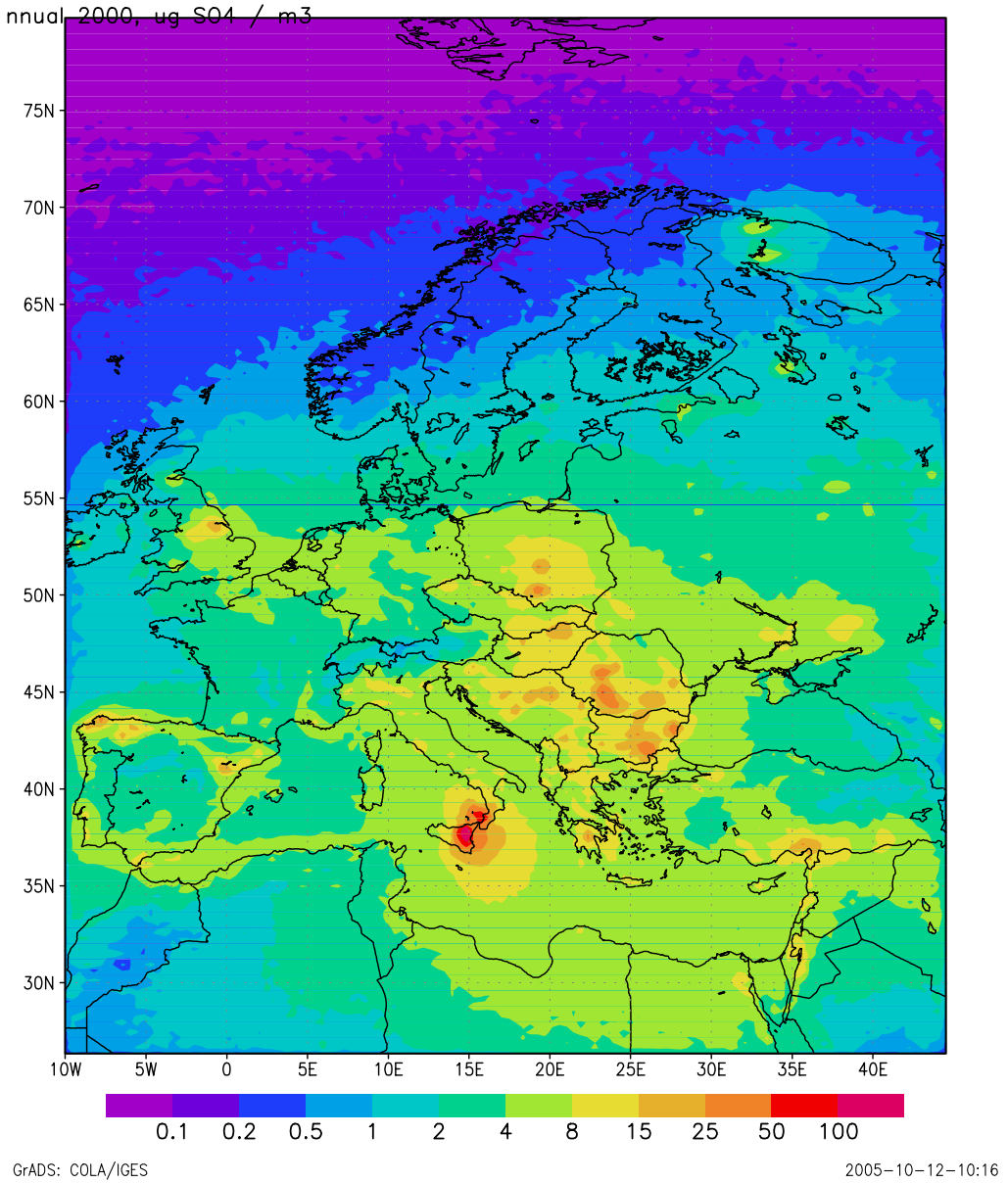
Emission: EMEP

Meteorology: HIRLAM

Dispersion: SILAM with DMAT chemistry

Unit: µg SO_4 / m^3

(up to 100 µ g SO_4 / m^3)



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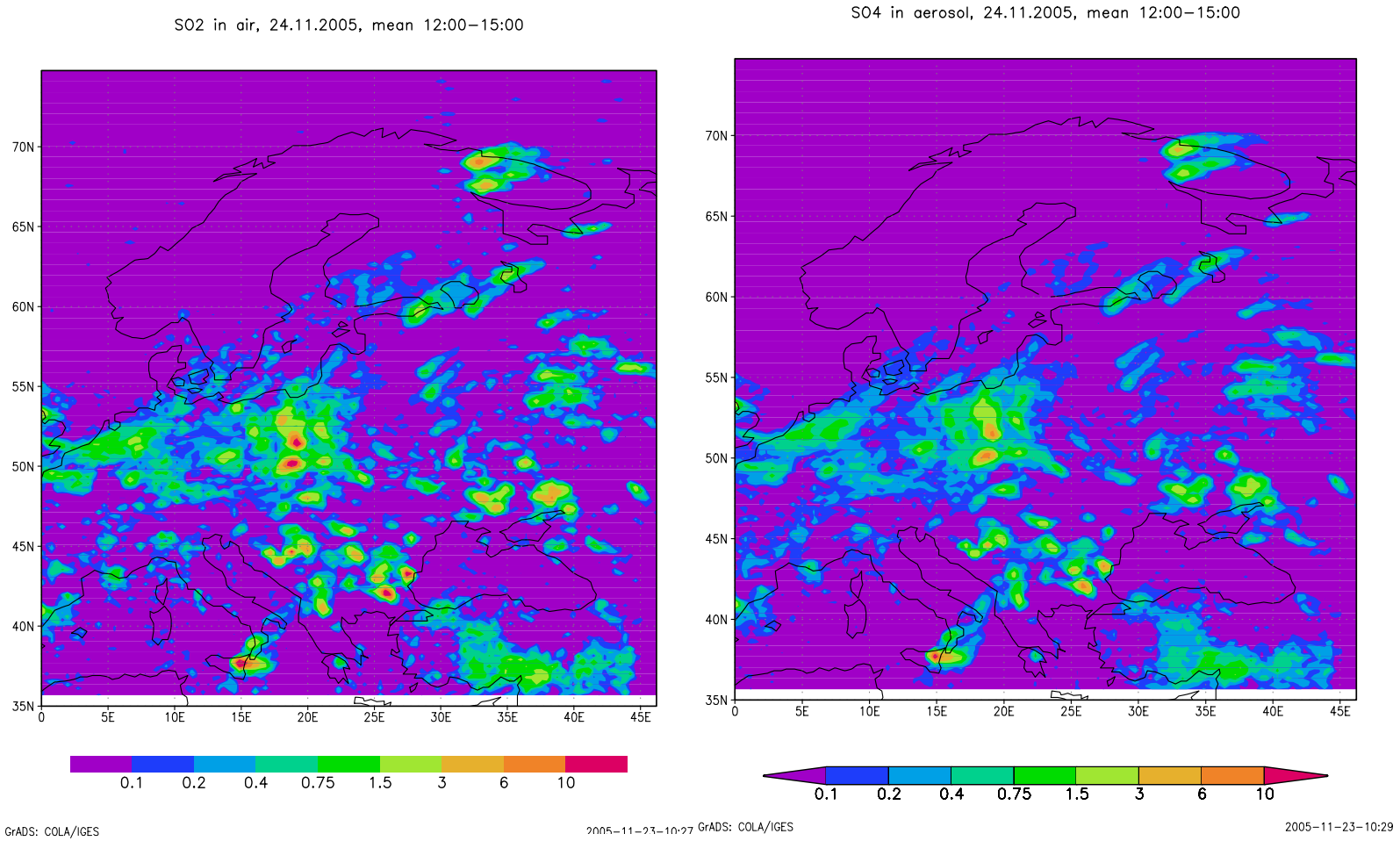
The daily air quality forecast for SO_2 (left) and SO_4 (right) on 24 November 2005, using the SILAM model



Hirlam RCR, resolution 25 km, @sambo, 1 week spin-up

Operational air quality forecasts

- **Available at http://silam.fmi.fi**
- **Modelling and set-up**
  - Emissions: EMEP 2003 + forest fires based on MODIS in near real time
  - Dispersion model SILAM v.3.8
  - Whole Europe, resolutions 1 hour, 30 km, forecast horizon 54 hours
  - Updates: daily, about noon
  - PM2.5, PM10, SO2, SO4 (and soon expected: sea salt)
  - computation costs: 70-80 CPU-hours on the SGI Altix Linux Cluster
- **Future challenges: secondary aerosol, aerosol dynamics & chemistry**

FINE-KOPRA computations

Aine	Helsinki	Suomi	Eurooppa	Pallonpuolisko
PM 2.5	2002	Perusjakso, 3 moodia: PM 0.1; PM 0.1-1; PM 1-2.5	Perusjakso	
PM 2.5 - PM 10		Perusjakso	Perusjakso	
PM yli 10		Perusjakso	-	
SOx, sulfaatit	yhteensä, 2002	Perusjakso	Perusjakso	
NOx, nitraatit				
Merisuola	-	-	2000-2002	
Aavikkopöly	-	-	-	1967 - 1988

Perusjakso: vuodet 2000-2002 kokonaisuudessaan sekä useita episodeja vuosilta 1999-2003
Euroopan päästödatassa ei ole jaottelua 5 kokoluokkaan, PM2.5 on käsitelty yhtenä luokkana
Merisuolalaskelmissa hiukkaset on jaoteltu useampaan kokoluokkaan
Aavikkopölylaskelmissa on käytetty hiukkaskokojakauman analyyttistä esitystä

KOPRA European and regional computations

	European scale	Regional scale (Finland)
Species	PM 2.5; PM 2.5-10; SOx; desert dust; sea salt; NOx; secondary organics	PM 0.1; PM 0.1-1; PM 1-2.5; PM 2.5-10; PM >10; SOx; NOx; secondary organics
Resolution	30 km; 1 day / 1 hour (observ. campaigns)	5 km; 1 day / 1 hour (observ. campaigns)
Period, meteodata	2000 (HIRLAM); 2001 - 2002 (ECMWF)	2000 (HIRLAM); 2001 – 2002 (ECMWF)
Emissions	split: 46 regional sources (EMEP merged with Finnish national)	Split: 4 sectors & 150 point sources & unit-emission source-receptor matrices
Temporal variation and vertical distribution of emissions	GENEMIS-95; EMEP SNAP-related vertical distribution	GENEMIS-95; area sources assumed under 100m, point sources determine the height explicitly

Blue font = almost done, red = undone

Comparison of the predictions with data

- **Comparison with EMEP data**
  - SO_2 in air, SO_4 in aerosol, SO_4 wet deposition, 2000 - 2002
  - Aerosol observations are scarce and do not include chemical speciation, however, work is in progress to compare the total mass concentrations (Primary PM2.5 or PM10 + SO_4 + SeaSalt $\Rightarrow$ ~ 80 % of PM)
  - Predicted annual averages are in a good agreement with measured data
  - Temporal correlation of monthly averages is somewhat low (probably caused by the 15 years old data on the seasonality of emissions)
  - Specific parameters – FMT, RMSE, RelDiff – are within fair-to-good limits

- **Comparison with some campaign results is in progress (e.g., BIOFOR 1999, Värriö 2003)**

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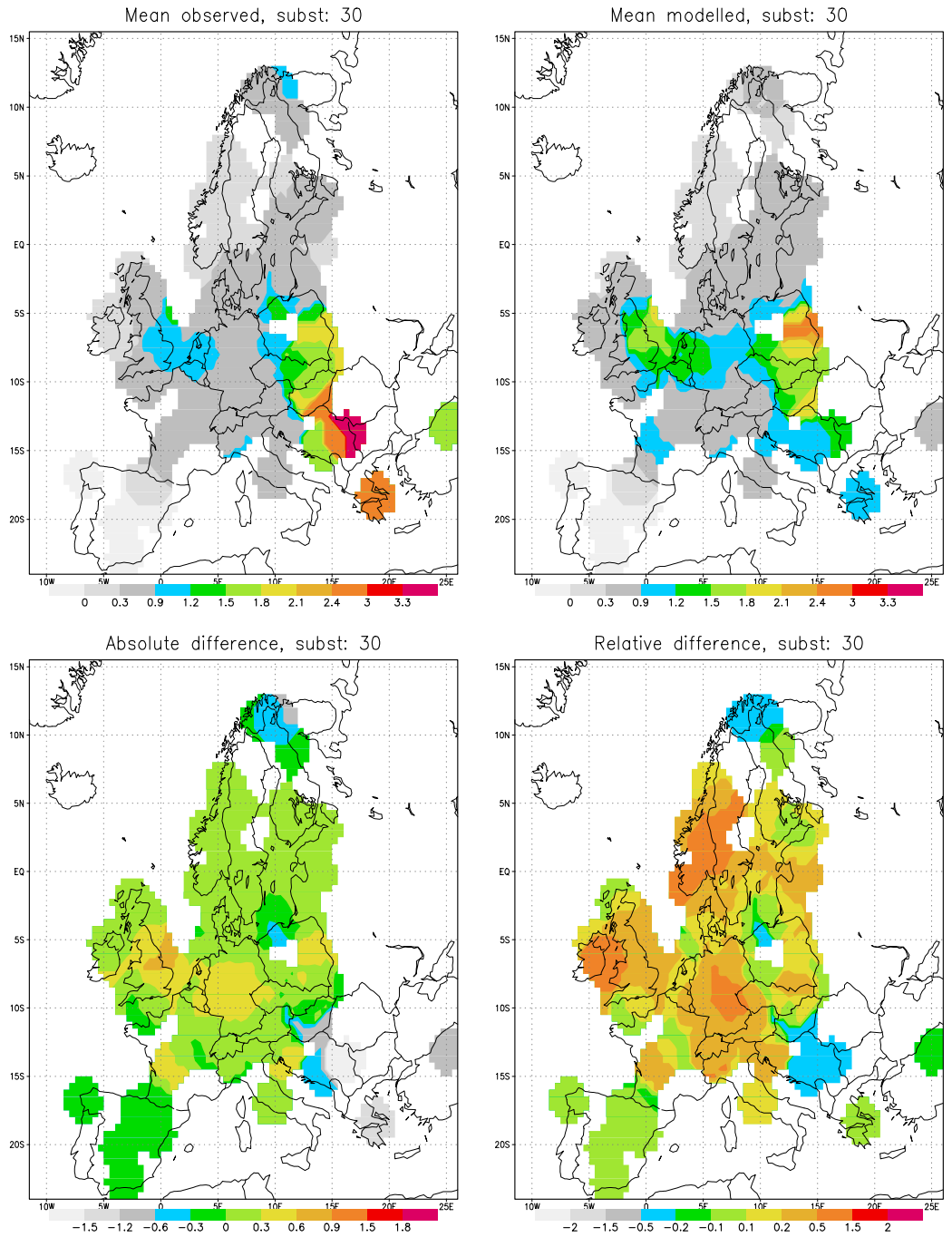
Examples of the comparison

SO_2 concentrations

µg S m^{-3}
year 2000
about 60 stations

<u>Upper panels:</u>
mean observed (left)
mean modelled (right)
<u>Lower panels:</u>
absolute difference (left)
relative difference (right)



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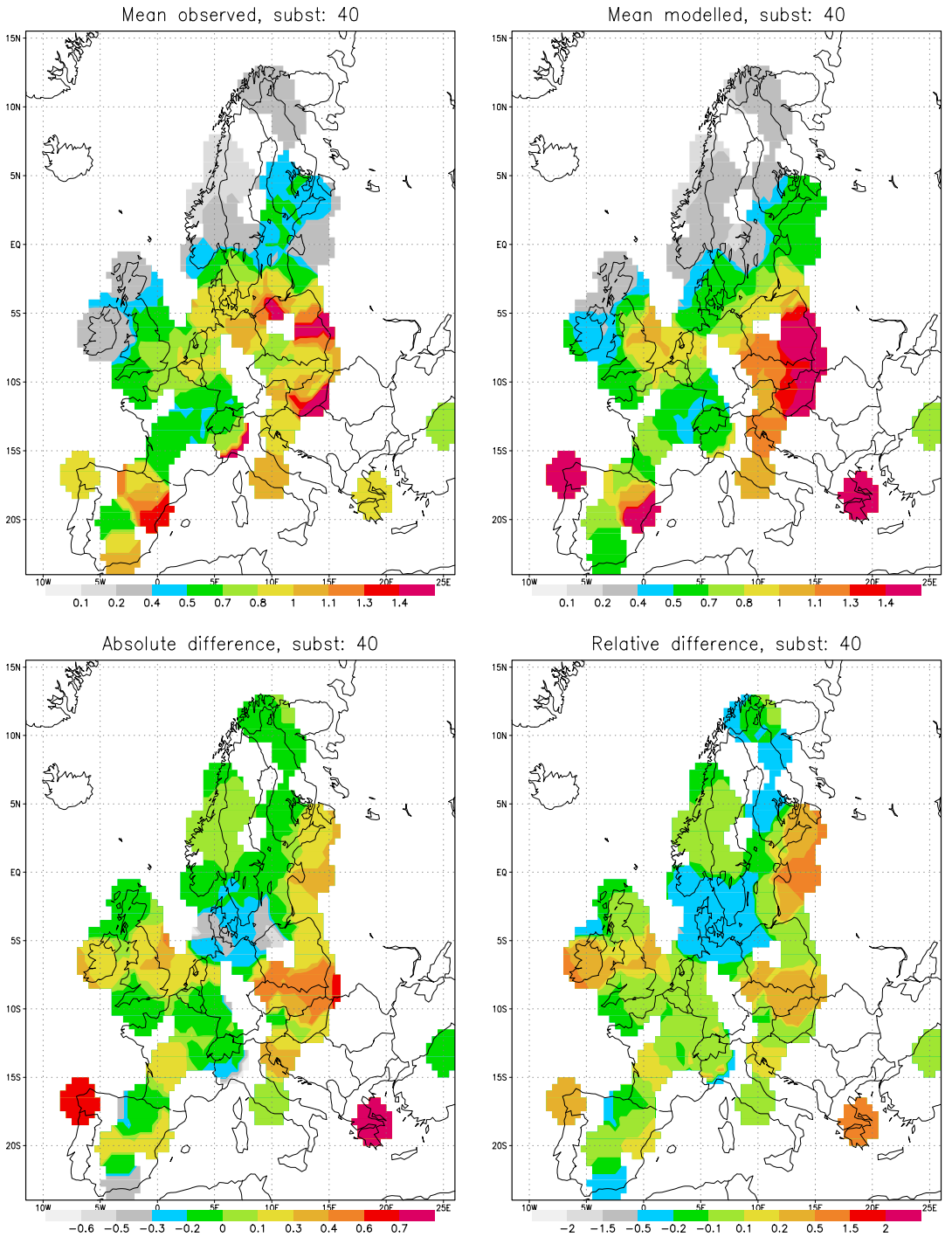
Examples of the comparison

SO_4 concentrations

µg S m-3
year 2000
about 60 stations

<u>Upper panels:</u>
Mean observed and mean modelled
<u>Lower panels:</u> absolute and relative difference



Conclusions from model evaluation

- **Aerosol mass closure:**
  - modelling includes primary anthropogenic particles, sulphate and sea salt
  - It does not include nitrates, secondary organic aerosol and wind-blown dust
- **Temporal correlation with observations is fairly good on a monthly basis, and expectedly deteriorates with shorter averaging time**
  - The temporal variation of emissions is based on old data
  - Limitation: resolution of emissions is 50 km, that of meteorological data is 30 km for HIRLAM and 40 km for ECMWF models, respectively

Future challenges

- **Aerosol mass closure**
  - wind-blown dust: sometimes somewhere dominating; approaches exist but have to be checked/refined for non-desert conditions
  - secondary inorganic aerosol: nitrates, ammonia (complex chemistry)
  - secondary organic and inorganic aerosols due to aerosol dynamics
    - module has been created but it is too resource-consuming for real simulations
    - a different feasible way to handle the problem exists but it requires a lot of work on chemistry and aerosol dynamics
  - wild-land fires: emission from satellites
- **Ozone**

A model for evaluating fine particulate matter mass concentrations in urban areas

Contributions to urban $PM_{2.5}$ concentration

$$PM_{2.5} = PM_{2.5}^{tr,e} + PM_{2.5}^{tr,n\text{-}e} + PM_{2.5}^{st} +$$

$$PM_{2.5}^{bg,urb} + PM_{2.5}^{bg,lrt} + PM_{2.5}^{wind}$$

Primary traffic + non-exhaust traffic + stationary sources + urban BG + long-range BG + suspended material from other sources than traffic.

Using the semi-empirical relation

$$PM_{2.5}^{bg,lrt} = b\, C_{ion}$$

and the simplest possible assumption for the non-exhaust term, the above-mentioned equation can be written as

$$PM_{2.5} = (1 + a)\, PM_{2.5}^{tr,e} + b\, C_{ion} + PM_{2.5}^{st} + c$$

where C_{ion} is the so-called ion sum, a and b are constants and c the the contribution of other sources except for local traffic, LRT and stat. sources

Tiitta, P., T. Raunemaa, J.Tissari, T. Yli-Tuomi, A. Leskinen, J. Kukkonen, J. Härkönen and A. Karppinen, 2002. Measurements and Modelling of PM2.5 Concentrations Near a Major Road in Kuopio, Finland. Atmospheric Environment 36/25, pp. 4057-4068.

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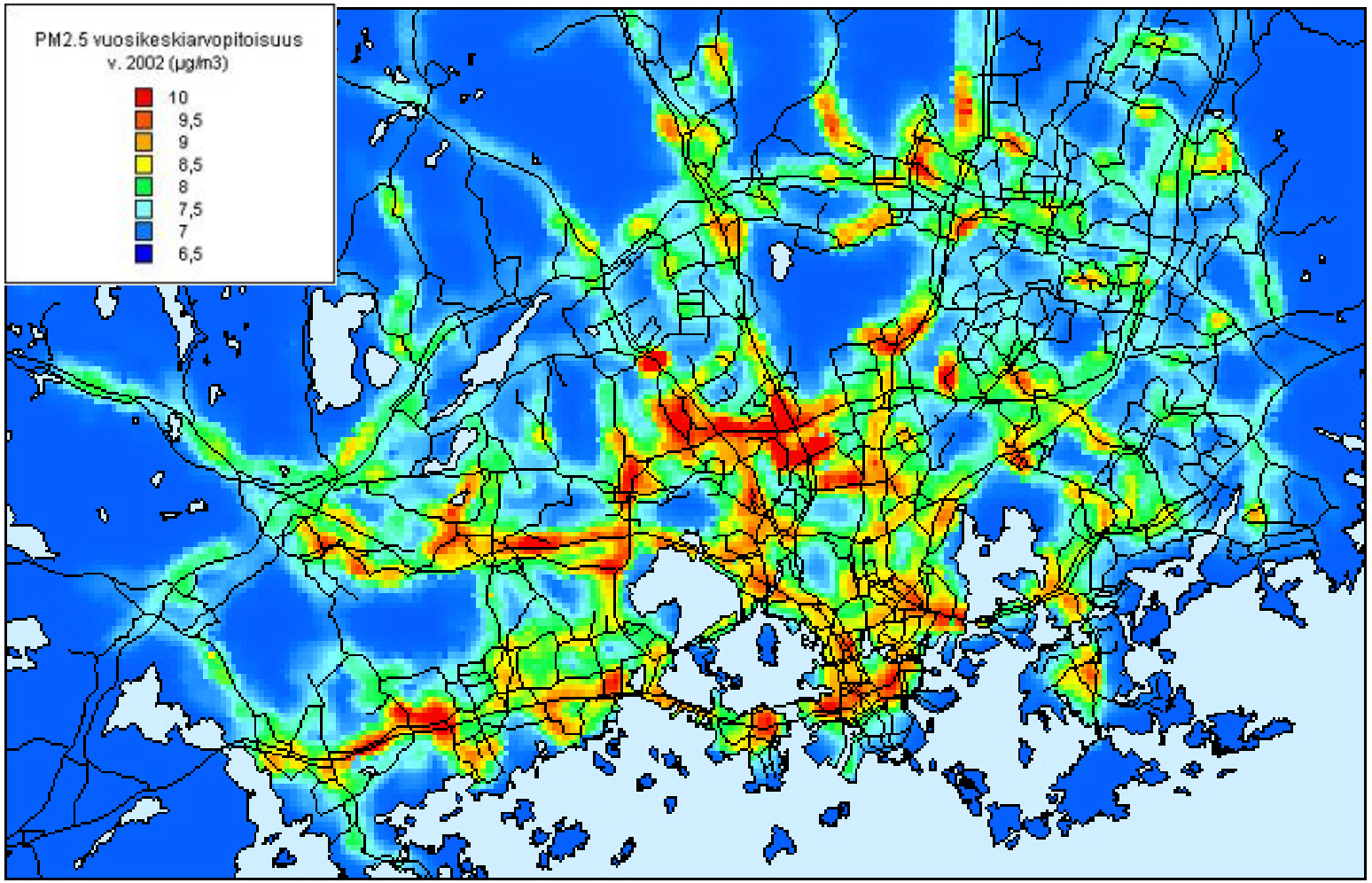
Predicted annual average of the $PM_{2.5}$ concentration in 2002



Interpretation of the predicted results

On an annual basis, the estimated contribution from regionally and long-range transported origin to the observed PM2.5 varies from less than 50 % in the centre of Helsinki to more than 90 % in the outskirts of the metropolitan area.

The influence of the cold-start and cold driving emissions on the total PM2.5 concentrations was found to be substantial. In winter ($T < 0$), cold starts and cold driving increased the amount of the exhaust emissions originated from local traffic approximately by 40 %.

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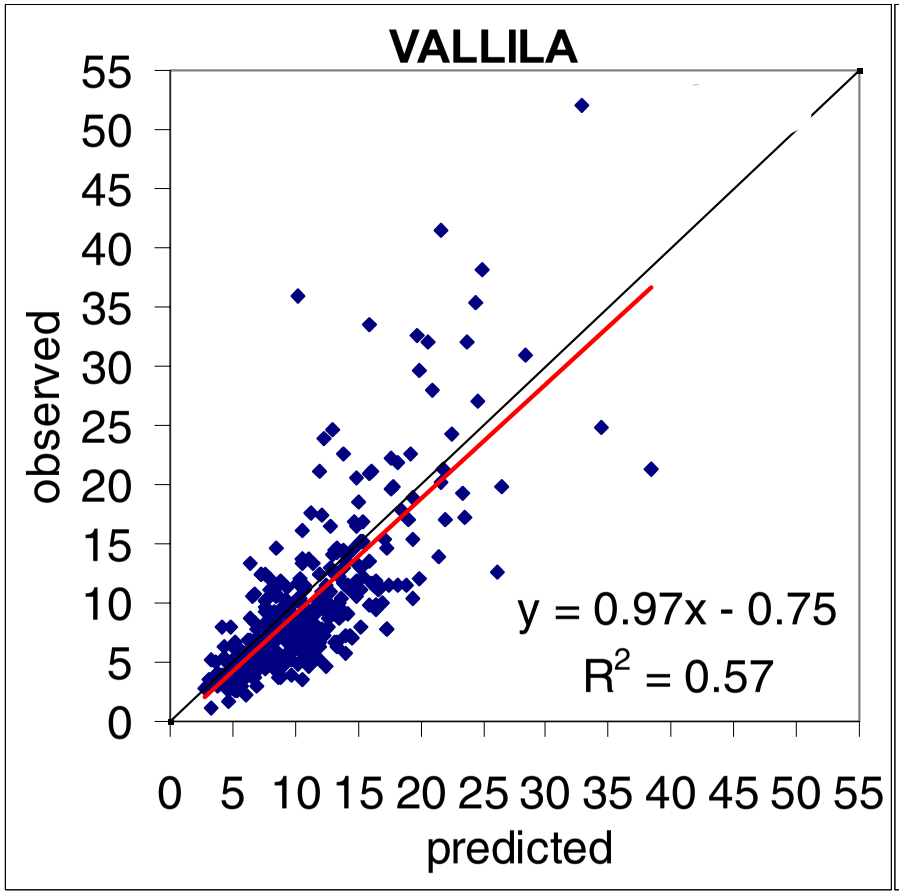
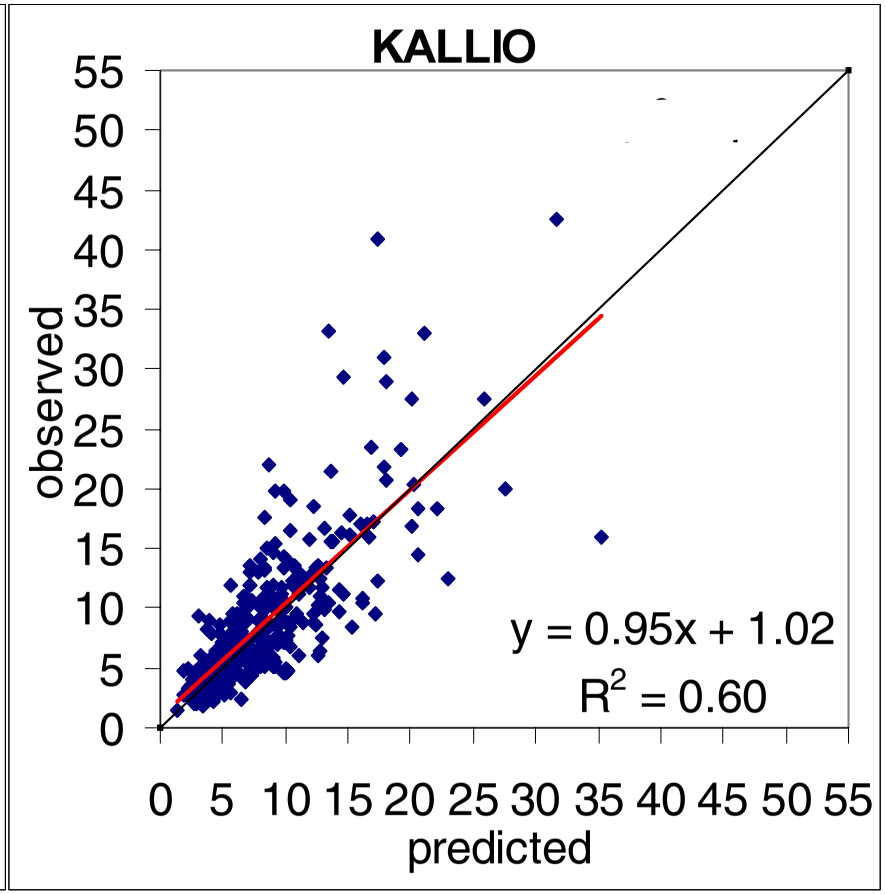
Predicted vs. observed daily mean
$PM_{2.5}$ concentrations at two stations – scatter plot, Correlation Coefficient squared (R^2) and Index of Agreement (IA)





VALLILA: $R^2 = 0.57$, IA = 0.84

KALLIO: $R^2 = 0.60$, IA = 0.86

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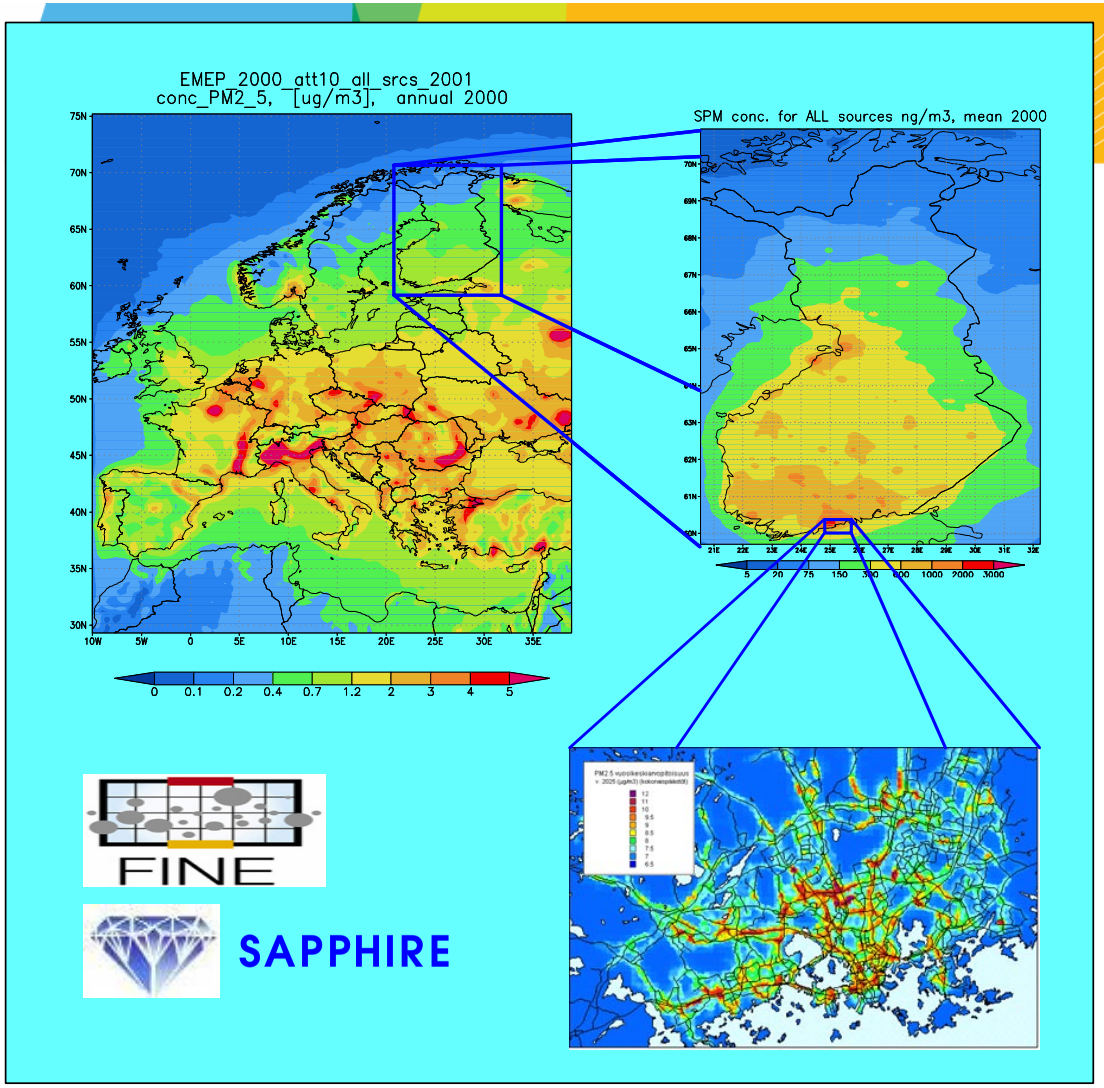
Multiscale modelling



SYKE ytv KTL

Predicted concentrations of primary $PM_{2.5}$ in Europe and in Finland in 2000, and $PM_{2.5}$ from all sources in the Helsinki metropolitan area in 2002 ($\mu g/m^3$). The results were computed using the emissions compiled by EMEP, SYKE and YTV, and the HIRLAM, SILAM, CAR-FMI and UDM-FMI models. The spatial resolution is 30 km for Europe, 5 km for Finland, and from 50 to 200 m in the Helsinki metropolitan area.

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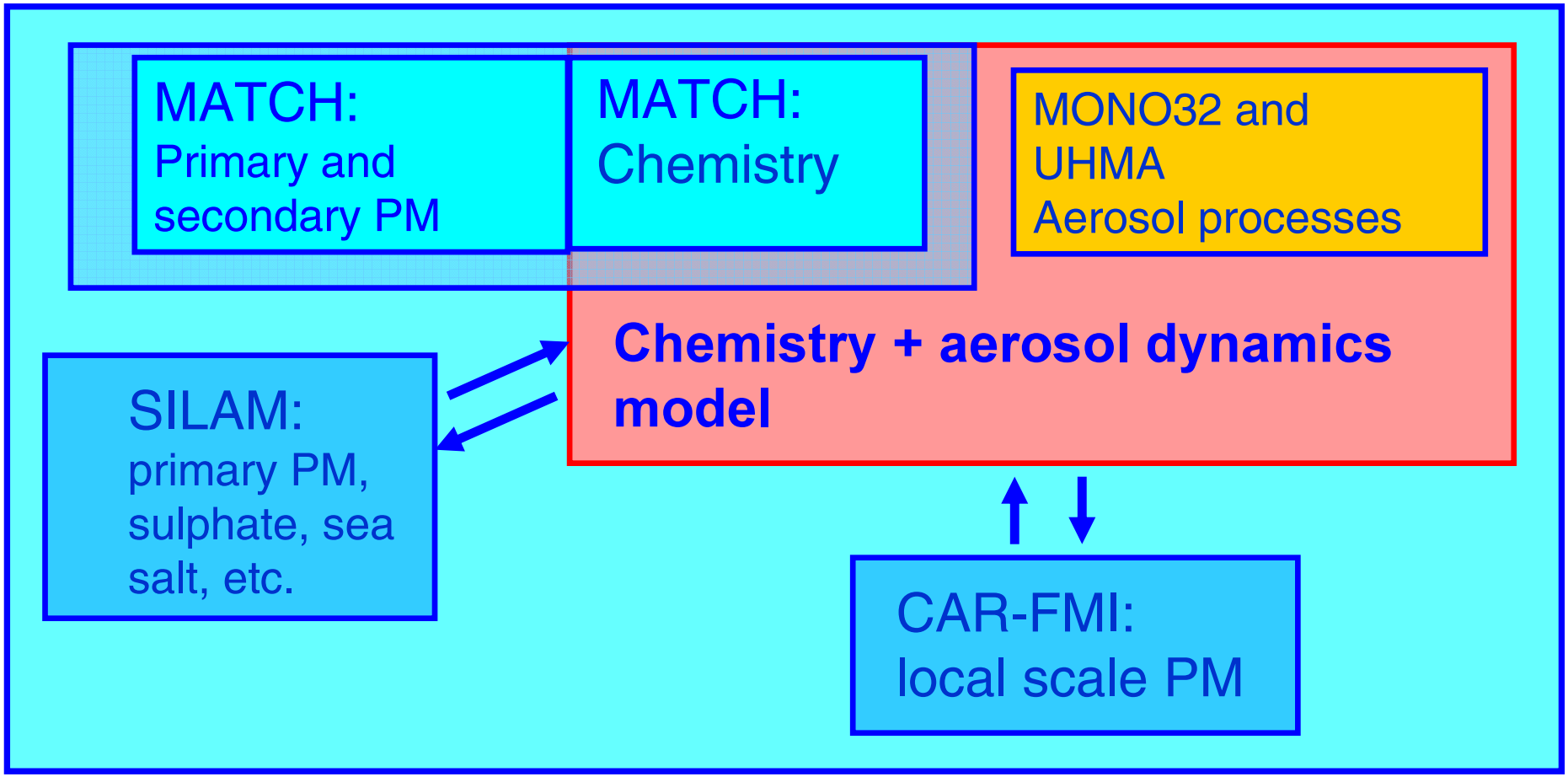
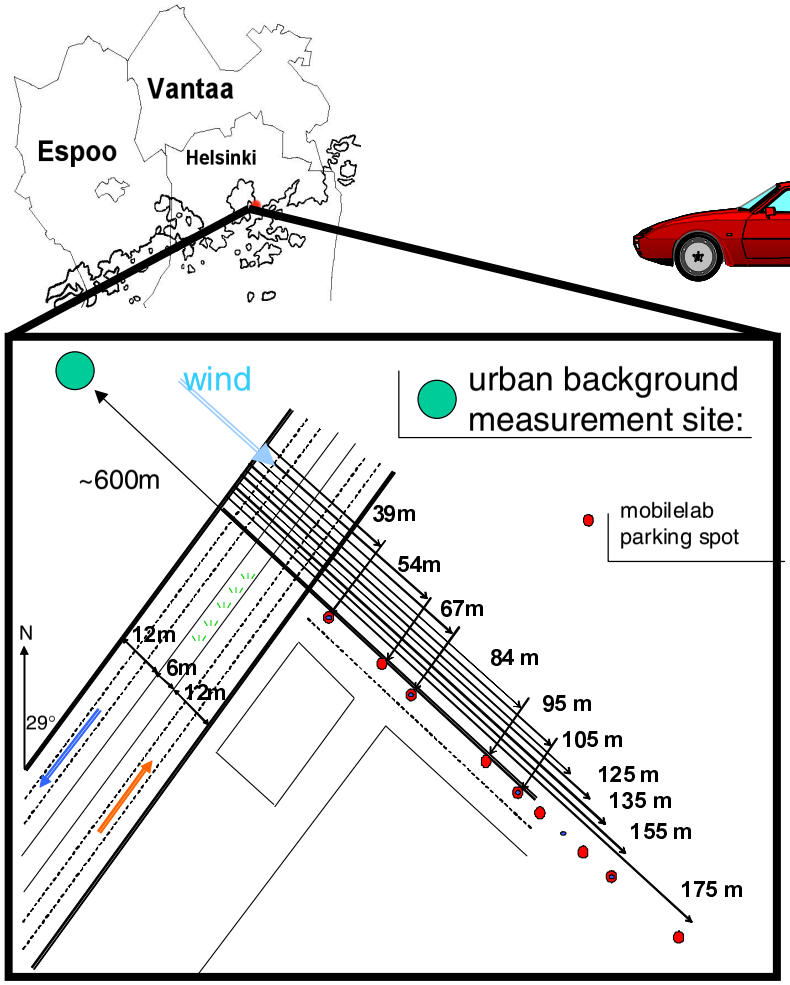
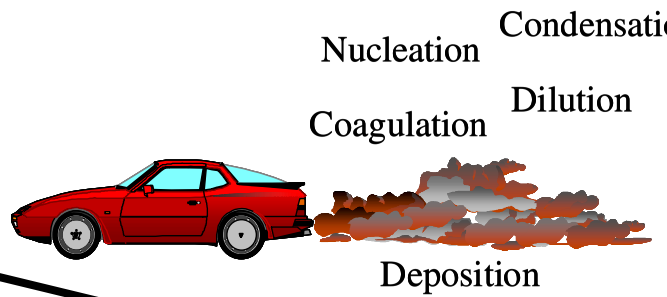
Modelling of primary and secondary PM, and combining the models



Modelling aerosol dynamics in the atmosphere using the MONO32 and CAR-FMI models

FMI, Helsinki Polytechnic and University of Helsinki





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Pohjola et al., 2005, Pirjola et al., 2005

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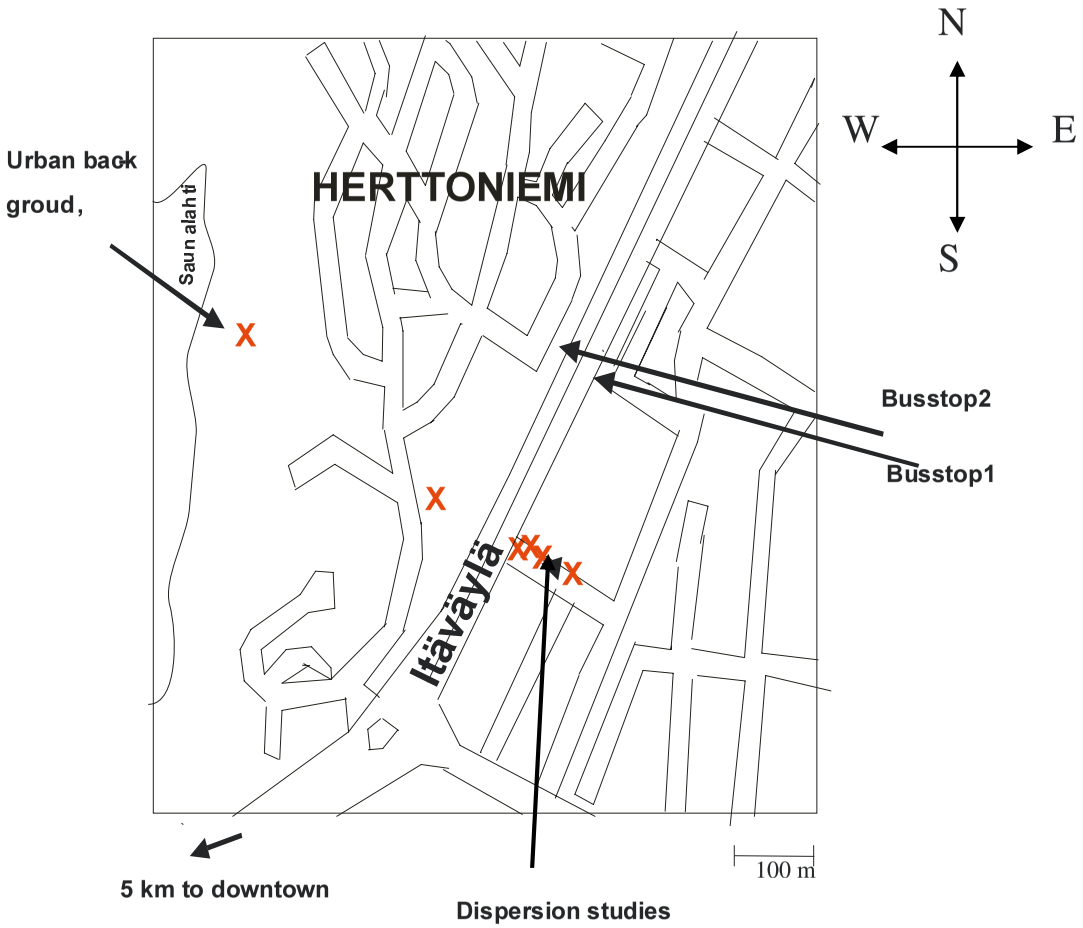
LIPIKA-campaigns at Itäväylä, Helsinki

(10-26 Feb 2003, 12-27 Aug 2003, 28 Jan-12 Feb 2004, 6-20 Aug 2004)



- width of the highway 30 m
- rush hours 7-9:30 and 15-18:30
- traffic flowrates

  4000 veh h^{-1} morning rush hours

  4500 veh h^{-1} afternoon rush hours
- one-minute averages, altogether 985 minutes (good quality)

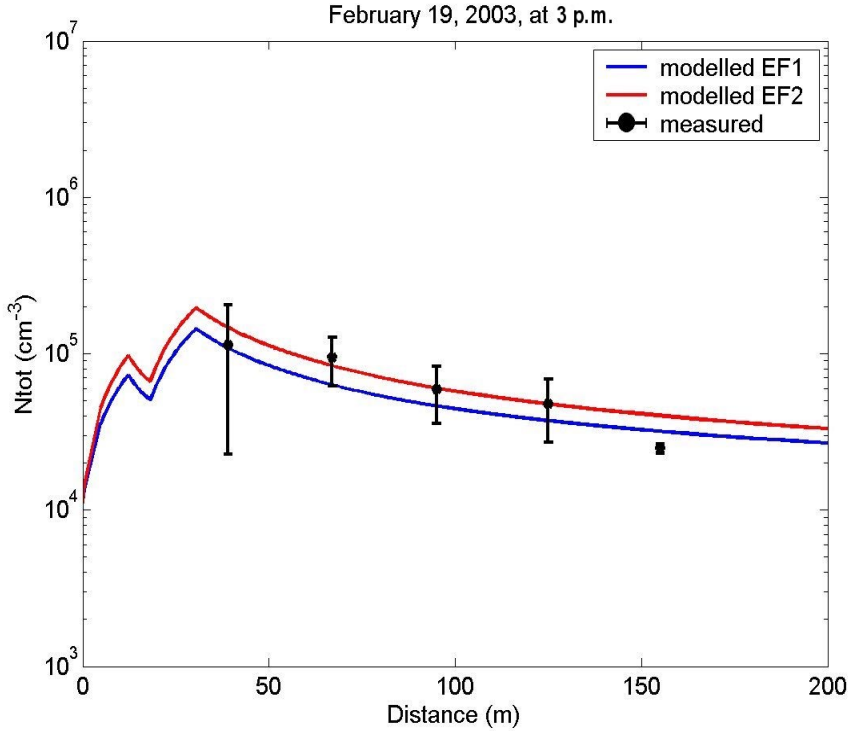
S1: wind blows to SW perpendicular to Itäväylä (255-345°)

S2: wind blows along Itäväylä to NE (5-55°) and to SW (185-235°)

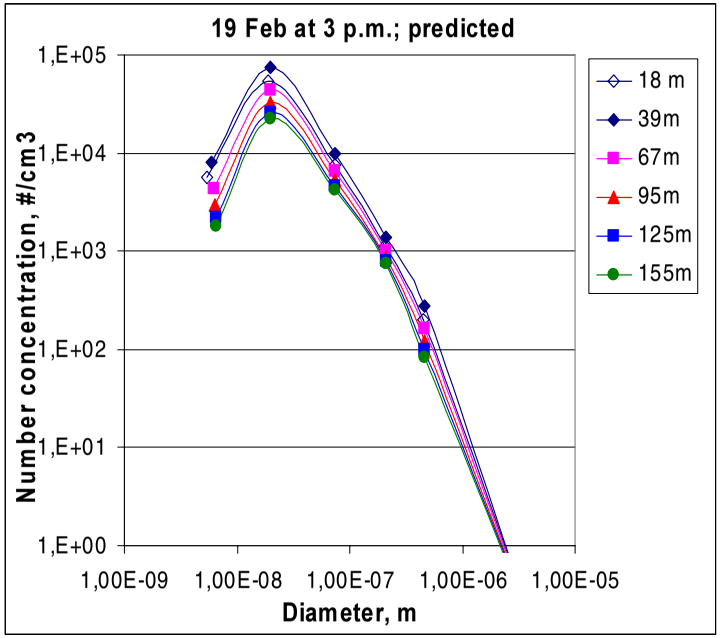
S3: wind blows to NW perpendicular to Itäväylä (75-165°)

- average T varied (-5.0) - (+1.3) °C in winter and 14.1-18.4 °C in summer

Total number concentrations against distance from a road



Predicted evolution of particle size distribution

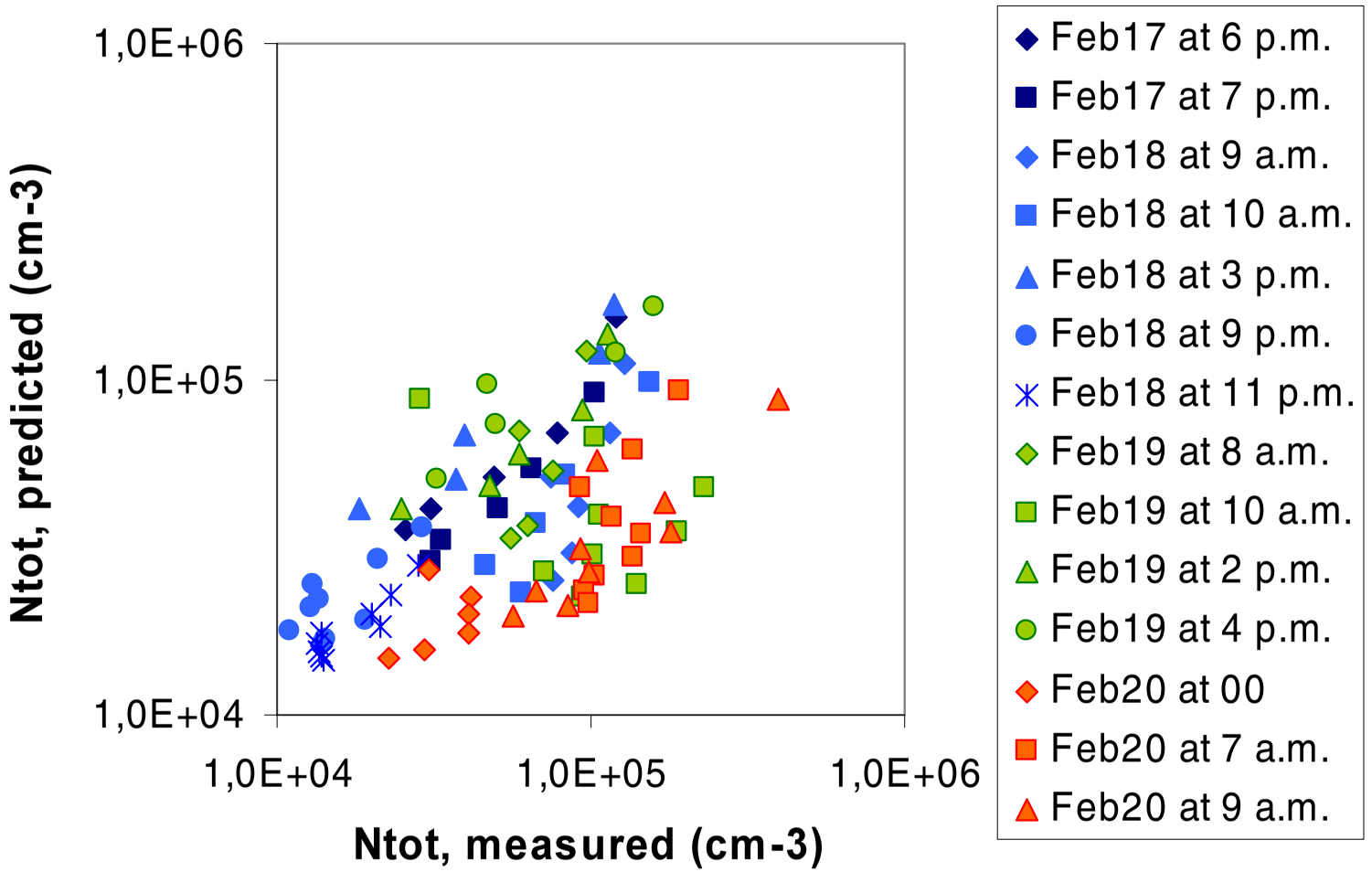


Lines: predictions using two sets of emission factors

Dots and error bars: measurements

Pohjola et al., 2005, Pirjola et al., 2005

Feb 17 - 20, 2003



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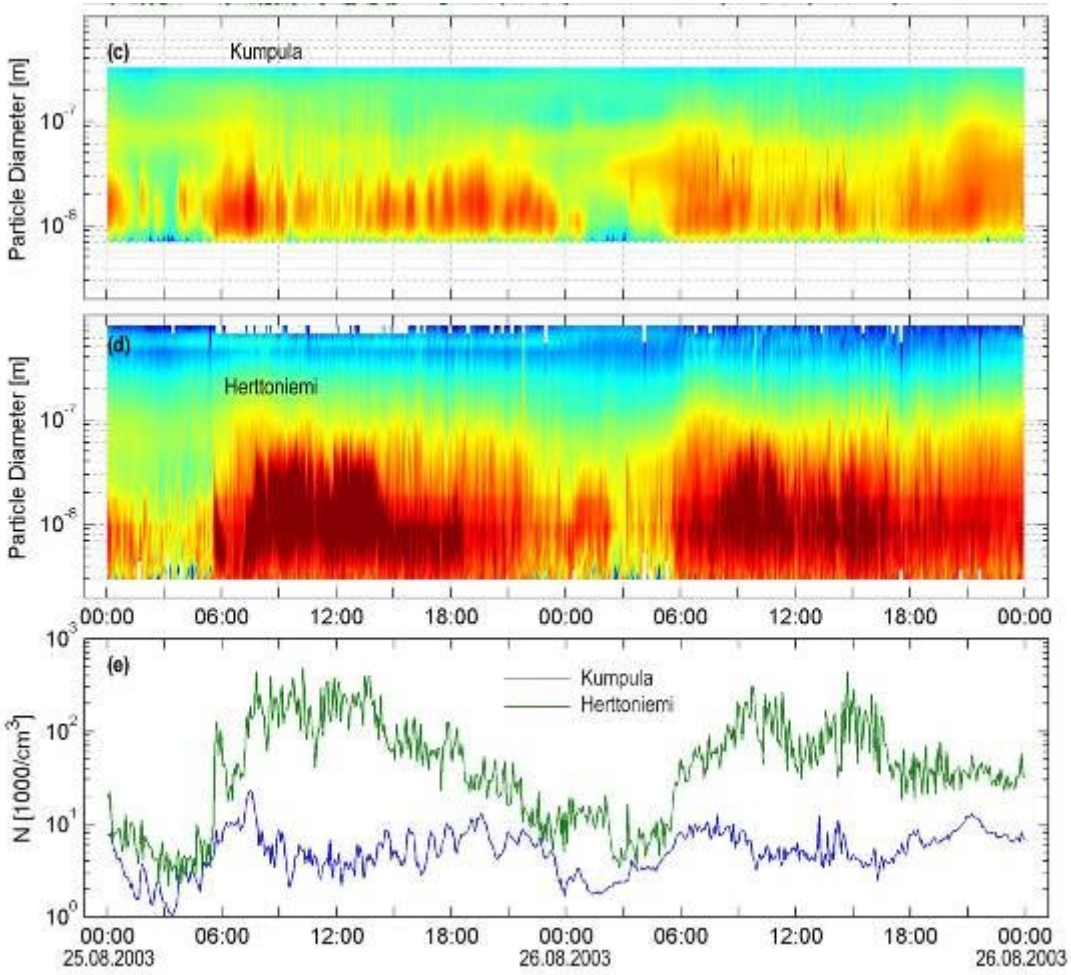
Analysis of measured particle number concentrations at an urban background site (Kumpula), compared with a roadside site (Herttoniemi)



Hussein T, A. Karppinen, J. Kukkonen, J. Härkönen, P.P. Aalto, K. Hämeri, V-M Kerminen, M Kulmala, 2006. Meteorological dependence of size-fractionated number concentrations of urban aerosol particles. Atmos. Environ. 40 (2006) 1427–1440.

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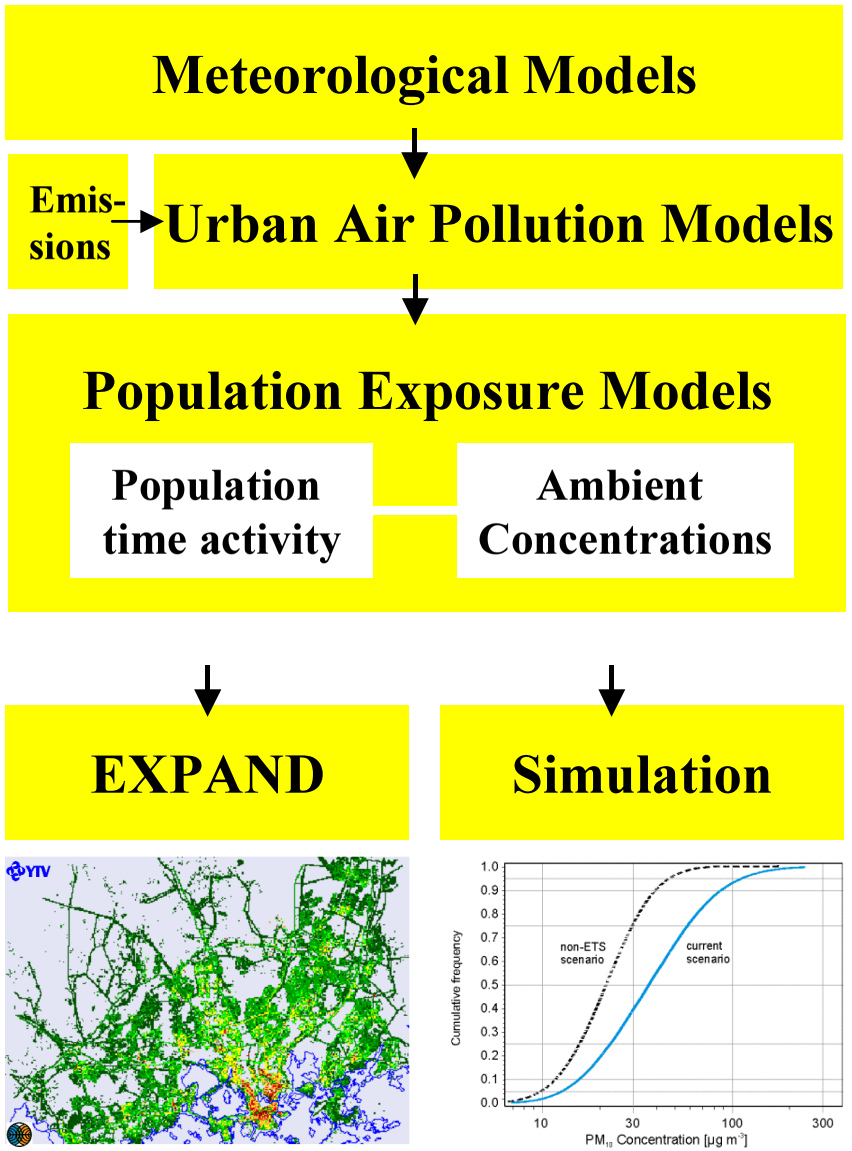
Two complementary exposure models– deterministic (EXPAND) and probabilistic (EXPOLIS)



Baklanov et al., 2006. Integrated systems for forecasting urban meteorology, air pollution and population exposure Atmos. Chem. Phys. Disc., Vol. 6, pp 1867-1913, http://www.copernicus.org/EGU/acp/acpd/recent_papers.html

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Modelled exposure to fine particulate matter ($PM_{2.5}$)

Location of population:
- at home
- workplaces
- other places

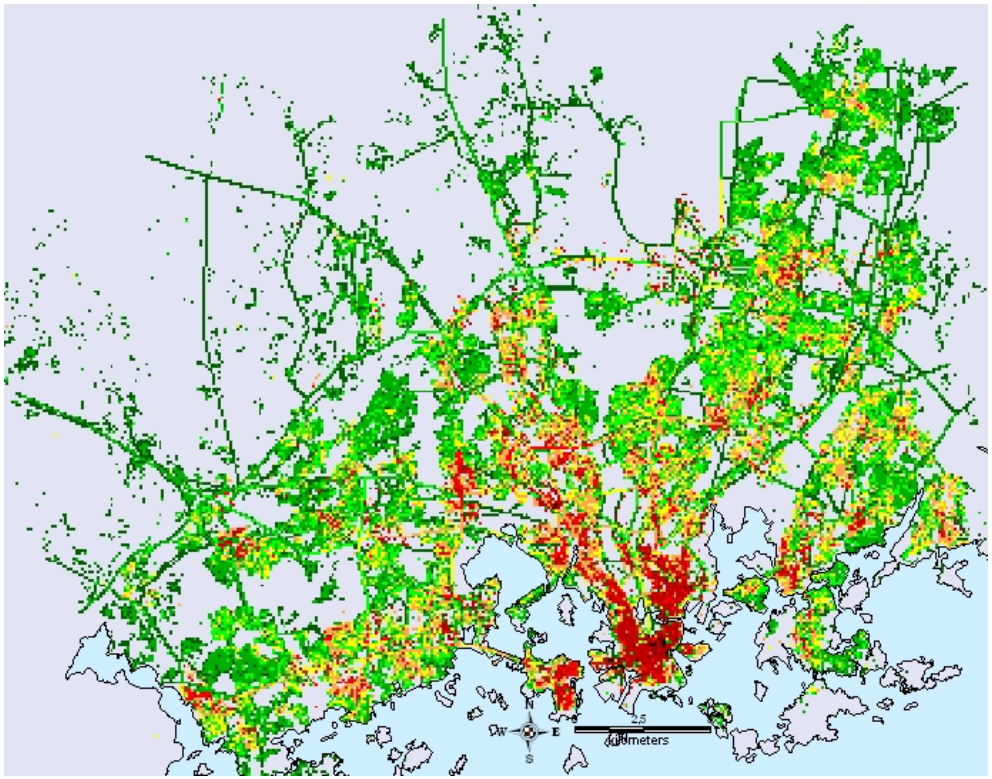
Time - microenvironment - activity data

Predicted traffic flow and ambient air concentrations

Activity of population

Numerical interpolation of concentrations and computation of exposure

GIS MapInfo:
Spatial distributions of the activity of population, concentrations and exposure on a map



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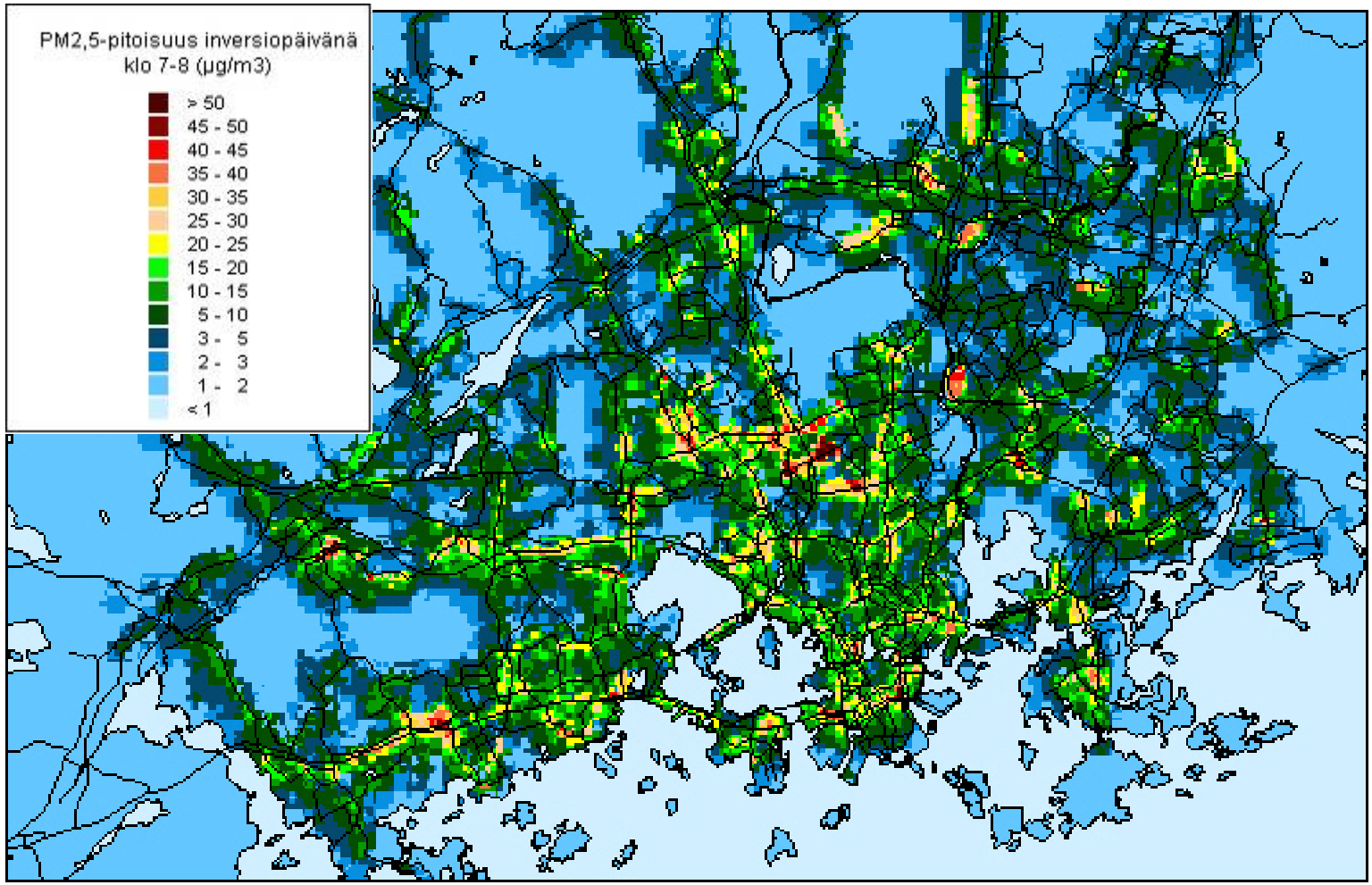
KTL ytv FINE

$PM_{2.5}$ -concentration during an episode induced by temperature inversion on 22 October 2002. Morning rush hour, 7:00 – 8:00 a.m.



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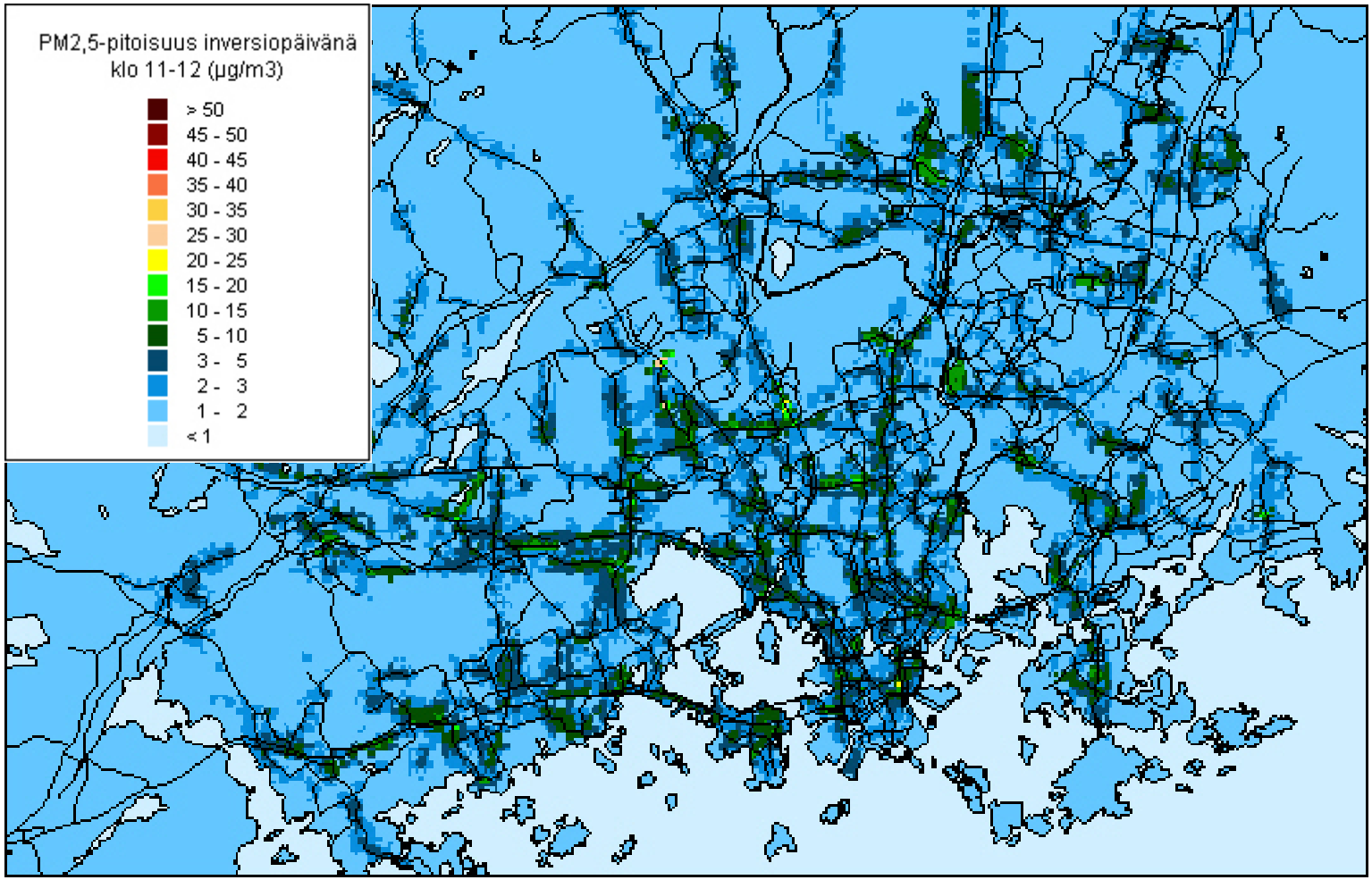
KTL ytv FINE

$PM_{2.5}$ -concentration during an episode induced by temperature inversion on 22 October 2002. Midday, 11:00 – 12:00 a.m.



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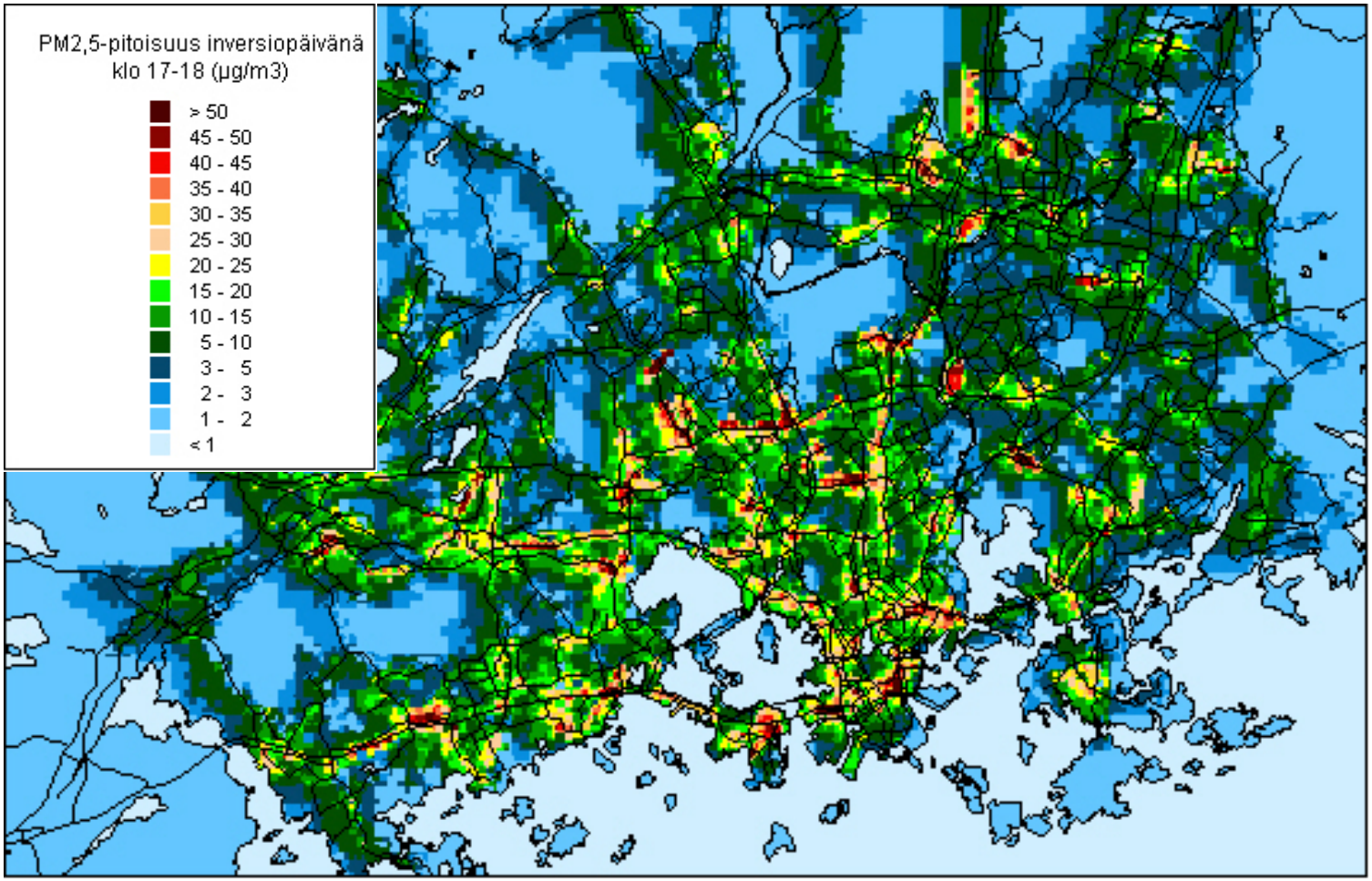
$PM_{2.5}$ -concentration during an episode induced by temperature inversion on 22 October 2002. Afternoon rush hour, 7:00 – 8:00 a.m.



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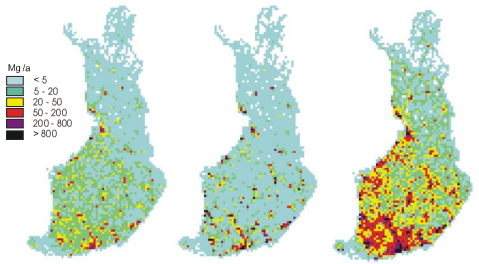
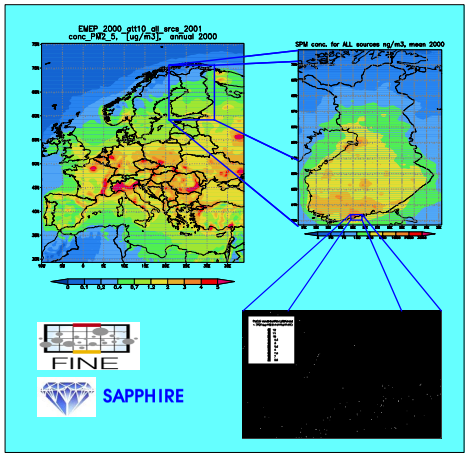
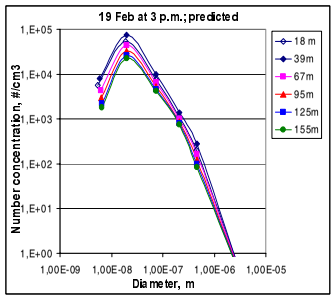
Conclusions 1/2

- The national emissions of primary PM and the main precursors have been evaluated using the FRES - model on a resolution of 1 x 1 km^2 for various source categories and scenarios in 1990 - 2020
- The cost efficiencies of various PM emission reduction strategies have been evaluated
- Primary-, sulphate- and sea salt- PM concentrations have been modelled regionally, and the total PM2.5 concentrations in the Helsinki Metropolitan Area
  - ✓ resolution of 30 km in Europe ja 5 km in Finland
  - ✓ predicted mass closure still incomplete
- New insight on the influence of aerosol processes, new measurement campaigns
  - ✓ small effect on the PM mass,
    but may be substantial for size distributions
  - ✓ unresolved issues still remain



$PM_{2.5}$ SO_2 NO_x





FINE

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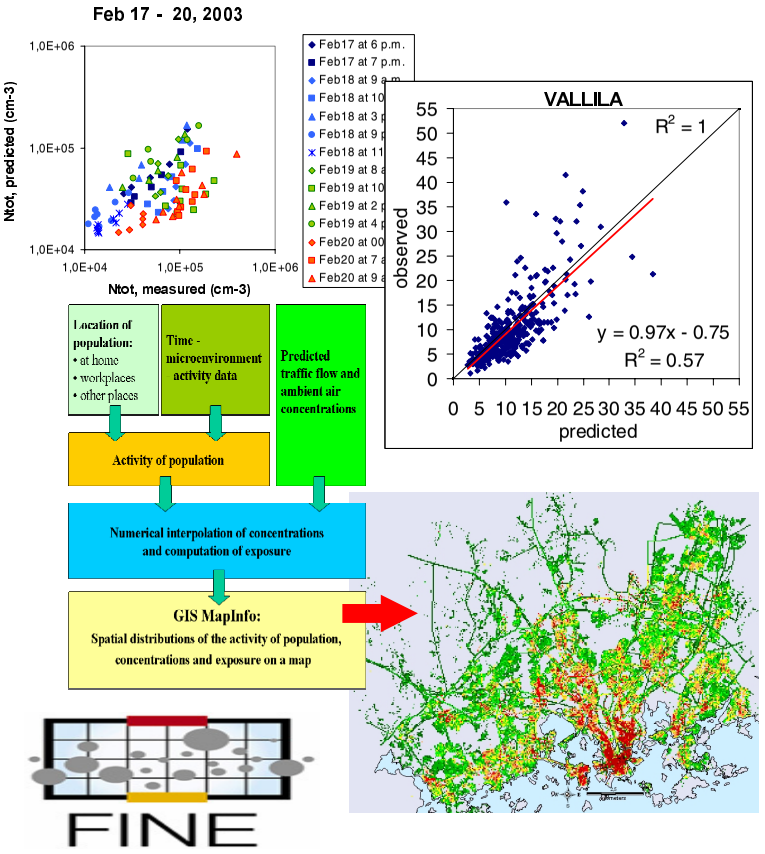
Conclusions 2/2

- Predicted concentrations have been compared with the data measured in various campaigns (e.g., LIPIKA, SAPPHIRE, Värriö), and the measured data of EMEP and YTV (Helsinki Metropolitan Area Council)
- The population exposure model EXPAND has been refined
- Intake fractions and source-receptor matrices have been evaluated for various European countries and nationally for various emission categories
- Health effects have been evaluated in terms of pollution sources and effect mechanisms
  - ✓ Small scale combustion and traffic are the most important ones
  - ✓ Premature mortality from national primary PM is about 200 / a (secondary PM not included)



Total mortality due to Finnish primary PM2.5 emissions

Code	Name	Lung cancer	Cardiopulmonary	Total	%
SCO	Kiinteät hajalähteet	1.0	11.9	12.9	6.8 %
SCD	Pienpoltto	6.0	69.4	75.4	39.6 %
SPR	Teollisuusprosessit	0.0	0.0	0.0	0.0 %
TRL	Liikenne, kevyt	1.0	12.0	13.1	6.9 %
TRH	Liikenne, raskas	0.5	6.3	6.8	3.6 %
TMM	Työkoneet	1.6	18.2	19.8	10.4 %
TRD	Pöly, liikenne	0.7	7.7	8.3	4.4 %
SDA	Pöly, maatalous	0.2	1.8	1.9	1.0 %
SDP	Pöly, turvetuotanto	0.7	8.3	9.0	4.7 %
SDO	Pöy, muut	0.6	6.7	7.3	3.8 %
LPC	Pistelähteet, poltto	1.5	17.9	19.5	10.2 %
LPP	Pistelähteet, prosessit	1.3	15.1	16.4	8.6 %
	Total	**15**	**175**	**190**	**100.0 %**

Some recent journal articles …

Pohjola, M A, Pirjola, L, Kukkonen, J, Kulmala, M. 2003. Modelling of the influence of aerosol processes for the dispersion of vehicular exhaust plumes in street environment. Atmospheric Environment 37 (3), pp. 339-351.

Karppinen, A., Härkönen, J., Kukkonen, J., Aarnio, P. and Koskentalo, T., 2004. Statistical model for assessing the portion of fine particulate matter transported regionally and long-range to urban air. Scand. J. Work Environ. Health, 30 suppl. 2: 47-53.

Sofiev M, P. Siljamo, I. Valkama, M. Ilvonen and J. Kukkonen, 2006. A dispersion modelling system SILAM and its evaluation against ETEX data. Atmos. Environ. 40 (2006) 674–685.

Hussein T, A. Karppinen, J. Kukkonen, J. Härkönen, P.P. Aalto, K. Hämeri, V-M Kerminen, M Kulmala, 2006. Meteorological dependence of size-fractionated number concentrations of urban aerosol particles. Atmos. Environ. 40 (2006) 1427–1440.

… and there are some extended abstracts of the work in progress, e.g., …

Pohjola M A, Pirjola L, Kukkonen J, Karppinen A, Härkönen J , and Ketzel M, 2005. Combination of a dispersion model and an aerosol process model for modelling roadside environment particles, and evaluation with measured data. In: Skouloudis, A.N. et al.: Proceedings of the 10th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, 17-20 October, 2005, Crete, pp. 422-426.

Kousa A, Aarnio P, Kukkonen J, Riikonen K, Alaviippola B, Kauhaniemi M, Karppinen A, Elolähde T and Koskentalo T, 2005. Refinement of a deterministic population exposure model, and its application for predicting the exposures of PM2.5 in helsinki in 2002, In: Sokhi, RS, Millán, MM, Moussiopoulos, N (eds.): Proceedings (CD) of the 5th International Conference on Urban Air Quality, Valencia, 29-31 March 2005, University of Hertfordshire, UK, 2005. ISBN 1-898543-92-5. (4 pages).

Karppinen A, Kukkonen J, Kauhaniemi M, Härkönen J, Nikmo J, Sokhi RS, Luhana L, Kousa A, Alaviippola B, Koskentalo T and Aarnio P, 2005. Evaluation and application of a model for the urban and regional scale concentrations of PM2.5, In: Sokhi, RS, Millán, MM, Moussiopoulos, N (eds.): Proceedings (CD) of the 5th International Conference on Urban Air Quality, Valencia, 29-31 March 2005, University of Hertfordshire, UK, 2005. ISBN 1-898543-92-5. (4 pages).