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Smart-SMEAR: on-line data exploration and visualization tool for SMEAR stations

Heikki Junninen[1)], Antti Lauri[1)], Petri Keronen[1)], Pasi Aalto[1)], Veijo Hiltunen[2)], Pertti Hari[3)] and Markku Kulmala[1)]

[1)] *Department of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland*
[2)] *Hyytiälä Forestry Field Station, University of Helsinki, FI-35500 Korkeakoski, Finland*
[3)] *Department of Forest Ecology, P.O. Box 27, FI-00014 University of Helsinki, Finland*

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Smart-SMEAR is an interface to visualize the data measured at the SMEAR II station in Hyytiälä, Finland. It is designed to be an additional tool for data mining and a simple tool for working together with trace gas and aerosol data, meteorological parameters and air mass back-trajectories, including numerous point sources. The web tool acts as an interface to the station database which can be reached with only few mouse clicks. The tool provides an overview of such a complicated dataset. The database contains all the data from the start of continuous SMEAR II measurements in 1996 until today. Here, we present also some examples of how to use Smart-SMEAR. We present examples of one typical atmospheric nucleation event day, one local pollution event with low photochemical activity, and one long-range-transport pollution day coupled with local pollution events with strong solar radiation. Smart-SMEAR, together with its search engine Smart-Search, has proven to be an efficient tool for studying atmospheric chemistry and atmospheric aerosol dynamics.

Introduction

Atmospheric aerosol particles and trace gases affect the quality of our life in many ways. In polluted urban environments, they influence human health and deteriorate visibility (e.g. Nel 2005, Pope and Dockery 2006, Hand and Malm 2007). On regional and global scales, aerosol particles and trace gases have a potential to change climate patterns and hydrological cycle (Chung and Seinfeld 2005, Lohmann and Feichter 2005, IPCC 2007). Aerosol particles also influence the radiation-intensity distribution that reaches the Earth's surface, and thus have a direct influence on the terrestrial carbon sink (Gu *et al*. 2002). Better understanding of the various effects in the atmosphere requires detailed information on how different sources (including biogenic sources) and transformation processes modify the properties of aerosol particles and trace gases. Trace gases and atmospheric aerosols are tightly connected with each other via physical, chemical, meteorological and biological processes occurring in the atmosphere and at the atmosphere–biosphere interface (e.g. Kulmala *et al*. 2004b, Kulmala *et al*. 2008).

In order to be able to answer wide and deep questions related to atmosphere–biosphere interactions and feedbacks, comprehensive stations have been established (Hari and Kulmala 2005).

The SMEAR (Stations for Measuring the forest Ecosystem–Atmosphere Relationships) stations nowadays include three stations (SMEAR I, Värriö, since 1991; SMEAR II, Hyytiälä, since 1994, Urban SMEAR III, Kumpula, Helsinki, since 2004). Each of them has a comprehensive scientific program to investigate aerosol and trace gas concentrations, biosphere–atmosphere interactions, aerosol formation and growth, as well as the biogenic background for processes leading to aerosol formation (Kulmala *et al.* 2001, Järvi *et al.* 2009).

During the past decades we have grown to understand that no discipline of science alone can solve, or even explain, global environmental problems (e.g. climate change, or effect of pollution on ecosystems and human health). This requires multidisciplinary approach and collaboration. In order to feed this need, many cross-scientific and multi-disciplinary joint research programs in the field of environmental and atmospheric sciences have been started in Finland and other Nordic countries (e.g., ABS; Atmosphere–Biosphere Studies and CBACCI; Biosphere–Carbon–Aerosol–Cloud–Climate Interactions). A special feature of these programs was to bring together researchers from different fields and to motivate them to work together in solving a common task.

Smart-SMEAR provides means for easy hands-on and insights to a complicated dataset. The database contains several measured and modelled quantities, each requiring special tools and knowledge to work with. The web-based tool presented here collects and processes all the data, so that in practice the users do not have to know anything about data treatment. This helps to explore the data, and to see relations between and behaviour of different quantities without losing time in collecting data, pre-treating it and learning special plotting tools (e.g. plotting maps and surface plots). However, the tool is also good for brief checks and for exploration of interesting special cases. Smart-SMEAR is a tool for data mining and a simple way to work together with air mass back-trajectories and measured air quality and meteorological parameters.

The aim of Smart-SMEAR is to see as many different data as possible at the same time, so that one can detect causalities directly from graphs. Above all, this tool is very useful for studying connections between air mass movements and observations on a stationary measurement site. Long-range transport of pollutants, effects of meteorology during the air mass travel, effects of air mass origin, and reasons for new particle formation or pollutant episodes are examples of problems that this tool can help to solve. Smart-SMEAR has already been used in three winter schools ('Physics and chemistry of air pollution and their effects' in 2007, 2008, 2009), twice in a university course ('Statistical analysis of observations using MATLAB' in 2007 and 'Statistical analysis of environmental field observations' in 2008) and in an academic work that resulted in a publication (Buenrostro Mazon *et al.* 2009).

In this paper, we describe the SMEAR II station and sampling facilities, present the data in SMEAR database, and finally describe the technical details and usage of web tools Smart-SMEAR and smart-Search. We also present three case studies to show how the data can be effectively presented, and how to answer related scientific questions. Since Smart-SMEAR is an on-line tool, resolution of graphics it produces is too low for print purposes. Therefore, the reader is encouraged to follow the case studies directly at http://www.atm.helsinki.fi/smartSMEAR/.

Methods

SMEAR II station

Data in the database were collected at the SMEAR II station (Station for Measuring Forest Ecosystem–Atmosphere Relations) in Hyytiälä, Finland (61°50´51´´N, 24°17´41´´E, 181 m a.s.l.). SMEAR II is a unique field measurement station designed for continuous measurements of phenomena in which physical, chemical and biological processes interact. At the station, comprehensive long-term studies are carried out by co-operating aerosol and environmental physicists/atmospheric chemists and forest ecologists. Furthermore, the station also operates automatically during winter, monitoring non-growing season processes. The facility is planned and implemented to determine material and energy flows in the atmosphere–vegetation–soil continuum at different temporal and spatial scales. The station is equipped with state of the art instrumentation for measurements of aerosol microphysics, atmospheric chemistry, micrometeorology, gas exchange and water balance of trees and soil processes (Hari and Kulmala 2005).

The station can be divided into five operational blocks: (1) atmospheric measurements (profiles, radiation and surface fluxes) accomplished using of a 72-m-high tower, (2) radiation and surface flux measurements using a 20-m-high tower, (3) tree measurements (shoot scale fluxes, sap flow and stem/xylem diameter changes) performed using of a 15-m-high tower, (4) soil measurements (profiles and fluxes) carried out on two catchment areas (watershed with weir), and (5) aerosol measurements (size distribution, physical and chemical properties) from 9 m above the ground.

Database

Currently, the database contains about 170 variables that can be divided into seven logical blocks: (1) gases: NO, NO_x, SO_2, O_3, H_2O, CO_2 and CO for all six sampling heights, (2) meteorological variables: temperature, pressure, RH (relative humidity), wind speed and direction, precipitation and visibility, (3) radiation: global radiation, diffuse global radiation, direct global radiation (global radiation – diffuse global radiation), reflected global radiation, net radiation, PAR (photosynthetically active radiation), reflected PAR, UVA and UVB radiation, (4) aerosols: number concentration and size-distributions (3–1000 nm, Differential Mobility Particle Sizer), black carbon concentration (7-wavelength aethalometer), optical properties (3-wavelength nephalometer), mass concentrations of particle smaller than 1, 2.5 and 10 μm in diameter (PM1, PM2.5 and PM10, impactor), (5) new-particle formation classification according Dal Maso *et al*. (2005), (6) back-trajectories calculated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (http://www.arl.noaa.gov/ready/hysplit4.html) for three arriving heights and four days back in time (together with trajectory coordinates, also the meteorology along trajectory has been saved to database), and (7) emission point sources from the European Pollutant Emission Register (http://eper.eea.europa.eu/eper/; 10000 facilities).

The data are saved in the MySQL database that is updated every two hours for meteorological, gas phase and some aerosol measurements. However, near on-line data are not quality controlled. The quality control is made manually every half a year and the database is updated with the verified data. The air mass back-trajectories are also updated every half a year.

Web interface

Smart-SMEAR (http://www.atm.helsinki.fi/smart SMEAR/) is a MySQL database and php-based dynamic web page. The graphs are created with JPGraph (PHP Graph Creating Library, http://www.aditus.nu/jpgraph/). The maps are made using Google Maps API (http://code.google.com/apis/maps/).

The value of the tool is its simplicity. To some extent it is even oversimplified and many variables and ways to explore the data have been left out. But they are left out on purpose! Since the idea is to give a quick first look and overview of only some selected values (slightly more than 20 variables from only one measuring height).

The only selection that the user can make is the date, time and length; and arriving height of back-trajectories. Everything else is locked and predefined. By this way the users are not distracted by the complexity of the data and can really focus only on the phenomena in question.

The user interface consists of daily plots of approximately 20 variables, automatically adjustable map for trajectories and aerosol size distribution. Additionally, the "Emissions" panel provides the user with a fully functional Google map interface with emission point sources that air mass trajectories are crossing. The Google map features zooming and satellite imagery. On the emissions panel, the user can also select which emitters are shown on the map, the options being All (all emitters included), CH_4, CO, CO_2, NH_3, NMVOC, NO_x, SO_x and PM10. Only those facilities that are in the area currently visible and are on the way of air mass trajectories are shown.

Smart-Search

Smart-search is an interface (http://www.atm.helsinki.fi/smartSMEAR/download) for downloading data from the SMEAR database. As mentioned above, in Smart-SMEAR some of the data are not shown, but in Smart-Search all the data from the database are available for download. Main additions to the downloadable data compared with the data in Smart-SMEAR are six sampling heights on the measurement tower, more meteorological parameters, precipitation, visibility and WMO SYNOP weather codes. Also full spectra of solar and global, direct and reflected radiation are available. Aerosol data are from the aethalometer (7-wavelength), impactor (PM1, PM2.5, PM10), the APS (Aerosol Particle Sizer, TSI) and the Differential Mobility Particle Sizer (Aalto *et al*. 2001) measurements.

Users of Smart-Search start by selecting the time interval of interest. The interface allows users to perform some time-averaging before the data are downloaded. Currently options for this are raw, 1, 3, 6, 8, 12, 24 hours, week, month, year and cyclic averages (hourly, week daily and monthly). When anything else than raw is selected, standard deviation is automatically added to the output. Raw is used as the default. Here "raw" means the sampling interval of a variable in the database, not the original acquisition interval. For example, all gas measurements are saved in the database as 30-minute averages of 1-min data.

The AJAX (Asynchronous JavaScript And XML) technology allows one to build web services with instant feedback, without a need for reloading the entire web page. Smart-Search uses the AJAX technology to communicate with the database even before the user has made the final decision to download any data. When the date and averaging time have been selected, the user chooses the type of data of interest. The options are gases, meteorological, radiation and aerosol data. When selecting the data type, Smart-Search connects to the database, checks the quality of the data and returns a table with downloadable variables and percentages of available data during the selected period. Result will also be colour coded, green meaning good-quality data (< 30% data missing), gray medium-quality data (< 70% data missing) and red low-quality data (> 70% data missing).

One would think that the quality check before downloading is time consuming because the software has to go through all the data. Luckily, the SMEAR database is optimized and the quality check is done completely in the MySQL database, so no data transfer is involved. This makes the process fairly fast and, for example, a quality check for one year of gas data takes about one second and correspondingly for five years about three seconds.

There are several advantages in the current approach. The data quality check is made on the server side, so the user's computer is not involved and overall performance is less affected by the speed of the user's computer. The data quality becomes a selection criterion and this is an important feature from the data analysis point of view. Now the user is prompted to acknowledge that some data are missing and, depending on missing data treatment methods available, the user can choose a different period or additional variables that would help filling the data gap (Junninen *et al*. 2004).

Downloadable data are available in CSV and tab-separated file formats. A CSV file is useful when data are imported to MS Excel or Igor Pro. A tab-separated file is useful when importing for example to Matlab.

Usage of Smart-SMEAR

The data visualizer consists of two parts: a selection panel and graphs. In the selection panel, days with new-particle formation are presented on a red-coloured background and non-events days on blue-coloured background (Fig. 1). For plotting, the date, trajectory arriving-height and length are selected. Graphs are generated automatically every time one of the selection criteria is changed.

The main view is the map with back-trajectories for a whole day, representing 24 trajectories, one for each hour. Trajectories with an arriving time from 00:00 to 12:00 are blue, those with an arriving time from 13:00 to 23:00 are red and the one that is selected from the hour panel is green. The altitudes of air masses along the trajectories are shown below the map (Fig. 1).

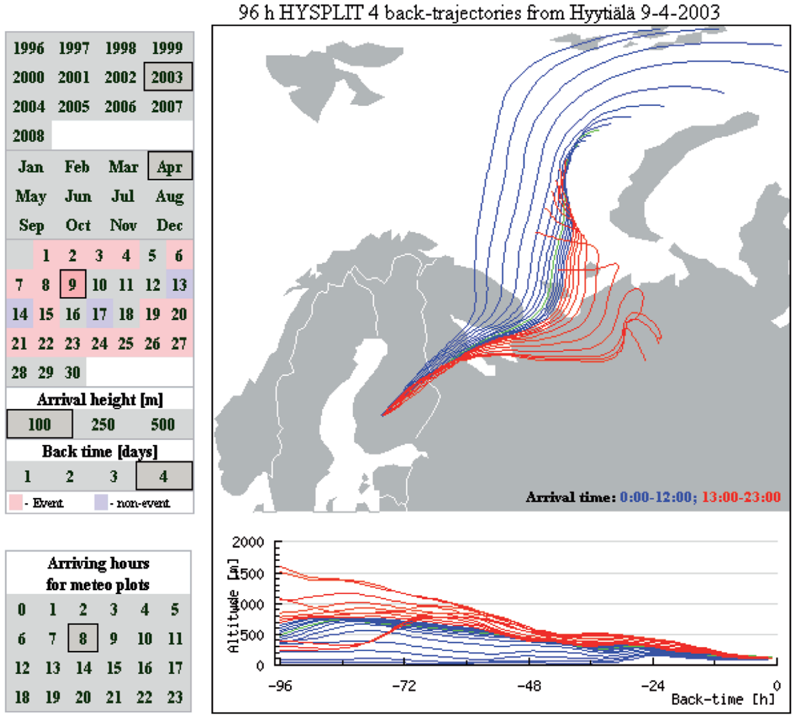

Fig. 1. Screenshot presenting the selection panel and the back-trajectories map.

Figure 2 presents meteorological parameters along trajectories for the selected hour. Available variables are the air temperature, potential temperature, pressure, relative and absolute humidities, mixing height and rainfall.

The measured meteorological and air-quality parameters are plotted on the right-hand side of the screen (Fig. 3). The data are from the SMEAR II measurement towers. The measurements of gas concentrations are conducted at six measurement heights, but for clarity only one is presented here (67.2 m and 16.7 m for CO). The data are plotted for a whole selected day, and the selected hour is indicated by a green vertical line. The variables made available are global radiation, pressure, temperature, wind speed, relative humidity, CO_2, NO, NO_x, O_3, SO_2, CO and H_2O.

Examples of usage

Case study 1: a nucleation event day

In new-particle formation, gas phase precursors nucleate and grow to large sizes (Kulmala 2003, Kulmala *et al*. 2004a). A new-particle formation event (22 April 2006) is clearly visible in the aerosol size distributions when plotted as an image (surface) plot (*see* upper right corner in Fig. 4). The image plot is a three-dimensional plot with time in *x*-axis, aerosol size in *y*-axis, and logarithm of concentration represented by colour, red being the high and blue the low concentration. New particles are formed before noon and are growing slowly (in Hyytiälä about 3 nm h^{-1}) to larger sizes. The growth pattern is not easily observable when the size distribution is from a specific time or when only time series of specific size ranges are plotted. Smart-SMEAR makes by default an image plot, together with a size distribution of a selected hour and time series of the total number concentration during that day.

In Fig. 4, the aerosol growth pattern is clearly visible in the plot in the top right corner. The aerosol size distribution plot (11:00) shows a clear new mode at 10 nm, and the particle number concentration is increasing during the afternoon due to new-particle formation.

New-particle formation events are associated with intensive solar radiation, often also with arctic air masses and low concentrations

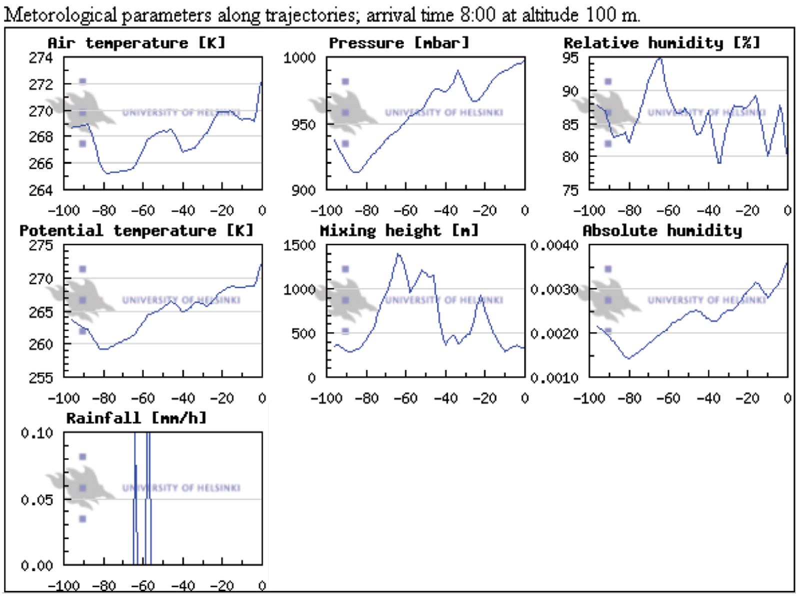

Fig. 2. Screenshot presenting meteorological parameters along trajectories.

aerosol particles larger than 100 nm in diameter. These observations are easily visible in Smart-SMEAR.

Case study 2: a pollution day

Short-lived local pollution plumes are detected in Hyytiälä when arriving air masses have crossed over the city of Tampere or close-by industrial facilities (< 200 km). The pollution plumes are characterised by simultaneous elevation of particle, CO_2, SO_2, and NO_x concentrations, the elevated SO_2 concentration being associated only with industrial emissions. Oxidation reactions of NO_2 by O_3 can be seen by depletion of O_3 during nighttime pollution plumes. When solar radiation is available, the oxidation of CO and VOC by OH radical produces O_3 so that plumes have high ozone concentrations.

Figure 5 illustrates an example of a pollution event when metal industry emissions in Harjavalta about 80 km away from Hyytiälä were clearly visible in gas and aerosol concentrations. The plume arrived at Hyytiälä at around 18:00 on 13 December 2007 and lasted for about four hours. During that time, the concentrations of CO_2, CO, SO_2, NO_x and particles were elevated while of that of O_3 decreased.

Under sunlit conditions inside plumes, oxidation of VOC, CO and NO produces ozone. This, however, was not the case here. In December, a day is very short at the latitude of Hyytiälä (61.85°), and the sun sets already at 15:00. High concentrations of NO_2 led to the depletion of ozone through NO_2 reaction with O_3 which produced the highly reactive nitrate radical. The reaction could be verified by the reaction stoichiometry. The increase in the NO_x concentration, as compared with that one hour before the plume, was roughly 2.4×10^{11} molecules cm^{-3} (9 ppb) and the decrease of O_3 was 2.9×10^{11} molecules cm^{-3} (11 ppp). The ratio of the decrease in O_3 concentration to the increase of NO_x concentration was 1.2, being very close to the theoretical value of 1.

When looking at the trajectories on the emission map in Smart-SMEAR, it is obvious that this plume was caused by metal industry in Harjavalta. Trajectories circulated over the industrial area for several hours at the altitude of 150 m. The facility has annual NO_x emissions of 25 tonnes and SO_x emissions of 2850 tonnes (European Pollution Emission Registery, http://eper.ec.europa.eu/). Air masses that are associated with the plume have minimal mixing with free troposphere and are not diluted since they stay below mixing height and very close to the surface (< 150 m) during all the time of travel (20 hours).

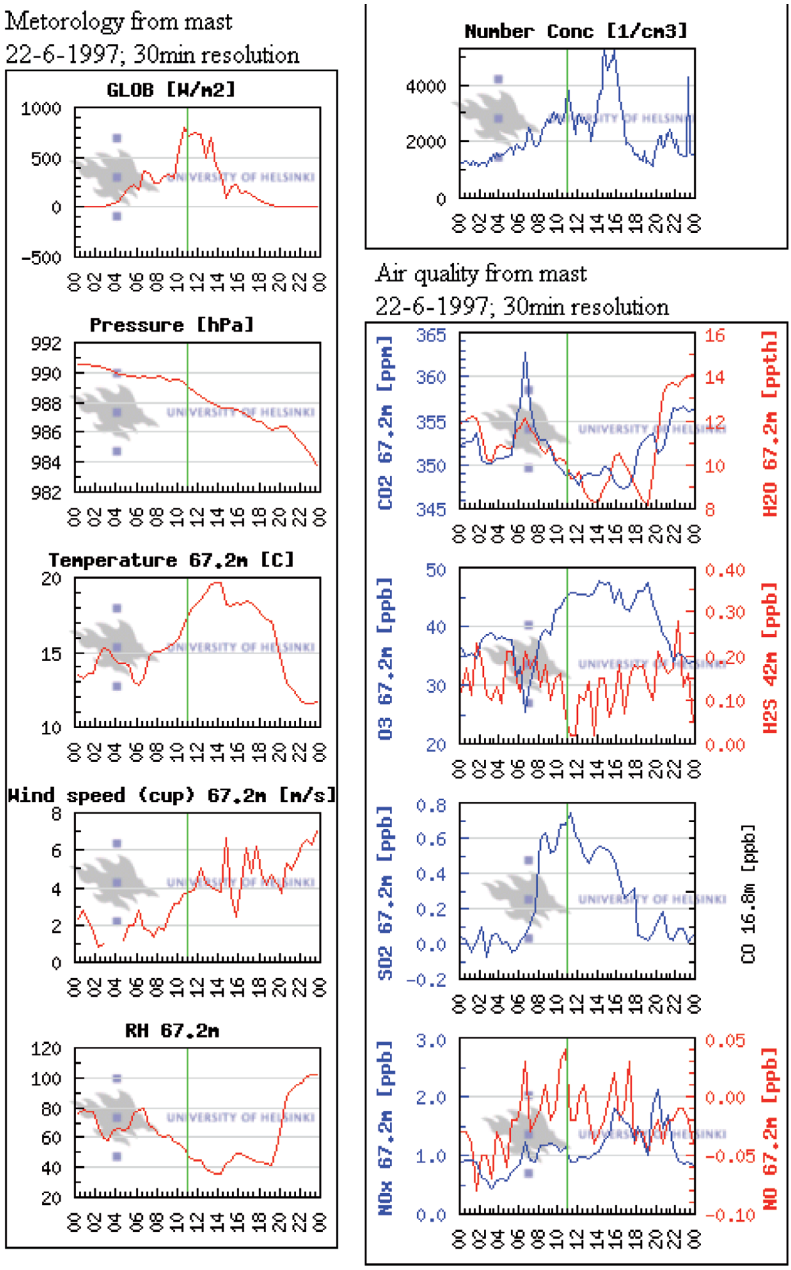

Fig. 3. Screenshot presenting aerosol data, meteorological and gas data.

Case study 3: long-range-transport episode

During long-range transport both direct emission and photochemical processes are observable from measurements. Long-range-transport episodes are characterised by high concentrations of accumulation size particles (> 100 nm) as well as high O_3, CO, CO_2, NO_x and SO_2 concentrations. The episode is strongest when air mass movements are slow and air travels at low altitudes which minimizes vertical mixing and dilution.

27 April 2006 is an example of a day when long-range transport was superimposed with local pollution from industry and power plants. The episode lasted for five consecutive days, and during that time the wind direction remained constant, air masses were travelling below mixing

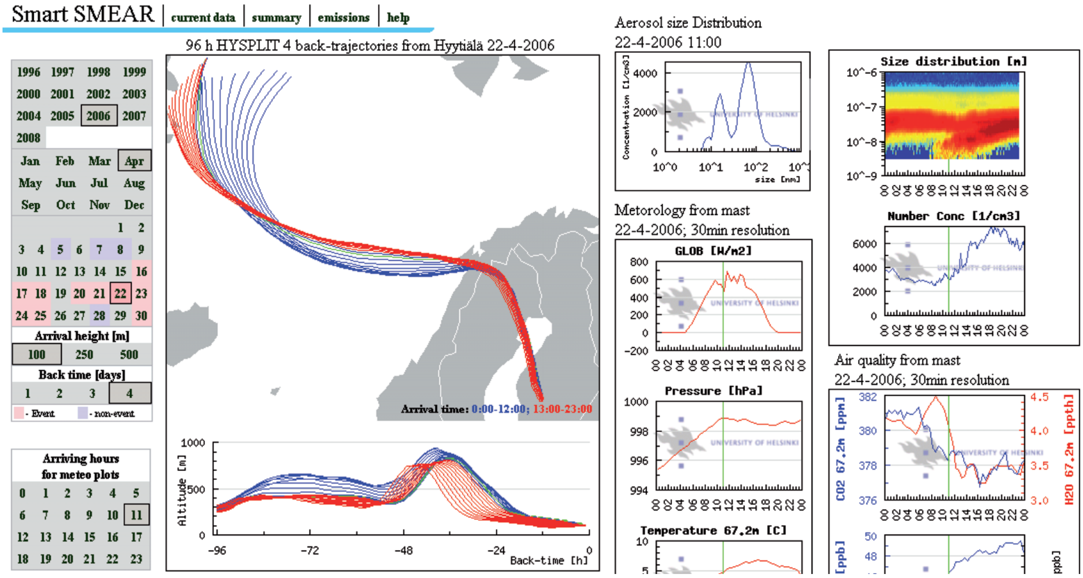

Fig. 4. Screenshot presenting a new-particle formation day, 22 April 2006. Note that the screen shot is not of a full screen.

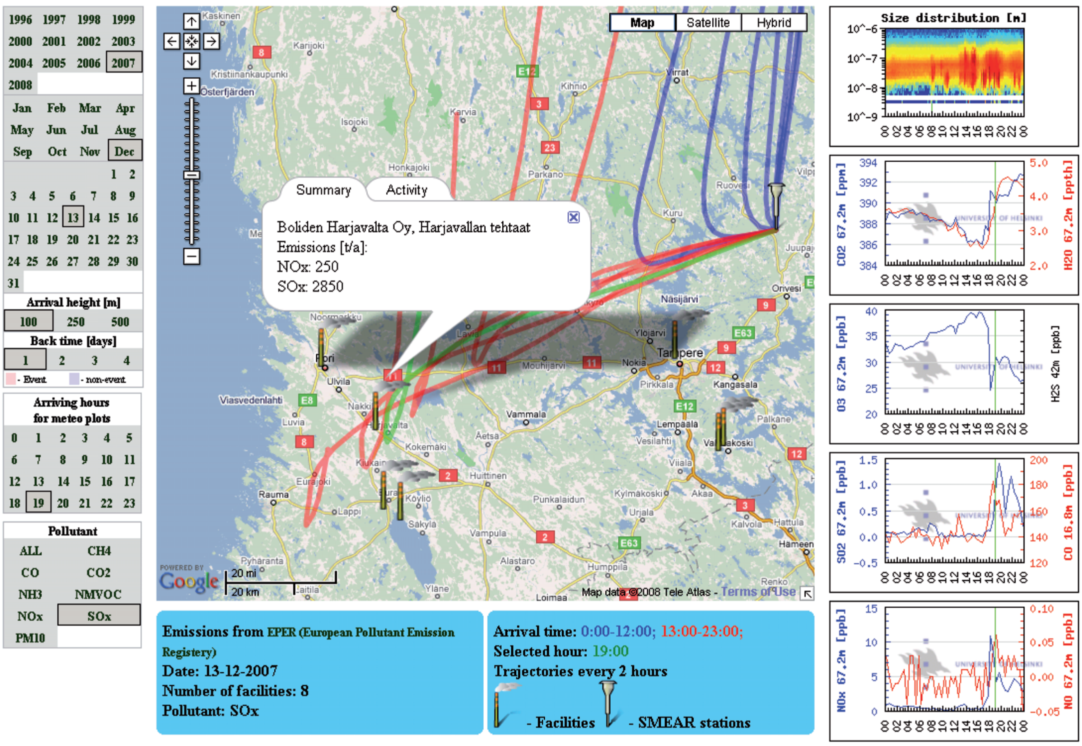

Fig. 5. Screenshot presenting a pollution event in Hyytiälä on 13 December 2007, only SO_x polluters are shown.

height and cloud cover was minimal. These conditions are optimal for the photochemical production of O_3, and concentrations were indeed the highest of that year. The daytime O_3 concentration was 75–85 ppb, dropping to about 50 ppb at nighttime (Fig. 6). In comparison, a few days earlier when the air masses came from the Arctic sea, the daytime O_3 concentration was < 50 ppb.

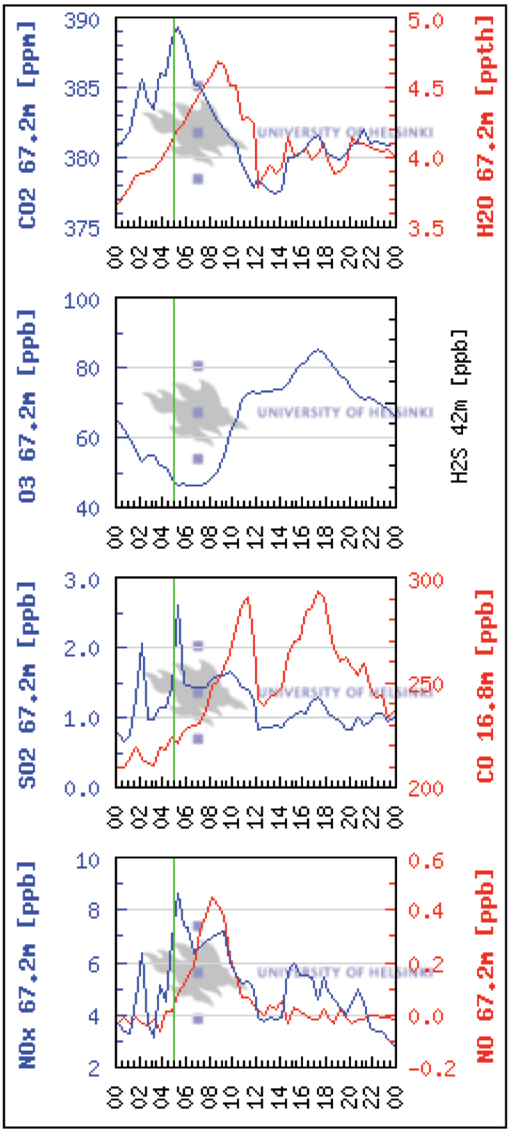

Fig. 6. Screenshot presenting gas concentrations measured at 67.2-m height on 27 April 2006.

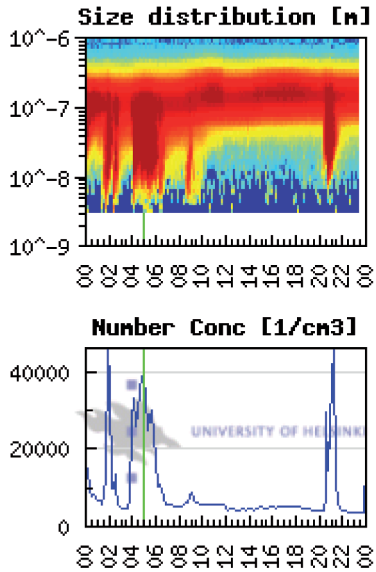

Fig. 7. Screenshot presenting aerosol size distribution and total number concentration on 27 April 2006.

The episode was very clearly visible also in the aerosol size distribution data, in which the total number concentration of > 100 nm particles was about 3000 cm^{-3}, being ten times larger than the corresponding concentration one day before the episode (330 particles cm^{-3}) (Fig. 7). The emission map in Smart-SMEAR indicates that the air pollution originated from St. Petersburg, Russia.

On 27 April 2006 also three local pollution episodes occurred. They originated from Finnish paper mills and power plants. Episodes arrived at Hyytiälä at 02:00, 05:00, and 21:00. The episodes were best visible in total particle number concentrations (Fig. 7), and also in SO_2 concentrations (Fig. 6). The first two episodes took place before the sunrise and had sharp peaks in SO_2 and particle concentrations. These two episodes were most likely caused by emissions from a power plant in Lahti that has an emission index 1900 tonnes $year^{-1}$ for SO_x (Fig. 8). The third episode taking place around 21:00 was caused by the Stora Enso industrial plant for pulp located in Heinola. Both factories are located about 100 km away from Hyytiälä. During the following day, the Saint Petersburg pollution episode was continuing but back trajectories moved slightly north from the area of Lahti and Heinola and there were no sharp peaks in particle concentrations. However, there was one SO_2 episode that could be pinpointed to UPM-Kymmene Oyj paper mill in Lappeenranta (data not shown).

Conclusions

The SMEAR II facility offers the capability to study cross-disciplinary environmental problems under the conditions of the natural boreal pine

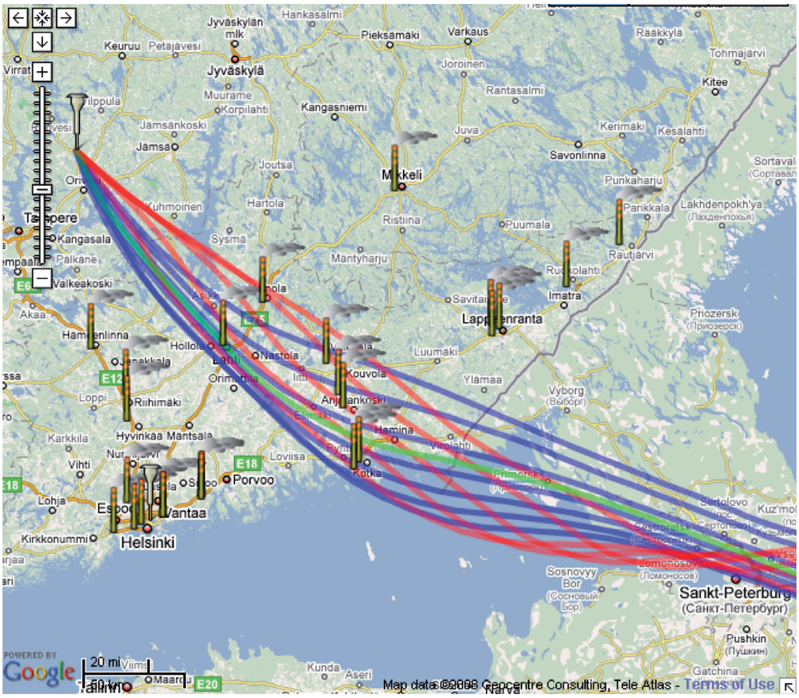

Fig. 8. Screenshot presenting air mass 48-hour back trajectories. Blue lines are before noon trajectories, red lines afternoon trajectories and green line is the trajectory arriving at Hyytiälä at 05:00.

forest. The combination of the SMEAR II setup and instruments for forest–atmosphere interactions with the holistic view of aerosol particles, atmospheric chemistry, fluxes and tree and soil process is unique in the world.

The recent development of comprehensive stations has given us huge amounts of continuous data (Kulmala *et al*. 2008). In order to be able to work with these datasets, improved tools are needed. Smart-SMEAR is an answer to this need. In practical use, Smart-SMEAR has shown to be effective in giving basis for case studies and look for larger datasets.

Smart-SMEAR can be used for rapid visualisation of daily, weekly, monthly and annual datasets. In order to be able to refine proper research questions, an overview of the data is needed. Besides, it has also been used for educational purposes and knowledge transfer.

In future, Smart-SMEAR will be further developed by including more data into it and by expanding to other two SMEAR stations. At first, the aerosol optics and aerosol chemistry data will be included as well as size and number concentrations of coarse particles and cloud condensation nuclei.

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