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Station for Measuring Ecosystem–Atmosphere Relations (SMEAR II)

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Here we present the ongoing SMEAR (Station for Measuring Forest Ecosystem–Atmosphere Relations) research program and also related future views. The main idea of SMEAR-type infrastructures is continuous, comprehensive measurements of fluxes, storages and concentrations in the land ecosystem–atmosphere continuum. The major coupling mechanisms between atmosphere and land surface are the fluxes of energy, momentum, water, carbon dioxide, atmospheric trace gases and atmospheric aerosols. Understanding of couplings and feedbacks is the basis for the prediction of changes in the system formed by atmosphere, vegetation and soil. A better quantification of the agents that cause climate change, as well as the emissions and removals of species, will provide more accurate projections of future atmospheric composition and hence climate.

Background

Utilization of fossil fuels, destruction of forest to get land for cultivation of crops and emissions of several gases by industrial processes have changed and will change the chemical properties of the atmosphere. The Intergovernmental Panel on Climate Change gave, in their report (IPCC 2001), an estimation of the global and annually averaged radiative forcing for direct and indirect contributions from both greenhouse gases and aerosols, along with natural changes associated with the solar energy output. Forests respond to changes in the atmosphere and may slow down the accumulation of CO_2 in the atmosphere (Law *et al*. 2003). Therefore we need more understanding on the responses in the forest functions caused by climate change.

The land surface–atmosphere interface is particularly crucial for the functioning of the Earth system through interactions via mass, energy and momentum fluxes, as well as through the biogeochemical cycles. At the same time, the climate variability and atmospheric processes, such as transport and deposition of chemicals, are major constraints on biogeochemical cycles, "natural" as well as anthropogenic ones. Human-driven changes in the land cover are likely to result in a significant regional and global climate change. In turn, the climate change affects terrestrial ecosystems at all spatial and temporal scales, maybe even to the extent of destabilizing large regions. The response of forests on climate change is versatile. The carbon flow generated by photosynthesis is the source of raw material for metabolism and growth. An increasing atmospheric CO_2 concentration accelerates photosynthesis and increases the concentrations of carbohydrates available for tree metabolism (Farquhar and Caemmerer 1982). Emissions of volatile hydrocarbons and root exudates will evidently also increase due to the excess of carbohydrates. The expected temperature rise will prolong the active period of plants and accelerate decomposition in the soil. The climate change will thus have a strong influence on forest ecosystems and the changes in the forests are reflected in the atmosphere.

Forest ecosystem and atmosphere form a complex system which has to be structured before a proper monitoring system can be planned and implemented. Trees are the functional units in a forest stand. They photosynthesize with the needles, take up water and nutrients from the soil, transport water in the woody components, form litter and emit volatile organic vapors. Microbes break down the litter in the soil, releasing CO_2 and other organic vapors into the air. Organic vapors in the atmosphere participate into chemical reactions as well as into aerosol formation and growth. Solar radiation is the primary source of energy for several processes, such as photosynthesis, turbulent mixing, snow melting and many chemical reactions in the atmosphere.

The processes and properties in a forest and atmosphere are strongly connected with each other. For example, the atmospheric CO_2 concentration influences photosynthesis and VOC emissions by trees affect aerosol formation. Simultaneous measurements of several phenomena in a forest ecosystem enables the combination of different processes and analysis of connections between the components of the system, including: (i) carbon fluxes which connect the atmosphere, trees and forest soil with each other, (ii) volatile carbon compounds emitted by trees or forest soil, being important to the formation of aerosol particles, and (iii) rainfall, transpiration, evaporation and run off which together connect the atmosphere, trees and soil.

Recently, the rapid development of measuring techniques has enabled versatile field measurements. New trace compounds can be measured under field conditions, the accuracy and precision of measurements are increasing, and the required response time is decreasing. For example, more than ten gases can be monitored with the present instrumentation using a chamber technique, which requires a response time of a few minutes. In addition, large measuring systems can be automated with digital techniques providing easy and useful data management.

In the present feature paper we describe the ongoing SMEAR research program which was originally planned at the beginning of 1990. Although there have been several improvements during the years, the basic idea of comprehensive, continuous measurements is still alive. In this paper we also present a few examples of the numerous results obtained from the SMEAR II station as well as views for the future.

SMEAR II measuring station

The SMEAR II (Station for Measuring Forest Ecosystem–Atmosphere Relations) station is located in a rather homogenous Scots pine (*Pinus sylvestris*) stand on a flat terrain at Hyytiälä Forestry Field Station of the University of Helsinki (61°51´N, 24°17´E, 181 m above sea level) 220 km North-West from Helsinki. The managed stand was established in 1962 by sowing after the area had first been treated with prescribed burning and light soil preparation. However, the intensive forestry in the stand and in the stands nearby generates disturbances in material fluxes. The station represents a boreal coniferous forest that covers 8% of the Earth's surface and stores about 10% of the total carbon in the terrestrial ecosystem. The largest city near the SMEAR II station is Tampere, located about 60 km from the measurement site and having about 200 000 inhabitants. For more details *see* e.g. Vesala *et al*. (1998).

The atmosphere below the free troposphere can be described by two compartments: the mixed boundary layer and the air inside the canopy. These two layers interact with each other by the flows of material, energy and momentum. Trees and other vegetation take up carbon from the atmosphere and circulate it back to there or feed the carbon pool in the soil. Aerosols, reactive gases and inert gases can be found in the mixed boundary layer, inside canopy and soil. Biological, physical, meteorological and chemical processes generate fluxes between the components and within them. The main pools and flows are outlined in Fig. 1. The SMEAR II measuring station was planned and implemented

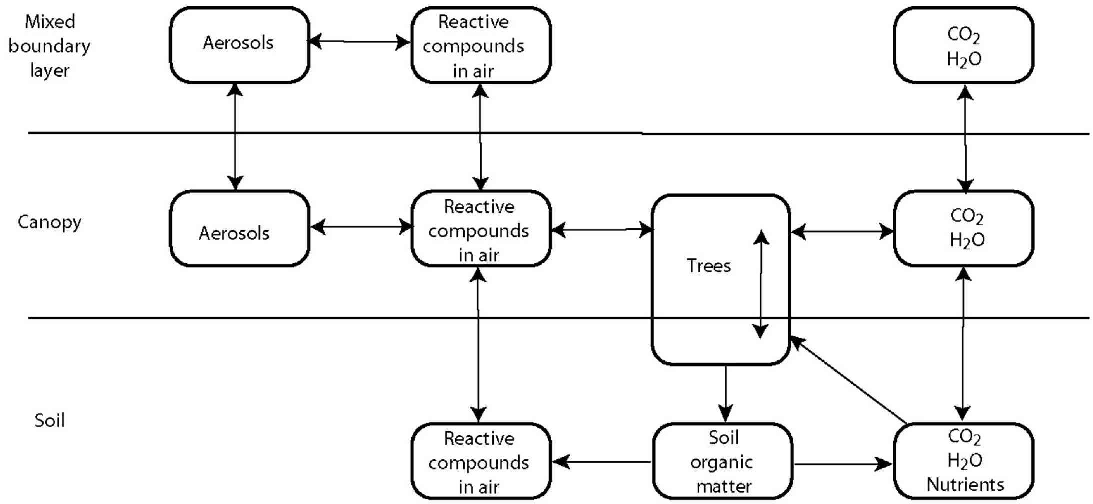

Fig. 1. Pools and main fluxes in soil–forest–atmosphere continuum. Boxes refer to pool size and arrows to flows.

(i) to monitor the flows presented in Fig. 1, (ii) to determine relationships between the processes generating the fluxes and environment, and (iii) to understand those processes.

Several different approaches have to be applied to monitor the fluxes and factors affecting the fluxes outlined in Fig. 1. Four methods are used to determine the material and energy flows. The surface between the trees and atmosphere, or between the soil and atmosphere, can be closed in a chamber and the flux is determined from the mass balance of the chamber. The fluxes above the canopy or soil surface are derived from simultaneous measurements of a three-dimensional wind speed and either the concentration of the gas in consideration or temperature. Electric sensors are available to measure radiation fluxes. An indirect method to determine the flux is based on the changes in the concentrations of compounds and their differences.

The rates of the processes generating the fluxes vary considerably over different time scales. An annual cycle can be seen in all processes and a daily pattern is also clear. The movement of clouds in the sky generates strong variations in irradiance and less pronounced variations in temperature, which is clearly reflected in the processes. The time scale of the movement of individual clouds is of the order of one minute or less while the time scale of turbulence is < 100 ms.

Variations in solar radiation, temperature, concentrations and biological activity generate changes in the rates of the processes. If the duration of the measurement of a flux is so long that the factors influencing the rate of the process generating the flux change during the measurement, the relationship between the flux and explaining factors is smeared, which disturbs the data analysis. Thus the duration of the measurement in SMEAR II has been taken so short that the explaining factors remain stable.

Some factors are changing more rapidly, being therefore less stable than other factors. For example irradiance, especially inside the canopy, has a clear spatial and temporal character. If the response area of a monitoring device is so large that it includes a considerable spatial variation in irradiance, the relationship between the rate of the process to be measured and irradiance is smeared by the spatial integration in the measuring system. Therefore we have chosen so small flux sensors that there are only minimal spatial variations in the light intensity within the sensors.

When monitoring concentrations or pool size, we have three different goals: (i) to describe the pools, (ii) to provide explaining factors for the analysis of fluxes, and (iii) to determine fluxes from the changes in the pool size. The daily patterns of the pool sizes are of primary interest in the description of the forest ecosystem.

A reliable detection of daily pattern of often noisy measurements requires over 20 observations during each day for a proper description of the system. If the concentration or pool size is used as an explaining factor in the analysis of processes, the measurement should be synchronized with the corresponding flux measurement. If the concentration or pool size measurement is used to determine the flux, the concentration and other factors affecting the rate of the process generating the flux must not change considerably during the interval between successive measurements. Thus we have selected the monitoring system to operate at a time scale of one minute. On the other hand, soil processes react mainly to the temperature that is rather stable in the soil, thus hourly measurements provide the necessary information.

The above analysis results in the requirement of a rather high daily number of measurements and rapid and small sensors. When automated and digitalized systems are used, the size of data files should be so small that the analysis of the measurements is not too tedious. The limitation of data storing capacity is not any more a relevant argument. Thus technical reasons do not limit the measuring intensity used at SMEAR II.

The SMEAR II station includes four main components: (i) an instrumented 73-m-tall mast, (ii) systems to monitor aerosols, (iii) instrumentation to monitor tree functions, and (iv) two instrumented mini catchments. The mast monitors CO_2, H_2O, CO, O_3, SO_2, NO and NO_2 concentrations, temperature and wind speed profiles, the properties of solar and thermal radiation of the stand, and the fluxes of CO_2, H_2O, O_3, aerosols and several volatile organic compounds between the canopy and atmosphere. The mast measurements are usually reported as half-hour means. For more details *see* also Vesala *et al.* (1998) and Kulmala *et al.* (2001b).

Aerosol and ion size distributions are measured in order to be able to detect ion, cluster and aerosol dynamics. Our focus in aerosol dynamics is the formation and subsequent growth of fresh atmospheric aerosols. Also dry deposition and wet scavenging of aerosols can be investigated. With size distribution measurements, and using the growth rate of nucleation mode aerosols as well as condensation and coagulations sinks, we can estimate the concentrations and source rates of condensable vapours (Kulmala *et al.* 2001a). The composition of aerosol mass is also determined. The relation between aerosol dynamics and photochemistry can be investigated, for example, by analyzing radiation fields and OH concentrations. Recently Boy *et al.* (2005) were able to find a closure between the calculated and measured sulfuric acid concentrations. The calculated concentrations were based on trace gas and aerosol size distribution measurements performed at the SMEAR II station.

A chamber technique is used to monitor tree processes generating the fluxes between trees or soil and atmosphere. The most relevant processes include photosynthesis, respiration, transpiration, NO_x emissions, NO_x deposition and emissions of volatile organic compounds. Depending on the focus of the measurements, several different versions of the chamber technique are used, such as for needle gas exchange (Hari *et al.* 1999, Altimir *et al.* 2002) and for stem CO_2 and soil CO_2 efflux (Pumpanen *et al.* 2001). Each method uses its own modification of the basic chamber structure. By locating most of the chambers on top branches inside the canopy, disturbances due to the temporal and spatial variations in photosynthetically active radiation is reduced.

The fluxes between the canopy air space and atmosphere are monitored with micrometeorological methods. In the eddy-covariance method a three-dimensional wind speed and the concentrations of CO_2, H_2O, O_3 and aerosols are measured at the frequency of 10 Hz or higher (e.g. Rannik *et al.* 2003). Thus fluxes of the above mentioned gases and aerosols as well as heat and momentum fluxes can be determined. In the relaxed-eddy-covariance method (e.g. Gaman *et al.* 2004) three-dimensional wind measurements control the sampling of air into two containers in such a way that during the upward movement the air is collected in the upward bottle and during its downward movement into the downward bottle. The concentrations of the bottles are measured with a regular time interval. The total flux between the canopy space and atmosphere is obtained in both methods. The SMEAR II station has been part of EUROFLUX and FLUXNET for years (*see* e.g. Valentini *et al.* 2000).

The fluxes between the soil and atmosphere, as well as between the soil and canopy are also important. At the SMEAR II station the thickness of the soil on the bedrock is very low, only 5–150 cm, due to the ice age. There are two mini catchments (900 and 300 m^2) close to the measuring cottage. These catchments are closed with a dam, and the run off from the area is monitored. The leakage of substances with the run off is monitored by taking samples for chemical analysis. The soil water content and tension, CO_2 and temperature profiles are monitored.

Solar radiation is the source of energy for several processes in trees and atmosphere. This is why irradiance, diffuse irradiance, photosynthetically active radiation and radiation balance are monitored above the canopy. The light distributions within the canopy are monitored with 200 sensors (Palva *et al*. 2001). The rainfall is monitored above and below the canopy. The diameters of the trees are measured on an annual basis. The shoot elongation is, however, monitored daily in early summer. The litter fall on the soil is monitored in a two-week interval. On the other hand, stem diameter changes are monitored both above and under the bark continuously with the precision higher than 1 μm. The water flow in the wood and in the phloem is calculated from the diameter changes (Perämäki *et al*. 2001).

One of the basic principles from the very beginning has been the utilization of continuous measurements. Therefore the system operates all year around, and only components that may be damaged by freezing water are turned off during winter. In addition, the growth of the trees around the measuring station has been measured retrospectively to the age of three years.

Examples of the utilization of SMEAR II data

The use of comprehensive, continuous observations made at the SMEAR II station in Hyytiälä is a challenge. Although we have managed to analyze many good examples of processes related to forest ecology, boundary layer meteorology, forest–atmosphere interaction as well as aerosol formation and growth, there are still plenty of data to analyze, processes to be understood and

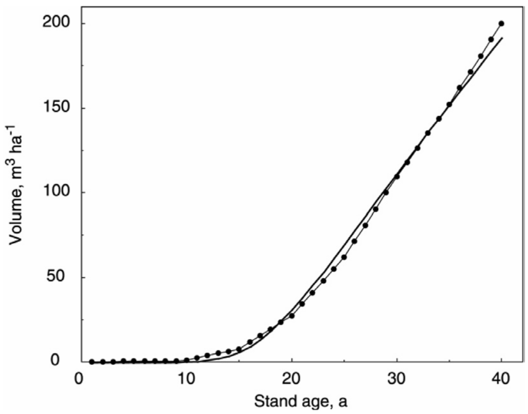

Fig. 2. Development of measured (dots) and modeled (line) volume in the stand around the measuring station SMEAR II.

interactions and feedbacks to be found. Here we present only some examples of our ongoing research.

The role of forest ecosystems in the carbon sequestration is an open question. Evidently most forests bind carbon, but to what extent they do it is not known. All relevant carbon flows within the ecosystem and between the ecosystem and its surroundings are monitored at SMEAR II. These measurements are an important source of information in forming a picture of the forest growth and development.

A dynamic model of the growth and development of a forest ecosystem, called MicroForest, describing the flows of carbon and nitrogen compounds in forest ecosystem, has been constructed. It connects the atmosphere and trees, describes processes within trees, deals with litter formation on the soil and finally the release of CO_2 by microbes. The basic underlying thinking of the model MicroForest is the same as that of the planning of SMEAR II. This is why the measurements at SMEAR II are valuable in the development of the MicroForest. The accumulation of carbon in the trees within the distance of 100 m in the stand can be derived rather satisfactorily starting from photosynthesis (Fig. 2).

The possible connections between carbon balance and aerosol–cloud–climate interactions are of significance in the studies of global climate. An interesting link and potentially important feedback between forest ecosystems, greenhouse gases, aerosols and climate exists via the increased photosynthesis and forest growth due to increasing temperatures and CO_2 fertilization (*see* Kulmala *et al*. 2004). An increase in forest biomass would increase emissions of non-methane biogenic volatile organic compounds and thereby enhance the production of organic aerosols. This couples the climate effect of CO_2 with that of aerosols in a novel way.

Kulmala *et al*. (2004) investigated the connection of forest–atmosphere carbon exchange with aerosol formation and growth in a continental boundary layer. They analyzed a six-year data set (SMEAR II data) of aerosol formation and growth rates and carbon dioxide fluxes as well as a two-year data set of monoterpene concentrations. The measurements were performed between April 1996 and December 2001. The results indicate two important connections in terms of seasonal variability: one between the growth rate of nucleation-mode aerosol particles and ecosystem gross primary production, and the other one between the formation rate of nucleation-mode particles and the ozonolysis of terpenes. In addition, the seasonal pattern of particle growth rates is similar to the formation of oxidation products from terpenes in reactions with the OH radicals. However, further analysis is needed in the future in order to be able to analyze the complex interactions and feedbacks of the photosynthesis–forests–aerosol–clouds–climate system.

One challenge in utilizing SMEAR II data is to analyze the connection between aerosol formation, different fluxes and biochemistry of photosynthesis in a rigorous way. In this type of analysis also a theoretical understanding of the processes involved is required. Therefore it is important to study the molecular properties of condensing species and their chemical reactions, nucleation and condensation mechanisms, aerosol and air ion dynamics, etc. using molecular-level simulations and also thermo- and hydro dynamical knowledge.

Conclusions and views for future research

The goal of the SMEAR II-type research is an improved understanding of how interacting physical, chemical, and biological processes transport and transform energy and matter through the land–atmosphere interface, particularly emphasizing interactions and feedbacks at all scales: from past to future and from local to global scale. The goals are pretty similar to the scientific aims of the international iLEAPS (Integrated Land Ecosystem Atmospheric Processes Study) Programme within the framework of the second phase of IGBP, the International Geosphere–Biosphere Programme.

The Earth system behaves as a complex, non-linear system. A new, holistic perspective in the sciences of the earth demands a new scientific approach. The properties and processes of components of the earth system, such as the composition and circulation of the atmosphere, still need to be investigated, but we must now study them as integral parts of a system in order to understand their interactions and feedbacks. Obviously, in the era of the global change, mankind must also be seen as a part of the Earth's system. The SMEAR II-type research and stations will provide new possibilities to scientists all over the world to perform their investigations in a new comprehensive multi- and cross disciplinary way.

One of the ideas behind the SMEAR II-type research is to improve tools, such as instrumental techniques, continuously. During the recent years new continuous measurements have been planned and implemented. As examples of these we can mention air ion measurements, ozone fluxes and development of chamber techniques. In the near future we plan to start the online measurement of aerosol composition using an aerosol mass spectrometer technique. Other examples of our future plans are continuous flux measurements of organic gases and NO_x.

The distribution of constituents in the atmosphere results from the characteristics of emissions, transport, transformation and deposition. Evidences of changes in atmosphere and biosphere require regular observations. Although the SMEAR II-type research is comprehensive, different environmentally relevant processes act at different temporal and spatial scales, implying that the evolution trends may not be representative of the global atmosphere. Long-term monitoring of key atmospheric species and their exchange with biosphere at several locations is therefore a necessity.

The development and implementation of new instruments and SMEAR II-type research in a global field station network are needed. It is very important to measure in the same site all relevant components of the soil–ecosystem–atmosphere continuum, including the mass and energy fluxes, dynamics, processes, etc. At present there are well-established, state-of-the-art networks in atmospheric sciences like Global Atmospheric Watch (GAW), EUROFLUX (Valentini 2003) and FLUXNET, but no network of stations for measuring simultaneously the atmosphere, vegetation and soil for the entire earth system exist. The challenge for the future is a network of SMEAR II-type stations. The overall attractiveness and credibility of this kind of infrastructure will be enhanced when they take part in harmonized cross- and multidisciplinary research as well as networking activities. Especially, if the activities merge the research communities devoted to the research of atmospheric particles and chemistry with those devoted to surface flux measurements of trace gases, and chamber measurements at plant level, the new insight in key processes, forest–atmosphere interactions and climate change will be achieved.

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