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A comprehensive network of measuring stations to monitor climate change

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The atmospheric CO_2 concentration and temperature have been rather stable at the time scale of millennia, although rather large variations have occurred during longer periods. The extensive use of fossil fuels and destruction of forests have recently increased the atmospheric CO_2 concentrations. Temperature and circulation of water on the globe are reacting to the increase in the atmospheric CO_2 concentration. Mankind urgently needs knowledge on the present climate change and on its effects on living nature. We propose that a network of comprehensive measuring stations should be constructed, utilizing modern technology to provide documentation of the climate change and data for research related to it. To be able to cover spatial and temporal variations, a hierarchy of stations is needed.

Background

In their 2007 report, the Intergovernmental Panel on Climate Change (IPCC) gave an estimate on the global and annually averaged radiative forcings from both greenhouse gases and aerosols, along with natural changes associated with the solar energy output (IPCC 2007). Emphasis was placed on the complexity of the combined direct and indirect forcings from both aerosols and gases, and on the need for improving our understanding of the role of these individual components in an integrated system. Such knowledge would reduce the uncertainty in current estimates of radiative forcing and enable a better prediction of the effects of anthropogenic activity on climate change.

The atmospheric CO_2 concentration has varied between ca. 200 and 300 ppm during the last 600 000 years (Augustin *et al*. 2004). Global temperature has also varied simultaneously with carbon dioxide in such a way that during periods of high CO_2 concentrations the atmosphere has been warmer than during periods of low CO_2 concentrations (Siegenthaler *et al*. 2005). Thus the global circulation system has not been in a stable state at the time scale of 100 000 years. The atmospheric CO_2 concentration has, however, been rather stable at the time scale of millennia (Kennedy and Hanson 2006). Reliable measurements of global surface temperatures did not start until the mid-18th century, and thus we have to utilize indirect information to evaluate the temperatures over most of the postglacial period. Tree rings and other biological material indicate rather stable temperatures during the last 10 000 years, although some variation has occurred. However, the differences between the cool and warm periods during Holocene were small when compared with those at the time scale of 100 000 years.

The Holocene stable period was long enough for ecosystems to adapt to the prevailing local climate, and location-specific vegetation types emerged. Human societies also evolved to meet the climate in each inhabited area, with food production systems that effectively utilize the features of the local climate. Strong expansion of agriculture around 200 years ago, and the associated clearing of forests to create more space for cultivation increased flows of CO_2 from forests into the atmosphere. The emissions from extensive use of fossil fuels exponentially increased the flow of CO_2 into the atmosphere during the 20th century. In addition, emissions of several reactive chemical compounds, including aerosol particles from industrial processes and energy production, had started at the beginning of the 20th century then increased exponentially and finally, at least in the case of SO_2, decreased during the last decades.

The atmosphere has responded to the increased inflows, and the concentrations of CO_2, reactive gases and aerosol particles have increased worldwide. Several processes react to the changes in concentrations, and therefore the flows generated by these processes are changing. As a consequence, the previously stable state on the globe has been thrown off balance and the climatic system is in transient state. The global temperatures are increasing (IPCC 2007), the transmission of solar radiation through the atmosphere has changed (Pinker *et al*. 2005, Wild *et al*. 2005), glaciers are retreating (Joughin 2006), and forest growth is increasing in several regions (Briffa 2000).

The atmosphere, vegetation, and top layers of soil include three functional flow systems; (i) energy flows as radiation and convection, (ii) carbon cycle driven by solar radiation energy, water and temperature, and (iii) water cycle. To a great extent, these three flow systems determine the global and local climate. Besides these three major cycles, it is important to observe other cycles, like those of nitrogen and sulphur, as well as the dynamical behavior of atmospheric oxidants, which all will significantly contribute to aerosol processes and atmospheric chemistry.

The processes converting energy or material into another form depend on light, temperature, and concentrations of gases, water and aerosol particles, thus generating linkages between the three main flow systems. These connections then produce stabilizing (negative) or destabilizing (positive) feedbacks. The increase in outgoing thermal radiation resulting from increasing surface temperature is the most important negative feedback, but others are also important, such as the acceleration of photosynthesis at increasing CO_2 concentrations (CO_2 fertilization). The enhanced decomposition of soil organic matter with increasing temperature is an example of the positive feedbacks. The magnitude of these two effects and their balance represent one of the major uncertainties in predicting future climate change (Friedlingstein *et al*. 2006).

Understanding the spatial distribution of atmospheric pollutants, and quantifying their climate and air quality effects requires comprehensive ground-based and satellite observations and also mathematical models covering ecosystems at regional and global scales. To understand the complex processes from molecular to global scale, hierarchical observation systems and models are needed to perform in a truly inter-, multi- and cross-disciplinary manner. In this feature article, we summarize the needs for this kind of information and the possibilities to produce it from an observational point of view.

Gaps and needs

For numerous processes, fluxes and storages, adequate data sets are missing, and continuous new measurement series should be started: e.g. continuous long-term data sets for relevant forest soil properties are needed. Generally, we can state that there is a need for continuous data sets for concentrations of single compounds in the atmosphere, and even more urgently for continuous comprehensive data sets. The available time series are typically too short to detect global climate and environmental change. The longest one — for CO_2 — started 1958 (e.g. Keeling 2008). EMEP (European Monitoring and Evaluation Programme) initially focusing on assessing the transboundary transport of acidification and eutrophication started in 1979/1980. On the other hand, the longest time series for secondary aerosol particle production has started in January 1996 (*see* Dal Maso *et al*. 2005). Since the climate system is currently in an unstable state, the detection of changes should be in highest priority. Although comprehensive measurements for carbon cycle have earlier been proposed (e.g. Raupach *et al*. 2005), measurements of atmospheric chemistry and aerosols have typically been lacking from those proposals.

On the other hand, it is of primary importance to fully utilize the valuable knowledge and data obtained from several (already existing) stations differing in their measurement strategy: e.g. weather stations that provide a record of meteorological data, in some cases spanning centuries; flux stations that monitor the exchange between atmosphere and vegetation; and Global Atmosphere Watch (GAW) stations that keep track of atmospheric concentrations. However, the tasks of these networks should be expanded to cover comprehensively the changes in biological activity, as well as those in physical and chemical climate, and their instrumentation should be developed to meet the novel requirements.

Hierarchical station network

The global energy, carbon and water flows are strongly interconnected with each other, since the processes generating the flows depend on radiation, temperature, carbon dioxide and water concentration. Besides these three main flows, also nitrogen and sulphur cycles as well as aerosol particles, trace gases and oxidants are well connected to those three main cycles and each other. We can only get a comprehensive picture of the response of different ecosystems to climate change by monitoring simultaneously all relevant aspects related to processes, biogeochemical cycles, chemical reactions etc. Thus the most important storages, flows and processes in a forest ecosystem and between the ecosystem and atmosphere should be measured as outlined by Hari and Kulmala (2005).

A system measuring all components is large, expensive and should be run properly. Thus the number of comprehensive stations to measure storages, fluxes and processes in an ecosystem and ecosystem–atmosphere interactions remains low. On the other hand, for proper spatial characterization of concentrations, temperature and fluxes we need a large number of stations. This discrepancy can be solved by creating hierarchy of stations, in which the basic stations are used for spatial characterization, so that the number of measuring points is large enough. For research and technical development, only few stations worldwide need to be constructed to get the whole picture of the storages, flows and processes in the ecosystems at a limited number of key sites.

We think that this network should include three levels in a hierarchical system: (i) a basic level, (ii) a flux level, and (iii) a "flag-ship" level. The aim of the basic stations is to provide information for spatial characterization, the flux stations provide information on fluxes in the ecosystem, the "flag-ship" stations provide information on processes generating the fluxes, develop instrumentation, and serve to train scientists and technical staff. The instrumentation of each station type is outlined in Table 1.

The number of basic-level stations to obtain a global coverage must be rather large (around 8000) to get sufficient coverage of different ecosystems and climates, thus the instrumentation must be simple and reliable. The flux instrumentation is more complicated and the interpretation of the results requires considerable sophistication. These facts clearly limit the number of flux stations to around 400 that represent different ecosystems and climates. The number of "flag-ship" stations is very limited due very demanding scientific and technical level needed. Therefore globally only something like 20 stations in different ecosystem can be constructed and maintained. The structure of the network and the required instrumentation on the stations should be carefully analyzed.

Table 1. Hierarchy of stations and their instrumentation.

Basic stations — Momentary measurements of:
- temperature profiles in atmosphere and soil
- aerosol concentrations
- O_3 and NO_x concentrations
- global radiation, photosynthetically active radiation and net radiation
- soil water content and tension
- precipitation
- snow depth and water content
- leaf area and mass
- amount of soil organic matter (annual)
- mass of woody components (annual)
- deposition of nutrients, such as nitrogen, phosphorus, potassium and calcium, and H^+ ions

Flux stations — All measurements done at basic stations plus following measurements:
- CO_2, H_2O, heat and momentum fluxes between ecosystem and atmosphere
- aerosol size distributions
- profiles of CO_2, O_3, SO_2, NO, NO_2, and N_2O in atmosphere and soil
- focused campaigns to determine the dependences of processes on environmental factors

Flag ship stations — All measurements done at flux stations, plus monitoring of processes and explaining factors at high spatial and temporal resolution:
- VOC (Volatile Orcanic Compounds) emissions from vegetation and soil
- VOC profiles in atmosphere and soil
- H_2SO_4, NH_3 and CH_4 in the air
- size distribution of ions in the air
- cloud radar
- PAR (Photosynthetically active radiation) distribution inside canopy
- monitoring of spectral light distribution
- monitoring of atmospheric turbulence
- monitoring of nutrient, such as nitrogen, phosphorus, potasium and calcium, and H^+ concentrations in soil water
- monitoring of water flow in wood
- CO_2 and H_2O fluxes between soil and atmosphere
- development of instrumentation
- use of stable isotopes in studies of processes, such as photosynthesis and decomposition of soil organic matter

Summary and conclusions

At present, the climate is changing rapidly. In order to understand the change and forcing and feedbacks related to it, reliable data is needed. Unfortunately nowadays long term measurements are lacking, and typically there is only a limited number of different measurements at a given measurement site.

Here we propose that the establishment of a hierarchical measurement network could be a solution. In "flag-ship" stations the processes can be studied. However, the lack of these stations is obvious. Our experiences over ten years at the SMEAR II and I stations (Kulmala *et al*. 2001 and Hari and Kulmala 2005) show that such a monitoring system can be constructed, that the stations work reliably when properly operated, and that the construction and maintenance costs are reasonable. By using comprehensive data sets unique results can be obtained (*see* e.g. Tunved *et al*. 2006). On the other hand, the recently establish FLUXNET network will cover a big fraction of flux stations (e.g. Baldocchi *et al*. 2001), and basic station can be established using weather stations.

We conclude that a comprehensive measuring station network is feasible, and that it will provide essential information for science and political decision making. This network will also offer crucial support to global scientific programs like IGBP (International Geosphere–Biosphere Programme), WCRP (World Climate Research Programme), and particularly their core projects iLEAPS (integrated Land Ecosystem–Atmosphere Processes Study and GEWEX (Global Energy and Water cycle EXperiment), in which ecosystem–atmosphere interactions are studied.

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