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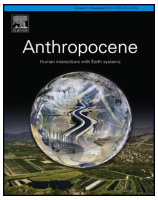

The significance of land-atmosphere interactions in the Earth system—iLEAPS achievements and perspectives

T. Suni[a], A. Guenther[b], H.C. Hansson[c,*], M. Kulmala[a], M.O. Andreae[d], A. Arneth[e], P. Artaxo[f], E. Blyth[g], M. Brus[a,h], L. Ganzeveld[i], P. Kabat[j], N. de. Noblet-Ducoudré[k], M. Reichstein[l], A. Reissell[a,j], D. Rosenfeld[m], S. Seneviratne[n]

[a] *Division of Atmospheric Sciences, Department of Physics, University of Helsinki, Helsinki, Finland*
[b] *Department of Earth System Science, University of California, Irvine, CA, USA*
[c] *Department of Environmental Science and Analytical Chemistry, Stockholm University, Stockholm, Sweden*
[d] *Biogeochemistry Department, Max Planck Institute for Chemistry, Mainz, Germany*
[e] *Division of Ecosystem-Atmosphere Interactions Karlsruhe Institute of Technology, Institute of Meteorology and Climate Research/Atmospheric Environmental Research, Garmisch-Partenkirchen, Germany*
[f] *Applied Physics Department, Institute of Physics, University of São Paulo, São Paulo, Brazil*
[g] *Centre for Ecology and Hydrology (CEH), Wallingford, UK*
[h] *Division of Atmospheric Sciences, Department of Physics, University of Helsinki, Helsinki, Finland*
[i] *Department of Earth System Sciences, Wageningen University, Wageningen, The Netherlands*
[j] *International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*
[k] *Laboratoire des Sciences du Climat et de l'Environnement, Unite mixte CEA-CNRS, Gif-sur-Yvette cedex, France*
[l] *Max-Planck Institute for Biogeochemistry, Jena, Germany*
[m] *Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel*
[n] *Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland*

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ABSTRACT

The integrated land ecosystem-atmosphere processes study (iLEAPS) is an international research project focussing on the fundamental processes that link land-atmosphere exchange, climate, the water cycle, and tropospheric chemistry. The project, iLEAPS, was established 2004 within the International Geosphere-Biosphere Programme (IGBP). During its first decade, iLEAPS has proven to be a vital project, well equipped to build a community to address the challenges involved in understanding the complex Earth system: multidisciplinary, integrative approaches for both observations and modeling. The iLEAPS community has made major advances in process understanding, land-surface modeling, and observation techniques and networks. The modes of iLEAPS operation include elucidating specific iLEAPS scientific questions through networks of process studies, field campaigns, modeling, long-term integrated field studies, international interdisciplinary mega-campaigns, synthesis studies, databases, as well as conferences on specific scientific questions and synthesis meetings. Another essential component of iLEAPS is knowledge transfer and it also encourages community- and policy-related outreach activities associated with the regional integrative projects. As a result of its first decade of work, iLEAPS is now setting the agenda for its next phase (2014–2024) under the new international initiative, future Earth. Human influence has always been an important part of land-atmosphere science but in order to respond to the new challenges of global sustainability, closer ties with social science and economics groups will be necessary to produce realistic estimates of land use and anthropogenic emissions by analysing future population increase, migration patterns, food production allocation, land management practices, energy production, industrial development, and urbanization.

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1. Introduction

The land-atmosphere interface is where humans primarily operate. Humans modify the land surface in many ways that influence the fluxes of energy and trace gases between land and atmosphere. Their emissions change the chemical composition of

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* Corresponding author.
E-mail address: hc@aces.su.se (H.C. Hansson).

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the atmosphere and anthropogenic aerosols change the radiative balance of the globe directly by scattering sunlight back to space and indirectly by changing the properties of clouds. Feedback loops among all these processes couple land, the atmosphere, and biogeochemical cycles of nutrients and trace gases extending the human influence even further.

The Earth is a highly complex system formed by mutually interlinked components (land, atmosphere, ocean), its interfaces (land-atmosphere, atmosphere-ocean, land-ocean) and processes operating on a wide range of temporal and spatial scales. Our capacity to understand the whole system is predicated on our capability to understand its various elements and their interactions. The land-atmosphere interface is a prime example of such interlinked elements, particularly crucial for the functioning of the Earth system through interactions via mass, energy and momentum fluxes as well as through biogeochemical cycles. The scientific understanding of the interface therefore contributes to our ability to describe, understand and predict the Earth system and its functioning as a whole. Exploring and quantifying the land-atmosphere interactions is thus extremely important.

The International Geosphere Biosphere (IGBP) program was reorganized in 2000 to emphasize the importance of scientific research at the interface of the major geosphere biosphere disciplines. The new structure included a new cross-disciplinary research program, called the integrated land ecosystem-atmosphere processes study (iLEAPS), aimed at improved understanding of the processes, linkages and feedbacks in the land-atmosphere interface (Fig. 1). This project was designed to build on key findings of previous IGBP projects, especially BAHC (biospheric aspects of the hydrological cycle) and IGAC (International Global Atmospheric Chemistry). The iLEAPS international project office was based at the University of Helsinki. iLEAPS activities, workshops and scientific conferences facilitated the establishment of a community with a common goal to enhance the understanding of how interacting physical, chemical and biological processes transport and transform energy and matter through the interface, particularly emphasizing interactions and feedbacks at all scales, from past to future and from local to global. A science conference highlighting the accomplishments of the first decade of iLEAPS was held in Nanjing, China in 2014 and coincided with the transfer of the international project office to Nanjing. The current iLEAPS scientific steering committee, activities and initiatives are described on the iLEAPS website (www.iLEAPS.org).

The scientific goals of iLEAPS are chosen to reflect issues and regions where previous research has shown that interactions, feedbacks and teleconnections play prominent roles and are essential to our scientific understanding. It is clear that understanding such a complex system is an enormous challenge that requires more integrative approaches and collaboration, crossing the boundaries among spatial and temporal scales as well as among the various science disciplines. iLEAPS meets these requirements with the aim of creating a deep understanding of the current challenging global issues. The research within iLEAPS covers the basic processes that link surface-atmosphere exchange with ecological and physiological processes on the one hand and with atmospheric dynamics, tropospheric chemistry and physical climate on the other. iLEAPS integrates the knowledge and expertise from several fields, such as biology, chemistry, physics, meteorology, hydrology and ecology. Moreover, addressing the complex issues related to global challenges requires bridging the gap between the natural and social sciences. In the current epoch driven by human activities, engagement of social sciences into the framework of iLEAPS research is necessary. Migration patterns, food production allocation, and land management practices are some examples of topics requiring a wide integrative approach facilitated by iLEAPS in its second phase. Here, we outline the development that has occurred in this field in recent years from the perspective of iLEAPS.

iLEAPS is not a specific research organization or project. It is, like other IGBP core projects, rather a research network that through its vast network including leading scientists inspires and supports groups of scientists to merge efforts and to focus on urgent scientific questions in our field. The scientific steering committee is comprised of about 16 diverse scientists, a mixture of

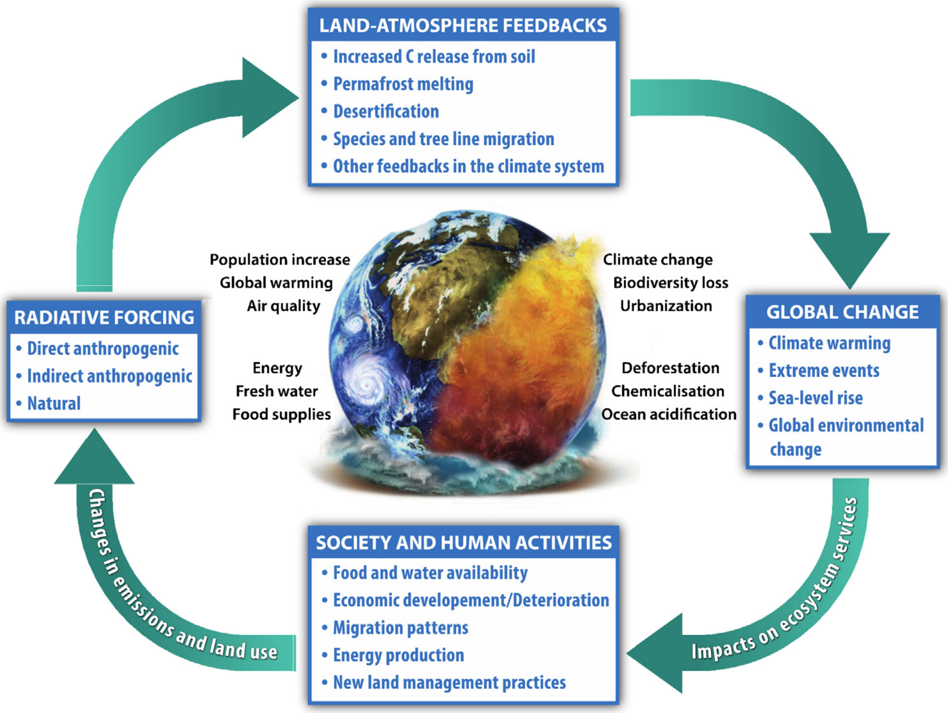

Fig. 1. The land–atmosphere-society processes under global change that are the focus of iLEAPS.

established world leading and young promising scientists from different parts of the world and representing different research expertise. They meet a few times a year, most of the time through internet meetings, and discuss various actions to launch different research initiatives such as workshops, discussion papers in leading journals or actual research projects. A very important part of iLEAPS is its International Project Office, which is essential in facilitating the intentions and executing the decisions of the SSC. The IPO is publishing newsletters, bulletins, assisting and supporting scientists in organizing workshops to initiate and/or emphasize research efforts in some specific area. The University of Helsinki in Finland has during the first 10 years of iLEAPS hosted the IPO which in 2014 moved to Nanjing University in China. The IPO has and is financed including support for workshops and conferences by the hosting university. The iGBP has supported an annual SSC meeting of all SSC with liaisons from IGBP and relevant core projects.

Phase I has been a time of awareness-raising and establishing a unified community of land-atmosphere scientists. Science conferences held in Helsinki (2003), Boulder (2006), Melbourne (2009), and Garmisch-Partenkirchen (2011) brought to light the importance of land-atmosphere processes and feedbacks in the Earth system, and a number of publications have shown the crucial role of terrestrial ecosystems as regulators of climate and atmospheric composition (Ciais et al., 2005; Kulmala et al., 2004; Andreae et al., 2005; Philippon et al., 2005; Andreae 2009a,b; Arneth et al., 2010a; Ganzeveld et al., 2009; Gutman and Reissell, 2010; Teuling et al., 2010). For example, the international initiative aerosols, clouds, precipitation, climate (ACPC) was founded during Phase I and it provided unprecedented insights of the long-term net impacts of aerosols on clouds and precipitation (Rosenfeld et al., 2008; Stevens and Feingold, 2009; Li et al., 2011). Subsequently, land cover change was emphasized as important results emerged from the model intercomparison project LUCID that showed how realistic land-use representation was essential in land surface modeling (Pitman et al., 2009; de Noblet-Ducoudré et al., 2012). As a consequence, iLEAPS launched the new IGBP synthesis initiative LULCC in 2011.

Throughout Phase I, the iLEAPS community has invested in creating new ways to observe and model the land-atmosphere continuum: observation systems have developed into networks of long-term flux stations and large-scale land-atmosphere observation platforms and, more recently, to combining remote sensing techniques with ground observations (Baldocchi et al., 2005; Hari et al., 2009; Guenther et al., 2011; Jung et al., 2011). Modelers have clearly shown the effect of neglecting land cover changes and other feedback processes and regional characteristics in current climate models and recommended actions to improve them (Arneth et al., 2010a; Bonan et al., 2011; Davin and Seneviratne, 2011; de Noblet-Ducoudré et al., 2012). In preparation for Phase II, the iLEAPS Scientific Steering Committee (SSC) reviewed current gaps in land ecosystem-atmosphere processes knowledge and formulated research priorities that form the basis of the new Action plan for iLEAPS Phase II. iLEAPS SSC members, affiliate projects, and community scientists have contributed directly to the IPCC Fifth Assessment Report (AR5), especially chapters on clouds and aerosols and on Chapter 7: Clouds and Aerosols, land-atmosphere flux studies and the "Extreme Events and Disasters to Advance Climate Change Adaptation" special report in the IPCC-AR5.

As evidenced by the selected science highlights discussed below in this document, human influence has always been an important part of iLEAPS science. In Phase II, iLEAPS will deepen this integration and work hand in hand with social science groups and experts in economics, agricultural, demography, globalization research, and psychology to produce realistic estimates of land use and anthropogenic emissions by analysing future population increase, migration patterns, food production allocation, land management practices, energy production, industrial development, and urbanization (see for instance, the IMECS initiative at www.iLEAPS.org). Phase II will integrate research groups with expertise in climate sciences, genetics and genomics, evolutionary biology, ecology, agronomy, social sciences and economics and sponsor projects that promote the use of this understanding to develop and implement sustainable land management strategies on a regional level and similar work will be undertaken in other areas as well. On a continental scale, the iLEAPS-sponsored Pan-Eurasian Experiment (PEEX, www.helsinki.fi/peex) will seek to find solutions to the great challenges facing humanity in the changing climate in the Arctic and boreal zone.

The overall goal of iLEAPS Phase II is to enhance the understanding of how interacting biological, chemical and physical processes transport energy and matter through the land-atmosphere interface at all scales from past to future and local to global, with particular emphasis on the human influence on these processes. A pathway toward achieving this goal was described by the iLEAPS SSC in a scientific and strategic Action plan for iLEAPS Phase II (2014–2024). The action plan two main themes are (1) understanding the dynamic processes determining the interaction between land, ecosystem and atmosphere in the human-Earth system and (2) developing management of human-dominated environments aiming at a sustainable land, ecosystem and atmosphere. Research priorities include observation networks, boundary-layer dynamics fundamentals, the role of land-cover changes in modulating land-atmosphere interactions, regional processes and their influence on global simulations, integrative land-surface and climate model evaluation and development, extreme events vs. gradual change and adaptation, interactions and exchange between managed ecosystems and atmosphere, impact studies of land management practices, societal-relevant indicators of land surface, and interactions among anthropogenic pollution and biogenic aerosols, clouds, and climate. Many of these priorities have given rise to new initiatives, developed in collaboration with other IGBP core projects: AIMES (Analysis, Integration, and Modeling of the Earth System), PAGES (Past Global Changes), and GLP (Global Land Project) especially for land cover change studies and the human dimension, IGAC (International Global Atmospheric Chemistry) for aerosol and atmospheric chemistry; iLEAPS also works extensively with the WCRP (World Climate Research Programme) core project GEWEX (Global Energy and Water exchanges) in the fields of land-surface modeling, soil and energy and thermal processes.

The scientific contributions of the iLEAPS community to Earth System Science exhibit a strong basis in observations and modeling over a range of scales aiming to answer pertinent scientific questions. The purpose of this paper is to give an overview of the iLEAPS research and especially present the contributions of iLEAPS scientists and from iLEAPS initatives to illustrate the importance of scientific leadership based on a bottom up process facilitating a continuous inflow of new scientific questions and initiatives. The research is presented in the following areas: observations, soil-vegetation-atmosphere society interactions; modeling, land-atmosphere-society interactions and the policy interface; capacity building followed by conclusions. Two thirds of the referenced papers are published by iLEAPS scientists.

2. Observations

The iLEAPS community has a strong expertise in both short-term and long-term observation of various ecosystems and their interactions with the atmosphere. Developing new observational systems across measurement community boundaries is central to iLEAPS and a Post-Conference Workshop on this issue was organised in September 2011 in connection with the 3rd iLEAPS Science Conference in Germany. The discussion at the Post-Conference Workshop led to a Newsletter issue on “Future land-atmosphere observation platforms” in 2012. Here, we present a brief summary of iLEAPS observation efforts with scientific highlights spanning most of iLEAPS Phase I (2004–2014).

2.1. Major observation campaigns and long-term monitoring

An innovative, comprehensive, multi-scale, multidisciplinary approach to land-atmosphere processes is a key element of iLEAPS observations. The success of ambitious multidisciplinary international field campaigns and long-term monitoring in Amazonia (Keller et al., 2009; Artaxo, 2012) has led to calls for similar projects to be set up to monitor other tropical forests, including those in Africa and south-east Asia (Hewitt et al., 2010). Perhaps the most fundamental innovation was that the project encouraged interdisciplinary collaboration among physicists, chemists, meteorologists and biologists. Unusually for the time, economists and social scientists were also introduced into the research program in order to fully understand all the factors influencing such a complex system (Artaxo, 2012) . Other key factors behind this successful project have been international cooperation and an open data sharing policy. In a recent review article, Davidson et al. (2012a,b) showed how agricultural expansion and climate variability have become important agents of disturbance in the Amazon basin: interactions between deforestation, fire and drought potentially lead to losses of carbon storage and changes in regional precipitation patterns and river discharge. The project found some signs of a transition to a disturbance-dominated regime, including changing energy and water cycles in the southern and eastern portions of the Amazon basin.

Long-term, multidisciplinary observations of atmospheric aerosol particles and their connections with atmospheric chemistry and clouds are a major focus in the iLEAPS community and have given rise to several long-term measurement campaigns around the world which have eventually led to significant larger initiatives (Williams et al., 2011; Ortega et al., 2014). The SMEAR II station in Hyytiälä is an example of a state-of-the-art observation platform advocated by iLEAPS with continuous, comprehensive measurements of fluxes, storages and concentrations of trace gases, reactive gases, and aerosols in the land ecosystem-atmosphere continuum (Hari and Kulmala, 2005) . In 2007–2011, the European Integrated project on Aerosol Cloud Climate and Air Quality Interactions, EUCAARI (2007–2010), brought together the leading European research groups, state-of-the-art infrastructure, and key players from third-world countries to investigate the role of aerosol on climate and air quality (Kerminen et al., 2010; Kulmala et al., 2011b), and most recently, the HUMPPA-COPEC campaign (Williams et al., 2011 in ACP special issue on HUMPPA-COPEC) continued the collection of observations in the boreal zone in a joint effort of more than a dozen institutes. Similarly, the role of biogenic gases and aerosol on climate and air quality have recently been investigated in temperate forests of North America with comprehensive international experiments conducted by participants from dozens of institutes (see ACP special issues on the Rocky Mountain Organic Carbon Study (ROCS), Rocky Mountain Biogenic Aerosol Study (RoMBAS) and Biosphere Effects on Aerosols and Photochemistry Experiment (BEARPEX)). Finally, the ACPC project (Aerosols, Clouds, Precipitation, and Climate) Science and Implementation plan (ACPC, 2009) outlined an ambitious programme, and ACPC has indeed provided unprecedented insights of the long-term net impacts of aerosols on clouds and precipitation (Rosenfeld et al., 2008; Stevens and Feingold, 2009; Li et al., 2011; Rosenfeld et al., 2013). Depending on cloud type, properties such as cloud-top height and thickness and rain can change according to aerosol-induced invigoration of upward winds or aerosol particle concentration within the clouds (Fig. 2) . Simulations using a cloud-resolving model have confirmed these observations. The ecosystem is a major source of secondary aerosols over unpolluted land areas thus determining the aerosol concentration and thus influencing the clouds and precipitation (Tunved et al., 2006). To some degree the ecosystem can influence its own climate.

A spin-off project of ACPC, the SAT-ACPC concentrated on the applications of remote sensing to aerosol-cloud-precipitation interactions. It inspired and triggered a proposal for a new satellite mission that will measure the CCN in the cloudy boundary layer based on the retrieval of the vertical evolution of the convective towers that grow from the boundary layer (Rosenfeld et al., 2012).

2.2. New datasets

Recent advances in up scaling and data integration across multiple data streams have enabled iLEAPS scientists to produce gridded datasets of regionally and globally explicit flux products. The sites that comprise the flux and spectral measurement networks FLUXNET and SPECNET have become an important source for “bottom-up” inputs to models that upscale flux quantities from canopies to landscapes and from landscapes to

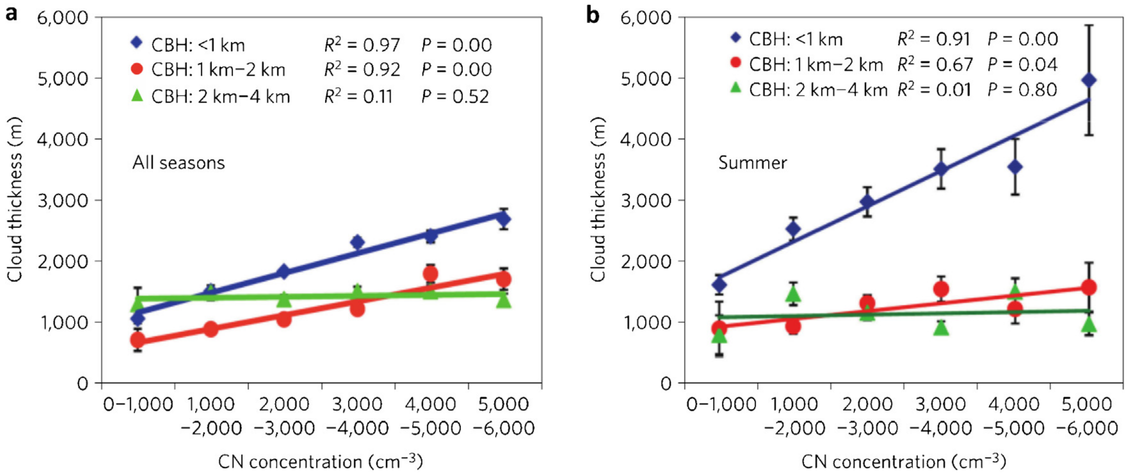

Fig. 2. Changes in cloud thickness with concentration of condensation nuclei (CN). (a) Changes for all seasons. (b) Changes in summers only. Clouds are divided into three ranges of CBH (<1, 1–2, and 2–4 km). Adopted from Li et al. 2011.

the globe (Baldocchi et al., 2001). Data from tower measurements also serve as a validation tool for top-down modeling based on satellite and aircraft optical measurements (Barkley et al., 2009). These capabilities have brought climate and ecosystem scientists within reach of quantifying carbon, water and energy fluxes 'Everywhere, and All of the Time'. They have also enabled insights into climate-ecosystem interactions and trends over a range of spatial and temporal scales; and particularly at the largest scales. Global datasets such as these have been used to reveal important connections among plant physiology and atmospheric composition. For example, Mahecha et al. (2010) found marked differences in the long-term fate of carbon taken up through photosynthesis, as well as in the availability of this carbon for respiration, across a number of sites in different biomes. The sensitivity of respiration to changes in temperature, however, fell within a narrow range, and proved to be independent of the mean annual temperature and biome. The global mean temperature sensitivity was also significantly lower than previous estimates. The authors attribute the difference to the exclusion of confounding processes in their analysis, such as the seasonal variability of biological activity. This finding could help to explain recent observations of feedbacks between climate and the carbon cycle that are weaker than those suggested by numerical models. The iLEAPS project WATCH (WATer and climate CHange) highlighted the significance of evaporation within the water cycle and produced a new global data set of evaporation from land for the period 1984–2007 that provides a unique breakdown of the components of evaporation. This breakthrough is due to the availability of high-quality satellite data, coupled with novel and innovative approaches taken by WATCH researchers (Harding et al., 2011). Early analysis of the data suggests that, contrary to the expectations, total global land evaporation has been reduced over the last ten years despite the warming climate. The data will allow future studies of global trends, of changes in regional evaporation, and across biomes (Stahl and Tallaksen, 2010). The EUCAARI project developed a new comprehensive dataset for aerosol studies combining ground-based, aircraft and satellite measurements and integrating them with existing data to produce a globally consistent dataset with higher accuracy along north-south and east-west transects within Europe (Kulmala et al., 2011a,b).

2.3. Remote sensing

In the last few years, Earth Observation (EO) satellites have shown the potential to become a major tool for observing some of the main processes in the land-atmosphere interface including the extremely wide and often unreachable northern areas of boreal Eurasia. The Eurasian boreal region is the largest terrestrial

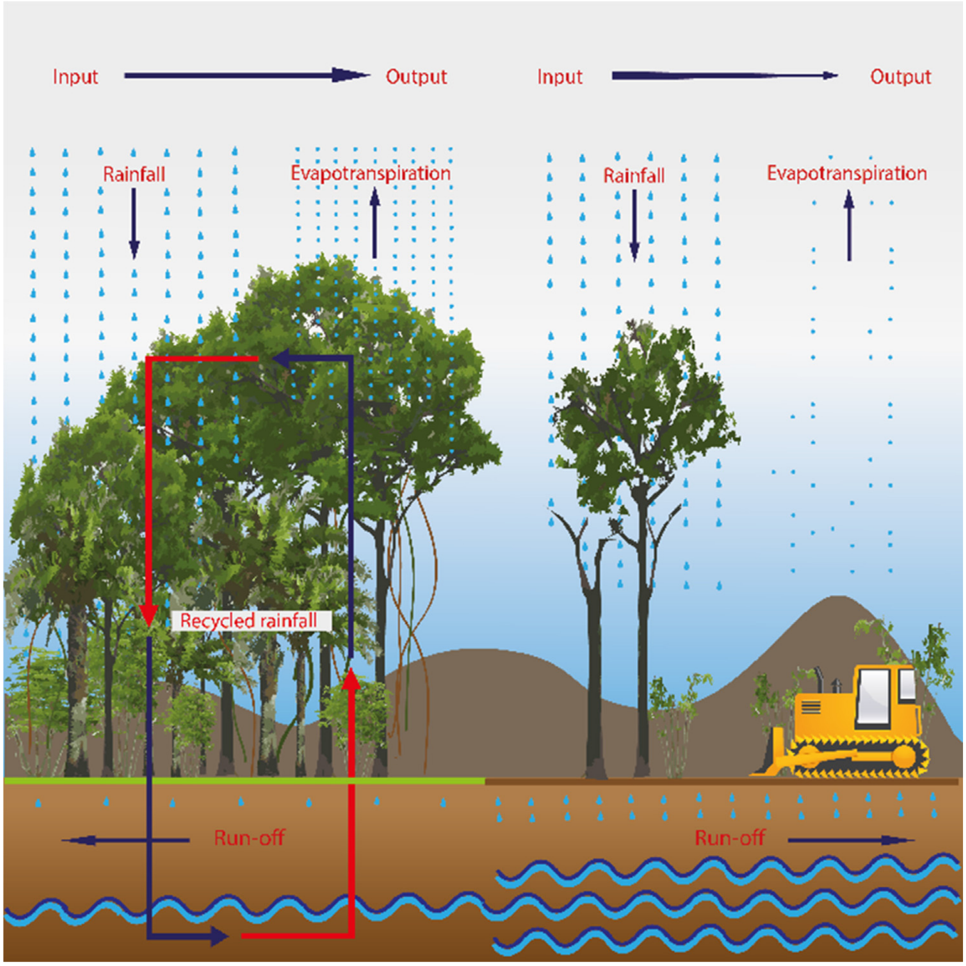

Fig. 3. Adapted from: "The rainforest's water pump", Luiz E. O. C. Aragão, Nature (2012) http://dx.doi.org/10.1038/nature11485-(a) Much of the rainfall over tropical forests comes from water vapour that is carried by the atmosphere from elsewhere. But a large component is 'recycled' rain–water that is pumped by trees from soil into the atmosphere through evapotranspiration. Water exits from forests either as run-off into streams and rivers, or as evapotranspirated vapour that is carried away by the atmosphere. The atmospheric transport of water vapour into the forest is balanced by the exit of water in the form of vapour and run-off. (b) Spracklen et al. (2012) analysis suggests that deforestation reduces evapotranspiration and so inhibits water recycling. This decreases the amount of moisture carried away by the atmosphere, reducing rainfall in regions to which the moisture is transported. Decreasing evapotranspiration may also increase localized rsun-off and raise river levels.

ecosystem on the planet, and understanding its role in the global Earth system is essential. Boreal forests play a vital role in mitigating global warming by storing billions of tons of carbon formed since the last glacial maximum around 20,000 years ago. Northern lakes and wetlands, on the other hand, are important sources of methane and other trace gases. Finally, boreal forests produce secondary organic aerosols that can scatter sunlight back to space and act as a basis for cloud droplet formation. In this context, the European Space Agency (ESA) in collaboration with iLEAPS launched the Atmosphere-LANd Integrated Study (ALANIS) (Kulmala et al., 2011a). Phase I of the initiative (2009–2012) was aimed at advancing the development and validation of novel advanced EO-based multi-mission based products, improved data sets and enhanced applications that may respond directly to the specific scientific requirements of the iLEAPS community in the boreal Eurasian region. In Phase I, ALANIS was divided in three themes: (1) **ALANIS Methane** considered wetland dynamics and methane emissions in the boreal Eurasia region. The main goal of the project was to produce and use a suite of relevant information derived from Earth Observation (EO) for this domain to validate and improve next generation land-surface models and thus reduce current uncertainties in wetland-related CH_4 emissions; (2) **ALANIS Aerosols** was a feasibility study of existing EO-based products for discriminating between natural aerosols emitted by boreal Eurasian forests and long-range transported anthropogenic aerosols (de Leeuw et al., 2011); (3) **ALANIS-Smoke Plumes** aimed at advancing toward the development and validation of novel EO-based multi-mission products and their integration into suitable land-atmosphere coupled models (responding directly to the specific scientific requirements of the iLEAPS community) for improving the estimation of plume injection height of biomass burning events that occur in boreal Eurasia and reducing current uncertainties in related greenhouse-gas and aerosol dispersion forecast.

Saigusa et al. (2010) showed the power of remote sensing in flux studies in their analysis of the influence of meteorological anomalies on photosynthesis in East Asia: the spatial pattern of photosynthetically active radiation was calculated by satellite data, and that of photosynthesis was estimated by a regression-type model, which was trained and tested by ground observation data. Furthermore, Spracklen et al. (2012) combined satellite remote-sensing data of tropical precipitation and vegetation with simulated atmospheric transport patterns to assess whether forests actually have an influence on tropical rainfall. They found that for more than 60% of the tropical land surface, air that had passed over extensive vegetation in the preceding few days produced at least twice as much rain as air that has passed over little vegetation. The authors demonstrated that this empirical correlation was consistent with evapotranspiration from the forested areas and estimated that deforestation in the Amazon will lead to reductions of 12 and 21% in wet-season and dry-season precipitation, respectively, by 2050 (Fig. 3). Finally, satellite data was combined with geospatial information to successfully develop a predictive modeling technique for human population distribution and abundance estimation in rural mountainous area in Kenya (Maeda et al., 2010; Siljander et al., 2011).

2.4. Evaluating and improving methodologies

Global comprehensive measurement networks are essential in land-atmosphere interactions research. Hari et al. (2009) suggested a way to improve and organize existing observation platforms into a hierarchical system to cover spatial and temporal variations. The network should include stations of (i) basic level (ii) flux level, and (iii) “flag-ship” level. The aim of the basic stations would be to provide information for spatial characterization, and the number of stations globally (~8000) should be large to obtain global coverage. The flux stations would provide information on fluxes in the ecosystem, and the approximately 400 global stations suggested would represent different ecosystems and climates; the number would be restricted by the infrastructure and instrumentation required. Finally, the flag-ship level stations (~20 globally), whose number would be limited because of the required scientific and technical level, would provide information on processes

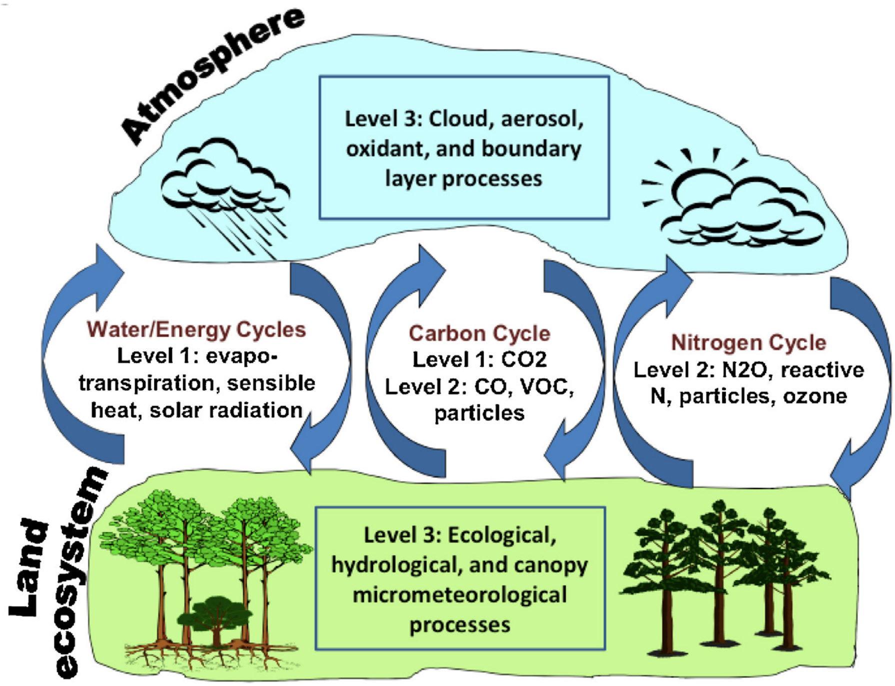

Fig. 4. Schematic of land ecosystem-atmosphere interactions and hierarchical observational levels that include basic (1), advanced (2), and comprehensive measurements at flagship sites (3). Adopted from Guenther et al. (2011).

generating the fluxes, develop instrumentation, and serve to train scientists and technical staff.

Building on this recommendation by Hari et al. (2009); Guenther et al. (2011) conducted a thorough review of current land ecosystem-atmosphere measurement capabilities and presented the status and needs for global observational networks (Fig. 4). They noted that the FLUXNET global network of eddy covariance tower sites is an important first step toward the development of the global land ecosystem-atmosphere observational network required for characterizing LEAP processes on landscape to global scales. Additional activities that were recommended include (1) stable funding to continue FLUXNET, (2) Long-term flux measurements of particles and reactive gases (e.g., ozone and biogenic volatile organic compounds) at selected FLUXNET sites, (3) Support of ICOS, NEON and other regional networks of long-term flux measurements of methane, nitrous oxide, and NOy, in Europe, North America and elsewhere, (4) “Flagship” level sites with a comprehensive suite of long-term multi-disciplinary measurements in each of the major global biomes, and (5) a strategy for locating sites in representative locations and for developing an optimal balance for distributing resources among basic, advanced and flagship sites.

3. Soil-vegetation-atmosphere-society interactions

iLEAPS observations often reveal crucial information about anthropogenic influence on environmental change. A prime example is the iLEAPS sponsored AMMA (African Monsoon Multidisciplinary Analyses) project in West Africa that studied the interplay between humans and the environment over a range of spatial and temporal scales. Observations of the physical and chemical properties of mineral dust and aerosol particles and of air mass trajectories in Senegal (Flament et al., 2011) suggest that the dust originates mainly in Northern Sahara but other aerosol particles stem mainly from local sources (domestic fires) rather than from remote sources such as open-field vegetation fires in the Sahel. Amogu et al. (2010) showed that despite the drought observed since 1970 in most of the West African Sahel, runoff and rivers discharges have increased in this region and is observable from the point scale up to the regional scale. This trend may be related to land use change rather than climate change, although trends have also been found in the absence of land use changes (Gardelle et al., 2010).

The iLEAPS observation community has also been instrumental in revealing new crucial land–atmosphere processes such as the formation of new aerosol particles from anthropogenic and biogenic gaseous precursors in the atmosphere; the role of soil and land processes in climate and atmospheric chemistry; and the close linkages among ozone, nitrogen cycle, and reactive compounds emitted by vegetation . The climatic relevance of aerosol formation has been confirmed in countless observations around the world within intensive initiatives such as EUCAARI (Kulmala et al., 2011b) and at established and continuous observation platforms founded in climatically important locations such as remote boreal forest (SMEAR II research station in southern Finland), cities (SMEAR III in Helsinki, Finland) and in semi-clean areas (Welgegund observation platform in South Africa). Among the most recent findings from Welgegund is Vakkari et al. (2011) who reported on record-high frequency of new particle formation and growth occurring on 69% of the observed days in the savanna conditions. Furthermore, Mauldin et al. (2012) proved the existence of a new atmospherically relevant oxidant, the Criegee

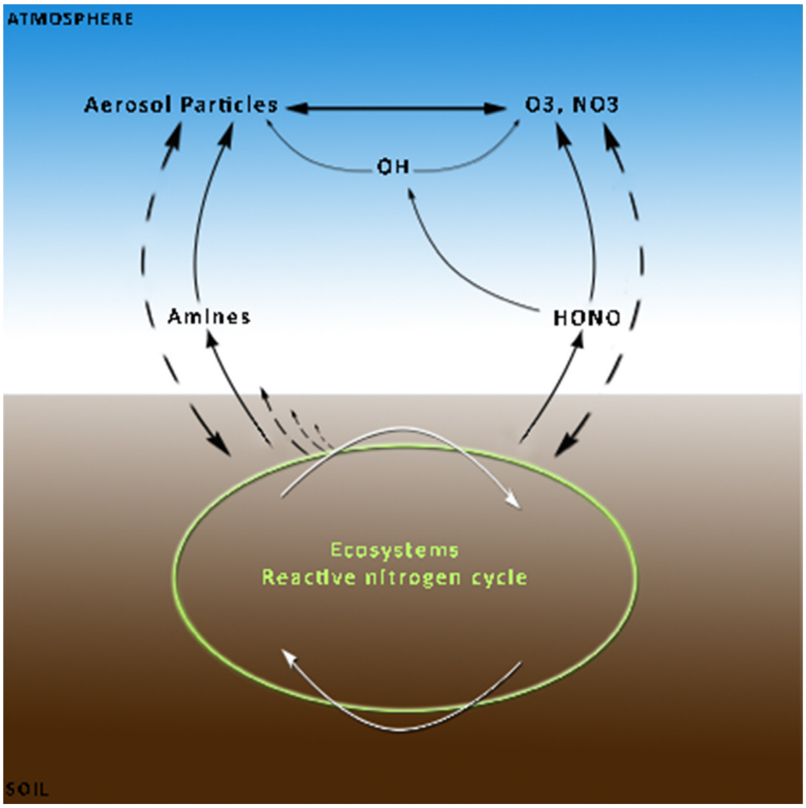

Fig. 5. Soil-atmosphere connections. Microbial activity in the soil and processes in the ecosystem (bottom) connect the nitrogen cycle (green) to atmospheric reactions (blue) involved in atmospheric chemistry and aerosol dynamics. Microbe-produced nitrite in soil feeds HONO emissions, which contribute to the creation of atmospheric OH. Amines contribute to aerosol formation. HONO and amine emissions from soil could increase as global temperatures rise and nitrogen fertilizer use increases, in turn affecting global climate. White arrows indicate reactive nitrogen cycle in the soil ecosystem. Adapted from Kulmala and Petäjä 2011.

radical that could have a significant role in atmospheric secondary aerosol formation.

A new and highly significant finding associated with the connection between soil processes and atmospheric chemistry is that soil nitrite can release HONO, a precursor of the hydroxyl radical (OH) which is a key component in atmospheric chemistry and in new-particle formation (Su et al., 2011) . The finding may account for the observed missing source of OH in some regions. A further link to agriculture exists because arable soils appear to be particularly strong sources of HONO and OH (Oswald et al., 2013). Thus, agricultural activities and land-use changes may strongly influence the oxidizing capacity of the atmosphere. Ghehi et al. (2011) found both biological and climatic controls for N_2O and NO emissions from soils in southwestern Rwanda; globally, tropical soils represent the second largest source for these compounds. Kulmala and Petäjä (2011) take these findings a step further and comment on the important role played by the global nitrogen cycle in the Earth system. Emission of HONO from the soil is a good example of how soil processes are linked with atmospheric chemistry (Fig. 5) : it is also an example of how trace amounts of reactive nitrogen link the nitrogen and sulfur cycles with the water and carbon cycles. It is necessary to document all the ecosystem-atmosphere cycles including the soil, atmospheric oxidation, and aerosol particles and their links and feedback loops to fully understand how the biosphere affects the atmosphere and the global climate (Arneth et al., 2009, 2010a). In order to do this, both extensive global modeling and continuous, comprehensive field measurements are necessary. Synthesis efforts among the large number of observations are crucial.

Ozone is a key constituent in the troposphere and plays a role in air quality, atmospheric oxidizing capacity, and climate change, and is closely linked with the nitrogen cycle and reactive gases (volatile organic compounds, VOC, such as terpenoids and isoprenoids) emitted by vegetation. Ozone is detrimental to human health, crops, and vegetation, and it regulates the oxidizing capacity of the atmosphere via production of the hydroxyl radical, the principal cleansing reagent in the atmosphere. Ozone is also a greenhouse gas that directly contributes to global warming. However, it has an indirect warming effect as well that has been estimated to be even stronger than the direct effect: it suppresses the land carbon sink because high ozone concentrations can lead to stomatal closure in plants, preventing the uptake of ozone but that of CO_2 as well (Sitch et al., 2007). In some developing/newly industrialized countries, such as China, a strong increasing trend in tropospheric ozone is observable (Ding et al., 2008). Wang et al. (2009) attributed most of this increase to the increased emissions of NO_2 (and possibly VOC as well) upwind, suggesting the need to consider distant sources when developing long-term strategies to mitigate local ozone pollution. Some trees produce isoprene that both increases ozone concentration via its interactions with nitric oxide and protects the isoprene-emitting trees from ozone damage (Lerdau, 2007; Vickers et al., 2009) . The ozone produced by the isoprene-emitting trees (oaks, palms, figs) damages other, non-isoprene-emitting tree species and gives an advantage to isoprene-emitters. As a result, there is an increase in regional isoprene production associated with the increased abundance of oaks, palms, figs, and other isoprene-emitters resulting in an increase in regional ozone concentrations, further favoring emitting over nonemitting species (birches, maples, hickories etc.) (Lerdau, 2007). The iLEAPS project VOCBAS has studied extensively the production, protective functions, and atmospheric influence of terpenoids and isoprenoids in plants and in the ecosystem-atmosphere continuum (Vickers et al., 2009; Loreto et al., 2009). Ecosystem-scale flux measurements have shown that in addition to producing VOC, vegetation is also efficient at cleansing the atmosphere from their oxidized forms (Karl et al., 2010) .

4. Modeling

4.1. Development of land-surface modeling

The parameterisation of Earth's land surface for numerical models of weather and climate has evolved greatly over the past three decades, giving rise to Land Surface Models (LSM). While the initial focus was the geophysical control of energy and water fluxes, the current generation of operational LSMs explicitly model plant physiological and biogeochemical processes, and now can simulate leaf phenology, the carbon cycle, community composition, and vegetation dynamics in response to prevailing meteorological conditions and climate (Bonan, 2008; Levis, 2010).

There are still some aspects of the Earth system that are not sufficiently captured in typical LSMs. They include linkages among biogeochemical cycles (such as carbon, nitrogen and phosphorus); soil biological processes; reactive gases and atmospheric chemistry (such as biogenic volatile organic compounds, nitrogen emissions, methane, ozone, and secondary organic aerosols); representation of wetlands, river flow, groundwater, and cryospheric processes; managed ecosystems, including cropland, forestry and pastureland; and urban areas.

The expanding breadth of LSMs is part of the growth of the atmospheric sciences toward Earth system science. Indeed, the ability to simulate biotic and biogeochemical feedbacks is one of the defining aspects of the evolution of climate models to Earth system models. The development and use of land models consequently spans a wide spectrum of research communities. The models provide a framework to integrate theories of physiological, ecological, biogeochemical, hydrological, and meteorological functioning; global models test the generality of these theories in a diverse array of ecosystems and environments across the planet. Some researchers apply the models to discover and understand feedbacks among soil moisture, surface energy fluxes, boundary layer development, and precipitation to improve weather prediction and climate simulation (Koster et al., 2004). Others are interested in longer-term processes (such as carbon cycle) that influence past and future climates (Sitch et al., 2008).

While the LSMs are designed for coupling with atmospheric models and specifically simulate terrestrial feedbacks with the atmosphere, an emerging frontier is to apply LSMs for climate change impacts, adaptation, and mitigation research and for studying regional climate feedbacks. For example, the models can be used to study the impacts of extreme weather events or climate change on water resources, biotic resources, and urban climate; societal adaptations to climate change; and land management policies to mitigate climate change over the twenty-first century (Adam et al., 2015). The models provide an integrated framework to assess physical, chemical, and biological responses to the multitude of anthropogenic perturbations in the Earth system, including climate change, CO_2, nitrogen deposition, water extraction, ozone, aerosols, and land use and land cover change. Underlying all this research is the recognition that Earth's ecosystems and watersheds, and their coupling with the atmosphere, are critical elements of global planetary change and planetary habitability.

4.2. Dynamic global vegetation models (DGVM)

A series of conferences and training schools (2007–2008) co-sponsored by iLEAPS addressed several land-atmosphere processes and their modeling: non-CO_2 surface-atmosphere interactions, recent progress of trace gas modeling in dynamic global vegetation models (DGVM), as well as the need for remote sensing, laboratory, and field data to evaluate the model results. One conclusion was that data of sufficient spatial and temporal coverage for parameterisation of those processes that lack mechanistic understanding is clearly lacking, and this will lead to large uncertainties in model calculations that may not be easily resolved in the foreseeable future. As more and more DGVMs develop their “non-CO_2 features”, rather contradictory regional and global emission estimates are expected to emerge. In fact, these estimates should indeed be inconsistent with one another: in the absence of observational constraints, modelers should abstain from the temptation of tuning their models to match results of others (Le Quéré, 2006). However, conflicting results should not lead to a general disbelief in the modeling approaches. Despite the large uncertainties, a number of studies (Arneth et al., 2007, 2011a,b; Lerdau, 2007; Sitch et al., 2007) have suggested that better descriptions of biological processes in emission simulations may yet reveal surprising new features in the chemistry-climate system (*Editorial, iLEAPS Newsletter 6).*

The programme also assessed present knowledge on how land surfaces influence climate variability and changes through their interactions with the atmosphere, at both regional and global scales; and what we know about the important feedbacks between the climate system and the land-surfaces (*Editorial, iLEAPS Newsletter 7*). Land-use transitions determine whether forest within a grid box is primary (old-growth) or secondary (recovering from previous human land-use activities). Carbon budgets and physical feedbacks between the land and the atmosphere are very different in these two forest types; therefore, land-use transitions should be included in all DGVMs contributing to the IPCC 5th assessment report. The conference drafted a wish list of datasets for representing land use in climate models, including details on crop management, irrigation, and fire suppression.

Finally, the programme outlined important processes hitherto omitted in climate modeling, including the role of microorganisms in atmospheric chemistry such as aerosol formation and photochemical processes and the role of volatile organic compounds emitted by vegetation. Soil-plant interactions and the human influence on the linked carbon-nitrogen-phosphorus cycles in plants and soil were also considered very important for better description of carbon, nitrogen, and phosphorus cycling.

4.3. Model evaluation

With so many new applications and new processes being introduced to the models, there is now a strong imperative to evaluate the models. The availability of new observational datasets, for instance for soil moisture or land surface fluxes (Seneviratne et al., 2010; Jung et al., 2010), offer exciting opportunities for better representing basic processes and their interactions with the climate. These evaluations focus on fluxes at diurnal to annual timescales, and there is a need to include biogeochemical processes and ecosystem states in a systematic evaluation of models across multiple spatial and temporal scales (Randerson et al., 2009; Luo et al. 2012). Models of the terrestrial carbon cycle must be additionally tested for long timescale (decadal to centennial) demographic processes (such as mortality), biogeochemical processes (such as litter decomposition and soil organic matter formation), and whole-plant physiological processes (such as carbon allocation). Matching flux tower data over the course of a day or year does not mean that the model performs appropriately for the transient response to climate change, CO_2 fertilisation, or nitrogen deposition. Consequently, the terrestrial carbon cycle and its feedback with climate are routinely assessed in transient simulations over the twentieth century forced with reconstructed meteorology (Sitch et al., 2008; Le Quéré et al., 2009) or in coupled carbon cycle-climate simulations (Friedlingstein et al., 2006). These carbon cycle evaluations must be integrated with the hydrometeorological evaluations (Blyth et al. 2011).

The interrelations of land surface processes mean that there is little to be gained from comparing the model against a single observation. Instead of testing the model against surface states and fluxes, we need to test it against the underlying functions of the model, such as the control of soil moisture on evaporation and runoff. A simple water balance model in combination with multidecadal observations can be utilised to evaluate more complex land surface models and to guide their further development (Koster and Mahanama, 2012). The assumption is that the soil moisture-evapotranspiration (evaporation from surfaces and transpiration by plants) and soil moisture-runoff relationships are, to first order, universal and that the simple model can provide estimates for the underlying relationships that operate in nature, which can then be evaluated against models. A similar proposal is made by (Luo et al., 2012) for the carbon cycle function of the land surface, who give a comprehensive list of possible sources of data for benchmarking the models, ranging from tower flux data, river flows, satellite products and experiments.

4.4. Modeling reveals the significance of land-atmosphere interactions on different scales

The iLEAPS community has clearly shown the crucial importance of including land use and land cover changes in the modeling of land surface processes: the crucial role of terrestrial biogeochemical feedbacks in the climate system is an excellent example. Arneth et al. (2010b) reviewed recent progress in understanding the terrestrial biosphere as a key regulator of atmospheric chemistry and climate. They showed that although research into land-atmosphere exchange processes in climate science has traditionally focused on the surface radiation budget and its effects on sensible and latent heat fluxes, and more recently on carbon-cycle-climate interactions, many more bidirectional land-atmosphere fluxes modulate atmospheric composition and climate. They highlight three principal pathways along which biogeochemical cycles interact with the atmosphere and climate: (1) climate change alters the biogeochemical cycling of greenhouse gases, which act directly as radiative forcing agents (CO_2, CH_4, influenced by N); (2) changes in atmospheric composition influence the biogeochemistry of radiatively active compounds (e.g. changes in O_3 levels influence photosynthesis); (3) climate change alters the biogeochemistry of substances that are not radiatively active themselves (O_3, NO_x, BVOC), but that affect the atmospheric concentration of other climatically active compounds (CO_2, CH_4, aerosols).

Seneviratne et al. (2006) tested regional simulations of recent and future climatic conditions with and without land–atmosphere interactions and found an increase in summer temperature variability predicted in central and eastern Europe mainly due to feedbacks between the land surface and the atmosphere. Furthermore, they found potential migration of climate zones with strong land-atmosphere coupling as a consequence of global warming; both these findings highlighted the crucial role of land-atmosphere interactions in future climate change. In a review of soil moisture-climate interactions, Seneviratne et al. (2010) presented soil moisture as a key variable of the climate system because of its ability to constrain plant transpiration and photosynthesis with consequent influence on the water, energy and biogeochemical cycles. Moreover, it is involved in a number of feedbacks at the local, regional and global scales, and plays a major role in climate-change projections (Jaeger and Seneviratne, 2011; Hirschi et al., 2011).

The WATCH project showed that some changes in land use can reduce evaporation and increase river flows, but that one type of land use, irrigation, has the opposite effect. Overall, results from WATCH confirm the need for land-use change to be considered alongside climate change, and any predictions of future climate ought to include the impact of land-use and land-cover change. Ganzeveld et al. (2010) studied the influence of future land use and land cover changes (LULCC) on atmospheric chemistry-climate interaction with the aim of looking further than the changes in physical climate and the carbon cycle. Using the chemistry-climate model EMAC (ECHAM5/MESSy Atmospheric Chemistry) constrained with present-day and 2050 land cover, land use, and anthropogenic emissions scenarios, they found that future LULCC may result in an increase in global annual soil NO emissions by 9% and a decrease in isoprene emissions by 2%. Boundary-layer ozone mixing ratios may increase up to 9 ppbv, and hydroxyl radical concentrations over deforested areas in Africa will more than double. However, compensating effects were also found, and the main conclusion was that the simulated impact of LULCC on atmospheric chemistry depends on a consistent representation of emissions, deposition, and canopy interactions and their dependence on meteorological, hydrological, and biological drivers to account for these compensating effects. Pitman et al. (2011a) showed the importance of background climate in determining the impact of land-cover change on regional climate: increased greenhouse-gas-driven changes in snow and rainfall affect the snow-albedo feedback and the supply of water, which in turn limits evaporation. These changes largely control the net impact of LULCC on regional climate. Capturing whether future biophysical changes due to LULCC warm or cool a specific region therefore requires an accurate simulation of changes in snow cover and rainfall geographically coincident with regions of LULCC. This is a challenge to current climate models, but also provides potential for further improving detection and attribution methods.

The iLEAPS community has shown the significance of regional differences in climate change effects. Pitman et al. (2011b) state that although global climate models simulate the Earth's climate impressively and reliably at scales of continents and greater, they exclude a suite of processes that are locally and/or regionally important. In areas where some of these regional drivers act strongly, existing regional projections may be wrong, and considerably wrong, because they do not include regionally significant processes. Such local and regional processes include fire, irrigation, land cover change (including crops and urban landscapes), and the emissions of biogenic volatile organic compounds by vegetation (Fig. 6). Many of these interact within the atmosphere via dynamical, physical, and chemical mechanisms that lead to boundary-layer feedbacks. Eventually, improving climate models for policy-relevant spatial scales will require adding regionally important processes into the climate models. Some processes will be more important than others and the case is already clear for land cover change. For other processes, a framework is required to develop modules to represent these processes and to examine and test them in well designed international programs. This will develop an understanding of which are important, where they are important, how important they are, and how they interact with the increasing greenhouse gases. Pitman et al. (2011b) recommend establishing a framework to identify key regional climate drivers, and then building, testing, evaluating, and choosing modules to represent key regional climate drivers well before the 6th assessment report of the IPCC. Beer et al. (2010) also emphasize the importance of regional processes: they show that water availability has a significant effect on terrestrial gross primary production (GPP) over 70% of savannahs, shrublands, grasslands, and agricultural areas and that this feedback effect implies a high susceptibility of these ecosystems' productivity to projected changes of precipitation over the 21st century; on the other hand, tropical and boreal forests will be robust against precipitation changes. Missing feedbacks such as this could help explain the large between-model variation in GPP simulated by state-of-the-art process-oriented biosphere models used for climate predictions. Most likely, the association of GPP and climate in process-oriented models can be improved by including negative feedback mechanisms (e.g., adaptation) that might stabilize the systems.

4.5. New types of models

The iLEAPS community has developed innovative models from local to global scale, combining social and natural science communities and various modeling and observation groups. An example is a modeling activity focused on the Taita Hills in the northernmost part of the Eastern Arc Mountains of Kenya and Tanzania, which is a globally important region for biological conservation. The indigenous cloud forests in this area have suffered substantial degradation for several centuries due to agricultural expansion. In the Taita Hills, currently only 1% of the original forested area remains preserved. In order to create effective policies to preserve the natural resources and biodiversity of the Eastern Arc Mountains, it is crucial to understand the causes and interactions involved in the landscape changes in the most degraded areas. In an innovative collaborative effort between natural sciences and humanities, Maeda et al. (2010) integrated geospatial technology tools and a landscape dynamic simulation

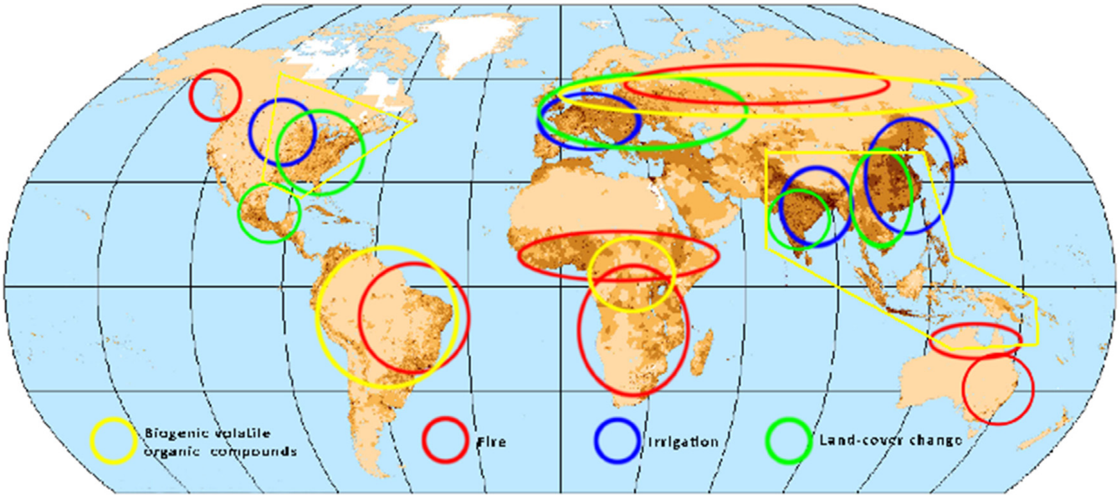

Fig. 6. Regions where emissions of reactive compounds, fire, irrigation, or land-cover change distort the predictions of global models. Adapted from Pitman et al. 2011b.

model to identify and evaluate the driving forces of agricultural expansion and simulate future landscape scenarios locally in Taita Hills. The results indicated that, if current trends persist, agricultural areas will occupy roughly 60% of the study area by 2030. Agricultural expansion will likely take place predominantly in lowlands and foothills throughout the next 20 years, increasing the spatial dependence on distance to rivers and other water bodies. The main factors driving the spatial distribution of new croplands were distance to markets, proximity to already established agricultural areas, and distance to roads.

A much larger-scale collaborative study combined meteorological data, observations provided by satellites, and observations from iLEAPS-affiliated project FLUXNET to produce the first synoptic empirical models of global biosphere-atmosphere carbon, water and sensible heat exchange (Jung et al., 2011). FLUXNET, a global network of eddy covariance towers, generates high spatial- and temporal- resolution measurements of wind speed, trace gas fluxes, and other atmospheric parameters. Combining these point measurements with the broad areal coverage of satellite observations, the authors produced a 0.5° by 0.5° spatial resolution set of monthly data that spanned from 1982 to 2008. Using a machine learning approach—a computational technique that sifts through vast data sets to identify underlying patterns—the authors developed a model that accurately estimated a number of ecosystem-atmosphere fluxes, including the amount of carbon used to fuel plant growth, the carbon produced by the ecosystem, and the latent and sensible energy transfer rates. The authors' model omits a number of known processes and gives up control over how each environmental dynamic is represented in order to generate a model based entirely on observational data. The model revealed many new large-scale patterns of atmosphere-biosphere exchange, such as hotspots of interannual variability and, supporting Beer et al. (2010), the strong control of the water cycle on the carbon cycle. This empirical approach is not meant to replace theoretically-derived simulations, but rather work with them to improve the understanding of environmental dynamics. The global Earth system modeling community is already profiting from this product: for instance, Bonan et al. (2011) used it for improving canopy processes in the Community Land Model version 4 (CLM4).

Finally, one of the largest challenges of surface-atmosphere exchange studies is to cope with the multitude of temporal as well as spatial scales at which land-atmosphere processes occur. Fig. 7 illustrates these scaling issues for surface exchange, but many more Earth system components, such as cloud processes, exhibit the same range of scales. A further complication is that measurements tend to cover a different domain compared to models.

5. Land-atmosphere-society interactions and the policy interface

Climate models used for future global warming predictions and attribution of past changes often consider only global climate drivers and do not take into account local drivers, such as land use change and urban effects (Betts, 2007). One of the main tasks of the iLEAPS community is to inform policy-makers that the impacts of climate change on seemingly separate phenomena such as the hydrological cycle, natural ecosystem and agriculture do interact with one another and will also feed back to climate (Betts, 2007). No climate-related phenomenon exists in isolation; all the phenomena are linked to several processes on land and in the atmosphere, and sometimes improving one aspect will deteriorate another. All these different viewpoints and factors must be taken into account in impact studies and especially when designing solutions toward sustainable development.

Artaxo, (2012) describes how scientists wanting to implement change must collaborate between disciplines in natural sciences and in social sciences as well and gives as a prime example the ambitious research activities that have been conducted in the Amazon. Investigators there have had unprecedented success in

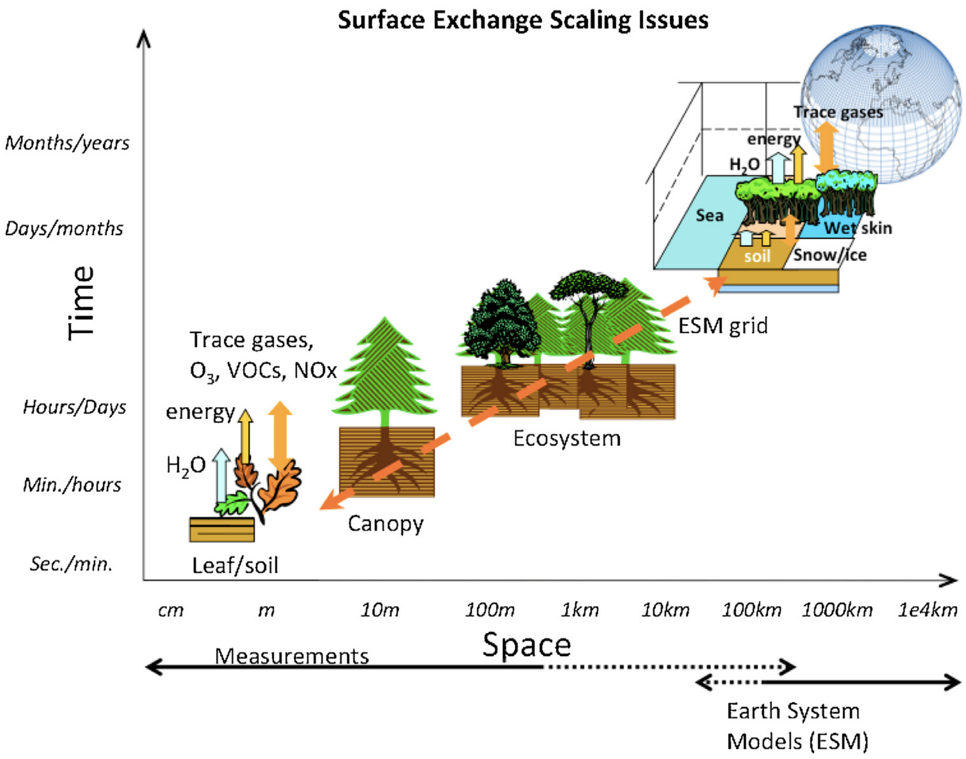

Fig. 7. One of the largest challenges of land-atmosphere processes research is to cope with the multitude of temporal as well as spatial scales. Fig. is courtesy of Laurens Ganzeveld.

enabling cooperation and collaboration between physicists, chemists, meteorologists and biologists, even economists and social scientists who joined in the research. This was necessary in order to fully understand all the factors influencing a complex system such as the climatically and anthropogenically influenced Amazon basin. Ongoing research programs now join forces with iLEAPS/IGAC project ACPC and many other agents in GoAmazon, a multi-organisation, multi-disciplinary field campaign on aerosol-surface flux–cloud interactions. The Amazon Basin has strong coupling between terrestrial ecosystems and the hydrologic cycle (Fig. 8). Combining ground-based and aircraft observations and modeling, GoAmazon will provide the necessary observations to study how aerosols and surface fluxes influence cloud cycles under clean and polluted conditions. The main aim is to develop a data-driven knowledge base for predicting how the present-day functioning of energy, carbon, and chemical flows in the Amazon basin might change, both due to external forcing by global climate change and internal forcing from past and projected demographic changes.

The iLEAPS-endorsed European Integrated project on Aerosol Cloud Climate and Air Quality Interactions, EUCAARI (2007–2010), brought together the leading European research groups, state-of-the-art infrastructure, and key players from third-world countries to investigate the role of aerosol on climate and air quality (Kulmala et al., 2011b). The objectives of EUCAARI were (I) reduction of the current uncertainty of the impact of aerosol particles on climate by 50% and quantification of the relationship between anthropogenic aerosol particles and regional air quality, and (II) quantification of the side effects of European air quality directives on global and regional climate. EUCAARI also contributed to technological developments in the aerosol measurements, enhancing future experiments and air-quality monitoring networks. New ground-based, aircraft and satellite measurements were integrated with existing data to produce a globally consistent dataset with the highest possible accuracy (Fig. 9). A European measurement campaign was designed along north-south and east-west transects around simultaneous multi-station observations, Lagrangian aircraft measurements and carefully selected “super-sites”. A hierarchy of models was developed based on the results of the laboratory and theoretical investigations. The models will be used to interpret the measurements and will be integrated into regional air quality and global climate models. The result was measurable improvements in the project’s climate and air quality models. The outcomes (scenarios, recommendations, models, harmonized datasets and new knowledge) were disseminated to authorities, policy makers, the research community, industry, instrument designers, and the EU-ESA Global Monitoring for Environment and Security (GMES) Program.

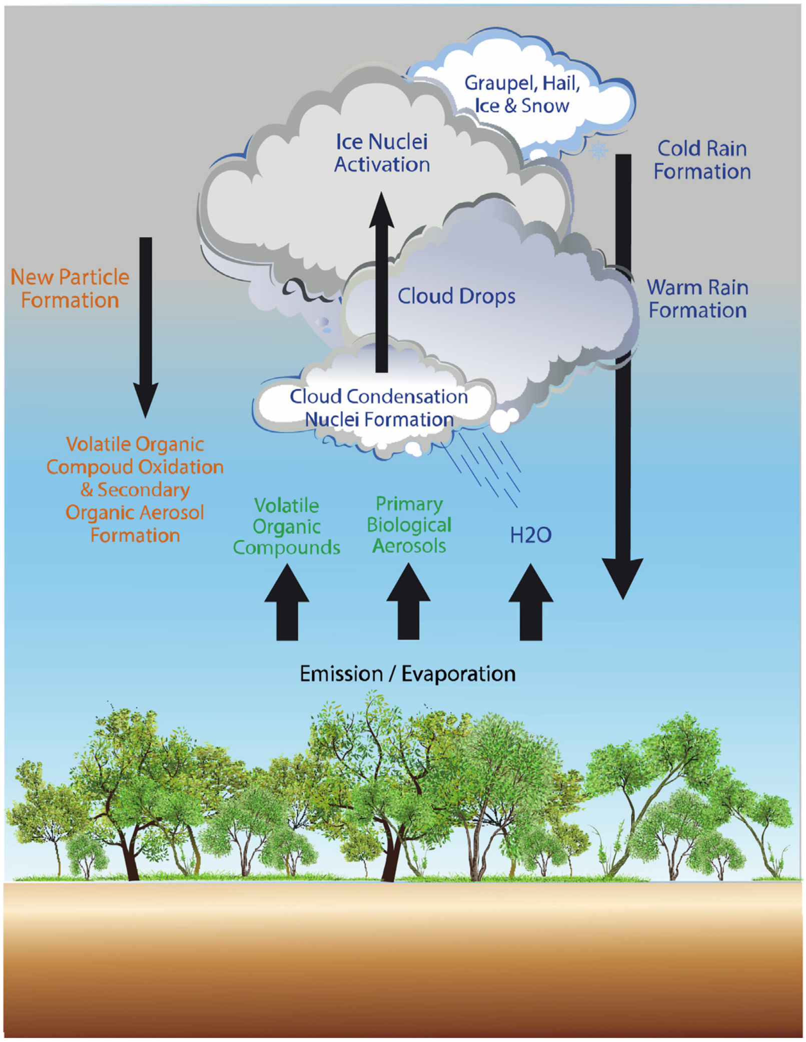

Fig. 8. Aerosol and water cycling over the pristine rainforest. Secondary organic aerosol formed by photo-oxidation of volatile organic compounds and primary biological aerosol emitted from biota in the rainforest (plants and microorganisms) serve as biogenic nuclei for cloud condensation nuclei and ice nuclei, which induce warm or cold rain formation, precipitation, and wet deposition of gases and particles. Adapted from Pöschl et al. (2010).

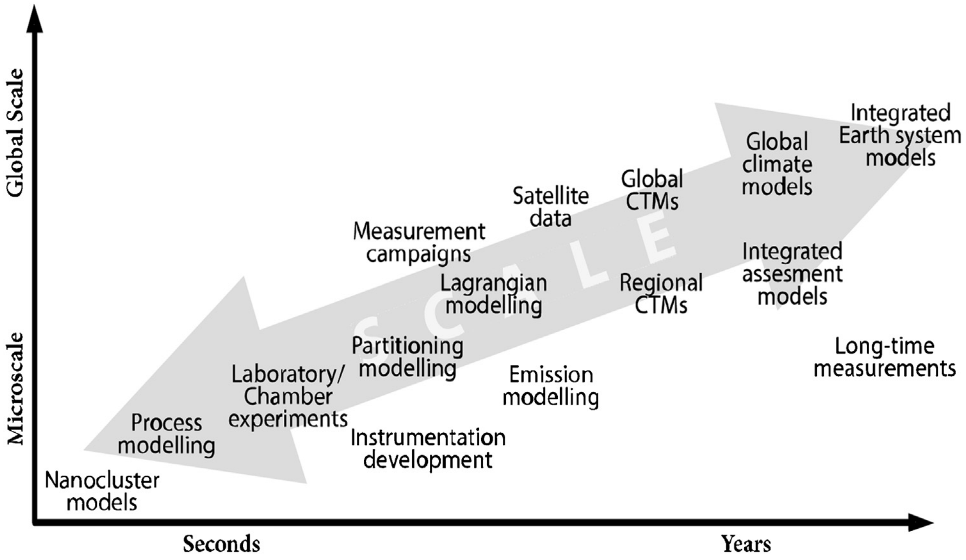

Fig. 9. The EUCAARI Approach: The EUCAARI scientific plan was designed as a research chain that aimed to advance our understanding of climate and air quality through a series of connected activities beginning at the molecular scale and finishing at the regional and global scale. Kulmala et al., 2011b.

6. Capacity building

iLEAPS events including conferences, workshops, annual summer and winter schools, and other training schools have proved effective in developing a community fluent in multidisciplinary process understanding and with a thorough understanding of the complexity of global change issues. The iLEAPS-Marie Curie training programme in 2007–2008 aimed at improving our understanding of those land ecosystem-atmosphere processes that drive global change. The training programme focused on the theoretical and methodological aspects of the transport and transformation of energy and matter between land ecosystems and the atmosphere. The programme consisted of four events: (1) Training course on “Integrated measurements over land ecosystem atmosphere boundaries”; (2) Conference on “Toward a process-based description of trace gas emissions in land surface models”; (3) Training course on “Physics and chemistry of air pollution and their effects: field course and data analysis”; and (4) Conference on “Feedbacks-Land-Climate Dynamics-Key Gaps”.

iLEAPS pays special attention to early-career scientists and provides state-of-the-art training on topics such as modeling, remote sensing, data analysis, communication and writing skills, and researcher/media/policy relations in the popular Conference Early-Career Scientist Programme and Early-Career Scientist Workshops (2006 Boulder, Colorado; 2009 Melbourne, Australia; 2011 Garmisch-Partenkirchen, Germany) and in Training schools (annual multidisciplinary, international summer schools on measurement techniques and data analysis on land-atmosphere interactions in Hyytiälä, Finland, and in 2011 in Tuczno, Poland). iLEAPS also supports participants from developing countries to conferences and training schools to ensure truly global coverage. The iLEAPS newsletter with a hard-copy circulation of ca. 3000 and available online to the whole community and beyond highlights important aspects of iLEAPS work to large audiences.

7. Conclusions

With the emerging Future Earth, iLEAPS will initiate and join integrated activities that aim at providing sustainable solutions via co-designing with funders, scientists, and private sector stakeholders relevant to the question at hand. The Initiatives that iLEAPS is developing in collaboration with its sister projects include the joint iLEAPS-GEWEX initiative Aerosols, Clouds, Precipitation, Climate (ACPC) that was restructured in early 2013; the joint iLEAPS-GLP-AIMES initiative Interactions among Managed Ecosystems, Climate, and Societies (IMECS); the joint IGAC-iLEAPS-WMO Interdisciplinary Biomass Burning Initiative (IBBI); the joint iLEAPS-GEWEX theme on Bridging the Gaps between Hydrometeorological and Biogeochemical Land-Surface Modeling; the joint iLEAPS-ESA initiative Biosphere-Atmosphere-Society Index; the Extreme Events and Environments (EEE) initiative that aims to connect the two separate communities working on temporary climate extremes and permanently extreme environments, respectively, to shed light on the adaptive capacities of the Earth’s ecosystems and societies; and the ambitious international programme The Pan-Eurasian Experiment (PEEX) that includes more than 40 institutes in Europe, Russia, and China. In addition to these active initiatives, more work is in preparation: iLEAPS is planning to engage with the adaptation community on hotspot areas especially in the Arctic and in Africa, with Latin America and East and South Asia in mind as well. The regional offices of iLEAPS (iLEAPS-Eurasia, iLEAPS-China, iLEAPS-Japan, and iLEAPS-Korea) are a crucial element of this work.

Over the last decade, the importance of land-atmosphere processes and feedbacks in the Earth system has been shown on many levels and with multiple approaches, and a number of publications have shown the crucial role of the terrestrial ecosystems as regulators of climate and atmospheric composition. Modelers have clearly shown the adverse effect of neglecting land cover changes and other feedback processes in current Earth system models and recommended actions to improve them. Unprecedented insights of the long-term net impacts of aerosols on clouds and precipitation have also been provided. Land-cover change has been emphasized with model intercomparison projects that showed that realistic land-use representation was essential in land surface modeling. Crucially important tools in this research have been the networks of long-term flux stations and large-scale land-atmosphere observation platforms that are also beginning to combine remote sensing techniques with ground observations.

The first decade of iLEAPS work (2004–2014) focussed mainly on natural, pristine environments. The result has been a substantial increase in our understanding of the processes controlling land-atmosphere interactions, but still the uncertainties related to their role in the Earth system are large. In addition, increasingly, the main influence modifying ecosystems is human society. Humans are now one of the strongest influences on climate and the environment in the history of the Earth, and can no longer be ignored in studies of the Earth system and land-atmosphere interactions. The second phase of iLEAPS (2014–2024) will concentrate on interactions between natural and human systems and on feedbacks among climate, atmospheric chemistry, land use and land cover changes, socioeconomic development, and human decision-making. iLEAPS will contribute to Future Earth's agenda to provide research and knowledge to support the transformation of societies toward global sustainability.

Appendix I.

Abbreviations

ACPC	Aerosols, Clouds, Precipitation, Climate
ALANIS	Atmosphere-LANd Integrated Study (an ESA-iLEAPS project)
ESA	European Space Agency
EUCAARI	The European Integrated project on Aerosol Cloud Climate and Air Quality Interactions
GEWEX	Global Energy and Water Exchanges (a WCRP core project)
IGBP	International Geosphere-Biosphere Programme
iLEAPS	Integrated Land Ecosystem–Atmosphere Processes Study
IMECS	Interactions among Managed Ecosystems, Climate, and Societies
LBA	Large Scale Biosphere-Atmosphere Experiment
QUEST	Quantification of Aerosol Nucleation in the European Boundary Layer
Sat-ACPC	Remote sensing applications in Aerosols, Clouds, Precipitation, Climate
SMEAR	Station for Measuring Ecosystem–Atmosphere Relations
WCRP	World Climate Research Programme

References

ACPC, 2009. Aerosols, Clouds, Precipitation and Climate - Science Plan & Implementation Strategy. IGBP/WCRP, Melbourne.

Adam, J., Stephens, J., Chung, S., Brady, M., Evans, R.D., Kruger, C., Lamb, B., Liu, M., Stöckle, C., Vaughan, J., Rajagopalan, K., Harrison, J., Tague, C., Kalyanaraman, A., Chen, Y., Guenther, A., Leung, F.-Y., Leung, L.R., Perleberg, A., Yoder, J., Allen, E., Anderson, S., Chandrasekharan, B., Malek, K., Mullis, T., Miller, C., Nergui, T., Poinsatte, J., Reyes, J., Zhu, J., Choate, J., Jiang, X., Nelson, R., Yoon, J.-H., Yorgey, G., Johnson, K., Chinnayakanahalli, K., Hamlet, A., Nijssen, B., Walden, V., 2015. BioEarth: envisioning and developing a new regional earth system model to inform natural and agricultural resource management. Clim. Change 129, 555–571.

Amogu, O., Descroix, L., Yero, K.S., Le Breton, E., Mamadou, I., Ali, A., Vischel, T., Bader, J.C., Moussa, I.B., Gautier, E., Boubkraoui, S., Belleudy, P., 2010. Increasing river flows in the Sahel? Water 2, 170–199. doi:http://dx.doi.org/10.3390/w2020170.

Andreae, M.O., Jones, C.D., Cox, P.M., 2005. Strong present-day aerosol cooling implies a hot future. Nature 435, 1187–1190.

Arneth, A., Niinemets, U., Pressley, S., Bäck, J., Hari, P., Karl, T., Noe, S., Prentice, I.C., Serca, D., Hickler, T., Wolf, A., Smith, B., 2007. Process-based estimates of terrestrial ecosystem isoprene emissions incorporating the effects of direct CO_2-isoprene interactions. Atmos. Chem. Phys. 7, 31–53.

Arneth, A., Harrison, S.P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P.J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S., Vesala, T., 2010a. Terrestrial biogeochemical feedbacks in the climate system. Nat. Geosci. 3, 525–532. doi:http://dx.doi.org/10.1038/ngeo905.

Arneth, A., Sitch, S., Bondeau, A., Butterbach-Bahl, K., Foster, P., Gedney, N., de Noblet-Ducoudré, N., Prentice, I.C., Sanderson, M., Thonicke, K., Wania, R., Zaehle, S., 2010b. From biota to chemistry and climate towards a comprehensive description of trace gas exchange between the biosphere and atmosphere. Biogeosciences 7, 121–149.

Arneth, A., Unger, N., Kulmala, M., Andreae, M.O., 2009. Clean the Air, Heat the Planet? Science 326, 672–673.

Artaxo, P., 2012. Break down boundaries in climate research. Nature 481, 239. doi:http://dx.doi.org/10.1038/481239a.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw, K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82, 2415–2434.

Baldocchi, D.D., Black, T.A., Curtis, P.S., Falge, E., Fuentes, J.D., Granier, A., Gu, L., Knohl, A., Pilegaard, K., Schmid, H.P., Valentini, R., Wilson, K., Wofsy, S., Xu, L., Yamamoto, S., 2005. Predicting the onset of net carbon uptake by deciduous forests with soil temperature and climate data: a synthesis of FLUXNET data. Int. J. Biometeorol. 49, 377–387.

Barkley, M.P., Palmer, P.I., De Smedt, I., Karl, T., Guenther, A., Van Roozendael, M., 2009. Regulated large-scale annual shutdown of Amazonian isoprene emissions? Geophys. Res. Lett. 36, L04803. doi:http://dx.doi.org/10.1029/2008GL036843.

Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, N., Arain, M.A., Baldocchi, D., Bonan, G.B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K.W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F.I., Papale, D., 2010. Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Science 329, 834. doi:http://dx.doi.org/10.1126/science.1184984.

Betts, R., 2007. Implications of land ecosystem-atmosphere interactions for strategies for climate change adaptation and mitigation. Tellus 59B, 602–615.

Blyth, E., Clark, D.B., Ellis, R., Huntingford, C., Los, S., Pryor, M., Best, M., Sitch, S., 2011. A comprehensive set of benchmark tests for a land surface model of simultaneous fluxes of water and carbon at both the global and seasonal scale. Geosci. Model Dev. 4, 255–269. doi:http://dx.doi.org/10.5194/gmd-4-255-2011.

Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320, 1444–1449.

Bonan, G.B., Lawrence, P.J., Oleson, K.W., Levis, S., Jung, M., Reichstein, M., Lawrence, D.M., Swenson, S.C., 2011. Improving canopy processes in the community land model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data. J. Geophys. Res. 116 doi:http://dx.doi.org/10.1029/2010 JG001593 G02014, 22 PP.

Ciais, P.H., Reichstein, M., Viovy, N., Granier, A., Ogree, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., de Noblet-Ducoudré, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ouscival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Santz, M.J., Schulze, A.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437 (22), 529–533.

Davidson, E.A., de Araujo, A., Artaxo, P., Balch, J., Brown, I., Bustamante, M., Coe, M., DeFries, R., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza Jr, C., Wofsy, S., 2012a. The Amazon basin in transition. Nature 481, 321–328. doi:http://dx.doi.org/10.1038/nature10717.

Davin, E.L., Seneviratne, S.I., 2011. Role of land surface processes and diffuse/direct radiation partitioning in simulating the European climate. Biogeosci. Discuss. 8, 11601–11630.

de Leeuw, G., Arola, A., Sogacheva, L., Kivekäs, N., Kerminen, V.M., Arneth, A., Christensen, T., Korhonen, H., Partanen, A.I., Lappalainen, H., Kolmonen, P., Mielonen, T., Sofiev, M., Kulmala, M., Pinnock, S., 2011. On the use of satellites to obtain information on the occurrence of natural and anthropogenic aerosols over the boreal Eurasian forest. iLEAPS in. Biogeosci. Discuss. 8, 8451–8483 special issue.

de Noblet-Ducoudre', N., Boisier, J.P., Pitma, A.J., Bonan, G.B., Brovkin, V., Cruz, F., Delire, C., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Müller, C., Reick, C.H., Strengers, B.J., Voldoire, A., 2012. Determining robust impacts of land-use induced land-cover changes on surface climate over North America and Eurasia; results from the first set of LUCID experiments. J. Clim. doi:http://dx.doi.org/10.1175/JCLI-D-11-00338.1.

Ding, A., Wang, T., Thouret, V., Cammas, J.-P., Nedelec, P., 2008. Tropospheric ozone climatology over Beijing: analysis of aircraft data from the MOZAIC program. Atmos. Chem. Phys. 8, 1–13.

Davidson, E.A., de Araujo, A., Artaxo, P., Balch, J., Brown, I., Bustamante, M., Coe, M., DeFries, R., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza Jr., C., Wofsy, S., 2012b. The Amazon basin in transition. Nature 481, 321–328. doi:http://dx.doi.org/10.1038/nature10717.

Flament, P., Deboudt, K., Cachier, H., Chatenet, B., Meriaux, X., 2011. Mineral dust and carbonaceous aerosols in West Africa: source assessment and characterization. Atm. Env. 45, 3742–3749. doi:http://dx.doi.org/10.1016/j.atmosenv.2011.04.013.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C., Zeng, N., 2006. Climate-carbon cycle feedback analysis results from the C4MIP model intercomparison. J. Clim. 19, 3337–3353.

Gardelle, J., Hiernaux, P., Kergoat, L., Grippa, M., 2010. Less rain, more water in ponds: a remote sensing study of the dynamics of surface waters from 1950 to present in pastoral Sahel (Gourma region, Mali). Hydrol. Earth Syst. Sci. 14, 309–324.

Ganzeveld, L., Bouwman, E., van Vuuren, D.P., Eickhout, B., Lelieveld, J., 2010. The impact of future land-use and land-cover changes on atmospheric chemistry-climate interactions. J. Geophys. Res. 115, D23. doi:http://dx.doi.org/10.1029/2010 JD014041.

Ganzeveld, L., Helmig, D., Fairall, C.W., Hare, J., Pozzer, A., 2009. Atmosphere-ocean exchange: A global modelling study of biogeochemical, atmospheric, and waterside turbulence dependencies. Global Biogeochem. Cycles 23 doi:http://

dx.doi.org/10.1029/2008gb003301 GB 4021, . Also published in Research highlights: Into the ocean (2009) Nature Geoscience 2, 670, :10.1038/ngeo653.

Ghehi, G., Werner, N.C., Cizungu Ntaboba, L., Mbonigaba Muhinda, L.L., Van Ranst, E., Butterbach-Bahl, K., Kiese, R., Boeckx, P., 2011. Spatial variations of nitrogen trace gas emissions from tropical mountain forests in Nyungwe, Rwanda. Biogeosci. Discuss. 8, 11631–11660.

Guenther, A., Kulmala, M., Turnipseed, A., Rinne, J., Suni, T., Reissell, A., 2011. Integrated land ecosystem-atmosphere processes study (iLEAPS) assessment of global observational networks. Boreal Environ. Res. 16, 321–336.

Harding, R., Best, M., Blyth, E., Hagemann, S., Kabat, P., Tallaksen, L.M., Warnaars, T., Wiberg, D., Weedon, G.P., van Lanen, H., Ludwig, F., Haddeland, I., 2011. WATCH: current knowledge of the terrestrial global water cycle. J. Hydrometeorol. 12, 1149–1156. doi:http://dx.doi.org/10.1175/jhm-d-11-024.1.

Hari, P., Kulmala, M., 2005. Station for measuring ecosystem-atmosphere relations (SMEAR II). Boreal Environ. Res. 10, 315–322.

Hari, P., Andreae, M.O., Kabat, P., Kulmala, M., 2009. A comprehensive network of measuring stations to monitor climate change. Boreal Environ. Res. 14, 442–446.

Hewitt, C.N., Lee, J.D., MacKenzie, A.R., Barkley, M.P., Carslaw, N., Carver, G.D., Chappell, N.A., Coe, H., Collier, C., Commane, R., Davies, F., Davison, B., DiCarlo, P., Di Marco, C.F., Dorsey, J.R., Edwards, P.M., Evans, M.J., Fowler, D., Furneaux, K.L., Gallagher, M., Guenther, A., Heard, D.E., Helfter, C., Hopkins, J., Ingham, T., Irwin, M., Jones, C., Karunaharan, A., Langford, B., Lewis, A.C., Lim, S.F., MacDonald, S. M., Mahajan, A.S., Malpass, S., McFiggans, G., Mills, G., Misztal, P., Moller, S., Monks, P.S., Nemitz, E., Nicolas-Perea, V., Oetjen, H., Oram, D.E., Palmer, P.I., Phillips, G.J., Pike, R., Plane, J.M.C., Pugh, T., Pyle, J.A., Reeves, C.E., Robinson, N.H., Stewart, D., Stone, D., Whalley, L.K., Yin, X., 2010. Overview: oxidant and particle photochemical processes above a south-east Asian tropical rainforest (the OP3 project): introduction, rationale, location characteristics and tools. Atmos. Chem. Phys. 10, 169–199.

Hirschi, M., Seneviratne, S.I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O. B., Formayer, H., Orlowsky, B., Stepanek, P., 2011. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. Nat. Geosci. 4, 17–21. doi:http://dx.doi.org/10.1038/ngeo1032.

Jaeger, E.B., Seneviratne, S.I., 2011. Impact of soil moisture-atmosphere coupling on European climate extremes and trends in a regional climate model. Clim. Dyn. 36 (9–10), 1919–1939. doi:http://dx.doi.org/10.1007/s00382-010-0780-8.

Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A.D., Arain, M.A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B.E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E.J., Papale, D., Sottocornola, M., Vaccari, F., Williams, C., 2011. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. J. Geophys. Res. Biogeosci. 116, G00J07. doi:http://dx.doi.org/10.1029/2010 JG001566.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G., Cescatti, A., Chen, J., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron, N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K., Papale, D., Richardson, A.D., Roupsard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U., Williams, C., Wood, E., Zaehle, S., Zhang, K., 2010. A recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature 467, 951–954.

Karl, T., Harley, P., Emmons, L., Thornton, B., Guenther, A., Basu, C., Turnipseed, A., Jardine, K., 2010. Efficient atmospheric cleansing of oxidized organic trace gases by vegetation. Science 330, 816–819.

Keller, M., Bustamante, M., Gash, J., Dias, P., 2009. Amazonia and Global Change. American Geophysical Union, Washington, DC, pp. 565.

Koster, R.D., Mahanama, S.P.P., 2012. Land surface controls on hydroclimatic means and variability. J. Hydrometeorol. 13, 1604–1620. doi:http://dx.doi.org/10.1175/ jhm-d-12-050.1.

Koster, R.D., Dirmeyer, P.A., Guo, Z.C., Bonan, G., Chan, E., Cox, P., Gordon, C.T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C.H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y.C., Taylor, C.M., Verseghy, D., Vasic, R., Xue, Y.K., Yamada, T., 2004. Regions of strong coupling between soil moisture and precipitation. Science 306, 1138–1140.

Kulmala, M., Arola, A., Nieminen, T., Riuttanen, L., Sogacheva, L., de Leeuw, G., Kerminen, V.-M., Lehtinen, K.E.J., 2011a. The first estimates of global nucleation mode aerosol concentrations based on satellite measurements. Atmos. Chem. Phys. 11 (21), 10791–10801.

Kulmala, M., Asmi, A., Lappalainen, H.K., Baltensperger, U., Brenguier, J.-L., Facchini, M.C., Hansson, H.-C., Ø. Hov, O'Dowd, C., Pöschl, U., Wiedensohler, A., Boers, R., Boucher, O., de Leeuw, G., 2011b. General overview European integrated project on aerosol cloud climate and air quality interactions (EUCAARI)-integrating aerosol research from nano to global scales. Atmos. Chem. Phys. 11, 13061–13143.

Kulmala, M., Petäjä, T., 2011. Soil nitrites influence atmospheric chemistry. Science 333, 1586–1587. doi:http://dx.doi.org/10.1126/science.1211872.

Kulmala, M., Suni, T., Lehtinen, K.E.J., Dal Maso, M., Boy, M., Reissell, A., Rannik, Ü., Aalto, P., Keronen, P., Hakola, H., Bäck, J., Hoffmann, T., Vesala, T., Hari, P., 2004. A new feedback mechanism linking forests, aerosols, and climate. Atmos. Chem. Phys. 4, 557–562.

Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., Bopp, L., Ciais, P., Conway, T.J., Doney, S.C., Feely, R.A., Foster, P.N., Friedlingstein, P., Gurney, K., Houghton, R.A., House, J.I., Huntingford, C., Levy, P.E., Lomas, M.R., Majkut, J., Metzl, N., Ometto, J. P., Peters, G.P., Prentice, I.C., Randerson, J.T., Running, S.W., Sarmiento, J.L., Schuster, U., Sitch, S., Takahashi, T., Viovy, N., van der Werf, G.R., Woodward, F.I., 2009. Trends in the sources and sinks of carbon dioxide. Nat. Geosci. 2, 831–836.

Le Quéré, 2006. Eos, Transactions. The Unknown and the Uncertain in Earth System Modeling, vol. 87. American Geophysical Union, pp. 496 490.1029/2006 EO450007.

Lerdau, M., 2007. A positive feedback with negative consequences. Science 316 (5822), 212–213. doi:http://dx.doi.org/10.1126/science.1141486.

Levis, S., 2010. Modelling vegetation and land use in models of the Earth system. WIREs Clim. Change 1, 840–856.

Li, Z., Niu, F., Fan, J., Liu, Y., Rosenfeld, D., Ding, Y., 2011. Long-term impacts of aerosols on the vertical development of clouds and precipitation. Nat. Geosci. 4, 888–894. doi:http://dx.doi.org/10.1038/ngeo1313.

Loreto, F., Bagnoli, F., Fineschi, S., 2009. One species, many terpenes: matching chemical and biological diversity. Trends Plant Sci. 14, 416–420.

Luo, Y.Q., Randerson, J.T., Abramowitz, G., Bacour, C., Blyth, E., Carvalhais, N., Ciais, P., Dalmonech, D., Fisher, J.B., Fisher, R., Friedlingstein, P., Hibbard, K., Hoffman, F., Huntzinger, D., Jones, C.D., Koven, C., Lawrence, D., Li, D.J., Mahecha, M., Niu, S.L., Norby, R., Piao, S.L., Qi, X., Peylin, P., Prentice, I.C., Riley, W., Reichstein, M., Schwalm, C., Wang, Y.P., Xia, J.Y., Zaehle, S., Zhou, X.H., 2012. A framework for benchmarking land models. Biogeosciences 9, 3857–3874.

Maeda, E.E., Barnaby, J.F., Clark, B., Pellikka, P., Siljander, M., 2010. Modelling agricultural expansion in Kenya's eastern arc mountains biodiversity hotspot. Agric. Syst. 103 (9), 609–620. http://EconPapers.repec.org/RePEc:eee:agisys: v:103:y:2010:i:9:p:609-620.

Mahecha, M.D., Reichstein, M., Carvalhais, N., Lasslop, G., Lange, H., Seneviratne, S.I., Vargas, R., Ammann, C., Arain, M.A., Cescatti, A., Janssens, I.A., Migliavacca, M., Montagnani, L., Richardson, A.D., 2010. Global convergence in the temperature sensitivity of respiration at ecosystem level. Science 329, 838. doi:http://dx.doi.org/10.1126/science.1189587.

Mauldin III, R.L., Berndt, T., Sipilä, M., Paasonen, P., Petäjä, T., Kim, S., Kurtén, T., Stratmann, F., Kerminen, V.M., Kulmala, M., 2012. A new atmospherically relevant oxidant of sulphur dioxide. Nature 488, 193–196.

Ortega, J., Turnipseed, A., Guenther, A.B., Karl, T.G., Day, D.A., Gochis, D., Huffman, J. A., Prenni, A.J., Levin, E.J.T., Kreidenweis, S.M., DeMott, P.J., Tobo, Y., Patton, E.G., Hodzic, A., Cui, Y.Y., Harley, P.C., Hornbrook, R.S., Apel, E.C., Monson, R.K., Eller, A. S.D., Greenberg, J.P., Barth, M.C., Campuzano-Jost, P., Palm, B.B., Jimenez, J.L., Aiken, A.C., Dubey, M.K., Geron, C., Offenberg, J., Ryan, M.G., Fornwalt, P.J., Pryor, S.C., Keutsch, F.N., DiGangi, J.P., Chan, A.W.H., Goldstein, A.H., Wolfe, G.M., Kim, S., Kaser, L., Schnitzhofer, R., Hansel, A., Cantrell, C.A., Mauldin, R.L., Smith, J.N., 2014. Overview of the Manitou experimental forest observatory: site description and selected science results from 2008 to 2013. Atmos. Chem. Phys. 14, 6345–6367.

Oswald, R., Behrendt, T., Ermel, M., Wu, D., Su, H., Cheng, Y., Breuninger, C., Moravek, A., Mougin, E., Delon, C., Loubet, B., Pommerening-Röser, A., Pöschl, U., Hoffmann, T., Andreae, M.O., Meixner, F.X., Trebs, I., 2013. HONO emissions from soil bacteria as a major source of atmospheric reactive nitrogen. Nature 341, 1233–1235. doi:http://dx.doi.org/10.1126/science.1242266.

Philippon, N., Mougin, E., Jarlan, L., Frison, P.-L., 2005. Analysis of the linkages between rainfall and land surface conditions in the West African monsoon through CMAP, ERS-WSC, and NOAA-AVHRR data. J. Geophys. Res. 110, D24115. doi:http://dx.doi.org/10.1029/2005JD006394.

Pitman, A.J., Arneth, A., Ganzeveld, L., 2011b. Regionalizing global climate models. Int. J. Climatol. doi:http://dx.doi.org/10.1002/joc.2279.

Pitman, A.J., Avila, F.B., Abramowitz, G., Wang, Y.P., Phipps, S.J., de Noblet-Ducoudre', N., 2011a. Importance of background climate in determining impact of land-cover change on regional climate. Nat. Clim. Change doi:http://dx.doi.org/ 10.1038/NCLIMATE1294.

Pitman, A.J., de Noblet-Ducoudré, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Müller, C., Reick, C.H., Seneviratne, S.I., Strengers, B.J., Voldoire, A., 2009. Uncertainties in climate responses to past land cover change first results from the LUCID intercomparison study. Geophys. Res. Lett. 36, L14814.

Pöschl, U., Martin, S.T., Sinha, B., Chen, Q., Gunthe, S.S., Huffman, J.A., Borrmann, S., Farmer, D.K., Garland, R.M., Helas, G., Jimenez, J.L., King, S.M., Manzi, A., Mikhailov, E., Pauliquevis, T., Petters, M.D., Prenni, A.J., Roldin, P., Rose, D., Schneider, J., Su, H., Zorn, S.R., Artaxo, P., Andreae, M.O., 2010. Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. Science 329, 1513–1516.

Randerson, J.T., Hoffman, F.M., Thornton, P.E., Mahowald, N.M., Lindsay, K., Lee, Y.-H., Nevison, C.D., Doney, S.C., Bonan, G., Stöckli, R., Covey, C., Running, S.W., Fung, I. Y., 2009. Systematic assessment of terrestrial biogeochemistry in coupled climate-carbon models. Global Change Biol. 15, 2462–2484.

Rosenfeld, D., Lohmann, U., GB, R., O'Dowd, C.D., Kulmala, M., Fuzzi, S., Reissell, A., Andreae, M.O., 2008. Flood or drought: how do aerosols affect precipitation? Science 322, 1309–1313.

Rosenfeld, D., Williams, E., Andreae, M.O., Freud, E., Pöschl, U., Rennó, N.O., 2012. The scientific basis for a satellite mission to retrieve CCN concentrations and their impacts on convective clouds. Atmos. Meas. Technol. 5, 2039–2055.

Rosenfeld, D., Wood, R., Donner, L., Sherwood, S., 2013. Aerosol cloud-mediated radiative forcing: highly uncertain and opposite effects from shallow and deep clouds. Res. Modell. Pred. Prior. 105–149.

Saigusa, N., Ichii, K., Murakami, H., Hirata, R., Asanuma, J., Den, H., Han, S.J., Ide, R., Li, S.G., Ohta, T., Sasai, T., Wang, S.Q., Yu, G.R., 2010. Impact of meteorological anomalies in the 2003 summer on gross primary productivity in East Asia. Biogeosciences 7, 641–655.

Seneviratne, S.I., Lüthi, D., Litschi, M., Schär, Ch., 2006. Land-atmosphere coupling and climate change in Europe. Nature 443, 205–209.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture-climate interactions in a changing climate: a review. Earth Sci. Rev. 4, 125–161. doi:http://dx.doi.org/10.1016/j.earscirev.2010.02.004.

Siljander, M., Clark, B., Pellikka, P., 2011. A predictive modelling technique for human population distribution and abundance estimation using remote sensing and geospatial data in rural mountainous area in Kenya. Int. J. Remote Sens. 32 (21), 5997–6023.

Sitch, S., Cox, P.M., Collins, W.J., Huntingford, C., 2007. Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. Nature 448, 791–794. doi:http://dx.doi.org/10.1038/nature06059.

Sitch, S., Huntignford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C.D., Prentice, I.C., Woodward, F.I., 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five dynamic global vegetation models (DGVMs). Global Change Biol. 14, 2015–2039.

Spracklen, D.V., Arnold, S.R., Taylor, C.M., 2012. Observations of increased tropical rainfall preceded by air passage over forests. Nature 489, 282–285.

Stahl, K., Tallaksen, L.M., 2010. In: Servat, E., Demuth, S., Dezetter, A., Daniell, T. (Eds.), RCM Simulated and Observed Hydrological Drought a Comparison of the 1976 and 2003 Events in Europé in Global Change: Facing Risks and Threats to Water Resources, vol. 340. IAHS Publication, pp. 150–156.

Stevens, B., Feingold, G., 2009. Untangling aerosol effects on clouds and precipitation in a buffered system. Nature 461, 607–613. doi:http://dx.doi.org/10.1038/nature08281.

Su, H., Cheng, Y., Oswald, R., Behrendt, T., Trebs, I., Meixner, F.X., Andreae, M.O., Cheng, P., Zhang, Y., Pöschl, U., 2011. Soil nitrite as a source of atmospheric HONO and OH radicals. Science 333 (6049), 1616–1618. doi:http://dx.doi.org/10.1126/science.1207687.

Teuling, A., Seneviratne, S.I., Stöckli, R., Reichstein, M., Moors, E., Ciais, P., Luyssaert, S., van den Hurk, B., Ammann, C., Bernhofer, C., Dellwik, E., Gianelle, D., Gielen, B., Grünwald, T., Klumpp, K., Montagnani, L., Moureaux, C., Sottocornola, M., Wohlfahrt, G., 2010. Contrasting response of European forest and grassland energy exchange to heat waves. Nat. Geosci. 3, 722–727. doi:http://dx.doi.org/10.1038/ngeo950.

Tunved, P., Hansson, H.C., Kerminen, V.M., Strom, J., Dal Maso, M., Lihavainen, H., Viisanen, Y., Aalto, P.P., Komppula, M., Kulmala, M., 2006. High natural aerosol loading over boreal forests. Science 312 (5771), 261–263. doi:http://dx.doi.org/10.1126/science.1123052.

Vakkari, V., Laakso, H., Kulmala, M., Laaksonen, A., Mabaso, D., Molefe, M., Kgabi, N., Laakso, L., 2011. New particle formation events in semi-clean South African savannah. Atmos. Chem. Phys. 11, 3333–3346. doi:http://dx.doi.org/10.5194/acp-11-3333-2011.

Vickers, C.E., Gershenzon, J., Lerdau, M.T., Loreto, F., 2009. A unified mechanism of action for isoprenoids in plant abiotic stress. Nat. Chem. Biol. 5, 283–291.

Wang, T., Wei, X.L., Ding, A., Poon, C.N., Lam, K.S., Li, Y.S., Chan, L.Y., Anson, M., 2009. Increasing surface ozone concentrations in the background atmosphere of Southern China, 1994–2007. Atmos. Chem. Phys. 9, 6217–6227.

Williams, J., Crowley, J., Fischer, H., Harder, H., Martinez, M., Petäjä, T., Rinne, J., Bäck, J., Boy, M., Dal Maso, M., Hakala, J., Kajos, M., Keronen, P., Rantala, P., Aalto, J., Aaltonen, H., Paatero, J., Vesala, T., Hakola, H., Levula, J., Pohja, T., Herrmann, F., Auld, J., Mesarchaki, E., Song, W., Yassaa, N., Nölscher, A., Johnson, A.M., Custer, T., Sinha, V., Thieser, J., Pouvesle, N., Taraborrelli, D., Tang, M.J., Bozem, H., Hosaynali-Beygi, Z., Axinte, R., Oswald, R., Novelli, A., Kubistin, D., Hens, K., Javed, U., Trawny, K., Breitenberger, C., Hidalgo, P.J., Ebben, C.J., Geiger, F.M., Corrigan, A.L., Russell, L.M., Ouwersloot, H.G., Vilà-Guerau de Arellano, J., Ganzeveld, L., Vogel, A., Beck, M., Bayerle, A., Kampf, C.J., Bertelmann, M., Köllner, F., Hoffmann, T., Valverde, J., González, D., Riekkola, M.-L., Kulmala, M., Lelieveld, J., 2011. The summertime boreal forest field measurement intensive (HUMPPA-COPEC- an overview of meteorological and chemical influences. Special issue on Summertime boreal forest atmospheric chemistry and physics (HUMPPA-COPEC 2010). In: Goldstein, A., Heard, D., Kanakidou, M. (Eds.), Atmospheric Chemistry and Physics Discussions, vol. 11. , pp. 15921–15973. doi:http://dx.doi.org/10.5194/acpd-11-15921-2011.