Integrated Land Ecosystem – Atmosphere Processes Study

iLEAPS

Newsletter

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Issue No. 11 – September 2011

International Geosphere-Biosphere Programme
GLOBAL IGBP CHANGE

New directions in land–atmosphere research

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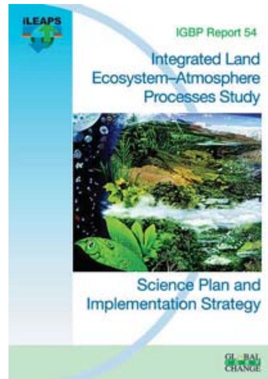

iLEAPS Science Plan and Implementation Strategy is available in English and in Chinese.

Get your paper copy by contacting ipo@ileaps.org or download the .pdf files from the iLEAPS web site at: *www.ileaps.org*

iLEAPS IPO GUEST SCIENTISTS

iLEAPS welcomes collaboration and interaction between the International Project Office (IPO) and the many researchers from a multitude of disciplines involved in iLEAPS activities. We welcome guests from professors and senior researchers to postdocs and PhD students.

A guest scientist can host a workshop, edit a book or journal special issue related to iLEAPS activities, guest–edit the iLEAPS Newsletter, develop new initiatives, plan and enhance national iLEAPS activities, construct a website, for example.

This is an opportunity for close collaboration with an international research program with a view of the activities all over the world, also an opportunity to develop new interactions and lines of research, obtain new contacts, and spend a shorter or longer time period in new surroundings.

Although budget constraints usually limit our ability to fund visitors, we provide for the office and computational needs of visitors who come with independent salary support.

If you are interested in spending a sabbatical, a shorter of longer period at iLEAPS IPO, please contact: *ipo@ileaps.org*

INSTRUCTIONS TO CONTRIBUTORS

The iLEAPS Newsletter informs on iLEAPS-related scientific activities. The theme of contributions should be relevant to iLEAPS and integrated land-atmosphere research. The Newsletter is published twice a year and it is released both in printed and on-line versions. For the paper version the specified word length according to these instructions is enforced. The author may provide additional material to be used on the iLEAPS web site.

SCIENTIFIC ARTICLES

Articles are 700–1000 words and cover 1–2 pages with accompanying 2–3 pictures or figures. Articles can contain the following:

- RESULTS of scientific research
- SUMMARIES presenting synthesis of recent scientific development in land-atmosphere research
- POSITION PAPERS stating views and directions in scientific research
- REPORTS presenting key scientific outcomes of programmes, workshops, or meetings.

EDITORIAL

Editorials are around 500 words with or without one accompanying figure. Editorials are by invitation and feature a personal interpretation and evaluation on the theme of the issue.

NEWS

Other than strictly scientific contents will be max 200 words and can be for

- **PEOPLE** presentation
- **ACTIVITIES** report and commentaries
- **ANNOUNCEMENTS** of coming events or other short news.

Text and graphs should be provided in separate files. Please do not send graphs, figures, logos, photos or other graphical material inserted into Word documents.

Text should be in Word doc or plain text.

Graphs and figures should be in its original format or else as high resolution .eps vector images. If you do not have the possibility to save the graph as an EPS file, save it as a very large pixel graph, minimum 300 dpi (TIF, TIFF or JPEG).

Photographs should be in TIF format, minimum 300 dpi. When you take photos, save them using the best possible resolution and quality available in your camera settings, with as little compression as possible. Generally digital cameras (and photo scanners) save photos in RGB format. Send the photos in the format saved by the camera, do not make any transformations. If you use Photoshop or some other program to edit the photo, then save the file in EPS format with resolution 300 dpi, no compression. If the program forces you to compress the file, select the best possible quality. Even .tif and very little compressed JPEG formats are applicable. In addition to EPS format, a good format for sending all kinds of photos is PDF, with resolution at minimum 300 dpi (in the size it will be printed in) and as little compression as possible.

The contributors are kindly requested to handle potential **copyright issues** of the material.

Contributions should be e–mailed to the Executive Editor at the iLEAPS IPO.

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Editorial

iLEAPS Co–Chairs Alex Guenther and Markku Kulmala

New directions in land–atmosphere research

There has been a steady progress towards the development of an iLEAPS community during the past seven years. The restructuring of IGBP (International Geosphere–Biosphere Programme) at the beginning of the new millennium focused on the interfaces between Earth System components and integrated the diverse communities investigating land–atmosphere interactions into the iLEAPS project. This has resulted in a closer integration of researchers investigating exchanges of carbon, water, energy, aerosol, greenhouse and reactive gases and their influence on the Earth System.

As IGBP now moves beyond global change to include a focus on sustainable development, there will be an increased emphasis on research activities that can inform resource managers about how to minimise environmental risks while at the same time meeting societal needs for food, health and energy. iLEAPS priorities are being updated to reflect a new emphasis on global sustainability.

This issue of the iLEAPS newsletter features four articles that describe high-priority activities.

Blyth and Jones (*pp. 28–31*) consider whether the increasing complexity of land surface models is improving their predictive ability. Standardised metrics, observational data, and simulation protocols are identified as key needs to enable the success of international initiatives to evaluate land surface models.

Noblet–Ducoudré *et al.* (*pp. 22–26*) consider the challenge of including humans in climate models by representing land–use induced land–cover changes. They describe the goals and first results of the LUCID (Land–Use and Climate, Identification of robust impacts) project that examines the influence of land–use and land–cover change mitigation strategies (such as reforestation).

Guenther *et al.* (*pp. 6–13*) outline a strategy for developing land ecosystem – atmosphere observational networks that can provide the *in situ* observations necessary for investigating land – atmosphere exchanges and interactions. They recommend a hierarchal approach that includes a large number of basic level flux sites, a smaller number of advanced flux sites, and a limited number of flagship sites with a comprehensive suite of measurements.

Finally, Reichstein *et al.* (*pp. 14–21*) examine strategies for performing model evaluations and identify problems with some approaches. They argue for pattern–oriented and system–oriented approaches that take advantage of Earth Observation data sets.

The September 2011 iLEAPS international science conference program highlights recent advances in land ecosystem – atmosphere research and demonstrates that this topic continues to be an active and exciting area of scientific discovery.

The conference themes of land–ecosystem–atmosphere observation, land–ecosystem atmosphere modelling, human drivers, and innovation in ecosystem–atmosphere interactions are focused on research areas that are a high priority for iLEAPS.

Specific areas of emphasis include

- integrated Earth System and Earth observations;
- boundary layer dynamics;
- land use/land cover changes and climate;
- integrative model evaluation (including isotopes);
- including humans in climate models;
- extreme events *vs.* gradual change;
- managed ecosystems;
- regional land–climate research;
- teleconnections;
- biogeochemical feedbacks in the climate system; and
- biosphere–aerosol–cloud–climate interactions.

The conference has an additional goal of preparing the next generation of scientists with activities that include an Early Career Scientist workshop, a career centre, and opportunities to connect with experienced scientists. The two–day post conference workshop on "Challenges and Opportunities of Integrated Long–Term LEAP Observations" will be organised after the conference to enhance general understanding and also to further develop comprehensive and continuous measurement networks.

We look forward to the continued integration and development of the iLEAPS community and the advances in understanding of the Earth System that result from the implemented activities.

We welcome suggestions for new directions and activities and encourage active participation in existing projects (contact *ipo@ileaps.org*). ■

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The iLEAPS Scientific Steering Committee and the Karlsruhe Institute of Technology warmly welcome you to participate in iLEAPS SC2011.

Conference website:
www.ileaps.org/science_conf_2011

Conference structure

The conference will consist of plenary lectures and invited speeches given by prominent scientists in LEAP (Land Ecosystem — Atmosphere Processes) research, poster sessions, and an Early–Career Scientist programme.

3rd iLEAPS International Science Conference

18–23 September 2011
Garmisch–Partenkirchen, Germany

Conference themes

1. Land ecosystem–atmosphere observation
2. Land ecosystem–atmosphere modelling
3. Innovative methods, ideas and challenges in ecosystem–atmosphere interactions
4. Human drivers and impacts of ecosystem–atmosphere interactions

All themes involve both modellers and observational researchers working at multiple spatial and temporal scales, with multiple observations, integration of observations into model development and evaluation.

Karlsruhe Institute of Technology

Invited speakers

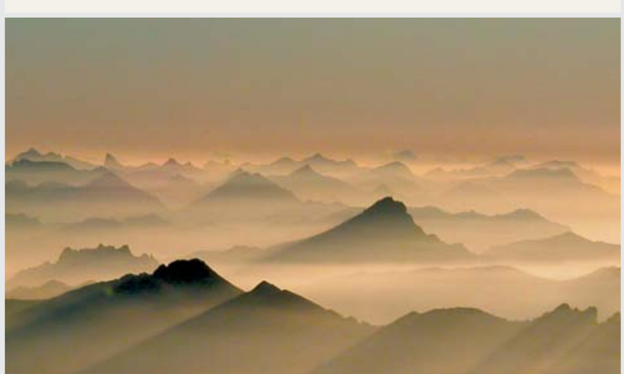
Almut Arneth (Lund University, Sweden)
Philippe Ciais (LCSE, France)
Joe Berry (Carnegie, USA)
Congbin FU (Nanjing University, IAP–CAS, China)
Sue Grimmond (King's College London, UK)
Axel Kleidon (Max Planck Institute, Germany)
R.S. Maheskumar (Indian Institute of Tropical Meteorology, India)
Arnold Moene (Wageningen University, Netherlands)
Julia Pongratz (Stanford University, USA)
Mark Rounsevell (University of Edinburgh, United Kingdom)
Steve Running (University of Montana, USA)
Hisashi SATO (Nagoya University, Japan)
Ulli Seibt (UCLA, USA)
Stephen Sitch (University of Leeds, United Kingdom)
Tong ZHU (Peking University, China)

***iLEAPS**, Integrated Land Ecosystem – Atmosphere Processes Study*, is an international interdisciplinary research program aimed at improved understanding of processes, linkages and feedbacks in the land–atmosphere interface affecting the Earth System.

iLEAPS is the land–atmosphere core project of IGBP, International Geosphere — Biosphere Programme.

iLEAPS–associated projects' speakers

Diego Fernandez–Prieto (ALANIS)
Alex Guenther (GEIA)
Richard Harding (WATCH)
Markku Kulmala (EUCAARI)
Nathalie de Noblet (LUCID)
Markus Reichstein (FLUXNET)
Danny Rosenfeld (ACPC & SAT–ACPC)
Sonia Seneviratne (LandFlux–EVAL)
Christopher M. Taylor (AMMA)



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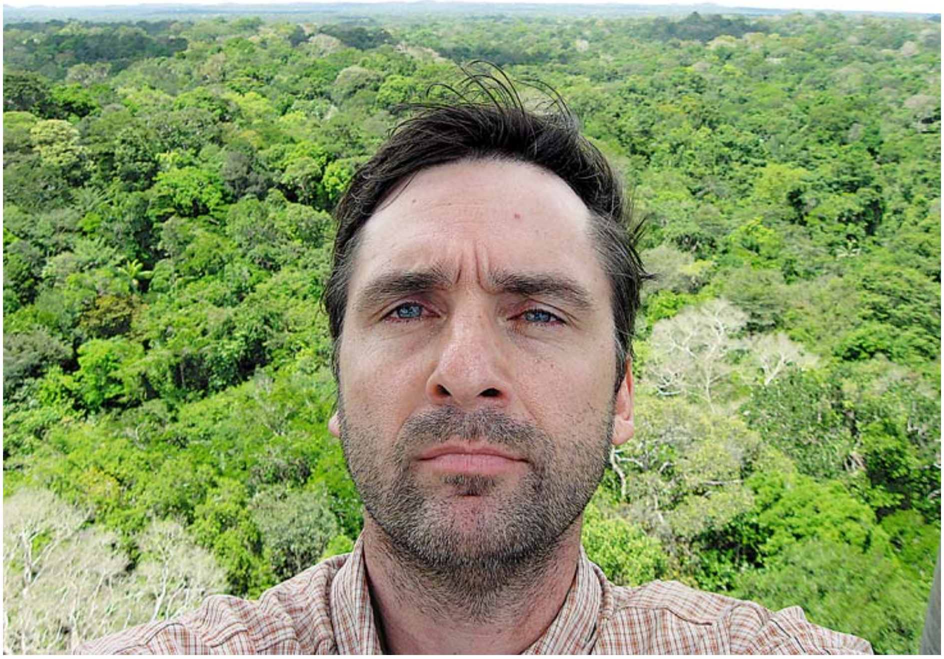

Alex Guenther is a senior scientist and section head in the Atmospheric Chemistry Division of NCAR and lead scientist of the NCAR BEACHON research program. He recently served as the co–chair of the GEIA activity and now serves as the co–chair of iLEAPS. He has investigated the role of reactive trace gases in biosphere–atmosphere interactions for more than 25 years and is the author of more than 200 peer reviewed publications (H index = 44). He is the lead developer of the MEGAN biogenic emission model that is widely used by the scientific and regulatory communities for simulations of regional and global air quality and climate. He has developed novel systems for measuring trace gas flux measurements and has led more than 40 integrative field studies on six continents in tropical, temperate and boreal ecosystems to provide the observations required to develop and evaluate MEGAN and associated Earth system models.

Alex Guenther[1], Markku Kulmala[2], Andrew Turnipseed[1], Janne Rinne[2], Tanja Suni[2] and Anni Reissell[2]

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Land ecosystem – atmosphere observational networks

Background

Global environmental problems including climate change, air quality, lack of fresh water, land–cover changes, food security, biodiversity and their interconnections and feedbacks have created an urgent need for comprehensive monitoring. We need reliable and precise information on present climate and environmental system change, especially for making sound policy decisions on national, regional and global level, for sustainable development.

The land surface – atmosphere interface is particularly crucial for the functioning of the Earth System (ES) through interactions via mass, energy, and momentum fluxes, as well as through the biogeochemical cycles.

At the same time, climate variability and atmospheric processes, such as transport and deposition of chemicals, are major constraints on biogeochemical cycles, natural as well as anthropogenic ones.

Human–driven change in land cover is likely to result in significant regional and global climate change. In turn, climate change affects terrestrial ecosystems at all spatial and temporal scales, maybe even to the extent of destabilizing large regions.

Earth system models are advancing to the point where they can begin to fully simulate the coupling between the physical, chemical, and biological processes in the climate system. This is facilitated by increases in computational power but a major limitation is the lack of suitable observations for developing and evaluating the quantitative relationships needed for realistic simulations of the controlling processes.

The integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS, *www.ileaps.org*) advocates studies of the implications of transport and transformation processes at the land–atmosphere interface to advance our understanding of Earth system dynamics that can then be incorporated into Earth system models. The scope of iLEAPS research, particularly on coupled interactions and feedbacks, is elaborated in recent articles [1, 2].

This recent progress has led to initial estimates of the potential magnitude of

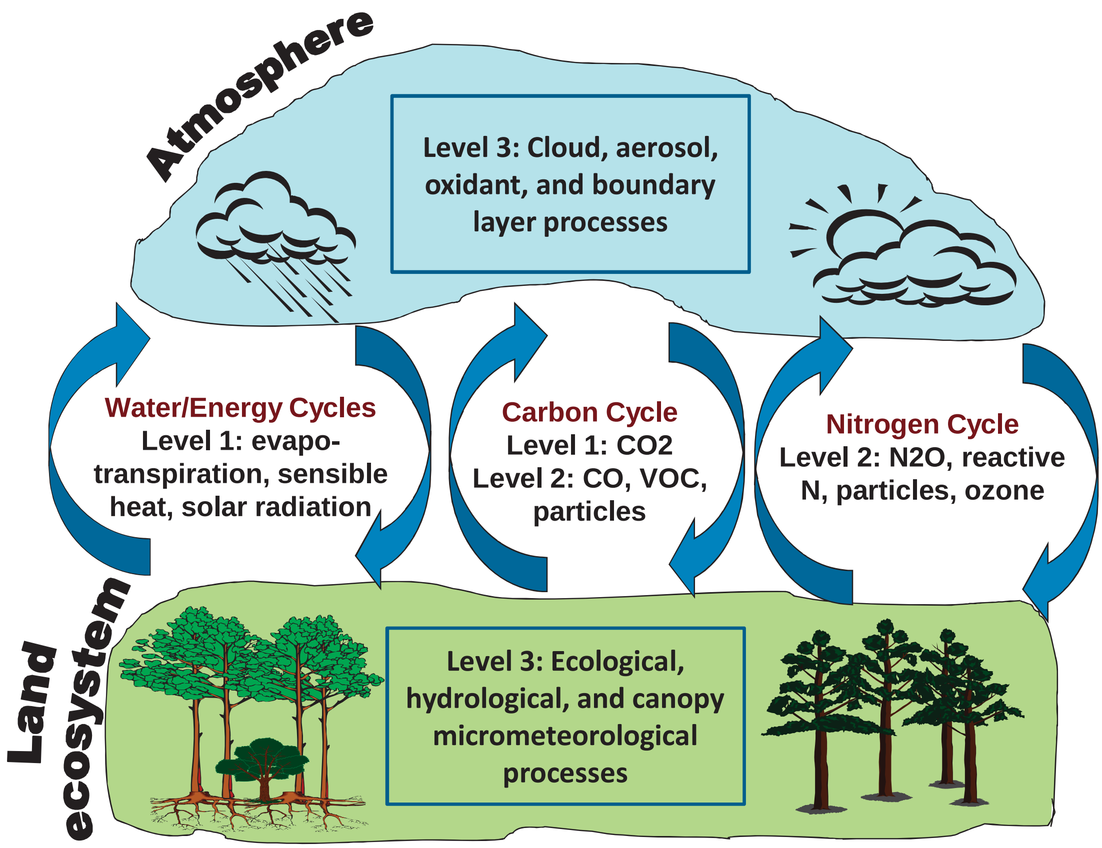

Figure 1. Schematic of land ecosystem–atmosphere interactions and hierarchal observational levels that include basic fluxes (level 1), advanced fluxes (level 2) and comprehensive measurements at "flagship sites" (level 3).

biogeochemical feedbacks associated with human–mediated changes in the biosphere. Importantly, the overall magnitude of biogeochemical feedbacks could potentially be similar to that of feedbacks in the physical climate system, but there are large uncertainties in the magnitude of individual estimates and in accounting for synergies between these effects [1]. Continued advances in quantitative modelling require simultaneous observations of a variety of constituents that can be used to improve modelling approaches.

The processes controlling the coupled Earth system are highly uncertain and not well quantified, precluding the full incorporation of these processes into ES models. In order to understand water and biogeochemical cycles, observing fluxes between different ES compartments, like atmosphere and ecosystems, is crucial. We also need to observe processes in the atmosphere, biosphere and soils; concentrations of greenhouse gases, reactive trace gases, aerosols.

To a significant extent, this is now possible with the recent, rapid development of measuring techniques. However, no systematic measurement networks to analyse the change and the interconnections between all energy, water and biogeochemical flows in the system of atmosphere, vegetation and topsoil are available.

Although independent studies of certain aspects exist, an international interdisciplinary research effort, establishing and quantifying links between these processes and potential feedbacks, is necessary to determine whether the biosphere has significant ability to control the Earth system through interactions with the atmosphere and hydrosphere. Upscaling the small–scale observations to the regional–scale interactions that must be represented in ES models requires biochemical cellular studies, plant physiology enclosure studies, above-canopy micrometeorological towers, and airborne and satellite sensors (*Fig. 2*).

Recently, Hari *et al.* [3] proposed a three–level hierarchical network of measuring stations: (i) basic level, (ii) flux level, and (iii) "flagship" level (*Fig.1*). The basic stations would provide spatial information, the flux stations would provide information on fluxes in the ecosystem, and the flagship stations would provide information on processes generating the fluxes, develop instrumentation, and serve to train scientists and technical staff. To obtain global coverage, the number of basic–level stations should be around 8000, the number of flux stations around 400, and the number of flagship stations around 20 globally [3].

Here, we build on the strategy proposed in [3] and describe the current status of global land ecosystem – atmosphere networks and consider needs for enhancements.

1. Basic flux level: Carbon dioxide, water vapour and energy fluxes

Until now, the implementation of a long–term land–atmosphere exchange observational network has focused on carbon dioxide, water vapour and energy. Micrometeorological techniques for quantifying land–atmosphere constituent exchange are the most direct means of measuring canopy to landscape scale fluxes.

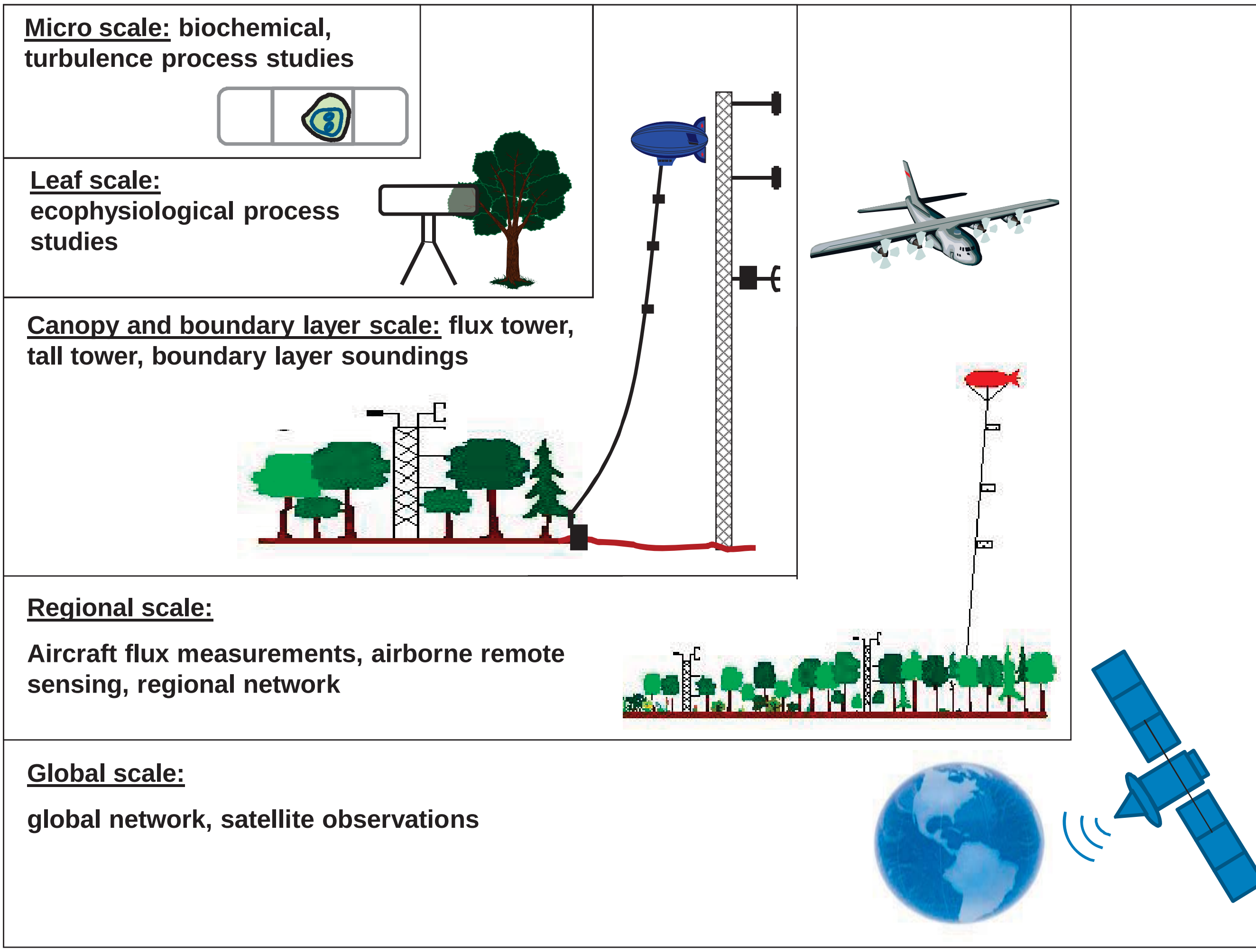

Figure 2. Scales and observational techniques for land ecosystem atmosphere observations.

Long–term continuous measurements of these fluxes began at a few sites about 20 years ago [4, 5] and the number of active sites steadily increased into the hundreds during the 1990s [6]. Many sites were integrated into regional networks which were joined through FLUXNET, a network of networks. FLUXNET has several important roles including archiving and distributing observations, calibration and intercomparison, and facilitating synthesis and communication within the FLUXNET community.

FLUXNET data have been used to determine net annual fluxes in important ecosystems and quantify diurnal, seasonal and interannual variability. The observations have been used to characterise ecosystem response to changing growing season, sunlight, temperature, and stand age [6]. The resulting insights into carbon, water, and energy dynamics have been used to improve the land surface components of Earth system models although comparisons of these models indicate that there are still large uncertainties associated with the representations of these processes in these models.

More recently, investigators have begun to directly integrate FLUXNET data with satellite observations and ecological data to produce regional– and continental–scale estimates of the magnitude and distribution of carbon fluxes [7]. This upscaling approach has the potential to improve carbon flux estimates in an approach similar to the use of data assimilation for weather forecasting.

The compilation of a global FLUXNET dataset, the LaThuile dataset, allows for a variety of conclusions regarding specific ecosystems and also on a global scale. As an example of the application of the global dataset of carbon dioxide flux measurements, Mahecha *et al.* [8] 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 the sites. Another example is a recent observation–based global terrestrial gross primary production (GPP) estimation that shows missing feedbacks in biosphere models [9].

Atmospheric and ecological sciences are established scientific fields with observatories sponsored by the research and resource management agencies associated with individual disciplines in many nations but this is often not the case for multi– and inter–disciplinary land–atmosphere measurements. The global CO_2, water, and energy flux measurement network began as a collection of individual scientific activities funded by agencies with a wide range of objectives. As these measurements become somewhat routine, and more sites and longer time series are necessary to obtain publishable results, it becomes more important to identify stable funding from institutions and agencies that are able to make a commitment to long–term observations.

2. Advanced flux level: Extending flux networks beyond CO_2, water, and energy

Water vapour, CO_2, and energy are not the only types of land–atmosphere exchange that are important for climate, air quality, and ecosystem functioning and yet there are few long–term observations of any other constituents. New harmonised networks for Earth system observations are now being developed in some regions, including Northern America and Europe. The European ICOS (Integrated Carbon Observation System) is designed to observe the fluxes and concentrations of the three major greenhouse gases, carbon dioxide, methane, and nitrous oxide.

The U.S. NEON (National Ecological Observatory Network) has broader aims that include biosphere–atmosphere fluxes. As these aim at harmonised long–term measurements covering major ecosystems, they may in the future provide a backbone for observational studies of biosphere–atmosphere gas exchange on these continents. In addition to these regional enhanced networks, global observational networks for additional constituents can be built by adding instrumentation to the existing FLUXNET sites.

In this section, we assess both the need for long–term observations of land–atmosphere exchange of individual Earth system constituents and the feasibility of these measurements. This includes discussion of how our understanding of the Earth system could benefit from these measurements as well as of the technical and logistical constraints associated with potential measurement techniques.

Methane (CH_4) and nitrous oxide (N_2O)

Methane and nitrous oxide are important contributors to global atmospheric radiative forcing. Therefore, an accurate understanding of their sources and sinks, and how they might change in the future, is necessary.

A major challenge associated with quantifying global land–atmosphere methane exchange is that the global total emission is comprised of many significant sources including termites, methane hydrates, wetlands, rice paddies, biomass burning, natural gas production and distribution, landfills, sewage treatment, animal waste, and enteric fermentation. Each of these sources contributes between 3 and 22% of the global total and should be considered in Earth system models.

The first generation of fast–response methane analysers could only be operated in cold temperatures provided by liquid nitrogen or cryo–cooling devices and only a few were stable enough to run unattended for longer periods. Thus, eddy–covariance measurements of methane were usually confined to short measurement campaigns, with the exception of some longer–term measurements [10, 11].

A new generation of fast–response instrumentation which does not need cryogenic cooling is now commercially available [12, 13]. These instruments are based on newer laser technology and have an optical multipass cell that is either open or closed. With these instruments, there is no need to supply the site with liquid nitrogen or with power necessary for a cryo–cooler. This enables long–term measurements at more remote locations.

However, experience on long–term perforance of any of the new instruments is still scarce.

Nitrous oxide is a significant greenhouse gas with a global source dominated by emissions from agricultural areas [14]. Nitrous oxide emissions may even determine the climatic profitability of biofuel production [15]. Ecosystem–scale measurements of nitrous oxide emission have suffered from the same instrumental limitations as those of methane. The new laser technology has also enabled longer–term measurements of this compound as the new generation of instrument does not require liquid nitrogen or cryo–coolers. These closed–path instruments operate in low pressure and need powerful pumps. Thus, they require an electric power line or a generator at the measurement site [16].

Networks of long–term methane and nitrous oxide eddy flux measurements in terrestrial ecosystems are important for characterizing variations in sources and sinks of these radiatively active gases and are now considered feasible. Also, measurements of methane and nitrogen are necessary in some ecosystems to close the carbon and nitrogen budgets. ICOS has identified long-term methane and nitrous oxide flux measurements as a high priority and is establishing a European network especially for these compounds. We need to expand this network to other parts of the world to characterise additional important biomes, building on the approach defined and lessons learned by this initial regional network.

Volatile organic compounds

Terrestrial ecosystems are the major source of volatile organic compound (VOC) emissions into the atmosphere [17]. In the atmosphere, the oxidation of VOC can influence aerosol particles, precipitation acidity, and regional ozone distributions [18]. Accurate predictions of biogenic VOC emissions are important for developing regulatory ozone and aerosol control strategies for at least some rural and urban areas [19].

There are tens of thousands of organic compounds that have been identified in plant tissues and more are discovered every year. A relatively small number of all organic compounds found within plants are known to be emitted at rates that can significantly influence the atmosphere although new compounds are regularly added to the list.

Isoprene is the single most important biogenic VOC (BVOC) with an emission that is about half of the global total emission of all BVOC [18]. Many monoterpenes have been observed in the atmosphere but only a few, such as α–pinene, make a significant contribution to the global total emissions. The dominant sesquiterpenes, such as β–caryophyllene, have lifetimes of only minutes in the atmosphere and so are present at very low levels but their reaction products may be an important source of secondary organic aerosol. Thus observations of land–atmosphere interactions must include not only primary emissions but also the large variety of reaction products that influence atmospheric oxidants and particle formation and growth.

Fast–response analysers suitable for eddy–covariance flux measurements of the most important BVOC are commercially available. They include a chemiluminescence analyser for isoprene [20] and PTRMS

(Proton Transfer Reaction Mass Spectrometry for a wide range of BVOC [19]. Several studies have reported long–term BVOC eddy flux measurements [21, 22]. These efforts have demonstrated the feasibility of long–term measurements and the value for improving understanding of the processes controlling these emissions. This is particularly important since these studies have shown that BVOC emissions are particularly sensitive to environmental and land–cover change.

However, the considerable expense and expertise required for operating these direct eddy covariance measurements may limit long–term BVOC measurements to relatively few sites, such as the flagship sites described in the following section. An alternative for a widespread network is the utilisation of another micrometeorological flux technique called REA (relaxed eddy accumulation). Inexpensive, low–power and reliable REA systems for measuring BVOC fluxes [17, 23] could be deployed at a large number of flux tower sites. However, the samples collected by the REA systems would probably have to be shipped to a laboratory for analysis. Consequently, VOC fluxes would not be measured continuously.

Reactive nitrogen

Nitrogen (N) plays a key role in regulating plant growth and photosynthesis. In the atmosphere, nitrogen is a key mediator in many photochemical processes and plays critical roles in tropospheric ozone production, acid deposition and aerosol formation. Nitrogen deposition can occur either from direct deposition of gaseous or aerosol nitrogen (dry deposition) or dissolved within precipitation (wet deposition). Wet deposition of nitrogen is the focus of several existing long–term observation networks [24–26] and will not be discussed here.

Dry deposition of N–species is rarely measured on a routine basis. The exchange of gas– and aerosol–phase nitrogen between the atmosphere and biosphere is exceedingly complex since all of the various forms of atmospheric nitrogen have their own deposition characteristics as well as different chemical production and loss mechanisms that operate on a range of time scales. Reactive nitrogen compounds can be classified into three main groups: (1) ammonia and amines, (2) aerosol–N (which includes ammonium and nitrate) and (3) oxidized–N which is often referred to as NO_y.

NO_y is typically used to refer to the sum of oxidized nitrogen species in the atmosphere. It consists primarily of NO, NO_2, HNO_3 and gas–phase N–containing organics (peroxyacetyl compounds, organic nitrates, etc.). There are smaller contributions from compounds such as HONO, N_2O_5, and NO_3, but because of their short atmospheric lifetimes, these are a small portion of the concentration budget. The intrinsic problem with NO_y deposition is that each species has different surface exchange characteristics and the concentrations vary with photochemical processing in the atmosphere. At present, the difficulty in measuring fluxes of all the individual NO_y species make long–term monitoring of exchanges of all the components of NO_y intractable; however, certain aspects of NO_y deposition could be targeted.

Knowing the total amount of oxidized nitrogen entering an ecosystem via dry deposition would be useful information for modelling of ecosystem productivity. Some existing instruments are capable of measuring eddy covariance fluxes of total NO_y. Whereas some of these are fairly specialized [27], some are commercially available with some minor modifications [28, 29]. The work of Munger *et al.* [28] also demonstrated the feasibility of using this modified–commercial system for long–term measurements over several years.

This technique is based on the familiar ozone–induced chemiluminescence detection of NO. The key for using this method for NO_y is to rapidly convert all of the different NO_y species to NO at the inlet of the instrument (close to the path of the sonic anemometer for eddy covariance measurements) by means of a heated gold catalyst. NO can then be transported through tubing to a commercial NO instrument. These analysers typically have adequate sensitivity and can be modified for the fast sampling rates (1 to 10 Hz) necessary. These measurements do require significant power (~500 Watts) and expertise. Thus, they may not be feasible at all locations.

NO and NO_2 (collectively known as NO_x) can be measured by eddy covariance although they rapidly interconvert on a scale of a few minutes and their respective fluxes depend on this photochemical partitioning. Adding to this that NO is emitted from soils whereas NO_2 is taken up via stomata in vegetation, the surface exchange of these compounds are often quite complicated. There are very few long–term studies of NO/NO_2 surface exchange [30, 27]; many studies to date have used long–term NO and NO_2 concentrations and then inferred deposition [31, 32].

Although several techniques exist for the detection of NO_2 (such as laser fluorescence), the most common (and commercially available) approach is to convert NO_2 to NO via either photolysis or a heated molybdenum catalyst. The NO produced is then detected via chemiluminescence, so that a single instrument can be used for both NO and NO_2.

Nitric acid (HNO_3) is of utmost importance for understanding the dry deposition of nitrogen. Along with ammonia, HNO_3 is deposited very rapidly to nearly all surfaces and typically constitutes a majority of the deposited NO_y.

However, there is currently no method specific to HNO_3 that has been used successfully to determine its eddy–covariance fluxes. Micrometeorological methods that rely on integrated samples, such as the gradient or relaxed–eddy accumulation techniques, are the only viable alternative [33]. However, these methods are often labour–intensive and as such, not very suitable for long–term continuous measurements.

A long–term reactive nitrogen land–atmosphere flux network is necessary to quantify nitrogen inputs to ecosystems and to understand biogenic contributions to atmospheric reactive nitrogen. Instrumentation exists for using eddy covariance for measuring the sum of some reactive nitrogen species although additional effort is necessary to characterise which species are being measured. NEON has identified long–term NO_y flux measurements as a priority and is including NO_y eddy flux measurements as a component of NEON. The experience gained by NEON will be valuable in determining whether and how to expand this measurement to a global reactive nitrogen flux network.

Ozone

Ozone is one of the most important atmospheric oxidants and plays a key role in atmospheric oxidation processes, so understanding all of its formation and loss processes (including deposition) is important for understanding tropospheric photochemistry. It also inhibits plant growth via its uptake into stomata of vegetation. Depending upon concentration level, these effects can be either acute or chronic. Chronic effects develop over long time scales (years) and thus, long–term monitoring is required to assess this type of plant damage.

Monitoring ozone concentrations is not sufficient for assessing ozone damage since it does not account for the amount of ozone that is taken up by a plant. Direct micrometeorological fluxes of ozone measure the sum of the uptake via the stomata as well as to other surfaces (cuticles, bark, soils). The stomatal uptake is the only component associated with ozone damage so assessments typically use models of stomatal conductance, along with measured ozone concentration, to estimate the stomatal deposition fraction. The parameters needed to model ecosystem–level stomatal conductance (vapour pressure deficit, latent heat flux, etc.) and the O_3 concentration are the necessary inputs for these models.

The technology for monitoring O_3 concentration using UV–absorbance is well developed, relatively inexpensive and requires little maintenance. Several new O_3 monitors now exist that operate at very low power, which means that O_3 concentration measurements could be added to nearly all of the existing flux sites at a relatively low cost and effort.

Quantification of the total atmospheric loss of ozone is necessary for understanding the photochemistry of ozone and requires a direct measurement of the total deposition flux. Furthermore, recent studies have also shown that the non–stomatal portion of the flux may, in part, be due to chemical reactions with highly reactive species (NO, organics) that are emitted from either soils or vegetation [34]. Rapid oxidation of high–molecular–weight organics by ozone may then contribute to aerosol formation. Therefore, both the total flux and the parameters necessary for modelling of the stomatal contribution need to be measured.

Several previous studies have reported on long–term continuous monitoring of ozone flux [28, 35–37]. Many techniques based on chemiluminescence are capable of sampling rates amenable to using eddy covariance. Note that all of the long–term studies mentioned above used a different method of ozone detection. All of these techniques must be run in parallel with a more stable, slow–response ozone analyser (typically a UV–absorbance monitor) for calibration purposes.

Recently developed fast–response instruments based on UV–absorbance [38] could alleviate many of the calibration and stability issues related to chemiluminescence instruments; however, these are still in development and not commercially available.

A long–term land–atmosphere flux network for ozone is necessary for quantifying the influence of this chemical on ecosystem health. A network would be particularly valuable for improving Earth system models if it could provide measurements of stomatal and non-stomatal components of ozone deposition. NEON has identified long–term ozone flux measurements as a priority and is including ozone flux–gradient measurements as a component of NEON. This could be a worthwhile approach for a global flux network although continued improvements in UV–absorbance techniques for ozone eddy covariance measurements could provide a better alternative.

Aerosol particles

Aerosol particles have important roles in both climate and air quality. However, they are among the most difficult to accurately represent in Earth system models because of their highly complicated production and loss mechanisms and complex atmospheric effects.

Long–term measurements of particle fluxes, including size–resolved measurements of chemical composition and physical properties, are necessary for understanding how atmospheric distributions and ecosystem inputs will respond to changes in the Earth system. Land ecosystems are a major source of atmospheric particles, including both direct emissions (dust, pollen, etc.) and the atmospheric formation and growth of particles from the surface emission of precursor gases (gas–to–particle conversion, [39, 40]. Dry and wet deposition to land surfaces is also a major loss process for atmospheric particles.

Particle number fluxes have been derived with the eddy covariance technique since the late 1970s [41]. Characterizing the chemical composition or resolved size distributions is more challenging but the eddy covariance approach has now been applied for this as well [42, 43]. Relatively low–cost and low–power fast–response sensors suitable for measuring total particle number using the eddy covariance technique with condensation particle counters or optical particle counters are commercially available. Size–resolved aerosol particle fluxes have been measured by eddy covariance with optical particle counter [44] or electric low–pressure impactor [45, 46], or by REA method [47, 48].

Recently, long–term observations of particle concentrations and their formation and growth rates have been performed all around Europe [49]. Long–term eddy flux measurements of particle numbers are feasible but have not been implemented in a regional or global network. Eddy covariance methods for quantifying size resolved chemical composition, particle fluxes and the chemical composition of particle fluxes would be particularly valuable for improving Earth system understanding but the available approaches require instrumentation that are currently suitable only for the flagship sites described below.

Other constituents

There are other constituents exchanged between terrestrial ecosystems and the atmosphere that have significant roles in the Earth system. These include carbon monoxide (CO), sulphur dioxide (SO_2), reduced sulphur gases, halogens, and particles containing elements such as phosphorus that can be a limiting nutrient in some ecosystems. Fast–response sensors suitable for eddy flux measurements have been developed for some of these, and could be developed for others, but their relatively high cost and operational constraints limit long–term flux measurements. Additional studies are required to determine if a long–term observational network of any of these land–atmosphere processes would be beneficial.

3. Flagship level: Comprehensive measurements

One of the most exciting aspects of the projects advocated by iLEAPS are the opportunities for scientific interaction among biologists, ecologists, hydrologists, micrometeorologists, atmospheric chemists and physicists, and other scientists.

Previously, multi–disciplinary collaboration was often limited to studies led by scientists of one discipline with participants from other disciplines in a relatively minor supporting role. Future advances in understanding land ecosystem – atmosphere interactions will likely stem from collaborative studies where participants tackle key scientific issues from the point of view of several different disciplines.

One of the most effective means of accomplishing this is through the development of flagship sites with a comprehensive suite of long–term multi–disciplinary measurements that can provide supporting information for intensive campaigns focused on a wide range of biological, physical and chemical processes. Among the core measurements for such sites are stable isotope measurements, ecosystem structure and functioning, mass spectrometer flux systems, boundary layer and cloud properties, and instrumentation for characterizing oxidants and particles and their precursors.

Since flagship stations are based on comprehensive, continuous measurements simultaneously observing greenhouse gases, reactive trace gases, and optical, physical and chemical properties of aerosol particles, their hygroscopicity and ability to act as cloud condensation nuclei (CCN), they can provide detailed data on different radiative forcing components. In addition, the data obtained from flagship stations can be utilised for investigating different feedbacks and linkages [40].

An example of a flagship station is the SMEAR II station (Station for Measuring Forest Ecosystem – Atmosphere Relations) in Southern Finland [50, 51]. This station has operated continuously since 1996, and it continues to provide comprehensive data sets in the fields of atmospheric chemistry and physics, soil chemistry, and forest ecology, all produced with an inter– and multi–disciplinary approach.

The power of long–term continuous measurements has been shown, for instance, in the study comparing new particle formation over solar cycles with cosmic–ray–induced ionization [52]. Observation programs at flagship stations should include air ions (their mobility and composition), and composition and fluxes of VOC using time–of–flight mass spectrometers.

Detailed measurements of ecosystem structure and functioning are another necessary component of a long–term land ecosystem – atmosphere measurement site. This includes information of variables such as the leaf area index (LAI), above– and below–ground biomass, plant species composition, and stable isotopes. Repeated airborne remote sensing using LIDAR and imaging spectrometers are necessary to provide a time series of detailed three-dimensional distribution of these variables across a site.

Stable–isotope techniques can improve our understanding of the sources and sinks of CO_2, water vapour, reactive trace gases, and particles including the partitioning of fluxes into individual components (transpiration and evaporation components of water vapour fluxes and photosynthesis and respiration components of CO_2 fluxes). Ecosystem manipulation studies (controlled drought, warming, CO_2 enrichment) are an important activity for comprehensive land ecosystem – atmosphere research sites.

Conclusions

The community investigating land–atmosphere interactions faces a daunting number of complex processes controlling transport and transformation at the land–atmosphere interface as well as an enormous diversity among the Earth's ecosystems. Quantifying these processes with the precision necessary for parameterising and evaluating Earth system models requires intensive campaigns focused on specific processes as well as long-term observation networks providing continuous and high–frequency time series of fluxes and driving variables.

The ecological, hydrological and atmospheric communities have separately developed networks of ecological field stations, instrumented hydrological watersheds and atmospheric monitoring networks. A continuation of these advances is necessary to obtain a global observational network that can transform our understanding of land ecosystem – atmosphere interactions and feedbacks that will improve the ability of Earth system models to address global environmental problems. This should include the following activities:

1. Stable long–term funding should be secured in order to continue the established FLUXNET activities
2. At a subset of FLUXNET sites, measurements should be extended to include fluxes of particles, ozone and biogenic volatile organic compounds (BVOC)
3. Regional networks, such as ICOS and NEON, that include long–term flux measurements of methane, nitrous oxide, and NO_y, should be extended to other regions.
4. "Flagship" level sites representing the major global biomes should be maintained or established with a comprehensive suite of long–term multi–disciplinary measurements providing sufficient information for investigating the complex linkages between biological, physical and chemical processes.

The support of surface, boundary layer, and satellite Earth observations and integration with Earth system models is essential for obtaining new and reliable knowledge for scientists and policy makers to the benefit of society. This requires increased collaboration, development and advancement of the land ecosystem – atmosphere networks that are vital to monitoring, understanding and predicting the Earth system. ■

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Elk–testing climate–carbon cycle models: a case for pattern–oriented system analysis

Summary

Process–oriented models are a primary tool being used to project future states of climate and ecosystems in the Earth system in response to anthropogenic and other forcing. Coupled climate–carbon cycle models receive tremendous attention, especially in the context of the 5th assessment report of the IPCC (International Panel on Climate Change). However, intercomparison of model scenarios indicate large uncertainties regarding predictions of global interactions between atmosphere and biosphere.

Rigorous scientific testing of these models is essential but very challenging, largely because it is neither technically nor ethically possible to perform global earth–scale experiments—we do not have replicate Earths for hypothesis testing. Hence, model evaluations have to rely on monitoring data such as ecological observation networks, global remote sensing, paleo proxy data, or small–scale manipulative experiments.

Here, we critically examine strategies of how model evaluations should be performed. We put a particular emphasis on the representation of terrestrial ecosystems, where the two key problems are:

1. weak (or inconclusive) 'validations' which do not take advantage of all the relevant information in the observed data, and
2. apparent falsifications: "false alarms" likely to occur when individual *system processes* (in the model) are compared to the overall emergent *system behaviour* (of the observed world).

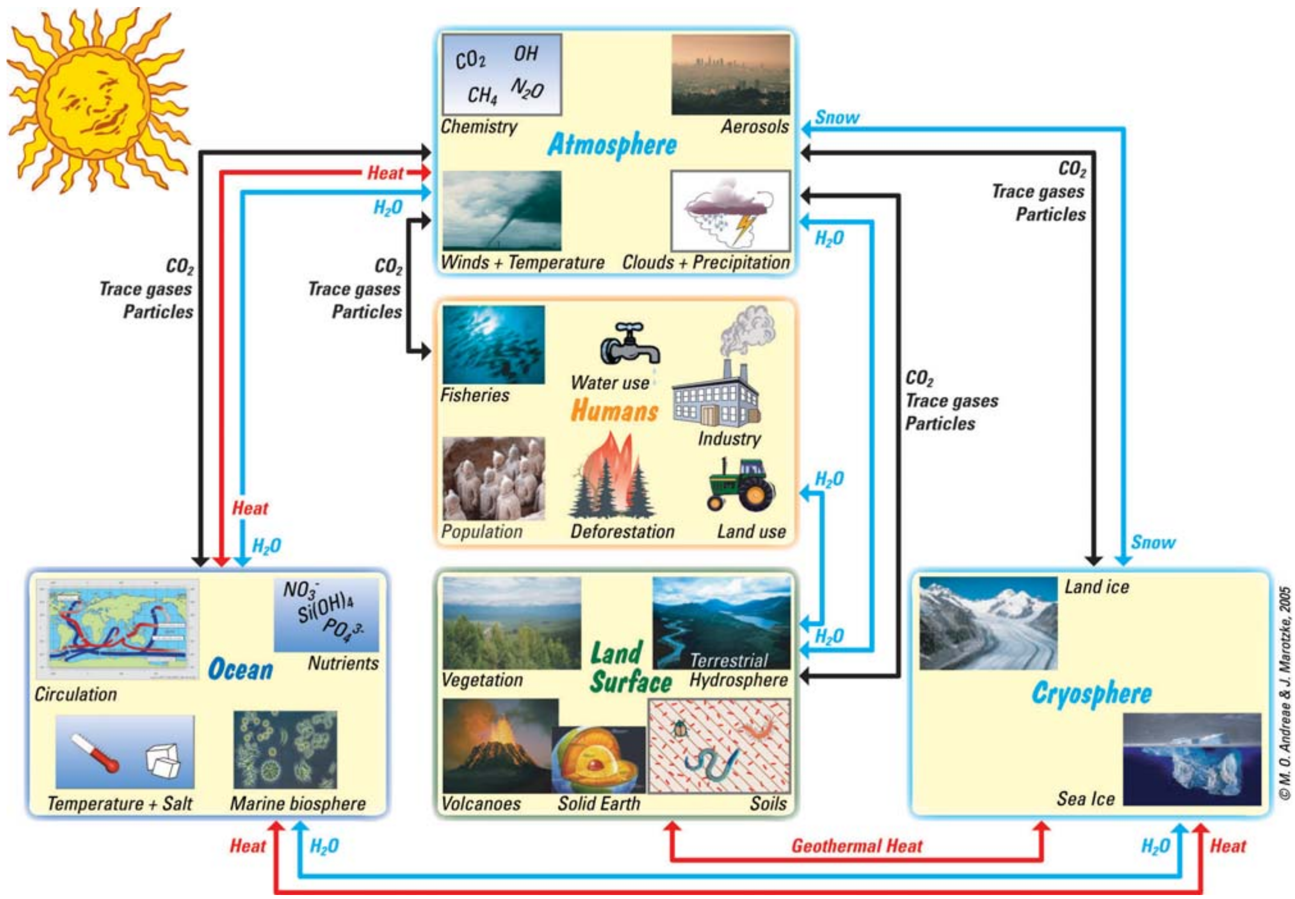

Figure 1. View on the Earth System with its subsystems and their interactions (from [22]).

Here, we argue that only a strong integration of recent advances in pattern-oriented and system–oriented approaches will lead to more satisfying Earth system model evaluations and developments. We show a few examples from terrestrial biogeochemical modelling and other disciplines. We assume in this context that it is crucial to take advantage of the multidimensional nature of arising Earth Observation (EO) data sets which should be matched by models simultaneously, instead of relying on univariate comparisons.

A novel generation of model-evaluation tools is required to assess the quality of future IPCC projections in order to distinguish plausible simulation trajectories from less plausible projections.

Introduction

Compared to other objects of scientific study, the Earth System is unique for three interrelated properties:

1. There are no replicate Earths available (or at least accessible) for scientific purposes.
2. The Earth System is the basis of human and thus scientists' life such that no independent external observations are possible.
3. Performing experiments affecting considerable parts of the Earth system is practically unfeasible and would be ethically doubtful.

Hence, the study of the Earth's behaviour relies to a large extent on our capacity to construct suitable models. Analogue models have been successful in representing specific aspects of the Earth System, for instance physical analogues of crust folding, or the transition from braided to meandering river flow [1].

However, models of this kind are not able to mimic large–scale and long–term interactions among Earth subsystems which are important to the dynamics of Earth as a whole. Moreover, not all aspects of the Earth are scalable such that relatively small analogue experiments may not be informative.

Contrary to analogue models, "digital" numerical models have become prominent research tools in the Earth system. Models are, by definition, only abstractions of the real world, and serve to describe certain aspects which are deemed important for the purpose of the model. Despite their high level of abstraction, numerical models can reach a much stronger comprehensiveness than is thinkable for the above–mentioned analogue models.

In fact, climate models which have traditionally been focusing on atmosphere dynamics are now becoming comprehensive Earth System models describing interactions among and within the main subsystems (atmosphere, ocean, cryosphere, and terrestrial biosphere) and with human perturbation (*Fig. 1*).

In the Earth system context, one of the most important purposes from the societal

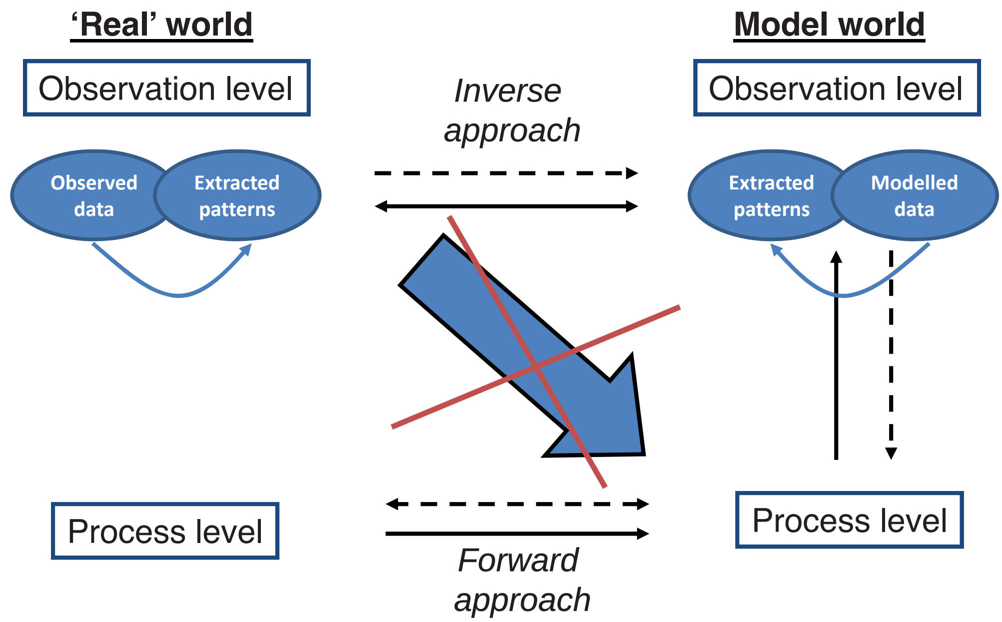

Figure 2. Combination of a hierarchical systems approach and pattern recognition for combining observations and models. Any inference in model–evaluation needs to be realised at the same level of organisation. The direct diagonal inference, instead may lead to severe misinterpretation. After [23].

point of view may be the projection of climate and its effects on the biosphere for the coming decades in a temporally and spatially resolved manner. In recent years, the importance of biogeochemical cycles, most prominently that of the carbon cycle has been recognised because of the intense feedbacks between the carbon cycle and the climate system. All the coupled carbon cycle climate model simulations that have been performed in the wake of the former IPCC report indicate a positive feedback between climate change and the terrestrial and marine carbon cycle, leading to an amplification of climate change.

However, models disagree on the global magnitude of the feedback: the regional distribution of vulnerable ecosystems that will lose carbon in the future. In addition, there are still large uncertainties regarding the processes and sensitivities governing the carbon–climate cycle feedback.

This has become particularly visible in the C4MIP (Coupled Carbon Cycle Climate Model Intercomparison Project) study (http://c4mip.lsce.ipsl.fr, [2]) which revealed a large discrepancy among state–of–the–art models regarding the carbon–cycle climate feedback. Here, one has to bear in mind that most models are not "completely independent" since they share concepts, ideas, and even model code.

The C4MIP models 'only' described the response of the carbon cycle to variations in atmospheric CO_2 concentrations and climate, mediated by water availability. If, however, scenarios are so different regarding just these two key processes, one may expect even bigger regional differences when accounting for additional processes such as disturbances, nitrogen interactions, land–use change and human management of ecosystems, amongst others.

During their development, models are usually tested against different observations until "sufficient agreement" appears to justify application. Obviously, not being able to distinguish among different (complex sets of) interacting hypotheses is a scientifically unsatisfying situation, and the question arises whether developing new and stronger tests is necessary.

Analogously to swerve–testing of cars (testing the stability of cars after suddenly swerving around an obstacle such as an elk), we called such test a *"Model Elk test": A strong test evaluating crucial features of a model under non–trivial conditions.*

For cars, the famous Mercedes A210 (A class) failed such an Elk test, falling on the side, an incident that promoted rapid and unprecedented improvements in car security by a broad establishment "Electronic Stability Control".

Scientific and practical motivation for Earth system model testing

"A model is our perception of how a system works. It is a hypothesis of the real world's functioning, codified in quantitative terms: a model of thought reflecting our theory." This statement was made by H.H.G. Savenije in the context of hydrological modelling [3]. Arguably, this statement equally applies to Earth system sciences. For the sake of precision, one could extend this statement and say that a model is a *collection of mutually linked hypotheses*. This collection of hypotheses on subsystem functioning encodes our current knowledge of terrestrial biogeochemistry and biogeophysics and ideally also represents state–of–the–art concepts of interactions between ecosystems and the atmosphere.

As anticipated above, model–building from first principles raises a conflict of interest: The underlying processes are to be approximated in sufficient detail while model complexity should be limited to the minimum amount necessary to achieve the required macro–behaviour (a principle referred to as Ocam's razor). It is a trade–off between practical issues of semi–empirical numerical modelling on the one hand and the ideal of achieving an acceptable comprehensiveness in process approximation on the other hand.

Hence, we have a two–fold motivation to work on a sound formulation of rigorous and meaningful tests for models:

1. from a purely scientific point of view, the comparative testing of different models scrutinises our current understanding of the dynamics in the Earth system and thereby becomes an important step for further developing environmental theory;
2. from a more societal perspective, the evaluation of current simulation is expected to identify a credible set of models.

Overall, we need to define a minimal set of requirements for model predictions of the future (benchmarks), to guarantee that we are considering a reasonable range of thinkable system trajectories.

Desired and undesired test properties

Two general design properties have to be considered in the construction of robust and informative scientific tests. These properties are related to Type I and Type II errors that need to be minimised:

Type II errors

A test has a high Type II error rate, when the null–hypothesis is likely not to be rejected although it should be.

In experimental studies this can be caused by poor design not accounting for confounding factors, noisy data, or insufficient sample sizes (for an example of this argumentation see, for instance, ref. [4]). In model evaluation, the 0–hypothesis would be "model and observations are drawn from the same distribution or from distributions with the same mean (for example)". In this context, modelled and observed data are usually compared against each other and judgments about the sufficiency of the model performance made, based on metrics such as explained variance or root mean squared errors.

Typical graphical representations of this include scatter plots around the 1:1 line, time-series plots of both modelled and observed data [5, 6]. How well model and data compare often depends on the total variance in the data. These bulk comparisons do not guarantee good model performance and do not exploit all the information in the data. For example, variance in observations may be dominated by the seasonal cycle forced by the sun; roughly matching this seasonal cycle can thus lead to high explained variance but may be trivial.

Nevertheless, tests of this kind are possibly weak (a source of type II errors) since they do not exploit all the information contained in observations and often lead to the notion of "model and observations agree reasonably well".

Type I errors

On the other hand, also "too credulous" tests falsely identifying models as being wrong need to be avoided—these are tests with a high Type I error rate (= unjustified rejection of a null hypothesis). These apparent falsifications of models can occur through too high confidence in the available data, ignoring data biases, and ignoring issues of scale mismatch.

Type I errors can partly be simply avoided by a more critical perspective on observations (for instance, by taking measurement uncertainties into consideration). However, there is an important and more fundamental conceptual problem which has sometimes led to erroneous suggestions of model failure. In these cases, different system levels have been mixed up and observed emergent behaviour of the system directly related to processes within the system (*Fig. 2*).

As in many coupled nonlinear systems, the macro–behaviour of system from the set of basic equations—our set of hypotheses of how the system works—often is not intuitive. Hence, Earth system models often depict complicated, not trivially predictable emergent patterns, and tests must contrast this emergent behaviour with the corresponding real world counterpart.

Prominent examples where different system levels should not be mixed up exist in the context of the response of the terrestrial carbon cycle to warming. For instance, ecosystem–level observations of respiration in warming experiments have shown that that the initial temperature response disappears after a couple of years. This may lead to the notion of biological acclimation, pointing out that this acclimation process is not incorporated in state–of–the–art carbon cycle models.

However, it could be shown that this apparent acclimation behaviour can be easily explained and reproduced by current multiple carbon pool models. Derived conclusions about model falsification were premature at that point.

Another example is the temperature sensitivity of respiration which is assumed to be constant in most carbon cycle models (more precisely: one parameter describes the temperature dependence of soil carbon decomposition rates, such as Q_{10}). Field researchers have, on the other hand, related observed time series of soil respiration and temperature and found highly varying Q_{10} values.

Again, these observations of behaviour have been directly related to processes and led to incorporation of, for instance, the Lloyd–and–Taylor equation [7] into many models. However, recent studies have clearly indicated that the varying Q_{10} at ecosystem level is caused by seasonally confounding factors [8–10], hence model falsification and subsequent development was based on an erroneously credulous test.

Pattern–oriented model evaluation

As a consequence of the described problems, two basic requirements to meaningful model testing become obvious:

1. all facets of information from the system behaviour need to be extracted in a highly differentiated way;
2. any test is only meaningful if we guarantee that comparisons of observed and modelled data are realised at the same level of system organisation (*Fig. 2*), avoiding apparent falsifications.

In other words, sets of "patterns" (definitions below) have to be extracted consistently from both modelled and observed data to allow for meaningful comparisons (*Fig. 2*). Moreover, the challenge with model evaluation is to interpret differences of modelled and observed data in a system–oriented way.

Extractable patterns within the Earth system may be classified into three types:

1. *Time-scale–related patterns*

Focussing on the temporal variability of model-data disagreements is a fundamental issue. However, processes within the different compartments of the Earth system typically vary on a wide range of time scales from seconds to millennia. Both land surface models and coupled C4MIP models aim to cover scales of variability between days, decades, and centuries.

Spectral analysis is one approach to discriminate different processes acting on different scales. A few recent studies have been performing model evaluations on multiple time scales [11–13], where, for instance, the phasing and amplitude modulation of the seasonal cycle can be evaluated separately from within–year model–data agreement, such as monthly variability or the temporal development of diurnal cycles. Multi–scale analysis allows identifying specific aspects of model–data disagreements that are likely to be obscured by the large co–variability of the seasonal cycles (or vice versa).

Also, qualifying response times can be seen as important benchmark of models. Hydrometeorological feedbacks, induced, for instance, via soil moisture storage have strong relevance for the climate system. This is why persistence in the system states (and associated memory effects) can also become a fundamental pattern for model testing, in particular when the role of extreme events such as heat waves and droughts is under question [14–16]. Analogously, Blyth *et al.* showed that the speed of reduction of evapotranspiration after rainfall can be used to identify another key model (dis–) function [17].

Overall, we assume that distinguishing time–scale–specific patterns in model-data mismatches is pivotal. Refined model-data agreement on discreetly separated time scales may reveal model–data (dis–) agreements that are otherwise overlooked.

2. *Spatial and spatio–temporal patterns*

Spatial structures relevant to land– atmosphere interactions are another salient feature to consider. The often non–stationary fields are, however, not trivially accessible to the evaluation of spatially explicit models.

Multiple analysis strategies are possible, such as combining the time–evolving spatial patterns of rainfall and NDVI (Normalised Differential Vegetation Index) in analysing where in the world vegetation growth was water–limited. Additionally, Beer *et al.* [18] inferred spatial patterns of productivity and its correlation with precipitation.

Such analyses allow the identification of global maps of water–stress which may serve as reference for global models. Often a statistical analysis of spatial variability in land surface temperature from satellite data can be used to identify discrepancies between the model responses to rainfall with reality: the soil types and the vegetation cover affect the dynamics of the temperatures from a dry land surface after a rainfall event [19].

A more general issue appears after these considerations about time–scale–specific patterns have been taken into account. Conceptually, one has to work towards spatio–temporal–pattern–oriented model evaluation. For instance, processes acting on different time scales may also induce multiple geographical gradients. To deal with this issue, it was proposed to integrate subsignal extraction and dimensionality reduction methods for comparing geographical gradients on multiple time scales.

Overall, it can be considered an advantage of space–explicit global studies that one may exploit model predictions over a wide range of climate regimes and land surface properties, although these do possibly not comprise the full range of possible scenarios.

3. *Functional patterns*

While the aforementioned patterns are extracted in geographical space considering also the time axis, functional patterns describe the system behaviour within the state and functional space of the system. This "space" is established by all observables within the system under study and external forcing.

Because these patterns reflect system internal properties, they may allow abstracting from biases in drivers. For example, when a model is driven by biased precipitation data, the resulting biogeochemical cycle quantities are also expected to be biased.

However, the responses of the modelled carbon cycle to precipitation and system internal properties (such as carbon gained per water transpired) should still be comparable to the respective observations. Correlations, sensitivities, response functions, as well as emergent functional properties (such as radiation–use efficiencies) may be interesting patterns to evaluate models against.

As an example, *Fig. 3* shows that the rain–use efficiency (gross primary productivity divided by precipitation) increases with increasing evaporative fraction along a latitudinal gradient (and differently between the northern and southern hemisphere). The same functional relation for whole Australia alone but along time is exhibiting the opposite trend (*Fig. 3b*).

Fig. 4 shows the sensitivity of estimated gross primary productivity [20] to precipitation preliminarily: here the sensitivity along spatial gradients and in time is of the same sign most of the time, but spatial sensitivity appears twice as high as the interannual sensitivity. These are examples where functional patterns in space and time maybe effectively compared with respective model behaviour.

Patterns can be extracted in a prescribed way according to *a priori* knowledge as in *Figs. 3* and *4*. However, particularly in a data-rich world, pattern extraction aided by machine learning offers potential advantages:

1. patterns can be extracted in an objective way, without perception bias which is typical for human brains;
2. new, hidden, and unexpected patterns can be found, leading to new findings and hypothesis about the system under study.

Given that a large set of spatially distributed variables varying in time span an extremely highly dimensional space (for instance, 360 x 180 grid cells x 20 variables),

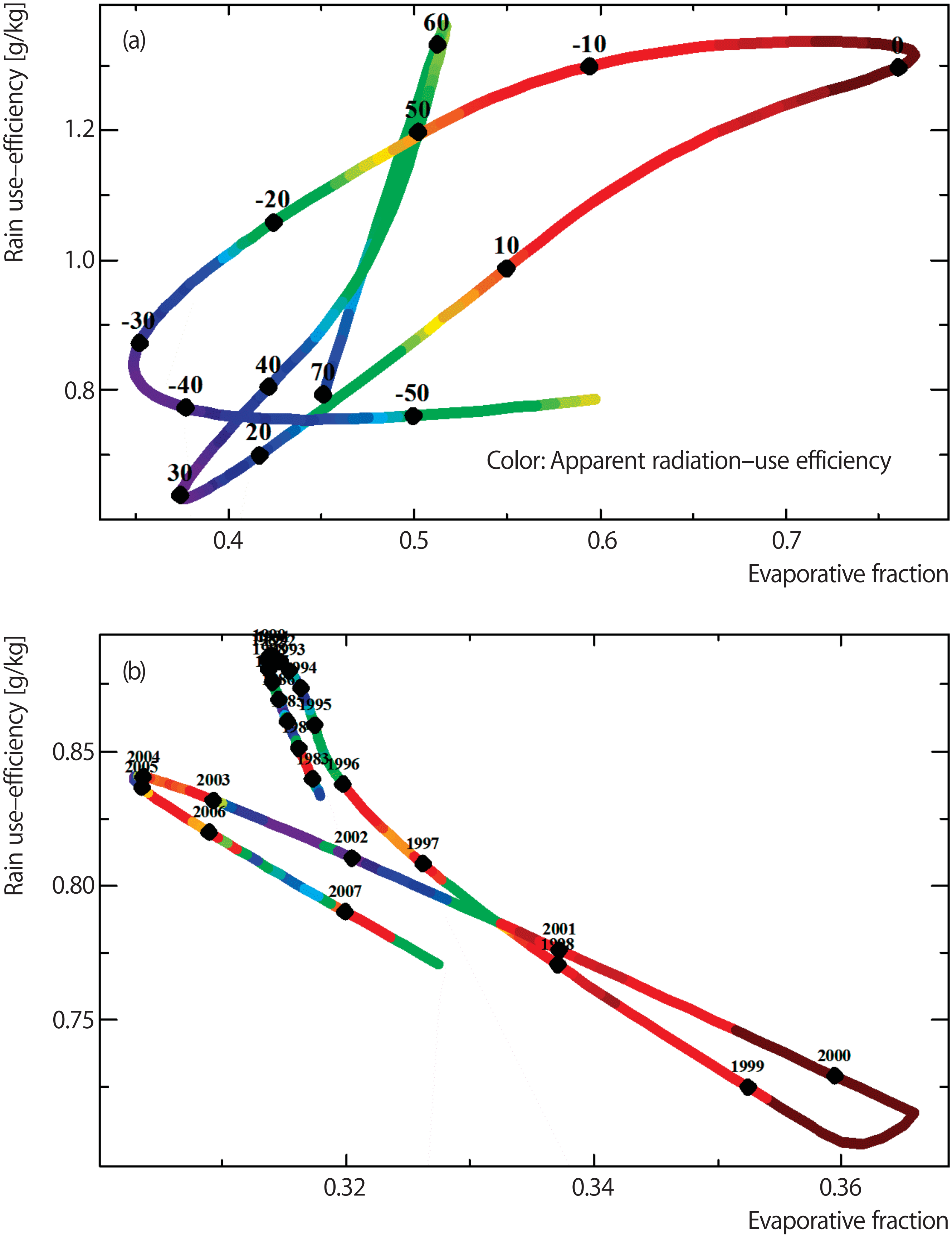

Figure 3. Examples of functional patterns derived from spatial fields of gross primary production and evapotranspiration and precipitation. Upper panel: Latitudinal band median rain–use efficiency versus evaporative fraction. Numbers indicate latitude. Lower panel: Temporal trajectory of rain–use efficiency versus evaporative fraction for Australia.

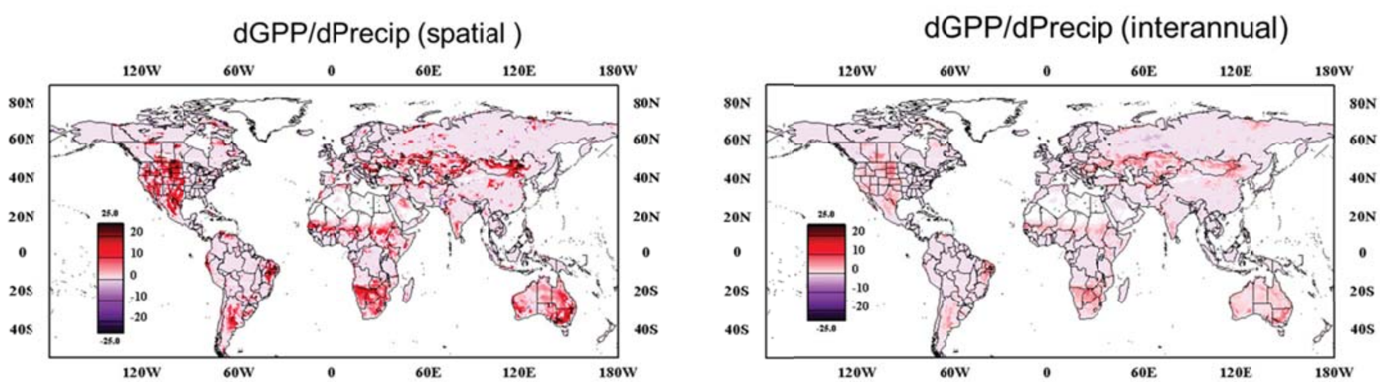

Figure 4. Spatial and temporal sensitivities of gross primary production (GPP) to Precipitation (Precip).

one foremost challenge is to find the dimensions dominating the variability.

Progress via non–linear pattern recognition approaches?

The pattern–oriented exploration of observed and modelled data streams is expected to substantially benefit from recent progress in the science of machine learning and pattern recognition [21]. Empirical inference of this kind is expected to stimulate and strengthen model building towards the formulation of a unified theoretical basis of the functioning of the different subsystems in the Earth system.

Relevance of pattern–oriented tests

Type III errors

We contend that with the above-mentioned approaches, Type I and II errors can be minimised. However, with scientific testing in a systems context, a less clearly defined but important error has emerged that is relevant also in the context of climate–carbon cycle model testing. This has been called Type III error and alludes to "irrelevant tests" or having asked the "wrong question" in the first place.

Transferred to model evaluation, this means applying tests that are not relevant for the purpose the model was built for. For example, if a global carbon cycle model is shown to be incapable to reproduce the interannual variability of the carbon cycle at site level because of specific ecosystem dynamics going on such as fruiting years which are not relevant for climate sensitivity and longer–term prediction, this failure may be thought to be irrelevant.

The problem is, however, more fundamental and the question is: "How do we rate the relevance of a test at one time–scale for the model purpose at a different time-scale?" For instance, if two models are compared with respect to annual CO_2 growth rates and one model performs better on the seasonal cycle while the other better describes the characteristics of the interannual variability, which model predictions for the next 100 years should we believe?

While important diagnostics have been defined in a deductive, hypothesis–driven way, such as the beta– and gamma factors for the CO_2 fertilisation and temperature effects on the global carbon cycle [2] or the Q_{10}–diagnostic for the short term temperature sensitivity of respiration [8], formal inductive algorithms are currently missing. In the context of carbon–cycle climate prediction, the goal of such algorithms will be to identify characteristic association between today's model behaviour and future model predictions.

Conclusion

We are facing a development of Earth system models towards more and more complexity. As shown in C4MIP experiments this increasing complexity does not necessary mean increased predictive power. The use of Earth observation from multiple sources has to keep pace with model development. The future challenge will be to extract generalised and useful information from respective data sets, confront these with model behaviour and interpret differences in a system–oriented way. Modern developments in machine learning and pattern recognition—often from other research areas—should be more strongly considered. ■

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Nathalie de Noblet–Ducoudré is a bioclimatologist that has spent most of her time trying to understand what roles the terrestrial biosphere plays in the climate system. She first turned her attention towards past climates (mainly the last glacial–interglacial cycle) and contributed to demonstrate that vegetation dynamics are an active player in the climate system that needs to be accounted for in order to simulate climatic transitions. More recently, she turned her attention towards human–induced land cover changes and their influence on climate at the global scale. With Dr. Andy Pitman and with the support of IGBP/iLEAPS and GEWEX/GLASS, Dr de Noblet–Ducoudré has launched the LUCID international intercomparison project discussed in this article. Essentially a modeller, she tries to see whether the knowledge of regional to global land–atmosphere interactions and their potential predictability can help anticipate the consequences of land–use strategies.

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Including humans in climate models: an issue for land–use induced land–cover changes

Human action is classically included in global climate models by means of the changes it induces to the atmospheric composition: increased greenhouse gas concentrations and changes in the amount and nature of aerosols [1]. These imposed changes in the concentration/distribution of atmospheric constituents will provoke a climatic response; hence, these changes are referred to as *climatic forcing*. Those forcings are considered external to the climate system. This means that they are not further modified by the climate change they induced.

There is another human–induced forcing that has not yet been considered, and that has the potential to lead to regional and global changes: land–use–induced land–cover changes (LULCC).

LULCC were included in only 3 out of 23 climate models in the last Intergovernmental Panel on Climate Change (IPCC) report [1] although these changes have been quite significant since pre-industrial times in the temperate regions and in East Asia (*Fig. 1*), and may change in the future due to both population growth and change of diets in many parts of the world.

However, LULCC will be included in the next IPCC report (CMIP5 simulations, http://cmip-pcmdi.llnl.gov/cmip5) but only together with other forcings. Those simulations will therefore not allow us to identify the specific impacts that one can attribute to LULCC. Consequently, we cannot examine LULCC–related mitigation strategies (such as reforestation) that may be significant at regional scales.

To fill in this gap in knowledge, the project "Land–Use and Climate, IDentification of robust impacts" (LUCID) was conceived under the auspices of iLEAPS, a core project of International Geosphere–Biosphere Programme (IGBP), and Global Land–Atmosphere System Study (GLASS), a core project of Global Energy and Water Experiment (GEWEX). LUCID explores those effects of historical LULCC that are robust—that is, above the noise generated by model variability and consistent across multiple climate models.

To achieve this, we launched a call among the modelling community. Researchers working with seven models (*Table 1*) came together to carry out a coordinated set of simulations (*Table 2*). Detailed results from these simulations can be found in [2, 3].

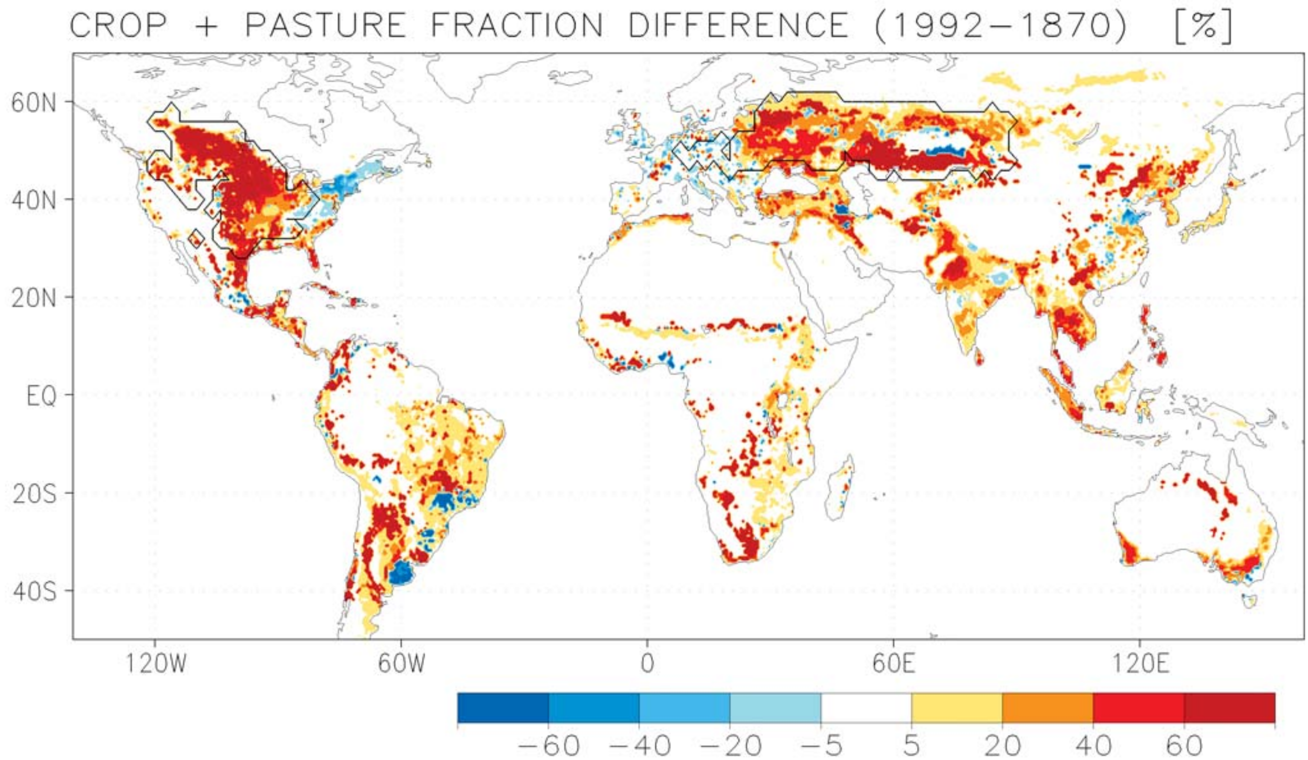

Figure 1. Changes in the extent covered with crops and pasture between present–day (1992) and pre–industrial times (1870). Yellow and red colours signify that the extent of anthropogenic areas has increased since pre–industrial times, and blue colours refer to abandoned lands. Contour lines indicate the regions that will be used for specific analysis in Figs. 2 and 4 (hereafter referred to as North America and Eurasia).

Name of Climate Model	Name of Land–surface Model
ARPEGE	ISBA
CCAM	CABLE
CCSM	CLM
ECearth	TESSEL
IPSL	ORCHIDEE
SPEEDY	LPJmL
ECHAM5	JSBACH

Table 1. List of climate and associated Land–Surface Models used in the first LUCID set of experiments.

Table 2. Description of simulations that each climate model carried out. Comparing PI to PIv or PD to PDv allows to explore the influence of LULCC on climate. Comparing PIv to PD or PI to PDv allows to compare the influence of changes in greenhouse gases and in sea–surface state since pre-industrial times (hereafter referred to as CO2SST). Each set of experiment comprises 5 simulations in order to assess the robustness of the simulated changes (by means of statistical analysis).

Experiment name	Description of the experiment	SSTs and Sea–ice extent
PI	Pre-industrial Simulation, with CO2, greenhouse gases, aerosols, land–cover map and SSTs being prescribed at their pre–industrial values	Prescribed 1870–1900
PD	Present–day Simulation, with CO2, greenhouse gases, aerosols, land–cover map and SSTs being prescribed at their present–day values	Prescribed 1972–2002
PIv	Pre–industrial Simulation with CO2, greenhouse gases, aerosols and SSTs being prescribed at their pre–industrial valueBUT with present–day land–cover map	Prescribed 1870–1900
PDv	Present–day Simulation with CO2, greenhouse gases, aerosols and SSTs being prescribed at their present–day valuesBUT with pre–industrial land–cover map	Prescribed 1972–2002

First results from LUCID

The historical changes in atmospheric CO_2 concentration, in sea–surface temperatures and sea–ice extent (hereafter referred to as CO2SST) provoke the known global and regional warming resulting mainly from the increased incoming energy at the surface (greenhouse warming). LULCC on the other hand lead to a cooling in the regions that have experienced the largest changes in vegetation cover. This cooling mainly results from the increased surface albedo that follows a shift to cultivation from forests or grassland, and that induces a decrease in the available surface energy.

Both warming and cooling turned out to be of the same order of magnitude (~0.5°C in absolute terms) (*Fig. 2*). This occurs despite the fact that changes in CO2SST lead to significant mean global annual temperature change (an average over the seven models of 0.432°C globally, and of 0.625°C over land only) while the response to LULCC is negligible at that scale (an average of –0.019°C over the globe and of –0.069°C over land).

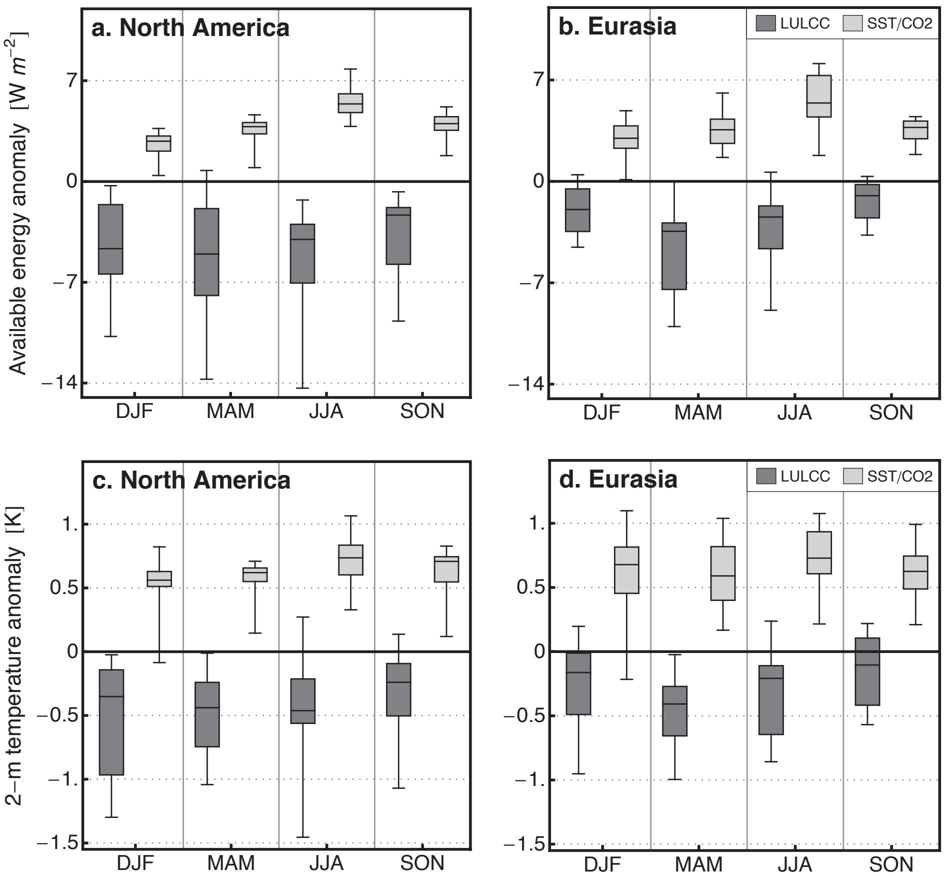

Figure 2. Box and whisker plots of the simulated changes between the pre–industrial time period and present day in a–b) available energy (*top diagrams*; W m^{-2}) and c–d) surface air temperature (*bottom diagrams*; °C) for all seasons and both selected regions (*left diagrams*: North America; *right diagrams*: Eurasia; located in Fig. 1). The plot was created by means of mean ensemble values of each individual model and each set of experiment (*i.e.* PD–PIv and PDv–PI for the CO2SST impacts, and PD–PDv and PIv–PI for LULCC effects).

This emphasises that the warming effects of CO_2 increase (and resulting surface ocean temperature changes) are *global* but the cooling effects of LULCC are *regional*. Therefore, looking at only global averages (e.g. the change in mean global annual temperature) when quantifying climate change is insufficient because it hides changes of similar importance over some specific (and densely populated) regions.

Figure 2 illustrates why restricting the quantification of climate change to only global numbers such as the change in mean global annual temperature (as is still quite often done in the literature) does not give a full picture. Important regional–scale changes do not pop out at the global scale [4, 5].

Moreover, the spread among the models' responses is somewhat larger when the models are forced with LULCC than when they are forced with CO2SST (*Fig. 2*). This implies that there will be more dispersed regional climatic responses to anthropogenic forcing in the upcoming IPCC simulations than there were in the previous set of simulations (for IPCC Fourth Assessment Report). The reason is the absence of consistent behaviour among the various models regarding how different land–cover types re–emit, towards the atmosphere, the incoming radiative energy in the form of either evapotranspiration, convective heat, or thermal emission.

Forcing models with changes in CO2SST leads to perturbation in incoming total energy provided to the land surfaces; not in the way this energy is partitioned between sensible and latent heat fluxes (sensible heat: atmospheric heat transport by rising warm air; latent heat: atmospheric heat transport by water vapour flux upwards from surfaces and vegetation). The increased incoming energy in CO2SST results in increased available energy that leads to warming in all models since ~75% of the available energy is used to warm the land.

Forcing models with LULCC leads to the opposite scenario: the way the incoming energy is partitioned into absorbed (radiative) and re–emitted (latent and sensible heat fluxes, thermal emission) energy is the central consequence. Not only is this absorbed energy (and thereby available energy) systematically reduced in all models in all seasons because of increased surface albedo (resulting from the amount of forests that were removed to grow crops), but the subsequent fractionation of this absorbed energy between the terms discussed above also changes (as a result of deforestation).

Despite the large dispersion the models show in response to LULCC (*Fig. 2*), there are a number of common robust features that they all share. Surface albedo, for example, increases in simulations by all the models because of deforestation and leads to a decrease in available energy at the surface. More of this available energy is used, in all models, to warm up the land (instead of being used for turbulent fluxes) at present–day than during the pre–industrial period. This results from the change in the roughness of the land surface: forests are rougher than crops and therefore more efficient to transfer the energy back to the atmosphere in the form of turbulent fluxes.

A remarkable finding is that these changes are proportional to the amount of forest removed in all models. As a matter of fact, although we have provided each modelling group with the same crop and pasture distributions for both time–periods, they have implemented those differently onto their own built–in land–cover map. Each model has its own vegetation map so in most cases the changes in crop area have simply been superimposed on it (*Fig. 3*). This has led to quite different vegetation distribution and therefore changes in forest areas from one model to another (*Fig. 4*).

The temperature response to LULCC varies among the models. Mainly, we attribute this variation to the way each individual model partitions the available energy into latent (LE) and sensible (H) heat fluxes in a specific time period, together with the way their turbulent fluxes (H and LE) change from one season to another in response to LULCC. In some models, deforestation leads to a decrease in both fluxes while in others H increases and LE decreases (or reversely). This is dependent on how these processes are represented in each individual land surface model [6].

Implications of implementing LULCC in climate models

The common features we have identified, and more specifically their dependence on the amount of deforestation that was prescribed in each model, suggest that, if the community agrees on the amount of deforestation that occurred over specific time periods, a significant part of the dispersion among the models may be reduced. The problem we are facing is that climate models and their land–surface components are commonly developed together with an assumed natural vegetation map, and it was not feasible for our simulations (nor was it for the CMIP5 simulations that are now running for the IPCC–AR5) to require all modelling groups to use a common natural vegetation map.

Our results focused only on the biogeophysical effects of LULCC. If we had included the biogeochemical feedbacks as well, as in [7], we anticipate that the dispersion among the models would have been even larger.

An urgent need exists, therefore, to carry out sensitivity studies using AR5 models to quantify the importance of a) using the same vegetation maps, or b) following a similar protocol that will ensure that the amount of changes in the main ecosystems is similar from one model to the other (e.g. fractional coverage by trees vs. by herbaceous types).

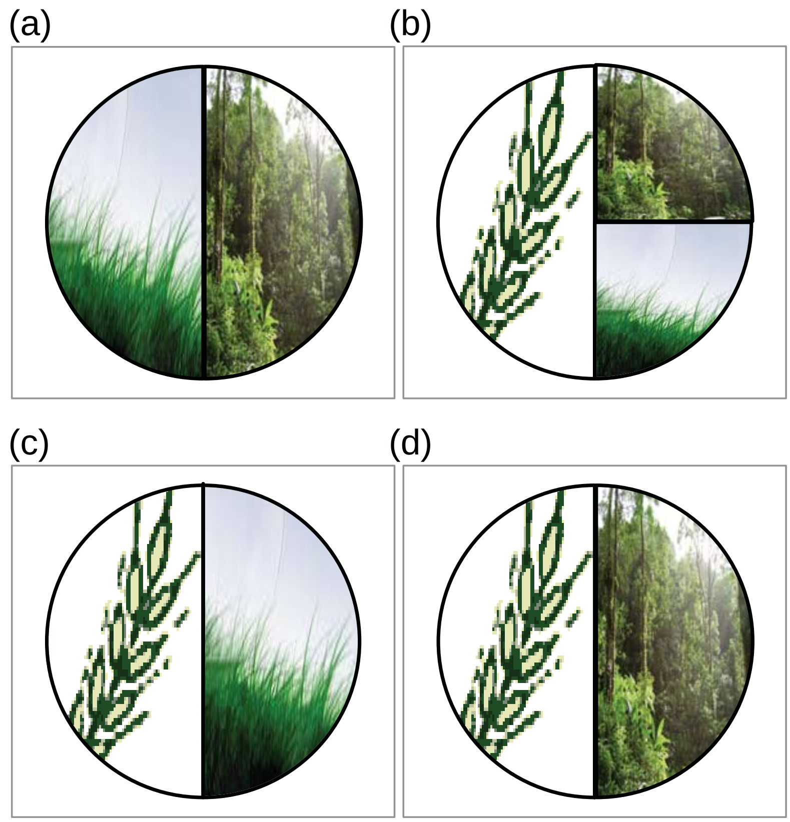

Figure 3. An illustration of how 50% of a natural landscape (50% forest, 50% grass) can be converted into very different combinations of vegetation via different but equally valid decisions: a) original natural distribution, b) each original vegetation type has been proportionally reduced, c) all forests have been cleared and grasslands have remained untouched (for example for grazing), d) all grassland have been converted into cropland while forests have remained untouched. Adopted from Pitman and de Noblet–Ducoudré (2011).

Implications for validation of land–surface models

The observation, derived from the LUCID results, that models are fundamentally different from one another in the way they partition their available energy in latent and sensible heat fluxes on the one hand, and in thermal infra–red radiation on the other hand is not new: the Project for the Intercomparison of Land–Surface Parameterisation Schemes (PILPS) has shown this many times [8, 9].

The new information our results bring is that this is what explains most of the spread between the models in an experiment where the land surface is perturbed (in this case by LULCC). PILPS showed that partitioning of available energy was vital to how a land surface model simulated the control climate; LUCID showed that this remains true in a perturbed system.

This finding reenergises the need to resolve uncertainties in how the land surface is parameterised, not just for a control climate, but also for simulations of perturbations. We now have a number of datasets that could be used to better evaluate our models (*e.g.* FLUXNET, remote sensing products and LandFlux–EVAL data base), and differences in the surface models' behaviour as large as the ones obtained within the LUCID models could probably be relatively easily overcome with improved coordinated validation (testing the fit between model and data) of our land–surface models.

A validation effort like this has already started from group initiatives in the US (C–LAMP project; www.climatemodeling.org/c-lamp/) and in Europe (iLAMB project; www.ilamb.org/), but we wonder whether this will be sufficient. What remains quite a surprise is that many of those land–surface models have already undergone rather exhaustive validation and therefore should not exhibit such extreme differences.

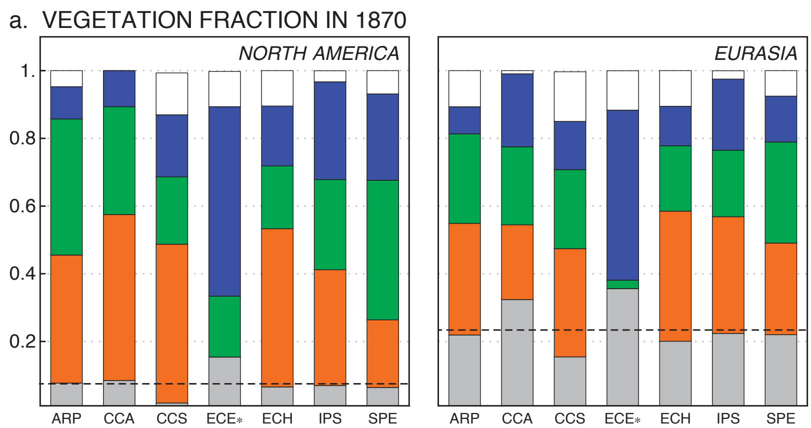

Figure 4. a) 1870–extent (in fraction of total area) covered by crops (*grey*), grassland types (*orange*), evergreen trees (*green*), deciduous trees (*blue*) and desert (*white*) for all seven models and two different geographical locations (North America and Eurasia; located in Fig. 1).

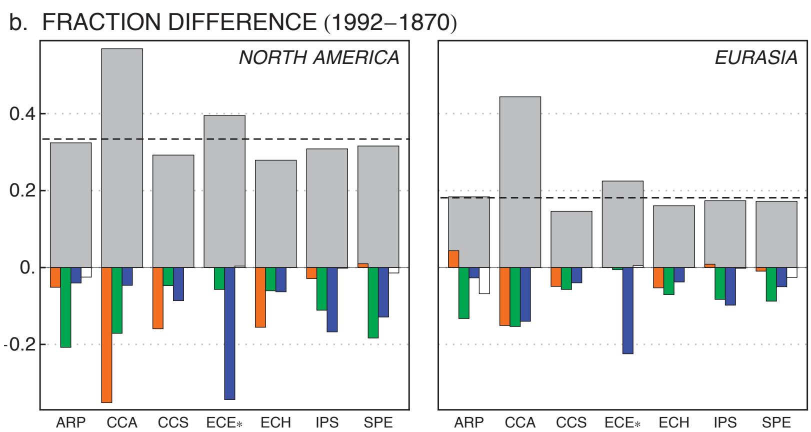

Figure 4. b) Differences (in fraction of total area) in each individual vegetation types between present–day (1992) and pre–industrial times (1870). *Dashed black lines* show crop extent and its changes provided to each model.

We recommend that new evaluations of land–surface models should try and account for atmospheric feedbacks, although we acknowledge this will be a rather hard task for all groups. Such evaluation should then be completed by series of analysis to see how well the models simulate the contrasting dynamic properties of various vegetation types, which are relevant for biosphere–atmosphere interactions such as water–use efficiency, dynamics of evaporative fraction, and effective temperature sensitivity of carbon balance.

Implications for detection/ attribution studies

Detection/attribution studies are simulations carried out to identify what causes the historical changes observed: natural climate variability, CO_2 increase, land–use changes, or aerosol changes, for instance.

Increased greenhouse gas concentrations in the atmosphere and the consequent changes in sea–surface temperatures and sea–ice extent are often used as the main drivers of terrestrial changes. Our results suggest that such an assumption may lead to erroneous conclusions regarding the land–surface effects of climate change since LULCC has, on a number of variables, an influence of similar magnitude as, but of opposite sign, to that of greenhouse gases.

Detection/attribution studies should therefore account for LULCC as well as they do account for other anthropogenic changes.

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The **ECSW** program includes scientific keynotes from invited speakers followed by panel discussions, training sessions and social events. The state–of–the–art keynotes will expand on topic such as modeling; atmospheric reactive gas traces measurements and interdisciplinary in teaching and scientific collaboration. The training sessions will provide tools for science career planning and development, hints for time management and training in media communication skills.

Post–Conference Workshop

PCW

Challenges and chances of integrated long–term LEAP observatories

25–26 September 2011

IMK–IFU, KIT,
Garmisch–Partenkirchen, Germany

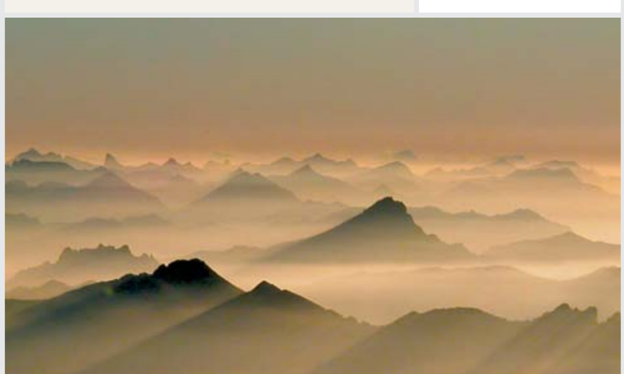
This event is by invitation only.
For more information, please contact:
Hape.Schmid@kit.edu

The objective of the **PCW** is to synthesize and discuss the experience gained by long–term observatories, the challenges faced and opportunities offered by integrated long–term LEAP observations.

KIT Karlsruhe Institute of Technology

ECSW invited keynote speakers

Almut Arneth, Lund University, Sweden
Guy Brasseur, Climate Service Center, Hamburg, Germany
Mary Anne Carroll, University of Michigan, United States
Thomas Karl, NCAR, United States
Francesco Loreto, Institute for Plant Protection, National Research Council, Italy
Laurens Ganzeveld, Wageningen University, Netherlands



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Eleanor Blyth has been working in land surface modelling and land–atmosphere interactions since 1990 when she joined the CEH team of experts in evaporation. Since then she has developed expertise in several relevant processes: evaporation, soil processes, soil freezing, snow processes, the generation of run–off, and photosynthesis. She focuses on using data to test and develop models and launched a novel benchmarking system for the UK Community model JULES (Joint UK Land Environment Simulator). Dr Blyth is a member of the iLEAPS Scientific Steering Committee as well as the GEWEX Science Steering Group.

Eleanor Blyth[1] and Chris Jones[2]

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Benchmarking land surface models in high latitudes

Over the last decade or so, a growing number of climate models have been developed to investigate the coupling between the climate system and the global carbon cycle and increasingly other components of the Earth System. Such Earth System Models (ESMs) have the ability to tell us about the future climate and its interactions with ecosystems. They are also finding more and more applications across different spatial and temporal scales from weather forecasting to climate predictions, and from site level to global scale simulations.

For instance, we have seen studies using land surface models that are classically used in climate models that now consider ozone pollution on vegetation, that model large-scale nitrogen fertilisation, forest fires, wetlands, agriculture and plant–emissions of organic compounds. At the same time, the representation of snow and hydrology has been upgraded. These changes have been fast and, in some cases, furious! A central group of modellers is working hard to incorporate the new science into the models.

However, as the models become more complex they also have the potential to become less constrained and more difficult to analyse or understand. Therefore, there is a growing need for systematic and targeted evaluation of these models against relevant observational datasets to ground–truth their behaviour at process level, and constrain their projections at an integrated level.

Seductive as it may be to add ever more processes to the models, it is important that we do so in a way that brings benefit rather than loss of skill. The question raised by everyone involved is: does increasing the number of processes described in land surface models improve model predictions?

Answering this question requires crucial information: exactly what are we trying to predict better? How good were the model predictions in the first place? What should we compare these model predictions against? What is the benchmark against which we will measure any improvement?

Past data–model intercomparison studies have strengthened the representation of key processes in land models, but often this information has not been easily accessible for other modelling teams or intercomparison studies.

Instead, several groups of land surface modellers have set out a standard set of tests that will remain in place and be delivered to the modelling community as a *benchmark*. The idea is to draw a line in the sand at a particular moment in time and quantify the performance of the model, which can then be referred to later as changes are made. An example of such a set of benchmark tests was made for the UK community model JULES (Joint UK Land Environment Simulator).

We set out to answer the following questions:

1. How well does the original model work with respect to some well established datasets?
2. How well does the model reproduce the seasonal river flows in the major rivers, the seasonal greening up and dying of the vegetation at the continental scale, and the seasonal fluxes of carbon dioxide (CO_2) and evaporation?

For JULES, we collected a simple 5–dataset benchmarking suite.

A full description of the datasets and their use in testing the performance of the JULES at the global scale is reported in Blyth *et al* (2011). We used ten FLUXNET sites, representing a range of climates and biomes to look at the fluxes of evaporation and carbon dioxide, and chose 7 river basins where we studied the river flow to check the overall modelled water balance upstream and the seasonal changes in NDVI (Normalised Differential Vegetation Index, "landscape greenness") which we compared with the modelled leaf–area index. We also looked at the atmospheric CO_2 concentrations which measures the integrated land fluxes of CO_2 at four stations.

The information that was given to the land surface model included soil maps, daily weather across the whole world and maps of plant–type. By studying how well the model recreated these observations of river flow and evaporation and carbon dioxide emissions, we could make some assessments of how well the model was performing in the different regions. The results are outlined in *Figs 1a–1f.*

For instance, by studying the performance of the model compared to the sub–set of the data that related to the northern latitudes, a consistent pattern was emerging: the modelled spring was appearing too early. This was apparent in the water

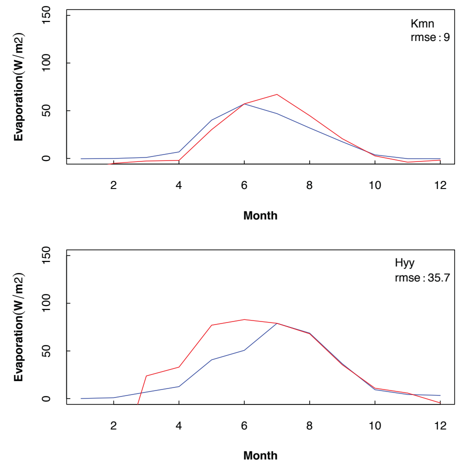

Figure 1a. Modelled (*red*) and observed (*blue*) evaporation fluxes at two FLUXNET sites.

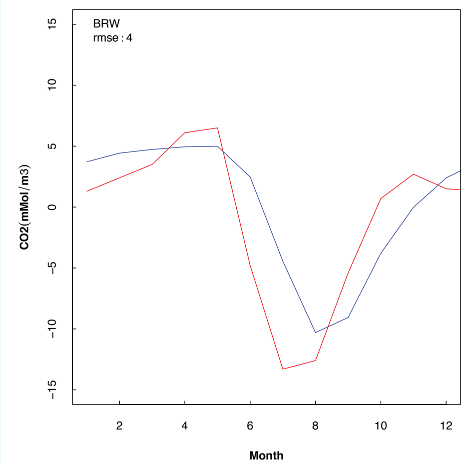

Figure 1d. Modelled (*red*) and observed (*blue*) seasonal atmospheric carbon dioxide BRW.

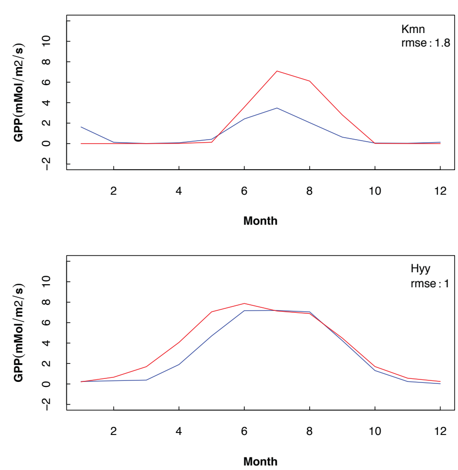

Figure 1b. Modelled (*red*) and observed (*blue*) GPP fluxes.

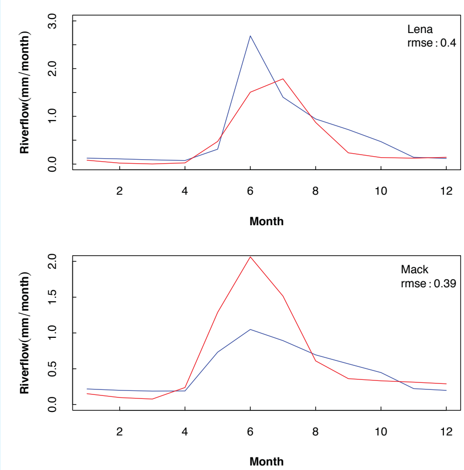

Figure 1e. Modelled (*red*) and observed (*blue*) seasonal river flow at two catchments

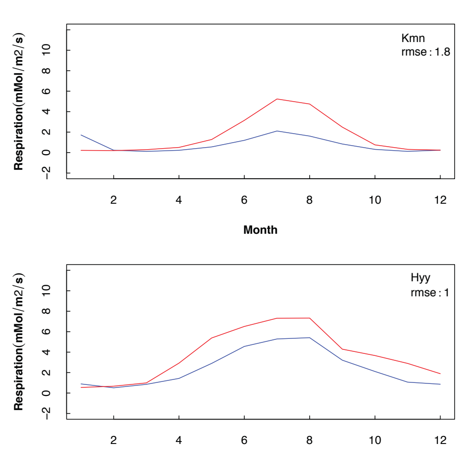

Figure 1c. Modelled (*red*) and observed (*blue*) respiration fluxes.

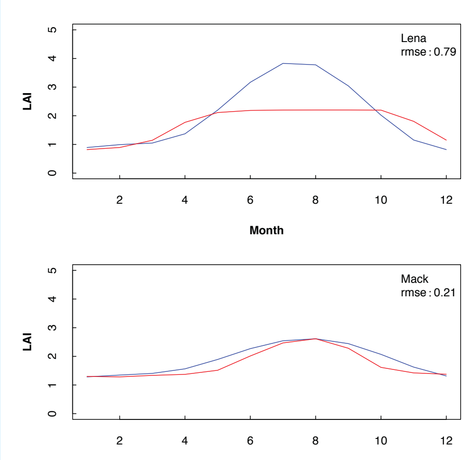

Figure 1f. Modelled (*red*, LAI) and observed (*blue*, scaled NDVI) phenology.

balance with an early increase in evaporation of two northern FLUXNET sites (Hyytiälä and Kaamanen, in Finland) which suggests that the plants had started to photosynthesise and transpire earlier than the observations. The flow of the two main rivers in the area, the Lena and the Mackenzie, also increased, indicating that the snow melt had occurred earlier.

An exceedingly early spring was also apparent in the simulated CO_2 dynamics: CO_2 fluxes were increasing early compared to the data, the NDVI seemed to be increasing earlier than the observations (although with scaling issues there is considerable uncertainty in this measure), and the drop in the atmospheric CO_2 concentration, which happens in the northern hemisphere every spring as the plants start to take up CO_2 from the air to grow, seemed to occur earlier in the model than in the observations. All these differences implied that, in the model, vegetation activity was starting up too early.

The timing of spring at the northern latitudes is controlled by thaw. Unlike in hot and dry regions where the greening up of the land is controlled by the start of periodical rains, at the northern latitudes one of the main factors limiting photosynthesis is the freezing of the soil. Our data seemed to imply that the thawing in the model simulations occurred too early.

This result was not all that surprising. We already knew that the model had a problem with soil freezing after a previous model–data comparison project: Project for Intercomparison of Land surface Parameterisation Schemes (PILPS–2e) and subsequently made some improvements.

However, investigating the effect this problem had on the simulation of plant phenology was interesting: we found that correctly simulating soil freezing and its influence on plant growth, on hydrology, and on CO_2 fluxes of these regions is complicated as the processes involved are highly interlinked.

We also demonstrated that to get both the carbon and the water emissions right at the same time is hard to achieve. This would not matter very much if either the Arctic was of little significance to the global energy and carbon evolution, or if the Arctic was not likely to change much (since observations could be used in place of a model).

However, neither is true. The Arctic is already warming significantly, and warming is expected to be fastest and greatest at high latitudes, 4–7°C over the next century [1]. In addition, the estimated carbon stocks in the Arctic soils and vegetation are considerable, albeit very uncertain.

Improving the land–surface models for high latitudes in particular has, therefore, become a priority. New datasets, such as FLUXNET, are appearing online. In particular, Earth Observation datasets are becoming more useful as the time–series become longer and practical applications develop. Previously, model development depended on the availability of point datasets but now we can now obtain datasets on global snow cover and depth (GlobSnow), soil moisture (AGADUC), wetland extent [2], and seasonal large–scale land–water store (GRACE). More of these are becoming available all the time (ESA: DUE permafrost).

We have entered a new era where data for testing and benchmarking models is easily available. What we need now is an international effort to co–ordinate the use of the data to test and improve the models.

By pooling our resources, we can make the best use of the investment the science community has put into delivering these observations. Hopefully, by intelligent use of combinations of data of carbon and water fluxes and storages, we can make the necessary steps to make the improvements we need for forecasting climate.

One such project is iLAMB (International Land Atmosphere Model Benchmarking: www.ilamb.org) which had its second workshop in January 2011.

iLAMB grew out of several activities – the US land model evaluation activity, Carbon Land Atmosphere Modelling Project C–LAMP (www.climatemodeling.org/c-lamp, [3]), benchmarking of the JULES land–surface model in the UK (described above [4]), and coupled Carbon–cycle GCM evaluation [5]. The goals of iLAMB are to:

1. develop internationally accepted benchmarks for land model performance;
2. promote the use of these benchmarks by the international community for model intercomparison;
3. strengthen linkages between experimental, remote sensing and climate modelling communities in the design of new model tests and new measurement programs;
4. support the design and development of a new, open source, benchmarking software system for use by the international community.

iLAMB aims to bring together experts from around the world in the fields of processes, models, and observations to enable optimal model–data integration. It also attempts to alleviate the large cost in developing the infrastructure to make meaningful model–data comparisons through pre–defined and programmed evaluation metrics against pre–assembled datasets. Such an open–source infrastructure can be centrally maintained but constantly developed by the community. In the same way that model development can benefit from a community approach, so can model benchmarking.

The iLAMB January 2011 workshop included general discussion of what the community means by benchmarking. The term is defined in several ways: it is commonly but misleadingly used to simply mean "evaluation," although a more legitimate meaning would be "a standardised evaluation or test of models". Benchmarking could also be seen to involve *a priori* setting of a performance standard which must be reached before a model is seen as "fit for purpose".

As well as the semantic aspects, the meeting addressed practical questions such as key model outputs to benchmark and which datasets to use. The workshop was very focused on achieving a tangible output in the near-term with particular emphasis on developing a 1st ILAMB product released in time to perform useful evaluation of both offline (TRENDY, http://dgvm.ceh.ac.uk/trendy-gcp) and coupled (CMIP5, http://cmip-pcmdi.llnl.gov/cmip5/index.html) land surface simulations: both key activities contributing to AR5, the Fifth Assessment Report by IPCC. Simultaneous evaluation of models against carbon, water and energy fluxes across a range of timescales will present a genuine challenge for current generation land–surface models.

Another international initiative is the PALS (Protocol for Analysis of Land Surface models), a web–based tool pioneered by the University of New South Wales (www.pals.unsw.edu.au) to bring modellers and data providers together. The idea behind PALS is to host data as well as the results of several land surface models so that the range of results of the models is being exposed to the scrutiny of the data providers as well as the other way round.

In addition to PALS and iLAMB, two GEWEX sub–groups: GLASS (GEWEX Land Atmosphere System Study) and GHP (Global Hydrology Panel) are also working identifying the best data to benchmark models of the energy and water cycle as well as tackling the thorny issue of defining *a priori* pass marks for land surface models against the chosen datasets.

Many challenges still exist such as determining which metrics should be used for which application and what observations provide a constraint rather than simply an evaluation (*Fig. 2*). The key to the whole process is identifying which observable quantities constrain the aspects we want to predict. Or can benchmarking be used to weight multi–model output to form an ensemble of projections? Should performance levels for models be pre–defined? This is an exciting and rapidly moving field of modelling.

At least one thing is certain: international cooperation through initiatives such as iLAMB and PALS will bring benefit to the land–surface community. This will happen through increased availability of relevant and standardised data; standardised metrics by which to evaluate the comparison quantitatively; and standardised simulation protocols to facilitate comparison of new developments and, hence, track progress. ■

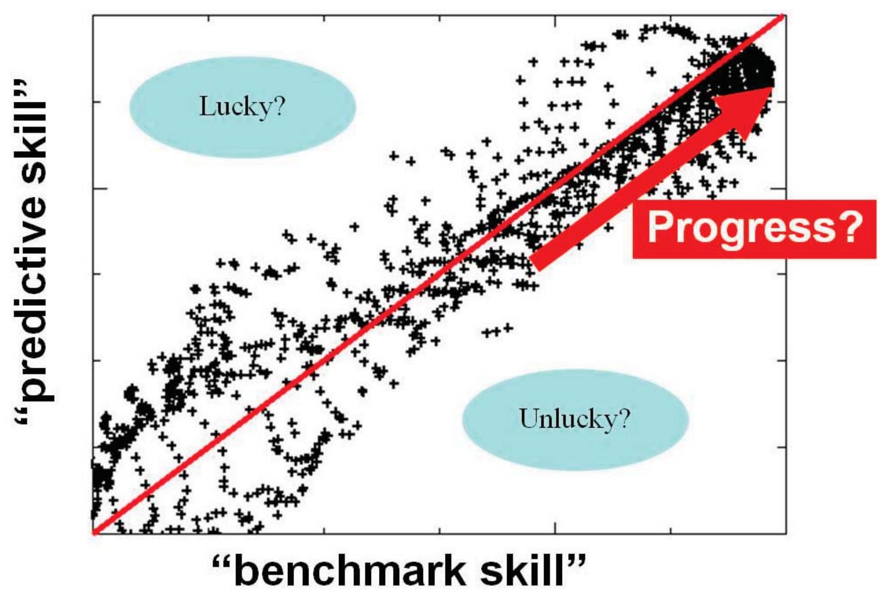

Figure 2. Can we ensure that benchmarking will improve prediction?

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Guntars O. Martinson is studying nutrient dynamics and trace gas fluxes in tropical forest ecosystems. He studied forest ecology and conducted his PhD research in the soil science group of Edzo Veldkamp at the University of Goettingen, Germany and the San Francisco tropical research station in Southern Ecuador. He investigated trace gas fluxes and nutrient controls on nitrogen and carbon cycling in tropical mountain forest ecosystems. Currently, he is working as a postdoctoral fellow in the biogeochemistry research group of Ralf Conrad at the Max Planck Institute for Terrestrial Microbiology in Marburg, Germany to study microorganisms in tropical canopy wetlands as controllers of atmospheric trace gases.

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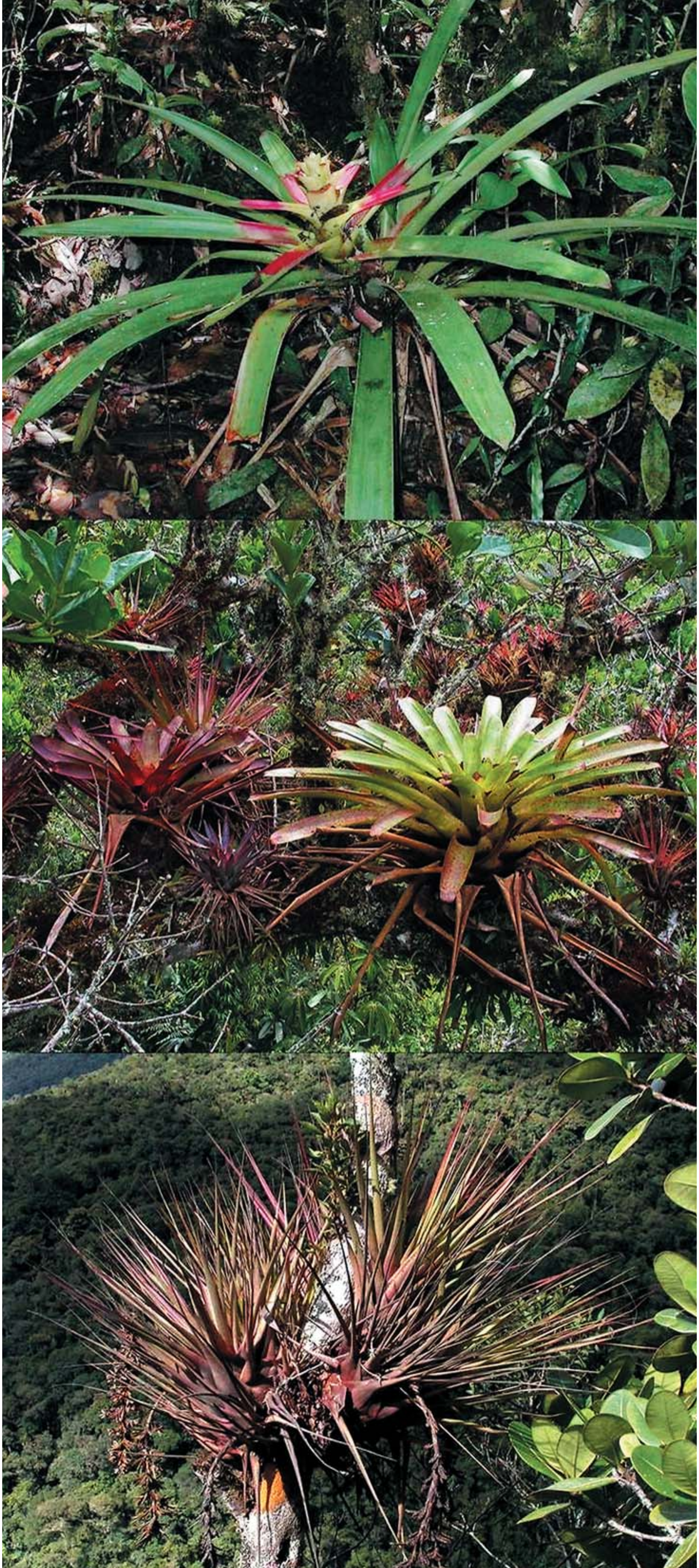
Methane emissions from canopy wetlands

Recent space–borne observations suggest high atmospheric methane (CH_4) concentrations above neotropical forests from currently unidentified sources [1, 2]. Natural tropical ground wetlands are a major source of CH_4 [3] but their distribution and CH_4 source strength have large uncertainties [4]. Therefore, underestimates in tropical ground wetland emissions may account for part of the discrepancy between space–borne and modeled estimates [2].

Phytotelmata, aquatic habitats in various plant parts, such as tank bromeliads that grow attached to forest trees (as *epiphytes*) and whose leaves form a centrally located water–holding tank [5] create a canopy subsystem in tropical montane forests with high rates of precipitation that act as "keystone" component at the ecosystem level. They enhance interception, storage and circulation of atmospheric–borne nutrients by effectively collecting water and leaf litter in their tanks where they are able to host a diverse microbial community [6, 7]. We hypothesised that this habitat should be ideal for methane producing anaerobic microorganisms.

Indeed, in a tropical montane forest at the Reserva Biológica San Francisco, Ecuador, we found out that tank bromeliads, common *phytotelmata* throughout neotropical forests, harbour an active community of methane–producing (methanogenic) mi-

Figure 1. Functional types of tank bromeliads. 'Ephemeral tank' (type I, *top*), 'absorbing trichome tank' (type II, *centre*), and 'intermediate atmospheric tank' (type III, *bottom*). [credits: Nature Geoscience, Nature Publishing Group (NPG)]



crobes (*Methanomicrobiales, Methanobacteriales, Methanocellales, Methanosaetaceae*) by using the molecular fingerprinting technique *terminal restriction length polymorphism* (T–RFLP) and clone sequencing. Hence, the complete degradation of organic matter to CH_4 and CO_2 may be possible.

For CH_4 flux measurements, 12 canopy trees were randomly sampled. There, tank bromeliads were carefully detached from the substrate and immediately lowered to the ground in a basket and carefully put into a plant incubation chamber. We took measurements from 167 tank bromeliads. Based on their architecture and ecological niche preference, we divided the tank bromeliads into three functional plant types (*Fig. 1*): Type I bromeliads grow in the under–storey and type II and III bromeliads grow in the mid- and over–storey, respectively.

We estimated the source strength of the bromeliad community at 3.6 g ha^{-1} d^{-1} [8] which is enough to compensate for atmospheric methane consumption in the soil at a rate of 3.1 g ha^{-1} d^{-1}.

All sampled tank bromeliads emitted CH_4 and each functional bromeliad type showed an exponential relationship between CH_4 emission rates and tank diameters (*Fig. 2*) indicating that tank volume may determine the amount of collected water, substrate and methane producing microbes. Furthermore, we found out that all bromeliad tank water samples were supersaturated with CH_4.

However, according to diffusion calculations, diffusion of CH_4 through the water surface into the atmosphere was not the main pathway from the bromeliad into the atmosphere. Instead, CH_4 emissions from the bromeliad leaves accounted for the major part of total CH_4 emissions from tank bromeliads (2.4 ng (CH_4) cm^{-2} leaf h^{-1}).

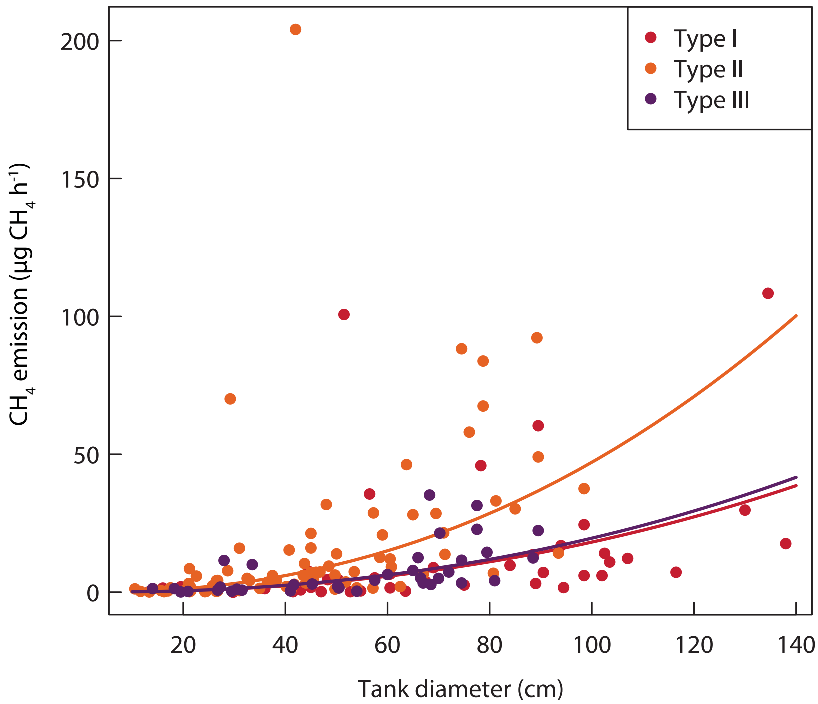


Figure 2. Methane emissions in relation to bromeliad tank diameters from functional types of bromeliads. We fitted an exponential function for every bromeliad functional type. Ranges of methane emissions were: 0.001–108.4 µg (CH_4) h^{-1} for type I, 0.08-204.1 µg (CH_4) h^{-1} for type II, and 0.05–35.19 µg (CH_4) h^{-1} for type III. Reproduced with permission from [8]. Credits: Nature Geoscience, Nature Publishing Group (NPG).

By means of ^{13}C stable isotope probing, we could prove that the dissolved CH_4 in the tank water was transported through the leaf and released from the leaf surface into the atmosphere. We suggest that dissolved CH_4 in the tank water may be taken up via active water transportation through absorptive foliar hairs (trichomes), diffused into air channels of the leaves (*aerenchymae*), transported to the stomata, and then released into the atmosphere. However, the exact transport mechanism remains unclear.

Extrapolating the CH_4 emissions from tank bromeliads at our study site to the whole neotropical forest area yielded a global source strength of 1.2 Tg CH_4 yr^{-1}. We are aware of the difficulties in extrapolating from a small regional site to a whole continent. Estimates of bromeliad and other *phytotelmata* densities in tropical forests have been limited so far. Furthermore, environmental controls on CH_4 production in *phytotelmata* have not been studied and could change dramatically with changing environment.

However, our estimated tank bromeliad CH_4 emissions do not suffice to explain the high CH_4 flux (4 to 38 Tg (CH_4) yr^{-1}) from neotropical forests that was estimated from a canopy layer budget model [2]. But Yavitt (2010) [9] suggests that there may be other, yet undiscovered obscure wetlands in tropical forests. Indeed, preliminary measurements from water samples of other *phytotelmata* than tank bromeliads at the altitude of 1000 and 2000 m in the Ecuadorian Andes show high dissolved CH_4 concentrations, which substantiate that *phytotelmata* are an ideal habitat for methanogenic archaea and that potential CH_4 emissions from canopy wetlands may be larger than our estimate.

CH_4 emissions from tank bromeliads and probably other *phytotelmata* differ fundamentally from ground wetland CH_4 emissions in that CH_4 is produced above ground in plant–based container habitats that create canopy wetlands. While tank bromeliads are restricted to the New World, other types of *phytotelmata* (*e.g.* hollow bamboo internodes, tree holes, non-bromeliad leaf axils, pitchers) are not and may constitute an important additional source of CH_4 from tropical and subtropical forests.

Our finding elucidates that we still don't know much about this unique canopy ecosystem that has been termed "the last biotic frontier" [10]. ■

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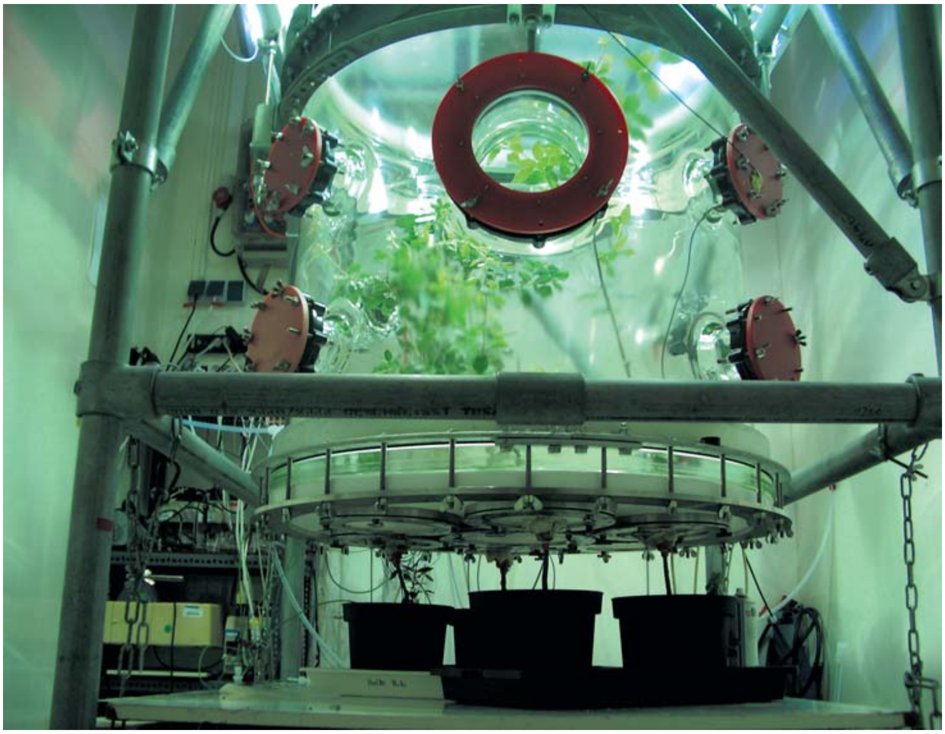

Figure 1. VOCBAS facilities for laboratory measurement of VOC emission and reactivity: the whole–tree gas–exchange chamber of the Institute Phytosphere – Research Centre Juelich, Germany (picture courtesy of Silvano Fares and Juergen Wildt).

Francesco Loreto

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Volatile Organic Compounds (VOCs) in the Biosphere–Atmosphere System: from VOCBAS to EuroVOL

VOCBAS in summary

The research and networking ESF (European Science Foundation) programme "Volatile Organic Compounds in the Biosphere-Atmosphere System" (VOCBAS) ran from March 2004 to September 2009 with the support of funding agencies from 13 European countries. The programme implemented, supported, and coordinated a series of research activities involving mainly plant biologists but also atmospheric chemists, pathologists, entomologists, agronomists and foresters to determine how biogenic volatile organic compound (VOC) emissions affect the relationship between the biosphere and the atmosphere.

VOCBAS brought together an outstanding scientific community carrying out internationally recognised research into the production and emissions of VOCs by plants in the context of global change and ecosystems from a wide range of disciplines. VOCBAS research activities spanned several topics:

- plant processes
- genetics
- ecosystem functioning
- plant defence against pathogens and pests
- environmental controls on VOC emission fluxes
- flux measurements and modelling of VOC on the leaf, canopy, ecosystem and regional scales
- VOC effects on atmospheric chemistry and biogeochemical cycles.

The scientific activities supported by the programme resulted in the publication of 72 research papers in scientific journals with some research published in top scientific journals and widely disseminated by press and media (see BBC report by Matt Walker "Climate change will make the world more 'fragrant'" based on [1]). Three special issues were dedicated to VOCBAS by the journals Plant Biology, Biogeosciences, and Trends in Plant Sciences (TiPS), a further indication of the excellent scientific impact of the research supported by the programme. The TiPS special issue (March 2010, see full list of references at the end of this paper) is an excellent showcase of VOCBAS results, some of which are summarised below.

VOCBAS brought European VOC research to the forefront of understanding how biogenic VOC emissions affect the present and future relationship between the biosphere and the atmosphere. Within iLEAPS, VOCBAS has been the main contributor to plant biology research.

Highlights

More on the below highlights can be found in the VOCBAS special issue in Trend in Plant Science (March 2010, vol. 15 issue 3, pp.115–184).

VOCs in biotic stress interactions

VOCs serve defence purposes against insects, fungi, herbivores, other plants and, when volatilised, are signals for pollinators, can mediate multitrophic interactions, and act as signals for conspecific herbivores. The aerial information network between different trophic levels is complicated, and only few interactions have been identified at the moment. How and to which extent these actions are exerted, is therefore largely unknown.

VOCBAS achievements principally contributed to demonstrate the involvement of VOCs, especially volatile isoprenoids, on the interaction between plants, herbivores and carnivores [2, 3]. Emissions induced or elicited by herbivores were investigated in laboratory and field conditions, and under the influence of future O_3 and CO_2 concentrations (for instance, in joint experiments with the Kuopio FACE (Free Air CO_2 Enrichment), and the EUROFACE consortium). A non–exhaustive selection of key results from VOCBAS sponsored research includes:

1. the discovery of bursts of constitutive (*i.e.* emitted by plants also before elicitation by stressors) and induced volatiles following the attack of herbivores, but also of pathogens such as moulds;
2. the finding that not only large–molecular–weight isoprenoids, but also isoprene may influence herbivore feeding decision, mainly deterring herbivores from feeding rather than attracting them, and disturbing the attraction of parasitoids and predators of the herbivores;
3. the assessment of genetic variations of the isoprenoids of pine resins and of the influence of mineral nutrition, pollutants (ozone) and association with other biotic organisms (such as mychorrizes, symbiotic fungi living on plant roots) on the formation of constitutive and induced isoprenoids and on the consequent level of induced defence against biotic stressors; and
4. the finding that monoterpene emissions are induced by herbivore feeding in isoprene–emitting plants, challenging the notion that isoprene emitters do not emit other isoprenoids.

VOCs in the plant–environment interaction

The emissions of VOCs depend on several environmental factors of which the well characterised ones are temperature and light. However, VOCBAS research has focused on yet poorly understood environmental controls as well as on the interactive effects of environmental changes driven by climate change [1].

VOCBAS investigations highlights include:

1. the emission of constitutive volatile isoprenoids was found to be resistant to environmental stresses such as salinity, drought and pollutants (ozone, UV radiation) and may even be temporarily elicited and augmented following stress occurrence, therefore decreasing the efficiency the photosynthetic CO_2 uptake and increasing the load of reactive hydrocarbons in the atmosphere;
2. a strong antioxidant effect of isoprene (endogenously emitted or exogenously supplied) in conditions of thermal stress, photoinhibition and under ozone episodes was demonstrated;
3. isoprenoids were demonstrated to take up and scavenge ozone both inside and (especially in the case of highly reactive isoprenoids) outside leaves (*see Fig. 1 for an outlook of the special chambers used for this experiment*). This explains why isoprenoi–emitting plants take up more ozone but are at the same time more protected by ozone damage, a very controversial observation which supplies key information for programmes intended to improve plant productivity and vitality under, for instance, heat waves such as during summer 2003;
4. environmental constraints also revealed the release of other VOCs (methanol, acetaldehyde and C–6 compounds) in leaves exposed to mechanical stresses, high temperature, and high light. Some of these compounds can now be used as *in vivo* early indicators of stress therefore improving our programming capacities in agro–forestry practices and helping with the optimisation of natural resources (namely irrigation water, which accounts for around 80% of the total water consumption in areas with intensive agriculture).

VOC biochemistry

The biochemical pathway leading to volatile isoprenoid formation was elucidated by seminal research in the 90's. Attention is now given to the control of carbon and energy fluxes in the isoprenoid pathway, and to the consequences for primary metabolism, including the photosynthetic carbon fixation pathway and the formation of essential hydrocarbons, lipids and proteins. Research developed under the frame of VOCBAS has contributed to clarify that

1. different carbon sources may be involved in volatile isoprenoid formation, especially when the photosynthetic carbon fixation pathway is inhibited by stresses. The sustained biosynthesis and emission of isoprenoids even in absence of fresh carbon acquisition by photosynthesis is unexpected. Why plants should waste carbon when they are at short of it? Isoprenoids must have a prominent, and yet not fully understood role.
2. The emission of isoprene and monoterpenes is inversely related with the pools of the substrates for isoprene and monoterpene synthases, which are the last non–volatile intermediates in the pathway of volatile isoprenoids formation. This finding indicates that isoprenoids formation is not limited by carbon availability, at least when carbon fixation by photosynthesis is not stress–limited.
3. An inverse relationship often occurs between isoprene emission and plant respiration (release of carbon dioxide), indicating that the two pathways may compete for the same carbon source, probably pyruvate;
4. a different line of research focused on the physico–chemical properties of VOCs, elucidating how these affect the volatility and solubility of these compounds. Physico–chemical properties explain the different emission rates and allow us to calculate liquid pools at the level of leaf intercellular spaces or in the specialised structures where isoprenoids accumulate;
5. stomata control the emission of oxygenated VOCs, namely methanol, whose emission is clearly of primary importance for plant metabolism, being related to leaf development and senescence and to the occurrence of biotic and abiotic stresses.

VOCs and the chemical and physical properties of atmosphere

VOCs are formed and emitted by plants at an estimated 1.1–1.5 Pg (C) yr^{-1} on the global scale. Although this emission accounts for approximately 2% of the total C–exchange of 69 Pg between the biota and the atmosphere, it has not been considered in global C cycling so far. Biogenic VOC emission rates can have both direct and indirect effects on the carbon cycle, and on the oxidation mechanisms of the atmosphere.

VOCBAS was the first to consider feedbacks between CO_2 and volatile isoprenoids, and we can now predict a much lower influence of global change on volatile isoprenoid emissions, because increasing CO_2 concentration and rising temperatures have an opposite effect on the biosynthesis of isoprene. Consequently, the scenarios about isoprene–driven atmospheric chemistry might need reassessment.

VOCBAS studies demonstrated that isoprenoids and other VOCs emitted by plants react with air pollutants [4]. This may lead to the destruction of VOCs and reduce atmospheric levels of pollutants locally in and above vegetation. The end products of atmospheric chemical reactions are detectable as products of isoprenoid oxidation (formaldehyde, methyl vinyl ketone, metachrolein) and secondary organic aerosols (SOA). The rapid formation of below–10–nm particles during nucleation is followed by the growth of particle size due to clustering of smaller particles. The initial number of formed particles can be higher over monoterpene emitters (*Pinus sylvestris*) than over isoprene emitters (*Populus* sp.). The emissions of isoprene and alpha–pinene have been associated to diurnal trends in the particle formation events over boreal forests [2].

However, field campaigns over Mediterranean ecosystems have not demonstrated substantial contributions of biogenic VOCs to the formation of photochemical smog and particles, for instance, over the megacity of Rome both in situ (in the periurban park of Castelporziano) and within the plume of the air mass driven by air circulation. Indeed, a VOCBAS field campaign confirmed a low emission of isoprene by Mediterranean vegetation whereas a seasonally important emission of monoterpenes and oxygenated VOC, especially methanol, was observed.

VOC modelling

Parameterisation on the basis of VOC dependence on a few environmental variables has provided good estimates of the actual emission rates of biogenic VOCs. However, such modelling is now under scrutiny as it provides inaccurate estimates of VOC emission in several environmental conditions such as under future higher levels of CO_2 and nutrients, leading to eutrophication (great increase of phytoplankton in water), or under atmospheric and soil pollution. Also important is to expand the study to volatiles other than isoprene.

By studying the molecular and biochemical basis of VOC synthesis, VOCBAS has provided the background to generate detailed mechanistic predictions of isoprenoid emissions currently and in response to future climate changes and stress pressures. It is now clear that both physiological and physico–chemical factors may limit and control the emission of different VOCs.

Studies outlining the inverse relationships between volatile isoprenoids and respiration, or between isoprene and metabolites involved in its biosynthesis, namely phosphoenolpyruvate help develop mechanistic models about the control of carbon sources, energetics and diffusive resistances on the pathway of isoprenoid formation and emission. Experimental results also revealed the strong stomatal control on the emission of acetaldehyde, methanol and other oxygenated VOC by leaves exposed to stress episodes. This has created the basis to develop a physico–chemical model that numerically predicts emission on the basis of pool sizes, resistances and volatility of the molecules.

VOCBAS projects have processed biochemical and physico–chemical information to put into operation a leaf–level isoprenoid emission algorithm which will serve as the main template for scaling isoprenoid emission to higher hierarchical levels. VOCBAS has also carried out upscaling of modelling to incorporate the effects of climate change factors that have not previously been considered but have turned out to be crucial.

Most remarkably, VOCBAS studies have pointed out that the decreasing effect of increasing CO_2 concentration on the emission of isoprene by European forests may counterbalance almost completely the predicted increase of biogenic emissions because of rising temperatures. The models developed in this study have enabled us, for the first time, to upscale from mechanistic to regional level the process–based estimates of isoprene emission [3].

VOC analysis

Through industrial collaboration with commercial partners, VOCBAS has achieved unprecedented technical advances. The PTR-MS (Proton Transfer Reaction–Mass Spectrometry) technology developed by Ionicon (Austria) has allowed partners to dramatically improve flux measurements in the field as well as to instantaneously detect constitutive and induced VOCs. PTR–MS has allowed

a) to refine flux measurements methodologies (such as disjunct eddy covariance [5] Davison et al. 2009); within the Castelporziano VOCBAS field campaign, intercomparison exercises have been carried out to establish proper comparability between experiments of VOC detection by PTR–MS and by GC–MS with off–line concentration in absorbents and between different flux measurements techniques such as relaxed eddy accumulation and disjunct eddy covariance (*Fig. 2*);

b) to follow kinetics of VOC response to fluctuating environmental conditions or stress events;

c) to plan and execute accurate labelling experiments that, in turn, shed light on metabolic pathways underlying VOC emissions;

d) to measure second–generation VOCs deriving from reaction of primarily emitted compounds with oxidants in the atmosphere or inside leaves.

Beyond VOCBAS

VOCBAS has acted as a powerful catalyst for research and training in the field of biogenic emissions, enhancing collaboration between participating organisations and other European and non–European research groups. VOCBAS has also propagated the interest in VOC studies among plant biologists, favouring interdisciplinary research with atmospheric chemists and environmental scientists.

Results stemming from the scientific activities of VOCBAS have produced major advances in understanding biosphere–atmosphere interactions, the biochemical and environmental control of VOC synthesis and emissions, and the role of VOCs in ecology. Future studies are necessary to deepen our knowledge about the diverse and pivotal roles of VOCs in the global

change –driven changes in plant–environment interactions. We also need to study further how VOCs can be manipulated to improve natural (biological) control of plant enemies (pests and pathogens).

The European VOC community has expanded to include new research areas and to examine pressing problems. This large and interdisciplinary community is now mature enough to develop research that goes beyond the simple networking structure implemented by VOCBAS.

To this goal, we have launched a new ESF (European Science Foundation) – Eurocores programme "Ecology of plant volatiles: from the molecule to the globe" (EuroVOL). More than 70 outstanding research institutions from 19 European countries have expressed interest in participating in this new programme – a critical mass even larger and more interdisciplinary than formerly in VOCBAS.

The general scientific objective of EuroVOL is to understand the roles of VOC in the food–web and in plant–environment interactions under current and future climate and under the changing land–cover conditions. The several projects of EuroVOL constitute a tight network that will aim specifically to:

1. understanding VOC synthesis and emission from leaf to globe; and
2. understanding VOC functions at biological level from individuals to communities, and VOC feedbacks on biological and biogeochemical cycles.

EuroVOL's highly interdisciplinary projects will attempt to uncover the links between biosynthesis of plant BVOC and their functional roles and determine the consequences for plant production and protection. EuroVOL will also act as a new interface between science and the society, facilitating dissemination and utilisation of scientific findings and innovations and networking between collaborating European academies, stakeholders, and end–users. ■

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Figure 2. VOCBAS facilities for field measurement of VOC emission and reactivity: The equipment for VOC flux measurements by micrometeorological techniques (disjunct eddy covariance) during the ACCENT–VOCBAS campaign in Castelporziano (Italy).

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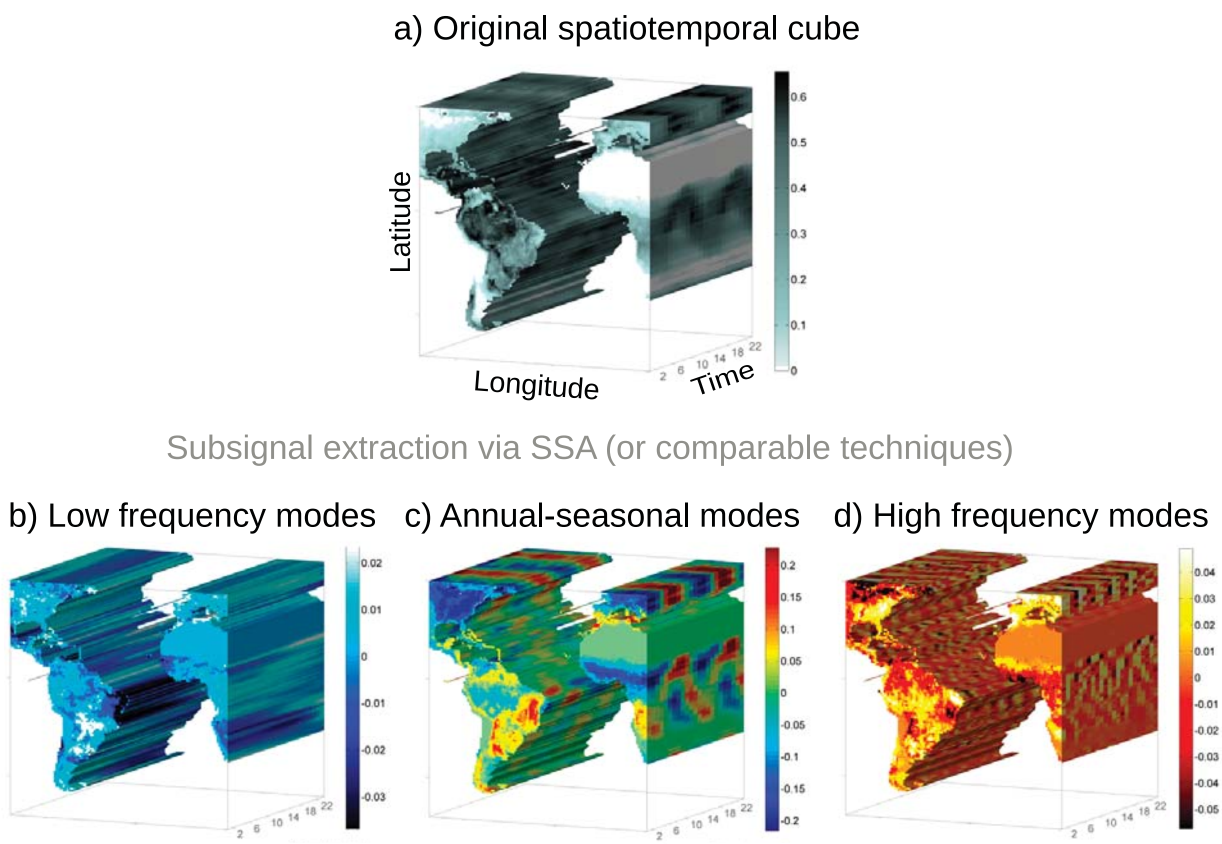

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FRINGES – Frascati Initiative on Global Empirical analysis of the Biosphere in Earth System

The atmosphere and the terrestrial biosphere are subsystems of the Earth System which influence each other by exchanging energy, matter and information. These exchanges or interactions are organised on different temporal and spatial scales. Presently, a better understanding of the interactions between the atmosphere, biosphere, and ocean across different time-scales and in space is necessary both for short–term and long–term prediction of the climate and Earth system behaviour (such as soil moisture–atmosphere feedback, El Niño sea surface temperature dynamics, carbon cycle feedback, vegetation–albedo feed–back).

In this context, a vast amount of data has been collected via *in situ* instrumental networks and by remote sensing observation in the last decades. So far, however, these data sets have not been sufficiently exploited. Traditional analysis strategies are often disciplinary and do not benefit from newly developed non–linear statistical techniques, which, for example, have been successfully applied in bioinformatics.

iLEAPS, the European Space Agency (ESA), and the Max Planck Institute for Biogeochemistry sponsored a workshop in Frascati, Italy, in November 2010 in order to

Figure 1. A cutout of the original FAPAR data (first 2 years) aggregated to 1° geographical and monthly temporal resolution. The data cube can be decomposed, for instance, by Singular System Analysis (SSA) and reconstructed as sets of distinct frequency classes (lower row). The subsignals add up to the original data without loss of information, except from the mean value [1].

bring together scientists which represent major Global Earth Observation data streams (*such as* fPAR; albedo, soil moisture, fire, surface temperature, climate data, atmospheric chemistry, ecosystem–atmosphere fluxes). The aim of the workshop was to establish a joint view on the multivariate, interdisciplinary datasets which simultaneously cover a broad range of biosphere–atmosphere related properties and to discuss novel data–analytical strategies for defining dimensions of a *land–ecosystem atmosphere index*.

Along the lines of discussion, novel data mining methods are going to be developed. The discussions revealed already existing strong links and synergies between optical, microwave and gravity–based remote sensing of land, ocean and atmosphere with the water cycle being an important nexus. For instance, an acceleration of global biogeochemical cycles may be first revealed in seasonal amplitude changes of the water cycle. Moreover, links between terrestrial primary productivity, water deficits, and fire activity became very evident.

Our goal for the coming year is to establish a harmonised multivariate global data set, develop analytic capabilities to extract the major dimensions of spatial and in particular temporal change from the highly multivariate and diverse observational data and later, to attribute those main changes to, for instance, climate or direct human forcing. Furthermore, these dimensions extracted from the data need to be interpreted from a process perspective: the observed patterns could be biogeophysical or biogeochemical components that co–vary in particular regions but not in others.

An internal web site has been established at www.bgc-jena.mpg.de/bgc-mdi/index.php/Main/Projects#activities for contributors – further contributions are welcome.

This work should enable us to develop series of diagnostics (and potentially a few indices) about the status of land–ecosystem-atmosphere interactions. Those diagnostics/indices are meant to become valuable iLEAPS products, regularly updated and accessible. Moreover, as an efficient description of the main patterns of terrestrial biosphere dynamics this work should help a more comprehensive evaluation of global coupled biosphere–climate models. ■

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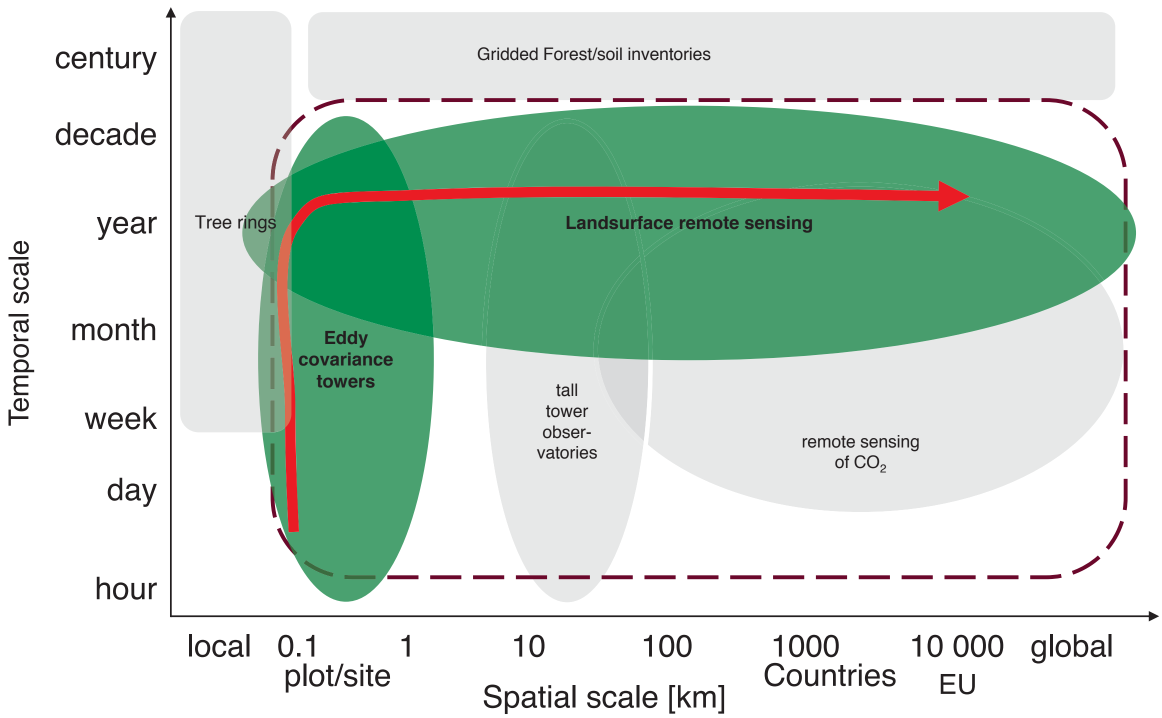

Figure 1. Observation systems spanning across time and space scales and the synergistic role of eddy covariance flux towers and remote sensing.

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FLUXNET – From point to globe

The advent of the eddy covariance method has revolutionised the science of terrestrial biosphere–atmosphere interactions, providing non–destructive measurements of carbon and energy fluxes which span across more than eight orders of magnitude in time. The power of the eddy covariance method has led to a rapid proliferation in world–wide research and organisation, with more than 520 sites now registered in the FLUXNET network.

In past decades, important ecosystem–physiological and eco–climatological questions have been successfully addressed at single sites and also integrated across regional and global networks. However, one fundamental question still remains: Can we infer information on global land carbon and energy cycles from FLUXNET?

Here, we illustrate recent advances in estimating global fields of carbon and water fluxes based on integration of FLUXNET with remote sensing and other Earth Observation (EO) data streams.

From one perspective, FLUXNET can be viewed as acupuncture of the biosphere; the global cumulative footprint area of all FLUXNET stations is not more than 0.003 ‰ of the terrestrial land–surface. There is a gap of 4–5 orders of magnitude in space between a flux tower footprint and the global land surface (Fig. 1). Statistical sampling theory tells us that a few hundred samples allow for accurate estimates of the average characteristics of a population—but only for well behaved distributions and only if the sample is representative of the population.

However, the FLUXNET network is not fully representative of the terrestrial biosphere because the sites are heavily clumped in areas with high population density and/or good infrastructure and research funding. Hence, deriving globally relevant information on biosphere–atmosphere exchanges remains a challenge. And yet, an opportunity exists to provide global coverage on carbon and energy exchange if generalised relationships between observed fluxes at the site level and corresponding variables with global coverage can be extracted and exploited.

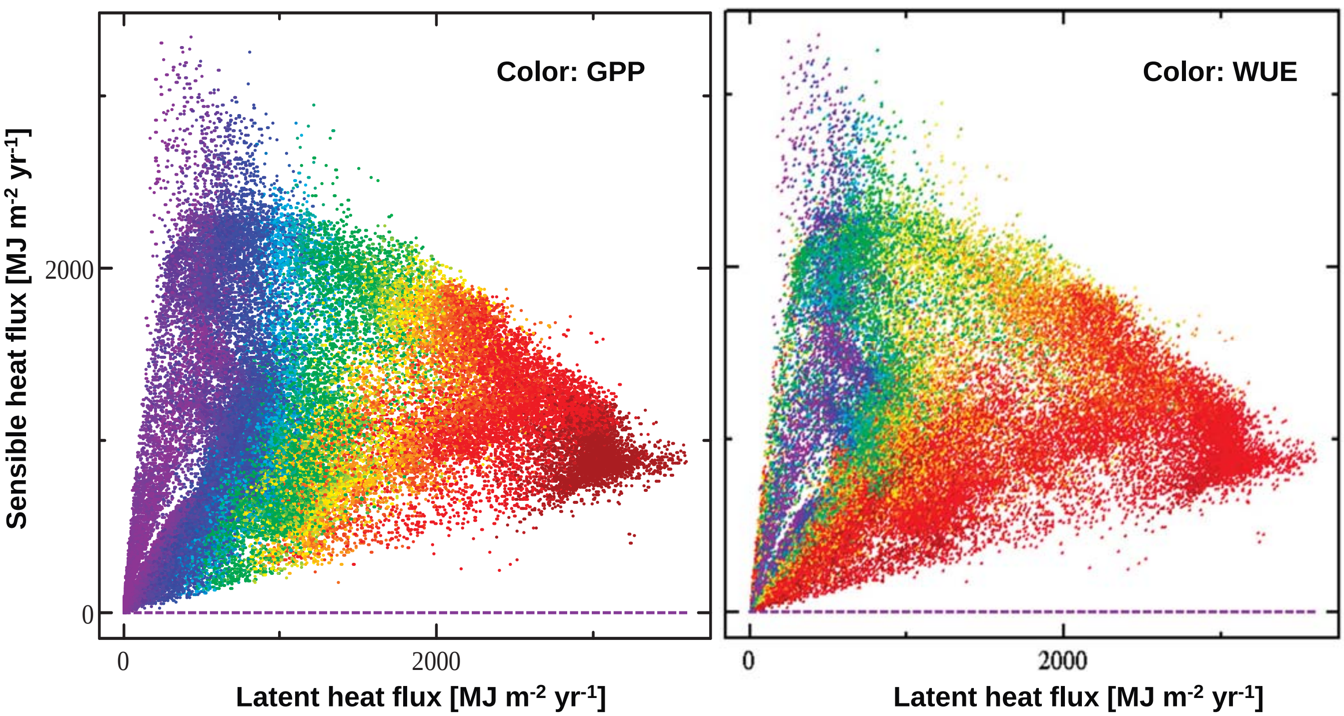

Figure 2. Global patterns of empirically derived annual biosphere–atmosphere fluxes. Both panels show sensible versus latent heat fluxes, where colours denote gross primary productivity (GPP) and water–use efficiency (WUE) on the left and right–hand side, respectively (*red*: high, *violet*: low). Derived from flux maps in [12].

The key is in establishing the level of synergy that exists between global satellite remote sensing products (many of which monitor relevant land surface properties at a spatial resolution compatible with flux tower footprints) and individual flux tower measurements. If this synergy exists, the capability arises for bridging the gap between local measurements and globally relevant information (Fig. 1).

There are many different conceivable ways of integrating flux data and remote sensing products with models. For instance, both data sources can be used as constraints for process–based models in a "data assimilation" approach. Results from such an approach contain knowledge or best guesses of land surface processes and represent a compromise between model assumptions and (new) observations. Data–assimilation in this way is an effective tool for minimising (but also quantifying) simulation uncertainties arising from uncertain parameter values. It also acts as a means for assessing the adequacy of the model structure [1, 2].

A conceptually different and somewhat radical methodology is a fully data–oriented or data–adaptive approach: "let only the data speak." In this case, the modeller refrains from injecting strong theoretical assumptions, such as functional relationships among variables. Such an approach relies on machine learning algorithms and non–parametric statistical methods. It has only become possible through recent developments in computational statistics [3] and the increasing data richness in EO itself.

Development and application of this methodology for observation of biosphere–atmosphere interactions is still in its infancy, but promising first examples exist at continental [4–7] and global scales [8–10]. Most recently, we have combined flux tower data with meteorological and remote sensing observations in just such a data–driven up–scaling framework, and this approach has allowed us to generate a new global data stream for Earth system science. Currently, the newly created data stream comprises 27 years of monthly fluxes at 0.5° resolution for biosphere carbon dioxide (CO_2), water vapour (H_2O), and energy fluxes, with the capability for yet greater spatial and temporal resolution enhancement.

Can we estimate the carbon balance of the land biosphere accurately from up-scaling FLUXNET measurements? The short answer is 'no', or 'not as a stand–alone product'. But perhaps in tandem with other EO data streams, we can. Currently, one major limitation to carbon estimation is the lack of global data on disturbance. We know that site history and past disturbances largely determine the mean carbon balance, and possibly other fluxes as well, at the local scale. While the FLUXNET network does include recently disturbed sites, the up–scaling capability is limited by the lack of globally available Earth Observation diagnostics which can link to FLUXNET sites and inform about past disturbances.

Once a map of disturbance history and intensity (fire, windthrow, harvests) and structural information about the vegetation (for instance from LiDAR (Light Detection and Ranging) laser measurements) is available globally, more realistic global estimates of the global carbon balance might be possible.

Other problems are related to the precision of the eddy–covariance method. The net global terrestrial carbon uptake inferred from atmospheric data is around 2 Pg (C) yr^{-1}, which equals approximately 15 g (C) m^{-2} yr^{-1} if we distribute these 2 Pg (C) yr^{-1} equally over the global vegetated area. As currently deployed, however, this is likely below the detection limit of the eddy covariance method. Hence, instead of hunting for the global carbon balance, it is more rewarding to extract robust global multivariate patterns of the relationships among the variables that describe biosphere–atmosphere exchange (as in Fig. 2). This approach enables insights into eco–climatological problems, biosphere–atmosphere feedbacks and eventually leads towards improved climate–carbon cycle models.

Integration of remote sensing data is also providing new opportunities for coupled climate–biosphere model evaluation that circumvents some of the conceptual problems with direct model–site comparisons. This is especially true when coupled with the machine–learning–based derivation of generalised relationships.

Advantages of this approach include:

1) up–scaled fields are integrated over the grid–box heterogeneity, hence the point–to–grid–box scale mismatch is largely avoided;

2) the generalisation reduces the importance of site particularities which might not be relevant for global models;

3) the representativeness problems (for instance, that site–based model comparisons are heavily biased towards temperate sites) of FLUXNET are greatly reduced.

Still, it is clear that these data–driven up–scaling products also depend on some assumptions and are subject to several conceptual limitations. For example, the choice of potentially relevant predictor variables is partly subjective and constrained by the availability and quality of corresponding global data sets. Furthermore, the prediction of carbon fluxes in response to rare or previously unseen conditions (such as climate extremes for which no training data are available) remains an extrapolation, and as such, is highly uncertain.

In addition, results from a machine learning approach in land areas, vegetation types and climate conditions that are not well sampled by FLUXNET measurements might still be heavily influenced by single, potentially unrepresentative sites. Hence, these products should not be taken as truth and used blindly for biosphere model evaluation. Any mismatch between biosphere and data–oriented models should be critically examined for respective weaknesses.

Nevertheless, we have gained confidence in the FLUXNET derived global data streams based on various consistency checks that have been performed with independent approaches [8–11].

In summary, the fusion of site–level flux data with satellite–based EO offers great opportunities for increasing the relevance of FLUXNET in Earth System science. Still, we must keep in mind that the aforementioned global data–driven up–scaling products depend on many assumptions, are subject to several limitations, and should always be critically evaluated against independent approaches. Even so, we think that the FLUXNET–derived global data stream contains robust patterns which can be used to constrain and reduce the uncertainty of process–based biosphere models.

Future directions include integration of information at scales not considered so far (such as organism– or landscape scale), other trace gases and isotope fluxes, hyperspectral, Radar and LiDAR remote sensing. Central to this endeavour will be the need to embrace novel developments in the field of machine learning and empirical inference in general (such as detection of causality). This effort will be greatly facilitated by a spirit of open data and code sharing across disciplines. ■

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New iLEAPS relevant Research Centre in Australia

In late 2010 the Australian Research Council (ARC) announced a list of successful Centres of Excellence, and this included the ARC Centre of Excellence for Climate System Science. This is a multimillion dollar initiative, over 7 years, substantially focused on the physical and biophysical climate system.

The goal of the Centre is "to resolve key uncertainties undermining the reliable projection of Australia's climate". To achieve our goal we will work with a suite of partners on understanding key aspects of the climate system using observations, parameterization development, and global and regional climate models.

We are currently developing several research programs but in terms of iLEAPS science, the land surface program will include model development, exploring how land processes contribute to observed trends in the means and extremes in the Australian climate, and the development of the Australian land surface model to include key processes of regional and global significance.

The Centre is hosted by the University of New South Wales in Sydney. The Partner Universities involved in the Centre are Monash University, The University of Melbourne, The Australian National University, and the University of Tasmania. We collaborate with a series of key groups nationally including the CSIRO (Commonwealth Scientific and Industrial Research Organisation), Australian Bureau of Meteorology, the National Computational Infrastructure (NCI), the Department of Climate Change and Energy Efficiency, the New South Wales Department of Environment, Climate Change and Water, and the Australian National Data Service.

Internationally, we partner with Centre National de la Recherche Scientifique (CNRS) in France, NASA, National Center for Atmospheric Research (NCAR), Geophysical Fluid Dynamics Laboratory (GFDL) and the University of Arizona in the USA, the Hadley Centre and the National Centre for Atmospheric Science in the UK.

In terms of iLEAPS science, the land surface program will include model development, exploring how land processes contribute to observed trends in the means and extremes in the Australian climate, and the development of the Australian land surface model to include key processes of regional and global significance.

A large number of research fellowship positions and PhD scholarships will be advertised through 2011. In addition, we will be encouraging exchange of scholars internationally over the next seven.

A web site at www.climatescience.org.au will provide details in due course. In the meantime any questions should be referred to Professor Andy Pitman, the Centre Director, at:

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11–16 July 2010, Dalhousie University, Halifax, Canada

12th iCACGP Symposium and 11th IGAC Science Conference

The iCACGP/IGAC (International Commission on Atmospheric Chemistry and Global Pollution / International Global Atmosphere Chemistry) conference took place in Halifax, Canada, in July 2010, under the title "Challenging the future" and organised around five themes:

1. Climate chemistry interactions
2. Observing atmospheric composition
3. Chemistry at the interfaces
4. Trace gas and aerosol source strengths
5. Pollutant transformation and loss.

All the 65 oral and over 400 poster contributions from approximately 370 participants (and many young scientists) are available via *www.icacgp-igac-2010.ca*).

Recurring themes in the presentations included:

- organic aerosols: formation processes, measurements (techniques) and modelling
- tropospheric halogen chemistry, its apparent ubiquity, and significance
- satellite observations, their increasing importance for atmospheric chemistry understanding, and their synergetic use in models
- source apportionment of gases and aerosols, using isotopes and other markers.
- modelling and measurement of HO_x (OH and peroxy) radicals, pointing to a lack of sufficient understanding of hydroxyl radical (OH) chemistry and to the potential role of recycling reaction pathways.

The underlying basic laboratory work in physical chemistry and kinetics is declining, under–represented at the conference, and would deserve strengthening. Similarly, cross–disciplinary presentations linking atmospheric chemistry to other components of the Earth system (land, ocean, stratosphere) were not sufficiently represented in the conference. Given the educational role of such conferences, this issue should be addressed in the future in close collaboration with SOLAS (Surface Ocean Lower Atmosphere Study), iLEAPS, and SPARC (Stratospheric Processes and their Role in Climate).

Integration of atmospheric chemistry with other Earth system science fields is an arduous but valuable exercise. Ongoing interactions are investigating

- air pollution and health
- the role of pollutants as short–lived climate forcing agents
- atmospheric chemistry and biosphere/cryosphere.

The processes involved in these interactions are not sufficiently understood to accurately assess future impacts on atmospheric composition and climate, and require both disciplinary and interdisciplinary research.

The two keynote speakers, John Seinfeld and Douglas Dockery, summarised well the challenges in the fields of climate modelling and understanding of pollution and health effects.

IGAC and iCACGP will actively keep identifying new directions for international atmospheric chemistry research: reaching out to other research fields, starting from a strong disciplinary understanding.

New members of the International Commission on Atmospheric Chemistry and Global Pollution (*www.icacgp.org*) and officers have been elected. The new officers are John Burrows (president), Frank Dentener (secretary), and Laura Gallardo (vice–president).

The next IGAC Conference on "Atmospheric Chemistry in the Anthropocene" will be held in Beijing, China, in September 2012.

The joint iCACGP–IGAC Symposium is planned for 2014, time and location to be decided. ■

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Photo: At the Academy of Finland, from left to right: Ossi Malmberg (Vice President, Academy of Finland, AF), V.M. Kotlyakov, N.S. Kasimov, N.P. Laverov, S.S. Zilitinkevich, Marja-Liisa Liimatainen (Coordinator of International Relations Unit, AF), Mikko Ylikangas (Finland–Russia Collaboration Program Manager, AF).

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16–18 March 2011, Helsinki, Finland

Finland – Russia Geoscience Days

This Finnish–Russian meeting aimed at strengthening cooperation in solving demanding environmental problems with emphasis on climate and climate change.

The distinguished Russian delegation included: Academician Nikolay P. Laverov (Vice President of the Russian Academy of Sciences, RAS), Academician Vladimir M. Kotlyakov (Chair of Section of Environmental Sciences, RAS, Director of Institute of Geography, RAS), Academician Nikolay S. Kasimov (Dean of the Faculty of Geography, Moscow State University).

The Finnish organizations participating in the meeting were Academy of Finland (AF), Finnish Academy of Science and Letters (FASL), Finnish Geological Survey (GTK), Finnish Radiation and Nuclear Safety Authority (STUK), Finnish Meteorological Institute (FMI) and the University of Helsinki (UH).

The meeting included presentations and discussions on the practical instruments and prospects for strengthening bilateral and wider international collaboration in the areas of common interest. iLEAPS, in particular, was included in the discussions during the meeting as a platform for international collaboration.

Several intense presentations were given during the 3–day event by experts for example on:

Conditions, dynamics and stability of the Eurasian permafrost; forcing mechanisms of environmental changes of the Baltic Sea and future scenarios; atmosphere–cryosphere interactions in the Arctic and Antarctic; atmospheric transport and dispersion of radionuclides; climate change in general context of geosciences; climate change and Earth's glaciation, environmental consequences of climate change, surface energy budgets and greenhouse gases in Tiksi station (Russia – Finland – USA cooperation), boundary layers as coupling instruments in climate system.

Both sides, Finnish and Russian, acknowledged the valuable results and prospects for mutually useful cooperation and agreed on the following further steps:

- proceed with strengthening bilateral and international cooperation in a wide range of geosciences using all available financial–support instruments;
- arrange in the near future the next *Russia – Finland Geoscience Days* in Moscow, Russia;
- create a joint RAS–FMI "Environment and Climate Change Laboratory" based on the following principles:

(i) Complex scientific approach: interdisciplinary (physics, meteorology, oceanography, geography, glaciology, etc.) and multi–scale (from local to global in space and up to the Earth-history periods in time);

(ii) Separate funding: the Finnish part of the Laboratory is to be funded by FMI, and the Russian part, by RAS;

(iii) Cooperative coordination: the Laboratory is headed by the two national co–directors appointed by FMI and RAS, respectively.

The agreement was confirmed by Petteri Taalas (Director General, Finnish Meteorological Institute) and Nikolay P. Laverov. ■

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8. Wageningen University, Wageningen, the Netherlands

GEWEX–iLEAPS LandFlux/LandFlux–EVAL Workshop

8–9 April 2011, Vienna, Austria

Over twenty scientists participated in the GEWEX (Global Energy and Water Cycle Experiment) – iLEAPS LandFlux/LandFlux–EVAL mini–workshop, which took place on April 8–9 in Vienna following the General Assembly of the European Geosciences Union.

The workshop, hosted at Technische Universität (TU) Wien and organised by ETH Zurich with logistical support from GEWEX (core project of World Climate Research Programme WCRP) and iLEAPS (core project of International Geosphere–Biosphere Programme IGBP), aimed to review the state–of–the–art in global evapotranspiration (evaporation from surfaces and transpiration by plants) and auxiliary datasets and to design and plan two upcoming products for the global assessment of turbulent fluxes on land (evapotranspiration (ET) and sensible heat flux (flux of warm air, H)): the LandFlux–EVAL bench-marking database based on existing global ET datasets, and the GEWEX Version 0 global ET and H (LandFlux) product.

The workshop consisted of four sessions including extended discussions among the participants. Chris Kummerow (Colorado State University, CSU), Sonia Seneviratne (Institute for Atmospheric and Climate Science, ETH Zurich), and Wolfgang Wagner (Technische Universität (TU) Wien) provided introductory words to the workshop.

First session

Co–chairs: Eric Wood (Princeton University, PU) and Matthew McCabe (University of New South Wales, UNSW)

The first session was dedicated to the review of challenges, current status, and outlook in the development of new satellite–based global ET products. It included introductory presentations on these products by the two chairs, including inputs from several data contributors, as well as short overviews on specific current products. Bob Su (University of Twente) presented the Surface Energy Balance System (SEBS); Han Dolman and Diego Miralles (Vrije Universiteit Amsterdam) presented the GLEAM (Global Land-surface Evaporation: the Amsterdam Methodology) dataset; and Markus Reichstein (Max Planck Institute, Jena) presented an empirically upscaled FLUXNET–based dataset.

Two main conclusions of this first session were:

- Uncertainties in forcing (such as radiation and wind) induce major uncertainties in current satellite–based ET products
- Most available ET datasets are not fully independent.

Second session

Co–chairs: Bill Rossow (City College New York) and Eleanor Blyth (Centre for Ecology and Hydrology, CEH)

The second session assessed possible forcing and land parameter data sets for the ET GEWEX products and multi–model inter-comparisons.

Bill Rossow provided an overview of GEWEX products (ISCCP, GPCP, SRB [International Satellite Cloud Climatology Project, Global Precipitation Climatology Project, Surface Radiation Budget dataset]), followed by a presentation on ground radiation observations by Martin Wild (ETH Zurich), and an evaluation of satellite radiation datasets using ground observations by Taiping Zhang (National Aeronautics and Space Administration (NASA) / Goddard Space Flight Center (GSFC)).

Chris Kummerow presented the status of current satellit–based precipitation datasets. Multi–variable forcing datasets prepared as input for model simulations or data product generation were presented by Fulco Ludwig (Wageningen University, EU project WATCH) and Justin Sheffield (Princeton University).

An overview on the current status of reanalysis datasets (reanalysis products of the National Centers for Environmental Prediction (NCEP) and the European Centre

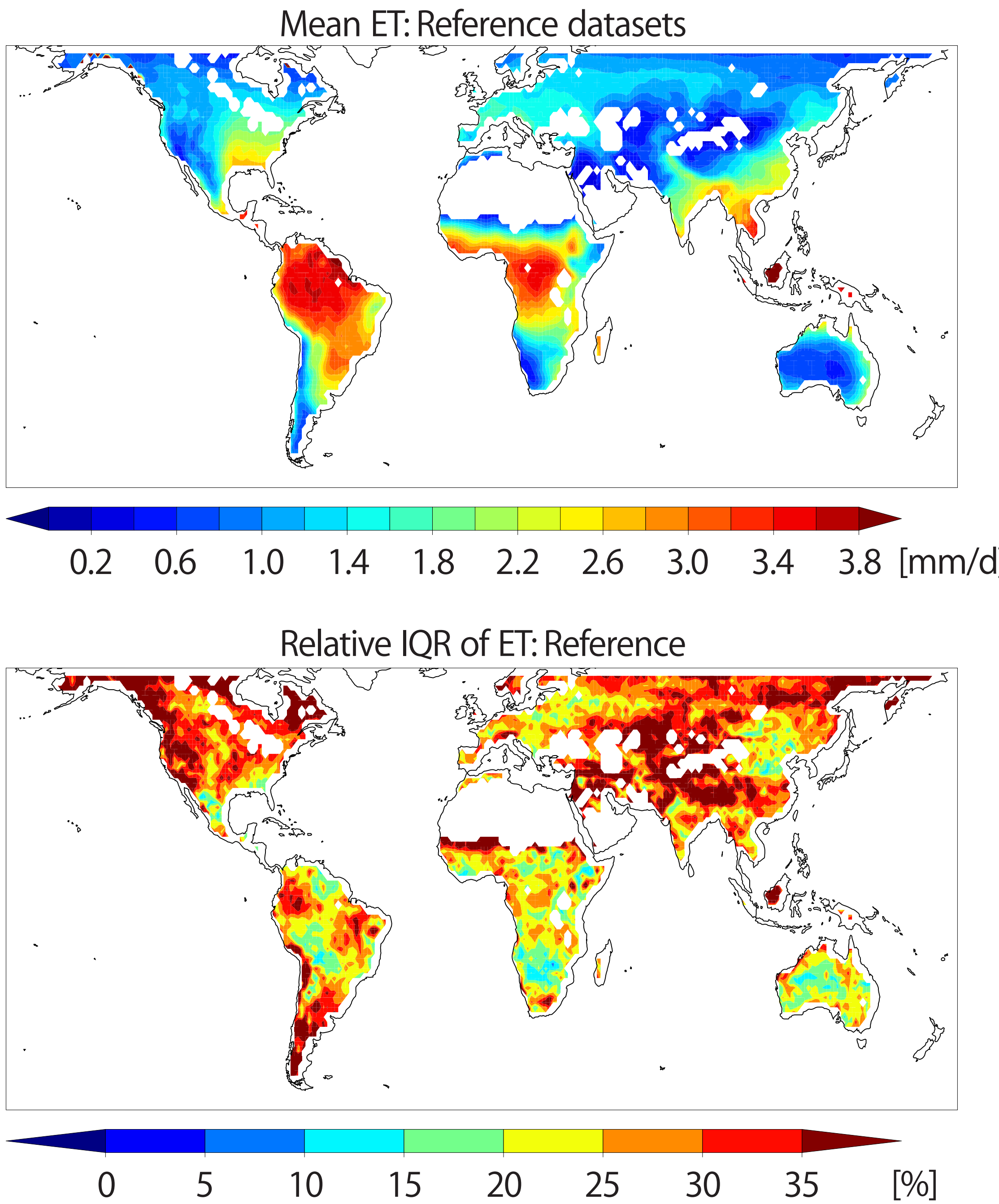

Figure 1. (*top*) Mean of 30 reference ET datasets in [mm/d]. The datasets include remote–sensing based estimates, reanalysis data, and output of land surface models driven with observation–based forcing. (*bottom*) Relative interquartile range of the datasets in [%]. From [1].

for Medium–Range Weather Forecasts (ECMWF), as well as the Modern Era Retrospective–Analysis for Research and Applications (MERRA)) was provided by Brigitte Mueller (ETH Zurich) based on inputs from the respective centres, and Sonia Seneviratne briefly reported on the planned CHEESE/GSWP3 (Coupled Hydro–Energy–Eco System Experiment / Global Soil Wetness Project Phase 3) initiative led by the University of Tokyo and UC Irvine.

The general conclusion of this second session was:

- For radiation forcing, SRB is adequate for ET applications although aerosols represent an important source of uncertainty
- GPCP currently has the best long–term climate record for precipitation.

Third session

Co–chairs: Sonia Seneviratne and Carlos Jimenez (Observatoire de Paris)

The third session assessed the status and development of the LandFlux–EVAL benchmarking database. Sonia Seneviratne highlighted the aims of the LandFlux–EVAL project, which—beside the evaluation of current datasets—also includes the deri-

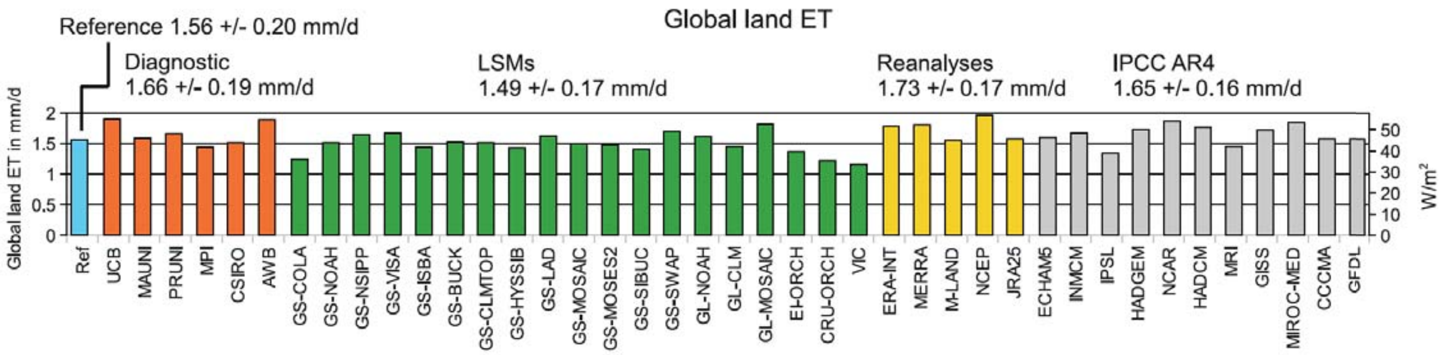

Figure 2. Mean annual global ET estimates in [mm/d] and [W/m^2] from 30 reference datasets and IPCC AR4 simulations. From [1].

vation of a benchmarking database. Carlos Jimenez and Brigitte Mueller provided overviews on two recent LandFlux–EVAL publications [1, 2] and on–going analyses.

Figure 1 displays the mean fields and relative interquartile range (IQR) from 30 ET datasets analysed in [1]. The datasets, as well as IPCC AR4 (Intergovernmental Panel on Climate Change, Fourth Assessment Report) simulations, are found to approximately agree on the global–scale land ET (Fig. 2), but large regional differences are found.

Eleanor Blyth highlighted currently on-going benchmarking initiatives, in particular as part of the new International Land Modelling Benchmarking (iLAMB) project. It was concluded that the LandFlux product and LandFlux–EVAL database would both be of high relevance to iLAMB.

The following decisions were made as part of this session:

- ETH Zurich will lead the compilation of the first LandFlux–EVAL database during autumn 2011, based on different data sources: remote–sensing based datasets, reanalysis products, and land surface models driven with observation–based forcing
- The database will also include measures of uncertainty (median, IQR) in contrast to previous studies on global ET.

Fourth session

Chair: Chris Kummerow

In the final session, the strategy for the development of the GEWEX v.0 ET (and SH) product(s) was discussed.

First, Chris Kummerow presented the vision and timeline for the GEWEX LandFlux product, including how it should be made compatible with other GEWEX products. The groups of B. Su, M. Reichstein, H. Dolman and E. Wood confirmed their contributions.

Additional contributions are possible and will be clarified by the GEWEX radiation panel.

The timeline for the first version of the LandFlux dataset is autumn 2011. Following these decisions, short presentations on consistency analyses and process–based evaluations for the resulting product were provided by Sonia Seneviratne and Markus Reichstein, and Wolfgang Wagner gave a presentation on the status of current soil moisture datasets and possible inter-comparisons with the resulting LandFlux ET product. At present, only the GLEAM product makes use of soil moisture information.

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The concluding discussion finished with decisions regarding common forcing products.

In conclusion, the GEWEX–iLEAPS LandFlux/LandFlux–EVAL mini–workshop allowed significant progress towards the development of the LandFlux–EVAL database and a LandFLUX ET product. First versions of these two products are planned by autumn 2011.

This progress is critical for several research communities, in particular for hydrological and climate change research. The organisers want to thank GEWEX, iLEAPS and TU Wien for significant support for this event.

References

1. Mueller B *et al.* 2011. Evaluation of global observations–based evapotranspiration datasets and IPCC AR4 simulations. Geophysical Research Letters 38, L06402, doi:10.1029/2010GL046230.
2. Jiménez C *et al.* 2011. Global intercomparison of 12 land surface heat flux estimates. Journal of Geophysical Research 116, D02102, doi:10.1029/2010JD014545

Meetings

The Arctic as a Messenger for Global Processes – Climate change and Pollution, University of Copenhagen, Copenhagen, Denmark, 4–6 May 2011

www.amap.no/Conferences/Conf2011/

More than 400 Arctic scientists and experts from 20 countries gathered at "The Arctic as a Messenger of Global Processes – Climate Change and Pollution" conference, organised by the Arctic Monitoring and Assessment Programme and the universities of Aarhus and Copenhagen. The aim of the conference was to consider pollution of the Arctic and climate change and its influence on the Arctic Cryosphere.

The following topics were covered:

- Climate change and its impacts on the Arctic Cryosphere – Past, Present & Future (Sea Ice, Greenland Ice Sheet, Arctic Ice Caps, Snow and Permafrost, Frozen Rivers and Lakes, Arctic Livelihood)
- Pollution of the Arctic – Sources, Pathways and Effects
- Global and Arctic Systems – Feedback Mechanisms
- Arctic Ecosystems – How Resilient are They
- Human Aspects of Climate Change and Pollution
- Science and Policy–Making (Actions taken in Response to AMAP Assessments).

BVOC Emissions Modelling and Applications Workshop, Lancaster University, UK, 17–18 May 2011

www.lec.lancs.ac.uk/bvoc

PhD student Kirsti Ashworth and Professor Nick Hewitt (LEC) hosted a two–day workshop to discuss biogenic volatile organic compound emissions models and their applications.

Over 60 attendees from 16 different countries heard presentations on the atmospheric chemistry of biogenic volatile organic compounds, the models used to estimate the emission rates of these compounds and their evaluation against measurements, and the application of these emissions models for air quality and climate modelling.

Discussions focused on the need to reduce the uncertainties in estimates of BVOC emissions and how this could be achieved. The workshop was financially supported by NERC's National Centre for Atmospheric Science.

European Geosciences Union (EGU) General Assembly, Vienna, Austria, 3–8 April 2011

http://meetings.copernicus.org/egu2011/

iLEAPS co–sponsored/related sessions at EGU2011:

- BG1.7 Earth Observation and modeling for land–atmosphere interactions and vegetation science (co–sponsored by iLEAPS and ESA).
  Conveners: A. Reissell, D. Fernández–Prieto, M. Marconcini, P. Palmer, E. Blyth, Z. Malenovsky, F. Morsdorf, A. Wolf, A. Damm, G. Schaepman–Strub
- BG2.1 Tropical ecosystem function and response to environmental change.
  Conveners: L. Mercado, L. Aragao, O. Phillips, S. Sitch, J. Lloyd
- AS2.1 Air–Land Interactions (General Session) (co–sponsored by iLEAPS).
  Conveners: T. Foken, A. Ibrom
- CL2.13 Seasons and phenology: Evidence from observations, reconstructions, measurements and models (cosponsored by USA–NPN, PAGES & iLEAPS).
  Conveners: T. Rutishauser, A. Menzel, J. Weltzin, A. Donnelly
- CL2.15 Land–climate interactions from models and observations: Implications from past to future climate.
  Conveners: B. van den Hurk, S. Seneviratne, P. Ciais
- AS1.16 African Monsoon Multidisciplinary Analysis (AMMA).
  Conveners: C. Taylor, H. Kunstmann, S. Janicot, B. Marticorena, L. Genesio
- BG2.10 Biosphere–Atmosphere Interactions: From biogenic primary exchange to atmospheric fluxes of reactive trace gases.
  Conveners: J. Kesselmeier, J.–P. Schnitzler, J. Rinne
- B2.5 Interacting Biogeochemical Cycles: Linking Carbon, Water and Nutrient Fluxes from Organisms to Globe.
  Conveners: D. Papale, M. Reichstein, A. Richardson, R. Vargas, D. Drewry
- BG5.1 Integration of Environmental, Socio–Economic and Climatic Change Studies in Northern Eurasia.
  Conveners: P. Groisman, A. Soja, A. V. Eliseev, C. Mátyás
- CL2.15 Land–climate interactions from models and observations: Implications from past to future climate.
  Conveners: Bart van den Hurk, S. Seneviratne, P. Ciais

1st International conference on Plant Proteases 2011: From biology to biotechnology, Hemawan, Sweden, 10–14 April 2011

www.plantproteases.se

The conference, organised by UPSC (Umeå Plant Science Centre), focused on the biology, biochemistry and molecular biology of plant proteases and collected together the foremost scientists in the field. The approach of the conference was broad, but a special emphasis was paid on a few topics listed below.

- Organellar proteases
- Metacaspases
- Subtilases
- Proteases in senescence and cell death
- Novel methods , such as proteomics and degradomics
- Proteases in xylem tissues and cell wall formation
- In addition, a minisymposium was organised on xylem development and wood formation.

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