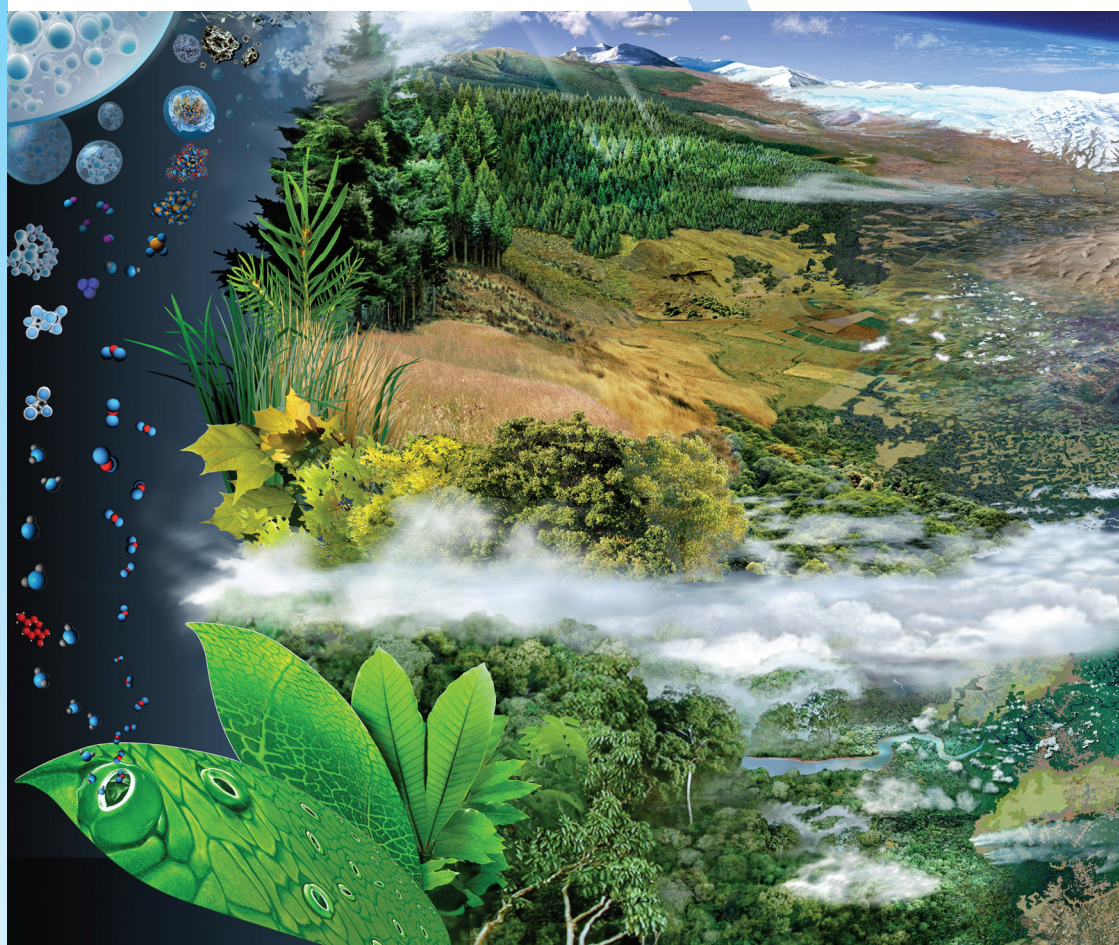




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# Integrated Land Ecosystem–Atmosphere Processes Study



## Science Plan and Implementation Strategy

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Editors: Meinrat O. Andreae, Pavel Kabat,

Almut Arneth and Anni Reissell

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Graphic Design: Hilarie Cutler

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iLEAPS International Project Office

Department of Physical Sciences

Division of Atmospheric Sciences

University of Helsinki

P.O. Box 68

00014 University of Helsinki

Finland

Web: [www.atm.helsinki.fi/ileaps](http://www.atm.helsinki.fi/ileaps)

# Science Plan and Implementation Strategy

## Prepared by the iLEAPS Scientific Steering Committee:

Meinrat O. Andreae (Co-chair), Germany

Pavel Kabat (Co-chair), Netherlands

Almut Arneth, Sweden

Paulo Artaxo, Brazil

Roni Avissar, United States

Mary Anne Carroll, United States

Torben Christensen, Sweden

Paul Dirmeyer, United States

John Finnigan, Australia

Laurens Ganzeveld, Germany

Sandra Harrison, United Kingdom

Michael Keller, United States

Markku Kulmala, Finland

Nathalie de Noblet-Ducoudré, France

Luanne Otter, South Africa

Daniel Rosenfeld, Israel

Xiaodong Yan, China

Kazuyuki Yagi, Japan

Anni Reissell, iLEAPS Executive Officer

## Preface

The iLEAPS Science Plan and Implementation Strategy defines the scientific objectives and key research issues of the land-atmosphere project of the International Geosphere-Biosphere Programme. It also outlines a strategy for addressing the key research questions.

The scope of iLEAPS research spans from molecular level processes – such as synthesis of volatile organic compounds in vegetation – to Earth System science issues, climate and global change. iLEAPS research emphasises the importance of connections, feedbacks and teleconnections between the numerous processes in the land-atmosphere interface. Due to the complexity and wide range of scientific issues, iLEAPS stresses the need for increased integrative approaches and collaboration, involving scientists from various disciplines, experimentalists and modellers, and international research projects and programmes.

## Acknowledgements

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The iLEAPS Transition Team members were:

Meinrat O. Andreae, Germany  
Pavel Kabat, Netherlands  
Almut Arneth, Sweden  
Paulo Artaxo, Brazil  
John Finnigan, Australia  
Laurens Ganzeveld, Germany  
Michael Keller, United States  
Markku Kulmala, Finland  
Luanne Otter, South Africa  
Vinay K. Dadhwal, India  
Pierre Friedlingstein, France  
Roger A. Pielke Sr., United States  
Andy Pitman, Australia  
Jan Polcher, France  
Xubin Zeng, United States

The following people also contributed to writing, reviewing and editing of this document:

Nuria Altimir, iLEAPS IPO  
Hanna Lappalainen, iLEAPS IPO  
Rick Lawford, GEWEX IPO  
Franz X. Meixner, Germany  
Colin Prentice, United States  
Mary Scholes, South Africa  
Will Steffen, Australia  
Tanja Suni, Australia  
Bill Young, IGBP Secretariat

Petter Kinnunen (Finland) assisted with the graphics, and the commissioned cover artwork was prepared by Glynn Gorick (United Kingdom).

Meinrat O. Andreae and Pavel Kabat  
Co-chairs, iLEAPS Scientific Steering Committee

December 2005

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# Executive Summary

The global environment is a complex system with numerous intricately linked processes. Changes in one process can feed back to the same process as well as to various others on time scales ranging from seconds to hundreds of years, and at spatial scales ranging from the molecular to the global. The Earth's climate system includes the terrestrial and the marine environments. The land surface–atmosphere interface plays a vital role in the functioning of the Earth System by controlling transfers of energy, momentum and matter.

iLEAPS – the Integrated Land Ecosystem–Atmosphere Processes Study – is the research initiative of the International Geosphere-Biosphere Programme (IGBP) that focuses on land-atmosphere interactions. The overall goal of iLEAPS is:

*to enhance the understanding of how interacting physical, chemical and biological processes transport and transform energy and matter through the land-atmosphere interface, particularly emphasising interactions and feedbacks at all scales, from past to future and from local to global.*

iLEAPS aims to study the implications of transport and transformation processes at the land-atmosphere interface for Earth System dynamics. Important questions are: (i) how did the land-atmosphere system function under pre-industrial conditions? (ii) how are human activities influencing the land-atmosphere system? and (iii) to what extent does terrestrial vegetation determine the physical and chemical environment on various temporal and spatial scales?

This Science Plan and Implementation Strategy presents the key science issues to be addressed during the ten-year study. The issues are detailed as four separate foci, but due to complex and intertwining connections, these are not considered to be separate thematic elements. These issues all contribute to regional and global climate on different temporal and spatial scales.

## Focus 1: Land-atmosphere exchange of reactive and long-lived compounds: key interactions and feedbacks in the Earth System

The land-atmosphere exchange processes of a variety of substances are tightly coupled, highly sensitive to climate change, and contribute to climate forcing through their effects on tropospheric chemistry and radiative flux. Long-lived gaseous compounds, such as carbon dioxide, methane, and nitrous oxide, as well as reactive volatile organic compounds and nitrogen oxides, are linked in the geochemical cycles of carbon and nitrogen. Of particular interest are the interactions between production, transport, transformation and deposition. Focus 1 spans biology, physics and chemistry.

## Focus 2: Feedbacks between land biota, aerosols and atmospheric composition in the climate system

Focus 2 considers the interaction of biogenic and anthropogenic aerosol particles with the climate system, and the coupling of biological and hydrological processes with atmospheric reactions to control the self-cleansing mechanism of the atmosphere. Focus 2 has a particular emphasis on the tropics. Studies under this focus will investigate direct emissions of natural and anthropogenic aerosols, as well as secondary aerosol formation and the production of cloud condensation nuclei. This research will contribute to the understanding of the direct and indirect effects of aerosols (including dust, biomass smoke and biogenic particles) on radiative flux and cloud-precipitation processes. Surface-atmosphere exchange processes are important in determining the concentration of hydroxyl radical – the main oxidant determining the rate of chemical removal of compounds from the atmosphere. Changes in land use and land cover directly or indirectly affect the oxidising capacity of the atmosphere and surface removal processes. Hence, surface-atmosphere exchange as well as mixing and transport, play key roles in regulating chemical transformations. Changes in gas-phase chemistry also affect aerosol formation and growth processes.

### Focus 3: Feedbacks and teleconnections in the land surface-vegetation-water-atmosphere system

To examine the magnitude of the exchange of various compounds, and the control exerted on these fluxes by land-atmosphere interactions, both hydrological and biogeochemical cycles have to be studied together. These studies must extend from small stream scale to continental basin scale. The ecosystems of the high-latitudes are particularly important due to rapid present and future climate change in this region, and potentially strong feedbacks on atmospheric methane and carbon dioxide concentrations. Landscape changes as a result of human influence can lead to large changes in the spatial redistribution of heat, moisture and energy. Multiple equilibria, thresholds and surprises in the climate system must be considered.

### Focus 4: Transfer of material and energy in the soil–canopy–boundary-layer system: measurements and modelling

Focus 4 investigates the types of measurements needed to study the various processes, interactions and feedbacks considered in Foci 1–3. Because of the complexity of the interactions between the numerous processes, measurements and modelling activities need to be explicitly linked. The measurement methods include surface flux measurements, boundary-layer budgets, aircraft-based measurements and remote sensing techniques. The integration of measurements and modelling include, for example, scaling from local observations to estimates of regional exchange, and sensitivity studies with fully coupled surface-atmosphere models.

Foci 1–3 highlight processes that are believed to be critical in the coupling of the biosphere and the atmosphere. These operate at time scales from seconds to decades and at spatial scales from molecular to global. The processes involve complex feedback mechanisms, and hence, it is insufficient to study individual processes. Foci 1 and 2 include examples of the complexity of the links involved. The close coupling between the hydrological cycle and the exchange of carbon and nitrogen compounds ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{NO}_x$ , VOC) with vegetation, is discussed first in Focus 1, followed by the role of aerosol formation in modulating the hydrological cycle through its effect on clouds and precipitation in Focus 2. Under-

standing and predicting complex processes relies on both modelling and measurements. Due to the nature of the processes presented in Foci 1–3, modelling and measurements are explicitly linked in Focus 4.

iLEAPS implementation strategies include strategic modelling and multi-parameter sensitivity studies in order to focus measurement activities and to select representative sites for field research. Research tasks may be chosen based on geographical boundaries to address regional issues, or according to common environmental factors in order to address key scientific uncertainties. Research themes can also be selected to develop iLEAPS tasks based on key processes or phenomena in the land-atmosphere system. iLEAPS will link with other relevant projects including IGAC, SOLAS, GLP and GEWEX.

Capacity building and knowledge transfer are essential components of iLEAPS. Knowledge transfer will include interdisciplinary training, capacity building and student outreach (initial contact and regional involvement, on-site training, follow-up workshops, databases) and communication. iLEAPS science will be published in international journals and communicated to a broad audience through the IGBP newsletter. An iLEAPS brochure, website, newsletter and press releases (for meetings and regional integrative projects) will be part of project outreach and communication. iLEAPS will encourage community- and policy-related outreach activities associated with regional integrative projects.

iLEAPS activities will include networks of process studies to elucidate specific iLEAPS scientific questions, field campaigns, modelling (tool development, validations and intercomparisons), long-term integrated field studies, large international cross-disciplinary campaigns, synthesis studies, databases, as well as conferences on specific scientific questions and synthesis meetings.

iLEAPS research is approved by the Scientific Steering Committee (SSC), and activities are coordinated through the International Project Office (IPO) located at the University of Helsinki, Finland. This Science Plan and Implementation Strategy includes guidelines for research proposal submission.



# Introduction

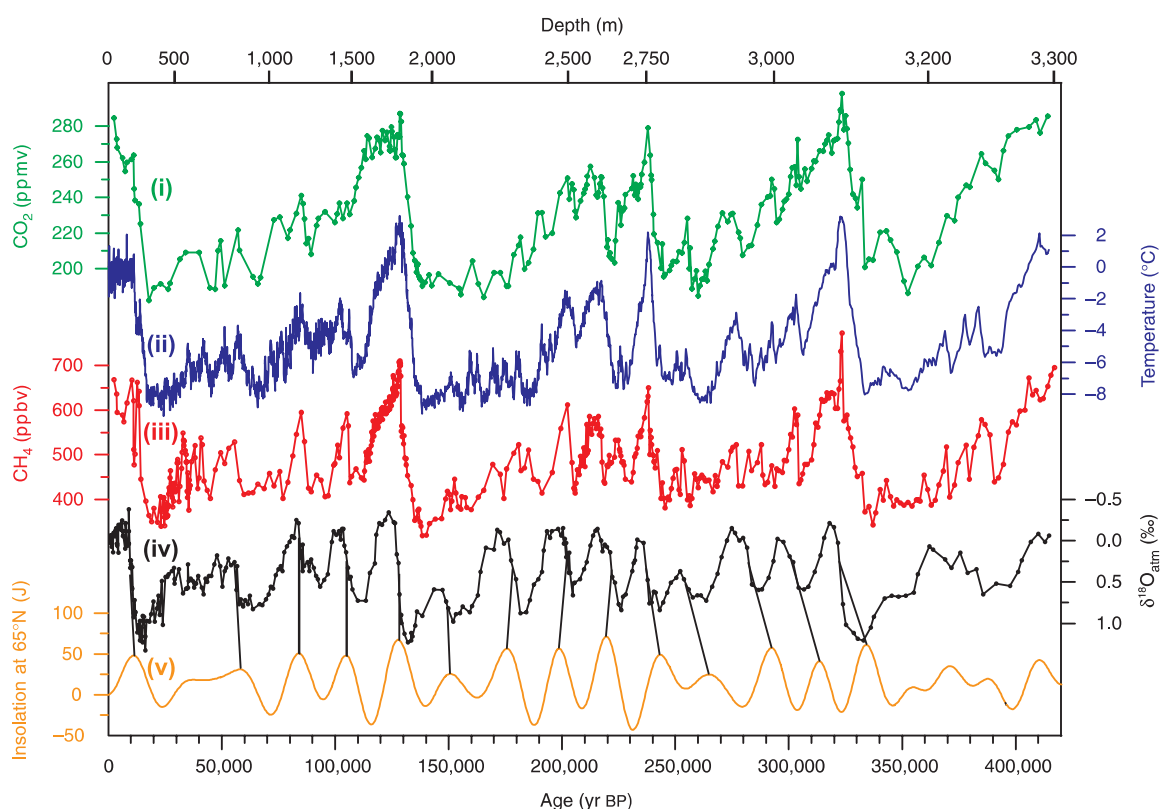
The past decade of global change research, under the umbrella of IGBP, has brought a fundamental change in the world view of the sciences of the Earth. It is now clear that global change – the impact of human activities on the environment – involves all components of the Earth System – the oceans, atmosphere, geosphere and biosphere. Moreover, it is now clear that these impacts cannot be considered in isolation, but that interactions and feedbacks between the components of the Earth System play powerful and essential roles (Steffen et al., 2004a).

A demonstration of the tight coupling between global climate and biogenic trace gases (carbon dioxide and methane) in the atmosphere, is evident in the Antarctic ice records from over 400,000 years (Figure 1). Such close covariance begs the question of cause and effect: are fluctuations in biogenic greenhouse gases driving climate

variations, or are externally forced climate variations responsible for changes that result in varying emissions of these gases? Current consensus suggests that it is not a simple either/or, but that the biota and their geophysical and geochemical environments have co-evolved, resulting in a multitude of complex feedbacks.

This implies that Earth's climate system is determined by both the abiotic and the living world – the biosphere. The land surface–atmosphere interface is particularly crucial for the functioning of the Earth System because of energy and momentum fluxes across the interface, and biogeochemical and hydrological processes. At the same time, climate variability and atmospheric processes, such as transport and deposition of chemicals, are major constraints on biogeochemical cycles, whether ‘natural’ or anthropogenically driven. For example, inter-annual vari-

Figure 1. Vostok data series and insolation against time (lower axis) and ice core depth (top axis). Series are (i)  $\text{CO}_2$ , (ii) isotopic temperature of the atmosphere, (iii)  $\text{CH}_4$ , (iv)  $\delta^{18}\text{O}_{\text{atm}}$ , (v) mid-June insolation at  $65^\circ\text{N}$  (in  $\text{W m}^{-2}$ ). Reproduced from Petit et al. (1999) with permission from Macmillan Magazines Limited.

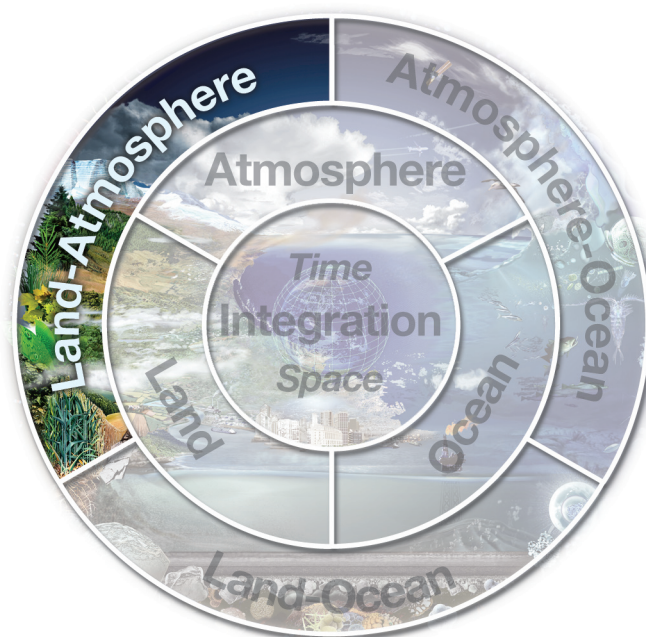


ability of carbon uptake at all spatial and temporal scales is strongly influenced by variations in climate, through the related feedbacks to physiology and productivity; this is one of the major outcomes of the Global Change and Terrestrial Ecosystems (GCTE) project of IGBP (Walker et al., 1999). Gases and aerosols deposited from the atmosphere can also strongly influence ecosystem functioning, sometimes acting as fertilisers, sometimes as toxic substances. A key lesson from the Biospheric Aspects of the Hydrological Cycle (BAHC) project of IGBP is that land use and land cover strongly affect the exchange of water and energy between the land surface and the atmosphere, making them important and integral components of the climate system (Kabat et al., 2004). Consequently, 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 destabilising large regions such as the Amazonian (Cox et al., 2000) or taiga forests.

Consequently, the Earth behaves as a complex system, and a fundamental characteristic of complex systems is that they often respond to change in highly non-linear, or abrupt ways. Under initial forcing, such systems may be well-buffered, but once a threshold is passed the system may shift abruptly into another state. There is strong evidence that the Earth System is prone to such abrupt changes, for example, the polar ozone holes or the rapid climate oscillations (“Dansgaard-Oeschger” events) of the last ice age (Ganopolski and Rahmstorf, 2001). Human-induced global change has pushed the Earth System into a no-analogue state – where climatic and other environmental conditions are outside of the range of the last half million years, increasing the likelihood of unpredictable changes with potentially harmful consequences (Steffen et al., 2004b, c). Exploring and quantifying Earth System interactions is therefore extremely important.

The new, holistic Earth System perspective demands a new scientific approach and innovative conceptual and technical tools. Separate Earth System components, properties and processes – such as the composition and circulation pattern of the atmosphere – still need to be investigated, but should be studied as integral parts of a system, so as to understand their interactions and feedbacks. Furthermore, in the era of global change, humanity must also be considered a part of the Earth System. IGBP has responded to this challenge by establishing a scientific structure, based around the major biogeophysi-

Figure 2. The IGBP scientific structure.



cal components of the Earth System (land, atmosphere and oceans), complemented by projects addressing their interactions and feedbacks (Figure 2).

iLEAPS addresses land-atmosphere interactions and feedbacks within this IGBP structure. The objective of iLEAPS is to provide understanding of how interacting physical, chemical and biological processes transport and transform energy and matter through the land-atmosphere interface. The scientific goals of iLEAPS have been chosen to reflect issues and regions where previous research has shown that interactions, feedbacks and teleconnections play prominent roles and are essential to scientific understanding. The issues and regions selected are also likely to represent some of the critical “switch” or “choke” points in the Earth System, where local and regional changes may have the strongest influence on the overall Earth System (Figure 3). The examples that follow illustrate some critical regions and issues.

One example for such a set of interactions is the massive perturbation of the tropical atmosphere by the combination of land use change (deforestation) and the emission of atmospheric pollutants – especially aerosols from industrial combustion and biomass burning. Since the tropics are the “heat engine” that drives large-scale atmospheric circulation, the perturbation of tropical cloud and rainfall processes is expected to affect global climate

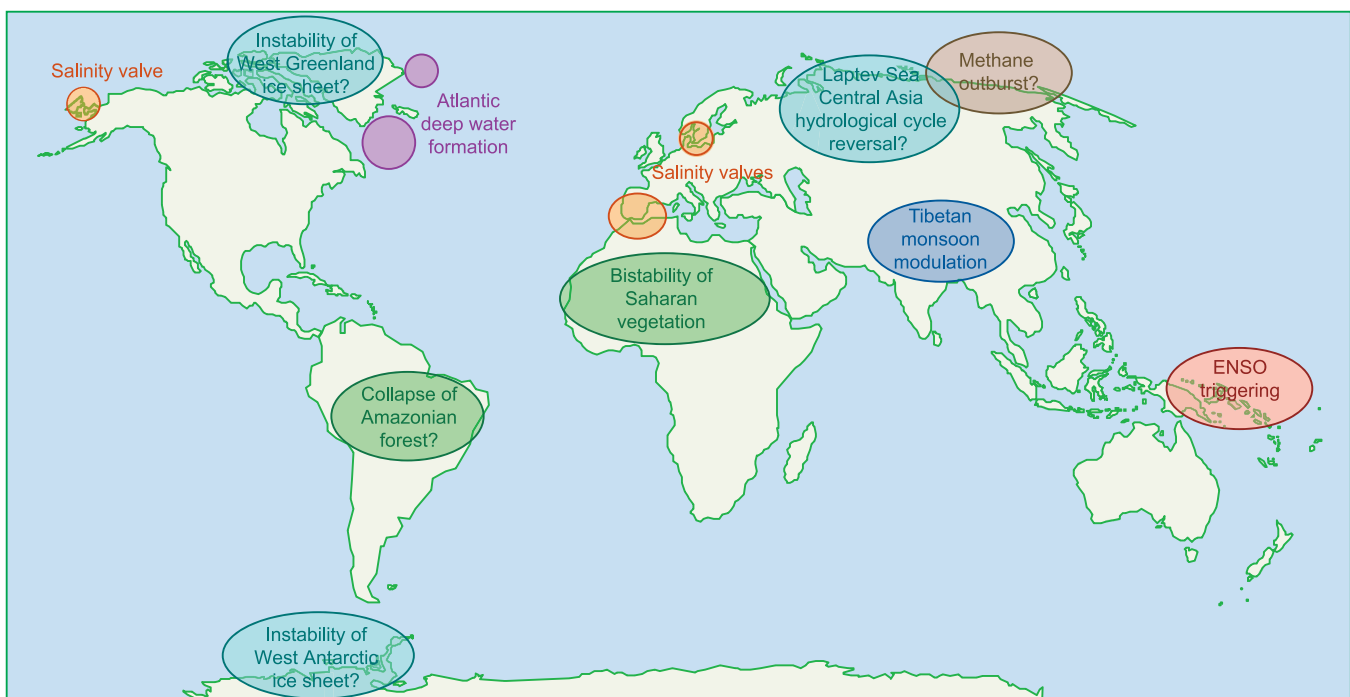
dynamics. Anthropogenic emissions of aerosols and their precursors, occurring mainly on the land surface, affect the properties of clouds and thereby the intensity and location of rainfall, as well as the vertical redistribution of pollutants in the atmosphere (Andreae et al., 2004). These effects feed back to the land surface by affecting the terrestrial water cycle, which in turn has consequences for water availability, agricultural productivity and the emission of trace gases from land ecosystems.

Going beyond the tropics, atmospheric aerosols are now considered to be a key issue in understanding past and future climate change, a major finding of the first decade of IGAC (Brasseur et al., 2003). The complexities associated with aerosol forcings and their feedbacks are becoming increasingly evident. When all their complex climate effects are considered, aerosol forcing may be of the same order of magnitude as greenhouse gas forcing, but of opposite sign (Anderson et al., 2003; IPCC, 2001). This opens up the possibility that the observed temperature change over the past century (about +0.7 °C globally), was driven by a rather small net global forcing, which would imply a very high climate sensitivity; that is, a large temperature increase *per* increment of anthropogenic radiative forcing (Andreae et al., 2005). This raises significant concerns about the development of the climate system in the 21<sup>st</sup> century. Aerosols are now known to have

very serious health effects, with substantial increases in mortality from a variety of diseases occurring at levels common in industrialised and developing countries (Pope et al., 2002). For this reason especially, aerosol emissions are expected to be reduced in the foreseeable future. The combination of aerosol reductions, growing greenhouse gas emissions, increased carbon fluxes from the biosphere due to climate and land cover change, and changes in land albedo due to changing ecosystems and snow cover in the Arctic, raises great concern about the risk of sudden and dramatic climate change in the coming decades.

Changes in the surface fluxes of reactive carbon and nitrogen compounds, coupled with hydrological and land use changes and altered vegetation dynamics, can significantly influence not only the climate system, but also the chemical functioning of the atmosphere. One of the key findings of IGAC was that biospheric activity and atmospheric composition are closely linked. Natural ecosystems have developed in close interaction with the pristine atmosphere, and the self-cleansing mechanism of the atmosphere (which removes the products of natural and anthropogenic emissions from the atmosphere) is in a tight feedback loop with these very emissions. As described in Focus 2, changes in surface exchange may be affecting this self-cleansing mechanism in profound ways and over large regions.

**Figure 3.** Critical areas with anticipated strongest influence on the Earth System. Adapted from Schellnhuber (2002) with permission from Springer.



At present, the most dramatic climate change is occurring in the arctic and boreal regions (ACIA, 2005). Temperatures and precipitation have risen rapidly in much of the region over past decades, river flows are increasing, and snow and ice cover are decreasing. As a result, vegetation zones are expected to shift, fires are increasing in frequency and extent, and significant impacts on society are likely. This region is therefore an ideal natural laboratory to study the changing interactions between physical climate, ecosystems, water and carbon cycles, and human society.

BAHC had already shown the terrestrial biosphere to be an essential determinant for the exchange of water and energy between the land surface and the atmosphere, and GCTE had highlighted the interactions between ecosystems, atmospheric CO<sub>2</sub> and climate. iLEAPS will bring these processes together at a higher level of integration.

iLEAPS, as an interface project, will collaborate closely with the projects addressing the land and atmosphere components in the IGBP scientific structure: the Global Land Project (GLP) and the International Global Atmospheric Chemistry (IGAC) project. However, from an integrated Earth System perspective, iLEAPS considers the implications for Earth System dynamics, and the role of humans in the Earth System. The results of iLEAPS are therefore intended to feed into a more comprehensive integration, which will occur within the IGBP project Analysis, Integration and Modelling of the Earth System (AIMES) and within the Integrated Regional Studies (IRS) of the Earth System Science Partnership (ESSP) of the four global change programmes of the International Council for Science (ICSU). iLEAPS will also closely interact with the World Climate Research Programme (WCRP), particularly with its Global Energy and Water Cycle Experiment (GEWEX) project, its Global Land/Atmosphere System Study (GLASS) and its Global Atmospheric Boundary-Layer Study (GABLS). Close links will also be forged with the Surface Ocean–Lower Atmosphere Study (SOLAS), the Past Global Changes (PAGES) project, the Global Emissions Inventory Assessment (GEIA), the Global Carbon Project (GCP) and the Global Water System Project (GWSP).

The Science Plan describes the key science issues to be addressed in iLEAPS. These are presented below as four separate foci, but these should not be considered as separate thematic units. Energy partitioning, emission

of chemical compounds, and carbon uptake by terrestrial biota, all contribute in various ways to regional and global climate on different temporal and spatial scales. The common thread of the research is to investigate interactions of various processes in (past) pristine environments and along gradients of environmental perturbation (including the role of extreme events). In most cases, research will be based around a combination of *in situ* measurements, process and case studies, satellite observations and modelling. Innovative theoretical foundations and observational methodologies will be critical.

# Science Foci

The iLEAPS research objective is to address the following four questions:

- (i) How do interacting physical, chemical and biological processes transport and transform energy, momentum and matter through the land-atmosphere system?
- (ii) What are the implications for the dynamics of the Earth System?
- (iii) How did the terrestrial-ecosystem/atmosphere system function under pre-industrial conditions, and how are human activities influencing it?
- (iv) To what extent does the terrestrial vegetation determine its physical and chemical environment on different temporal and spatial scales?

Research to address these questions is organised into the following four Foci (Figure 4):

**Focus 1:** Land-atmosphere exchange of reactive and long-lived compounds: key interactions and feedbacks in the Earth System.

**Focus 2:** Feedbacks between land biota, aerosols and atmospheric composition in the climate system.

**Focus 3:** Feedbacks and teleconnections in the land surface-vegetation-water-atmosphere system.

**Focus 4:** Transfer of material and energy in the soil-canopy-boundary-layer system: measurements and modelling.

The sections below describe these four Foci, including brief reviews of the key relevant processes in the land-atmosphere system and the specific questions to be addressed.



Figure 4. iLEAPS science foci span from molecular level to global scale integrating measurements and modelling.

## Focus 1: Land-atmosphere Exchange of Reactive and Long-lived Compounds: Key Interactions and Feedbacks in the Earth System

The land-atmosphere exchange processes of many substances are tightly coupled together, highly sensitive to climate change, and in turn, contribute to climate forcing via their effects on tropospheric chemistry and radiative flux. A large variety of gases are exchanged between the biota and the atmosphere (Scholes et al., 2003), the most abundant being carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), volatile organic compounds (VOC), reactive nitrogen compounds ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) and water vapour ( $\text{H}_2\text{O}$ ). Other compounds of importance are dinitrogen oxide ( $\text{N}_2\text{O}$ ), ammonia ( $\text{NH}_3$ ) and various sulphur and halogen compounds. The biosphere supplies the atmosphere with fuel for a myriad of chemical reactions; atmospheric chemistry and dynamics determine the transport and distribution of these compounds and their reaction products, which are often found far from their sources.

**Figure 5.** Focus 2 research topics include emission, transformation and deposition of a variety of compounds.



The tight links between the carbon and nitrogen cycles are conceptually well understood. Nitrogen is a major nutrient and component of photosynthetic enzymes (e.g. Rubisco), and increasing nitrogen availability due to anthropogenic nitrogen emissions stimulates photosynthesis and growth in some environments. In a world with increasing  $\text{CO}_2$ , acclimation can be more marked in some nitrogen-limited plants, and the stimulation of plant growth can be decreased

or even eliminated when nitrogen is limiting. Rising atmospheric  $\text{CO}_2$  may elicit long-term decline in plant nitrogen fixation and has been recently attributed to the decrease in availability of other nutrients such as molybdenum, a key constituent of nitrogenase (Hungate et al., 2004). Nitrogen supply to plants may be modified by long-term interactions between plants, by soil and plant interactions, and/or by a modified water cycle. This may explain differences in carbon uptake and storage observed at the plant level compared to the ecosystem level (Stitt and Krapp, 1999; Lloyd and Farquhar, 1996). Interactions at the ecosystem level also need to be considered when studying the release of nitrogen oxides to the atmosphere, which depends on the rate of nitrogen cycling in soils. With regard to VOC, emissions of some major compounds (such as isoprene) are directly linked to photosynthetic carbon assimilation and therefore estimates of future emission rates need to consider not only effects of possible change in the physical aspects of the climate system, but also effects of  $\text{CO}_2$  fertilisation on assimilation rates. Additionally, methane production in wetlands may be linked to root exudates and hence carbon and nutrient cycles.

Gaseous compounds vary greatly in their reactivity with the three main atmospheric oxidants: hydroxyl radical ( $\text{OH}$ ), nitrate radical ( $\text{NO}_3$ ) and ozone ( $\text{O}_3$ ) (Atkinson, 2000). Fast reactions (order of minutes) can take place below the canopy involving for example, a mixture of VOC and nitrogen oxides, whereas less reactive compounds, such as  $\text{N}_2\text{O}$  and methane, escape into the atmosphere. Due to limitations in sampling and analytical methods, only a small portion of the chemical transformation products of VOC have been identified, let alone quantified. Changes in environmental conditions, emissions and the oxidising capacity below and above the canopy, can affect the lifetime, nature and magnitude of exchanged gases and therefore also deposited and escaping compounds.

To predict the impact of future changes to air quality, climate and ecosystem function, there is a critical need to understand the details of carbon and nitrogen cycling within and between the terrestrial and atmospheric systems. Many

of the processes are not understood to the level of detail necessary to close budgets, to quantitatively predict carbon and nitrogen cycling in the face of changing global climate, or to study interactions and feedbacks between the terrestrial biosphere and the atmosphere.

In the short term, major feedback loops include the effects of plant stomatal control and soil water balance on evaporation and other scalar emissions. The direct coupling of evaporation to the land surface energy balance is well known: closing of stomata reduces plant transpiration, which increases the conversion of incident radiation to sensible heat. This increased surface sensible heat flux drives increased entrainment of drier air from the troposphere resulting in drying of surface air and hence increased evapotranspiration. On time scales of years to centuries, additional feedbacks play an important role. These feedbacks are due to the time lag between nutrient availability, primary production and carbon loss via respiration or episodic events (fire, herbivory), and the dynamics of vegetation cover. The multitude of interactions between the various compounds on all temporal and spatial scales, presents a major challenge for quantifying the role of each compound in the land-atmosphere system.

The wide range of interactions that take place within the land-atmosphere system are briefly described above. For clarity and structure, some key trace gases and compound groups are considered separately in the sections below. However, it is the interactions between production, transport, transformation and deposition – in other words between biology, physics and chemistry – that will be specifically considered within iLEAPS.

### Sub-focus 1.1: Carbon Dioxide

The atmospheric concentration of CO<sub>2</sub> – the main anthropogenic greenhouse gas – has increased by more than 30% over the last 150 years due to fossil fuel burning and subsequent changes in land cover and land use. This increase represents approximately half of the anthropogenic emissions, indicating that a similar amount has been absorbed by the oceans and by the land biosphere (Prentice et al., 2001).

A major source of uncertainty in quantifying the carbon uptake by the terrestrial biosphere, is the lack of understanding of the mechanisms driving the increase in uptake on the global scale. One possible direct mechanism could be the increase of carbon assimilation and the subsequent increase in productivity. Several processes, such as changes in climate or increases in productivity (either through enhanced

nitrogen deposition or increased soil nitrogen availability) can indirectly affect carbon uptake. Also, changes in land use and forestry practices may contribute to the increase in the terrestrial carbon sink. However, the contributions of land cover and/or land use changes to regional and global carbon budgets, are highly uncertain because the translation of vegetation changes into net CO<sub>2</sub> fluxes (to, or from the atmosphere) is non-trivial (Houghton, 1999). Additional complications are due to time lags between increased (or decreased) carbon assimilation, productivity and respiratory CO<sub>2</sub> loss from the terrestrial biosphere. In many cases the least studied mechanisms are those contributing to the respiratory part of the budget. Also, the role of disturbances and episodic events (e.g. fires, herbivory, windthrow and flooding) and their interactions with productivity and climate are still poorly understood (Schimel et al., 1997; Arneeth et al., 1998; Knohl et al., 2002).

The possible processes affecting the net CO<sub>2</sub> uptake by the terrestrial biosphere at the local scale have been studied extensively in controlled experiments. More research is needed to understand how these various processes control the atmosphere-land fluxes of CO<sub>2</sub> from the regional to global scale, and to quantify the associated feedbacks in the climate system. Coupled climate-ecosystem model simulations suggest that feedbacks may be significant (Cox et al., 2000; Friedlingstein et al., 2001). In order to make progress, comprehensive databases containing data of the potential forcing mechanisms should be established. The data should be combined with mechanistic models of the terrestrial biosphere, and compared with land and atmosphere-based data from long-term observation systems. State-of-the-art dynamic global vegetation models (DGVM) are beginning to address these issues (Cramer et al., 2001) but require further development. For example, a realistic representation of fires (natural and human-induced) is only in early stages of development (Thonicke et al., 2001). Similarly, more research is required to understand the impact of fires on biosphere functioning, and on fluxes of CO<sub>2</sub> and reactive gases. Studies should strive to understand the coupling between CO<sub>2</sub> and the other compounds in the biosphere-atmosphere system. Biospheric fluxes of gases other than CO<sub>2</sub> (methane and VOC – see below) are generally related to land-atmosphere CO<sub>2</sub> exchange. For example, a link exists between methane production from wetlands and CO<sub>2</sub>-producing decomposition, with the balance between these two trace gases depending on the soil water conditions. VOC emissions by forests are coupled in part to the photosynthetic activity of the plants. Such linkages require the development of DGVMs that

account for multiple chemical compounds in a consistent way, and the comparison of model results with local scale measurements of CO<sub>2</sub> and other gases (e.g. FLUXNET) and with atmospheric measurements at larger scales (e.g. GLOBALVIEW network and remote-sensing data).

## Sub-focus 1.2: Methane

Methane is one of the most potent contributors to the greenhouse effect. The radiative forcing potential of one mass unit of methane is 23 times that of CO<sub>2</sub> over a time horizon of 100 years (Ramaswamy et al., 2001). Methane (as well as other hydrocarbons, see Sub-focus 1.3) is oxidised by reaction with the hydroxyl radical. Global methane emissions are therefore not only important for radiative forcing in the Earth's energy budget, but also for the oxidative capacity of the atmosphere (see Focus 2). An important link exists between methane, other VOC and the nitrogen cycle. In the presence of NO, the oxidation of methane and other VOC produce nitrogen dioxide (NO<sub>2</sub>), which in turn, through photolysis and subsequent reaction forms ozone. This sequence is of importance for the tropospheric ozone budget (Monson and Holland, 2001; Brasseur et al., 2003) and also for hydroxyl radical concentrations, since hydroxyl radicals are mainly formed from the photolysis of ozone. Due to increased emissions of NO<sub>x</sub>, carbon monoxide (CO) and VOC, all of which are oxidised in relatively rapid reactions with OH, the atmospheric lifetime of methane has probably increased over recent decades.

During the last four glacial-interglacial cycles the atmospheric concentration of methane has varied within relatively well defined bounds (400–700 ppbv) in a similar fashion to atmospheric CO<sub>2</sub> (Petit et al., 1999). Since the onset of industrialisation, however, the atmospheric methane concentration has increased approximately 2.5-fold to reach the current level of around 1,750 ppbv (Prather et al., 2001). Superimposed on this general increase since industrialisation, are substantial, and currently unexplained inter-annual variations. Also unexplained, is the more recent (1990s) slackening in the rate of methane concentration increase and its short-term greater variability (e.g. Dlugokencky et al., 1998; Lelieveld et al., 1998; Prather et al., 2001).

The most significant anthropogenic contributions to the atmospheric methane loading are associated with food production, and include direct emissions from ruminants, emissions from animal wastes and flooded rice paddies. Microbial processes in natural wetlands have always been a major source of atmospheric methane, and are estimated to

still account for 40% of total emissions (Walter and Heimann, 2000). Methane emissions from natural and managed wetlands vary from year to year due to fluctuations in weather and water management. On time scales of months to years (for wet conditions beyond a certain threshold) methane emission is mainly controlled by temperature and plant species composition (Christensen et al., 2003). These variables influence microbial activity as well as the diffusion of methane through the soil and plant pore spaces (Conrad, 1997). Substrate availability, influenced by net primary production and microbial decay, is also indirectly controlled by temperature and other climatic factors, and is a third major constraint to methane production since it determines emission capacity. For example, root exudates have recently been suggested as major regulating factors for wetland emissions (Ström et al., 2003). The observed fluctuations in atmospheric methane increases are thought to be largely attributable, directly or indirectly, to climatically induced variations in wetland methane emissions. Variability in inundation is the most important control mediating the alternate states of methane consumption and production, where dry soils act as methane sinks, and inundated saturated soils act as methane sources (Harriss et al., 1982). This dominant control forms the basis of models of methane emission (Walter and Heimann, 2000).

Global process-based model studies on natural wetland methane emissions estimate source strength ranging from 92–260 Tg yr<sup>-1</sup> (Cao et al., 1996; Walter et al., 2001) with the northern latitudes and the tropics being the key source regions. Despite large discrepancies in absolute values, process models agree on a dominant contribution of the tropics to global annual totals, although the northern latitudes contain by far the largest wetland area. Models based on the inversion of atmospheric concentration data also place the strongest wetland methane sources in the tropics (Hein et al., 1997; Houweling et al., 1999).

Methane production in northern latitudes is constrained by a short biologically active season. Models predicting future climate suggest that temperatures will rise, and that precipitation may increase. The recovery of biological activity following winter dormancy is triggered by above-freezing temperatures in these ecosystems, and consequently they are sensitive to warmer and/or wetter environmental conditions which would cause an extension of the biologically active period. In addition, with climate warming the annual soil thaw depth would increase in permafrost areas. In discontinuous permafrost areas, the permafrost itself may disintegrate causing spatial expansion of methanogenic activity (Chris-



tensen et al., 2004). Methane emissions might increase due to increased temperature, or decrease as a result of soils drying out due to increased transpiration and evaporation. Important indirect feedbacks may include increased fixation of carbon due to lengthening of the biologically active period, increased respiratory CO<sub>2</sub> flux from boreal ecosystems due to temperature rise, and changes in the regional hydrological balance.

Unknown factors in the global methane budget are geothermal sources and methane hydrates. Methane hydrates are essentially crystallised water with a high content of methane (Kvenvolden, 1988); they are only stable under high pressures and low temperatures. In tundra regions and offshore environments with permafrost sediments, methane hydrates are particularly close to the surface. The release of methane hydrates is a natural process, but estimates of the magnitude of the natural release are very uncertain (Kvenvolden, 2002). In particularly sensitive areas a warmer climate could cause methane hydrates to destabilise, resulting in a substantial release of methane to the atmosphere, hence increasing the greenhouse effect. The most sensitive areas are thought to be near-shore arctic sediments, where a warmer ocean is expected to have the most rapid effect on the relatively shallow permafrost (Kvenvolden, 1988, 2002; Harvey and Huang, 1995; Glasby, 2003).

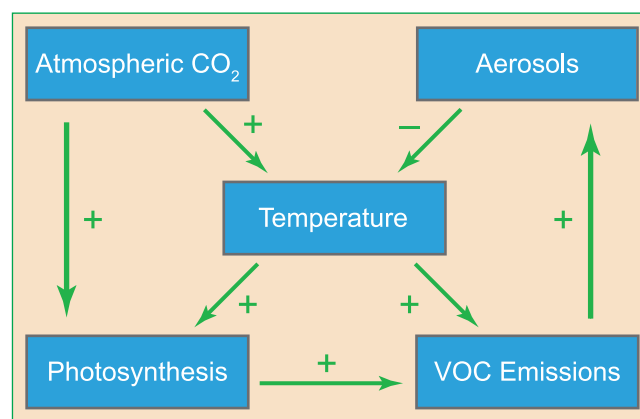
It is evident that changes in the land surface and land use have the potential to significantly alter regional and global patterns of methane emissions. Human-induced draining or drying as a consequence of warmer temperatures and/or less precipitation, will reduce emissions from wetlands. As noted above however, in a warmer climate some current permafrost areas may become methane sources. Other human factors that affect methane emissions include changes in the methane oxidation capacity of soils due to nitrogen fertilisation and the deposition of nitrogen as acids (Smith et al., 2000; Priemé and Christensen, 1999).

### Sub-focus 1.3: Volatile Organic Compounds

VOC are a large class of compounds of anthropogenic and natural origin. When excluding methane, the most prevalent biogenic VOC are isoprene, methylbutenol and the monoterpenes (e.g.  $\alpha$ - and  $\beta$ -pinene), but an important fraction of biogenic emissions consists of sesquiterpenes and oxygen-containing compounds such as alcohols, carbonyls and organic acids (Kesselmeier, 2001). Compared to methane which has natural sources and sinks mainly in soils and sediments, the other biogenic VOC are predomi-

nantly produced by plants. Similar to methane, there are large VOC emissions from biomass burning and substantial anthropogenic VOC emissions from landfills and fossil fuel burning. The global anthropogenic VOC flux is estimated as  $1 \times 10^{14}$  g C yr<sup>-1</sup>, while biogenic emissions may be of a factor of ten higher ( $1.2 \times 10^{15}$  g C yr<sup>-1</sup>; Guenther et al., 1995). There are, however, significant variations in emissions amongst ecosystems and regions. Most VOC have short atmospheric lifetimes compared to methane (Atkinson, 2000), and as for methane, oxidation contributes to the formation of tropospheric ozone, aerosol particles (Kulmala et al., 2001) and hydroxyl radical.

**Figure 6.** Proposed simple feedback loop between CO<sub>2</sub> concentration, air temperature and carbon assimilation, and VOC emissions and aerosol formation (various spatial and temporal scales are not separated). Adapted from Kulmala et al. (2004).



The range of VOC synthesised and emitted by plants, and their emission strengths, vary according to plant species. For some VOC, an ecophysiological feedback is known to affect production and release (Kesselmeier and Staudt, 1999). It has been proposed that isoprene—a key biogenic VOC—helps chloroplast membranes adapt to high temperatures (Sharkey and Singaas, 1995), but why plants synthesise and emit isoprene is not yet fully understood. Interestingly, more primitive plants (e.g. *Sphagnum* sp. ferns) also emit isoprene, indicating an ecophysiological adaptation from early evolution (Hanson et al., 1999). Isoprene is never stored in leaves, but rather, is released immediately after production. The production and emission rates of isoprene are strongly dependent on light and temperature, due to their effects on leaf biochemistry and physiology. Monoterpenes are generally produced and released in a similar manner to isoprene, but some plant species can store monoterpenes in special compartments. Release of volatile compounds from these storage pools is primarily temperature-regulated, unless

storage structures are damaged, which leads to higher release rates. Emission of all VOC is constrained by water and nitrogen availability (via effects on primary production and physiological regulations) and by leaf development stage.

The emission of VOC may represent a substantial loss of carbon for the plant and the ecosystem (Kesselmeier et al., 2002). The flux of reactive carbon may be small relative to gross primary productivity on a diurnal to annual basis, and also at the ecosystem scale, however, on the biome scale (when compared to net biome production) may amount to a significant proportion of the carbon balance. At the ecosystem scale, a significant fraction of the carbon released as VOC is deposited as organic acids or organic particles, and therefore both emission and deposition budgets must be considered when estimating the effects of VOC on net ecosystem production.

Photo-oxidation and ozonolysis of mono- and sesquiterpenes may produce condensable reaction products, and therefore also secondary organic aerosols. Recently, low-volatility photo-oxidation products of isoprene have been measured in aerosol particles in the Amazonian rain forest (Claeys et al., 2004). Depending on conditions, particle nucleation from organic vapours can either increase the total number concentrations, or the low-volatility organic compounds can predominantly condense on existing particles. The condensing compounds can increase particle size, and therefore make them more efficient as cloud condensation nuclei (CCN). However, the formation mechanisms and sources of secondary organic aerosols are poorly known, and therefore their global source strength is uncertain by an order of magnitude (Fuzzi et al., 2005; Penner et al., 2001). Fire also provides a massive source of aerosols, dominating the tropical atmosphere in the dry season. Biogenic and pyrogenic aerosols strongly scatter and absorb solar radiation, and thereby reduce surface actinic flux and heat the atmosphere, decreasing the atmospheric lapse rate. Through this mechanism, and through their activity as CCN, organic aerosols interact with cloud and rainfall formation and the hydrological cycle (see Sub-focus 2.1). Moreover, VOC contribute to the regulation of tropospheric hydroxyl radical concentration (see Sub-focus 2.2) and thus may play an important role in determining the rate of atmospheric methane increase.

### Sub-focus 1.4: Nitrogen Oxides

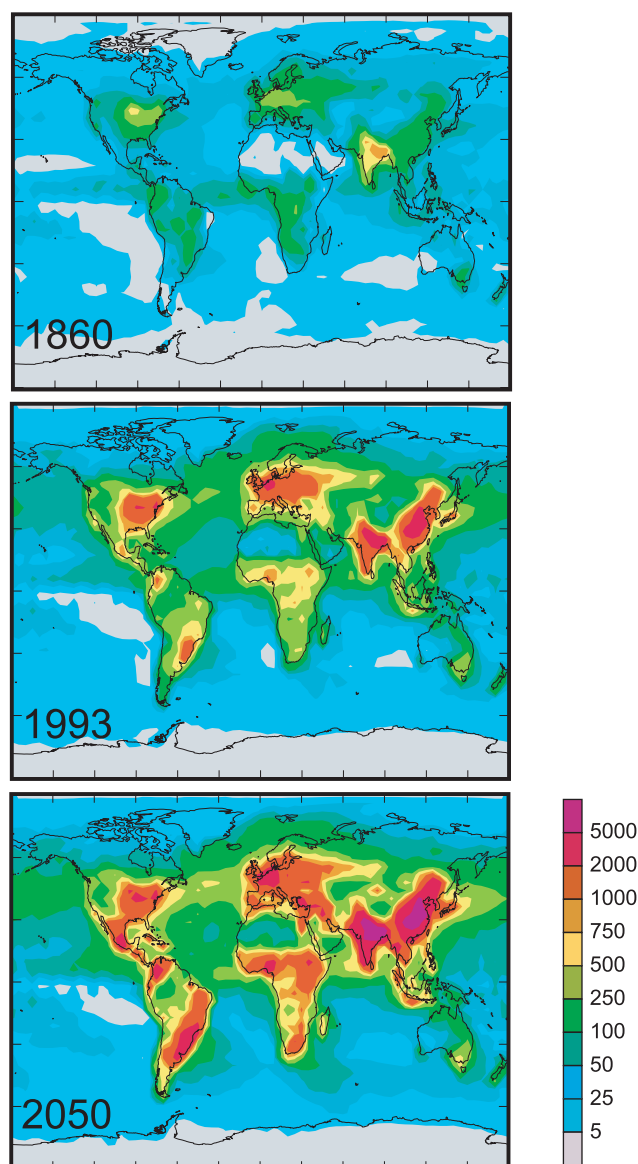
Both short- and long-lived oxides of nitrogen are important in the land-atmosphere system. Tropospheric ozone is formed through the interaction of VOC and  $\text{NO}_x$  in the

presence of sunlight, and the  $\text{NO}_x$  to VOC ratio is particularly important in determining whether ozone is produced or destroyed in the troposphere (see Sub-focus 2.2). Organic and inorganic  $\text{NO}_x$  oxidation products (such as peroxyacetyl nitrate, alkyl nitrates and nitric acid) are also important as they impact atmospheric photochemistry in areas significantly downwind of anthropogenic sources, and their deposition or uptake affects terrestrial and aquatic ecosystems (Figure 7).  $\text{N}_2\text{O}$  is an important greenhouse gas with a lifetime of over 100 years, and an atmospheric growth rate of  $0.8 \text{ nmol mol}^{-1} \text{ yr}^{-1}$ .

Globally, anthropogenic and biogenic emissions of  $\text{NO}_x$  are comparable:  $15\text{--}29 \text{ Tg N yr}^{-1}$  and  $6\text{--}18 \text{ Tg N yr}^{-1}$  respectively (Delmas et al., 1997). Soils are the major source of biogenic  $\text{NO}_x$  emissions (Potter et al., 1996; Delmas et al., 1997) as well as significant  $\text{N}_2\text{O}$  emissions due to leakage during nitrification and denitrification. The  $\text{NO}_x$  and  $\text{N}_2\text{O}$  fluxes are therefore controlled by soil parameters such as temperature, moisture and nitrogen content (Saad and Conrad, 1993; Davidson, 1993; Conrad, 1997), and hence fluxes vary temporally and spatially. For example, similar to what has been observed for  $\text{CO}_2$  (Arneeth et al., 1998; Kelliher et al., 1999), the first rains after the dry season produce a pulse of  $\text{NO}$ , leading to a ten-fold increase in emissions (Davidson 1992; Meixner et al. 1997, 1999; Scholes et al., 1997).  $\text{N}_2\text{O}$  fluxes also increase following wetting of dry soil, but to a lesser degree.  $\text{NO}_x$  emissions to the atmosphere are controlled by a complex interplay of production and consumption processes, and the relative magnitudes of these processes differ under varying environmental conditions (Galbally, 1989; Saad and Conrad, 1993; Conrad, 1996, 1997). The environmental factors vary spatially and temporally, and it is difficult to extrapolate from local soil measurements to regional or global scales. Both  $\text{NO}_x$  and  $\text{N}_2\text{O}$  are also produced from biomass burning. Recently, UV-induced  $\text{NO}_x$  emissions have been observed from boreal forest (Hari et al., 2003), providing evidence for a new feedback mechanism between terrestrial vegetation activity and atmospheric chemistry, since  $\text{NO}_x$  contributes to the formation of ozone, OH and aerosol particles that subsequently affect the radiative properties and thus  $\text{NO}_x$  emissions. This result warrants further investigation so as to quantify the contribution of the boreal biome to the natural atmospheric self-cleansing processes (see Sub-focus 2.2).

Due to the reactivity of nitrogen oxides, the actual surface  $\text{NO}_x$  exchange also depends on interactions between soil emissions, turbulence, chemistry and dry deposition within the canopy. Because of these interactions, a surface dry

**Figure 7.** Modelled spatial patterns of total inorganic nitrogen deposition ( $\text{mg m}^{-2} \text{yr}^{-1}$ ) in 1860 (top), early 1990s (middle) and 2050 (bottom). From Galloway et al. (2004) reproduced with permission from Springer.



deposition flux can be observed despite the presence of a soil emission flux (e.g. Ganzeveld et al., 2002).  $\text{NO}$ ,  $\text{NO}_2$ , and their photochemical reaction products, can be taken up by plants or deposited on their leaves (Jacob and Bakwin, 1991; Sparks et al., 2001), thereby removing  $\text{NO}_x$  within the canopy before it escapes to the troposphere (see Sub-focus 2.2). In models, this is referred to as the “canopy reduction factor”. Canopy reduction factors vary between landscapes due to differences in vegetation type and extent; more studies on canopy reduction factors are essential. More research should also be undertaken on the speciation of deposited nitrogen, the relative contributions of wet and dry deposition, the role of organic nitrogen compounds in ecosystem

processes (including the role of the microbial community on leaf surfaces in the mineralisation of deposited organic nitrogen), the role of the canopy in the uptake of gaseous and mineralised nitrogen, and the extent to which photolysis of deposited nitrogen leads to the remobilisation and re-emission of gaseous nitrogen.

Land use changes could alter the amount of nitrogen reaching the troposphere, as there are numerous land management practices (biomass burning, cropping, tilling and fertiliser application) that alter nitrogen fluxes. Additionally, ecosystem stresses caused by changing atmospheric composition and climate, could alter foliar uptake of gaseous and deposited reactive nitrogen species.

A challenge for the future is to improve models of the changes in  $\text{N}_2\text{O}$  and  $\text{NO}_x$  fluxes with land use and land cover change. Attempts at modelling these fluxes at the regional or global scale have been made (Potter et al., 1996; Kirkman et al., 2001; Holland and Larmarque, 1997), but these assessments remain uncertain.

## Issues of Scale

Once trace gases are produced and released, their tropospheric lifetimes vary by many orders of magnitude. The lifetime of  $\text{CO}_2$  is 5–200 years (the range due to the uptake rates of different removal processes), and the lifetime of methane more than eight years in the modern atmosphere. In contrast, reactive VOC may be transformed in rapid reactions from one compound to another within minutes or less; VOC tropospheric lifetimes depend not only on the compound itself, but also on the oxidant it reacts with. For example, the calculated tropospheric lifetime of  $\alpha$ -pinene is of the order of minutes to hours, depending on the reactant (hydroxyl radical, nitrate radical or ozone) and reactant concentration; methanol can react within days or last for several years (Fuentes et al., 2000; Atkinson, 2000). Reactive VOC may also act as aerosol precursors, or precursors of less reactive compounds, and are therefore transported within the atmosphere and deposited elsewhere. For some plant species, the lag that occurs between monoterpene production and emission due to storage needs to be taken into account. For rapidly reacting compounds (such as sesquiterpenes), emission measurements and inventories will diverge significantly from measured atmospheric concentrations. Diurnal, seasonal and annual cycles of emissions, transformation and removal have to be considered in nearly all cases, as they reflect changes in physiological activity and in the physico-chemical environment. These cycles are illustrated by variations due to seasonal dry-wet environments and dry versus

wet years, because soil water supply to the surface affects all relevant processes. Variations over decades and centuries reflect changes in surface cover and vegetation activity. These modify the emission/removal capacity of the surface, and may reflect the aging of ecosystems or altered surface cover due to changes in the climate system or extreme events.

## Research Topics

Land surfaces emit and absorb a variety of compounds of significance for the radiative forcing potential of the atmosphere, for cloud microphysical processes and for tropospheric chemistry. The physical and chemical aspects of the climate system are directly or indirectly mediated by soil moisture patterns through the surface energy balance, trace gas emissions, fire frequency/severity, boundary-layer development and convective activity. Therefore, the investigations of biologically and chemically active compound cycling discussed in herein, must be closely linked to the study of the terrestrial water cycle and the role of the biosphere in the self-cleansing of the atmosphere (Foci 2–4).

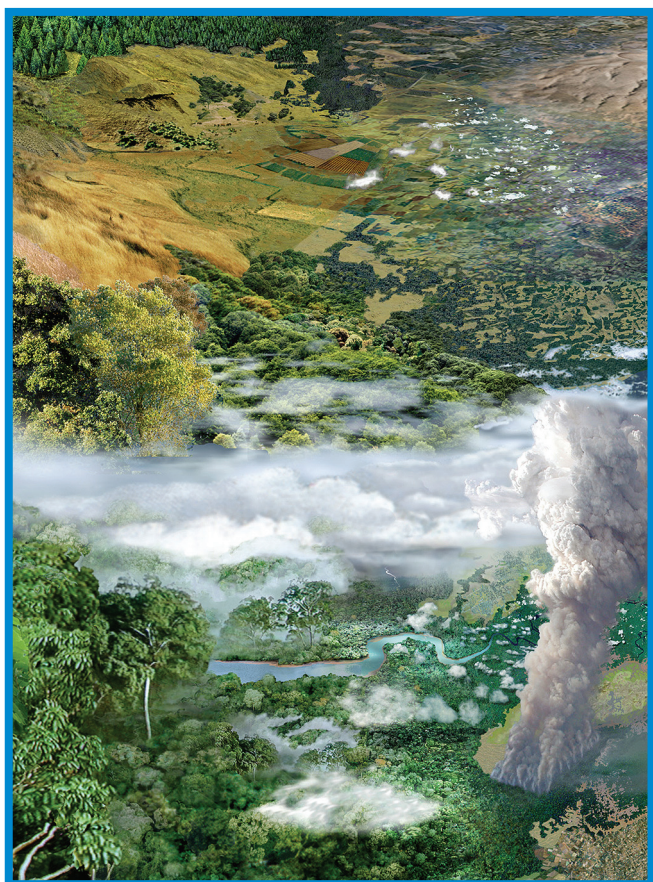
The following questions illustrate some of the most important aspects in this regard:

1. **What controls emission and deposition of biologically and chemically active trace gases in the land-atmosphere system at regional to global scales over diurnal, seasonal, inter-annual, decadal and centennial time scales? What are the links between the various control processes? For example:**
  - How is the land-atmosphere exchange of CO<sub>2</sub> linked to the exchange of other compounds such as nitrogen oxides, methane and VOC? How large is the flux of reactive carbon in various temporal and spatial perspectives?
  - What are the canopy processes, and how do compounds with different lifetimes contribute to locally measured concentrations?
  - What are the processes that govern, for example, the exchange of reactive nitrogen and carbon compounds between the soil, canopy and boundary layer?
2. **How do the controlling processes affect the net land-atmosphere exchange in and above ecosystems/catchments/landscapes, and how have they done so in the past?**
  - Can a closed budget for the nitrogen cycle of key terrestrial ecosystems be obtained? How are these fluxes changed by human activities?
  - Is there a self-regulation mechanism that determines the concentration of VOC (and hence aerosols and CCN, see Sub-focus 2.2) in pristine environments?
  - How can the various temporal and spatial scales related to VOC emissions be addressed, particularly with respect to net biome productivity, and medium to long-range transport, transformation and deposition?
3. **Which of the processes are critical, and what is the level of complexity required in models to investigate net exchange at various spatial and temporal scales?**
  - Is it possible to quantify trace gas and aerosol production/destruction and the feedbacks to tropospheric chemistry and climate associated with environmental threshold conditions for the survival of given vegetation types (e.g. breakdown of wetlands or shrub encroachment in grasslands)? Do these thresholds imply abrupt or transient changes in the cycles of key trace gases and associated feedbacks?
  - What causes the inter-annual variation in atmospheric methane increases?
  - What are the feedbacks to the atmospheric part of the hydrological cycle, and in turn, to aerosol production and nitrogen emissions?
  - Is it possible to incorporate all the controlling factors of nitrogen oxide and VOC emissions into models to accurately predict fluxes at regional and global scales?
4. **What effect will change in land use and land cover have on interactions and feedbacks of key trace gas fluxes and on net ecosystem exchange?**

## Focus 2: Feedbacks Between Land Biota, Aerosols and Atmospheric Composition in the Climate System

Anthropogenic transformation of the Earth's surface by the combined impacts of land use change, deforestation, urbanisation and industrialisation is progressing most rapidly in tropical and subtropical regions. These transformations radically change the interactions between the land surface and the atmosphere, and the resulting perturbations affect the entire Earth System. The most fundamental and far-reaching consequences of change in the tropics are likely to come from anthropogenic impacts on two processes: (i) the interaction of biogenic and anthropogenic aerosols with the climate system, including the water cycle (Sub-focus 2.1); and (ii) the coupling of biological, hydrological and meteorological processes with the atmospheric reactions that control the self-cleansing mechanism of the atmosphere (Sub-focus 2.2).

**Figure 8.** Focus 2 research topics encompass the tropics and effects of forest fires.



While at first these may seem separate issues, a closer look reveals that they are tightly linked both geographically and biophysically. In both cases, the tropics are especially important because they are the basic heat engine of the atmospheric circulation system, and a large amount of the heat transfer is through evaporation at the surface, and recondensation of the water vapour in clouds. The amount, rate, location and character of precipitation are of central importance for the way tropical ecosystems exchange trace gases, water and energy with the atmosphere. Changes in precipitation may even lead to the instability of tropical forest ecosystems over large regions due to a cascade of events (Nepstad et al., 1999). Atmospheric self-cleansing is also predominantly occurring in the tropical troposphere, because the hydroxyl radical that initiates the removal of most trace gases is most abundant here (Crutzen, 1995). The hydroxyl radical is formed by chemical processes that involve trace gases from the terrestrial biosphere and from anthropogenic emissions.

Human perturbation by land use change, urbanisation and industrialisation is the dominant driver of change for both aerosol-climate interactions and atmospheric self-cleansing. The emissions of trace gases and aerosols are changing, as tropical forests are being replaced by grazing lands, croplands, roads and cities. Fire – used for the original clearing of the land, for the maintenance of the human-controlled ecosystems and as a domestic energy source – plays a key role as a source of reactive trace gases and climatically active aerosols. Finally, there are strong interactions between aerosol and trace gas chemical processing, and the perturbation of atmospheric transport mechanisms due to aerosol-driven modifications of cloud properties.

iLEAPS research in this area will be closely coordinated with IGAC. IGAC will focus on the emissions from anthropogenic (especially urban) sources, on vertical and lateral atmospheric transport, and on chemical and physical processes in the atmosphere. iLEAPS will focus on exchange processes between the terrestrial biota and

the atmosphere, and on the feedbacks between changing atmospheric properties, the water cycle and ecosystem behaviour.

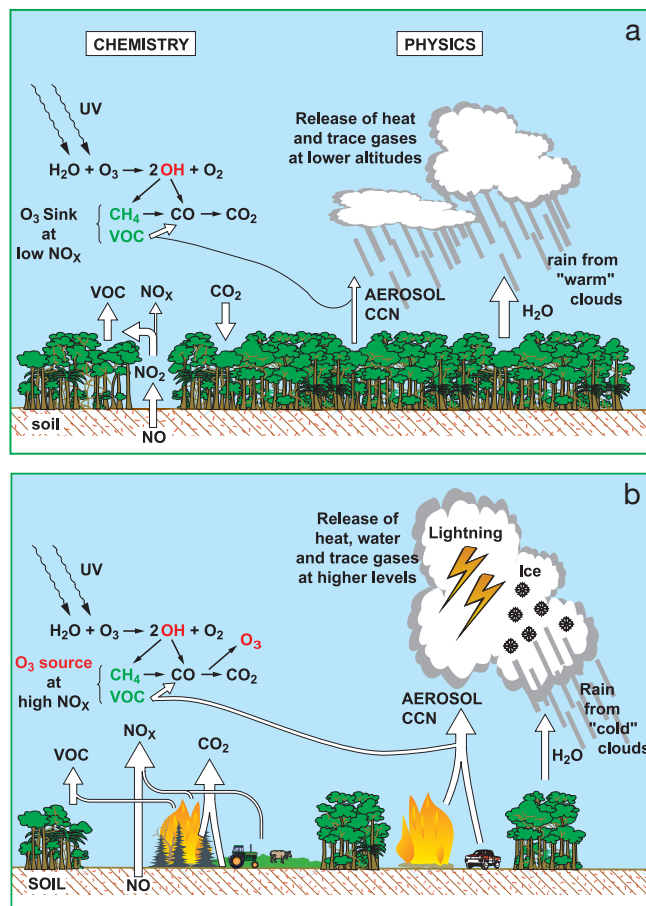
## Sub-focus 2.1: Biosphere-Aerosol-Cloud Interactions

The direct effects of aerosols (the interaction of sunlight with the aerosol particles themselves) and their indirect radiative effects (the effects resulting from the modification of microphysical cloud properties) have received increasing attention in recent years. The inclusion of the direct effect in Global Circulation Models has already led to substantial improvements in the ability of these models to reproduce the observed global annual mean temperature increase over the last 150 years (Mitchell et al., 2001; Stott and Kettleborough, 2002). Significant progress has been made in determining the direct radiative forcing of anthropogenic aerosol particles and their effects on regional and global climate.

However, the indirect effects of aerosols remain a major uncertainty in regional and global climate studies. The increase in cloud albedo caused by increased CCN concentrations from anthropogenic sources is now reasonably well understood conceptually, but still difficult to quantify. The effects of aerosol particles on precipitation processes are even more uncertain. The large range in aerosol size distribution that is generally observed in aerosol mixtures originating from natural processes, will produce a broad cloud droplet size distribution that promotes precipitation development. Enhanced aerosol particle concentration due to anthropogenic emissions (including biomass burning) will decrease the droplet radii and narrow the range of the droplet size distribution, consequently modifying or inhibiting precipitation processes (Andreae et al., 2004). If the aerosols are strongly absorbing (for example, black carbon) they may significantly heat the atmosphere and reduce the heating of the land surface, leading to reduced formation and the accelerated evaporation of clouds (Hansen et al., 1997; Koren et al., 2004).

By providing most of the CCN to the “natural” atmosphere, the biosphere has a strong influence on cloud radiative and microphysical properties, and thereby on both climate and the hydrological cycle (Andreae et al., 2002). Organic aerosol particles emitted directly from natural sources are effective CCN (Bauer et al., 2003), and in remote continental regions (such as the central Amazon Basin) organic aerosols of primary biogenic

**Figure 9.** The Great Tropical Reactor – biosphere-atmosphere interactions for trace gases, aerosols and clouds over the tropics under (a) natural conditions, and (b) after deforestation and development. Courtesy of Meinrat O. Andreae (Max Planck Institute for Chemistry).



origin (for example, vegetation detritus, microbes, spores) may even dominate the CCN population (Andreae et al., 2002). Indirect CCN formation from biogenic precursors has recently received increased attention, and the formation of small aerosol particles and their subsequent growth to CCN sizes have been observed at remote continental sites. The formation of initial molecule clusters is attributed to inorganic vapours and subsequent growth to condensable organic compounds originating from the biosphere (Kulmala et al., 2001; Graham et al., 2003; Guyon et al., 2004). This aerosol production mechanism is particularly important in boreal ecosystems, whereas in the tropics, production of new organic aerosols from the gas phase seems to be rare, as the condensation of organic vapours predominantly leads to the growth of pre-existing particles. The direct or indirect formation of CCN by vegetation may control CCN concentrations in pristine

environments, thereby modifying precipitation and changing the duration of cloudiness.

In the tropics, the regulation of CCN concentrations by terrestrial biota has recently been investigated. In a pristine environment, and in the absence of fire, CCN concentrations remain low (similar to concentrations over the oceans), emphasising the impact of human activities (Roberts et al., 2001). Formation of aerosol particles by natural vegetation-induced processes is easily overwhelmed by anthropogenic aerosol production. In the Amazon Basin, anthropogenic aerosols lead to CCN “over-seeding” manifested as a shift from the typical marine-type convection dynamics present during the wet season, to the types of clouds observed above polluted continental areas, with increased importance of ice-phase processes and lightning activity (Andreae et al., 2004). In more perturbed regions (such as Africa and the developed continents of the Northern Hemisphere), the same fundamental transformation of cloud physics already prevail. Due to the central role of the tropical continents as the heat engines of atmospheric circulation, changes in the transfer mechanisms between latent and sensible heat in these regions are of particular concern for climate dynamics. At the same time, the perturbation of cloud physics by increased CCN is expected to reduce the self-cleansing efficiency of the atmosphere by decreasing the scavenging efficiency for aerosols and some trace gases. As a result, significant amounts of pollutants are transported to the middle and upper troposphere.

The main source regions of atmospheric mineral dust particles are also located in the subtropics and tropics, under the subsiding branches of Hadley circulation cells (Tegen, 2003). Dust forms through a highly non-linear action of the wind over dry surfaces. Significant source regions may be highly localised, yet the transport of dust brings mineral aerosol from Asia to North America, and from the Sahara to both North and South America. The deposition of dust provides important and sometimes limiting nutrients to both terrestrial and ocean ecosystems, while at the same time the delivery of nutrients by dry and wet deposition is determined by the vegetation itself (Swap et al., 1992). In addition to wind, the extent of dust mobilisation from the surfaces depends on surface soil size distribution and soil moisture. The optical properties of dust depend on the chemical characteristics of local soil. Deforestation and agricultural management practices can lead to soil drying and soil

disturbance which may enhance mobilisation. The direct effect of anthropogenic dust on climate change is not well known, due to inadequate knowledge of the optical properties of dust from various sources and a lack of data on source strength. Dust may, under some conditions, become associated with water-soluble compounds (such as sulphate and nitrate) and thereby act as CCN (Yin et al., 2002). Dust particles also play an important role as ice nuclei. Carbonaceous particles and dust have an effect on climate by changing cloud physics and precipitation, as well as by modifying the vertical transport of sensible and latent heat and chemical compounds to the upper troposphere. Feedback processes associated with climate change can also change the source strength for mineral aerosols (Tegen et al., 2004).

The effects of aerosol processes on cloud dynamics and their interplay with the hydrological cycle are poorly understood. As noted above, in the tropics the cloud dynamical regime may be changing from one dominated by maritime-type clouds to one which favours the formation of continental-type convection as CCN numbers increase. This may modify local and regional precipitation regimes, and the deposition of nutrient compounds, thus feeding back to ecosystem behaviour. Because of the central role of tropical deep convection in the climate mechanism, perturbation of tropical cloud dynamics is likely to affect global climate, but these effects are not yet well understood (Werth and Avissar, 2002; Nuber et al., 2003). Increased CCN may also enhance lightning frequency and support the transport of both aerosols and trace gases to the upper troposphere. The effect of these changes on the wet removal of aerosols and trace gases is still poorly understood and needs to be quantified.

The response of vegetation to the quality of the impinging light (including the direct-diffuse radiation ratio, the light-dark interval and spectral properties) requires study. The timing of the different events within the diurnal cycle is crucial for correct predictions of system behaviour. Current work indicates that carbon uptake is enhanced on partly cloudy days; the most popular explanation being that diffuse light illuminates the canopy more uniformly, while reduction of radiation intensity by clouds limits vapour pressure deficit. However, the relative importance of radiation characteristics versus vapour pressure deficit (or indeed, that of other factors) is not well known.

## Sub-focus 2.2: Surface-atmosphere Exchanges and the Self-cleansing Mechanism of the Atmosphere

Vast amounts of reactive chemical compounds are continually emitted into the atmosphere, the largest share being methane and other hydrocarbons from biogenic sources, with a combined flux of more than  $1 \text{ Pg yr}^{-1}$  (Prather et al., 2001; Sub-focus 1.3). These compounds are constantly being removed from the atmosphere by oxidation into water-soluble compounds (e.g. polar organics or  $\text{CO}_2$ ), and the subsequent uptake by liquid water, snow or ice and removal by precipitation and surface dry deposition. The most important initial step in the chemical removal mechanisms is the reaction with the hydroxyl radical – the atmospheric “detergent” (Crutzen, 1995). The primary hydroxyl radical source is the photo-dissociation of ozone and subsequent reaction of oxygen atoms with water. Because of the high levels of UV radiation and water vapour in the tropics, hydroxyl radical concentrations are highest in the tropics, and most of the oxidation of methane, CO and other trace gases occurs in the “Great Tropical Reactor” – the region of high hydroxyl radical concentrations in the tropical troposphere (Figure 9). The tropical region thus plays a key role not only in regulating physical climate, but also in maintaining the chemical composition of the atmosphere. Because the reaction with hydroxyl radicals is also the dominant sink for methane, changing hydroxyl radical concentrations also affect the lifetime and thus the atmospheric concentration of this important greenhouse gas. In spite of the dominant role that the tropical atmosphere is believed to play in the chemical oxidant cycle and the self-cleansing of the troposphere, observations are too scarce to validate model predictions.

The relative amounts of hydrocarbons and  $\text{NO}_x$  play crucial roles in the photochemical oxidation of hydrocarbons. At very low levels of  $\text{NO}_x$ , hydrocarbon oxidation removes ozone and consumes hydroxyl radicals, while at higher  $\text{NO}_x$  levels more ozone and reactive radicals are produced. Under pristine conditions, the biosphere is the dominant source of both hydrocarbons and  $\text{NO}_x$  in the lower and mid-troposphere, and hence the  $\text{NO}_x$  to VOC ratio is such that  $\text{NO}_x$  concentrations are low and consequently the troposphere is in a low-ozone state (see Sub-focus 1.4).

In the rainforest regions of the tropics this is achieved by a tight interaction of biological, chemical and physical

processes, which allow efficient turnover of nitrogen but prevent it from escaping easily into the atmosphere.  $\text{NO}$  is produced during the nitrogen turnover that accompanies the breakdown of organic matter in soils, and part of this gas can escape into the air layers above the soil. Here, it can react with ozone to form  $\text{NO}_2$ , which is efficiently deposited on plant surfaces in the forest canopy and made available for plant growth. Only a modest fraction of the  $\text{NO}$  emitted from the soil can therefore escape into the atmosphere above the forest to contribute to ozone formation.

Deforestation and subsequent replacement of the tree canopy by grassy vegetation break this tight  $\text{NO}_x$  recycling system. Because of the short distance from the soil to the top of a grass canopy, there is much less chance for oxidation of  $\text{NO}$  to  $\text{NO}_2$ , and for the deposition of  $\text{NO}_2$  on leaf surfaces. As well as more  $\text{NO}_x$  escaping, the vegetation change reduces biogenic VOC emissions and alters their composition. Biomass burning for deforestation and land management supplies additional  $\text{NO}_x$  and hydrocarbons to the regional atmosphere. The consequence is a transition from the low-ozone state of the Great Tropical Reactor to a high-ozone photochemical smog (Keller et al., 1991).

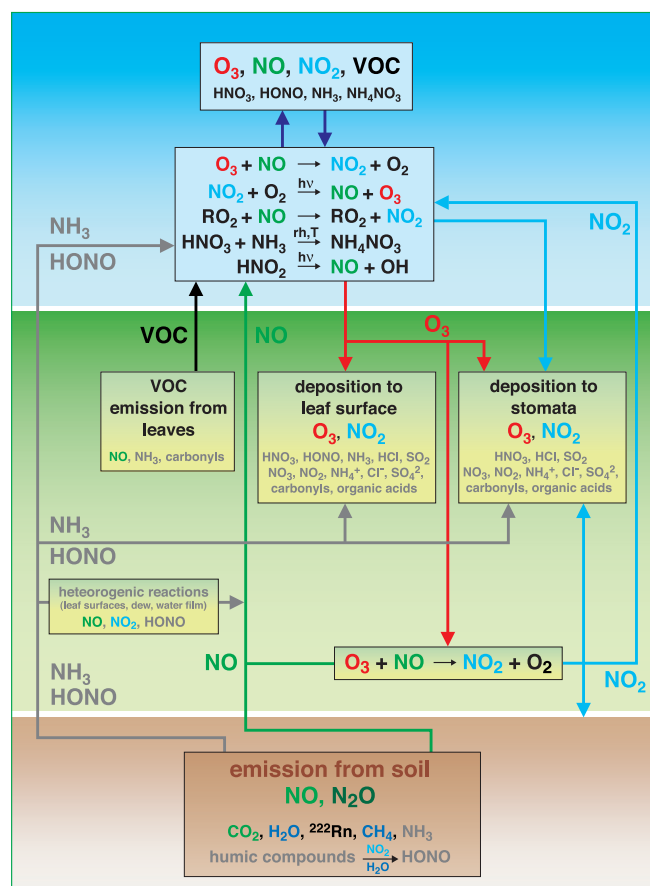
A change in gas-phase chemistry also has consequences for aerosol production. Under natural conditions the aerosol yield from the photo-oxidation of terpenes is quite low, because the prevailing reaction chains lead to relatively volatile compounds that do not readily condense into particles. However, at higher ozone concentrations more low-volatility compounds are formed, which can form aerosol particles (Kanakidou et al., 2000).

Because of the highly non-linear character of the chemical processes in the atmosphere, mixing and transport play a key role in regulating chemical transformations. The water cycle strongly affects the dynamics of physical transport – especially in the humid tropics, largely by the regulation of soil water content. Land use change and the resulting perturbation of the hydrological cycle are thus expected to perturb the oxidant cycle and atmospheric self-cleansing over tropical regions.

Land use and land cover changes, and resulting changes in micro-meteorology and the hydrological cycle, are also expected to change the removal of trace gases and aerosols by wet and dry deposition. Changes in biomass and surface roughness typically alter dry deposition of atmospheric constituents due to changes in turbulent



**Figure 10.** Processes and interactions in the soil–canopy–surface-layer. Courtesy of Franz X. Meixner (Max Planck Institute for Chemistry).



exchanges and surface uptake efficiency (see also Sub-focus 4.4). Assessment of the impact of changes in wet deposition due to changes in the hydrological cycle is complicated, as this process includes not only dissolution, aqueous-phase chemical transformations and rain-out, but also feedbacks of the chemical composition to the cloud and rain droplet spectrum and consequently to cloud and precipitation formation and convective transport. The complex role of multi-phase chemistry also hampers the quantification of some of the impacts of land cover and land use changes on dry deposition due to the changes in surface wetness that follow rainfall and dewfall interception. A challenging research issue is how changes in the oxidising capacity and wet and dry deposition can impact the functioning of the plant-soil system by affecting biogeochemistry; for example, soil acidification and eutrophication and the direct exposure of vegetation to enhanced oxidant concentrations.

The overall objective of Sub-focus 2.2 is to determine how changes in terrestrial ecosystems directly and indi-

rectly affect the oxidising capacity of the atmosphere and surface removal, and how this feeds back to ecosystems and biogenic emissions.

## Research Topics

The research topics for Focus 2 are given by Sub-focus below; the research topics for Sub-focus 2.1 can be stated as four major (and several subsidiary) questions as follows:

1. What are the processes that regulate the rate of near-surface formation and growth of various aerosols types? What controls aerosol particle mass and number concentration, and CCN concentration?
  - What regulates the abundance and the chemical, optical and microphysical properties of biogenic aerosols (primary and secondary, carbonaceous and inorganic), and how are they affected by global change?
  - Which biogenic VOC are important for the production of aerosols and by which mechanisms are secondary organic aerosols formed? How does the production of these aerosols depend on trace gas chemistry?
  - What are the current and prior magnitudes of the global dust loading? What is the direct radiative effect associated with dust? What is the change of dust source strength with climate change and variability?
2. What is the role of terrestrially generated aerosols (biogenic aerosols, smoke and dust) in changing the properties and behaviour of clouds?
  - How do these aerosols affect the dynamical driving forces in clouds and the vertical transport of sensible and latent heat and chemical compounds to the upper troposphere?
  - What is the influence of biogenic and pyrogenic aerosols on ice formation, and which of these particles are involved in ice-phase physics and microphysics?
  - To what extent are the spatial variations in water and aerosols coupled or correlated?
  - What is the importance of aqueous-phase chemical transformations of natural and

anthropogenic carbonaceous aerosols for changes in the optical properties of particles and the solubility of compounds?

3. What are the local, regional and global effects of the changes in aerosol population and distribution from anthropogenic emissions, including biomass burning?

- What are the effects of aerosols on the radiation field and how does this affect biological activity, including primary production? What is the effect of diffuse radiation on land-atmosphere exchange processes?
- What are the feedbacks to the atmospheric part of the hydrological cycle, and in turn, to aerosol production and nutrient cycling?

4. How well are the above biospheric-atmospheric interactions represented in global climate models, and how can these representations be improved?

- What are the effects of ecosystem change on the fluxes of methane, VOC and  $\text{NO}_x$ ?
- How do changing water vapour fluxes affect boundary-layer chemistry?

4. Do ozone control strategies need to consider the role of the biosphere and anticipated biospheric changes? Can long-term changes in biospheric fluxes significantly affect air quality?

The research topics for Sub-focus 2.2 can also be stated as four major (and several subsidiary) questions as follows:

1. What is the quantitative role of atmosphere-biosphere exchange processes for the atmospheric oxidising capacity as a function of location and time?

- What is the role of biogenic VOC emissions and the transport and chemistry of partly oxidised hydrocarbons in the oxidising capacity of the regional and global atmosphere?
- What are the responses of terrestrial ecosystems to changes in the oxidising capacity of the atmosphere? Are productivity, plant species composition, biogenic emissions and dry deposition affected?

2. What is the role of emissions from vegetation fires in perturbing the self-cleansing capacity and thus the composition of the atmosphere?

3. How do the direct and indirect effects of changes in terrestrial ecosystems influence atmospheric oxidising capacity?

## Focus 3: Feedbacks and Teleconnections in the Land Surface-Vegetation-Water- Atmosphere System

Land surface–atmosphere interactions occur through two intricately linked pathways: the biophysical and the biogeochemical. Momentum, radiative energy and sensible heat represent biophysical transfers, while carbon dioxide and many other trace gases are associated with biogeochemical activity at the plant or soil surface. Latent heat – as evaporated or transpired water vapour – and aerosols are exchanged by both biophysical and biogeochemical processes. In both pathways non-linear feedbacks often occur that can be either positive (enhancing) or negative (damping). Feedbacks in both pathways directly affect the near-surface energy, momentum and moisture (latent heat) fluxes (for example, Nair et al., 2003; Adegoke et al., 2003).

**Figure 11.** Focus 3 research topics include the northern latitudes and the cryosphere.



### Sub-focus 3.1: Lateral Hydrology-Biogeochemistry Connections

One objective of iLEAPS is to understand the dynamics of land-atmosphere interactions, how physical, chemical and biological processes transport and transform momentum, energy and material between the land and the atmosphere. An explicit focus is to understand the magnitude of, and controls on, the exchange of reactive compounds, where one of the key boundary conditions is established by the connections between the hydrological and biogeochemical cycles. These connections can functionally be considered along a gradient through river catchments: from essentially aerobic soil conditions with sparse water, through saturated zones at the interface between land and flowing water, to flowing water itself. Catchments integrate hydrological and biogeochemical cycles from small subcatchment- to regional- and then continental basin-scale.

The outgassing of CO<sub>2</sub> and methane from freshwaters to the atmosphere is one example of the connections between the hydrological cycle and biogeochemical processes (see Focus 1). The partial pressure of CO<sub>2</sub> dissolved in river water represents a very simplified expression of the coupling of the water and carbon cycles between terrestrial and fluvial environments. The concentrations of CO<sub>2</sub> in river water, almost always much greater than in the atmosphere, depend on a sequence of complex biological and weathering processes and interactions, reflecting both internal carbon dynamics and external biogeochemical processes in upstream terrestrial ecosystems. The downstream expression of this coupling of internal dynamics and external processes is the amount of organic matter and dissolved inorganic carbon transported into and through a river system, augmented by in-water or riparian primary production and respiration. Estimates of outgassing in the tropics and in more temperate systems exceed 1 Pg yr<sup>-1</sup> (Richey et al., 2002).

### Sub-focus 3.2: Regional Issues

High-latitude ecosystems have received particular attention in recent years because of their suspected climate sensitivity, as highlighted in the conclusions of the Arctic Climate Impact Assessment (ACIA, 2005). Recognising the biophysical feedbacks of the cryosphere to the climate system, WCRP established the Climate and Cryosphere (CliC) project in 2001 to improve the understanding of the cryosphere (including snow cover, sea, lake, and river ice, glaciers, ice sheets, ice caps and ice shelves) and its interactions with the global climate system. An important example of a biophysical feedback is the surface albedo feedback, which occurs because vegetation is generally darker and absorbs more radiation than bare soil or snow. In the boreal zone this leads to the so-called taiga-tundra feedback, where snow-covered forest (taiga) has a much lower albedo than snow-covered tundra, thus absorbing more radiation, generating a warmer surface climate and promoting its own growth (Bonan et al., 1995). However, the biogeochemical role of the northern latitudes and the cryosphere has not been widely recognised. High-latitude systems are characterised by high carbon densities – approximately 15% of the terrestrial carbon is stored in permafrost areas (Prentice et al., 2001). This pool may be affected by changes in temperature or precipitation, and by the associated changes of thaw depth, with potentially strong feedbacks to atmospheric methane and CO<sub>2</sub> concentrations and thus to climate. There is debate as to whether warming of high latitudes will cause a decline in modern northern carbon sinks, or result in a sink-source transition. It has also been suggested however, that increasing temperatures may promote soil nutrient release, thus increasing productivity and carbon uptake.

Recent studies have provided evidence for significant non-CO<sub>2</sub> biogeochemical exchanges among boreal vegetation, ice/snow and the atmosphere. For instance, new particle formation has been detected above boreal forest ecosystems (Kulmala et al., 2001) and has been the focus of intensive research (see Focus 1 and 2). Nucleation may require the release of highly reactive VOC in these remote areas (Spanke et al., 2001), and mechanisms for nucleation events in continental areas have recently been suggested (O'Dowd et al., 2002). Ozone depletion has been observed in the polar atmospheric boundary layer in the Arctic, sub-Arctic and Antarctic (e.g. Wessel et al., 1998) and field and laboratory experiments have revealed snow photochemistry (e.g. Honrath et al., 1999; Cotter et al., 2003). In response to these findings, an Air-Ice Chemistry Interactions (AICI)

task has been endorsed by IGAC and SOLAS (SOLAS, 2004), which will also be of relevance to iLEAPS.

Regional issues of global consequence are studied in the Integrated Regional Studies of ESSP. The regions and issues selected are usually relevant to some of the “switch” or “choke” points in the Earth System, where local and regional changes may have strong influences on the Earth System (Figure 3). BAHC played an essential role in the first Integrated Regional Study – the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). Similarly, iLEAPS will cooperate with other international projects in the Monsoon Asia Integrated Regional Study.

### Sub-focus 3.3: Global Issues

Natural oscillations of the climate system in a given region can have global consequences through teleconnections, that is, influence on other processes across thousands of kilometres. El Niño-Southern Oscillation (ENSO) events are prime examples of such global consequences (Wu and Newell, 1998). In warm ENSO events, thunderstorms develop over the central and eastern tropical Pacific Ocean as a result of above average sea surface temperatures, while during average years, thunderstorm activity is low in the region. The spatial differences in heating of the atmosphere has global scale climate effects. On a seasonal and regional scale, changes in the initial soil moisture regime at the beginning of a growing season may strongly affect climate for the rest of the year (Pielke et al., 1999). Wet initial stages may increase mean evaporation (and decrease surface temperature) in some regions. The effects of initial soil moisture conditions, however, may not always be only local. For example, snow cover in western Eurasia correlated inversely with the subsequent summer monsoon strength in India (Bamzai and Shukla, 1999).

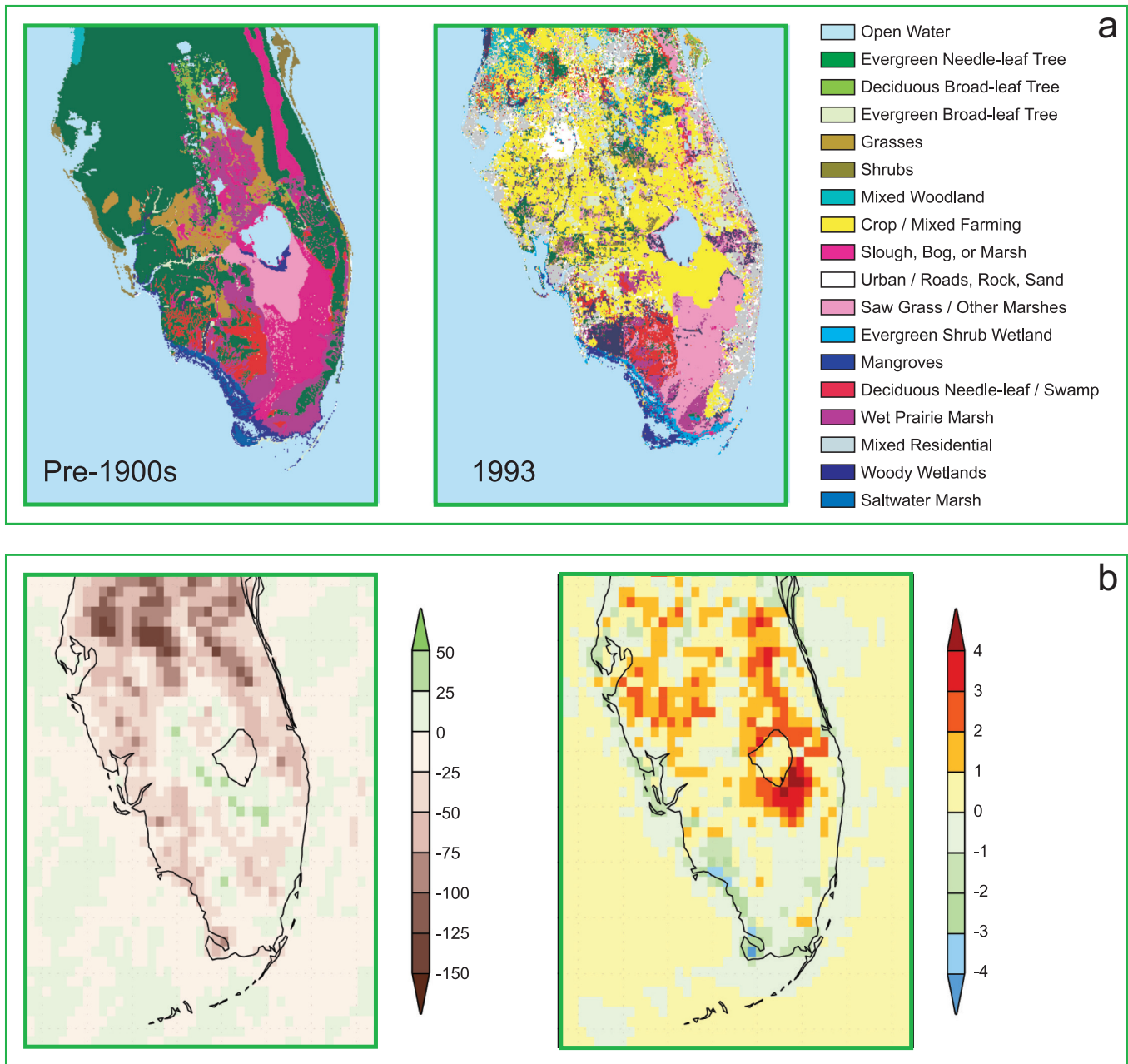
Riehl and Malkus (1957) have shown that the reason for the major role of tropical thunderstorms in the climate system is that they are able to transport vast quantities of heat, moisture and kinetic energy across large distances. Since most thunderstorms occur over tropical and continental locations, land cover changes in these regions may have a global impact equivalent to or even more pronounced than that of ENSO. Tropical forest areas have been diminished considerably since 1980 (DeFries et al., 2002), and in the future, further human-induced reduction of tropical forest cover is likely. The trend and inter-annual variability of global scale fractional vegetation cover in recent decades has been estimated by Zeng et al., (2003). Surface cover and cover change resulting from

human interference or from ‘natural’ vegetation dynamics have a large effect because of long persistence, large magnitude and large spatial coherence (Pielke, 2002).

The spatial redistribution of heat, moisture and energy due to landscape changes causes major alterations in the local, regional and global climate system, and not only in the tropics (Chase et al., 2001; Pitman et al., 1999; Zhao et al., 2001; Werth and Avissar, 2002; Zhao and Pitman, 2002; Avissar and Werth, 2005). Based on results from

a coupled atmospheric–land surface model, the effect of increased levels of carbon dioxide on biogeochemistry is also important in climate change. For example, Eastman et al. (2001) have shown that the increase in above-ground biomass of short and tall grasses (due to higher CO<sub>2</sub> levels) affected temperatures and precipitation during the growing season in the central United States. According to Narisma and Pitman (2003) such a biogeochemical feedback can cancel out the effect of land use change on temperature in Australia. Landscape change

**Figure 12. Southern Florida, United States:** (a) United States Geological Survey land cover data for pre-1900s natural land cover (top left) and 1993 land use (top right); (b) simulated accumulated convective rainfall (mm) (bottom left) and simulated average daily maximum shelter-level temperature (°C) (bottom right) for July–August 1989 both expressed as the difference between pre-1900s land cover and 1993 land use conditions. From Marshall et al. (2004) with permission from the American Meteorological Society.



may confound attempts to reconstruct a global surface temperature record, as local and regional influences on temperature have not been fully investigated (Hanamean et al., 2003; Pielke et al., 2002). At the regional scale, Marshall et al., (2003, 2004) have shown how landscape changes in Florida appeared to affect both summer and winter climate. In model simulations, July–August rainfall averaged over the southern portion of Florida was reduced by over 10%, while daytime maximum temperatures increased on the order of 1 °C (Figure 12). The duration and intensity of freezes were greater in crop areas as a result of wetland draining.

Recent studies have proposed the existence of multiple equilibria in the unperturbed land-atmosphere system, at least in some regions. For example, Wang and Eltahir (2000) illustrated how the coupling between the atmosphere and ecosystem dynamics in the West African region could produce an arid or a wet state, depending on initial conditions of the coupled system. As discussed by Claussen (2003), various models have predicted multiple climate equilibria in northwest Africa, but the stability of the vegetation-atmosphere system may change through time. It is uncertain if multiple equilibria are possible outside the subtropics, at least for present-day and Last Glacial Maximum climates. The overall importance of multiple equilibria lies in their potential to explain abrupt vegetation structure changes (Brovkin et al., 1999; Claussen et al., 2003). The modelling study of Zeng et al. (2004) demonstrated the existence of multiple equilibrium states in Inner Mongolia – grassland and desert – due to the interaction between vegetation and soil with prescribed vegetation. These examples show that the transitions between equilibrium states may be abrupt, climatic surprises (Rial et al., 2004). Furthermore, human-induced landscape disturbance can decrease the stability of regional climate. Sea surface temperature also plays an important role, and so climate system stability is an Earth System-level question involving linkages between land, the atmosphere and oceans. Identification of thresholds in multiple equilibria systems should be a priority research area within ESSP, as the consequences to society could be enormous. Progress in understanding multiple equilibria will require major contributions from iLEAPS.

## Issues of Scale

The tightly coupled nature of the biophysical feedbacks and teleconnections described above can be illustrated by considering the exchange of momentum, energy and CO<sub>2</sub> at a series of scales. At the leaf scale, stomata operate

to optimise the CO<sub>2</sub> assimilated versus the water vapour transpired, modulating the partitioning of radiative energy at the leaf surface into sensible and latent heat minute by minute (Cowan, 1982). This biological control is finely balanced between limits set by the available light and by the capacity of the enzyme Rubisco (Farquhar et al., 1980; Collatz et al., 1991). At the canopy scale, this leaf-scale behaviour is integrated into the canopy structure via genetically programmed patterns of carbon allocation that respond to the environment. This structure, together with evaporation from the underlying soil determines momentum absorption, albedo and evapotranspiration at time scales of days to seasons (Kelliher et al., 1995; Lu et al., 2001; Narisma and Pitman, 2003). As the spatial scale increases from tens to hundreds of kilometres, biological determination of evapotranspiration is offset each day by convective boundary layer (CBL) feedbacks.

The turbulent CBL plays a critical role in the timing and effectiveness of the vertical transport of biogenic materials from the surface to the layer of cloud formation and the free troposphere. Boundary-layer evolution is affected by mechanical factors, such as wind strength, surface topography and roughness, and thermodynamic factors, such as latent and sensible heat inputs from the surface. Soil moisture has a dominant influence on the depth of the boundary layer due to its effect via evapotranspiration on the partitioning of energy into sensible and latent heat. Due to reduction in plant transpiration by closing stomata or shedding leaves, a larger fraction of the radiation incident at the ground is converted to sensible heat. This in turn increases the entrainment of dry air due to the inversion at the top of the CBL, drying the boundary layer and increasing evapotranspiration (Raupach, 2000). At the landscape scale over a period of several days, even these feedbacks are overridden by the major limitations of water availability and energy supply by radiation. This leads to bulk formulae like the Priestley-Taylor equation for which vegetation at the landscape scale is often considered to play an indirect role in energy partitioning and evaporation, by affecting water availability (Raupach et al., 2002).

The importance of CBL evolution can be illustrated through the feedbacks between evapotranspiration, low cloudiness, the surface radiation balance and carbon uptake in forests (Freedman et al., 2001; Gu et al., 2002). Quantification of these requires study of the radiative and turbulent fluxes at the surface, and the ability to accurately simulate cloudiness and the growth of the CBL. How entrainment warms and dries the CBL, determines whether

or not clouds will form on a particular day. The correct link between the visible boundaries of the cloud and the radiation that arrives at the surface needs to be identified. The effects of aerosols and clouds on radiation properties and therefore on vegetation, are discussed in Sub-focus 2.1.

At longer time scales, various other factors affect biophysical feedbacks and teleconnections. Thus the long-term responses of vegetation must be considered, since biomes and landscapes respond to changing patterns of temperature, rainfall, irradiation and wind, and to the direct impacts of human activities. Radiative properties (such as albedo), structural properties (such as aerodynamic roughness) and properties related to surface wetness, are all affected by the amount and type of vegetation cover. The near-surface climate due to the interplay between large-scale weather and local surface fluxes can either stimulate or limit vegetation development.

## Research Topics

Synergies and feedbacks between the land surface, the atmosphere and other components of the climate system, influence the variability of the regional climate and its interactions with the global climate system. Surface soil moisture content, radiation absorption and energy partitioning are key factors in the local, regional and global land surface-vegetation-water-atmosphere system. These conditions change dynamically throughout the day, seasons and the year. But natural as well as human-induced vegetation type, land cover and landscape changes can have additional major effects because of their persistence and large spatial scale, which lead to the following four research questions:

1. How do biophysical and biogeochemical processes interact at the continental to global scale?
  2. What is the relative role of short-term (diurnal to inter-annual) surface-atmosphere exchange versus land use change and vegetation dynamics within the surface-vegetation-water-atmosphere system?
    - What are the effects of changes in radiation properties on land-atmosphere exchange processes?
    - How and where do initial soil moisture patterns interact with seasonal and long-term land-atmosphere exchanges of mass and energy? How will the combined changes in soil moisture and temperature, phenology and vegetation affect the release of carbon from soils?
  3. How have human-induced changes in land cover contributed to climate changes in the past? How will these ongoing changes influence future climate change?
    - Can we evaluate the impact of human-induced changes in land cover on climate variability including abrupt and extreme events, and thresholds that cause movement towards a different equilibrium?
    - What is the appropriate metric for measuring the impact of landscape change on climate?
    - What are the land cover changes that matter at the Earth System-level?
    - To what extent can the growing understanding of the strength of the coupling between the land surface and climate help guide land use decisions?
  4. By what means do perturbations of the surface-atmosphere exchange processes propagate to remote locations?
    - Are aerosols a potential agent of teleconnection?
    - Is the perturbation of mid-latitude systems that is induced by tropical deforestation comparable to the perturbation induced by an ENSO event?
- What will be the effects of projected global warming on the stability of permafrost and the potential release of methane and CO<sub>2</sub>? How do biophysical and biogeochemical processes in the high latitudes and in the cryosphere interact, and what are the feedbacks within the climate system?
  - Is the projected instability of Amazonian forest in response to projected global warming a result of the lack of correct parameterisation of biodiversity in such environments?
  - Where and how do the dynamics of vegetation influence the variability of climate?
  - How do changes in phenology and vegetation distribution affect the atmospheric dust loading?

## Focus 4: Transfer of Material and Energy in the Soil–Canopy–Boundary-layer System: Measurements and Modelling

Foci 1–3 highlight processes that are believed to be critical in the coupling of the biosphere and the atmosphere. These operate at time scales from seconds to decades, and at spatial scales from molecular to global; they involve complex feedbacks, and therefore the study of components in isolation is insufficient. Understanding and predicting complex processes relies on both modelling and measurement. Modelling is needed to pose hypotheses, and measurements are needed for the empirical testing of these hypotheses. The nature of the processes considered in Foci 1–3 places new demands for data and understanding, that can only be met by an explicit integration of modelling and measurement; this is the domain of Focus 4.

**Figure 13.** Focus 4 research topics include integration of modelling with data from towers, aircraft and satellites.



Many examples of the complex feedbacks are described in Foci 1 and 2. For example, the close coupling between the hydrological cycle and the exchange of carbon and nitrogen compounds ( $\text{CO}_2$ , methane,  $\text{NO}_x$  and VOC) with vegetation is discussed in Focus 1, while the role of biogenic aerosol formation in modulating the hydrological cycle via the effect on clouds and precipitation is emphasised in Focus 2.

As a result, four key ecological and hydrological themes have been identified, where improved analyses by measurements and models are necessary: (i) net ecosystem carbon uptake, photosynthesis and respiration; (ii) exchange of energy, momentum, particles and reactive trace gases

between the atmosphere and land ecosystems; (iii) budgets of carbon, water, nitrogen and other nutrient elements (phosphorus, sulphur and potassium); and (iv) interactions between, and inter-annual variability of, all these processes.

Since iLEAPS focuses on land-atmosphere interactions, the primary concern is to measure and model fluxes of the important carbon and nitrogen compounds and aerosols, as well as the fluxes of energy and momentum between the atmosphere and the land surface, particularly through the soil-vegetation layer.

Until about a decade ago, micrometeorological measurements of land-atmosphere exchange were undertaken mainly in campaign mode (Box 1). Sites and measurement periods were chosen to approximate ideal conditions of horizontal homogeneity, airflow stationarity and source-sink distribution, and these assumptions were implicit in model frameworks, upon which data analysis was based. More recently, long-term flux data records from FLUXNET sites (Baldocchi et al., 2001) have revealed unexpected richness in atmospheric transport processes, and have shown that assumptions of ideal flow conditions are inadequate for continuous long-term measurements (Finnigan et al., 2003; Finnigan, 2004). It has become clear that the extra information on spatial and temporal variability in land-atmosphere exchange that is needed to augment local measurements, can be supplied most efficiently through systematic application of data-assimilation methods at scales from the tower patch to the region. Such methods require the development of appropriate predictive models that can be used in inverse mode as a basis for data assimilation, hence closely linking measurement and modelling.

As the scales of interest grow beyond the tower patch, new data sources are required. Boundary-layer budget methods extend the aerodynamic approach (Box 1) from the tower patch to the region, while remote sensing provides data with unprecedented spatial coverage but poor time resolution. Conversion of this kind of infor-



mation into measures of land-air exchange requires new approaches that extend past conventional data assimilation methods. These are referred to as ‘multiple constraint’ methods. In this context, iLEAPS will co-operate closely with GLP (GLP, 2005) and GCP (GCP, 2003).

Foci 1–3 consider a suite of compounds whose exchanges with the biosphere need to be quantified. Fluxes of biogenic aerosols and reactive compounds such as VOC, methane, ozone and  $\text{NO}_x$ , require not only new measurement technology, but also an extension of the forward models that serve as the basis of data assimilation to deal with the flow and transport of non-conservative species in the canopy and the boundary layer. Just as for water vapour and  $\text{CO}_2$ , the exchange of these other compounds between the surface and the atmosphere is not necessarily controlled by turbulent transfer processes. Instead, it is processes at the leaf surface, the stomata or the snow-ice layer, that determines transfer rates.

Two tasks can be identified; the first is to understand these controlling surface processes. In general terms (perhaps with the exception of the stomatal contribution to the removal of a small number of trace gases) the current knowledge of the surface uptake of gases and aerosols relies largely on empirical information, and the understanding of the underlying processes is limited (Gallagher et al., 2002). For example, dry deposition is an important sink for some gases such as ozone, nitric acid,  $\text{NO}_2$  and  $\text{SO}_2$ , as well as for aerosols. Recent studies indicate that the removal of a variety of trace gases such as oxygenated VOC and peroxides is much larger than previously assumed (Karl et al., 2004; Ganzeveld et al., 2005). This suggests a significant contribution by non-stomatal uptake, which is consistent with previous similar findings for ozone deposition (Altimir et al., 2004). The role of soil and vegetation wetness is poorly understood, involving aqueous-phase chemistry, co-deposition and leaf excretion. The second of the two identified tasks is to understand the mechanisms of atmospheric transport of these compounds, so that aerodynamic methods (Box 1) can be applied to measuring area-averaged exchange rates.

The long-term goals of Focus 4, reflecting both these considerations and the needs of Foci 1–3, are therefore to:

- (i) promote consistent long-term measurements of land-atmosphere exchange at local to regional scales by integration of data from flux towers, boundary-layer budgeting, remote sensing and other monitoring techniques with modelling, under a general framework of data assimilation;
- (ii) extend long-term measurement capability beyond energy and  $\text{CO}_2$  to a wider suite of biogenically active compounds; and
- (iii) use these measurements in combination with modelling to answer critical questions in ecology and hydrology.

Many of the critical problems in flux measurement and the handling of data have been crystallised by the experience of BAHC, GEWEX and other projects. Flux measurement networks (such as FLUXNET) are providing results of high temporal resolution over multi-annual periods which are changing the research community’s expectations of ecological data. While measurement difficulties exist at all scales, the primary challenge for iLEAPS is to extend the spatial scope of flux tower footprints from patch to region without losing their high time-resolution, and to augment the data with the measurement of other important species, such as aerosols and reactive gases.

### Sub-focus 4.1: Development of Sensors for Turbulent Flux Measurements

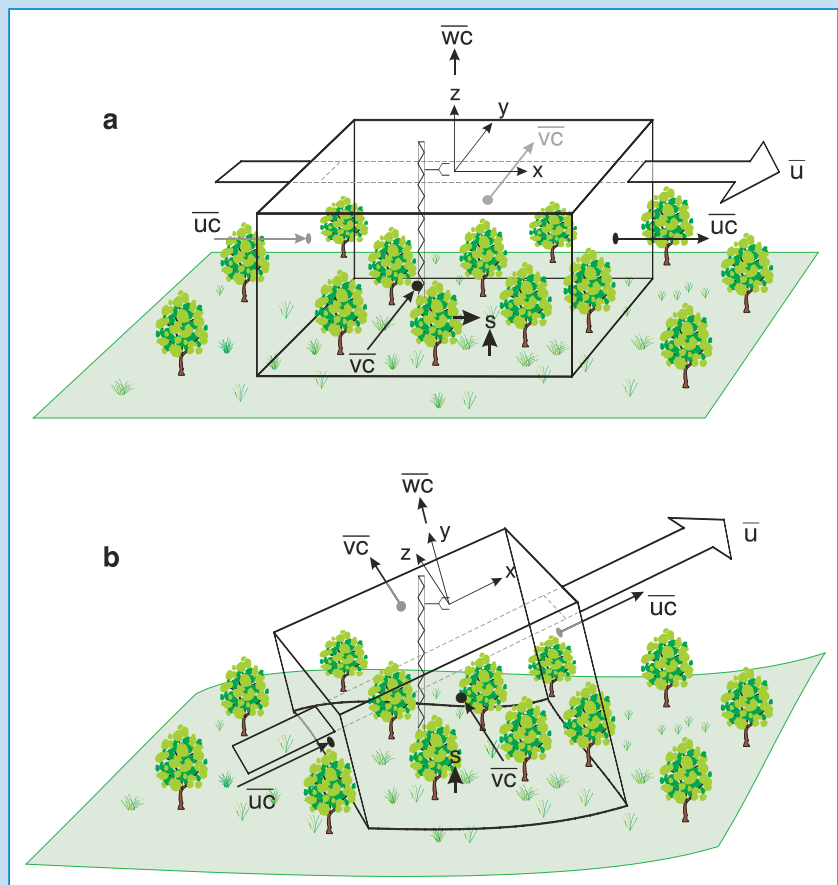
Fast-response, open-path sensors have been available for some time for heat, water vapour and  $\text{CO}_2$ . Rapid closed-path systems such as tuneable diode lasers are able to measure an increasing variety of biogenically important compounds (for example, methane and  $\text{N}_2\text{O}$ ) with high frequency (Friborg et al., 2000). Recently, proton-transfer-reaction mass spectrometers have been combined with micrometeorological techniques (e.g. disjunct eddy covariance or relaxed eddy accumulation) to provide new possibilities of measuring a range of VOC fluxes (Rinne et al., 2001). NO has been measured by chemiluminescence (Rummel et al., 2002) and  $\text{NO}_x$  by rapid catalytic techniques. More often though, the concentrations of “difficult” trace gases can be measured to the required precision only at low frequency, and therefore only eddy-accumulation or gradient methods can be used for measuring fluxes. However, the domain of application of gradient methods is limited; in fact, flux-gradient relationships break down completely within and just above plant canopies (Denmead and Bradley, 1987). Even more indirect techniques are necessary to estimate the fluxes of aerosol particles (Rannik et al., 2003).

## Box 1. Aerodynamic methods for measuring surface exchange

Leaf cuvettes, branch bags and soil chambers have long provided unambiguous measurements of gaseous exchange between components of the soil-vegetation continuum and the overlying atmosphere. As such, they are invaluable sources of information on particular local processes like photosynthesis and soil respiration, but using these methods for estimating biosphere-atmosphere exchange at local or regional levels, leads to crippling sampling problems. To circumvent the sampling problem these direct enclosure methods have (on rare occasions) been scaled up to enclose sections of whole forest canopies, but such canopy enclosures unavoidably disturb aspects of the radiative balance and turbulent exchange, so are confined to very particular applications (Dunin and Greenwood, 1986). For at least four decades, micrometeorologists have applied aerodynamic methods that use the turbulent mixing that is an inseparable part of atmospheric flow as an averaging operator to circumvent these sampling problems.

The aerodynamic method consists of erecting a notional control volume over a representative patch of surface, measuring the flows in and out of all the aerial faces of this volume, together with changes of concentration within it (usually called the storage term), and then deducing the surface exchange by difference (Figure 14). In tower-based measurements the lid of the control volume is assumed to pass through the highest sensor measuring the flux of the quantity of interest (Figure 14). This height in turn is dictated by the need to have the sensor ‘see’ a representative patch of surface, and is calculated using footprint analysis (Schmid, 2002).

**Figure 14.** Notional control volumes over a canopy patch: the shape and orientation of the volume is determined by the mean wind field: (a) control volume with steady flow over horizontally homogeneous terrain; advective terms sum to zero and only vertical exchange through the lid of the control volume need be measured; (b) control volume over complex terrain; the mean wind vector is no longer necessarily parallel to the local surface, and horizontal advection terms must be included. Adapted from Finnigan et al. (2003) with permission from Springer.



The shape of the control volume is dictated by the coordinate system used to write the mass balance equation, and by the flow field. In Cartesian coordinates with horizontally homogeneous flow, the volume is a rectangular box with vertical walls and a lid parallel to the ground (Figure 14a). With the same coordinates, but with flow over complex terrain, the walls and lid are not perpendicular and parallel to the ground (Figure 14b; see also Finnigan et al. (2003)). When applied to steady, horizontally homogeneous flows where the storage term can be ignored, the mass balance in the volume reduces to equality between the measured vertical flux at lid height, and the exchange across the ground surface. In unsteady flows the rate of change of concentration in the volume must also be counted in the mass balance, and in advective conditions, horizontal flows across the upstream and downstream walls of the volume are not in balance either, so that horizontal flux divergences also enter the calculation of surface exchange.

For the biologically important scalars (heat, water vapour and  $\text{CO}_2$ ) the flux measurement in the lid of the box is generally achieved using eddy covariance techniques. Previously methods such as eddy accumulation or assumptions of gradient diffusion transport mechanisms were used. These approaches are still used for exotic scalars where fast response sensors are unavailable.

Although initially developed in the context of tower measurements, the same mass balance philosophy lies behind airborne measurements and boundary-layer budget techniques. Unlike the case of the tower, where a flux measurement is made at a single point in the lid of the volume, aircraft can record the flux along a flight line of many kilometres, but other components of the mass balance (such as the storage term and horizontal advection) must be estimated indirectly. Conversely, boundary-layer budgets employ the entire PBL as the control volume, but in this case, the quantity measured most precisely is concentration, which must be supplemented by estimates of entrainment fluxes at the top of the PBL and advective fluxes, before surface exchange can be deduced. Not surprisingly, aerodynamic methods often work best when more than one of these approaches can be used in combination.



**Figure 15.** A flux tower in a tall forest canopy: Ozflux site, Tumbarumba, New South Wales, Australia.

## Sub-focus 4.2: Measurements at Tower Patch Scale

At present, over 240 flux towers apply the aerodynamic method (Box 1) to continuously measure the exchange of CO<sub>2</sub>, water vapour and energy between the biosphere and the atmosphere (Baldocchi et al., 2001). The data obtained provide unprecedented temporal detail on ecological processes within the tower ‘footprint’, as well as daily and annual sums of terrestrial carbon exchange across a wide range of ecosystems. Despite these advantages, some significant problems remain in interpreting flux tower data. Symptoms of these problems are failure to close the daytime surface energy balance, and underestimation of CO<sub>2</sub> respiration on calm stable nights.

As a result, uncorrected flux tower results give globally and regionally averaged values of net biome production that are 2–5 times larger than those from atmospheric inverse and biological inventory studies, particularly in the tropics (Schimel et al., 2001; Malhi and Grace, 2000; Phillips et al., 1998). These discrepancies may result from several types of problem. The first type of problem is those that affect the comparison of tower results (which are measures of net ecosystem exchange) with biomass inventories and large scale inversions (which measure net biome production). These causes can include: (i) bias in the location of the flux stations – predominantly over forests in Europe and the United States (Falge et al., 2001) – leading to skewed samples of biome type, history and climatic regime; (ii) unmeasured losses of carbon in the form of volatile hydrocarbons or dissolved carbon in groundwater (Guenther et al., 1995; McClain et al., 1997); and (iii) systematic errors in the estimates of the disturbance fluxes or in atmospheric inverse results. However, none of these possible reasons for the discrepancies seem likely to lead to large and systematic differences for sink estimates between towers and other methods.

The second type of problem pertains to the tower flux measurements themselves. The magnitude and sign of these errors may differ between day and night as transport mechanisms change with atmospheric stability, leading to systematic bias in tower estimates of net energy exchange (Moncrieff et al., 1996). The specific causes can be listed as:

- (i) **influence of topography:** many flux stations are located in complex terrain where advection is possible because of differential absorption of solar energy with slope and aspect, differing soil moisture content and

vegetation type, and flow distortion caused by the topography (Finnigan, 2004; Raupach, 1998).

- (ii) **averaging, filtering and coordinate rotation:** the methods of time-series averaging and coordinate rotation used at most FLUXNET sites are equivalent to high-pass filtering of the eddy covariance, leading to loss of low-frequency contributions to the eddy flux. Increasing the averaging time to as long as 2–4 hours and changing the coordinate rotation method may be required to close the energy budget at some sites (Finnigan et al., 2003; Lee et al., 2004).
- (iii) **advection caused by gravity currents:** nocturnal respiration fluxes are often underestimated by the aerodynamic method compared to simultaneous biological measurements. The discrepancy between the methods is particularly apparent in very stable atmospheric conditions (Goulden et al., 1996). Measurements at several sites with complex topography strongly suggest that advection caused by gravity currents leads to some of the above discrepancies.
- (iv) **under-sampling of intermittent transport events:** a currently unquantified possible source of systematic error is the intermittency of turbulent transport at times of strong stability (even over flat terrain) and spatial sampling errors due to preferential venting of high CO<sub>2</sub> concentrations from the canopy airspace at sunrise.

Networks of flux towers are vital in advancing our understanding of ecosystem processes, and iLEAPS will foster the addition of sensors for the range of species discussed herein at established tower sites. This takes advantage of existing infrastructure, and the old and new measurements will provide invaluable mutual constraints. With this strategy in mind, improving confidence in the aerodynamic component of long-term tower measurements must also be a priority. Three complementary approaches are necessary:

- (i) Measurement problems in the case of advective flows, whether caused by topography in neutral conditions, topography in combination with stable stratification, or by changing surface cover (Wilson et al., 2001), cannot be

solved merely by installing more flux towers. Even if cost were not a factor, it would be impossible to make sufficient measurements to solve this problem. Instead, accumulated knowledge of how the atmosphere flows over complex terrain can help develop and verify models to be used as a basis for systematic data assimilation.

- (ii) The existence of low-frequency eddy fluxes reveals that the flux-transporting mechanisms of the planetary boundary layer (PBL) are not completely understood.
- (iii) Understanding the character of intermittent, nocturnal stable-layer turbulence and the character of the PBL during the morning and evening transitions is critical to setting confidence limits on tower budgets at all but the best behaved sites.

### Sub-focus 4.3: Non-conservative Scalars

Traditional applications of the aerodynamic method (Box 1) assume that the measured scalars are conserved. This assumption is not valid when they undergo chemical reactions or when a change in particle size distribution takes place. In this event, the models used as a basis for data assimilation (even in ideal conditions where the model is merely an assumption of horizontal homogeneity and stationarity) need to include equations for chemical reactions or particle agglomeration. As noted in Foci 1 and 2, some important scalars involved in interactions between the biosphere and atmosphere undergo chemical or physical changes on timescales comparable to the processes governing physical transport in the canopy and boundary layer. A key priority in Focus 4 therefore, will be to combine models of canopy exchange with those of atmospheric chemistry, to test the combined models, and to use them as tools for data assimilation to infer surface exchange of reactive and non-conserved scalars.

### Sub-focus 4.4: Boundary-layer Budget Methods

Boundary-layer budget methods extend the aerodynamic approach (Box 1) from a notional control volume over the tower patch to the entire PBL. Unfortunately, no method exists for continuous measurements at the PBL scale, and in general, PBL data are limited to measurements of concentration and isotope ratio profiles from

balloons and aircraft, or to continuous measurements at one or a few levels. To convert these data into surface exchange values, therefore requires assimilation of data into a PBL scalar transport model.

Boundary-layer budget methods have mainly (but not exclusively) been applied to the daytime CBL, and are most successful when the surface flux is much larger than the entrainment flux through the top of the boundary layer. Two other factors often compromise this approach: poor knowledge of the atmospheric state above the temperature inversion, and advective fluxes driven by horizontal and temporal heterogeneities. Some of these problems could be solved by improved sampling technology such as unmanned aerial vehicles (UAVs). These should be complemented by improved models of CBL dynamics as a basis for assimilation. Above complex terrain particularly, where advection is as problematic as at the tower scale, the one-dimensional PBL models currently used as the basis for data assimilation should be replaced by more sophisticated models (e.g. Weaver and Avissar, 2001).

Night-time stable layers create a different set of problems for boundary-layer budget approaches. The “well mixed” assumption that is typically used in CBL models must be abandoned. During night-time however, more problems are encountered in conditions of stable stratification due to topographically forced advection. Moreover, strong stability produces intermittent turbulence that precludes the use of boundary-layer budget methods, according to current knowledge.

Combining boundary-layer budgeting and tower measurements is an essential step in extending tower flux measurement data to areas beyond the tower patch. A priority is to determine the conditions when current boundary-layer budgeting techniques are applicable, and to promote the use of more sophisticated PBL models as the basis for applying boundary-layer budget techniques to less ideal conditions.

### Sub-focus 4.5: Airborne Measurements of Fluxes and Atmospheric Composition

Measuring fluxes from aircraft was a central part of almost all integrated programmes of the 1990s. The purpose was to obtain large-scale, average fluxes and the spatial variations of fluxes. Airborne flux measurements are another member of the class of aerodynamic approaches detailed in Box 1. Although airborne flux measurements

are still difficult, problems of discrepancies between airborne and tower measurements have essentially now been solved (Isaac et al., 2003; Lenschow, 2004). Concentration and isotope ratio measurements of various compounds (including CO<sub>2</sub>) seem to have been more successful than direct flux measurements, but the portability and accuracy of instruments should be improved (Andreae et al., 2002; Lloyd et al., 2002; Styles et al., 2002). iLEAPS will promote further development and interpretation of airborne measurements, including the slow, low-flying light aircraft and UAV technology needed to improve turbulent flux estimates.

### Sub-focus 4.6: Remote Sensing

While they cannot deliver measures of surface exchange directly, remote sensing techniques are essential in providing data to extend process models from leaf and plot scales to regional and global scales. For example, availability of CO<sub>2</sub> satellite measurements in the future will allow large scale atmospheric inverse approaches. Ground truthing of remote sensing products should be a feature of the ecological experiments that usually accompany flux tower measurements. In close collaboration with GLP, iLEAPS will promote further development of remote sensing algorithms for deriving seasonal, annual and decadal maps of the biophysical properties and parameters of vegetation. These properties are important for models of photosynthetic carbon uptake, and for models of the physiologically coupled release of water and its effects on surface energy budgets. The wide range of spatial and temporal data obtained from various technologies should be integrated using the new data assimilation approach of model-data fusion.

iLEAPS will also support further development of new technologies for fast measurement of aerosol chemical composition and flux. The algorithms that are used to interpret satellite measurements and infer aerosol properties and distribution need further evaluation. The emission inventories of pyrogenic and terrestrial aerosol particles need to be improved as better satellite measurements of vegetation type and burned area become available. At present, the measured and modelled aerosol total optical depths differ due to uncertainties in emission estimates (Penner et al., 2001).

### Issues of Scale

When studying the production, transport, transformation and destruction of trace gases in the land-atmosphere system, a wide range of scales must be considered. Physiological reactions generally take place within milliseconds to minutes, and soil and leaf emissions and upward and downward transport in the canopy by diffusion or turbulence can be comparably fast. If the atmosphere is stable, turbulent transport is suppressed, and concentrations of trace gases may increase to levels that affect physiology.

Carefully planned studies are required to address the numerous scales encountered in iLEAPS research. Ideally, the studies will combine measurements at various temporal and spatial scales (e.g. chambers, eddy covariance, stable isotopes, airborne and satellite information) with appropriate models to account for the production, transport and transformations taking place between measurement scales. Modelling is also the only tool able to address the spatial heterogeneity that is evident in most landscapes (e.g. topography, presence/absence of vegetation, vegetation type and age), and which affects production and deposition processes. This heterogeneity makes quantification of land-atmosphere interactions by measurements alone impractical.

### Research Topics

The wide variety of physical and chemical processes mediating the sources, sinks and transport of energy, momentum and material in the land-surface atmosphere system, either completely precludes direct measurement with currently available techniques, or requires careful adjustments and corrections to measured data. iLEAPS will therefore promote further development of theories, models and measurement techniques to improve the quantification of land-atmosphere exchanges of various compounds for a wide range of land-surface structures. Often the combination of various measurement techniques with modelling will be the only realistic approach, and hence the following questions need to be addressed:

1. **Boundary-layer processes: what are the relative contributions of biological activity and the evolution of boundary-layer state (e.g. height, stability and turbulent structure) in characterising the diurnal patterns of surface-atmosphere fluxes of various trace gases?**

- How does topography influence exchange within and above the canopy?
- How do canopy processes influence exchange of reactive gases and aerosols?
- What kind of canopy microclimate models are needed to describe exchange within and out of the canopy at a variety of space and time scales, given the intermittent exchange and uneven mixing of chemicals in canopies?
- How does the evolution of the CBL, particularly during mixing with the residual layer from the previous day, affect surface-atmosphere exchange?
- How complex, relative to CBL height, can the terrain be before current modelling techniques fail?

2. **Surface processes: landscapes are typically complex mosaics of varying vegetation types, snow and ice or bare soil. How well can the exchange characteristics of each of these surfaces be characterised, and how can they be combined to accurately represent their average exchange in larger-scale models?**

- What are the mechanisms that control uptake by non-vegetated surfaces (soil and ice)?
- How is emission and deposition affected by the surface wetness of soil and canopy?
- How well do we need to characterise vegetation type and canopy structure, both vertical and horizontal in relation to the topography, in order to describe exchange dynamics at various scales?

3. **Problems of measurement: aerodynamic methods of surface exchange measurements at scales from soil chambers to boundary layer budgets typically assume simple flow conditions (e.g. horizontal homogeneity**

**and/or stationarity) and conservative species. How can these techniques be extended to remove these restrictions?**

- What is the origin of advective and low-frequency fluxes within the PBL, what is their contribution to scalar transport and can systematic corrections be made?
- What is the contribution of advection caused by stable drainage flows to night-time exchange, how can it be characterised and can systematic corrections be made?
- What are the mechanisms of spatial and temporal heterogeneity of turbulent exchange in strongly stratified flows, and how do they affect night-time flux measurements?
- How can non-conservative species (reactive chemicals and aerosols) be accommodated in aerodynamic methods of surface exchange measurement?
- Can mesoscale three-dimensional models capable of simulating contrasts in surface energy balance be used as the basis for boundary-layer budgets?

4. **Data assimilation, model-data fusion and multiple constraint approaches: can process models be developed for non-conservative species, terrain forced heterogeneity and non-stationarity, that will serve as a basis for data assimilation approaches so as to extend measurement methods?**

- What are the optimum forms of model for data assimilation that correct flux tower measurements for heterogeneous flows?
- Can simple models of transport be developed for non-conservative scalars to enable data assimilation that extends aerodynamic measurements to these species?

# Implementation Strategies

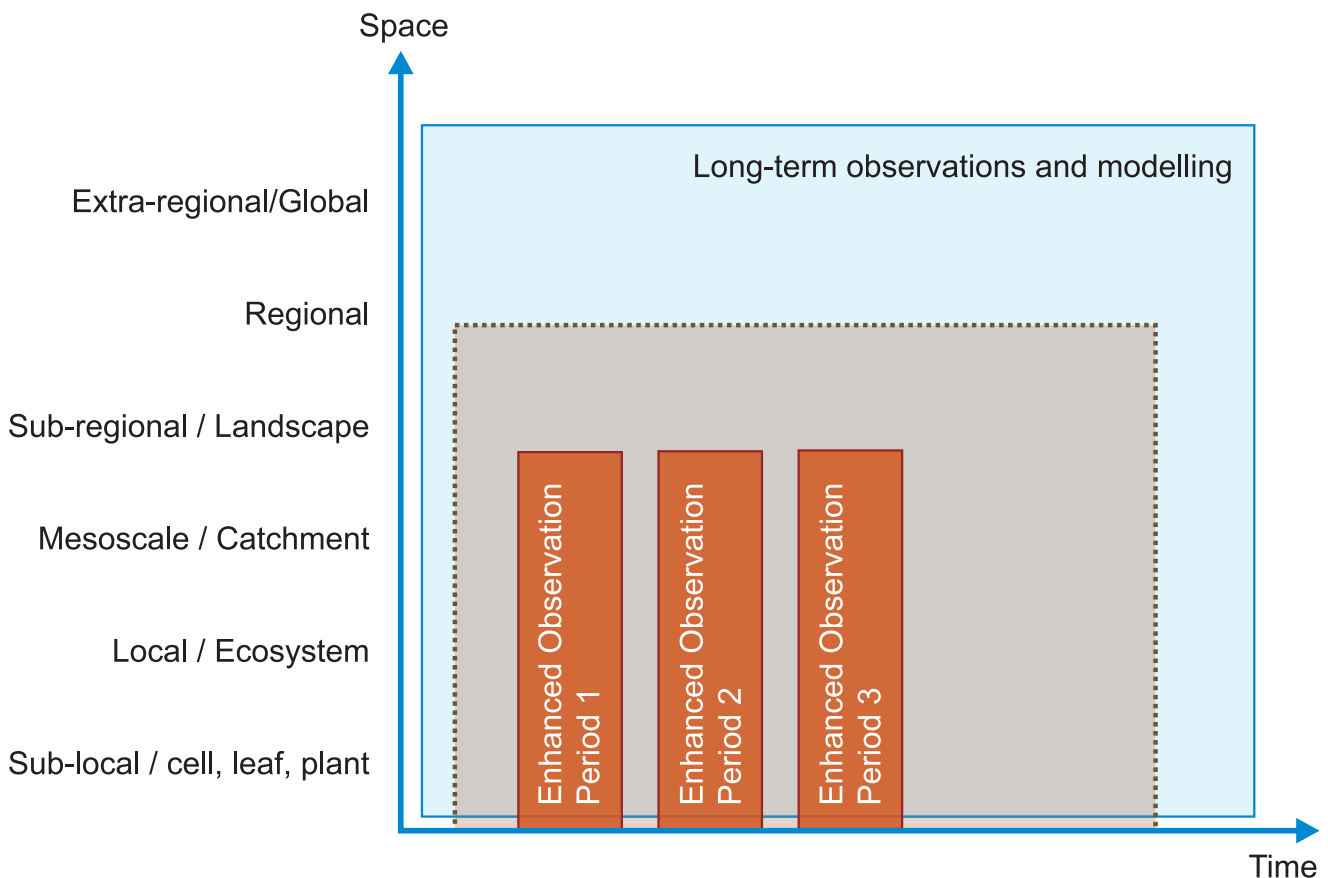
## Observational and Modelling Strategies and Integration

iLEAPS research is typically integrative and includes simultaneous consideration of a multitude of scales, processes and variables. To approach such complexity, certain experimental design techniques are useful, for example, *a priori* strategic modelling and multi-parameter sensitivity studies. By *a priori* definition of the most sensitive parts of the system, measurements can be focussed so that large experiments become more feasible. Strategic large-scale modelling, combined with remote sensing, should also be used to define, in advance, field sites locations that are representative of large ecosystem types (e.g. forests,

agricultural systems and wetlands), developmental stages (e.g. disturbance and re-growth) and biome (e.g. tropics, boreal/sub-Arctic and Mediterranean).

iLEAPS research activities should ideally include a combination of enhanced observation periods, long-term monitoring and modelling that span across a wide range of spatial and temporal scales (Figure 16). Transects along cross-cutting links, feedbacks and integration issues are of importance. The catchment as a well-defined landscape element may in many cases be a suitable study unit.

**Figure 16.** The ideal research activity in Earth System research combining experimental studies with observations and modelling at a wide range of temporal and spatial scales. Similar approaches will also be adopted in iLEAPS.





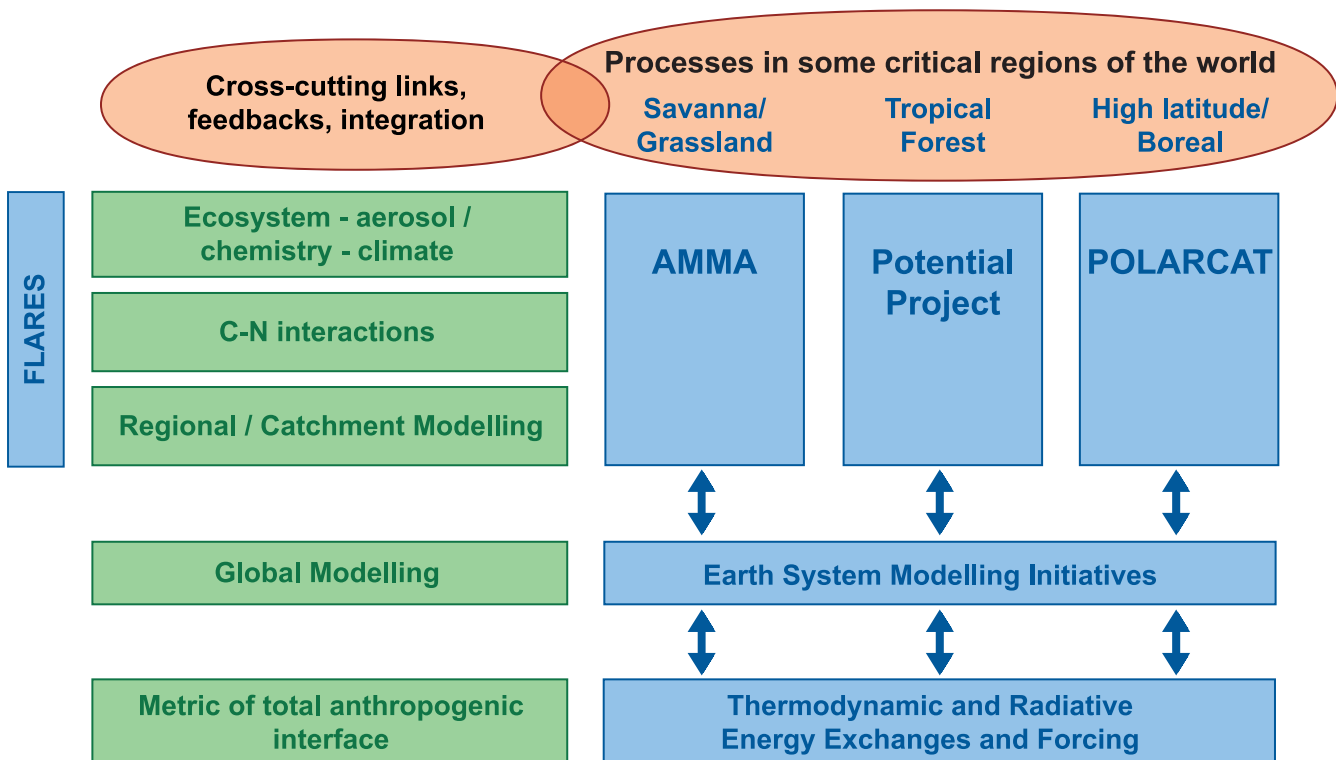
Research tasks may be chosen according to geographic boundaries in order to address regional ‘hot spots’ (e.g. Amazonia) or according to common environmental factors in order to address key gaps in understanding (e.g. permafrost areas and Mediterranean climates). The critical areas with the strongest anticipated influence on the Earth System are shown in Figure 3 and, in addition to areas mentioned above, include monsoon regions in West Africa and Asia. iLEAPS affiliated research activities in ‘hot spot’ regions with global implications (Figure 17) are the African Monsoon Multidisciplinary Analyses (AMMA) in West Africa, and the International Polar Year project POLARCAT (Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models, of Climate, Chemistry, Aerosols and Transport) in the Arctic region.

iLEAPS supports the use of the traditional IGBP transects (Figure 18) organised along important global change gradients of temperature, precipitation and land use in a broad sense. The IGBP terrestrial transects were established in critical regions of the world to cover most environmental conditions and biomes/ecotones. This approach was adopted to enable global change research to address large spatial phenomena with regional and

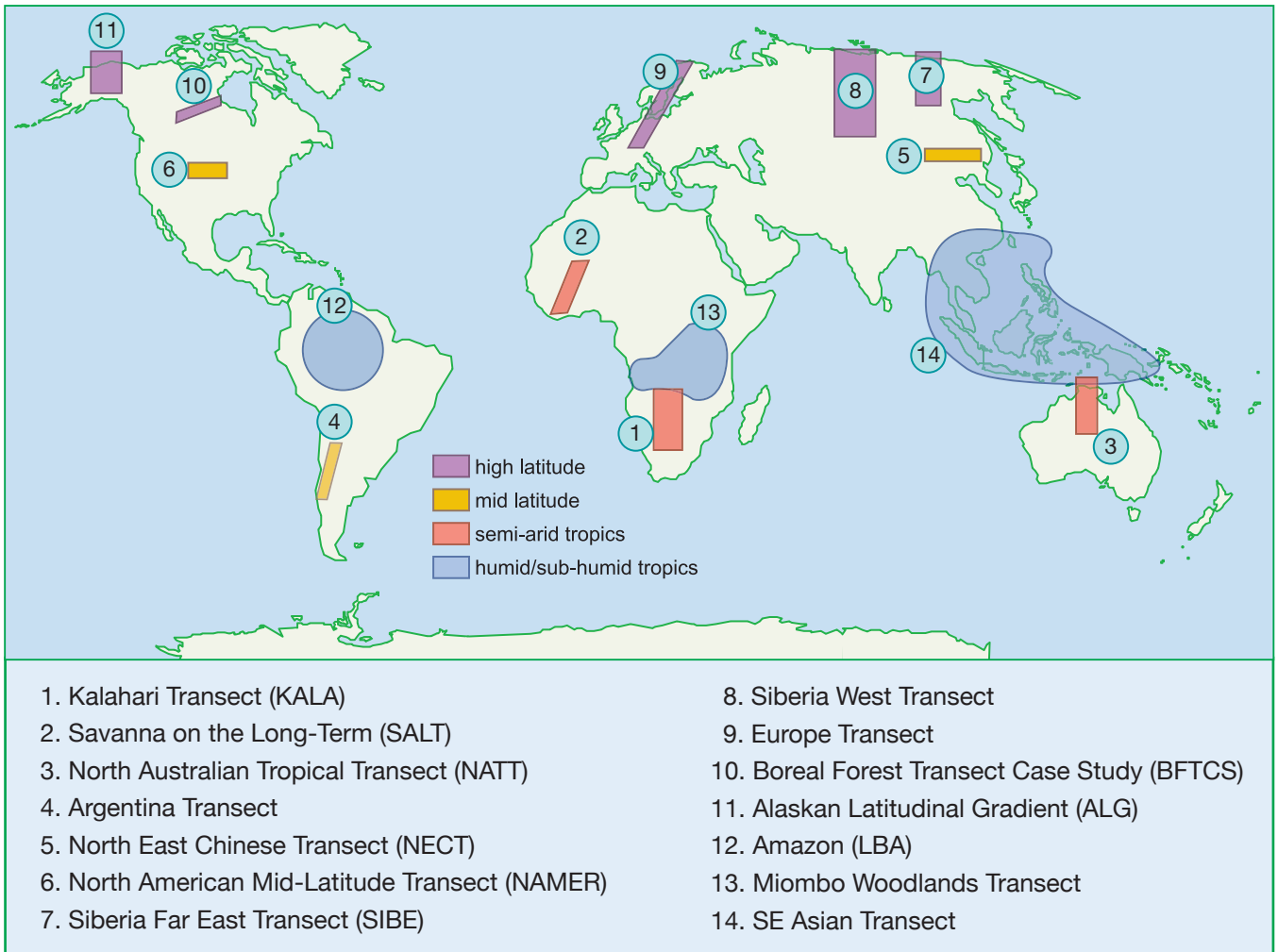
global implications. Special focus is given to highly sensitive regions such as high latitudes (due to global warming) and tropical regions (due to rapid land use change) (Steffen et al., 1992; Koch et al., 1995). When combined with field experiments along single environmental gradients, transects are powerful for testing mechanistic knowledge critical for model development and validation. Information obtained from transects can be scaled by modelling and using spatially explicit information (remote sensing data) to regional, continental and global levels. In iLEAPS, the transects can be used with networks of process studies and observational networks such as FLUXNET.

An alternative way to select research themes will be to develop iLEAPS tasks based on key processes or phenomena in the land-atmosphere system. An example is a cross-cutting study on the role of fire in the land-atmosphere system (Figure 17). iLEAPS project FLARES (Fire-Land-Atmosphere Regional Ecosystem Studies) is a cross-cutting study that reaches across disciplines (ecology, climate, chemistry and physics) and geographic regions, and works towards a broad integration and comparative analysis.

**Figure 17.** Examples of existing and potential iLEAPS research activities (in blue) focusing on regional processes as well as around cross-cutting research themes.



**Figure 18.** Traditional IGBP terrestrial transects. Transects 12-14 are based on a conceptual gradient of land-use change intensity. Adopted from Canadell et al. (2002) with permission from Opulus Press.



## Combining Models and Measurements: Tools to Connect Scales

Progress in understanding the numerous feedback mechanisms in the land-atmosphere system requires measurements conducted at a multitude of scales, combined with regional and global models that use physically and biologically accurate methods. iLEAPS research therefore needs to develop new tools for scaling various combined and inter-active physical, biological and chemical processes. In this context, development of model-data assimilation will be of central concern.

iLEAPS aims to develop and couple local, regional and global climate models that include the terrestrial carbon cycle, atmospheric chemistry and hydrological processes. This key focus area will be undertaken in close collaboration with partner activities within IGBP, WCRP and ESSP. The coupled models increase the mechanistic understanding of emissions and the associated feedbacks with the carbon and water cycles, radiative effects and the climate system. Also, models that describe the interactive cycle between vegetation, emissions of aerosols and aerosol precursors and the hydrological cycle need to be developed. Existing models that couple aerosols with the climate system at the process level and at large scale need to be evaluated. At present, there exists a fundamental disconnect between microphysically detailed models at the cloud scale, and highly parameterised representation of cloud processes at the global climate scale. This is one of the greatest obstacles to progress in understanding the role of aerosol-cloud interactions in climate change.

In order to achieve the goals stated herein, enhanced collaboration of modellers with field and laboratory scientists is needed. The integration of measurements and modelling and model development and evaluation should include the following (as described further in the paragraphs below): (i) scaling from local observations to regional models; (ii) improving the treatment of land-surface heterogeneities in coupled regional models; (iii) integrating biophysical modelling with biogeochemical and dynamic vegetation modelling; and (iv) benchmarking.

The numerical models used to address regional and global issues still operate on spatial scales that are large relative to

observations. Also, only short-term measurement data is available from many large field campaigns using non-automated measurement techniques ranging from chamber measurements to airborne techniques. Suitable approaches must be considered and evaluated in view of new methodological questions arising from the scaling of combined and inter-active physical, biological and chemical processes. With the large amount of field data available, combined model-data products such as re-analyses of climate, trace gas and other data are valuable. As the re-analyses contain a mixture of data and modelling, it is important to determine the circumstances when they can and cannot be used as the standard to run and test models.

The scaling up of the effects of surface heterogeneities to grid scale is still problematic. For example, the importance of mesoscale heterogeneity due to contrasts in surface energy balance (inland sea breezes) has been acknowledged for some time (Pielke, 2002; Weaver and Avissar, 2001), but the effects in nature have mainly been demonstrated in isolated case studies. The three-dimensional mesoscale models that are capable of simulating such phenomena have generally not been used as a basis for data assimilation in boundary-layer budgets. When the differences in horizontal temperatures are large (water-land interfaces), low-cloud climatologies are the first steps, and forced cumulus clouds become useful tracers. For example, the formation and dissipation cycles of the clouds test coupled soil-vegetation-atmosphere-transport and CBL parameterisations.

While the biophysical modelling of land-surface energy and water fluxes and their linkage to photosynthesis is relatively well established, biogeochemical and dynamic vegetation modelling will benefit from multiple competing efforts, at least for the first five years of iLEAPS. Consistency among biophysical, biogeochemical and dynamic vegetation models is crucial in these efforts. For example, most biophysical land models assume a one-layer canopy, whereas some dynamic vegetation models use two-layer canopies – the forest and the grass beneath (Foley et al., 1998). In the second five years of iLEAPS, a synthesis of the biogeochemical and dynamic vegetation modelling will be necessary.

More coupled experimental and modelling case studies are necessary to identify and rank the sensitivity of various processes to uncertainties, and to identify some key feedback loops. Systematic evaluations of the carbon cycle or climate models have been carried out in the past, but mainly on a global scale. Similar systematic evaluations could be carried out at local and regional scales using both flux measurements with large towers and runoff measurements. The evaluations will be a joint research effort of iLEAPS, GEWEX-GLASS and CCMLP and AIMES. Carbon cycle models should be developed to reproduce the seasonality and inter-annual variability of CO<sub>2</sub> and H<sub>2</sub>O fluxes at flux measurement sites, and similarly, the variability of atmospheric CO<sub>2</sub> concentration and isotopes at concentration measurement stations. Sensitivity studies with fully coupled surface-atmosphere models can be used to assess the importance of teleconnections of regional land use or land cover change and aerosol and greenhouse gas emissions to global climate.

## Collaboration with Related Activities

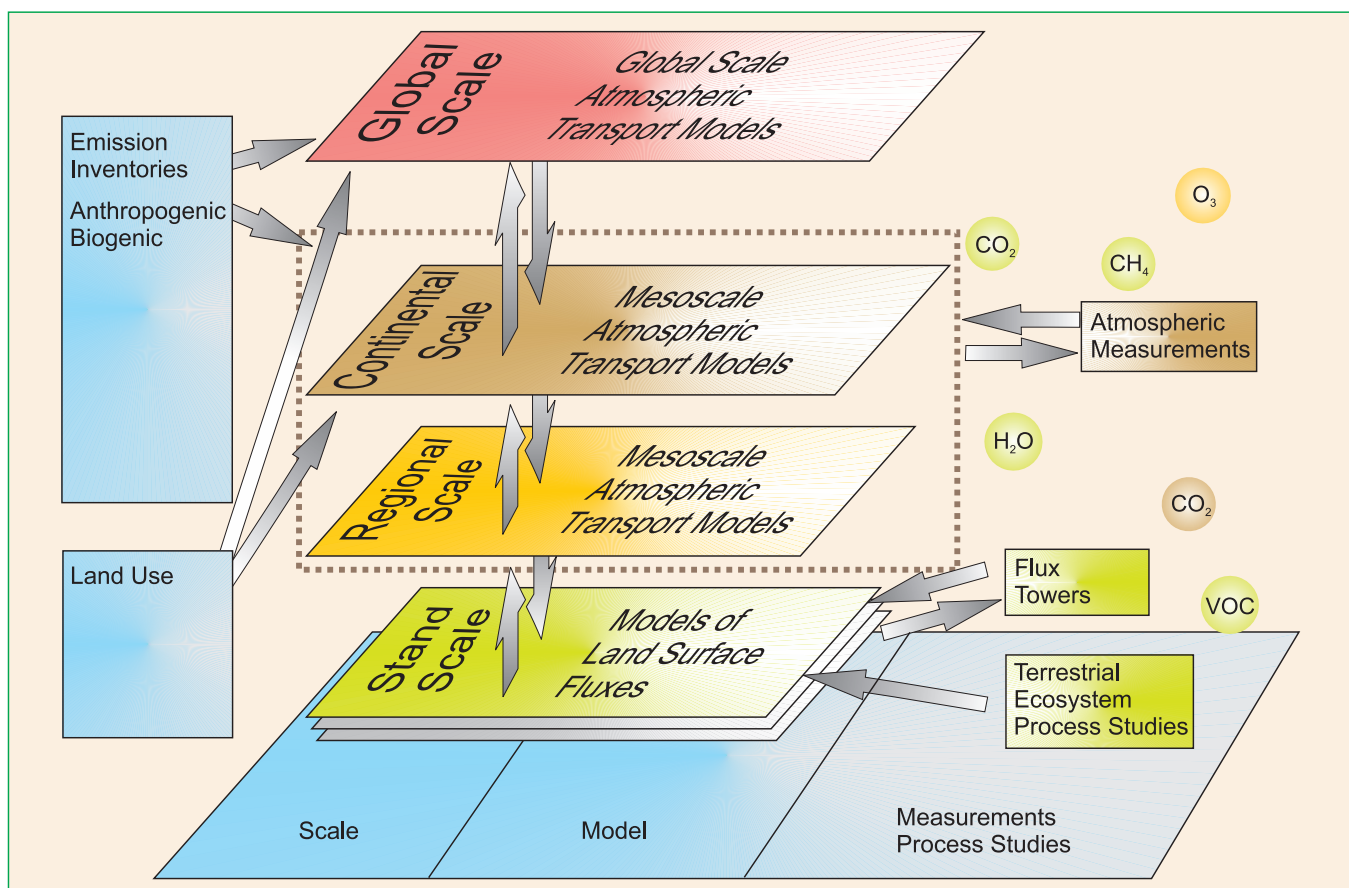
The planned iLEAPS research covers the basic processes that link land-atmosphere exchange, climate, the water cycle and tropospheric chemistry. The planned activities have a variety of linkages with other existing projects. The most obvious connections are to IGAC (which includes a number of projects studying atmospheric processes, including long-range transport) and GLP (which addresses issues related to terrestrial ecology, land use and land cover, with a strong human dimension component). However, iLEAPS shares with SOLAS a strong need for a sound theory for atmospheric boundary-layer behaviour and its interactions with the underlying surface, and the need for improved flux measurement technology.

iLEAPS will also develop a close partnership with WCRP, which has already instigated important research in collaborative areas: land surface processes and atmospheric coupling (GEWEX-GLASS), satellite remote sensing and

land surface climatology (GEWEX-ISLSCP), the physics of boundary-layer development (GEWEX-GABLS), processes in the Arctic environment (CliC) and coupled modelling (WGCM). All iLEAPS modelling activities will benefit significantly by close interaction with AIMES.

Specific iLEAPS projects will develop synergies by working, for example, with the satellite remote sensing community (e.g. GOF) which is developing a number of burned-area products and vegetation products, or with the GEWEX-GCSS project, which is aimed at improving cloud parameterisations in climate models. Fluxes of reactive, non-CO<sub>2</sub> carbon compounds cannot be treated separately from CO<sub>2</sub> fluxes, requiring collaboration with the ESSP joint project on global carbon (GCP). FLUXNET should be a major activity with which to interlink iLEAPS. On palaeo aspects of land-atmosphere interactions iLEAPS will collaborate with PAGES.

**Figure 19.** Schematic illustration of a collaborative and integrated research approach.



## Organisational Structure

### Project Management

New SSC members are nominated by the SSC for approval and appointment by the IGBP Officers. The Chairs and other SSC members serve three-years terms with the possibility of one renewal. In accordance with the IGBP terms of reference, the major tasks of the SSC are to: (i) provide scientific guidance and oversee project development, planning and implementation; (ii) promote iLEAPS within the scientific community, including by appropriate acknowledgement of iLEAPS, IGBP and ICSU in publications; (iii) demonstrate progress and achievements by defining and monitoring milestones and results; (iv) encourage national, regional and international funding agencies to support iLEAPS research; and (v) encourage appropriate collaboration between iLEAPS and other programmes and projects. Some SSC members will serve as liaisons to partner activities within IGBP and ESSP.

iLEAPS activities are coordinated by the IPO located at the University of Helsinki, Finland. The IPO is responsible for: (i) assisting in planning and implementation of research, database management, data synthesis and training activities; (ii) actively promoting communication within the iLEAPS community; (iii) assembling and disseminating information about training courses and summer schools; and (iv) assisting the SSC in assembling and synthesising iLEAPS research.

### Activities

iLEAPS will initiate and promote iLEAPS research activities including long-term integrated field studies, field campaigns, model development, synthesis studies, conferences and workshops. iLEAPS will recognise “tasks” with clearly defined goals and a finite lifetime, including: (i) networks of process studies to elucidate specific iLEAPS scientific questions; (ii) field campaigns; (iii) modelling (tool development, validations and intercomparisons); (iv) long-term integrated field studies; (v) large international interdisciplinary campaigns; (vi) synthesis studies; (vii) databases; and (viii) conferences on specific scientific questions; and (ix) synthesis meetings. Tasks can be suggested by the scientific community for approval and periodic review

by the SSC. Certain tasks – such as the development and maintenance of global databases – will be ongoing, and undertaken in close collaboration with iLEAPS partner projects (e.g. AIMES, IGAC, SOLAS and GLP). Integrated multi- and cross-disciplinary tasks are “recognised projects”, and other tasks are “recognised supporting activities”. iLEAPS Science Conferences will promote exchange of scientific results and interaction amongst the research community; these will be organised throughout the world to ensure broad geographic representation.

### Research Guidelines

iLEAPS will facilitate the research outlined in Foci 1–4 to improve understanding of land-atmosphere processes, and thus also of the Earth System. iLEAPS will adopt both bottom-up and top-down approaches: it will initiate essential research, and will recognise appropriate activities proposed by scientists. Research implementation will be largely left to the scientific community to ensure due consideration of novel ideas and process understanding, measurement and modelling. Nonetheless, all iLEAPS research should: (i) consider multiple scalars and their interactions and feedbacks in the land-atmosphere system as described herein; (ii) foster process-based understanding of the land-atmosphere system on a broad variety of temporal and spatial scales; (iii) incorporate (from the outset) measurements together with modelling and integration; (iv) be driven by scientific questions of regional and global importance; (v) operate across traditional scientific and organisational boundaries; (vi) be international and open to participants from all countries and organisations, with participant selection based on scientific contributions; and (vii) contain a capacity building component. Some very focussed tasks, such as a network of process studies to answer a specific science question, may not completely fulfil these guidelines.

### Proposal Guidelines

Tasks proposals should be based on the basic *Research Guidelines* above. Task proposals may be submitted to the IPO at any time; the IPO will forward eligible proposals to the SSC for comment and approval (where appropriate). The IPO will write a letter of recognition

on behalf of the SSC, who will appoint one of its members as the main contact for a task.

A proposal should be no longer than ten pages and include: (i) task title; (ii) task coordinators with contact details; (iii) background; (iv) description including science questions addressed; (v) scale of activities (temporal and spatial); (vi) measurements and modelling; (vii) regional and global aspects; (viii) participants with contact details; (ix) timetable and completion date; (x) funding; (xi) knowledge transfer and capacity building efforts; (xii) data archiving; and (xiii) outputs including peer-reviewed manuscripts and data.

Approved tasks will be reviewed at the annual SSC meeting. Task coordinator(s) should submit a task summary (not exceeding three pages) six weeks prior to the SSC meeting addressing: (i) scientific activities and achievements; (ii) deliverables in line with the approved proposal; and (iii) changes to the originally proposed activity. Published manuscripts and other material of relevance should accompany the annual report.

iLEAPS welcomes tasks seeking recognition from multiple IGBP and WCRP projects, as many international and national tasks may have research objectives relevant to more than one project; the African Monsoon Multidisciplinary Analyses is an example.

### Benefits and Responsibilities for Recognised Activities

The advantages for iLEAPS recognised activities are: (i) participation in iLEAPS development, planning and implementation; (ii) enhanced scientific value due to access to complementary studies and information; (iii) faster communication of results via iLEAPS workshops, conferences and publications; (iv) interaction with other international programmes and projects; (v) increased chances of obtaining national and international funding; (vi) international iLEAPS training schools for students and early career scientists; and (vii) enhanced networking opportunities for students and early career scientists.

The responsibilities of iLEAPS recognised activities are to: (i) accept the iLEAPS principles and goals; (ii) conduct research in accordance with the relevant aspects of the Science Plan; (iii) assist in iLEAPS planning and development through task management bodies; (iv) provide task data to the wider scientific community; (v) report progress

annually to the SSC; and (vi) acknowledge iLEAPS in activity products including scientific papers.

### Capacity Building and Knowledge Transfer

Capacity building and knowledge transfer are essential components of IGBP and therefore also of iLEAPS. Both cross-disciplinary training and capacity building via student outreach are important to iLEAPS as described below.

Research projects conducted within iLEAPS must be cross-disciplinary, particularly since iLEAPS research covers the land and the atmosphere. Although multi-disciplinary projects have become more common in recent years, more training is needed in cross-disciplinary approaches. The lack of training is apparent at the post-graduate level, but also at the lecturer level in developing countries. Widely used training activities are summer and winter schools and intensive training courses. iLEAPS will therefore identify and advertise appropriate existing schools and workshops dealing with atmospheric physics and chemistry, land processes and land-atmosphere interactions. Scientists involved in iLEAPS tasks are encouraged to contribute to, and lecture in, such training activities.

All iLEAPS research is essentially capacity building and this is particularly important in regional integrated studies and long-term observation and research projects. The majority of research has been conducted in developed countries where amenities are easily accessible. There is however, a growing need for regional studies in developing countries (such as LBA in Brazil), particularly where land use changes are extensive. In order to continue long-term studies in these regions it is crucial to build local capacity. This can be achieved through post-graduate students, student exchange, in-region or on-site courses and training, and through developed-country scientists spending sabbaticals in developing countries.

All projects recognised by iLEAPS will include capacity building and student training. Some of these activities may be initiated in collaboration with START, IAI and APN, which work to provide integrated projects and partnerships in developing countries. Possible mechanisms as described below are: (i) initial contact and regional involvement; (ii) on-site training; (iii) follow-up workshops; and (iv) data outputs.

In order to have regional scientists and students involved in projects, contact should be made prior to the start of a project. The iLEAPS IPO will keep a list of regional IGBP representatives and national committees that can assist investigators in contacting interested scientists in the region. Regional workshops help establish face-to-face contact, and help explore opportunities for involvement. Regional governments often have specific regulations covering the work of foreign scientists. These must be considered and respected from the outset. The involvement and support of host-country governments is a prerequisite of successful campaigns.

Developing countries often lack equipment or knowledge for measurement techniques. Training can be incorporated into projects by organising on-site training courses. This will not only teach students and researchers about techniques and equipment, but also about how to establish an entire land-atmosphere measuring station. This could be linked to, or run in parallel with, a summer or winter school. If there are enough students in a developing region interested in participating in a summer or winter school, bringing the lecturers to the students may be more cost effective.

Workshops can be held either during or after the completion of a regional project, and are important report-back sessions. The final report-back should not be only in the form of scientific conferences, but also in a forum where the public, schools and government can participate. The latter has the biggest impact for the region, and should demonstrate that the initial goals have been achieved. This is important promotion for the regional project as well as for iLEAPS.

A method for sharing data must be incorporated into all regional projects. This should include a database as a minimum, however, other mechanisms of data transfer are often required in developing countries. In some regions, internet access is very poor and therefore appropriate strategies must be used (e.g. data CD distribution).

## Communication

For the promotion of iLEAPS, activities and successes must be visible to scientists, communities, politicians and the general public. Public and media relations will be co-ordinated through the iLEAPS IPO and will involve the following activities:

- (i) **Production and distribution of a brochure** describing iLEAPS and its research will foster understanding of the Earth System. The brochure will be used to promote iLEAPS and to raise regional awareness before the start of regional activities.
- (ii) **Publication of iLEAPS articles in the IGBP** and other newsletters to create awareness and highlight the results of iLEAPS research.
- (iii) **Establishing and maintaining an iLEAPS website and newsletter**, primarily for scientists involved in iLEAPS activities. These will inform scientists of relevant present and future activities, meetings and workshops, courses, summer or winter schools.
- (iv) **Preparation of press releases for meetings and large regional integrative projects**, to inform the public about iLEAPS activities. Task coordinators should liaise with the IPO regarding the content and date of press releases.

iLEAPS will work in close cooperation with IGBP to plan and implement various activities, including capacity building and knowledge transfer activities. iLEAPS will also establish regular contacts with the Global Change National Committees. iLEAPS will encourage community- and policy-related outreach activities associated with the regional projects, to ensure maximum impact and media coverage at the local scale.



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# Acronym List

ACIA	Arctic Climate Impact Assessment	GTOS	Global Terrestrial Observing System
AICI	Air-Ice Chemistry Interactions	GWSP	Global Water System Project
AIMES	Analysis, Integration and Modelling of the Earth System	IAI	Inter-American Institute for Global Change Research
AMMA	African Monsoon Multidisciplinary Analyses	ICSU	International Council for Science
APN	Asia-Pacific Network for Global Change Research	IGAC	International Global Atmospheric Chemistry
BAHC	Biospheric Aspects of the Hydrological Cycle	IGBP	International Geosphere-Biosphere Programme
CBL	convective boundary layer	iLEAPS	Integrated Land Ecosystem–Atmosphere Processes Study
CCMLP	Carbon Cycle Model Linkage Project	IPCC	Intergovernmental Panel on Climate Change
CCN	cloud condensation nuclei	IPO	International Project Office
CliC	Climate and Cryosphere	IRS	integrated regional study
DGVM	dynamic global vegetation model	ISLSCP	International Satellite Land Surface Climatology Project
ENSO	El Niño-Southern Oscillation	LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
ESSP	Earth System Science Partnership	PAGES	Past Global Changes
GABLS	Global Atmospheric Boundary Layer Study	PBL	planetary boundary layer
GCP	Global Carbon Project	SOLAS	Surface Ocean–Lower Atmosphere Study
GCTE	Global Change and Terrestrial Ecosystems	SSC	Scientific Steering Committee
GEIA	Global Emissions Inventory Assessment	START	Global Change System for Analysis, Research and Training
GEWEX	Global Energy and Water Cycle Experiment	UAV	unmanned aerial vehicle
GLASS	Global Land-Atmosphere System Study	VOC	volatile organic compound
GLP	Global Land Project	WCRP	World Climate Research Programme
GOFC	Global Observation of Forest Cover	WGCM	Working Group on Coupled Modelling
GOLD	Global Observation of Land Cover Dynamics		

## iLEAPS

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