Introduction

This volume is a synthesis of the research undertaken by the Biospheric Aspects of the Hydrological Cycle (BAHC) Core Project of the International Geosphere-Biosphere Programme (IGBP) since its inception in 1990. Before reading about the wealth of new insights that are presented in this volume, it is important to return to the origins of BAHC and our level of understanding of global change and the nature of the Earth System at that time.

The original aim of BAHC was to improve our knowledge of how terrestrial ecosystems and their components affect the water cycle, freshwater resources and the partitioning of energy on Earth. To address this overall goal, the project had four quite specific objectives:

- Development, testing and validation of models representing the transfer of water through the soil, vegetation and the atmosphere;
- Progress on how to aggregate the land-surface properties and fluxes from varied landscapes from local to regional scales;
- A study of the temporal and spatial diversity of biosphere-hydrosphere interactions;
- Development of a weather generator to both characterise an important part of the hydrological cycle and to provide time-varying boundary conditions to models.

These objectives reflect the state of understanding in the late 1980s. The dominant paradigm then was that the Earth's environment was largely controlled by the coupled dynamics of the planet's two great fluids – the atmosphere and the oceans. There was much debate in the global change community on whether biology had any significant role at all to play in Earth System dynamics. The terrestrial vegetation was considered to be a passive recipient of the impacts of changes in ocean-atmosphere dynamics; it was a spectator rather than a player in the functioning of the Earth System. Water and energy exchange between the land and the atmosphere was regarded in the same way. Indeed, the specific BAHC objectives listed above are highly suggestive of the terrestrial vegetation being thought of as a lower boundary condition for the atmosphere, where all of the action occurred.

Now, a decade later, one of the most important overall findings of IGBP research, highlighted at the Global Change Open Science Conference in Amsterdam in July 2001 and in the Amsterdam Declaration on Global Change, is that biology is a much more important player in Earth System dynamics than was earlier thought. More than any other core project in IGBP, BAHC research led to that conclusion. The achievements of BAHC over the past decade, as presented in this volume, thus go well beyond its original, more narrow remit; rather, the authors provide a new perspective on the interplay between two important components of the Earth System – the hydrological cycle and the terrestrial biosphere, i.e. vegetation.

Since 1990, the BAHC project has also gradually evolved to encompass additional questions, such as:

- To what extent are lateral fluxes of water, nutrients and sediments by rivers dependent on climate variability and/or direct human activities such as land use, pollution or river engineering?
- How can the dynamic context of Earth System changes and rapid human development – and their associated uncertainties – be expressed as vulnerabilities and risks that ultimately need to be dealt with?

Through more than a decade of BAHC activities, from local-scale experiments in areas comparable in size to a General Circulation Model grid square, large, regional field campaigns such as the LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia) or Asian GAME (GEWEX Asian Monsoon Experiment), to developing regional and global models, another important BAHC task gradually developed:

- How to consolidate the land-use and water data sets at different spatial and temporal resolutions.

All these stages of the BAHC project have been synthesised in the five parts of this book.

In *Part A* evidence is presented which convincingly demonstrates that the land surface does matter in weather and climate. This evidence comes from a whole range of spatial scales, from point and local measurement all the way up to global scale, multi-century modelling. The vegetation-atmosphere interactions that regulate local weather and hydrological balances and the regional climate have been fully demonstrated through a set of major international field campaigns, e.g. in the Sahel, Canada, China, Thailand and the Amazon, which were co-organised by BAHC scientists. These experiments brought about a step-by-step improvement in our knowledge on basic energy- and water-exchange processes such as precipitation, evaporation, transpiration, infiltration, surface runoff and on the related fluxes of trace gases and aerosols. These studies were carried out in major world biomes from the tropical wet forest to the boreal forest and thus have yielded important insights into the richness of response evoked by different land surfaces across the globe. These experiments also pointed out the importance, in ways not appreciated a decade ago, of feedbacks within the climate system caused by land-use and land-cover change such as deforestation and agriculture.

Model-based interpretation of palaeobotanic evidence of large-scale vegetation change – for example the greening of the Sahara and the shift of the boreal tree line several thousand years ago – leads to the conclusion that vegetation not only follows changes in the atmosphere, but it amplifies climate changes via its interaction with the other components of the natural Earth system. It is concluded that without consideration of biogeochemical, biogeophysical and biogeographical feedbacks, attribution of recent climate change as well as assessment of climate change in the upcoming decades are most likely to be incomplete.

As discussed in more detail in *Part B*, BAHC has played a major role in the planning and coordination of a series of international field experiments. The aim of these experiments has been to quantify how the land surface functions at the regional scale and to provide the data to allow the fluxes of heat, water vapour and carbon to be represented in regional and global scale models. The experimental philosophy has been to measure all the components of the land surface-atmosphere interaction over areas of around 100 km by 100 km. Experiments have been completed, or are under way, in key biomes of the world – concentrating on those which are likely to be vulnerable to climate change, or where land use change may influence climate (please see Table C.1 for a list of field experiments).

Part B critically examines the progress made by this series of integrated land-surface experiments and assesses the development of our ability to measure each of the components of the land surface-atmosphere interaction at different time and space scales. As a recommendation for future integrated experiments, the early involvement of social science is stressed and a need for a regional extension of research into the tropics is emphasised.

Arguably, the scientific efficacy of Earth System science today greatly depends on data co-registration, standardisation, assimilation, consolidation, maintenance and distribution. *Part C* of the book presents the scientific and technical tools needed to achieve the land-surface and water-related data consolidation at the interdisciplinary level. Data consolidation is the bringing together of related datasets from disparate sources, in differing spatial and temporal resolutions and in various formats, into an organised, standardised, co-registered and fully documented database for redistribution. Consolidation has two main facets. The first is the synthesis of disparate datasets across space and time to produce continuous, high-quality data. The other aspect is the standardisation of formats, documentation, attribution, and tools to generate access and distribute the consolidated datasets. Whereas synthesis makes the data useful, standardisation makes it useable.

The best path to data consolidation is a joint effort from both the largest and smallest data providers and users, including institutions that have historically restricted the free dissemination of data. Consolidation can only work if the providers of data are rewarded for their extra efforts, in the form of recognition and citation whenever their data are used. Success of data consolidation also requires a change in the thinking of scientific funding organisations. Non-operational data streams from individual scientific projects with little infrastructure must have motivation and support to participate in consolidation. The interdisciplinary and inter-project exchange that today's programme managers advocate would be much easier to attain if they specifically supported data management in each grant. Regardless of the approach, it is also necessary that all programmes cooperate and support a common set of standards across both national and disciplinary boundaries.

The global change research community has mostly focused its attention on the question of climate change and variability. A primary goal of *Part D* of this synthesis has been to assess the importance of additional factors shaping the character of rivers and associated drainage basins. This work has emphasised the nature of interactions among the physical, biological, and social dimensions of the land-based water cycle, expressed through the conceptual framework of the *drainage basin* as a functioning hydrological unit. A variety of spatial and temporal scales was considered, ultimately the full spectrum from patch-to-globe, from literally minutes-to-millennia.

These complex interactions between humans and the Earth System are illustrated in a set of three case studies: the River Amazon (Brazil), the River Elbe (Germany) and the Mgeni River (South Africa), representing multiple climatic, population density and economic development gradients. Humans exert an influence on the water cycle that goes beyond greenhouse warming and includes land cover change (deforestation for agriculture and timbering, urbanisation), industrialisation, pollution, and water resources development.

Major human-derived impacts also include large increases in the residency time of river waters on land, large increases in erosion followed by interception of a substantial fraction of sediment destined for the world's oceans, order-of-magnitude increases in riverine nutrient flux in industrialised regions, severe loss of discharge to the coastal zones of river with large-scale irrigation works and flow diversion, virtually instantaneous changes in discharge regime due to reservoir operations, water balance feedbacks through widespread land-cover change. Semi-arid river basins such as the Colorado, Nile, Murray, Amu Darya, and Huang He are the most sensitive ones, combining high water use and regulation with extreme climate variability and they bear important consequences for freshwater resources, for ecosystems and for humans living in the coastal zone.

Part D promotes the use of Integrated Water Resource Management which should now integrate basin-wide, water-demand management within a broader Earth System perspective. Management of water systems must increasingly take into account not only their natural hydrology and biogeochemical cycles, but also their hydraulics and water management systems. IWRM is essential to the wise management of what are becoming, in many parts of the world, scarce water resources and can be used in fruitful ways to help manage regional water systems, including the politically sensitive issue of transboundary water systems.

Part E concludes that the involvement of land surface processes as a major influence on regional and global climate variability and change significantly complicates the ability to project future climate in response to human disturbance. As a result of this lack of skillful predictive ability, we discuss the use of vulnerability assessments as the primary methodology to evaluate risks associated with environmental variability and change, including those risks associated with climate. Even when skillful projections are possible, starting with vulnerability assessments provides the quantification of the greatest threats to a resource.

The vulnerability paradigm is illustrated with several specific examples. A mathematical framework is introduced, and definitions of terms used are provided. This more holistic framework with which to evaluate environmental risk associated with human-caused and natural Earth System variability and change offers a more complete framework for policymakers than the reliance on projections which provide only a subset of future conditions.

This synthesis makes important contributions to the development of a holistic Earth System science approach. One of the strengths of BAHC has been its ability to place its work into the broader context of the Earth System and to engage and collaborate with others to generate new insights into the workings of our life support system. The research presented here on the coupled ocean-atmosphere-land dynamics shows how the nonlinear dynamics of the Earth System, revealed through the increasingly rich palaeo-record, can only be understood by considering the interactive coupling of components of the Earth System, some of which are now directly managed by humans, such as, for example, the biogeochemical cycle of nutrients within impacted and/or regulated river basins at the regional to global scale.

The past decade has been one of achievement, excitement and surprise, and it has raised new questions and challenges that have caused us to reflect on the nature of global change science and its ability to rise to these new challenges. The outstanding success of BAHC encourages us to meet these challenges. The science presented in this volume provides a critical underpinning for, and acts as a bridge to, the new approaches and structures needed to build a more integrative Earth System science. The BAHC community will now split; some parts are spearheading the development of a new IGBP project focused on the land-atmosphere interface, others are developing a project on global change and the water system, with a much stronger emphasis on terrestrial water resources and links to the socioeconomic and biodiversity sciences, while others will continue to contribute to the GAIM (Global Analysis, Integration and Modelling) goals and its reformulation, and to the emergence of an integrated Earth System perspective in IGBP.

These developments would not have been possible thirteen years ago. This volume, built on the efforts of a large international community of scientists, attested by the great number of contributors to this volume and of related papers, describes the exciting journey of understanding that has changed our view of the way in which the hydrological cycle interacts with terrestrial ecosystems and humans, from a lower boundary condition on a physical system to a central, dynam-ic feature of a single, integrated Earth System including the present-day Human dimension.

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The Editors