IGBP REPORT 49

International Geosphere–Biosphere Programme

GTOS REPORT 28

Global Terrestrial Observing System

IHDP REPORT 13

International Human Dimensions Programme on Global Environmental Change

Global Change and Mountain Regions

The Mountain Research Initiative

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Edited by

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Implementation Strategy

This document describes an implementation strategy for Global Change and Mountain Regions as an Initiative for Collaborative Research and is approved by the Scientific Steering Committees of the projects of the International Geosphere-Biosphere Programme BAHC (Biospheric Aspects of the Hydrological Cycle), GCTE (Global Change and Terrestrial Ecosystems), PAGES (Past Global Changes), LUCC (Land-Use and Land-Cover Change), The Global Terrestrial Observing System (GTOS). LUCC is a joint project of IGBP and the International Human Dimensions Programme on Global Environmental Change (IHDP).

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Cover illustration: The Dischma Valley in Switzerland, exemplifying the linkages between hydrological, ecological and land-use processes in mountain regions. Photo: Harald Bugmann

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Contents

Foreword

Global change is a reality. A wealth of scientific information, from paleo studies of past variability of the Earth's environment, from observations of current changes, and from model-based projections of the future evolution of the Earth System, shows that the changes are more rapid and profound than in the past millennia and will continue for at least the next century. The effects of global environmental change, however, will be felt much differently at the regional level.

The Global Change and Mountains Region Research Initiative is based on a geographical feature – mountain regions – that may experience the impacts of the rapidly changing global environment more strongly than others. Mountains are a source of inspiration and recreation for a crowded world but they also serve as the 'Water Towers of the World', and with a growing emphasis globally on water resource issues, this function is crucial for human well-being. Also, mountains, with their sharp altitudinal gradients, often intensify and transmit environmental impacts to lowlands. These same altitudinal gradients result in distributions of species that may change markedly during global change and may be sensitive indicators of subsequent impacts to lowlands. Water yield is affected by the biological community covering the watershed.

This Initiative spans a range of activities – monitoring, detection of change, fundamental process research and modelling, and policy and management applications – which are essential components of studying global environmental change. It is thus appropriate that three international global environmental change organisations - the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the Global Terrestrial Observing System (GTOS) – endorse this Initiative.

IGBP has been involved from the beginning of the Initiative's development, through support of the initial scoping workshop and the participation of many IGBP-associated scientists in the evolution of this prospectus. The Initiative, especially Activities 2 and 3, have drawn on, and will contribute to, the scientific agendas of three IGBP core projects, BAHC, GCTE and

PAGES, and one core project, LUCC, which is jointly sponsored by IGBP and IHDP. The detailed tasks within the prospectus are linked explicitly to science and implementation plans of the core projects, and provide a strong framework within which to build interaction and collaboration.

Activity 4, with its focus on changes in forest resources, agricultural systems and water resources, is of particular interest to the IHDP. The links to the LUCC project are strong, but in addition because of the institutional dimensions of resource use in mountain areas the Initiative could contribute to the scientific agenda of the IDGEC project and studies of changes of resources and the vulnerabilities of humans living in mountain areas to such changes can be linked to the work of the GECHS project.

The Global Terrestrial Observing System (GTOS) is charged with developing the data and information needed to understand global change and its potential impacts on sustainable development. However, before this can be accomplished, there is a need (i) to strengthen the ability of existing observations and related research, (ii) for scientists to share and exchange information, and (iii) to collaborate on global change studies. Activity 1 (Long-term monitoring and analysis of indicators of environmental change in mountain regions) of the Global Change and Mountains Region Research Initiative provides an excellent opportunity to improve collaboration in mountain regions.

A strong feature of the Global Change and Mountain Regions Initiative is the integration of work across its major components. This provides a bridge between the research taking place in the scientific community and the observations and synthesis being undertaken in the international organisations. This will facilitate the linking of mountain issues with more immediate resource management problems and policy issues.

We thank the many scientists who have contributed to the design and development of this prospectus, in particular, Alfred Becker and Harald Bugmann, who have seen this effort through to the publication of this document. The mountain research community has important challenges to meet in implementing this Initiative and we look forward to some exciting results and enhanced understanding in this area of global change science in the coming years.

Will Steffen	Jill Jäger	Jeff Tschirley
Executive Director	Executive Director	Programme Director
IGBP	IHDP	GTOS

Preface

Recognising the significance of mountain regions for global change research, the IGBP core projects BAHC and GCTE, together with START/SASCOM, organised a workshop in Kathmandu, Nepal (March/April 1996), which resulted in IGBP Report #43: "Predicting Global Change Impacts on Mountain Hydrology and Ecology".

Immediately after the workshop, the results were discussed in a special session at the first IGBP Congress (Bad Münstereifel, Germany, 18 – 22 April 1996), which was attended by members of the SSCs and representatives of the IGBP core projects BAHC, GCTE, LUCC, PAGES and GAIM and by the IGBP Secretariat, in particular the IGBP Executive Director. The session participants welcomed the results of the Kathmandu Workshop and representatives of LUCC and PAGES enthusiastically expressed an interest to participate in the further development of the initiative.

Two important follow-up events, which complemented the results of the Kathmandu Workshop, were a LUCC Workshop on "Dynamics of Land Use/Land Cover Change in the Hindukush-Himalayas" in Kathmandu, Nepal (April 1997), and the "European Conference on Environmental and Societal Change in Mountain Regions" in Oxford, UK (December 1997).

The reports from these meetings, together with IGBP Report #43, served as the basis for developing a draft document for this Initiative on "Global Change and Mountain Regions" at a joint IGBP/IHDP (BAHC, GCTE, LUCC, PAGES) workshop in Pontresina, Switzerland (16-18 April 1998). Fifteen experts attended the workshop, sponsored mainly by the Swiss Academy of Natural Sciences (SANW). The participants of the Pontresina workshop emphasized the need for interdisciplinary environmental change research in mountain regions, involving both natural and social scientists. Thus, in addition to the IGBP and its core projects mentioned above, IHDP and its science projects IDGEC and GECHS, as well as START and its regional programmes were suggested to be invited to join the group of collaborators. Moreover, at a meeting of the BAHC SSC in April 1998 in Paris, the official representatives of WCRP/GEWEX, Rick Lawford, and of UNESCO/IHP, Mike Bonell, expressed the interest of their programmes to participate in the initiative and provided input to it.

At the Second IGBP Congress in Shonan Village (Japan) in May 1999, the Initiative was formally endorsed by the four IGBP Core Projects BAHC, GCTE, PAGES, and LUCC. The Initiative will be implemented as an inter-core project collaboration among these Core Projects, with tight linkages to the other programmes mentioned above.

We would like to thank all contributors to the document as listed below as well as the sponsoring organisations and projects for their support and contribution. We also would like to emphasise that the IGBP Mountain Research Initiative did not actually start to form in 1996, but it is rather the product of an awareness building process that lasted several decades and was carried through by a fairly small number of visionary scientists. We are grateful for their lasting efforts.

Potsdam and Boulder, June 1999 Alfred Becker
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Executive Summary

Mountain regions occupy about one fourth of the Earth's surface and provide goods and services to about half of humanity. Accordingly, they received particular attention in the United Nations system, lastly by the UN Declaration for the year 2002 to be the "International Year of Mountains".

The strong altitudinal gradients in mountain regions provide unique and sometimes the best opportunities to detect and analyse global change processes and phenomena because

- meteorological, hydrological, cryospheric and ecological conditions change strongly over relatively short distances; thus biodiversity tends to be high, and characteristic sequences of ecosystems and cryospheric systems are found along mountain slopes. The boundaries between these systems experience shifts due to environmental change and thus may be used as indicators of such changes.

- the higher parts of many mountain ranges are not affected by direct human activities. These areas include many national parks and other protected environments. They may serve as locations where the environmental impacts of climate change alone, including changes in atmospheric chemistry, can be studied directly.

- mountain regions are distributed all over the globe, from the Equator almost to the poles and from oceanic to highly continental climates. This global distribution allows us to perform comparative regional studies and to analyse the regional differentiation of environmental change processes as characterised above.

Therefore, within the IGBP an Initiative for Collaborative Research on Global Change and Mountain Regions was developed, which strives to achieve an integrated approach for observing, modelling and investigating global change phenomena and processes in mountain regions, including their impacts on ecosystems and socio-economic systems.

The ultimate objectives of the Initiative are:

- to develop a strategy for detecting signals of global environmental change in mountain environments;

- to define the consequences of global environmental change for mountain regions as well as lowland systems dependent on mountain resources (highland-lowland interactions); and

- to make proposals towards sustainable land, water and resource management for mountain regions at local to regional scales.

To achieve the above objectives, the research under the Mountain Initiative will be structured around four Activities, each of which is divided into a small number of specific Tasks:

Activity 1: Long-term monitoring and analysis of indicators of environmental change in mountain regions

This Activity will be accomplished through the coordination of ongoing research and, where required, the initiation of new projects in mountain regions around the world. A set of four mountain-specific indicator groups of environmental change is considered:

- Cryospheric indicators related to snow conditions, glaciers, permafrost and solifluction processes (Task 1.1);

- Terrestrial ecosystems, particularly mountain plant communities and soils (Task 1.2);

- Freshwater ecosystems, in particular high mountain streams and lakes (Task 1.3);

- Watershed hydrology, i.e. water balance components of high mountain waterhsheds/headwater basins (Task 1.4).

Contemporary monitoring will be arranged within the context of reconstructions of longer-term past trends and variability, provided through close collaboration with relevant aspects of the IGBP core project PAGES.

Activity 2: Integrated model-based studies of environmental change in different mountain regions

To achieve the overall goals of the Initiative, it is necessary to develop a framework that permits to analyse and predict hydrological and ecological characteristics and their linkages with land use and climate at various spatial and temporal scales. Accordingly, this Activity is organized in the following four research themes:

- Development of coupled ecological, hydrological and land use models for the simulation of land cover and land surface processes in complex mountain landscapes and river basins under current and changing atmospheric and socio-economic conditions (Task 2.1);

- Development of regional scale atmospheric models for mountain regions capable of providing high resolution areal distribution patterns of atmospheric driving forces, in particular precipitation, for the study of land surface processes (Task 2.2);

- Integrated analysis of environmental change in mountain regions by means of fully coupled land-atmosphere models, where feasible and appropriate, or by qualitative assessments (Task 2.3);

- Regional scale mountain land experiment to support the development, application and validation of the above models (Task 2.4).

Activity 3: Process studies along altitudinal gradients and in associated headwater basins

Ecological and hydrological field studies and experiments, including manipulative ones, along altitudinal gradients and at sensitive sites can provide invaluable data on potential responses of mountain ecosystems to anthropogenically induced environmental change as well as increasing understanding of the associated biotic feedbacks. They are also required to support modelling (Activity 2) and for the identification of indicators of global change. Research themes to be addressed within this

Activity include:

- Development of indicators of mountain ecosystem response to environmental forcing factors, based on an improved process understanding of these unique systems insofar as they are sensitive to global change forcings and for a process-related interpretation of historical and paleorecords (Task 3.1);

- Assessment of runoff generation and flowpath dynamics on steep hillslopes and in headwater catchments, including the examination of the role of biogeochemical 'hot spots', for instance for N transformation in mountain areas (Task 3.2);

- The relationship between diversity and ecosystem function, taking advantage of the strong changes of diversity along altitudinal gradients and an assessment of the associated changes in ecosystem functions (Task 3.3).

Paleoarchives will be used to explore system responses to both natural variability and anthropogenic impacts.

Activity 4: Sustainable land use and natural resources management

The overall objective of this Initiative is to evaluate and enhance sustainable land, water, and resource management strategies for mountain regions. Three priority areas are suggested for assessment:

- Changes in forest resources, with potential implications for agriculture, rates of erosion and magnitude of floods, and biodiversity (Task 4.1);

- Intensification and/or extensification of agriculture (including grazing), with potential implications for food security, rates of erosion and magnitude of floods, and biodiversity (Task 4.2);

- Changes in water resources due to factors such as changing agricultural practices, increasing temporary or permanent population, and/or increasing energy generation, with implications for downstream water supply, energy availability, flooding, and sediment transfer (Task 4.3).

Work on these linked themes will include paleoresearch, local knowledge and scientific investigation, e.g. with respect to evaluating optimal combinations of traditional and innovative land use and resource management systems.

I. Introduction and Rationale

Mountain regions occupy about one fourth of the Earth's surface (Kapos et al. 2000), they are home to approximately one tenth of the global population, and provide goods and services to about half of humanity (Messerli and Ives 1997; see Box 1). Accordingly, they received particular attention in "Agenda 21", a programme for sustainable development into the next century adopted by the United Nations Conference on Environment and Development (UNCED) in June 1992 in Rio de Janeiro. Chapter 13 of this document focuses on mountain regions, and states:

> "Mountain environments are essential to the survival of the global ecosystem. Many of them are experiencing degradation in terms of accelerated soil erosion, landslides, and rapid loss of habitat and genetic diversity. Hence, proper management of mountain resources and socio-economic development of the people deserves immediate action."

Moreover, mountain regions often provide unique and sometimes the best opportunities to detect and analyse global change processes and phenomena:

1) Due to the often strong altitudinal gradients in mountain regions, meteorological, hydrological (including cryospheric), and ecological conditions (in particular vegetation and soils) change strongly over relatively short distances. Consequently, biodiversity tends to be high, and characteristic sequences of ecosystems and cryospheric systems are found along mountain slopes. The boundaries between these systems (e.g. ecotones, snowline, and glacier boundaries) may experience shifts due to environmental change and thus can be used as indicators; some of them can even be observed at the global scale by remote sensing.

2) Many mountain ranges, particularly their higher parts, are not affected by direct human activities. These areas include many

national parks and other protected, "near-natural" environments, including biosphere reserves. They may serve as locations where the environmental impacts of climate change alone, including changes in atmospheric chemistry, can be studied directly.

3) Mountain regions are distributed all over the globe, from the Equator almost to the poles and from oceanic to highly continental climates. This global distribution allows us to perform comparative regional studies and to analyse the regional differentiation of environmental change processes in mountains as characterised above. Moreover, mountain regions typically offer a wide variety of ecosystems within a small geographical area, thus providing a small scale model for latitudinal changes.

The continued capacity of mountain ecosystems to provide the goods and services listed in Box 1 may be threatened by the increasingly global scope of human impact on the Earth. Global environmental change can be broadly classified into two categories: systemic vs. cumulative changes (cf. Turner et al. 1990). Systemic changes affect the environments at global scales (e.g. trace gas induced climate change). Cumulative changes are generated by processes that operate at a local scale but that are becoming globally pervasive (e.g. land cover/use change, air pollution, loss of biodiversity).

A third source of change in mountain environments is globalisation, i.e. the growing global integration of social, political and economic relationships. Globalisation as it affects mountain environments is reflected in (1) demographic changes, such as population growth, seasonal (including tourism) and permanent migration, and changing age/sex structures; (2) the incorporation of mountain economies into extra-regional economies; (3) the increasing influence of urban processes and perspectives, through urbanisation and new communications, including transport and various electronic media; (4) increases in consumption; and (5) changes in the location of decision-making and institutional arrangements, resulting from policy developments at all scales (Programme Advisory Committee, 1999).

Box 1: Goods and services provided by mountain regions.

Goods provided by mountain regions to those living in these regions as well as to populations in lowlands include:

- water (for consumption, irrigation, energy production);
- food (crops, domesticated and wild animals);
- wood (for energy and construction);
- non-timber forest products (fibres, foodstuffs, medicinal plants);
- minerals.

Services provided by mountain ecosystems include:

- maintenance of soil fertility and structure, and associated limitation of soil erosion (particularly of local benefit);
- downstream movement of soil nutrients (upstream loss, downstream gain);
- avoidance/mitigation of damaging impacts of disastrous events, such as floods, landslides, avalanches (of both local and downstream benefit);
- provision of landscape as amenity (mainly of benefit to extra-regional tourists and recreationists, but also to local amenity migrants and those depending on the tourist economy);
- biodiversity (of local benefit, but also of extra-regional value in terms of existence value and genetic potential);
- cycling and storage of carbon and soil nutrients (of importance at the global scale).

For all the reasons mentioned above, mountain regions are of particular significance for various aspects of global change research.

For the next few decades, globalisation processes are likely to be at least as important as environmental changes as factors promoting change in mountain regions. At the same time, the cumulative and systemic environmental changes may significantly threaten the ability of mountain regions to provide the critical goods and services described above, both to mountain inhabitants and to supply the extra-regional demands of other communities. Therefore, in order to mitigate these threats, this integrated workplan describes a series of co-ordinated experimental, observational, and modelling studies, with the aims of detecting and articulating the consequences of global environmental change and informing policy processes at local to global scales (Figure 1).

II. Objectives

The IGBP Initiative on Global Change Research in Mountain Regions is based on an integrated approach for observing (detecting, monitoring), modelling and investigating global change phenomena and processes in mountain regions, including their impacts on ecosystems and socio-economic systems. Both environmental aspects — in particular land use/land cover changes, atmospheric and climatic changes — and socio-economic aspects — in particular social, economic, and political driving forces and changes — as well as their complex interactions and interdependencies will be taken into account.

The objectives of the Mountain Research Initiative are:

1) to develop a strategy for detecting impacts of global environmental change on mountain environments;

2) to define the consequences of global environmental change for mountain regions as well as the downstream lowland systems dependent on mountain resources; and

3) to develop sustainable land, water, and resource management strategies for mountain regions at local to regional scales.

The emphasis of the first objective is on monitoring change in the biophysical environment, and on understanding the interacting ecological and hydrological processes in mountain regions, both with and without local human interference, along altitudinal and other gradients (e.g. land use). Such work recognises the unique value of many mountain ecosystems that have been and remain relatively uninfluenced by direct human activities, especially in protected areas such as parks and biosphere reserves. The aim of this objective is to develop a network of observation sites in mountains to serve as an 'early warning' system for detecting global change impacts.

The emphasis of the second objective is to increase our understanding of the consequences of global environmental change for people and ecosystems.

Credible impact assessments form the baseline for informing policy-makers on issues of global environmental changes at local to global levels (cf. Figure 1). In addition, information from impact assessments has direct application to policies and strategies for resource management that are implemented at local and regional scales.

The emphasis of the third objective, developing sustainable development strategies, is to define a set of potential human responses to global environmental change implementable at local and regional scales. Scientific results developed under this objective would assist policymakers by indicating the extent of degradation of key mountain resources, and by evaluating interactions between alternative resource management strategies at local and regional scales and trajectories of change generated by globally-scaled factors.

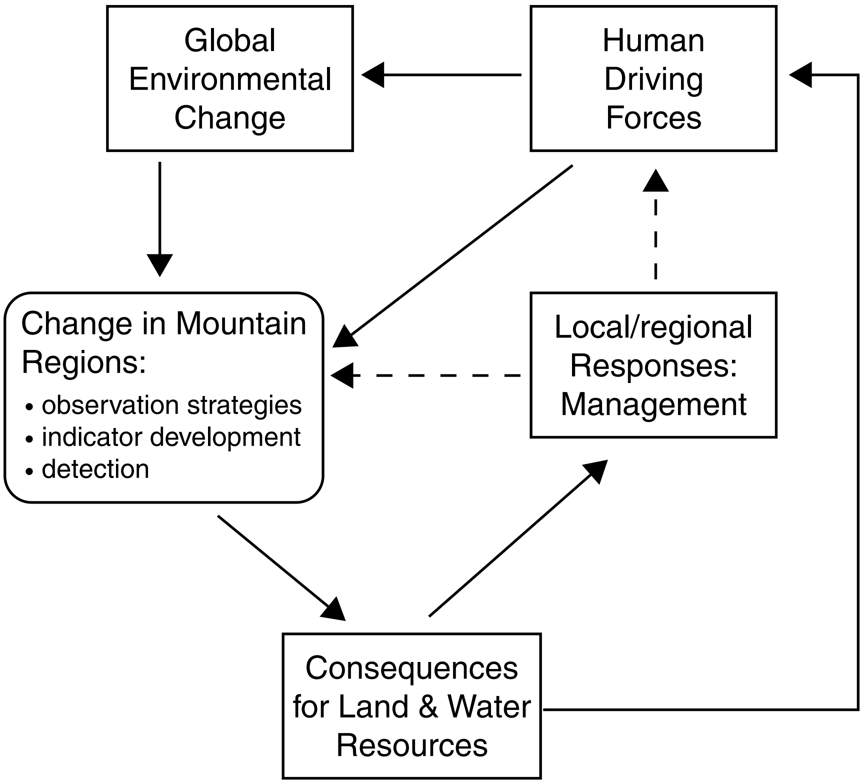
A particular value of the integrated approach described here is the explicit nesting of the evaluation of local and regional management strategies into a broader framework of global processes and impacts (Figure 1). This approach to integration thus adds value to the well-developed theories and practices that fall under the heading of 'environment and development' studies by embedding them in a global context.

Research-based knowledge on past landscape development can greatly enhance our understanding of current and future conditions. For example, the present-day status of terrestrial ecosystems, glaciers, and areas of permafrost is strongly influenced by the environmental conditions that prevailed years, decades, centuries, or even millennia in the past. Studies of past environmental change in mountains are extremely important and valuable in this context, and they form an excellent basis for reconstructing the associated impacts on ecosystems and humans with a much higher spatial resolution than elsewhere. Processes such as climatic forcing and ecosystem dynamics operate and interact on a wide range of time scales, from individual extreme events to century- and millennial-scale variability. Long-term records of past changes from mountain regions may provide specific types of information needed for a more complete understanding of past global changes at several scales.

Documenting process dynamics on all of these time scales requires a diversity of methods and archives, and understanding the full interplay of processes requires that insights from all these methods be used in conjunction so that the complex reality of mountain ecosystems, as they change through time, is reflected in the synergy between the various scientific approaches used to study them.

Figure 1

Conceptual framework for the integrated study of global environmental change in mountains, emphasising feedbacks that occur both within a given mountain region (inner loop) as well as at the global scale (outer loop).



III. Integrated Interdisciplinary Approach

The IGBP Mountain Research Initiative strives to achieve an integrating, interdisciplinary character and comprehensiveness, which implies the following:

1) Integration and further development of ongoing monitoring and observation networks in mountain regions, equating to Level 3 of the Global Hierarchical Observation System (GHOST), i.e. including sites from the World Glacier Monitoring Service, high mountain ecological field stations, research watersheds, biosphere reserves, etc., with a particular emphasis on including long historical and paleorecords covering a broad variety of disciplines. These long-term observation systems will be used to detect and analyse signals of global change (Activity 1).

2) Comparative assessment of the sensitivity and vulnerability of the mountain regions of the world with respect to environmental and societal change, including their complex interactions and feedbacks. This will be based on the development and application of an integrated modelling framework (Activity 2).

3) Further development and integration of our understanding of mountain-specific hydrological, ecological, and socio-economic processes so as to improve our ability to detect and analyse signals of global change (cf. item 1, above) and to contribute to the development of the integrated modelling framework (item 2, above). This will be achieved through process studies in mountain environments, in particular along altitudinal gradients and in associated headwater basins (Activity 3).

4) The derivation of strategies for sustainable resource management in mountain regions, which are intended to avoid or mitigate damaging effects of disastrous events (Activity 4).

Glaciers and snow are belonging to the hydrosphere and are subsumized and included thereunder even if not explicitly mentioned.

To achieve its overall objectives, the research under the Mountain Initiative will be structured around the above four Activities. Below, a number of cross-cutting issues are discussed, and a nested design for research activities is proposed. Then, the four Activities outlined above are refined by setting up specific research Tasks, including descriptions of their suggested implementation.

There are a number of general issues that need to be kept in mind when implementing the research under the four Activities:

1) It is necessary to understand and describe both the separate effects and the potential interactions of key drivers of environmental change, as many of them operate at global scales and have an impact on mountain environments. These include the separate as well as interactive effects of increasing concentrations of CO_2 and other trace gases, nitrogen deposition, greenhouse-gas induced climatic change, increasing UV-B radiation, and changes in land use and land cover. It should be kept in mind that the importance of these global change forcing factors will vary from region to region, and a critical step will be the appropriate assessment of the interactions between climate and land surface processes in complex mountainous terrain, using both present day observations and reconstructions from paleodata.

2) The understanding developed under item 1) needs to be applied to project the direction and rate of change of key indicators of environmental change in mountain environments under differing drivers. Candidate indicator variables might include: glacier characteristics (extent, mass balance etc.); snowline; catchment runoff; streamflow chemistry; species occurrence, abundance, and phenology; trends in lake status recorded in recent sediments, ecotone dynamics, etc. Comparison of different scenarios of change will allow an estimation of the sensitivity of the different indicators to global environmental change, and consequently their classification in terms of response times (phase shifts) and the establishment of generalised interrelations.

3) The observed or reconstructed trajectories of key indicators need to be compared with those predicted under different scenarios of change with particular attention to region-to-region variation. 'Detection' of global change effects in mountain systems will be based on an identification of spatial and temporal patterns of change in a suite of indicators that are consistent with predicted patterns derived from the scenario analyses in item 2).

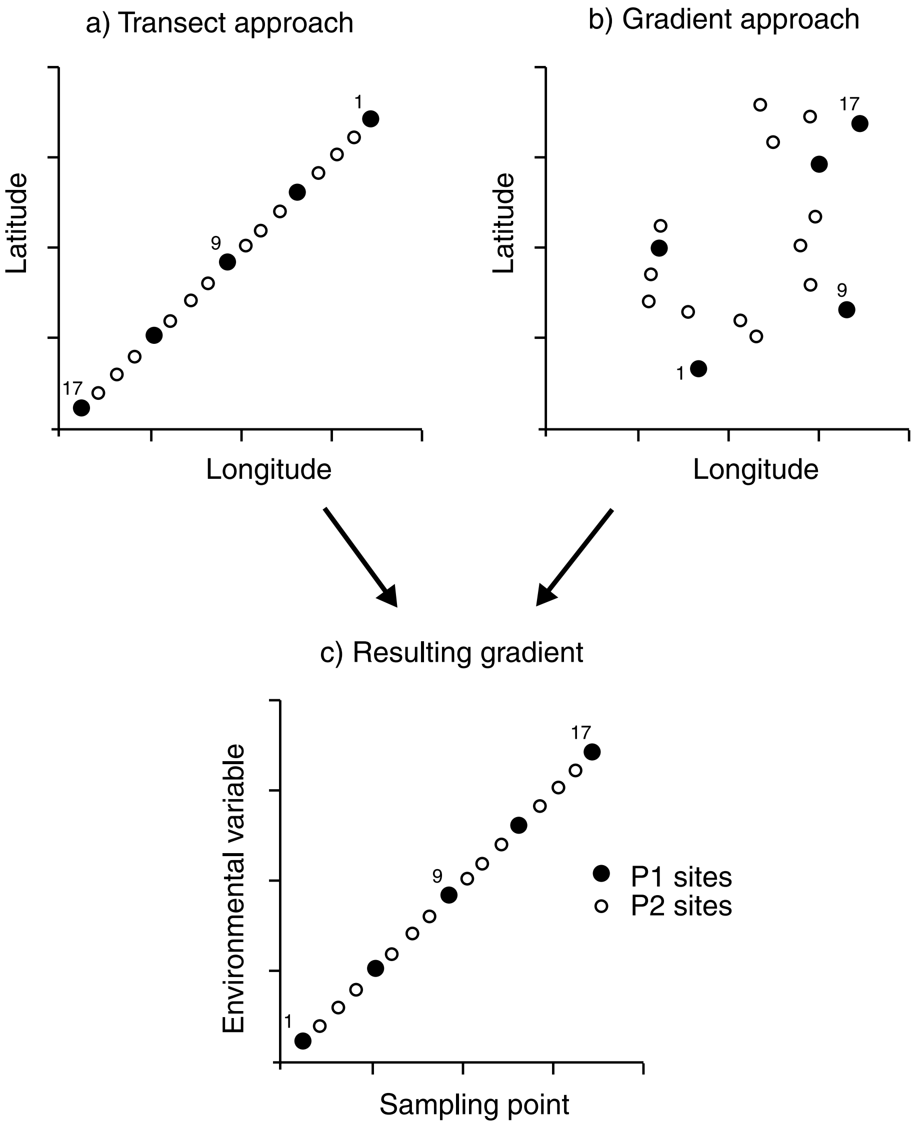
4) A key supporting argument for the imprint of human activities on patterns of mountain ecosystems will be a series of indicator variables that exceed the range of variability reconstructed for pristine systems. In many cases (e.g. treeline, retreat rates of glaciers) these data are readily available, e.g. from various PAGES archives. For example, natural “background” rates of chemical deposition are recorded with annual resolution in ice cores from mountain glaciers. Varved sediments in lakes provide records of natural variability in climate and lake ecosystem dynamics with a similarly high resolution. For the past century, anthropogenic effects, ranging from catchment disturbance to inputs from both local and remote sources of atmospheric pollution, are also reflected in these records.

In the application of the approach, i.e. across all the research activities described below, a “nested design” should be used that is capable of capturing the systematic variation of ecological, hydrological and socio-economic processes across various spatial scales, and in particular along strong altitudinal gradients. Often, a watershed approach is most appropriate because numerous process gradients change at watershed boundaries. Within a watershed, a major subcatchment should be identified, and successively smaller subcatchments within it should be selected until the highest (topmost) subcatchment in the watershed is identified. In the ideal case, this will provide a series of nested watersheds along an altitudinal gradient which will encompass the scale-related variation in the larger watershed. Assuming that instrumentation and monitoring activities are allocated equally to each subcatchment, finer scale processes can be examined in the smallest subcatchments and scaled up to the entire basin with quantitative adjustments made for altitudinal changes (made possible because of the inherent altitudinal transect of the instrumented nested design). Where lakes occur within nested catchment systems, their sediment record can serve as a basis for combining temporal with spatial integration.

The intensity of such a nested design implies that it cannot be implemented widely. It will be important to have broad geographic coverage and to be able to support monitoring systems over the long term. This approach must be coupled with an extensive, low-effort monitoring programme. Therefore, similar sites and basins should be indexed to the intensive site (“master station“) by collecting data at lower spatial and temporal resolutions (cf. Fountain et al. 1997). With this approach, a small number of “master stations” and “headwater catchments“, where detailed, high-intensity sampling is conducted with high priority (P1 sites; cf. Figure 2), can be complemented by a substantially larger number of lower-intensity sampling sites and watersheds (P2 sites), where only a subset of the measurements of the P1 sites is conducted. Thus, it becomes possible to elucidate and test hypothesised relationships between properties measured only at P1 sites and those measured at P2 sites, including scale relations, which then serve to describe the systematic variation of the properties of interest across the whole gradient and range of scales.

Figure 2

Idealised setup of altitudinal gradient studies distinguishing “master stations“ / “headwater catchments” (P1 sites) vs. secondary sites and watersheds (P2). The design in geographical space (panels a and b) should be arranged so that the sampling points define a monotonic gradient of the underlying environmental variable (e.g. temperature, soil moisture, CO_2, etc.) that is of interest (panel c).



IV. Research Activities and Tasks

Activity 1: Long-term monitoring and analysis of indicators of environmental change in mountain regions

Due to the often strong altitudinal gradients in mountains and accordingly remarkable changes over relatively short distances in meteorological, hydrological (including cryospheric), and ecological conditions (in particular land cover, soil, and related conditions), mountain regions provide unique opportunities for the detection and analysis of environmental change processes (cf. Box 2). This element of the IGBP Mountain Research Initiative will focus on mountain-specific indicators of environmental change, which are sensitive to changes in climate, atmospheric chemistry, radiation, and land use / land cover. Sets of such indicators are defined below that can be used (1) to detect and analyse signals of environmental change, and (2) to study both direct cause-effect relationships in individual systems as well as changes that derive from the complex interactions of different drivers of global change.

Box 2. Empirical evidence of the climatic sensitivity of mountain systems.

Recently, evidence was provided by re-sampling studies in the central Alps (Grabherr et al. 1994) that species richness has increased at the majority of investigated high summits since the turn of the century, suggesting that the warming recorded since that time has been ecologically relevant (cf. Pauli et al. 1996).

Similarly, climate change during this century has significantly affected the cryosphere. For example, glaciers have retreated worldwide (cf.

Haeberli 1995), and the temperature of the permafrost layer in the European Alps now appears to change remarkably (Haeberli and Beniston 1998, Vonder Mühll et al. 1998).

Mountains therefore provide a large variety of both ecological and physical indicators, whose combined use might serve as a unique chance to observe and detect signals of global environmental change.

Monitoring and the study of ongoing changes and their complex dependence on the different atmospheric driving forces, topography, land use/land cover, soil properties, and other features (cf. Activity 3) should be complemented by the reconstruction of longer time series of relevant indicators from historical and paleorecords. Therefore it is crucial that new research sites, altitudinal gradient and headwater basin studies in different mountain regions are located at or near sites where historical and paleorecords can be made available, so that the results from recent observations and research can be related directly to those records.

The following set of indicators are considered in more detail below:

- cryospheric indicators related to snow cover, glaciers, permafrost and solifluction processes (Task 1.1);

- terrestrial ecosystems, particularly mountain plant communities and soils (Task 1.2);

- freshwater ecosystems, in particular high mountain streams and lakes, together with the sediment record they contain (Task 1.3);

- watershed hydrology, i.e. the water balance components of high mountain watersheds and headwater basins (Task 1.4).

These indicators have been chosen based on the current understanding of the special process dynamics in mountain systems and their sensitivity to climate and land use change. However, since our understanding of these processes is incomplete, additional studies and experiments are required to refine the definition of suitable indicator variables and their link to specific environmental forcing factors (cf. Activity 3).

All studies under Activity 1 will build first of all on data sets and results available from existing long-term research networks (e.g. high mountain field stations, biosphere reserves, gauged watersheds and paleoenvironmental research sites, which are supported by various national funding agencies and trans-national bodies, e.g. the European Commission). Where required, new monitoring projects will be initiated in mountain regions around the world.

Task 1.1: Cryosphere

Background

Cryospheric systems have long been known to be sensitive to changing environmental conditions, as evidenced by the well-known advances and retreats of glaciers that have been observed during the past few centuries (cf. Box 2). Cryospheric systems thus provide unique opportunities for monitoring environmental changes, in particular in mountains with their strong altitudinal gradients. Many of these indicators can easily be measured, and a long measurement record including paleoarchives is available, thus providing a means to separate short-term variability from long-term signals (cf. Gäggeler et al. 1997).

Objective

- To monitor and analyse on a global scale cryospheric and the controlling atmospheric variables that can serve to detect the impacts of anthropogenic environmental changes on cryospheric systems.

Implementation

Cryospheric indicators and the controlling atmospheric variables as listed below need to be analysed simultaneously to determine where single cause-effect relationships are prevailing, and where complex interactions of several input parameters are integrated. Their measurement or sampling should be quick and easy. The following preliminary list of indicators needs to be refined and augmented as new research results become available:

A. Atmospheric input variables:

- parameters of energy and water fluxes, such as temperature, precipitation (rain, snow), radiation, cloudiness and albedo

- pollutants and dust (e.g. Döscher et al. 1995).

B. Cryospheric indicators:

- seasonal snow - water equivalents, duration, first and last appearance, snow temperature

- snow chemistry - ion composition, dust content, isotopes, organic matter

- glaciers - area, length, mass balance (at index stakes), ice velocity, occurrence of perennial ice patches (cf. the GCOS Terrestrial Network project for Glaciers, GTN-G, and the Global Land Ice Monitoring (GLIMS) project of the US Geological Survey)

- lake freeze-up/break up

- permafrost - temperature and thickness of active layer, temperature depth profiles, permafrost creep (rock glaciers) (cf. the efforts of the International Permafrost Association, GTN-P)

- solifluction - frost heave / thaw settlement and frost-induced soil movements.

In the monitoring activities, special emphasis should be placed on those indicators whose behaviour in the past is known well from historical and paleorecords. In this regard, the environmental paleoarchives of greatest value are those that preserve a high resolution, accurately dated, potentially quantifiable record continuing uninterrupted through to the present day and capable of providing information that can be realistically compared with results based on contemporary measurements.

The research under this Task should be set up to contribute to and complement the GCOS/GTOS observation systems (Cihlar et al. 1997, WMO 1997), and should be coordinated with the WCRP Task Group on Climate and the Cryosphere.

Task 1.2: Terrestrial ecosystems

Background

Ecosystems at the low temperature limits of plant life (arctic and alpine environments) are generally considered to be sensitive to climate change. (e.g. Beniston 1994, Guisan et al. 1995; cf. particularly Körner 1994, 1995a). Because of strong topographic and thus climatic variation, mountain regions are among the world's hot-spots of biodiversity (Chapin and Körner 1995a, Barthlott et al. 1996, 1997). Due to their continuous exposure to extreme environmental conditions, mountain systems have developed well adapted but still sensitive forms of life which respond in characteristic ways to continuous and/or abrupt environmental changes (cf. Box 2). Accordingly, the record of events that have influenced the dynamics of mountain systems is archived in lake sediments, wetlands, tree rings, vegetation patterns and structure, and also in glacial ice.

Many high mountain ecosystems have been influenced by human activities, but many others have remained in a rather natural stage. Thus, global change effects that are primarily transmitted via the atmosphere are likely to be detectable in high mountain ecosystems. Moreover, mountain ecosystems are not only useful to follow past and present environmental changes, but they can also serve as reference sites for comparison with changes in lowland ecosystems, which are under more complex pressures, especially land use change and intensification, and which often are better buffered.

High-elevation mountain systems form an important component of paleoecological research and provide insights on the influence of environmental parameters on, e.g. plant growth (tree rings) and vegetation composition (pollen and macrofossil profiles from lakes and mires) across several centuries to millennia. Consequently, such archives are an invaluable source for determining, among others, the natural variability and lag effects of biological indicators along altitudinal gradients and across different mountain regions.

Objective

- To monitor on a global scale short, medium, and long term changes of mountain terrestrial ecosystems, particularly vegetation and soils, at various spatial scales in parallel with atmospheric parameters.

Implementation

Special emphasis should be placed on representing the major life zones on Earth (tropical, subtropical with seasonal precipitation, subtropical arid, Mediterranean, wet temperate, temperate, cold arid, boreal) by at least one mountain monitoring region.

Ecological and atmospheric indicators should be identified, monitored and analysed by applying the principles outlined in Task 1.1 concerning single cause-effect relationships or complex interaction of several input parameters. Their measurement (sampling) should also be quick and easy. A list of preliminary indicators is suggested as follows:

A. Changes of the atmospheric input:

- parameters of energy and water fluxes, such as temperature, precipitation (rain, snow), radiation, cloudiness and albedo

- atmospheric fallout and deposition of nutrients, pollutants etc. as a component of global biogeochemical cycling

B. Changes in vegetation and soil biota:

- seasonal and inter-annual changes: phenology of vascular plants; dynamics of seedling and sapling banks; mortality rates for selected species; estimates of net primary production; tree ring records

- changes up to decades and a few centuries: vascular plant diversity, vascular plant composition (invaders from warmer, drier, or wetter habitats, appearance of exotics, extinctions), functional types composition (vascular plants, mosses, soil organisms such as nematodes and functional groups of microbes); soil temperature in the root layer; tree ring records

- decadal to century or even millennial scale changes: landscape diversity expressed as richness in communities and composition, beta and gamma diversity (vascular plants, mosses), and community patterns.

The indicators should be recorded along altitudinal gradients which are arranged according to the "single mountain" or the "multi-summit" approach (i.e. mountain tops of different altitude in a particular mountain region; cf. also Figure 2 and the related general considerations). These permanent plots should be placed at ecotones, e.g. at lower and upper treeline, at the dwarf shrub-grassland and the shrub-giant rosette ecotone, at the upper limit of closed vegetation, and at the upper limit of plant life.

However, physical and ecotonal boundaries are not necessarily sensitive to environmental change. For example, some ecotones are known to respond with very long lag times to environmental changes (e.g. Davis 1989), and some boundaries may not be sensitive at all with respect to certain environmental changes (e.g. Hättenschwiler and Körner 1995, Körner 1998, Bugmann and Pfister 2000). Many ecotones exist as the result of disturbance, rather than climate, and in many cases these ecotones are causing climatic gradients (e.g. wind, evapotranspiration) rather than vice versa. The selection of appropriate boundaries and ecotones thus will be crucial for this Task.

Given the diversity of sampling designs and methods used in terrestrial ecology, it is planned to develop a handbook that describes the recommended sampling and measurement protocols as well as the handling of data sets. The approaches used in the ITEX project (cf. Henry 1997), and particularly the ITEX manual (Molau and Mølgaard 1996) could serve as a useful template. This handbook should identify different levels of activities and the minimum set of observations that are required (cf. Figure 2).

Task 1.3: Freshwater ecosystems

Background

High-elevation freshwater ecosystems (streams and lakes) are characterised by a relative lack of direct anthropogenic influences. This and the fact that they are among the first recipients of atmospheric pollutants makes them prime candidates for detecting atmospheric signals of environmental changes and specifically of the ecological impacts of changing atmospheric composition.

High-elevation lacustrine sediments also comprise a core PAGES proxy record. In identifying indicators of global change impacts along altitudinal gradients, attention should be paid to the added value provided by an accurate reconstruction of the long term past behaviour of the potential indicator, and its response to pre-anthropogenic global climatic variations. Assessing the lag times associated with ecotone response to environmental change is also an area of active research within PAGES.

Objective

- To identify and monitor on a global scale changes of atmospheric inputs to and the pertaining physical, chemical and ecological responses of high-elevation freshwater ecosystems.

Implementation

To use high-elevation streams and lakes for detecting signals of global change, we propose to adopt indicators that define atmospheric inputs and the pertinent responses of these systems as follows:

A. Atmospheric inputs:

Parameters of energy and water and biogeochemical fluxes: air temperature, precipitation (rain, snow), wet and dry deposition (e.g. inorganic and organic pollutants, heavy metals), chemical quality of precipitation (e.g. pH, electric conductivity, ion composition)

B. Limnological responses:

Lakes:

- physical stability and stratification characteristics, heat budgets

- chemical composition (water quality characteristics)
- trophic status and biological community composition
- bioproductivity (chlorophyll)
- biodiversity
- sedimentary sinks and sources of nutrients
- sedimentary records.

Streams:

- quantities and chemical composition of streamflow
- species/population diversity based on selected groups.

There are a number of crucial requirements for high-altitude lakes if they are to be useful in the present context:

- remote, not directly influenced by human activities
- above the treeline, i.e. in the alpine and nival zones
- moderately buffered (pH)
- removed from direct human influences
- responsive to acid (N, S) and nutrient (P, N, S) inputs
- low pollutant background
- known food web
- temporal variability measurable.

This Task links to two recently established initiatives within PAGES Focus 3 (Human Interactions in Past Environmental Changes): (1) LUCIFS (Land Use and Climate Impacts on Fluvial Systems during the period of agriculture) uses a river drainage basin/case study approach, and among the case studies are several that include mountain regions; (2) LIMPACS (Human

Impact on Lake Ecosystems) also has a focus on high-altitude lakes and their recent sediment record.

Task 1.4: Watershed hydrology

Background

Precipitation, evapotranspiration and runoff as basic components of the water balance of any reference area at the land surface represent essential indicators of climate and environmental change, particularly of extreme hydrological events. In addition, they directly influence many of the indicators mentioned in Tasks 1.1 to 1.3. Therefore, the three water balance components and their interdependence should be studied simultaneously in a number of selected gauged mountain watersheds that do not experience direct human impacts. High mountain watersheds, especially in wilderness areas or national parks, are best suited for such studies and thus provide an excellent core for a network of climate change monitors. Moreover, these systems are often characterised by natural vegetation only, which itself might serve as an indicator of global change.

Objective

- To monitor and determine on a global scale the temporal variation of the three basic water balance components (precipitation, runoff, evapotranspiration), their interdependencies and extremes in high mountain catchments / watersheds not directly influenced by human activities.

Implementation

In the first phase of implementation, appropriate mountain gauged watersheds need to be selected that can form a part of the global network to be established. Where required, additional watersheds may be suggested to fill gaps in the existing global network. Within all these basins, the current network of precipitation stations needs to be evaluated with reference to the special requirements for precipitation monitoring in mountain regions. Steps need to be taken for improvements where required.

The first step in the analysis itself is to calculate on a continuous basis (e.g. daily) actual evapotranspiration from meteorological data and land surface characteristics. These data, together with the recorded discharge and precipitation series, are then used for a continuous water balance calculation over the whole observation period and for the determination of the temporal variation of total basin water storage required to apply the water balance check as suggested in IGBP Report #43 (Becker and Bugmann 1997). The resulting time series of water balance components (in corrected form) may then serve (i) to identify systematic changes which may be due to climate change, and (ii) also for larger-scale comparison and analysis (up to global).

Finally, the results of this analysis will be compared and combined with those received from other indicators of global change (cryospheric, ecological, etc.) to get a more complete picture of environmental change at the relevant scales. Moreover, special studies will be carried out on extreme hydrological events, in particular floods and their effects in terms of inundation (extent, damage, etc.), erosion, landslides, debris flows, sediment transport and accumulation, etc. Results of these studies will serve not only as a basis for the planning of flood protection measures and flood risk management but also for the improved understanding of the processes and of paleorecords, in particular sediment cores form rivers, lakes and valleys.

Paleorecords in general will be used to reconstruct past dynamics of climate and hydrological and ecological conditions. Most important in this context are:

1. lake studies, both via reconstructions of flood related sedimentation layers, shore-line fluctuations and salinity-linked biotic variations in the sediment record;

2. the analysis of cores taken from ice, snow and even permafrost, in particular those providing information on fluctuations in the amount and sources (e.g. using stable isotopes) of past precipitation in mountain regions; and

3. tree ring analyses in regions where moisture availability is or was the dominant stress on tree growth.

The anticipated watershed network should form a component of the Global Terrestrial Observing System (GTOS).

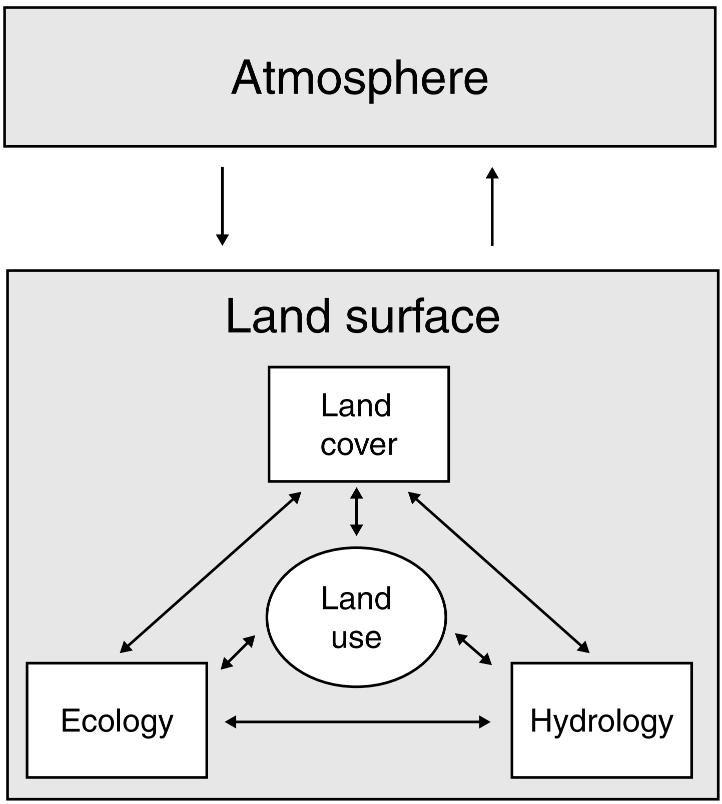
Activity 2: Integrated model-based studies of environmental change in different mountain regions

To implement the integrated approach described in Section III of this Initiative, it is necessary to develop a framework that permits us to analyse and assess the predictability and vulnerability of hydrological and ecological characteristics and their linkages in mountain regions as influenced by current as well as possible future climate and anthropogenic land surface conditions. The core component of such a framework will be a system of coupled ecological, hydrological, land use/land cover models, and also atmospheric models that allow to synthesize and analyse field data, to perform sensitivity analyses, and to assess the potential effects of environmental change. Great care needs to be taken to ensure the compatibility of these models so as to allow for their coupling (Figure 3).

Such a framework and corresponding model systems are needed for different spatial and temporal domains, i.e. from global to regional and even local scales and for time horizons from days and weeks to centuries. As a matter of fact, mountain regions, due to their complex topography, are inappropriately represented in current global and regional models. Therefore, special efforts are required to develop improved models for studies of environmental change in mountains. It is recognized in the global change modelling community that regional studies in mountain areas are urgently needed, not only for the understanding and analysis of environmental change and its *impacts* on mountain regions themselves, but also with respect to the *feedbacks* from mountain regions to continental and global scale processes (Figure 3).

Figure 3

Components of an integrated model for assessing the effects of environmental changes in mountain regions. The terms "Land cover" and "Land use" are used here to refer to the direct anthropogenic influences on land surface properties (e.g. conversion of forest to pasture).



To achieve this objective, research is suggested under the following four Tasks (cf. Figure 3):

1) Development of coupled models of ecological dynamics, hydrological processes and anthropogenic land cover/land use changes in complex mountain landscapes and river basins under current and changing atmospheric and socio-economic conditions. Efforts towards this objective will benefit from progress made in the land use/cover change modelling community, in particular, their efforts to develop improved theory and empirical methodology for coping with heterogeneity (LUCC Scientific Steering Committee 1999). Where appropriate paleodata are available, these will be used to constrain and evaluate the models under different conditions of climate and land cover (Task 2.1);

2) Development of regional scale atmospheric models for mountain regions capable of providing high resolution areal distribution patterns of atmospheric driving forces, including precipitation, for the study of land surface processes (Task 2.2);

3) Integrated analysis of environmental change in mountain regions by means of fully coupled land-atmosphere models, where feasible and appropriate, or by qualitative assessments (Task 2.3);

4) Regional scale mountain land experiment to support the development, application and validation of the above models (Task 2.4).

In the context of Activity 2, it will be important to identify those changes in mountain land and/or water resources that are driven by environmental change and bring about changes in the ability of a given region to support current and future livelihoods, i.e. its vulnerability. The paleorecord provides the potential to document such changes and their impacts on time scales that are at one and the same time beyond the reach of direct observations, yet well within the time frame of direct concern for future sustainability.

In these studies, particular attention will be placed on those characteristics that are of particular interest for sustainable development in view of environmental change (cf. Activity 4), namely:

- changes in forest resources (area and/or composition and structure),

- intensification and/or extensification of agriculture (including grazing), with implications for food security, availability of water resources (quantity and quality), rates of erosion, slope stability, magnitude of floods, and biodiversity;

- changes in water regimes and resource availability due to factors such as changing agricultural practices, increasing permanent or temporary population, and/or increasing energy generation with implications for downstream water supplies, energy generation, flooding and sediment transfer.

Consequently, special models to describe these key systems need to be developed (Task 2.1) and applied (Tasks 2.1, 2.3, 2.4), and their sensitivity to environmental change processes needs to be examined based on comparative regional case studies. Again, paleorecords could be very helpful in testing the capabilities of the models to represent:

a) the interplay between atmospheric variability and changes in glaciers, water cycles, vegetation, soils and the intensity of exploitation by human populations

b) the implications of processes operating on decadal or longer time scales

c) non-linear system responses within the complex interactions under study

d) changes in magnitude-frequency relationships and their consequences in terms of resource depletion and of hazard to human populations.

Mathematical models represent hypotheses regarding a set of processes. Therefore, their testing and evaluation through field studies needs to be an iterative process, and models should be viewed as continuously evolving rather than static research tools. Model development should always be performed in close collaboration with monitoring (Activity 1) and process studies (Activity 3), taking into account the complexities generated by topographic diversity and the associated steep and interacting environmental gradients. The co-evolution of regional-scale modelling and monitoring strategies has clear linkages to the IGBP Land Use and Cover Change project's framework which emphasizes the flow of information between intensive case studies, extensive direct observations, and integrated models.

Moreover, modelling activities are always problem- and scale-specific. Hence, it is not suggested that one single model structure should be developed that might be used for answering all the different questions. But basic capabilities such as the ability to generate altitudinal gradients of atmospheric, hydrologic and ecosystem processes will always be essential for their application in mountain research. An important aspect will be to study, for instance, the temporal evolution and spatial manifestations of hydrological and ecological changes that have occurred as a result of climate changes in the past, such as across the Holocene.

Task 2.1: Coupled ecological, hydrological and land use models

Background

In mountain regions, changes of ecosystem structure and composition, ecosystem function, hydrology, atmosphere and land use are intimately linked with each other and have strong impacts on the overall functioning of these regions (e.g. Cernusca 1989). If critical thresholds are exceeded within one of the subsystems, dramatic and often long-lasting impacts may occur in other sub-systems (e.g. increased surface runoff may lead to landslides, which change landscape pattern, carbon balance, vegetation distribution, etc.). Therefore, models capable of describing these processes and interdependencies, their spatial variability and effects are required (cf. Figure 3).

Objectives

- To develop, test and apply coupled ecological, hydrological and land use models for the simulation of land surface processes in complex mountain landscapes and river basins under current and changing atmospheric conditions and land use.

- To combine descriptions of the dynamics of ecosystem structure, biogeochemistry, hydrology, and land cover/land use, to effectively explore mountain ecosystem linkages and their response to changing climate and land use.

Implementation

There are a number of challenges to the development of coupled ecological, atmospheric, hydrological and land use models in mountain regions and to the testing of their capability to represent the observed altitudinal variation along mountain slopes (cf. Box 3). These include:

- linking models of ecosystem structure with biogeochemistry models. Historically, most modelling attempts have focussed on either structural aspects of ecosystems (e.g. Shugart 1998), or on biogeochemical cycling (e.g. Running and Coughlan 1988). Recent models that address these linkages (e.g. Friend et al. 1997, Bugmann et al. 1997) need to be developed and tested further.

- incorporating the interactions between different life forms of plants and their altitudinal variations in a single model. There are large gaps in space and time that need to be bridged in modelling competition between different life forms such as grasses and trees (e.g. Fulton 1993).

- linking combined models of ecosystem structure and function with hydrological models. The integration of hydrology (water fluxes) and biogeochemistry (specifically, carbon, and nitrogen fluxes) has reached a preliminary stage (e.g. Band et al. 1991, Krysanova et al. 1998, Baron et al. 1998). But the specific flow paths that water and associated biogeochemical fluxes take in mountain environments are not yet fully understood and accordingly not adequately described in the models. Moreover, *predictive* models of ecosystem structure have hardly ever been coupled to hydrological models.

- incorporating the impacts of land cover/land use changes on ecological, atmospheric, and hydrological dynamics as related to altitude and other mountain-specific attributes. A number of studies exist on the impacts of drastic changes in land cover/land use, such as deforestation and urbanization, on regional climate and hydrology. Typically, these changes are represented in ecological and hydrological models by imposing land cover/land use masks (i.e. sensitivities to change). However, it is impossible to predict anthropogenic land-cover/land-use dynamics as such far into the future; this applies particularly for the complex conditions in mountain regions.

A number of challenges arise in integrating land use and cover change into ecological and hydrological models. Models must be able to simulate, for example, the long-term effects of different harvesting regimes on vegetation structure, biogeochemistry, and hydrological properties. Moreover, where consequences are cumulative but non-linear, and their detection and impacts are deferred only until critical thresholds are transgressed, the longer time perspective of paleoresearch may be invaluable, especially for the collaborative work between present day ecologists and paleoscientists.

Box 3: Basic requirements for ecological, atmospheric and hydrological models.

To assess the predictability and vulnerability of hydrological and ecological processes in mountain regions, altitudinal gradients have an important role because they provide a unique means for testing ("validating") models along systematically changing environmental conditions. Specifically, to assess predictability these models need to fulfil the following requirements:

- The models need to successfully simulate the properties of interest along environmental gradients. If a model fails such a test, it cannot predict the effects of transient changes of climate.
- The models need to correctly simulate the occurrence of thresholds vs. continuous changes of system properties (e.g. Pacala and Hurtt 1993, Schenk 1996).
- The models need to be tested for their ability to simulate ecological and hydrological properties under a wide range of different but realistic climatic conditions, since climatic change may represent environmental conditions that are not or rarely found in a given region today. Studying the behaviour of a model along altitudinal gradients in different biogeographical and climatic regions can constitute such a test, as can comparing model performance with paleodata that reflect different past conditions.

To evaluate the behaviour of hydrological, atmospheric and ecological models along altitudinal gradients, a series of studies should be conducted in different mountain regions. It would be desirable if these studies could meet a part or all of the following requirements:

- they extend across several vegetation zones, i.e. they include several ecotones
- they include both continuous changes and thresholds of the properties of interest
- they are designed similarly across different mountain regions
- they include a large number of sampling sites that allow to address spatial scaling issues (cf. Figure 2).

There are a number of fundamental requirements that ecological and hydrological models need to fulfil if they are to become part of regional integrated models of mountain regions (cf. Box 3). Taking into account that less than 5% of all ecological studies are longer than 5 years (cf. Kareiva and Anderson 1988), the modelling activities proposed here need to be closely coordinated with the long-term monitoring and process studies conducted under Activities 1 and 3, and especially with the research on past dynamics based on paleorecords as outlined above.

Task 2.2: Regional scale models of land-atmosphere interactions

Background

Spatially explicit studies of ecological, hydrological and socio-economic processes as influenced by environmental change are crucially dependent on the availability of high-quality atmospheric data sets. Such assessments are particularly essential in mountain regions due to their complex topography, but at the same time they are extremely difficult, especially with respect to precipitation. Regional scale models of atmospheric processes that have an explicit interface to land surface properties and processes and take into account information and data from ground based monitoring systems can be very helpful to address these issues.

Objectives

- To develop, test and apply regional scale atmospheric models for mountain regions which provide more reliable areally distributed data fields of the atmospheric variables, in particular precipitation, and of land surface processes, taking into account the interactions and feedbacks between terrestrial ecosystems and the atmosphere.

Implementation

High resolution mesoscale atmospheric models have now reached a state of development that allows us to apply them to realistically describe the atmospheric controls of land surface processes, in particular precipitation, even in complex mountain landscapes (cf. Pielke 1984, 2000). The computed conditions are compared with available data and information from ground-based stations and networks in order to detect discrepancies and take steps to overcome them by applying, for instance, the water balance check as suggested in Becker and Bugmann (1997), and other appropriate approaches.

The models will be used to investigate the blocking and uplifting of airflow by mountains, i.e. their influence on the larger scale atmospheric circulation and on the resulting regional climate in different climatic zones, different parts of the mountain region (upstream, centre and lee), and during different seasons and weather conditions. Suggestions will be developed as to how to adequately represent mountain regions in General Circulations Models (GCMs), and how to use the high resolution regional models in mountain areas to determine operationally and on a routine basis the spatial patterns of atmospheric variables, including precipitation.

Another relvant aspect is the reconstruction of paleoclimate by means of paleoarchives from which atmospheric trajectories and sources may be inferred, such as ice cores and, less directly, lake sediments. In both of these, but especially in the former, the stable isotope record often contains a distinctive 'signature' from which precipitation sources and trajectories can be inferred. The changing types and concentrations of different atmospherically derived contaminants in both ice cores and lake sediments may also provide evidence for air mass sources and trajectories.

Task 2.3: Integrated analysis of environmental change

Background

It is increasingly recognized that changes in regional and global land use/ land cover and atmospheric conditions interact with each other (Pielke et al., 1998; Pitman et al., 1999) (cf. Figure 3). Thus, for this reason and others the widely applied downscaling approach that starts from large-scale circulation patterns being fed into limited area atmospheric models, in order to provide regional and local changes in the climate, which are then used to determine the resulting impacts on mountain systems, is inappropriate when applied to GCM climate change scenarios. Rather, a consideration of the interactions between atmospheric characteristics and land use/ land cover is required to describe their changes at the regional scale (e.g. Pielke et al. 1993, Stohlgren et al. 1998). Hence, research activities conducted under Tasks 2.1 and 2.2 need to be coupled to arrive at integrated assessments of the overall effects of environmental changes on mountain regions and the feedback from those regions to larger scales (i.e., continental and global).

Objectives

- To assess the impacts and feedbacks of environmental change in different mountain regions of the world, taking into account the dependencies between atmospheric dynamics and land surface processes at a range of spatial and temporal scales.

Implementation

Integrated analyses of environmental change in mountain regions can be achieved in two ways: (1) by explicit "on-line" coupling of dynamic models of all the subsystems (Figure. 3), thus giving rise to fairly large, complex models; or (2) by coupling research results gained under Task 2.1 and 2.2 in an "off-line" mode, i.e. by synthesizing the new knowledge and incorporating it in the relevant submodel. Depending on the research questions being asked and the existing expertise and modelling tools, integrated assessments of the impacts and feedbacks of environmental change may be achieved in both these ways for a given mountain region. As a matter of fact, the results from a carefully derived qualitative assessment can be superior to those obtained from very complex quantitative models that are faced with difficult questions relating to error propagation, etc.

The concept of modular modelling should be applied, so that modules can be exchanged easily and simulation models can be set up that allow us to answer specific questions in different mountain regions, based on the different availability of input data.

Clearly, the mountain specific strong variation of physical and ecological forcings and responses to environmental change needs to be taken into account in modelling mountain landscapes. Three different scales are most relevant here: (i) the hillslope scale, (ii) the valley or headwater basin scale, and (iii) the regional scale. Modelling coupled with monitoring in mountain environments at these different scales should provide information on (1) scale dependent process characteristics, (2) scaling rules, (3) background levels of variability required to detect significant trends and environmental change impacts at the different scales, and (4) the dynamics of emergent properties of ecosystems that are scale-sensitive, including natural hazards, such as floods, fires and debris flows (cf. Task 3.2). To avoid misinterpretations, strong links between these investigations and monitoring and process studies as suggested in Tasks 2.4 and Activity 3 are of paramount importance. Only integrated interdisciplinary monitoring, experimentation and modelling is likely to be capable of providing the required information on mountain ecosystem processes and guidance for the sustainable management of mountain resources.

The degree of similarity of the integrated modelling and monitoring systems across sites within a global mountain network will depend on several aspects: (1) the scales of the systems being studied; (2) the ecological or hydrological questions being asked; (3) the socio-economic pressure being placed on the mountains (e.g. national parks in the U.S. and Europe vs. agro-forestry in the Himalayas). However, having a core data set at each site and the scaling capabilities of ecological and hydrological models can ensure a sufficient degree of cross-site comparability to function as a global network to document environmental changes.

Once validated, the models will be used to generate new hypotheses concerning ecosystem dynamics, to estimate responses to environmental change 'stressors', to suggest and assess improved management strategies, and to evaluate ecosystem sensitivity or thresholds, which in turn could improve the efficacy of monitoring programmes.

Task 2.4: Regional-scale field experiment

Background

Large field experiments have proven to be an important tool in the investigation of land surface processes, their spatial and temporal variability and their interaction with the atmosphere. Several such experiments have been implemented during the last fifteen years, such as HAPEX-MOBILHY in southwestern France, FIFE in Kansas/USA, EFEDA in Spain, HAPEX-SAHEL in Niger, BOREAS in Canada, and LBA in the Brazilian Amazon (still ongoing). All these experiments were set up in more or less flat or only hilly terrain. Due to their complex topography, mountain environments up to now were considered to be too complicated and therefore to be investigated later. It is now timely to plan such an experiment in the frame of the IGBP Mountain Research Initiative, which aims at better understanding and adequately modelling meteorological, hydrological and ecological processes in mountain environments and their interdependency and interaction at different scales.

Objective

- To implement in a mountain region a regional-scale field experiment that provides reliable data for the development, application and validation of integrated land-atmosphere models (cf. Task 2.3) for mountain regions/river basins.

Implementation

Considering the special requirements in the preparation and implementation of such an experiment, a careful planning is necessary in cooperation with the experienced IGBP and GEWEX/ISLSCP scientific communities. The selection of a mountain region where the conditions for the implementation of the experiment are best or appropriately fulfilled will be initiated as the immediate first step of this Task.

Activity 3: Process studies along altitudinal gradients and in associated headwater basins

Ecological and hydrological field studies and experiments, including manipulative ones, along altitudinal gradients and at sensitive sites (e.g. high elevation catchments) can provide invaluable information and data on potential responses of mountain ecosystems to anthropogenically induced environmental change as well as increasing understanding of the biotic feedbacks that accompany environmental change and influence mountain ecosystem function and hydrological processes (cf. Clausen 1948, Mooney and Billings 1965, Rawat and Purohit 1991, Prock and Körner 1996). In particular, such experiments provide the required basis for modelling efforts (cf. Activity 2), for the identification of ecological and hydrological indicators of global change along altitudinal gradients (cf. Activity 1), and for the assessment of the sensitivity of the ecological and hydrological systems to environmental forcing factors. This effort also contributes to our understanding of the biotic feedbacks that accompany environmental change and their subsequent influence on ecosystem function and hydrological processes.

The agents of global change (e.g. climate change, land use change, atmospheric chemistry) vary in importance in different mountain regions. Therefore, studies are required in different regions and at different spatial scales from whole catchment studies to the hillslope and plot level, depending on the environmental factor of concern, the goal of the study, and the resources available for the research. Some studies may be more intensive and carried out at a few sites, while others may be less intensive and carried out in a broader network (cf. Figure 2). A considerable body of research has already been conducted, and a lot of it is still ongoing. The studies conducted under the umbrella of the IGBP Mountain Research Initiative thus should make the best use of existing programmes or networks (e.g. ITEX, EMAP, LTER, MAB, and Biosphere Reserves) to avoid duplicating research efforts.

The combination of experimental and direct monitoring approaches provides only a narrow time frame for process studies, many of which operate on decadal time scales or longer. Models may overcome this limitation, but only if they are grounded in reality. Part of the empirical basis for model development and validation and much direct evidence for the operation of longer term processes will come from paleostudies, provided the Mountain Research Initiative can generate an environment within which experimental, observational, modelling and paleoendeavours interact in an iterative and mutually reinforcing manner. Research devoted to, for example, reconstructing variability from (1) dendroclimatological studies, (2) past ecotone shifts, (3) Equilibrium Line Altitudes (ELA's) in glaciers, and (4) species composition changes in terrestrial and aquatic ecosystems in response to climate forcing, may contribute to developing a more realistic sense of the full range of interacting processes that affect mountain systems.

Task 3.1: Indicators of ecosystem response to environmental forcing factors

Background

The high degree of ecological change across relatively short spatial gradients in mountains provides a useful framework in which process studies associated with global environmental change can be done. Process studies and experiments are a critical step to identifying specific responses of ecosystems to directional changes in the environment brought on by human activities. Concurrent measurement of climate, atmospheric chemistry, water, energy, carbon and other gaseous fluxes between the land surface and the atmosphere, and of hydrological and ecological properties within ecosystems will provide a correlational approach to detecting responses to environmental change. These studies should be complemented by experimental studies utilizing careful manipulations of the environment, and by paleo-data to elucidate long-term relationships.

Objectives

The overall objective for hydrological-ecological monitoring and manipulative experiments along elevational gradients in mountain terrain is to improve our process understanding of these unique systems insofar as they are sensitive to global change forcings. This knowledge can then be used to

- derive biological and hydrological indicators sensitive to particular environmental forcing factors;
- provide experimental information on the potential response of ecosystems to global change to improve modelling efforts;
- facilitate a process-related interpretation of historical and paleorecords.

Implementation

The appropriate selection of environmental drivers to be studied in a given region is essential and should be emphasized in determining the research approach. Below, recommendations for research questions are given together with approaches that should be used to achieve the goals of this Task. Also here, the experiences from the ITEX project (Henry 1997, Henry and Molau 1997) will be quite valuable:

A. Climate change and its impacts:

- Basic meteorological monitoring and synthesis to analyse climate change and variability: Climate change in mountain regions may be expressed through a wide range of phenomena, including changes of averages, variability, seasonality, the incidence of extreme events, the form of moisture (snow/rain partitioning), etc. What do we already know about these climate changes in mountain systems? How do these changes vary along altitudinal gradients, and how do they affect plant growth, moisture availability, or runoff?

- Climate manipulations. Experimental modification of climatic parameters should be used to simulate anticipated future changes, which will serve to answer questions like: What changes in biotic composition and function will accompany climate change? What feedbacks will these have on biogeochemical and hydrological processes?

    a) *in-situ* warming:

        a) ITEX chambers (Marion et al. 1997, e.g. decrease convective cooling in herbaceous systems)

        b) IR heat lamps (e.g. Harte et al. 1995)

    b) *in-situ* cooling and precipitation increase (e.g. snow fences)

    c) microcosms: controlled environment experiments – greenhouses and growth chambers with intact chunks of communities.

- Altitudinal gradients as a proxy for climate change and gradients across slopes differing in exposure (at the same elevation): Such studies can be employed to examine the phenotypic and genetic responses of species (e.g. Callaway et al. 1994). A possible restriction here is that these gradients need to be relatively short, because $p(CO_2)$ and UVB also change systematically with altitude.

- Stream and lake water chemistry as sensitive indicators of climate change, integrating the response and subsuming the variability of individual catchment processes. Stream chemical changes in baseflow composition will reveal alterations to the systems that cause changes in subsurface contact time and moisture regime. By the same token, lakes exhibit such sensitivity and have the added advantage that it can be reconstructed continuously to the present day from the sediment record - as witness, for example, the essential contribution of paleolimnology to understanding acidification and eutrophication and the use of recent sediments to reconstruct phosphorus loadings. Where suitable lake sediment sequences exist, there are the added advantages of being able to establish pristine baseline conditions and trace longer term trends from the sediment record in increasingly quantitative ways.

- Fluxes of water, energy and trace gases (especially C and O_3) at the land surface/atmosphere interface: The sustainability of mountain ecosystems with respect to their carbon exchange properties need to be investigated on a long term perspectives. Changes in climate and extreme events can significantly affect the carbon fluxes of high altitude ecosystems, altering net ecosystem production, the rates of biogeochemical cycling, and the vulnerability to soil erosion. Long term carbon, water and energy flux stations in mountain regions will be used to assess the intra- and inter-annual variability of gaseous exchanges. They will supplement the monitoring system used for the analysis of the impact of environmental changes on ecosystems functions, in particular the FLUXNET initiative. – A special aspect is ozone formation by high altitude ecosystems, which have a significant role in the oxidation capacity of the atmosphere. Due to the high radiation load and the significant rates of biogenic volatile organic compound emission by mountain vegetation, there is a high potential for ozone formation at high altitudes. In regions where the anthropogenic impact determines high NO_x emissions (e.g. the European Alps), the potential for ozone formation becomes very high as evidenced by the increasing trend in recent years. These processes and associated management and mitigation will be studied.

B. Increases in N deposition

What changes in terrestrial and aquatic ecosystems will occur as a result of increasing N deposition? Will invasive species become more abundant (Vitousek et al. 1997)? What impact will community changes have on ecosystem function (Bowman and Steltzer 1998)? Will plants become more susceptible to stress under elevated N inputs (Aber et al. 1989)? What is the fate of anthropogenic N deposition, i.e., what ecosystem components will be sinks (or sources) for N? How does hydrology control N cycling? To answer these questions, the following approach is suggested:

- Basic monitoring: both wet and dry deposition: e.g. bucket samplers (e.g. NADP network in U.S.), aerochem samplers

- N fertilization experiments: low level (e.g. 1-10 g m^{-2} y^{-1}) to mimic projected increases

- ^{15}N pulse-chase experiments: determine uptake and loss of N by plants, microbes, and soil

- $\delta^{18}O$ in NO_3^- as a tracer (e.g. Durka et al. 1994) used to separate the various sources of atmospheric N and cycling through the system

- Hydrologic study of snowmelt recharge of high NO_3^- water: Does this water run-off during the melt season to the stream, or does it recharge groundwater that then contributes to stream baseflow some months later (Burns et al. 1998)? Understanding the coupling between the root zone and the lower groundwater zone will be important for interpreting stream NO_3^- dynamics and ecological processes in mountain environments.

C. Increases in UV-B radiation

While plants from high altitudes appear to be better adapted to UV-B irradiance than lowland plants, they may also be at the limit of biological adaptation to UV-B. Differences in susceptibility among species will most likely lead to changes in community composition (Caldwell et al. 1998). What will these changes be, and what impact will they have on ecosystem function?

- UV-B monitoring systems: need for long-term data on trends in mountain systems

- UV-B lamps in field plots and controlled environment conditions.

Task 3.2: Runoff generation and flowpath dynamics

Background

The hydrology of mountain areas is different from that in other regions of the world due to the steep terrain, special geological and soil properties, which all control runoff generation and water movement. Topographic position is therefore an excellent surrogate for lateral flow direction and soil moisture distribution, since gravity dominates total water potential in steep terrain. Surface runoff (overland flow) and subsurface stormflow are flashy, with short streamflow response times to rainfall and snowmelt, and thus they can be generate floods. However, direct runoff generation mechanisms are still not fully understood. The spatial and temporal variation of soil infiltration capacity which determines infiltration excess overland flow generation is generally high due to the spatial heterogeneity of the land surface and difficult to model. The same is true for the determination of temporarily saturated areas where saturation excess overland flow is generated. Many of these areas vary dynamically in extent during rainfall events according to soil thickness, texture, geological conditions and surface as well as bedrock topography.

Even more complicated and less understood is the generation of subsurface stromflow consisting of quick returning subsurface flow through preferential flow paths (macropores, pipes etc.), piston flow, ground water ridging where displacement processes of old (pre-event) water by event water play a major role so that, although the streamflow response times are short, residence times of the water are quite long. These residence times, however, determine the subsurface water contact time with the surrounding geologic material, and thus its chemical composition, i.e. water quality. All these processes and their interdependencies are not yet fully understood and further research is clearly required (Bonell 1998).

Another aspect concerns the runoff controlling linkage between vegetation and soil moisture, which is quite sensitive in mountain regions. Vegetation stabilizes the soil and affects the runoff process by reducing surface flow. If vegetation is removed, or changes its elevational extent, overland flow and erosion may occur and increase; this increases both streamflow and stream sediment concentration. Finally, narrow and highly incised valley-bottoms often limit the extent of riparian zones, a key landscape position for nitrogen transformation (Cimo and McDonnell 1997).

Objectives

- To improve our knowledge of lateral flowpath dynamics on steep hillslopes and capability to model flow components contributing to streamflow.

- To examine the role of biogeochemical 'hot spots' for N transformation in mountain areas (riparian zones, hollows, etc).

- To test how digital elevation data can be used to model water redistribution in the mountain landscape and to identify soil moisture patterns and related influences of vegetation.

- To use this combined understanding to identify key hydrological indicators of global change in mountain environments.

Implementation

The catchment as a fundamental landscape unit integrates many of the ecological, geochemical and hydrological processes that signal environmental change. Therefore, monitoring the water, sediment and nutrient fluxes in nested mountain catchments along altitudinal gradients enables quantification of ongoing and future potential changes (e.g. the U.S. LTER programme, EMAP, etc.). Paired watershed studies in mountain environments will be used to quantify the effects of prescribed manipulations that simulate anticipated change phenomena (e.g. forest cover alteration), with one watershed kept unchanged.

Where the catchment framework includes lakes or reservoirs within which the output from the system has been continuously and efficiently trapped, the sediment record can provide both a spatial and a temporal integration of the environmental processes operating both on the land surfaces and within the aquatic system itself. This has many advantages, ranging from documenting human impacts and interacting processes on many time scales, to providing realistic targets for practical remediation.

The paired catchment approach has proved a valuable tool also in paleoresearch, notably in identifying on a continental scale the dominant factors responsible for widespread surface-water acidification. This implementation strategy therefore provides a basis for both contemporary and *post-hoc* experiments, and a powerful tool for uniting the methodologies and perspectives required to address the challenge of future environmental change in mountain regions.

Most of the studies as proposed above require the coordinated application of multiple approaches including conventional monitoring, advanced field experiments, tracer techniques, remote sensing, topographically-based modelling, nested catchment studies. Some aspects in monitoring should particularly be mentioned:

A. Measurements and experimentation, combined with modelling and remote sensing, to understand and improve models of

- the spatial and temporal variation of soil moisture pattern and the occurrence and temporal variation during rainfall and snowmelt events of saturated areas generating direct overland flow taking into account topographical, soil, vegetation and other controlling features, including the “topographic index“.

- N-flushing in steep dissected mountain topography (cf. Creed et al. 1996).

B. Tracer techniques combined with modelling to identify subsurface flow paths, their dynamics, in particular travel times / residence times of the flowing water and associated substances:

The most essential tracers are:

- $\delta^{18}O$ to assess the geographical source of streamflow in mountain catchments (Kendall and McDonnell 1998).

- CFC and SF6 tracers to quantify groundwater and stream baseflow residence times and water ages (Plummer et al. 1994).

- ^{18}O of NO_3^- to trace different sources of atmospheric N (Durka et al. 1994).

- conservative chemical tracers at the hillslope scale, which help to identify the major flowpaths on mountain slopes (to be linked with modelling; cf. Anderson et al. 1997).

C. Paleolimnological studies:

Particularly where suitable lake sediment sequences are available, paleolimnological studies can be used to tie recent experimental and monitoring activities to sediment-based research. This applies specifically (i) to calibrate paleorecords, (ii) to get better insight into long term processes, and (iii) to contribute to the use of paired catchments as a study framework based on a *post-hoc* sediment-based approach.

Task 3.3: Diversity and ecosystem function

Background

There is considerable debate about the role of diversity in controlling ecosystem properties and the effects of environmental change on this relationship (cf. Körner 1995b, Chapin and Körner 1995b). Mountain regions are very suitable for studies addressing this controversial topic because the strong changes in the existing biological diversity along altitudinal gradients can be used to assess biotic changes induced by environmental changes, preferably in an experimental framework. The relationship between function and diversity of an ecosystem, and how this will impact the response of the system to global change is a critical component, and is perhaps best addressed in mountain ecosystems. There is increasing evidence that changes in vegetation and soil microbial communities will mediate the response of ecosystems to environmental change, providing feedbacks that may be as important as the environmental change which initiated the biotic response. Thus, a better understanding of the link between diversity (defined variously as richness, combination of richness and evenness, or variety of Plant Functional Types [PFTs], e.g. Woodward and Cramer 1996) and function would facilitate our predicting the response of systems to environmental change.

Objectives

- To elucidate the relationships between biological diversity and ecological function.

- To determine how changes in diversity will feed back to the response of mountain systems to environmental change.

Implementation

Research under this task will be coordinated closely with the activities of the DIVERSITAS Initiative. In February 1999, a planning meeting for a "Global Mountain Diversity Network" was held in Switzerland, which laid down the conceptual principles and a plan for its implementation (cf. Körner 1999).

Elements of the implementation of this Task include:

- Evaluation of changes in diversity along altitudinal gradients: How does diversity change along altitudinal gradients? Does the composition of PFTs change systematically and predictably with changes in altitude (Körner 1995b)?

- Investigation of diversity-functional relationships along altitudinal gradients: How do diversity, productivity and resource use vary (Steffen et al. 1992)? Is there higher productivity and resource use in more diverse communities? Can sets of PFTs be defined that will be useful for predictive modelling studies (e.g. Bugmann 1996)?

Activity 4: Sustainable land use and natural resource management

As indicated in Section II, the overall objective of this initiative is to evaluate and enhance sustainable land, water, and resource management strategies for mountain regions. This Activity builds on the insights gained from the integrated investigations outlined in the previous three Activities; it aims to assess current strategies and contribute to developing alternative strategies that could lead mountain regions towards more sustainable development trajectories, taking particularly into account the impacts of recreational and touristic uses, which have become economically important for many mountain communities.

Sustainable resource management in mountain regions requires understanding that future changes will be driven simultaneously by global phenomena (e.g. greenhouse-induced climate change) as well as local and regional resource management schemes (cf. Figure 1). Activities pursuant to this objective will provide the links between scientific understanding of processes of change and the consequences of those changes for adaptation and mitigation options. As depicted in Figure 1, we are particularly interested in the feedback between management strategies and trajectories of change, especially as such feedbacks threaten the ability of specific regions to support current and future livelihoods.

Three priorities are suggested for assessment (cf. Activity 2):

- changes in forest resources, with potential implications for agriculture, rates of erosion, slope stability, and magnitude of floods, and biodiversity;

- intensification and/or extensification of agriculture (including grazing), with potential implications for food security, rates of erosion and magnitude of floods, and biodiversity;

- changes in water resources due to factors such as changing agricultural practices, changing seasonal or permanent population size, where the former is often due to tourism, or increasing energy generation, with implications for downstream water supplies, energy availability, flooding, and sediment transfer.

Work on these linked themes must involve local people in defining and implementing research, recognizing the complementarity between local knowledge and scientific investigation. Approaches such as “Participatory Rural Appraisal" (Mukherjee 1993) should be used to determine local people's perceptions of environmental change, and their related needs and priorities. The results of these efforts should be tightly linked to the research activities aimed at determining best practices for ecosystem management:

- evaluating optimal combinations of traditional and innovative resource management systems, in order to ensure the stability and resilience of both natural and human-managed ecosystems and the conservation of biodiversity;

- assessing appropriate institutional arrangements, based on an understanding of traditional arrangements, the processes which contribute to changing them (including tourism), and the alliances and interactions between mountain communities and interest groups at different levels;

- evaluating economic instruments to achieve a new balance between production and the provision of societal benefits in relation to driving forces of global change, including climate change (especially changing frequencies of extreme events), migration and the evolution of communication networks.

Historical perspectives also provide valuable means of exploring the sustainability of resource management strategies. Many mountains of the world have a long history of human influence, e.g. some 5,000 years in the European Alps, and more than 10,000 years in Central America and the Andes. There is a strong relationship between the natural environment and human activities during these times. The interaction and feedbacks between human activities, land use, climatic and environmental change, and disastrous events are recorded in paleorecords in these areas. Reconstructing and understanding these interactions provide an important foundation for the development of sustainable management schemes for the future.

Task 4.1: Forest resources

Background

Mountain forests are changing in extent, structure and composition at an accelerating rate under the influence of forces associated with both global change (e.g. climate variability, increasing nitrogen deposition) and local and regional management strategies (e.g. intensification of resource extraction, exclusion of fire) (cf. Price and Butt 2000). While forest cover is declining in most of the world's mountain systems, there are significant deviations from this trend. Over the last 100 years, forests have been re-established on abandoned agricultural land in eastern North America and western Europe. Over the last several decades, forest restoration projects have had local success in mountain regions in both Asia and Latin America, with benefits to local economies as well as downstream water quality.

This Task addresses the sustainable management of forest resources, recognizing that they form a major component of many mountain economies. The scope of this Task is broadly defined to include resource extraction activities and concomitant modification of forest ecosystems that range in intensity from collection of firewood, non-timber forest products and construction materials, to small-scale selective logging, to commercial logging and species conversions; as well as from short-term to permanent conversion to agriculture. The Task is complementary to those in this document that investigate agricultural systems. For example, forests and agriculture are linked by nutrient flows from forests to agricultural systems (e.g. organic input into agriculture derived from forest products) as well as the linkages in transition states between forest and agriculture in land use dynamics.

The relevance of this Task is threefold. First, successful sustainable management of forest resources has direct economic benefits to stakeholders, including local communities and other land owners, forest product firms, and regional and national governments. Second, forested mountain watersheds provide services to adjacent lowland communities (Price 1990), such as maintaining water quality (Hamilton and Bruijnzeel 1997) and mitigating hazards (Mayer and Ott 1991, Hewitt 1997). Third, management of mountain forest resources is of increasing importance as an international policy issue driven by the role of deforestation as a source of greenhouse gases and by the recognition of the role that maintaining or renewing mountain forests might play in sequestering carbon (e.g. Lasco and Pulhin 1998).

Objectives

- To assess the consequences of changes in forest area, composition, and/or structure for a suite of linked issues including, but not limited to, sustainable harvesting practices, production of non-timber forest products, tourism, watershed protection, conservation of biodiversity, and carbon storage vs greenhouse gas emissions.

- To develop sustainable forest management practices by using models developed under Activity 2 that consider changes in forest resources due to potential environmental change.

Implementation

This Task seeks to integrate scientific findings and models with resource management strategies at local, regional and global scales. Several implementation issues arise from this integration:

- Case studies must be organized to simultaneously account for covariation in key biophysical driving factors with altitude (e.g. Koch et al. 1995a,b, Becker and Bugmann 1997) as well as gradients in land use intensity (e.g. Lebel et al. 1998). Unlike biophysical gradients organized by elevation, land use intensity gradients are conceptual, organized by gradations in intensity of use. In order to examine covariation of land use intensity and biophysical gradients such as temperature, comparative case studies would be located according to both a spatial gradient in temperature as well as the gradient in land use intensity. In many mountain regions, such comparative case studies can take advantage of pairing altitudinal gradients in biological reserves, where human modification is minimal, with altitudinal gradients in locales with intensive human use. Biosphere reserves, which themselves include gradients in land use intensity, may be particularly appropriate for such studies. Research under this Activity will benefit greatly from coordination with GCTE Focus 3 efforts to understand global change impacts on agriculture, forestry and soils, as well as LUCC Focus 1 efforts to understand processes of land use change, and Focus 2 efforts to define land-cover change 'hot spots'.

- A number of studies document the influence of local factors on patterns of forest resource use; e.g. the well-documented relationship between road construction and deforestation (Hamilton and Bruijnzeel, 1997). However, we need an improved understanding of how external drivers, operating at multiple scales and associated with urban centers (e.g. markets; trade policies) influence land use changes in more remote forest regions. Extra-local factors that are known to influence forest management schemes include commodity prices, policies and programmes to develop rural infrastructure, and property regimes. As an example, we need a better understanding of how economic growth and urbanization influence demand for grazing land to produce meat, or tree plantations for pulp and lumber production. Research under this Activity will benefit greatly from coordination with LUCC Focus 3 activities as well as IHDP activities.

Task 4.2: Agriculture

Background

Mountain agriculture systems are often perceived as being particularly vulnerable to global change due to such factors as:

- low productivity due to short growing seasons and soils of low fertility;
- limited accessibility due to terrain conditions, seasonal hazards and high cost of transport;
- limited scope for resource-use intensification and upgrading through infrastructure due to terrain constraints; and
- limited opportunity for production gains associated with scale of operation (such as green revolution of lowlands; cf. Jodha 1997).

These factors are likely to increase in importance as demands for food increase due to increasing population and affluence. In many mountain regions, trajectories are likely to occur towards increasing intensification of agriculture and, especially in developing countries, further conversion of forest to agriculture. These trajectories become non-sustainable when conversion and intensification lead to land degradation and decreased food security. Embedded in this issue is the role of natural climate variability as it influences agricultural production. A full understanding of the diverse interactions between climate and food production must also include socio-economic factors - such as access to irrigation, and indigenous or new soil and water conservation practices that make production systems more or less vulnerable to climatic variation (Liverman 1992, 1994, Price and Barry 1997).

Objectives

- To assess the vulnerability of mountain agricultural systems with respect to environmental changes, especially as they are modified in their impact by social and economic factors.
- To suggest ways for integrating agricultural development with growing demands for water, energy, and biodiversity conservation by using models developed under Activity 2 to explore interactions between agriculture systems and regional patterns of land and water use.

Implementation

This Task seeks to integrate a traditional crop model-based assessment of agricultural productivity with a broader set of factors that govern sustainability of productivity as well as landscape-scale environmental implications of changes in agricultural production. Thus, elements in the implementation of this Task must include the following:

- A strong strategy for linking agricultural production to biophysical and socio-economic factors that influence sustainability is to identify key sources of vulnerability of a regional agricultural system to climate variability (e.g. Downing 1995, Liverman 1992, 1994, Jodha 1997). Factors to be considered in assessing vulnerability include intensity of land and water use; traditional and new soil and water conservation measures; effects on water resource availability (quantity and quality); population immigration into marginal areas; tourism; access to economic resources; dependency on external economic resources; feasibility of traditional production systems; infrastructure for hazard response; and health status of potentially affected populations.

- Intensification of agriculture almost always leads to a sharp loss of biodiversity at a local level, and very often involves the introduction of alien species as part of the production system (Walker and Steffen 1997). Traditional mountain agricultural systems are characterised by high diversity in terms of microclimate, crop varieties, land use patterns, and agronomic techniques (Jodha 1997, Ramakrishnan and Saxena 1995, Swift 1996). Increasingly, traditional systems are reduced in diversity as a result of efforts to increase production and in the shift from subsistence to commercial production. A key question that arises from these trends is the degree to which the diversity of mountain agriculture systems, at genetic, species and landscape levels, is related to trends in food security and overall sustainability of livelihoods (Swift et al. 1996).

- Intensification of agriculture is often associated with changing spatial arrangements of agricultural elements, non-agricultural land use, and infrastructure (e.g. change in field size) with consequent impacts on biodiversity, water resources availability, and provision of fresh water, soil stability, retention of nutrients, flood control, and propagation of pests and diseases. The sustainability of agriculture is thus linked to other resource issues, especially water supplies and flood control. Integrated analyses that link and assess consequences of change in these systems are of particular importance in mountain regions as 'high energy' hydrologic and geomorphic environments.

Research on all of these issues will benefit greatly from coordination with the IHDP Science Project on Global Environmental Change and Human Security (GECHS). Further, the case studies developed under this Task will address the LUCC Focus 1 objective of identifying institutional, economic, political, and biophysical conditions that exacerbate vulnerability.

Task 4.3: Water resources

Background

Mountain regions have been referred to as 'water towers for the 21st century' (Mountain Agenda 1998), reflecting the fact that more than half of humanity relies on fresh water that accumulates in mountains for domestic use, irrigation, hydropower, industry, and transportation. Mountains play a disproportionate role, relative to their area, in the global hydrologic cycle due to the key role of topography in triggering orographic precipitation. Further, mountain systems store water as snow and ice during the cold season and distribute water to lowlands during the warm season when demand from plants is often critical (Bandyopadhyay et al. 1997).

Assessing the sustainability of water resources requires integrated analyses of trends in supplies and demands. Several aspects of Activities 1 through 3 address the impact of climate variability and land use change on water supplies. The contribution of this Task is to integrate those analyses with assessments of the potential ways in which increasing population and consumption may increase demands above levels of supply. The Task also addresses the question of how changes in climate and land use/land cover may alter not only the quantity of water, but also the quality and/or timing of water flow which, in turn, has implications for sediments as major pollutants of surface waters, and for increased flood hazards – especially those resulting from the interaction of extreme meteorological events and land use.

Objectives

- To assess the interacting impacts of human activities and of their consequences at all relevant scales on mountains on the regional water resources.

- To assess options for managing increasing demands for fresh water, including downstream demands, while safeguarding other mountain resources, including agricultural and agroforestry systems and biodiversity.

Implementation

This task seeks to integrate models as developed in Activity 2 with a suite of factors that influence variation in water supply and quality as well as variation in patterns of demand. Elements to be considered under this Task include:

- The various interdependencies and interactions between land use/land coverb (and thus forest and agricultural management practices as mentioned above) and hydrology and water resources availability in quantity and quality need to be assessed adequately in the integrated models to be applied.

- Assessment of the sustainability of water resources must explicitly account for interactions between mountains as sources of water and lowlands as generating demand. This relationship is made more complex as increased development within mountain regions reduces the quality and quantity of flows downstream on which lowland communities depend. In addition, changes in the frequency of extreme events due to climate change must be considered.

- The sustainability of water resources is increasingly influenced by the potential for conflict when water flows across political boundaries between regions and nations. World-wide, 214 river basins, serving 40% of the world's population, are shared by two or more countries (Mountain Agenda 1998). A key research question in this area is an assessment of how various institutional arrangements foster reliable and equitable distribution of water among different interest groups.

Research on these issues will benefit greatly from coordination with the IHDP GECHS Science Project. In addition, research under this Task will benefit from coordination with the LUCC Focus 3 objective of developing suitable interfaces for linking hydrologic models with models of land use and associated socio-economic phenomena.

V. Conclusions and Recommendations

Mountain regions provide unique and valuable settings in which to study the specific facets and links of environmental change, regional consequences and resource management strategies. This conclusion is not newsworthy in and of itself, as the value of mountain regions as sites of scientific inquiry has long been recognized (see, for instance, reviews in Ives and Messerli 1997). However, the vast majority of work to date has not been structured to facilitate a synthetic understanding of the interactions between climate, land surface processes, and human activities, taking into account the specific conditions in mountain environments. At present, the relevant tools and observations suffer from mismatches in scale and gaps in coverage. The rationale for an initiative on "Global Change and Mountain Regions" thus rests on the potentially large payoff of a strategy that links mountain regions of the world as sites for monitoring and understanding the processes of change as well as places where a predictive understanding of the consequences of change is critical for sustaining land and water resources.

In developing this Initiative on "Global Change and Mountains" over the past years, two facts became increasingly evident: first, that mountain regions provide unique opportunities and challenges for global change research, many of which are not given in other environments; and second, that an integrated approach is required that takes into account climate and hydrology (BAHC), ecology (GCTE), land use and associated socio-economic (LUCC) as well as paleoaspects (PAGES). This understanding forms the backbone of the present document.

Further, the scope of the initiative and the suggested integrated approach call for involvement of IGBP partner programmes and other organizations, in particular WCRP/GEWEX, IHDP, UNESCO/MAB and IHP, DIVERSITAS, FAO, IGU, IAHS (see Box 4). To organize this cooperation most efficiently, we propose to use the existing programme structures, rather than to establish a new, separate programme for mountain research. This scheme builds on the existing IGBP core projects and partner programmes and avoids a splitting and possible weakening of the limited resources available for mountain research.

Efficient coordination of such diverse resources requires, however, a focused, well structured organization of work across the contributing IGBP core projects and partner programmes. Accordingly, we suggest that the initiative be framed as a cross-cutting activity within the IGBP with the four core projects BAHC, GCTE, LUCC and PAGES as its main collaborators. The first steps towards the implementation of the initiative will immediately be taken after this document has been officially endorsed. They will start with inventories of existing research sites, stations, river basins, regional studies etc., followed by science reviews, the selection of study areas suited for collaborative research, and initiation of related projects.

In time, other partners may become involved, depending on the relevance of this initiative to their overall goals. There are clear indications that the initiative is highly relevant to the goals of some of the partner institutions listed in Box 4. As an example, UNESCO was the first to officially express interest in the cooperation, and this will strengthen the planned research considerably.

Finally, the timeliness of this initiative is reflected in the recent decision of the United Nations General Assembly to declare the year 2002 the "International Year of Mountains". This proclamation underscores the critical role of mountain ecosystems in providing such goods and services as water, forest products, refugia for biodiversity, the storage of carbon and soil nutrients, and attractivity for tourists. The proposed initiative on Global Change and Mountain Regions will contribute not only to the scientific understanding of the ongoing processes of change, but in the end to suggestions for action to preserve the ability of mountain regions to sustainably provide the goods and services on which humanity has come to depend. As such, the initiative is well suited to serve as the basis for the preparation of IGBP's and its partner programmes' contribution to the "International Year of Mountains".

Box 4. Potential partnerships for the IGBP Mountain Research Initiative.

The list below is neither complete nor meant to be exclusive.

AMA	African Mountain Association (Univ. of Bern, Switzerland)
AMA	Andean Mountain Association (Univ. of Athens, USA)
CGIAR	Global Mountain Initiative of the Consultative Group on International Agricultural Research, eventually for Africa, Asia, and Latin America. Coordinated by CIP, but the only active element

	at present is the African Highlands Initiative, coordinated by the International Centre for Research on Agroforestry (ICRAF, Nairobi)
CONDESAN	Consortium for the Sustainable Development of the Andean Ecoregion, coordinated from the Centro Internacional de la Papa (CIP, Lima, Peru)
DIVERSITAS	International Programme of Biodiversity Science, which is co-sponsored by the following organizations: International Union of Biological Sciences (IUBS), Scientific Committee on Problems of the Environment (SCOPE), UNESCO, International Council for Science (ICSU), IGBP, and the International Union of Microbiological Societies (IUMS)
FAO	Food and Agriculture Organization of the United Nations: the Forestry Department is Task Manager for Chapter 13, but other departments/divisions are active in mountain areas. FAO is partially responsible for GTOS
GTOS	Global Terrestrial Observing System
IAHS	International Association of Hydrological Sciences
ICIMOD	International Centre for Integrated Mountain Development
ICMH	International Committee on Mountain Hydrology
IGU	International Geographical Union
IHDP	International Human Dimensions Programme on Global Environmental Change
IUCN	The International Union for the Conservation of Nature has many projects in mountain regions, especially in protected areas
IUFRO	International Union of Forestry Research Organizations
SCHC	Standing Committee on Headwater Control
START	Global Change System for Analysis, Research and Training

UNESCO	United Nations Educational, Scientific and Cultural Organization, especially
- IHP	International Hydrological Programme
- MAB	Man and the Biosphere programme, Division of Ecological Sciences, responsible for the global network of biosphere reserves
UNU	United Nations University PLEC programme, including projects in mountain areas in Vietnam, West Africa, and elsewhere
WCRP	World Climate Research Programme, particularly:
- GEWEX	Global Energy and Water Cycle Experiment
WMO	World Meteorological Organization. Working Group on Climate Change Detection includes the development of a network of reference climatological stations.

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Appendix I: List of Acronyms

BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
BOREAS	Boreal Ecosystem-Atmosphere Study
ECHIVAL	European International Project on Climatic and Hydrological Interactions between Vegetation, Atmosphere and Land Surface
EFEDA	ECHIVAL Field Experiment in Desertification Threatened Areas
ELA	Equilibrium Line Altitude
EMAP	Environmental Monitoring and Assessment Programme (EPA)
EPA	Environmental Protection Agency (United States)
FAO	Food and Agriculture Organization (UNO)
FIFE	First ISLSCP Field Experiment
FLUXNET	International Network for Long-Term Measurements of CO_2, Water Vapour, and Energy Exchange
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCM	General Circulation Model
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GECHS	Global Environmental Change and Human Security (IHDP)

GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GHOST	Global Hierarchical Observation System
GTOS	Global Terrestrial Observing System
HAPEX-MOBILHY	Hydrological and Atmospheric Pilot Experiment - Modélisation du Bilan Hydrique
HAPEX-SAHEL	Hydrological and Atmospheric Pilot Experiment in the Sahel
IAHS	International Association of Hydrological Sciences
IDGEC	Institutional Dimensions of Global Environmental Change (IHDP)
IGBP	The International Geosphere-Biosphere Programme
IGU	International Geographical Union
IHDP	International Human Dimensions Programme on Global Environmental Change
IHP	International Hydrological Programme (UNESCO)
ISLSCP	International Satellite Land Surface Climatology Project
ITEX	International Tundra Experiment
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LIMPACS	Human Impact on Lake Ecosystems (PAGES)
LTER	Long-Term Ecological Research Programme (United States)
LUCC	Land Use/Land Cover Change (IGBP/IHDP)
LUCIFS	Land Use and Climate Impacts on Fluvial Systems during the period of agriculture (PAGES)
MAB	Man and the Biosphere Programme (UNESCO)
NADP	National Atmospheric Deposition Programme (United States)

PAGES	Past Global Changes (IGBP)
SANW	Swiss Academy of Natural Sciences
SASCOM	South Asian START Committee
SSC	Scientific Steering Committee
START	Global Change System for Analysis, Research and Training (IGBP, WCRP and IHDP)
UNCED	United Nations Conference on Environment and Development
UNESCO	United Nations Educational, Scientific and Cultural Organization
WCRP	World Climate Research Programme

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