Global Terrestrial Observing System

GCOS/GTOS Plan for Terrestrial Climate Related Observations
Version 2.0

June 1997

GTOS - 12
GCOS - 32
WMO/TD - No. 796
UNEP/DEIA/TR.97-7

Terrestrial Observation Panel for Climate

Josef Cihlar, Chairman, Canada Centre for Remote Sensing, Canada
Roger G. Barry, CIRES, University of Colorado, USA
Enrique Ortega Gil, National Meteorological Service, Mexico
Wilfried Haeberli, University of Zurich-Irchel, Switzerland
Ken-Ichi Kuma, Japan Meteorological Agency, Japan
Jurate M. Landwehr, U.S. Geological Survey, USA
David Norse, University College London, UK
Steve Running, University of Montana, USA
Robert Scholes, CSIR, South Africa
Allen M. Solomon, U.S. Environmental Protection Agency, USA
Shidong Zhao, Chinese Academy of Sciences, China

In addition, the following people were members of the original Terrestrial Observation Panel and contributed significantly to Version 1.0 of the Plan, much of which was incorporated into Version 2.0:

Max Beran, TIGER Programme Office, Institute of Hydrology, UK
Stephen Briggs, National Environment Research Council, UK
Claudio Caponi, Ministry of Environment and Natural Resources, Venezuela
William Heal, University of Edinburgh, UK
John Townshend, University of Maryland, USA
Diana Verseghy, Atmospheric Environment Service, Canada
Duncan Wingham, Mullard Space Science Laboratory, UK

The Terrestrial Observation Panel for Climate (TOPC) created two expert working groups to assist in the revison of this Plan. Members of these working groups who are not members of the TOPC, are:

Michael Bonell, Division of Water Sciences, UNESCO, France
Donald Cavalieri, NASA, USA
Jing Chen, Canada Centre for Remote Sensing, Canada
Ute Enderlein, WHO, Switzerland
Barry Goodison, Canada Climate Centre, Canada
Wolfgang Grabs, Global Runoff Data Centre, Germany
Alan Gustard, Institute of Hydrology, UK
Jelle Hielkema, FAO, Italy
Zdzislaw Kaczmarek, Institute of Geophysics, Poland
Zhanqing Li, Canada Centre for Remote Sensing, Canada
Harry Lins, US Geological Survey, USA
David Robinson, Rutgers University, USA
John Rodda, UK
Bruno Rudolf, Global Precipitation Climatology Centre, Germany
Datius Rutashobya, Ministry of Water, Tanzania
Alan Taylor, Canada

Contents

Acknowledgements

In addition to the funding and support from the co-sponsors, this work has been partially supported from a grant from the U.S. Environmental Protection Agency (CX-822924-01), which is gratefully acknowledged. In addition, generous contributions to the Climate Observing System Fund by the USA and Canada have supported this effort. The contents of the Plan have not been subjected to administrative or peer review procedures by these organizations, and do not necessarily reflect their views.

Preface

This Plan for terrestrial observations has been prepared by a Terrestrial Observation Panel for Climate (TOPC) jointly sponsored by the Joint Scientific and Technical Committee (JSTC) of the Global Climate Observing System (GCOS) and the Scientific and Technical Planning Group for the Global Terrestrial Observing System (GTOS). The Plan presents the minimum set of terrestrial requirements for GCOS and the climate change requirements for GTOS. It complements both the GCOS and GTOS programme plans.

The Plan provides an initial assessment of the requirements for climate-related observations which will be required to predict, detect and assess impacts of climate change. These requirements were developed in three meetings of the TOPC, but will be subject to revision as the Plan is reviewed, observational requirements change, and the scientific concepts and observational capabilities develop and improve. Future activities will focus on refining the requirements, prioritizing the requirements, and the initial implementation. It is intended that the Plan will be implemented through existing programmes.

Suggestions for additions or improvements should be forwarded to the GCOS Joint Planning Office,

c/o World Meteorological Organization,
P.O. Box No. 2300,
CH-1211Geneva 2,
Switzerland.

Dr Michael Glantz
Chairman
GTOS Steering Committee
Global Terrestrial Observing System
(June 1997)

Professor John Townshend
Chairman
Joint Scientific and Technical Committee
Global Climate Observing System
(June 1997)

Executive Summary

The objective of the TOPC Plan is to provide a rationale for the structure and implementation of the initial observing system. It describes the minimum set of terrestrial[1] observations that are required to detect, predict and to assess the impacts of climate change. Annex I to the document contains a detailed description of each of the variables. While it has taken considerable work to arrive at a consensus on this set of variables, it is recognized that these are a beginning, to be refined as our understanding of the observational requirements and capabilities improve. The Plan recognizes that a comprehensive observing system must address the critical variables by making measurements with sufficient accuracy, spatial and temporal resolution, and long-term continuity. The data must be compiled and collated in a fashion that is useful to the users.

Ultimately, the products that are generated by GTOS and others must include ones that are in a form that can be easily utilized by policy- and decision-makers. For much of the land and climate system, such comprehensive observations, databases and associated products are not yet available.

In spite of the fact that a considerable amount of work needs to be done before a comprehensive observation system can be completely implemented for the terrestrial components of the GCOS or the climate change portion of the GTOS, a number of actions can be taken to begin implementing some of the required observations. Those observations which can be made from satellites offer the best hope of globally consistent data sets, and consequently research to increase the number and quality of observations that can be made from space is highly encouraged. At the same time, these data must be made readily available to countries that do not have a programme of space-based observations.

It was recognized that many hundreds of variables are potential candidates for global monitoring and there are many thousands of potential sample locations. However, it is neither feasible nor desirable to measure everything, everywhere, all the time. This reality led to a five-tier hierarchical sampling scheme in which at the one extreme a few variables are measured infrequently at many locations and at the other extreme a large number of variables are measured frequently at a few locations.

Regarding *in situ* measurements, most of the requirements are already being made at a number of sites that clearly fall within the proposed sampling scheme. Existing sites have been contacted as part of the development of the overall plan for GTOS, and from those sites willing to participate, the ground-based observations should be implemented as soon as possible. Making historical data from these sites available via the Internet should also receive high priority. Working with the GCOS/GTOS/Global Ocean Observing System (GOOS) Data and Information Management Panel, a network-based system for data management must be developed over the next year and a half. It is expected that this system should work in close

[1] In this Plan, terrestrial refers to both managed and unmanaged land-based ecosystems, the hydrosphere and the cryosphere

cooperation with the International Geosphere-Biosphere Programme - Data and Information System (IGBP-DIS) and UNEP'S Global Resource Information Database (GRID) programme. The system must provide access to both space-based and *in situ* observations.

1. Introduction and Background

1.1 Introduction

This Plan (Version 2.0) has been developed by the Terrestrial Observation Panel for Climate (TOPC) to meet the terrestrial requirements for the Global Climate Observing System (GCOS) and the climate change requirements of the Global Terrestrial Observing System (GTOS), and represents a significant update of Version 1.0 (GCOS-21). The TOPC is a joint panel established by the GCOS and the GTOS to ensure that a coordinated Plan is produced and implemented. The data and information management needs identified in the Plan have been passed to the GCOS/GTOS/Global Ocean Observing System (GOOS) Data and Information Management Panel (JDIMP) for implementation in conjunction with other GCOS, GOOS and GTOS needs. Likewise, for those observations which can best be made from space, the requirements have been passed to the GCOS/GTOS/GOOS Space-based Observation Panel (SOP) for coordination with the world's space agencies. The strategy for implementing the *in situ* aspects of the Plan will be a joint effort between GCOS and GTOS, in cooperation with the World Climate Research Programme (WCRP), the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP), and other international and national institutions. It is intended that the Plan will be refined and updated as required.

The land-atmosphere interactions, which link the land surface with the atmosphere, are critical processes for understanding and assessing the impact of climate change. An integrated global observing system is needed to address critical questions in these links. For example: Is the carbon storage in the terrestrial biosphere growing? If so, at what rate? Is the tundra permafrost melting? If so, at what rate? (If it does, millions of tons of carbon dioxide and methane could be released into the atmosphere, greatly accelerating the rate of global warming.) Are there shifts in species and vegetation patterns in response to a changing climate?

The objective of this Plan is to provide a rationale for the structure of the initial operational system and to outline basic guidelines for its implementation. It describes the minimum set of land-based variables that are required to understand the climate system and its variability and to predict, detect and assess the impacts of climate change. The Plan outlines a strategy which will enable collection of the observations so that consistent global data sets can be produced.

To develop a rational approach to planning the global observing systems, the TOPC undertook a series of tasks, described in the subsequent chapters:

- Analysis of the climate- and climate change-related mechanisms governing the function of the key terrestrial components of the climate system, including identification of the key variables that need to be measured: biosphere (Chapter 2), hydrosphere (Chapter 3), and cryosphere (Chapter 4);

- Discussion of sampling requirements and problems, leading to the conceptual definition of a global sampling system for terrestrial observation building on existing systems and facilities (Chapter 5);
- Discussion of data and information system requirements and issues (Chapter6);
- Development of an implementation plan, with emphasis on the initial operating system (Chapter 7);
- Description of individual terrestrial variables to be measured by the COS/GTOS, including their specific attributes (frequency, accuracy, current status, measurement method, research and development (R&D) and action required, etc. (Annex I).

1.2 The Global Climate Observing System (GCOS)

The Global Climate Observing System (GCOS) is a joint initiative of the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environment Programme (UNEP), and the International Council of Scientific Unions (ICSU). GCOS provides an international forum for the development of a comprehensive long-term global observing system that will improve our understanding of climate. A more complete description of GCOS can be found in the Plan for the Global Climate Observing System (GCOS-14).

In the current debate about climate change, it is evident that information available to governments is inadequate to enable them to obtain answers to critical scientific, economic and policy questions. This gap is likely to be more critical in the future as the earth’s climate, its biosphere and human activities respond to increasing greenhouse gas concentrations. In particular, systematic and comprehensive global observations of the key variables are urgently needed and should be made available to nations to enable them to:

- Detect and quantify seasonal, and inter-annual climate changes at the earliest ossible time;
- Document natural climate variability and extreme climate events;
- Model, understand and predict climate variability and change;
- Assess the potential impact on ecosystems and socio-economical conditions;
- Develop strategies to diminish potentially-harmful effects and amplify beneficial ones;
- Provide services and applications to climate-sensitive sectors; and
- Support sustainable development.

Objective of the GCOS

The objective of the GCOS (GCOS-14) is to provide the observations required to meet the needs for:

- Climate system monitoring, climate change detection and response monitoring especially in terrestrial ecosystems and mean sea-level;
- Application to national economic development;
- Research towards improved understanding, modelling and prediction of the climate system.

Background to the GCOS

International concern regarding climate change is encapsulated in the Framework Convention on Climate Change (FCCC) signed by over 160 nations in June of 1992 at the Earth Summit in Rio de Janeiro. Ratified by over 50 of those countries, the Convention came into force on 21 March 1994. The Convention clearly recognizes that climate change due to human activities may *"adversely affect natural ecosystems and humankind"*. It further recognizes that actions concerning climate change must be taken in the overall context of sustainable development. In addition to the Climate Convention described above, the Convention on Biodiversity and the United Nations Convention to Combat Desertification both require climate observations, and in particular systematic terrestrial observations for their full implementation.

A substantial capability for the required observations from both *in situ* and space-based observations already exists, principally in operational programmes (e.g., World Weather Watch (WWW) for operational meteorology, National Aeronautics and Space Administration (NASA)/National Oceanic and Atmospheric Administration (NOAA) Pathfinder programme) and in research programmes (e.g., WCRP, IGBP). Despite the scope of these programmes, even when taken collectively, they are inadequate to meet the objectives described above. To be comprehensive, an observing system must address the critical parameters by making measurements with adequate precision, sufficient spatial and temporal resolution, and with known long-term continuity. The products must be in a form that can be easily utilized by policy- and decision-makers at national, regional or global levels. For much of the land and climate system, such comprehensive observations and associated products are not available.

GCOS will improve the situation by taking a comprehensive, integrated view of the requirements for all the climate system components, including the global atmosphere, the oceans, the biosphere, the hydrosphere, the cryosphere and the linkages among them. Such an integrated view is necessary to adequately interpret climate variability, as well as to determine the naturally- and anthropogenically-produced climate changes. This Plan deals with three of these elements: the land biosphere, the cryosphere, and the hydrosphere.

1.3 The Global Terrestrial Observing System (GTOS)

The GTOS is a comprehensive land surface observation programme, with focus on five priority issues: land use and land cover change and degradation; water resources management; pollution and toxicity; loss of biodiversity; and climate change. This Plan deals directly with only one of these issues, i.e., climate change, but its recommendations have important implications for the others.

It is impossible to foresee all the critical environmental issues of the future. For example, who could have predicted the depletion of the ozone layer or the damaging effect of DDT on birds of prey? Once identified, how long did it take to get action? While the need for integrated and systematic terrestrial ecosystem monitoring has been recognized for over 100 years, there was no substantive international action to achieve it until the early 1970s. The Stockholm Environment Conference in 1972 catalyzed a number of monitoring activities which have made a positive contribution, but collectively they fall short of what is required. As a joint initiative of ICSU, WMO, the Food and Agriculture Organization of the United Nations (FAO), UNESCO, and UNEP, GTOS provides a comprehensive international forum for the development of an effective terrestrial observing system.

Objectives of the GTOS

The central mission of GTOS is to provide policy makers, resource managers and researchers with the data needed to detect, quantify, locate and give early warning of changes (especially reductions) in the capacity of terrestrial ecosystems to support sustainable development and improvements in human welfare, and to help advance our understanding of such changes. It should be accomplished through the development of an equitable partnership between the generators and users that meets both the short-term needs of national governments and longer-term needs of the global change research community. GTOS data collection and analysis has four main objectives:

- Identification and quantification of the natural and anthropogenic factors that affect terrestrial ecosystem function and structure;
- Determination of the relative importance of these factors at the national, rgional or global level and their interactions;
- Distinguishing short-term natural variations or perturbations from long-term changes of anthropogenic origin;
- Assisting modelling and multidisciplinary dynamic analysis of possible future changes in terrestrial ecosystems.

Background for the GTOS

Terrestrial ecosystems are the primary source of food, freshwater, fuel, clothing, and shelter for humankind and will continue to be so in the foreseeable future. They provide the main source of income and/or subsistence for the majority of the world’s population, and for much of the developing world they are the dominant economic sector and source of substance and foreign exchange earnings. GTOS will provide the observational requirements that will allow governments to plan for and achieve sustainable development while mitigating environmental changes resulting from a number of anthropogenic factors, including climate change and desertification.

The initial planning for GTOS calls for pilot activities and progressive implementation over a number of years, with relatively low expenditure in the early stages. It has been designed to complement the other global observing systems, GOOS and GCOS, with the maximum use of common procedures.

1.4 Use of the Data

The principal uses of GCOS/GTOS climate-related data are: (1) development of plans for sustainable economic and social development; (2) short-term climate prediction (seasonal to inter-annual); (3) long-term projections of future climate conditions (including climate model initialization, determination of boundary conditions, and validation); (4) climate change detection; and (5) assessment of climate change on ecological and societal systems. Some variables will assist all five uses and some are specific to a single group. It is important to realize that the primary users to be served by GCOS/GTOS will require both historical and current *in situ* and remotely-sensed (primarily from satellite-borne instruments) data.

The global data sets produced by GCOS/GTOS are a pre-requisite for improving our understanding of the global climate system and its components (atmosphere, biosphere, hydrosphere, cryosphere, and lithosphere). Improved computer models of the climate system, capturing our best knowledge of the mechanisms of climate processes and climate-related interactions between the various components, can be produced using the data sets. Of special importance are general circulation models (GCMs), biogeochemical global climate (BGC) models, and trace gas models.

Both data sets and the understanding/models are employed in tracking the variability, changes and impacts of the climate system, as defined by GCOS/GTOS objectives. The resulting findings will be essential for a variety of purposes, mostly at the national level, related to economic and social development, national security, health, international cooperation, environmental protection, and others. Note that the observing systems need to be responsive to feedbacks from the end uses and also to new insights into the climate system and the mechanisms governing its behaviour.

Climate change data are a critical factor in planning and managing sustained economic development, particularly in the field of agriculture and land use (e.g., sea level rise). GCOS/GTOS will help improve the reliability of predictions, both in the short and long term, as to which areas are likely to experience drought and which increased precipitation. This will have direct implications for enhanced international cooperation in terms of regional and national response strategies.

For climate prediction and the development of scenarios, two complementary time scales are of interest: (1) the seasonal-to-inter-annual time scale in which the predictability of certain phenomena can be exploited for socio-economic benefit; and (2) the decadal-to-centennial time scale in which the stability of the climate with respect to anthropogenic influences and the early detection of any climate change must be assessed and the future climate state predicted. Accurate predictions of seasonal and interannual climate variability, such as El Niño/Southern Oscillation (ENSO) events, are of immediate application and a large economic value in many regions of the world. Our ability to accurately predict climate on various time scales is a pre requisite for any rational plan to adapt to or mitigate negative consequences of climate changes. Accurate climate projections are critical to planning for long-term sustainable development. More directly, the ability to predict climate on a seasonal basis will be directly useful to many economic activities world-wide.

Improvements in our understanding of climate change and terrestrial ecosystem interactions, and in the predictive powers of GCMs and other global environmental models, is critically dependent on the greater integration and analysis of the data on socio-economic driving forces and the biophysical and bio-geochemical responses. Key socio-economic driving forces include population growth and density, *per capita* income levels and growth rates, and technological change. Data on these forces are commonly subject to wide errors, collected at irregular intervals, and seldom geo-referenced. It is therefore important that GCOS and GTOS: (a) assure improved collection and accessibility of terrestrial data; (b) coordinate their activities with the various national and international bodies that are focusing more directly on filling the socio-economic data gap (e.g., the Consortium for International Earth Science Information Network (CIESIN); the International Human Dimensions Programme); and (c) ensure that the data management system will allow terrestrial data to be readily integrated with socio-economic data once it becomes available.

It is well known that the earth's temperature is controlled by the balance between incoming radiation from the sun and outgoing radiation from the earth. Certain atmospheric constituents (e.g., water vapour, carbon dioxide, tropospheric ozone, and methane) absorb outgoing radiation. In general, as concentrations of these constituents increase, the temperature of the earth is predicted to increase.

Currently at issue is the stability of the climate system when perturbed by significant emissions of greenhouse gases into the atmosphere. The best current estimate is that by the year 2100 global mean temperatures will have risen by 2.0 degrees C (Watson *et al.*, 1996). Regional temperature changes may differ substantially from the global mean, but it is not yet possible to say by how much. While there are uncertainties, the balance of evidence suggests that human activity over recent decades has contributed to recent climate change (Watson *et al.*, 1996).

These changes are likely to affect not only the temperature but also patterns of precipitation, floods, droughts, storm frequency or intensity, length of the growing season, water availability to plants, and other related phenomena with direct impact on the human population. Changes in the total amount of precipitation and its frequency are likely and will directly affect the magnitude and timing of runoff and the intensity of floods and droughts (Arnell *et al.,* 1996). As a result of such meteorological variations, many other sectors of the society would be profoundly affected. If we are to manage change for the benefit of humankind, it is critical to detect the change that is occurring on a regional as well as global basis and assess the amount of change taking place due to climate. For example, global change has potential consequences for changes in the distribution, viability, and sustainability of ecosystems on which humans depend. Global changes are caused by a number of specific anthropogenic stresses, including climate change, land use change, habitat loss, landscape fragmentation, and desertification resulting from land management practices.

The value of better information about climate change is large. To continue to address climate requirements, long-term global observations of many climatological/meteorological, oceanographic, chemical, and biospherical parameters, are vital (Watson *et al.*, 1995). If the climate-related objectives of GCOS/GTOS are met, nations will be able to significantly improve their ability to predict short- and long-term climate, detect the impacts of change and assess the influence of climate on global change, thus improving their ability to plan for effective sustainable development.

2. Climate Impact on the Biosphere

2.1 Introduction

This chapter is divided into two parts. After defining the fundamental relationships between climate and the biosphere, it examines the interactions between the vegetation, soils, land cover/land use and the climate system. It then discusses the nature of explanatory and predictive models of these climate and ecosystem interactions. Each part highlights some (but not all) of the reasons for measurement of specific environmental variables.

2.2 Understanding Climate Impact on the Biosphere and Feedbacks to Climate

On the scale of regions to continents (e.g., >105 km2), climate is the dominant arbiter of the productivity and distribution of vegetation. For example, minimum winter temperatures constrain broad-leaved deciduous trees from invading and excluding higher latitude boreal evergreen conifers at their mutual border, and from being invaded by more productive subtropical species at their lower latitude border (Prentice *et al.*, 1992). Soil moisture determines whether forest or steppe occupies a region. Its seasonal availability can determine whether forests are dominated by needle-leaved evergreens or by broad-leaved deciduous trees (Waring and Schlesinger, 1984) and whether steppes are dominated by grasses or by shrubs (Haxeltine *et al.*, 1996).

Vegetation and climate, in turn, combine with substrate features to determine soil characteristics.While climate directly determines rates of substrate breakdown, organic matter decomposition and soil erosion, climate indirectly determines other soil features through its control of vegetation. For example, it permits the dominance of conifers that acidify soils, or of steppe grasses which contribute to high concentrations of soil organic material.

Feedbacks of vegetation and soils to climate are lesser but important features of climate biosphere interactions. The differences in albedo between one soil or vegetation and another can have significant effects on the radiation balance (Robinson *et al.*, 1983) and hence on climate, while the evapotranspiration regime of different vegetation types can help determine atmospheric moisture concentrations, cloud properties (Dickinson *et al.*, 1991), and the regional contribution of soil moisture to precipitation (Lettau *et al.*, 1979; Shukla *et al.*, 1990). On smaller scales of a few 10s of km2, soil, topography and land use history combine to determine productivity and distribution of vegetation and the land use options available at any specific location. Vegetation productivity refers to rates and amounts of carbon fixed from the atmosphere. Temperature and soil moisture are known to exert fundamental control of photosynthesis (carbon fixation) and respiration (carbon release), both of which respond differently to those climate variables (Schimel *et al.*, 1995). Also, the rate of carbon accumulation increases at higher CO2 concentrations, at least in short-term greenhouse experiments, although there is yet no direct evidence that it does so in natural vegetation. Thus, the rate at which climate-controlling CO2 accumulates in the atmosphere will be directly related to changing temperature and precipitation patterns and possibly, to changing atmospheric CO2 concentrations.

Consideration of vegetation productivity leads directly to the examination of biogeochemical cycles. These include the cycling of the elements which are essential to life and which are strongly influenced by living organisms, between the biosphere, atmosphere, hydrosphere and lithosphere. The carbon (discussed above), nitrogen, phosphorus and sulphur cycles are most important because they underlay all primary production and trace gas emission models. Nitrogen is the principal limitation for the operation of the carbon cycle in most terrestrial ecosystems, including agroecosystems. N2O and NO are climatically important trace gases. Phosphorus is the principal constraint for the operation of the carbon cycle in many tropical terrestrial ecosystems and most aquatic ecosystems. Phosphorus also controls the input of nitrogen to ecosystems via biological nitrogen fixation. The sulphur cycle operates in tandem with nitrogen and carbon. Sulphur aerosols are very important to the radiative balance of the earth and are the main component of acid rain.

The impact of the four cycles on the climate occurs via the emissions of radiatively-active trace gases as a result of biogeochemical cycling (CO2, CH4, N2O; ozone precursors such as NO and CO; and aerosols) and via the land surface characteristics such as biomass and leaf area which are constrained by biogeochemical considerations. Since biogeochemical cycling is strongly influenced by climate, this constitutes one of the major avenues for both impacts and feedbacks. It is obviously impossible to separate the vegetation structure and processes of productivity from the atmospheric, soil, and hydrological processes produced by changes in land cover and land use. Shifts in temperature and precipitation will affect energy, carbon and water balance, which in turn will cause changes in soil properties and in distribution and density of vegetation. Climate will have a major influence on land use change, and both of these directly affect the vegetation patterns. In turn, shifts in vegetation patterns feed back directly to hydrological cycles, radiative properties of the atmosphere, and the climate system.

Vegetation

Most of the impacts of climate change on the terrestrial biosphere are expected to manifest themselves through changes in vigour of species populations and the resulting changes in the composition, structure and distribution of vegetation; and through changes in biogeochemical, energy, and water fluxes between ecosystems and the atmosphere. Climate change will affect the terrestrial biosphere through changes in the regional energy balance (Dickinson, 1983) and associated changes in the regional water balance (Eagleson, 1986). Temperature, humidity, wind, precipitation and runoff affect the water balance by influencing soil moisture, evaporation and transpiration. Hence, these are critical observations for understanding the effect of climate change on terrestrial ecosystems and on subsequent feedbacks to climate. Seasonal shifts in the water balance may occur because of changes in precipitation patterns (Lettenmaier and Sheer, 1991) or volume (Dolph *et al.*, 1992). For example, a significant decrease in runoff and soil moisture will affect soil properties such as carbon content, nitrogen and phosphorus.

Changes in the hydrological cycle also influence moisture fluxes between vegetation and the atmosphere. These fluxes strongly depend on the area of photosynthetic surface available to accept radiation, to transpire water, and so on. The usual surface measure is the leaf area index (LAI) which is defined as one half of the total projected green leaf per unit ground area. LAI is hypothesized to describe a fundamental property of the plant canopy in its interaction with the atmosphere, especially as it concerns the momentum, radiation, energy, and gas exchange of the atmosphere (Monteith and Unsworth, 1990). Typically, the LAI will vary along moisture gradients, being high enough to ensure a maximum amount of photosynthetic surface and productivity, but low enough to prevent damage to leaves and plants during periods of moderate drought conditions (Woodward, 1987).

Since the structure of vegetation (species composition, density and three-dimensional configuration) is controlled by a number of environmental factors such as seasonal water availability, temperature, length of the growing season and nutrient availability, climate change will affect the structure as well as the distribution of the system components. For example, as water availability decreases, LAI should decline, thus decreasing productivity but conserving water. Conversely, the parallel increase in concentrations of CO2 may actually stabilize or increase LAI by increasing water use efficiency of leaves (Melillo *et al.*, 1996). At the stand level, radiometer analyses, or allometric equations linking tree diameters to leaf area, permit estimates of LAI. In estimating variables such as LAI and net primary production (NPP) over large areas, remote sensing should play an increasingly important role. Spectral vegetation indices such as the Normalized Difference Vegetation Index (NDVI) derived from ratios of near infrared and red spectral reflectances or radiances have correlated with estimated LAI especially well (Sellers, 1989) and future availability of data from active microwave sensors (radars) should be useful in determining water-related properties of vegetation.

Recent model projections of global vegetation distributions controlled by climate change suggest that up to half of the natural vegetation of the earth could undergo change from a climate characteristic of one biome type to that of another (Kirschbaum *et al.*, 1996). Vegetation responses to changes of this magnitude will obviously affect biodiversity through habitat modification, and it will affect ecosystem function through increasing mortality and decreasing productivity. Hence, variables describing habitat deterioration and those measuring mortality could be particularly useful. Because especially slowly growing forests are unlikely to keep pace with rapidly shifting climates, the monitoring programme should take cognizance of processes by which species migrate (seed transport and establishment followed by growth, maturity, seed production and seed transport again) and of the environmental constraints on both migration and subsequent forest development.

Seedling variations should be monitored because seedling establishment is usually the limiting process in both forest development and in immigration.

The terrestrial role in the global carbon cycle defines a critical set of measurements. The terrestrial biosphere stores three times as much carbon as the atmosphere. On an annual basis, the flux of carbon between the atmosphere and land surfaces is equal to about 20% of the atmospheric content. Thus, the CO2 flux to the atmosphere is an important observation. The standing stock of ecosystem carbon at any given time is highly variable from place to place but can be broadly estimated from carefully placed measurements of the biomass (both above and below ground) and the necromass. In addition, wildfire releases measurable quantities of carbon from the land surface (Goldammer, 1990). Hence, carbon standing stocks, necromass and areas burned are important observations for understanding the carbon cycle.

To understand, model or monitor carbon or any of the other three biogeochemical cycles (N, P, and S), information needs to be obtained on the size of the pools, the magnitude of the fluxes, and the factors which control the fluxes. In practice, all cycles can be simplified to some degree by considering only the major fluxes and pools. Generally, only one flux will be ‘rate-limiting’ at a time, and its controlling factors need to be known in detail. For example, carbon assimilation by plants is a rate-limiting step in the carbon cycle, while nitrogen mineralization is limiting in the nitrogen cycle.

The fluxes of CO2 are largely controlled by photosynthesis and respiration (autotrophic and heterotrophic). Temperature and moisture are critical elements that affect photosynthesis and respiration which in turn are important in determining the NPP. CO2 concentrations may also be found to control NPP. NPP along with ecosystem respiration determine the net ecosystem production (NEP). NEP characterizes the status and ability of an ecosystem to store carbon and consequently is critical in understanding the carbon cycle in terrestrial ecosystems. To detect changes in the storage of carbon, observations on NPP and particularly NEP are required. Existing terrestrial ecosystem sites routinely make these measurements, but space-based observations are required to obtain NPP/NEP estimates over large areas.

Changes in terrestrial vegetation composition, distribution, and structure affect terrestrial carbon storage and thus provide a feedback to climate. Equilibrium analyses using different vegetation models and climate scenarios generally show that under doubled CO2 conditions a terrestrial biosphere without agricultural land use will store more carbon than today, and will act as a negative feedback to climate change (Smith *et al.*, 1992); with agricultural land uses, the terrestrial biosphere cannot store as much carbon as today and acts as a positive feedback on climate change (Solomon *et al.*, 1993; Dixon *et al.*, 1994). Analyses of the more realistic situation which includes transient response of vegetation to climate change suggest that vegetation redistribution could also lead to a transitional release of CO2 to the atmosphere for a period of about 200 to 400 years (King and Neilson, 1992; Smith and Shugart, 1993; Solomon, 1996).

In addition to carbon, methane, and nitrous oxides also clearly depend on terrestrial ecosystem processes and will respond to changes in vegetation types. For example, the production of methane from wetland areas depends on the duration of inundation and temperature, both of which are likely to change with a changing climate. Currently, we lack sufficient data to accurately predict the net effect of climate on the production of methane on a global basis. Hence, at least the areas covered by freshwater wetlands (streams, lakes, bogs, marshes, swamps) should be monitored through remote sensing.

Soils

Soils are a key component of terrestrial ecosystems. They are important in global biogeochemical cycles, accounting for 2/3 of the terrestrial carbon stocks. Their physical properties are critical to climate because they can control albedo and act as a porous medium for water storage and movement. Soils are the site of mineralization and provide the majority of nutrients that control plant growth. The interactions between these properties and climate determine the rates of decomposition, carbon storage, moisture availability, trace gas production, and nutrient supply. Thus, observations on soil carbon, nitrogen, phosphorus, bulk density, surface state, and particle size distribution are needed.

Changes in soil moisture, nutrients and evapo-transpiration will have large impacts on biome types, since the distribution and abundance of these resources are controlled to a large extent by the volume and seasonality of available soil moisture (Woodward, 1987). Where changes in the regional water balance are significant, major shifts in vegetation patterns and condition are a likely result (Kirschbaum *et al.,* 1996). Modelled effects of global climate change on the water balance produced substantial loss in the amount of the forest cover in the continental U.S. (Neilson, 1995), assuming that humidity and wind are the primary mediators of evapo-transpiration of soil moisture. Data documenting rooting depth are important in this regard because soil rooting depth determines the volume within which moisture, carbon and nutrients are stored to support plant growth. Adequate spatial and temporal resolution of soil moisture observations in the rooting zone are particularly hard to obtain because of the transient nature of soil moisture.

Soil scientists have developed two principal types of information which will be of value to GTOS and GCOS. These are soil maps of regional and global coverage, and chemical and physical measurements on soils. When combined, they provide important spatial information concerning soil characteristics. The shortcomings in both data sets limit their present usefulness. Currently, the best global soil map is the UNESCO-FAO Soil Map of the World, released in digital form at a scale of 1:5 million. While this represents a comprehensive and valuable resource, at this scale most mapping units consist of a mixture of soil types, thus soil conditions cannot be characterized with sufficient accuracy.

Land cover and land use

Changes in land cover and land use, including agricultural use, can both drive changes in the climate system and result from climatic change. The physical and biological characteristics of the soil and vegetation surface influence the absorption of energy at the surface, which in turn influences the relative amounts of latent and sensible heat exchange, local hydrology and transfer of momentum from the atmosphere (Dickenson, 1983). Human activities that modify the earth's vegetation cover, for example by changing agricultural practices, deforestation and biomass burning, represent a significant influence on the global climate. Land use also has a significant effect on the carbon fluxes that influence atmospheric CO2 concentration. For example, tropical deforestation in the 1980s was estimated to contribute between 2.0 and 2.8 Gt carbon per year (Houghton *et al.*, 1990), or approximately 25-35% of the total biosphere emissions of carbon. Land cover information is needed by existing general circulation models (grid scale 250 km). For those climate models which will be implemented in the next five years the identification of incipient change requires a stratified approach, with some observations at much higher spatial scales (20-500 m) over limited areas. Local models of terrestrial biosphere dynamics and interactions with climate also depend on land surface processes at the same fine resolutions, but globally-comprehensive biosphere models require land cover data at minimally 1 km covering all terrestrial areas.

Multi-temporal satellite observations can be used to define land cover and land condition. The most consistent data are from NOAA Advanced Very High Resolution Radiometer (AVHRR) satellites. Global data sets at a resolution of 8 km and a temporal resolution of 10 days are being assembled and will be used to prepare the required parameters on a continuing basis. An experimental global data set at 1 km resolution has been collected for 1992-1996, although these data will not portray all the heterogeneity of terrestrial ecosystems which occurs at finer spatial resolutions. High resolution data from sensors such as the Landsat Thematic Mapper (30 m) and the Satellite Probatoire d'Observation de la Terre (SPOT) High Resolution Visible (HRV) (10-20 m) are available in principle, but their high cost has limited their use to date. Nevertheless, this cost is much less than that of conventional monitoring methods, especially for large and remote areas. While the heterogeneity of a single ecological unit would not be described, high resolution data collected on a systematic global basis would substantially capture the heterogeneous nature of terrestrial ecosystems. Algorithms could be developed that would allow statistical interpretation of the heterogeneity of the 1km AVHRR data sets (GCOS-15).

In summary, vegetation structure, biogeochemistry, soil condition and the energy and water balance are tightly coupled. Detecting and assessing the response of any one of these to climate change requires observations of the others. To understand the effects climate change is likely to have on vegetation and water resources, it is essential that the analysis integrate both hydrologic and biogeochemical processes. Anthropogenic influences on land cover and land use must also be considered in projecting future climate-biosphere interactions. In this regard, the implementation of this Plan should be done in cooperation with the IGBP Land Use and Cover Change (LUCC) project which is linked to the intersection of natural and human/societal research on global change.

2.3 Modelling Approaches

There are three principal types of models relevant to simulating climate-biosphere interactions at the watershed to global scales: physiognomic vegetation models (biogeographic models), vegetation succession models (gap and migration models), and biogeochemical models (NPP models). Simulating physiognomy (the species composition and 3-dimensional arrangement within plant communities) is useful in assessing the potential limits to physical feedbacks between vegetation and climate. Vegetation physiognomy affects surface albedo, roughness and evapo-transpiration. Vegetation succession is an expression of temporal processes which control lagged (transient) vegetation responses to a rapid climate change. These responses must be understood *a priori* for proper use of monitoring data: decades and even centuries may be required before many critical vegetation responses to current changes can become evident. Biogeochemical processes, such as annual carbon cycling and primary productivity, affect trace gas concentrations in the atmosphere. Furthermore, components of all three model types are interrelated and affect each other. Biogeochemical processes are critical for determining the distribution of vegetation, just as species available and physiognomy affects biogeochemical processes. Consequently, in order to simulate climate-biosphere interactions, these three model components need to be linked together in a biologically and hydrologically consistent manner (Melillo *et al.*, 1996).

Biogeographic modelling approaches

Geographic redistribution of vegetation to be expected at some time following cessation of directional environmental change (Prentice and Solomon, 1990), can be projected by several available models. Commonly, an empirical classification is developed that relates derived climatic variables with biome distributions, which is then used to draw new biome distributions from a different climate distribution. The fundamental flaw of this approach is that dynamic equilibrium of vegetation distribution cannot be expected very soon, not even for centuries, following an environmental equilibrium which itself is not likely in the foreseeable future.

The Holdridge Life Zone Classification (Holdridge, 1967) was applied in a globallycomprehensive way to estimate vegetation geography (Emanuel *et al.*, 1985a and 1985b) and forest standing stock (Sedjo and Solomon, 1989). However, the Holdridge system and its modified versions (e.g., Prentice and Fung, 1990; Smith and Shugart, 1993) share the problem that variables with which it classifies “life zones” (annual warmth, annual precipitation) do not control the current distribution of vegetation. To solve this problem, a biogeography model was developed for assessing geographic responses of vegetation zones to expected climate changes (BIOME; Prentice *et al*., 1992). Unlike other static models, it utilizes physiological thresholds of temperature minima, warmth and water stress maxima in order to define a set of plant functional types (PFTs), each characterized by the minimal set of known climate constraints and each free to recombine under different climates with PFTs which are not now associates. BIOME was used to project future biogeographic patterns and associated carbon stocks under past, present and future doubled-CO2 climate

(Prentice *et al.*, 1993b), and in the absence and presence of agriculture (Solomon *et al.*, 1993).

More recently, global integrated assessment models (GIAM) have been developed which combine biogeography changes with simulations of land use and cover, the latter as a function of changing human population size, resource demand, atmospheric chemistry and climate. The goal is to calculate the resulting atmospheric concentrations of greenhouse gases. The most comprehensive GIAM, IMAGE 2 (Alcamo, 1994; Leemans *et al.*, 1997) was applied in several chapters of the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report to calculate future land use effects on forest growing stocks (Solomon *et al.*, 1996), maximum potential carbon storage in forests grown to take up atmospheric carbon (Brown *et al.*, 1996), and to back-calculate carbon emission chronologies necessary to reach atmospheric carbon concentration goals at specified times in the future (Alcamo, 1994).

Successional modelling approaches

Other vegetation models have been developed to simulate vegetation transient responses. Probably most important is plant succession, a process whereby rapidly-growing shade-intolerant species are gradually replaced by more slow-growing, shade-tolerant species. During the succession, carbon storage values are thought to follow an s-curve, increasing early and after some 50-500 years, asymptotically approaching a maximum that depends on soil and climate characteristics. Forest gap models (Botkin *et al.*, 1972; Shugart, 1984) were developed to simulate forest succession after a tree death caused a gap in the forest canopy, a common means by which mid and low latitude forests reproduce themselves in the absence of more catastrophic forms of mortality (e.g., wind throw, wildfires, pest epidemics, etc.). These models simulate annual changes in establishment, growth and mortality of mixed species on small forest plots based on the relative abilities of tree species to compete for sunlight, water, nutrients and space. Several different forest gap models have been developed for different purposes and applied to simulate the response of forest stands to climate change (Solomon, 1986; Prentice *et al.*, 1993a; Bugmann and Solomon, 1996). Unfortunately, we lack the natural history information from less studied regions required to parameterize the models (e.g., maximum known height, diameter, and age; shade tolerance, cold tolerance, drought tolerance, etc.). Hence, they are not yet ready to apply on a global scale. These parameters may be gleaned eventually from a combination of tier 4 observations with isolated data already available.

The other major transient process, species migration, is only now becoming amenable to globalscale modelling. Measurable tree migration responses will probably not become locally visible for 100 to 200 years (Solomon and Bartlein, 1992; Solomon, 1996), but their potential is great thereafter for inducing regional extinctions and reducing carbon carrying capacity. Current research (e.g., Collingham *et al*., 1997; King *et al.*, 1997) demonstrates that development of reliable predictive models will depend on uniform global knowledge of species seed production, weights and transport modes. Predicting migration of species that depend on animal transport will also require mapped distribution of birds of the *Corvidae* genus (crows and jays), land use and land cover mapped at 0.2-1 km resolution, and characterization of natural histories of the species. Species depending on wind transport will also require estimates of vertical and horizontal wind structure, especially the frequency and intensity of highest wind speeds (as a proxy for up and down drafts).

Biogeochemical modelling approaches

Two conceptual approaches have been used to develop biogeochemical models: correlating net primary productivity directly with climate, and modelling ecosystem processes based on ecophysiological principles. The correlation approach is straightforward in that regression is used to relate observed net primary productivity to climate variables (Lieth and Whittaker, 1975). This approach can be used to simulate future NPP, but they provide results of unknown reliability because the relationship between the few climate variables used and NPP could change under future climates due to the complexity of climate-vegetation interactions.

More complex biogeochemical models are based on physiological principles. They assume that leaf-level processes can be scaled directly to the level of the biosphere (hence the name “big leaf” models). They typically treat the carbon and nitrogen cycles (Rastetter *et al.*, 1991) and may incorporate the hydrologic cycle (BIOME-BGC, Running and Hunt, 1995). Approaches to scaling up have included interpolations of outputs between sites (Kittel and Coughnor, 1987); running a gridded model version based on interpolated climate data (Raich *et al.*, 1991); and initializing a gridded model with satellite remote-sensing data and driving it with interpolated climate surfaces (Running *et al.*, 1989). Although these models can be used to simulate changes in NPP and biogeochemical processes under changed climates, they cannot simulate vegetation redistribution. Therefore, they cannot be used alone to either simulate biophysical feedbacks (surface roughness and albedo) to the climate system, or the carbon dynamics associated with vegetation redistribution.

A new approach combines the biogeographic models (Section 2.3) with big-leaf physiological models (VEMAP, 1995). These calculate photosynthesis, respiration, and nutrient uptake as a function of leaf area permitted by available moisture, sunlight, warmth and nutrient availability, and scaled to values characteristic of each biome (e.g., BIOME 2, Haxeltine *et al.*, 1996; DOLY, Woodward *et al.*, 1996; MAPPS, Neilson, 1995). The transient processes (Section 2.3) are not yet simulated in the integrated biogeography/geochemistry models, but rather instant migration and ecosystem development is assumed to match any climate change. Terrestrial NPP and NEP measurements will be critical to validating and modifying the models to increase their accuracy.

In summary, to understand the impacts of climate on terrestrial ecosystems, and the feedbacks from the terrestrial systems to climate, the variables listed in Table 2.1 are critical. Current models use vegetation structure, climate data, land cover and land use to infer several critical parameters such as surface roughness, albedo and evapotranspiration. The models now require more complete and consistent information than is readily available. Much of the information now in use is anecdotal and inconsistent. Techniques to provide consistent information in terms appropriate for the models are available, and the required data are being acquired, but not necessarily saved or fully processed.

Table 2.1. Key variables for biosphere observations

BIOPHYSICAL PROPERTIES OF VEGETATION	Rainfall chemistry
Leaf area index (LAI)	Volcanic sulphate aerosols
Net primary production (NPP)	LAND COVER/LAND USE and DISTURBANCE
Net ecosystem production (NEP)	Fire area
Biomass - above-ground	Land cover
Biomass - below-ground	Land use
Necromass	SOIL PROPERTIES
Roughness - surface	Soil cation exchange capacity
Spectral vegetation greenness index	Soil moisture
Stomatal conductance - maximum	Soil total carbon
Vegetation structure	Soil total nitrogen
BIOGEOCHEMISTRY	Soil available phosphorus
Biogeochemical transport from land to oceans	Soil total phosphorus
Dissolved organic C, N, and P in water	Soil bulk density
Dry deposition of nitrate and sulphate	Soil particle size distribution
Emissions of CO2, NOX and SOX from combustion of fossil fuels	Soil pH
Fertilizer use N and P	Soil surface state
Leaf biomass - peak of nitrogen fixing plants	Rooting depth (95%)

.

3. Climate Impact on Hydrological Regimes

3.1 Introduction

This chapter is divided into three parts: (1) hydrological observations required to understand the impact of climate change on hydrological regimes' feedback to climate; (2) hydrological observations required for GCMs; and (3) hydrological observations required for biospheric modelling. The first three sections are not meant to be mutually exclusive and the reader will notice many variables are repeated in all three sections. These three sections lead to the selection of a minimum set of variables that are to be included in the Initial Operational System (IOS). The reader is referred to Annex I for details on each variable, including a rationale, and the required temporal and spatial resolutions.

3.2 Understanding Climate Impact on Hydrological Regimes and Feedbacks to Climate

The hydrologic cycle is intrinsic to the earth's climate system. The processes by which water, in all its phases, moves through the atmosphere, and moves to and from the various repositories on the earth's surface are inter-meshed with those governing the earth's energy budget (Brutsaert,1984). However, the processes are not adequately understood and are the subject of current research, e.g., in various Global Energy and Water Cycle Experiment (GEWEX) activities. The quantity and quality of water affects human society, both directly and indirectly through its control of the biosphere functioning. The availability of water is a major controlling factor in the distribution and abundance of vegetation and of biological productivity.

One of the most significant consequences of climate change will be a geographical shift of regional hydrological regimes, and associated changes in the availability of water resources which are a critical factor in planning for economic and sustainable development. In turn, changes in the hydrological cycle will create feedbacks to the global climate system. Our ability to characterize the current state of the hydrological cycle, globally and regionally, and to make quantitative predictions about the nature of potential changes depends on consistent, quality information with adequate spatial and temporal coverage. Such hydrologic data sets are currently lacking for many regions of the earth.

Availability of adequate water of appropriate quality is a major factor in planning for sustainable development. Consequently, studies providing evidence that both water quality and quantity can be reduced by climate change raise valid social concerns (Revelle and Waggoner, 1983). Gaining an understanding and knowledge of the water and energy budgets are critical first steps in detecting, assessing and predicting the global climate change. Unlike data relating to radiance or surface thermal regimes such as albedo and surface temperature which are fairly readily obtainable from satellites, many observations relating to the hydrological cycles require *in situ* measurements. Further, many hydrological data are collected locally and/or nationally and are not adequately shared internationally.

To understand the interactions between climate and the hydrological cycle, it is necessary to understand the relative distribution as well as fluxes of water among its various repositories, as well as the basic composition of the atmospheric and terrestrial water balance (Rhodes *et al.*, 1994). The approximate distribution of the available water is as follows. About 97.3 % of the earth's water supply is in the oceans. Most fresh water is captured in ice sheets, ice caps and glaciers (2.05% of the total). The 0.7% remaining includes 0.68% as groundwater, 0.01% in surface lakes, ponds and man-made reservoirs, 0.005% characterized as "soil moisture", 0.001% in the atmosphere, 0.0001% in rivers and approximately 0.00004% bound up in the biosphere (Berner and Berner, 1987). The rate of exchange within these reservoirs ranges from thousands of years for the oceans and ice sheets, to hundreds to thousands of years for groundwater, to years for surface impoundments, to months for soil moisture, and days for atmospheric, river channel and biospheric reservoirs (Nance, 1971; L'Vovich, 1979). It is significant that the smallest and most quickly exchanged repositories are those of most importance to humans and potentially most responsive to changes of climate.

Whereas a regional atmospheric water vapour balance can be summarized as:

E - P = Q + D

The fundamental relationship for the terrestrial water balance is:

P - E = R + D SGW + D SSM + D SSS + D SB

where:
E represents evapotranspiration;
P represents precipitation;
Q represents the precipitable water in the water column;
D represents horizontal divergence (convergence), that is, water transported out of (into) the regional water column;
R represents runoff (in-channel flows due to atmospheric contribution);
D SGW represents the change in ground water storage;
D SSM represents the change in soil moisture storage;
D SSS represents the change in surface storage, such as lakes, reservoirs and wetlands (technically, D SSS can also include storage of water in its solid phase, such as glaciers or seasonal snow mass, but these will be treated here as components of the cryosphere.);
and D SB represents the change in water in biomass storage.

There is a complementarity between the atmospheric and terrestrial phases of the hydrological cycle. It should be noted that for the terrestrial phase, the global water balance has sometimes been written as simply: - E = R by assuming that in the long term, an equilibrium condition exists and there is no net change in the other terrestrial reservoirs (Baumgartner and Reichel, 1975; Korzun, 1978). This abbreviated relationship draws attention to the fact that discharge, a quintessentially hydrologic phenomena, can serve as an integrating phenomenon, summarizing the behaviour of two highly variable (in space and time) parameters, precipitation and evapotranspiration. However, if one allows for the possibility of climate change rather than just long-term climate variation, this simplified depiction of the water balance is inadequate to study hydrospheric balance.

All of the variables of the terrestrial water balance equation are affected by, and serve as, feedbacks to the climate system, and consequently should be monitored if an assessment of climate variation over some interval is to be made. However, several of the variables such as E, D SSM and D SB are very dynamic on short temporal scales and very variable on small spatial scales, so that the choice of a time step or spatial aggregate to be monitored is determined by the impact being studied. Information on these three very important hydrologic and climatic variables is generally not available on any long-term or spatially large aggregate basis. Whereas measurements of E and SSM are frequently found in seasonal watershed or regional agricultural studies, information regarding SB is generally infrequent and only an estimate. These three variables should be considered as potential enhancements in any long-term regional or global monitoring programme, although there is currently no consensus on how to make measurements or how to aggregate measurements once made.

Because of its rapid atmospheric exchange rate, precipitation is potentially a highly sensitive indicator of climate variation and change. It is the only input in the water balance of the earth's surface (evapotranspiration and runoff represent the main losses). In addition, it plays an important role in the energy cycle of the atmosphere due to the release of latent heat associated with the condensation of water vapour. The 1990 IPCC assessment noted that precipitation appears to be increasing outside of tropical areas, with a tendency for decreases in the subtropics. However, the highly variable nature of precipitation and the inadequacy of global precipitation networks make it difficult at present to characterize long-term trends.

Evapotranspiration is the process by which water is returned to the atmosphere. Over land surfaces, it is difficult to distinguish contributions obtained by purely physical evaporation processes and those due to transpiration by living plants, hence the term evapotranspiration which combines the contribution from both sources. Because of its highly variable spatial and temporal nature, evapotranspiration is a difficult parameter to measure (Oliver, 1983). Methods of measurement range from the use of evaporating pans and lysimeters, to mass budget estimates based on terrestrial regional water balance, to calculations based on energy budget derivations (Brutsaert, 1984; Shuttleworth, 1993), to flux measurements above the canopy (Baldocchi *et al.*, 1988). Although collections of evaporation data have been published in the past (e.g., Farnsworth and Thompson, 1982) and in spite of recent intense international interest in evapotranspiration measurements, including remote sensing-based methods, (e.g., Brutsaert *et al.*, 1988), no one method of measurement or aggregation is currently agreed on for regional or
global studies.

The net balance between precipitation and evaporation is reflected in runoff and change in the storage values. Because stream flow is an integrating phenomena, it may in some specific cases provide an amplified, early-warning signal of climate change. Thus, the climate change detection objective needs to emphasize large rivers draining major continental areas and long time series, preferably at sub-annual scales sufficient to study seasonal variation. It also stresses the need for data from smaller but near-pristine river basins because of the difficulties in separating climateinduced change from other simultaneously occurring changes due to land- and water-use developments (Slack and Landwehr, 1992).

One of the key terms in the global liquid water balance that has generally not been taken into account is the contribution of groundwater to the world's oceans, either directly at the land-ocean interface or indirectly, due to anthropogenic mining of groundwater from aquifers with minimal recharge. Indeed, it has been suggested that the contribution of groundwater to the world oceans over the last century has been a significant factor in sea level rise (Sahagian *et al.*, 1994), at least as large as that attributed to the melting of mountain glaciers.

Soil moisture is a critical variable not only in theoretical studies of global water balance (Milly, 1994) and global biogeochemical cycling (Raich *et al.*, 1991; Rastetter *et al.*, 1991) but also in analyses/studies related to commerce and farming (Sonka *et al.*, 1992). It is intimately related to evapotranspiration rates and, like evapotranspiration, is highly temporally and spatially variable. Some progress has been made in studies to develop remote sensing methods to measure soil moisture, but soil moisture data sets are generally only available for spatially and temporally limited studies.

The stage and extent of large lakes and reservoirs can serve as useful indicators of climate change. They have a tendency to filter out short-term variability and respond to long-term changes in the hydrological cycle. Man-made reservoirs may be constructed to diminish extreme climate effects on the society (Thomas, 1959). The growth in the numbers of reservoirs and incorporation of natural lakes probably has had a dampening effect on sea level rise (Newman and Fairbridge, 1986). Recently, it has been suggested that globally, reservoir surfaces may serve as sources or sinks for two greenhouse gases, carbon dioxide and methane (Kelly *et al.*, 1994). Hence, some accounting should be made of the temporal fluctuations of surface water pondings, especially in hydrologically closed areas. Remote sensing is able to provide information on ponded areas at an appropriate spatial resolution but *in situ* observations are necessary to assist with issues such as distinguishing open water from wetlands of different types, estimating the volume of water involved, and tracking seasonal occurrences.

Biomass water storage is a conceptual parameter for studying the impacts of climate change and is necessary to bring closure in regional and global water balances, albeit only a tiny fraction of the global water balance. While it is practically impossible to measure directly, it can be estimated through the water balance equations. It is closely tied to questions of land cover and vegetation dynamics over a region, and approximate estimates may also be obtained from the knowledge of biomass, leaf area index, or greenness (Tucker *et al.*, 1985). This variable is mentioned for the sake of completeness only, it is not proposed to measure this variable at this time due to the measurement difficulties involved.

Rivers are the major means of transport of nutrients such as carbon, nitrogen and phosphorus from land to ocean and play a significant role in the sulphur cycle as well. Sediment loads can affect climatically significant ocean processes, but are also indicative of terrestrial changes. Concerns pertaining to the quantification of pollutant effects and loss of biodiversity, whether or not directly reflective of climate change, make sediments a significant variable. Thus, an additional factor - movement of sediments and concomitant biogeochemical substances such as nutrients, carbon and heavy metals, transported from the land by rivers to be measured at the mouths of major rivers - has been added to the list of variables suggested for observation for two reasons: this variable is relevant both to water balance and to coastal zone ecology questions, and it is an integrating variable which is related to climatic conditions.

3.3 Hydrological Variables Required for GCMs

A distinction must be drawn between numerical weather prediction (NWP) models and GCMs. NWP models predict a future state of the atmosphere on short time scales (hours to days), based on a set of initial conditions. The initial conditions for the model runs are derived from parameter fields incorporating assimilated observed data at the initial time. Validation is carried out by comparing model predictions of the atmospheric state at the final time with observations. GCMs, on the other hand, simulate the evolution of the atmosphere over longer time scales, years to decades. Because the atmosphere is a chaotic system, predictions of actual future instantaneous atmospheric states cannot be made with any confidence over periods longer than a few days. Validation is carried out by comparing model output fields with multiple year averages of observed fields (usually summarized as monthly averages). These must be provided on global grids, at resolutions equal to or greater than the model grid. At present, this is generally quite coarse for GCMs in the horizontal; however, in order to fulfil future needs such as regional scale modelling, observational data will probably be required within the decade on scales of the order of a few (5-50) km.

Large-scale features of the free atmosphere can be validated using NWP model outputs obtained by four-dimensional data assimilation of observed variables. However, the terrestrial and near surface assimilated fields (surface fluxes, soil moisture, screen air temperature, etc.) are not useful for validation because they are heavily influenced by model parameterizations of unresolved, sub-grid scale processes and are therefore highly model-dependent. Validation of model-generated surface fields must therefore be undertaken on the basis of remotely-sensed data and surface observations. Although numerous variables are useful as inputs or for model validation, those of special significance for modelling are listed below. Precipitation drives the land surface hydrology. It is, unfortunately, also one of the most difficult variables to measure in a spatially comprehensive manner. On an annual time scale, the correct simulation of discharge together with precipitation, provide indirect validation of the modelled surface evapotranspiration rate. The collection of discharge data also presents fewer problems than that of evapotranspiration, which is both difficult to measure and highly spatially variable. To complement the existing databases, however, there is a requirement for accurate runoff estimates by major river basins. Important steps would be the provision of a global digital map of basin boundaries for the catchments being monitored; and a series of corrections to the raw discharge data, describing the amount of water removed from the river for human use (irrigation, municipal water supplies, etc.).

The ongoing collection of snow extent data using visible satellite imagery provides useful first order validation data for snow modelling in GCMs. However, the actual modelled variable is snow water equivalent. A rigorous validation of the performance of GCMs with regard to the simulation of snow requires the development of a long-term database of snow water equivalent. Climate simulations, unless multi-decadal, can be markedly sensitive to initial soil moisture, particularly for deep soils. Ongoing efforts to produce global soil moisture climatologies are therefore important, despite the problems of spatial heterogeneity. This item is given low priority currently, not because it is unimportant, but due to the severe difficulties associated with its measurement. An alternative to direct observations might involve the modelling of soil moisture on a continuing basis, using a high quality soil database, updated meteorological observation (e.g., from the WWW) and constraints based on stream flow records.

To enable the realistic modelling of surface fluxes, the characteristics of the land surface must be specified in such a way as to reflect as accurately as possible ambient conditions. Information is therefore required on land cover, vegetation characteristics, extent of water bodies and wetlands, and soil parameters.

3.4 Hydrological Variables Required for Biospheric Models

Since biological systems are tightly coupled to water, most ecological models related to climate change require as input hydrological data or outputs from hydrological models. The models described below are intended to demonstrate the types of hydrological data required by these biological models. A more detailed discussion of the biological models themselves is contained in Chapter 2.

Climate change is likely to have significant impacts on stream flow and water resources (Kaczmarek *et al.*, 1996, Arnell 1996), and these in turn control biological processes. Global biospheric priorities for hydrological data are somewhat different from those which hydrologists define. For example, biospheric models need the areal gridded runoff estimates, not data from river mouths. Also river carbon and nutrient transport from land surfaces are needed by global ecologists. Biogeochemical data are not commonly taken at standard hydrological stations. Biological models also require accurately defined spatially gridded precipitation and runoff data. While biological models need soil moisture to a depth of 1-2 metres, knowledge of surface wetness can be useful. Surface energy partitioning reacts most quickly to surface (as opposed to soil profile) wetness. Also, nutrient decomposition, trace gas flux and seed germination are ecological processes whose modelling would benefit from surface wetness if available at high temporal frequency. Surface wetness observations are required for various ecosystem types although it appears that satellite-borne sensors will not be able to detect surface wetness under thick or high-biomass vegetation canopies.

Most of the biological models described below and in Chapter 2 compute evapotranspiration at daily to monthly steps. Recent technological advancements now make the concept of a global tower flux network for continuous measurements of water and CO2 fluxes possible. Although only a limited number of sites can presently be supported by this technology because of the costs involved, even 10 well-distributed sites of *continuous* water vapour flux measurements would be immensely valuable for calibrating and validating global biospheric models.

Relative humidity is another critical variable in many biogeochemical models because of its importance to carbon assimilation rates. The derivation of radiation and humidity data from the original precipitation and temperature observations needs to be done with consistent logic and algorithms. In several respects, the global four-dimensional data assimilation forecasting models are the best current methodology for ingesting daily observations, error checking, spatial extrapolation, and derivation of variables at the appropriate scales of resolution for use in biospheric models. The IGBP Biospheric Aspects of the Hydrological Cycle (BAHC) Project's Focus 4 (Weather Generator) is exploring these issues.

The importance of extreme but infrequent hydrological and meteorological events is critical to the ecosystem response. For example, minimum temperatures, particularly frost events, have profound control over vegetation. Major flooding events or particularly intense periods of precipitation are also important. It is crucial that derived and archived data must not be aggregated if such aggregation results in removing extreme events from the record. Numerous applications of hydrologic models, based on empirical relationships between measured temperature/precipitation and catchment runoff, have been used to evaluate climate impacts on stream flow. Revelle and Waggoner (1983) used an empirical model to evaluate discharge from several catchments in Arizona, USA, and found that a 2K air temperature increase with a 10% decrease in precipitation would result in a 40% reduction of catchment runoff. Lettenmaier and Sheer (1991) used a conceptual hydrologic model to evaluate climate change effects on stream flow in several California, USA, watersheds and found that snow melt would occur much earlier and that the shape of the annual hydrograph would be altered, increasing the chance of winter flooding and reducing spring and summer stream flow. The models used in such analyses are based on a description of physical processes, and are calibrated to historical data. They do not account for, or predict, the distribution of soil moisture, infiltration, evaporation or runoff over the basin. However, they may estimate evaporation as a function of temperature and available precipitation. This latter type of model is calibrated to the climatic conditions of the data record, and should not be extended to conditions outside the range of the calibration data.

The most appropriate modelling approach for climate change analysis is the water balance model (Gleick, 1987) because it can be used to account for the effects that variation in climate parameters may have on the hydrologic processes represented in the water balance equation. It thus allows assessing the sensitivity to climate variation of hydrologic processes such as infiltration, evaporation, snow melt, and runoff. The water balance approach also provides a flexible basis for model development because it accommodates varying degrees of complexity in the terms of the equation representing individual hydrologic processes, from simple empirical parameterizations to fully mechanistic representations. This allows the staged development of a model depending on application and available data.

The basic approach to water balance modelling was developed by Thornwaite (1948) to evaluate the importance of different hydrologic parameters under a variety of hydro-climatic conditions. Standard methods for calculating water balance developed during the past 50 years (Dunne and Leopold, 1978) have been applied generally to point data, or used in a limited way in catchment (Gleick, 1987) or zonal models (Beven and Kirkby, 1979; Hornberger *et al.*, 1985). Beven and Kirkby (1979) used a simple water balance approach in their development of a zonal model, which was improved by Beven *et al.,* (1984) for catchment scale simulations, and for a more detailed treatment of soil moisture by Famiglietti *et al.,* (1992). However, these models are limited to catchment scale, and do not include vegetation interaction in the water balance calculation.

Table 3.1 summarizes the minimum set of hydrological variables that are required to detect climate change, assess the impacts of climate change, predict seasonal to interannual climate and to simulate long-term climate changes:

Table 3.1. Summary list of the key hydrological observations required for climate purposes. (Details on each variable are given in Annex I.)

Atmospheric water content near the surface (relative humidity)
Biogeochemical transport from land to oceans
Evapotranspiration
Discharge (runoff)
Ground water storage fluxes

Precipitation
Sediment load at large river mouths
Snow cover area and snow water equivalent (see cryosphere chapter)
Soil moisture
Surface water storage

4. The Cryosphere and the Climate System

4.1 Introduction

This chapter is broken into two parts. These are: (1) cryosphere observations required to understand the impact of climate change on the cryosphere and feedbacks to climate; and (2) cryosphere observations required for GCMs. These are not meant to be mutually exclusive and the reader will notice many variables are repeated in both sections. These two sections lead to the selection of a minimum set of variables that are to be included in the IOS. The reader is referred to Annex I for details on each variable, including a rationale, and the required temporal and spatial resolutions. The cryosphere includes components such as snow cover that respond to daily forcing and others such as continental ice sheets that respond primarily to long-term (century or longer) effects. Here, we focus on components of the cryosphere that offer useful information in monitoring the climate system and in detecting natural trends or changes due to human activities on decadal time scales. It is recognized that sea ice is in the domain of the ocean component of GCOS, but is presented here so that a complete picture of the cryosphere can be obtained.

The cryosphere contains 80% of the world’s fresh water and is very sensitive to climate change (Fitzharris *et al.*, 1996). Monitoring of the cryosphere is of importance for improved understanding of global climate, hydrologic systems and sea-level change, as well as for impact assessments and earth system modelling. The complex nature of most cryospheric variables has necessitated that observations be made using a variety of methods involving surface and remote sensing measurements and a range of sensors. Currently, efforts are underway to combine the preferred features of each method in order to obtain optimal representations of the important parameters. Hence, there is unlikely to be a unique observational solution in many areas of cryospheric monitoring. In several instances (permafrost conditions, ice sheet mass balance), there are currently no routine observations, while other measurements (snow water equivalent, sea ice thickness) are still in a research mode. In the case of surface observations of snow cover and freshwater ice thickness, major efforts are still needed to assemble and quality-check archival records. The type and quantity of data on frozen ground conditions and their location are only just beginning to be inventoried.

The IPCC reached the following major conclusions (Fitzharris *et al.*, 1996) regarding the cryosphere:

- Many components of the cryosphere are sensitive to changes in atmospheric temperature because of their thermal proximity to melting. The extent of glaciers has often been used as an indicator of past global temperatures;
- Projected warming of the climate will reduce the area and volume of the cryosphere.
- This reduction will have significant impacts on related ecosystems, associated people and their livelihoods;
- There will be striking changes in the landscapes of many high mountain ranges and lands at northern and high latitudes. These changes may be exacerbated where they are accompanied by growing numbers of people and increased economic activity.

The requirements for monitoring cryospheric variables have recently been reviewed and documented in two workshop reports (Crane, 1993; Barry *et al.*, 1995). The parameters and necessary frequency of observations for snow cover, sea ice, glaciers, ice sheets and permafrost are summarized in Annex II (Tables 1 to 4). The availability of data sets for use in monitoring assessments has also been discussed in a number of papers by Barry (1985) and (1986), Barry and Armstrong (1987) and Walsh and Barry (1990).

4.2 Interaction Between the Cryosphere and the Climate System

Snow cover

The seasonal snow cover has high spatial variability as a result of the effects of land cover and terrain irregularities, and its extent and depth are variable on a daily time scale, at least in the transitional seasons and in the marginal snow areas. Nevertheless, its crucial role in albedotemperature feedbacks as demonstrated empirically by Groisman *et al.* (1994a) using the record of satellite-derived data, as well as its significance for hydrological processes, make certain snow cover characteristics of first-order importance (Annex II, Table 1). The overall extent and area covered by snow (in practice defined for some snow masking depth, due to the influence of vegetation) is a first-order variable. The weekly Northern Hemisphere maps of snow cover produced by NOAA from AVHRR data represent what may be called a “flagship” product that has been widely applied in trend studies for the period from 1972 to the present time and used to infer linkages between snow cover - hemispheric temperature anomalies and circulation patterns (Gutzler and Rosen, 1992; Karl *et al.*, 1993). Groisman *et al.* (1994b) identify regions of high priority for monitoring based on the interannual variability of the snow cover. The application of passive microwave brightness temperature data to hemispheric and regional snow mapping was illustrated by Chang *et al.* (1987, 1990) and Baumgartner and Rango (1991).

Recent efforts to assemble and evaluate long-run records of station snowfall and depth observations in North America (Groisman and Easterling, 1994; Karl *et al.*, 1993; Robinson, 1993), Switzerland (Fohn, 1990; Rohrer *et al.*, 1994), Austria (Mohnl, 1991), the Victoria Alps, Australia (Duus, 1992), the former Soviet Union

(Barry *et al.*, 1994) and elsewhere, have demonstrated that there exists a substantial potential for using such information for monitoring purposes, provided that proper consideration be given to the application of appropriate corrections for changes in observational procedures and gauge characteristics over time (Groisman and Easterling, 1994).

What are the most appropriate parameters of ground snow data to consider? The important indicators of changes in the snow conditions include: dates of the beginning and ending of a stable cover, depths, maximum snow pack water equivalent on certain fixed dates, and the duration of depths exceeding specified threshold values (Goodison and Walker, 1993). The date of snow cover disappearance has been studied on a regional scale in Arctic Alaska and Finland as a climatic indicator by Foster, 1989; and Foster *et al.*, 1992, but a similar approach has not yet been applied to mountainous regions for monitoring purposes. Changes in snow line elevation since the beginning of the century have been investigated in Chile (Kerr and Sugden, 1994) and elsewhere.

Sea ice

Sea ice is seasonal in both the Antarctic and Arctic shelf seas, as well as in the Hudson Bay, the Sea of Okhotsk and the Baltic Sea, and perennial in the central Arctic Ocean. Its extent and thickness reflect not only thermodynamic processes, but also the dynamic effects of forcing by the wind and ocean currents which cause drift, deformation, shear and divergence. These factors create openings (linear leads and larger irregular polynyas) in the ice as well as ridges where the motion is convergent. Hence, changes in ice extent, areal coverage and thickness, which are of special importance to climate, are a complex response to interactive atmospheric and oceanic processes.

Hemispheric ice extent in both polar regions has been reliably mapped on a weekly basis since the advent of AVHRR data in 1972 and the time series of these data are reported in Halpert *et al.* (1994) for example. They show irregular fluctuations rather than any persistent trends. Maps for the Arctic, based on more limited aircraft reconnaissance, ship and coastal observations, with satellite images from the 1960s are available from 1983 and have been subsequently digitized by Walsh and Johnson (1979) from several different sources. Russian observations have existed since the 1930s for the Eurasian sector of the Arctic and these are expected to become available within 1 to 2 years.

The fractional coverage (or total concentration) of sea ice is less accurately known. Passive microwave data have been used to derive 3-day concentrations of first- and multi-year ice from the Nimbus 5 single channel Electrically Scanning Microwave Radiometer (ESMR) for 1973-76 and for 1978-87 from the Scanning Multifrequency Microwave Radiometer (SMMR) (Parkinson *et al.*, 1987; Gloersen *et al.*, 1992). The latter series has been extended by the daily mapping capability of the Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Programme (DMSP) series of satellites (Barry, 1990). Brightness temperature data collected by the SSM/I and derived ice concentration products, both in a 25 km grid format, are distributed on compact disks by the National Snow and Ice Data Centre (NSIDC) in Boulder, Colorado, USA.

Areal extent may be determined from the weekly operational charts prepared by the US National Ice Centre (NIC). Both these weekly charts and the retrospective satellite-derived research products, available daily since 1987, represent "flagship" products that need to be supported on a continuing basis.

For the Arctic, Russian ice charts and the NIC data are now archived in format for the archival of sea-ice data in digital form (SIGRID) for the period 1967-92 in the WMO Global Digital Sea-Ice Data Bank (GDSIDB) maintained at the Arctic and Antarctic Research Institute (AARI), St. Petersburg and at the World Data Centre (WDC-A) for Glaciology/NSIDC, Boulder. The Russian data provide more detailed information on stages of ice development, although the spatial coverage is less complete than in the NIC data. The creation of a merged, optimised product is under consideration.

From a monitoring perspective, Parkinson and Cavalieri (1989), and Parkinson (1991), identify areas in both hemispheres where greater sea ice sensitivity to climatic fluctuations is to be expected. Fluctuations in hemispheric sea ice extent and ice concentrations have been analysed for the SMMR record by Parkinson and Cavalieri (1989) and Gloersen and Campbell (1991). For the Arctic, Chapman and Walsh (1993) have studied the ice extent record from 1961. These studies suggest decadal-scale and interannual fluctuations that differ regionally in sign, but with no consistent sustained trends in either hemisphere. Strong longitudinal contrasts reflect the wave structure of the atmospheric circulation.

Ice thickness is an important variable in detecting climate change. Ice thickness (strictly ice draft below the sea surface) is recorded in the Arctic Ocean by upward-looking sonars (ULS), either on board submarines or at moorings. To date, few data have been released from the former, so that even the seasonal ice thickness climatology is not reliably established (Bourke and McLaren, 1992). Most ULS moorings were installed only a few years ago, but are delivering reliable and detailed point records of ice draft. In the Antarctic, thickness data have been acquired by laboriously drilling holes. Analysis of submarine measured ice draft for repeated 50 and 100 km transects at the North Pole made between 1958 and 1992 show large interannual variability with a range from 2.8 m in 1986 to 4.4 m in 1970 (McLaren *et al.*, 1992; McLaren *et al.*, 1994); the authors reported that there was no clear evidence of any trend, although Wadhams (1995) considers that the data, and his own analyses north of Greenland for 1976-87, both indicate thicker ice in the earlier years. Thus, ice monitoring needs to include information on ice motion fields from drifting buoys and satellite data.

Glaciers and ice caps

The response to climate of perennial surface ice bodies to changes in mass varies in accordance with their size over a wide range of time scales. Relatively small mountain glaciers react passively to climatic forcing and show rapid changes in geometry within decades, for example (McClung and Armstrong, 1993), whereas large ice sheets actively influence global climate and dynamically adjust to mass changes over hundreds of thousands of years (Van der Veen, 1991). Over time periods of a few decades, corresponding to the dynamic response time, cumulative length change of mountain glaciers predominantly depends on glacier size and quantitatively reflects long-term mass changes (Haeberli, 1990). The critical measurements relating to perennial surface ice bodies are summarized in Table 2 of Annex II. Length change and mass balance are primary indicators of change in mountain glaciers. Together, they constitute a key element of change detection strategies due to their pronounced climatic sensitivity and the remarkable memory, filter and enhancement functions involved with latent heat exchange, albedo and mass balance/altitude feedbacks as well as thickness/length change transfer functions.

Overall, mid- and low-latitude glaciers show widespread shrinkage in this century (Haeberli, 1995). The average mass balance of 35 annually-measured glaciers distributed over 11 mountain ranges in North America, Eurasia and Africa showed a loss of 30 cm water equivalent per annum during the decade 1980-1990. Melting of this ice thickness corresponds to an additional energy flux of some 3 watts per square metre and, hence, roughly corresponds to the estimated annual anthropogenic radiative forcing. A similar, or even a slightly accelerated rate of change was observed in the first three years of the decade 1990-2000 (International Association of Hydrological Sciences (IAHS)/International Commission on Snow and Ice (ICSI)/UNEP/UNESCO, 1994). Based on records from 48 glaciers worldwide, Oerlemans (1994) estimated a summer warming of 0.66°C since the 1880s. Meier (1984) used a selection of the 35 mass balance records to assess glacier contributions to global sea-level rise and concluded that land ice may represent about half of the total rise. It is worthwhile underlining the fact that glacier fluctuations can yield useful estimates of regional changes in integrated climatic conditions which are especially valuable in mountain areas of the world with sparse networks of conventional measurements; the latter in any case are often unrepresentative of the mountain conditions (Barry, 1993). Glacier data from central Asia are potentially of great value in this regard.

Temperature profiles in areas of cold firn at high altitudes and high latitudes (including the accumulation areas of the two large ice sheets) contain important information about decadal to secular warming trends. The temperature of the firn areas is also critical to sea level considerations in that the transition from cold to temperate firn determines whether melt water runoff in the warm season can take place in such areas or not. In connection with global warming, migration displacement of this boundary could potentially affect extended areas in mountain ranges and polar zones.

Ice sheets

In regard to the impact from the earth's surface on the global climate system the two large ice sheets in Greenland and Antarctica are much more important than the world's glaciers and ice caps. Together they contain 80% of the earth's fresh water. In order to understand their impact on climate and consequences of climate change, we must be able to monitor their mass balance. Unfortunately, with presently available methodology and because of a paucity of observations, even the sign of their mass balance remains in doubt. An example of the importance of monitoring their mass balance is that the exchange of water between ice sheets and the oceans, which is a function of the mass balance, remains the largest uncertainty in determining the contribution of ice sheets to sea-level rise.

The consequences of a warming climate will be very different for the two ice sheets. Warming temperatures will increase precipitation over the Antarctic Ice Sheet, but temperatures will remain too cold for significant surface ablation. However, significant increases in surface ablation will occur from the Greenland Ice Sheet. The surface ablation could increase by 50% for a 2%C warming, according to an energy balance model (Van der Waal and Oerlemans, 1994), doubling the current contribution to sea-level rise. Taken together, these effects may cancel, but the uncertainty in this estimate is equivalent to 0.5 mm/yr of sea-level change.

It is possible that atmospheric and oceanographic changes at the Antarctic Ice Sheet margins may affect the discharge of the ice sheet into the ocean. Changes at the ice sheet margins have already been observed on the Antarctic Peninsula with the collapse of the Wordie and Larsen Ice Shelves (Doake and Vaughan, 1991). There is considerable uncertainty at present as to the impact of such changes, since conditions at the bed of the ice sheet, largely insulated from the ocean and atmosphere, greatly influence the flow (MacAyeal, 1992).

As previously stated, there are large uncertainties in the present knowledge of the mass balance and the contribution of the ice sheets to eustatic sea level. Precipitation measurements have been accumulated over this century from shallow ice cores (Drewry, 1983; Ohmura and Reeh, 1991). These are irregularly distributed, with a density biased towards the more frequently visited coasts. Measurements of the calving rate, or more particularly, the flow across the point at which the ice starts to float, are sparse: less than half the outlet glaciers of Antarctica have been observed. Even in the Greenland Ice Sheet, measurements of surface ablation, from which predictions of the consequences of climate warming are made, are restricted to points on the margins and isolated traverses (Braithwaite and Olesen, 1990; Ambach, 1993).

The mass balances of the ice sheets may be determined from measuring the change in average elevation if accuracies of 5 cm/yr can be achieved. Presently, the European Remote Sensing Satellite (ERS-1) altimeter enables present measurements to be made with 10 cm/yr accuracy to 82 degrees of latitude, an accuracy that will improve to 5 cm/yr with the ERS-2 altimeter. Change measurements over longer time intervals are possible using historical observations. Zwally (1989) has estimated a 1.6 m thickening in southern Greenland by determining the different elevations over a seven-year interval from the Seasat and Geosat satellites. This measurement may be affected by orbital uncertainties (Braithwaite, 1993) which are not present in the newer satellites.

However, radar altimeter performance is significantly degraded at the steeper margins of the ice sheets, which are regions of highest mass turnover and which are most sensitive to oceanographic and atmospheric changes. Laser altimeters around the turn of the century may provide accurate change measurements at the ice sheet margins, which with modern orbit determination may achieve 3 cm/yr accuracy. An important independent constraint on ice sheet mass balance may also arise from sensitive measurements of vertical uplift and temporal variations in the gravity field (Wahr *et al.*, 1995).

Satellite imagery also has a very important role in determining changes in ice sheet extent. The disintegration of the Wordie and Larsen Ice Shelves, and the widespread retreat of glaciers on the Antarctic Peninsular were observed from changes in airborne, Landsat and Synthetic Aperture Radar (SAR) imagery. The geography of the interior of ice sheets is itself uncertain. Fahnestock *et al.* (1993) have recently observed undiscovered large scale ice flows in northern Greenland. The recent development of interferometric techniques to determine displacement fields (Goldstein *et al.*, 1993) provides a method to observe in great detail dynamic flows at the ice sheet margins.

A better understanding of accumulation and ablation processes on the Greenland Ice Sheet is essential to secure predictions of its mass balance. Although ablation rate cannot be measured by satellite, the mapping of the melt zones is possible with passive microwave data and SAR data. Mote *et al.* (1993) show from SSM/I data that the extent of summer ablation in Greenland varied widely during summers 1987-89. The combined SSMR and SSM/I record will permit an extended assessment of any trends. To date, surface accumulation has not been successfully measured by satellite, although passive microwave measurements are sensitive to accumulation rates.

Freshwater ice

The freeze-up and break-up of lakes and rivers are closely correlated with air temperatures in the transition seasons. Analysis of lake records in North America and Eurasia has shown that the dates of ice cover formation and disintegration each vary about 4-7 days/degree C change in mean air temperature during the corresponding seasons (Skinner, 1993). There is a better and more robust correlation in the autumn than in the spring when snow cover on the ice, discharge from small streams and wind effects modulate the basic energy exchange processes. The timing of freeze-up and break-up of ice may be used as an indicator of air temperature trends.

Lakes selected for monitoring should preferably be of a similar size, covering an area of a few hundred square kilometres, and relatively shallow. An extensive surface introduces the effects of wind fetch; large lakes are also unsuitable as only a small area may be visible from shore, and they are often deeper, with greater heat storage. Barry and Maslanik (1994) suggest that satellite monitoring could greatly augment the number of lakes that can be studied; they show that although cloud obstruction may be more frequent in the autumn, there is quite close agreement between ground and satellite estimates of freeze-up dates. There are surface records spanning 25 to 45 years for some 250 lakes in Canada (Skinner, 1988) and much longer ones for lakes and rivers in Scandinavia (Kuusisto, 1993) and the former Soviet Union.

Permafrost

Permanently frozen ground underlies some 25% of the earth's land surface. It is widespread in Canada and Alaska, northern Russia and parts of north-east China, but it also occurs in many mid-latitude high mountains and on the Tibetan Plateau (Barry, 1985). Permafrost is believed to form gradually over very long time intervals (105 years), occurring continuously where mean annual air temperature is <-7 C. Along the margins, where it is thin and discontinuous, permafrost degradation can be monitored. Changes in the permafrost and the overlying summer active layer can have important effects on hydrological regimes, ecological and geomorphological conditions, and structures (Koster and Nieuwenhuijzen, 1992; Nelson *et al.*, 1994). In areas of thick continuous permafrost, changes are detectable in profiles of ground temperature measured in deep boreholes. Lachenbruch and Marshall (1986), for example, reported 2 to 4 C warming in the upper 100 to 150 m of boreholes in Arctic Alaska, which they related to a temperature rise over the last 100 years or so. However, changes in ground temperature reflect a complex response to surface temperature and moisture conditions, vegetation cover, winter snow depth and any disturbances due to fire, plant succession, or human activity. Moreover, the air temperature record at Barrow does not suggest a sustained warming. Increased recognition is being given to the active layer data for monitoring and model validation. Gilichinsky (1986) provides illustrations of the seasonal course of active layer temperature and snow depth at three sites in the steppe and steppe-woodland zones of western Siberia over a ten- year period. However, there are currently no generally available data sets for research use. Planning for appropriate databases for purposes of monitoring, model validation and development, and applications is being actively pursued by the Data and Information Working Group of the International Permafrost Association (IPA) (Barry and Brennan, 1993). In several mountain areas, a ground temperature monitoring programme has been initiated (Haeberli *et al.*, 1993) and initial results indicate a recent rapid rise in ground temperature at various sites in central Asia and the European Alps.

3 Variables Required for GCMs

The impact of the cryosphere on global climate change is further emphasized by the sensitivity of GCMs to fluctuations in large ice sheets (Clark *et al.*, 1995). Topography and albedo of the then existing ice sheets explain most of the cooling of the Northern Hemisphere during the latest ice age (Manabe and Broccoli, 1985). Many well known ice sheet/atmospheric interactions are common results of several independent GCMs. Better use of existing glacier inventory and permafrost distribution data could help in validating GCMs, particularly where poor weather records exist.

However, there are several issues of impact on climate of large ice sheets that still need to be explored, and hence a need for an expanded observing system. A basic requirement for modelling the influence of ice sheets on climate is improved data on distribution of temperature, precipitation and runoff on the surface of the ice sheet. Clark *et al.* (1995) also emphasized the need for a database of three-dimensional ice-sheet geometry to be developed for the large ice sheets of the globe. If more detailed information on ice sheet dimensions, insolation and atmospheric composition can be obtained to study interannual variability, coupling of ice sheet models to GCMs will be a useful tool to solve the existing problems in understanding the mass balance of large ice sheets.

Another important issue which may be studied by GCMs is the inter hemispheric communication between ice sheets in the Northern and Southern Hemispheres which takes place through the general circulation of the atmosphere and the oceans. Such studies may call for coupled ocean atmosphere GCMs, which treat heat transport linked to thermohaline circulation that originates in the North Atlantic.

Also relevant to the above issue and mentioned by Clarke *et al.* (1995) is the need to understand the causes of the episodic discharge of icebergs from the Greenland Ice Sheet which at present are unknown. These discharges of icebergs may have a crucial effect on climate of the Northern Hemisphere through controlling the salt content of the thermohaline circulation in the North Atlantic.

Table 3.1 summarizes the minimum set of cryospheric variables that are required to detect climate change, assess the impacts of climate change, predict seasonal to interannual climate and to simulate long-term climate changes:

Table 3.1. Key variables for cryospheric observations.

Sea ice concentration/extent
Sea ice motion
Sea ice thickness
Snow cover area
Snow depth
Snow water equivalent
Ice sheet mass balance
Ice sheet geometry
Glaciers and ice caps
Lake and river freeze-up and break-up (timing)
Permafrost - active layer
Permafrost - thermal state

5. Sampling Design: Concept, Measurement Strategy and Selection of Site and Variables

5.1 Introduction

Observational systems of the terrestrial environment require both local observations, often measured *in situ*, and broader scale data frequently obtained by remote sensing. The success of this integrated system is highly dependent on the sampling strategies employed. Current ones are deficient in a number of respects and we outline in this section the principles for designing the sampling strategies for the global biosphere, hydrosphere, and cryosphere. Successful execution of the GCOS and GTOS programmes requires that information about numerous variables be obtained for the global terrestrial environment and converted into homogeneous data sets. Such data sets are necessary to achieve the GCOS objectives such as climate change detection, assessment of seasonal and interannual variability, model validation; and the GTOS objective of detecting and assessing the impact of climate change on terrestrial ecosystems, among others. To obtain the data sets typically implies that each variable is measured at many locations around the world with the necessary temporal frequency, accuracy and consistency so that the global data sets can be generated from these measurements. Since most variables of interest vary both in time and in space, often quite rapidly, this poses a formidable challenge.

Criteria for the design of the GCOS/GTOS sampling scheme were adapted from those of the US Environmental Monitoring and Assessment Program (EMAP; Overton *et al.*, 1990).The criteria are:

- Responsiveness - The design is responsive to the needs of users;
- Adaptability - The design must accommodate changing perspectives, objectives, user needs and increased knowledge;
- Flexibility - The protocols and design structures need to be flexible and capable of accommodating a wide variety of methods, and space/time resolutions; and be able to incorporate existing international monitoring programmes;
- Simplicity - It must be understood by all and it must be implementable with varying degrees of sophistication;
- Rigour - Quality assurance procedures need to be developed and approved by an international GCOS/GTOS methods working group.

5.2 Concept

The various climate objectives, including those relating to economic and sustainable development - regardless of whether they require observations of the hydrosphere, cryosphere or biosphere - imply different design criteria. Change detection is favoured by placing a sample in the path of probable change. Change quantification requires a systematic, representative and unbiased sampling strategy. Model development and future projections may require intensive data collection for relatively few sites which span the range of global conditions present, without necessarily being statistically representative. Model operation needs complete and coherent sets of variables. When the individual temporal and spatial characteristics of a large number of variables are added to these considerations, it is clear that the data gathering system needs to be flexible and multi-purpose, besides being cost-effective.

The fundamental constraint of global observing systems is that it is not practically feasible to make all the measurements all of the time everywhere. It is therefore necessary to design a sampling system which still retains adequate spatial and temporal resolution, but is affordable and practical. For example, one of the efficient sampling designs is stratified random sampling in which the distribution of samples is based on the distribution of the variance within the population of interest. The highly variable portions (or strata) of the population are then sampled more intensively than those with less variability.

A hierarchical tier system in which at the one extreme a few variables are measured continuously in a large number of places, and at the other extreme a large number of variables are measured in a few locations, provides a practical compromise between the conflicting requirements for accuracy, representatives, and affordability. In principle, the tiers will be defined in relation to individual variables (Section 5.3). Since many variables of interest vary in similar manner so that their stratifications more or less coincide (e.g., biogeochemical variables in relation to biome distribution, hydrological variables based on catchments), it is possible to co-locate the measurements at research stations or observation sites. Examples of such existing sites are longterm ecological reserves, agricultural research stations, and experimental watersheds.

A variable of interest may often be measured in different ways. For example, soil organic matter content can be measured directly through chemical analysis, indirectly using spectrophotometry, or simply related to soil colour through the use of colour charts. The available procedures generally differ in accuracy, complexity, and costs. Various measurement techniques also provide results over different spatial domains. Thus direct, detailed measurements can be applied at only few locations because of logistics and costs. On the other hand, indirect methods such as satellite observations provide the means of covering the whole globe, with high or low spatial resolution that can be selected through sensor design and mission management. The hierarchical tier concept can readily accommodate these differences, thus affording optimized use of the available resources.

The hierarchy of terrestrial measurements required for a global observing system divides fairly naturally into five tiers, each with distinct characteristics and roles. They range from tier 1, where measurement techniques employed for the variable of interest are more complex and the measurements are made at few locations, to tier 5 with few variables measured at many locations using indirect methods, principally remote sensing. Specific sites can be assigned to tiers on the basis of the number of GCOS/GTOS variables measured at the same location, the accuracy/precision of the methods used to measure the variables, and the spatial frequency with which the variables are sampled. The tier concept is applicable to the three main areas of concern in the relationship land surface/climate change - the land surface, freshwater ecosystems and cryospheric surfaces - each of which may have their own hierarchy, culminating in a shared tier 5. The main characteristics of the tiers are given in Table 5.1.

Table 5.1. Tier characteristics.

TIER	ROLE	CHARACTERISTICS	INDICATIVE NUMBERS
1. Large area experimentsa) e.g., IGBP, large catchment studies	Understanding of spatial structure and processes, interactions among processes and ecosystem components detecting change in these at regional scale; study of scaling issues; and development of models describing these	. Large-scale experiments Intensive measurement of a large number of variables over a ‘site’ of several hundred square kilometres or a transect of several hundred kilometres long, over a limited period of time. Examples are the IGBP Megatransects, GEWEX large catchment studies ISLSCP projects, etc. May later continue observations of selected variables (as tier 2 or 3 sites).	10
2. Research centres e.g., LTERS, large agricultural research stations.	Understanding processes within biomes, change detection, experimentation, method development, data synthesis.	Research centres with a large staff(>10 participating scientists) and sophisticated infrastructure (varies with the research focus but may include laboratories, data loggers for continuous measurement, flux towers and gauging weirs, etc.). They tend to	100b)

		focus on one biome type for unmanaged ecosystems(e.g. the US-LTERs) or one crop type in the case of agricultural centres (e.g. CIAT, IRRI). In principle, there should be one or more sites per major crop type, biome type, aquatic system type and cryospheric type	
3. Stations e.g., Biosphere reserves, smaller national agricultural an ecosystem research sites, research catchments, small polar stations.	Long-term measurement of variables which vary over periods from weeks to years; seasonal and interannual variations across the range of variability within each major ecosystem, crop system, aquatic system or cryospheric system; calibration and validation remotely-sensed variables; trends of variables.	Research stations with permanent presence on site. Many hydrological observation sites fall into this category, as do ecological field stations and many agricultural research stations. The observations do not require very expensive, sophisticated or continuous measurements.	1 000b)
4. Sample sites e.g., US EMAP program, UK country survey.	Direct measurements and change detection of variables not observable by remote sensing; calibration and validation of remotely sensed variables; status and trends of biome health; provide statistically valid spatial information for extrapolating findings from the other tiers.	Sites which are revisited regularly but infrequently (once every 5-10 years).	10 000b)
5. Satellite remote sensing (e.g. AVHRR, SPOT, Landsat, Radarsat).	Spatial and temporal interpolation as detailed as1 day and 10-30 metres. Extent of biomes, ice sheets, etc., status and trends of a biome health	The principal feature is the reliance on remote sensing, which is usually quasicontinuous in both time and space, but can provide data for only some of the variables of interest. This tier also includes other measurement or mapping techniques which result in spatially extensive data sets(e.g., topographic, soil data sets); however, the vast majority of future data will be obtained through satellite remote sensing.	Not applicable

Notes:

a. May or may not include a tier 2 research centre or tier 3 station, very likely to include at least several tier 4 sites.
b. Approximately in the ratios 30 natural ecosystems: 30 agroecosystems: 10 rivers: 10 lakes/estuaries: 10 cryosphere.

Space resolution, time resolution, and thematic detail are the main organizing principles of the tier hierarchy. The hierarchy is partially nested, in other words, only some of the locations at one tier are components of a location at the next lower tier. For example, research centres are not necessarily made up of research stations, stations by sites, and so on; but in most cases there are strong linkages between the tiers. Within the hierarchies for the land, freshwater and cryosphere, there is a balance between different types of systems: for instance between natural, agricultural and urban ecosystems on the land; between rivers, lakes, estuaries and groundwater in freshwater systems; and between ice sheets, ice caps and glaciers in the cryosphere. There is also a geographical balance: coarse representation at tiers 1 and 2, detailed representation at tier 3, unbiased sampling at tier 4, and complete coverage at tier 5.

An important feature of the hierarchy is its vertical and horizontal integration. Horizontal integration means that the data at one tier are sufficiently complete both spatially and thematically to make useful products at that level; they are mutually supporting within a conceptual model operating at that level. Vertical integration means that the tiers are not independent. Each major theme is covered at all tiers by interrelated and compatible variables, allowing the detail and mechanistic insight obtained at higher tiers to be spatially elaborated and validated at lower tiers. For example, global wall-to-wall land cover is mapped in broad classes using remote-sensing at tier 5; this is enriched with ground observations of vegetation cover and land use at tier 4; further enriched with temporal detail (the seasonal progression of intercepted radiation) at tier 3; supported with mechanisms at tier 2 (the landscape-scale dynamics of leaf area and architecture) and elaborated with spatial processes at tier 1 (for instance the ‘green wave’ which travels seasonally along a regional temperature/moisture gradient). This integrative logic has been applied to all variables.

Tier 1 - The primary objective of tier 1 is to characterize climate and climate change-related processes in the terrestrial environment, at a range of spatial scales and for seasonal or shorter time scales; and to develop procedures and models for upscaling findings from local sites to the region and eventually the globe. Tier 1 involves intensive experimental studies over large areas or along transects crossing environmental gradients. Such studies focus on the development and validation of models that mimic the climate-terrestrial interactions and the response of the terrestrial environment to changing climate, including feedbacks. This requires a small number of regional scale, relatively short-term (5 years or so) studies, although measurements over extended periods are likely to continue at many of these sites. Facilities at this tier add measurements of processes generally not quantified at lower tiers (e.g., trace gas exchange), and they address mechanisms of spatial integration and scaling up of the various processes from local to regional and larger areas.

The proposed IGBP transects and the existing or proposed large-scale surface experiments (e.g., Hydrological Atmospheric Pilot Experiment (HAPEX-Sahel), and the Boreal Ecosystems Atmosphere Study (BOREAS)) already total the appropriate order of magnitude. The spatial scale for these sites should include a core area in the order of at least (10 km)2, and studied surroundings of 104 km2 or more. Although these studies are short term, it would be highly beneficial for the sites to continue long-term measurements beyond the experimental period. In most cases, this would imply a change from tier 1 to tier 2 or 3 for the long term. In any case, GCOS/GTOS need to ensure long-term availability of the data and models resulting from these experiments/sites.

Tier 2 - The objective at this tier is to understand the processes and the way they respond to global change over a range of time scales. To enable studies of mechanisms, the sites may involve manipulative experiments in addition to monitoring. Tier 2 includes major research centres, usually with a biome, regional or crop focus. There will be at least one (preferably two or three) centres in each of the major biome types (about 20 in all) and a centre for each major crop and plantation forest type, for a global total in the order of 100. Sites at this tier will be well-equipped and staffed, and they may include subsidiary research stations or off-site experiments. Hallmark measurements added at this tier include diurnally resolved weather; soil moisture; isotopic studies of soil nitrogen and carbon; and continuous monitoring of fluxes of CO2, water, and energy. For larger countries, there will be one or a few sites per country. For smaller countries, tier 2 sites can serve as regional centres.

The Consultative Group on International Agricultural Research (CGIAR) crop centres would fit into this tier, as would some of the better-developed ecological research sites in the US, Europe, and China. Together, these already total well over 100 sites. Extrapolation of measured data are made via periodically-updated inventory information. Some centres may need to be promoted (or sustained) in the lesser-developed parts of the world.

Tier 3 - The primary objective at this tier is to provide dynamic data over time at the sub-annual temporal resolution (e.g., phenology, net primary production, snow water equivalent, glacier mass balance) as well as to provide spatial context. Tier 3 includes many of the existing national ecological and agricultural research stations, experimental watersheds and cryosphere research sites. They will comprise some 1,000 facilities, each covering areas of up to approximately 10 km2. This is also the tier of closest linkage to weather stations and for calibrating remote sensing- derived data products. Tier 3 sites will usually have small permanent staff and modest facilities (e.g., a weather station, balances, drying ovens, communications, data handling facilities). Because an approximate balance across biomes, agro-ecological regions and farming system types is a high priority, these sites will need to be selected with care. However, it is not necessary that all ecosystems be represented at this tier in proportion to their extent. It is estimated that 80% or more of these stations already exist. Where gaps occur, especially in the developing world, international efforts may be needed to establish new ones.

Tier 4 - The objective of this tier is to establish the representatives of the data obtained in tiers 1, 2 and 3, and in some cases also to provide additional ground data for satellite-based estimates. Tier 4 has the unique function of providing accurate and spatially-resolved data on variables which at present cannot be remotely-sensed. An example is the soil carbon content, which is important because it is the largest biospheric carbon pool, is subject to change, and influences other factors such as the soil water holding capacity. It cannot be observed from space. In addition, tier 4 sites can act as calibration and validation points for remotely-sensed variables; tiers 2-3 also provide these data, but may have insufficient sites to represent all the ecosystem classes. In this sense, tier 4 is intended to bridge the gap between satellite observations, which are quasi-continuous in space and time (tier 5), and the permanently-staffed but non-optimally distributed tier 3 ground stations. It is important to separate the unique roles of tier 4 from the additional roles, because they have different sampling requirements. Tier 4 points should be placed in a statistically unbiased manner. Among all the tiers, tier 4 is the least established one as only a few countries have sampling programmes at this level. The implementation thus poses special challenges which are discussed later (Section 7.2).

Tier 5 - The objective of this tier is to allow extending the data and knowledge from tiers 1-4 to the large areas such as country, region, and the globe. Such extension is typically accomplished using tier 5 data sets in conjunction with data from higher tiers and models from tiers 1-3. Tier 5 must also provide data to detect and classify natural and human activities such as changes in albedo, snow cover, sea ice concentration, vegetation composition and structure, forest clearing, urbanization, and other types of land cover change. While remote sensing is the dominant measurement technique at tier 5, other tools (topographic surveying, field mapping of soils, etc.) can be important for specific data sets. In general, it is expected that the spatial resolution will be better (smaller areas) than 1 square kilometre globally, though for specialized observations, resolution will be provided for more local data sets at 30 metres or less. The main source of data at this tier will be satellite-borne sensors and associated data processing facilities. The implementation of tier 5 thus relies on close collaboration with space agencies and is further considered in Section 7.2.

5.3 Measurement Strategy

The proposed measurements are intended to capture the status and dynamics of terrestrial ecosystems essential for climate purposes. The proposed variables (Annex I) have been selected to be the minimum set needed to observe, understand and predict changes in critical life supporting terrestrial processes involving climate. They are intended to be internally consistent and mutually supporting and enhancing. The measurements must be as globally applicable and standardisable as possible.

At tier 1 locations many variables are measured with precise, often expensive and time consuming methods, and with a high temporal frequency. At the other extreme, relatively few variables are measured at tier 5 using remote sensing but with a high spatial frequency because of the ability to provide complete coverage of the area of interest. In general, the accuracy at tier 5 will not be as high as for other methods because of the necessary conversion of electromagnetic measurements into the variables of interest.

In addition to producing integrated information using data from the global observing systems, models will play a central role in filling the gaps in space and time unavoidably left by incomplete sampling. In general, tiers 1 and 2 yield models which are validated, run and interpolated using data from tiers 3, 4, and 5.

The variables measured at each tier are listed in Table 5.2. The requirements have been carefully analysed to ensure that a minimum set of the important variables is chosen. It is evident that numerous variables are measured at several tiers, although the details differ (time resolution, measurement method, etc.). The rationale and specifics are discussed individually for each variable in Annex I.

5.4 Site Selection

The objective of the selection is to take maximum advantage of existing facilities while ensuring an appropriate global distribution of the measurement sites. It is essential that the sites be carefully chosen so as to meet the objectives of GTOS and GCOS. The different objectives associated with the tier 1-5 facilities impose different criteria on site selection. This section outlines basic guidelines for identifying sites at the individual tiers. The site selection process is further considered in Section 7.

5.5 Selection of Variables

Details on the variables selected for measurement are given in the sections on the biosphere, hydrosphere, and cryosphere below and in Annex I. The variables were selected to conform to three criteria:

Relevance - the variables address the core issues of the effect of the land surface on the global climate and the effect of the climate on the land surface. They focus on exchanges of water, energy, and key elements (such as carbon and nitrogen) between the atmosphere and the land, and the impact of these under a changing climate (see Sections 2.3, and 4);

Priority - the variables form a minimum (and highly-integrated) data set. They consist of essential data required to understand and predict the functioning of the land-atmosphere interface, and comprise primary variables (those quantifying the interchange directly) and secondary variables (those required to derive or interpret the primary variables);

Practicality - variables are obtained by proven, stable methods, globally robust, repeatable, affordable and already widely applied.

Table 5.2 indicates the importance of each of the selected variables in relation to GCOS/GTOS objectives. It is evident that some variables are critical to several objectives while others only to few or one. Nevertheless, the achievement of the objectives depends on these data being available with the resolution, sampling frequency and accuracy indicated in Annex I.

While some variables are measured at several tiers, others are obtained at one tier only. The relationship of variables to tier measurements are shown in Table 5.3. It is likely that where a variable is measured at several tiers, the measurement method will vary among the tiers. This has been considered in Annex I in relation to individual variables where the item ‘Measurement method’ lists the measurements at the various tiers.

The TOPC considered various options for identifying the highest priority variables for initial implementation. The criteria selected for prioritizing the variables are related to importance and feasibility (Table 5.4):

- What is the impact of the variable in both depth and breadth?
- How well will the variable help meet a specific GCOS objective?
- What is the cost of implementing?
- What is the existence of implementing structures?

It is important to note that important variables exist without a feasible measurement methodology (e.g., soil moisture). These gaps point to priority areas for further research and development of measurement programmes.

In addition to the surface sampling system based on *in situ* sites, there are a number of satellites which provide essential data at tier 5. Landsat and SPOT are particularly useful to the terrestrial community for a number of measurements including monitoring radiation, leaf area index, and detecting changes in land cover and land use. The AVHRR of NOAA has provided useful data at >1 km resolutions as noted above. Several new sensors are due to be launched in the next five years which will revolutionize land remote sensing to the benefit of programmes such as GCOS. They include the Moderate Resolution Imaging Spectroradiometer (MODIS), vegetation instrument on SPOT-4, and the Medium Resolution Imaging Spectrometer (MERIS) to provide improved data at resolutions 250 m to 1 km.

6. Information Management: Biosphere, Hydrosphere and Cryosphere

6.1 Introduction

Data and information management are crucial issues for terrestrial observations

Descriptions of the GCOS Data and Information Management Plan (GCOS-13) and the proposed GTOS plans for data management, access and harmonization (ICSU *et al*., 1996), have been published and the reader is referred to these and reports of the GCOS Data and Information Management Panel for more details. The following description is intended to provide the reader with an overview of the guiding principles of the information management system needed for terrestrial observations for climate purposes.

Need for data and information management

There is a clear requirement for systems that will promote and facilitate the access by individuals, institutions and national entities to relevant global and regional level information. Especially for the land, observations are often scattered and need to be assembled from a large number of sources and locations and may often require substantial analysis to create internally consistent databases.

Components of data and information management systems

There needs to be explicit links with a variety of different existing data systems. Data sets lie at the heart of any Data and Information System (DIS), including both in situ, remotely-sensed data and also increasingly model outputs. In addition, there is requirement for high quality meta-data describing data sets including such attributes as location, time of collection and data quality. For both the data and meta-data there is a need for tools for input, storage, management, retrieval, display, analysis and output. Rather than any sort of centralized systems, a highly dispersed system is envisaged. What is crucial from the point of view of the TOPC is that for every key observation, responsibility is taken by an organization or entity to carry out these tasks. Another essential aspect of data and information distribution is to ensure agreement to, and implementation of, data policy that leads to free and open access to the data sets.

Making maximum use of existing programmes and expertise

To the fullest extent possible, the GCOS/GTOS data and information systems will rely upon existing national and international programmes. Systems operated by these programmes, such as the ICSU World Data Centres, WWW of the WMO, GOOS, UNEP'S Global Resource Information Database (GRID) and many others, should be enhanced as necessary to meet data requirements rather than creating new entities. While GCOS and GTOS should oversee development of a coordinated information system design that identifies the responsibilities of all cooperating agencies and programmes, it should not normally need to create new institutions to carry out the tasks required for its implementation. Instead, these tasks will be performed by the existing world and national observing systems, telecommunications networks, and data and processing centres. GCOS and GTOS should act to ensure data are collected, validated, processed and archived to the exacting standards necessary. They should also review, monitor and coordinate activities between groups to ensure proper data are being collected and can be exchanged easily.

Ensuring data are of appropriate quality and consistency

In order to meet its exacting scientific objectives, data and products must be of the appropriate quality and consistency to meet stated objectives. GCOS will promote the development of, and adherence to, minimum quality and documentation standards for all relevant data and products. Experts will be invited to review these data sets regarding their quality and documentation to ensure they are of a standard that is acceptable to peers using similar data. Metadata (e.g., calibration and other information about the data themselves) will be assembled and maintained so that it is easily accessible to participants. Achieving harmonization, i.e., internal consistency, can be particularly demanding for terrestrial *in situ* observations. Considerable attention has been paid in recent years to the harmonization of the legends of databases of properties such as land cover and land use. But there are many other aspects of data harmonization relating to categorical data, continuous data fields such as those from remote sensing, and in situ observations which often require substantial efforts.

Overall system design

To make the best use of existing facilities and expertise, the GCOS data and information system will be based on a hierarchy of local, national, regional, and global institutions. Local centres responsible for data produced by the research community should provide short-term archival and access to pertinent data that they hold, production of data sets, analyses and products, and should forward data and information of enduring value to designated centres. National organizations should be responsible for long-term observation, basic quality control, and routine transmission to world centres. Designated centres should be responsible for advanced quality control (e.g., international comparisons and bias adjustment) and for operational production of data sets, analyses and products.

6.2 Data Management for the Biosphere

It is clear that data and information management for the biosphere will have to rely primarily on the efforts of national institutions. Among recent national developments of international significance is the Distributed Active Archive Centre (DAAC) system in the US developed as part of NASA’s Earth Observing System (EOS). In terms of an overall framework for providing international linkages, it is recommended that the data and information management system for terrestrial observations work closely with the World Data Centre System, IGBP-DIS and develop cooperation with UNEP’S GRID programme. After the initial data centres are established, it is expected that others will be added to the system.

World Data Centre System

Originally set up to handle data from the International Geophysical Year, the World Data Centre System of the International Council of Scientific Unions has a number of centres whose work is relevant to the biosphere, including soils at Wageningen in the Netherlands and remotely-sensed data for land cover at the Earth Resources Observation Systems (EROS) Data Center in Sioux Falls, USA. However, it is also apparent that there are many types of observations relevant to the biosphere not currently covered by the WDC system.

International Geosphere-Biosphere Programme Data and Information System

The Data and Information System of the International Geosphere-Biosphere Programme (IGBPDIS) was set up because of the key role of data and information in the scientific success of IGBP. IGBP-DIS is not, and was never intended to be, a hardware-based, data centre responsible for receiving, processing and supplying all data for IGBP. That scale of effort would be an inefficient use of resources, duplicating the efforts of various international and national agencies. Instead, the rationale for IGBP-DIS stems from a number of generic issues for data acquisition and management which cut across the activities of core projects and relate to their integration.

Among the most important of these issues are:

- The increasingly integrated nature of global environmental science as a whole requires greater exchange of data from diverse sources within and between projects;
- The current lack of many crucial data sets needed by several core projects for model development and operation;
- The very large volumes and novel character of many new data sets expected to be available from space platforms in the late 1990s, with distinctive problems of information manipulation and extraction;
- The need to ensure the provision of long-term data sets to detect significant global changes in environmentally important parameters;
- The need for data system plans for individual core projects and other framework activities.

Current projects include efforts leading to the creation of a global land data set from the AVHRR, a global land cover product derived from the AVHRR data set, a pedon database describing global soil properties, specification of a global fire database, work with the Committee on Earth Observation Satellites (CEOS) to analyse the implications of their data policy for research applications and development of integrated meta-database systems to permit improved use of high spatial resolution products.

Global Resource Information Database

The Global Resource Information Database (GRID) was established as part of the Global Environmental Monitoring System (GEMS) but subsequently became a separate entity. GRID objectives include enhancing the availability and open exchange of global and regional environmental geo-referenced data sets, providing the United Nations (UN) and intergovernmental bodies with access to improved data management technologies and enabling countries to make use of GRID-compatible technology for national environmental assessment and management. A major GRID activity has been the development of data archives and a metadata catalogue for data referral purposes. The availability of data through GRID is enhanced by a network of GRID cooperating centres currently in eleven countries (Brazil, Canada, Denmark, Kenya, Japan, Nepal, Norway, Poland, Switzerland, Thailand, and the USA).

6.3 Data Management for the Hydrosphere

Modern data systems can exist nowadays in a distributed form connected and integrated through Internet which does not require a large central office. While the research community will produce many of the required derived products from the raw data, some products may require a central office whose function is to interpret the data. Examples of its activities would be to make timely summaries, or to derive spatial fields by assimilation or by aggregation of the raw data. In the hydrological field, examples include precipitation and runoff. Derived products include gridded fields for monthly data. Other products include zonal, continental or regional totals and their time variation. These are combined with changes in surface and subsurface storage to compute water budgets and assist with model validation.

There are two data centres which can form components of the initial data management programme, the Global Runoff Data Centre (GRDC) and the Global Precipitation Climatology Centre (GPCC). It is essential that GRDC and GPCC be adequately staffed in order to meet these needs. The work of the International Satellite Land Surface Climatology Project (ISLSCP) which is part of WCRP's GEWEX project provides a useful example of the integration of data sets.

The Global Runoff Data Centre

Recognizing the role of river discharge in hydrological and climatological research and monitoring, the GRDC was established in 1988 under the auspices of WMO and is operating at the Federal Institute of Hydrology in Koblenz, Germany. The Centre has close links with other major hydrological data centres including the Water Global Data Monitoring Centre at Burlington, Ontario, Canada, which stores and processes the data for UNEP'S GEMS Water network, the GPCC in Offenbach, Germany, and the UNESCO Flow Regimes from International Experiments and Network Data (FRIEND) Project. Mean daily and monthly discharge data are collected on a global scale. For meteorological and climatological applications, the scope of the use of the data are primarily on the global and regional scale. For use in operational hydrology, the scope of the use of the data is mainly on the regional and basin scale.

The Steering Committee of the GRDC at its first meeting in June 1994 recommended that the GRDC should closely liaise with, and participate actively in, GCOS. This sets the path for the expected cooperation of the GRDC with GCOS. Currently the centre has limitations, because of the reluctance of individual nations to send data. To become a fully useful and operational data centre, individual nations must be willing to share data through the centre. Without the cooperation of these nations, whether through GRDC or elsewhere, the utility of a hydrological observing system for GCOS and GTOS is limited.

The Global Precipitation Climatology Centre

Precipitation plays an important role in the global energy and water cycle. The compilation of digital maps and data sets of precipitation covering the earth's land surface worldwide is the task of the GPCC, which was initiated by the WMO in 1988. The GPCC is a member of the GEWEX Hydrometeorology Panel within the WCRP. The GPCC also participates in the Global Precipitation Climatology Project (GPCP), which is represented in the GEWEX Radiation Panel. The purpose of the GPCP is to derive gridded data sets of monthly precipitation totals covering the entire globe including the oceanic areas, where satellite-based observations are the main data source. The specific functions of the GPCC in the framework of GPCP are defined by the GPCP Implementation and Data Management Plan (WMO/TD-No. 367) and comprise:

- The collection of gauge-measured precipitation data world-wide received via the Global Telecommunication System (GTS) and acquisition of non-GTS precipitation data as fast as possible;
- Quality-control for all data before application and spatial analysis;
- Calculation of areal mean monthly precipitation totals on the basis of conventional measurements (over land) using objective analysis methods;

- Merging these analyses with monthly precipitation estimates from other observation techniques (satellite images provided by other GPCP centres);
- Determination of the error range of the result for each individual grid area and month.

The GPCC also contributes to other international programmes and projects as to the development of the GCOS. The GPCC is planning to compile and operate an Arctic Precipitation Data Archive for the WCRP Arctic Climate System Study (ACSYS). In this framework, the GPCC's functions will be extended to the collection of snow cover and depth data and to analysis of the liquid water equivalent.

The GPCC is operated by the Deutscher Wetterdienst (DWD, National Meteorological Service of Germany) and is located in Offenbach, Germany.

The GPCC products are gridded area-means of monthly total precipitation, meta data as well as statistical results on the grid and on a monthly basis. The current grid size is 2.5 by 2.5 degree geographical latitude and longitude. The beginning of the data evaluation period is 1986. It is planned to reduce grid size to 1 by 1 degree. Up to now, the following products are available on a monthly basis for 2.5 degree grid cells:

- The 10-years "GPCC interims product" of terrestrial monthly precipitation, based on rain gauge-based data worldwide from about 6,700 stations, are available for the period 1986 to 1995;
- The climate monitoring product of terrestrial monthly precipitation, based on observations from about 6,000 stations worldwide. This product has been vailable since January 1996 on a routine basis with a delay of not more than two months;
- The verification product of terrestrial monthly precipitation will be based on the data from about 40,000 stations, supplied by more than 120 countries. First monthly test analyses for the year 1987 are now available;
- The GPCP combined data set of monthly precipitation over land and ocean, based on the GPCC interims product (1), infrared and SSM/I satellite observations developed at NASA Goddard Space Flight Center in collaboration with the GPCP participants) is now available as version 1a for the period 1988 to 1995.

These gridded products are freely available. Access is possible using FTP. The products are partly published on CD-ROM, too.

The only directly observed information on precipitation results from *in situ* rain gauge measurements. However, the data represent geographical points only and need to be integrated over areas using interpolation techniques.

Error studies have shown that data from about 10 stations per 2.5 degree gridcell or area of about 50,000 km2 are required for the calculation of area mean precipitation on the grid within an error benchmark of 10%. If this approach is extrapolated to the total area of the earth's land surface, it is added up to a number of 40,000 stations, which largely exceeds the amount of the routinely exchanged precipitation data, which are disseminated via GTS and actually available from about 6,000 stations only.

The GPCC data collection includes monthly precipitation totals of more than 40,000 stations, delivered from about 120 countries. However, the spatial distribution of the stations is very unequal, and large data gaps are still existing. The maximum coverage is in the year 1987 (status of data collection in June 1996). Since the data flow from national agencies to the GPCC is voluntary and not generally regulated, the availability of these data is largely delayed.

The station-related observational data are not distributed by the GPCC to other users in order to respect the interests of the data supplying countries.

The GPCC expects from GCOS an internationally regulated exchange with regard to the specific requirement of a higher network density for spatial analysis of precipitation.

International Satellite Land Surface Climatology Project (ISLSCP)

ISLSCP has been carrying out large-scale experiments on Land Surface Climatology for several years and forms part of the WCRP's GEWEX. Recently it has compiled a wide variety of data sets from various sources all on a common global projection and with the same 1 degree resolution and made these available on a CD-ROM. Comments on the quality of the data sets are also included. Several of the data sets also have direct relevance to the biosphere.

6.4 Data Management for the Cryosphere

A strong organizational framework exists for the archiving and dissemination of snow and ice data and information. There are four ICSU World Data Centres for Glaciology: Boulder, Colorado, USA; Moscow, the Russian Federation; Cambridge, UK; and Lanzhou, China. It is proposed that these four centres provide the initial data and information management system for the IOS. WDC-A for Glaciology at the US NSIDC in Boulder, Colorado, has an active programme of archiving and distributing all forms of snow and ice data. WDC-D at the Lanzhou Institute of Glaciology and Cryopedology is assembling data on glaciers and permafrost in China.

The ICSU/Federation of Astronomical and Geophysical Services (FAGS) and UNEP/GEMS World Glacier Monitoring Service in Zurich, Switzerland, assemble data on glacier extent and mass balance. The IPA is sponsoring a project for a Global Geocryological Database. Through NASA's Mission to Planet Earth, the NSIDC DAAC manages satellite and *in situ* snow and ice data for global change research and the Alaska SAR Facility DAAC manages polar radar data. There are several major limitations to current data management capabilities:

- Many cryospheric observations have not been adequately documented and archived. This is particularly serious for snow water equivalent and permafrost data. Steps should be taken to identify the most crucial of these observations and to mount a data rescue programme;
- Many permafrost records collected by private-sector organizations, as well as agency surveys of glaciers, may be at risk due to cutbacks in programmes. The most important of these should be identified and attempts made to save these in long-term archives;

- Older station observations of snow cover and snow course surveys of water equivalent are not readily accessible either because they are not digitized, nor centrally archived. Digitization and archiving of the most important of these should be attempted;
- Some national agencies are also curtailing access to their data sets by international centres wishing to assemble and distribute global databases. Through GCOS, GTOS and ICSU efforts must be taken to ensure the continuing availability of these data for scientific and related purposes.

6.5 Conclusions and Recommendations for Improvements to Data and Information Management

Apart from the specific recommendations and conclusions with respect to the biosphere, hydrosphere and cryosphere, there are a number of general conclusions and recommendations with respect to data and information management.

The terrestrial community in terms of data management is not well served for many observations. This community urgently needs the assistance of the DIMP to remedy these deficiencies. A related but separate problem is the ability of centres to acquire the data they need for the user communities and to have access to it in appropriate formats;

- It is important that the needs of countries with inadequate access to the Internet have their needs met by the provision of data in other formats;
- or the terrestrial community there are many inadequacies in data handling capabilities especially within the ecological and hydrological areas. There are some nominated centres such as the GRDC and GPCC, but further capabilities are needed. A World Data Centre for Soils is in existence. UNEP’S GRID holds several data sets collated from other sources;
- For ecological observations, the situation is less satisfactory though there have been proposals within WDC-A to help rectify the situation;
- There is a continuing problem in data being made available to centres in the appropriate format, such as long-term records collected for synoptic purposes which are in analogue format;
- It is important that the needs of countries with inadequate access to the Internet are satisfied by the provision of data in other formats. While Internet access is increasingly available, problems associated with bandwidth and charges are likely to inhibit its use by many users for several years;
- TOPC should cooperate with the WDC system and other organizations such as the IGBP in further evaluating needs for data management;
- The TOPC, with the assistance of the DIMP, should identify and assess existing data centres to determine if its needs can be met;
- The possible benefits of archiving more of the data collected through the World Weather Watch GTS system should be explored, especially in view of the development and application of web technology.

7. Implementation of the Tier Sampling Scheme

7.1 The Challenge of Implementation

Turning the Plan into an operational routine collection of observations is a challenging task. The following overall approach has been adopted. First, summarize the present situation with respect to each of the main areas of interest (biosphere, hydrosphere and cryosphere); second, identify which are the crucial observations which must be continued; third, identify enhancements that are required to satisfy the needs outlined in the previous chapters. An additional issue which will need more effort is to identify the international bodies who would play a coordinating role for each of the observations and how they will interact with national bodies to ensure the observations are collected. In the area of atmospheric observations collected primarily for operational weather forecasting, there are mechanisms organized through the WWW by WMO to achieve this goal. Comparable mechanisms need to be developed for many of the other observations described within this report.

This chapter deals with two principal issues. The first is the global implementation of the tier sampling scheme discussed in Chapter 5. Special attention is given to tier 4 whose implementation poses unique challenges. It is anticipated that the overall implementation will be a gradual process, with a full-up global system not being in place for some years. Therefore, the initial period is considered in more detail in the second part. The initial system must start with programmes and facilities now in place or in the process of implementation. Fortunately, there are many initiatives that are directly relevant to the objectives of GCOS/GTOS and can make very important contributions to the initial observing system. This section reviews some of the existing systems for the monitoring of the biosphere, hydrosphere, and cryosphere.

7.2 The Tier Sampling Scheme

The tier structure described in Chapter 5 is a classification system to aid implementation, not a rigid formula for implementation. This enables maximum use to be made of existing data sets, sites and facilities. All the tiers are necessary, but not all the variables need to be measured at all tiers. For example, few hydrospheric variables are measured at tier 4 because the characteristic time scale of hydrological processes tends to be too short to benefit from infrequent sampling. The key tiers for early implementation are 2, 3 and 5, because they are served by existing structures.

Guidelines for site selection

The objective of site selection is to take maximum advantage of existing facilities, including biosphere reserves while ensuring an appropriate global distribution of the measurement sites. It is essential that the sites be carefully chosen so as to meet the objectives of GTOS and GCOS. The different objectives associated with the tiers 1-5 (see also Table 5.1) impose different criteria on site selection. However, all GCOS/GTOS sites have to satisfy the conditions of representatives and sufficiency. This section outlines basic guidelines for identifying sites at the individual tiers.

Tier 1: These major, intensive experimental sites should be located with a primary emphasis on spatial diversity of regional ecosystems, land-use patterns, the availability of regional process integrators like catchments, and feasibility. Capturing the range of the major biome types is a critical priority, but the location within biomes will be opportunistic. Several sites can be drawn from the sites of past or present large-scale experiments, including perhaps BOREAS (boreal forest - Canada), Abracos (ARCS) (tropical evergreen forest - Brazil), Harvard Forest (temperate mixed forest - USA), Oasis (dry land agriculture - Australia), and HAPEX. The actual sites will consist of core areas of 100 km2 or less, plus a surrounding region of 104 - 106 km2. It is critical to select tier 1 sites so that they include a range of tier 2, 3 and 4 sites.

Although all tier 1 data and research findings are important to GCOS/GTOS, special attention needs to be given to long-term measurements. Tier 1 sites are large experimental areas and various adjustments are required before they can become part of a long-term monitoring programme. The long-term measurements will be a subset of those made during the initial experimental period but the transition from intensive field campaigns to continuous monitoring will require careful planning.

The responsibility for tier 1 sites during the initial period rests with research programmes such as IGBP, GEWEX, etc. Once the initial programme is completed and adjustments are made to institute a long-term measurement programme, the responsibility for the monitoring programme is likely to rest with a national agency. In most cases, tier 1 sites will be converted to tier 2 or 3 for the long-term monitoring. The responsibility of GCOS/GTOS should be to assure that the data are available and that there are links to the data. Lessons learned at these sites should be incorporated into monitoring programmes where appropriate.

Tier 2: The 100 or so tier 2 centres should be chosen to encompass the major climatic zones, ecosystem types, and land management practices. Ideally, tier 2 sites should be located near the centre of the range of environmental conditions (though not necessarily near the centre of the geographical range) of the system which they are representing. The actual locations will depend more on existing infrastructure and feasibility than on strict spatial guidelines, but the need to capture a broad range of ecosystem types may require developing some new sites. Since the proposed measurement scheme emphasizes a mix of point measurements and spatial studies, the spatial context of each site will be an important consideration. The best spatial context will be large enough regions of relatively homogeneous ecosystems to allow careful assessments against remote sensing, but enough diversity to allow access to a broad range of ecosystem structure and dynamics.

Tier 2 sites should be located in the major natural land cover (evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forests, mixed trees and shrubs, closed shrublands, open shrublands, woody savannahs, savannahs, grasslands and permanent wetlands); aquatic systems (lakes, rivers, estuaries); and cryospheric systems (permafrost, ice sheets, ice caps and glaciers).

Tier 3: These are the sites that are most congruent with the existing networks of agricultural and ecological research stations in China, Europe, the USA, and other countries; experimental watersheds; and cryosphere sites. The requirement for permanent staffing and frequent measurements necessitates locating the sites where there is reasonable access, funding, and interest. There is no requirement for spatial representatives at this tier. Although some sites will be needed in under-represented areas, the number of new sites should be a small fraction of the total. Since this tier will provide a primary link with remote sensing observations, selection criteria will include emphasis on reasonable spatial homogeneity over a few kilometres, but this emphasis should not preclude the selection of sites in mountainous zones or in regions with heterogeneous land use or disturbance. Tier 3 sites are intended to sample the range of variation present in the system which they represent. This means that some of them will be close to the average of the various environmental factors which make up the environmental range of the system, while others will be closer to the extremes, and perhaps even at the ecotone of transition to a different system.

Tier 3 sites should be located in natural (see tier 2 above) as well as in managed (12 most important food and fibre crops and agricultural management systems (rice, wheat, maize, potato, sorghum and millet, cassava, sugar cane, extensively-grazed livestock, vegetables, tropical fruits, temperate fruits, and cotton)) ecosystems. The important aquatic systems are rivers, lakes and estuaries; and the cryospheric systems are permafrost, ice sheets, ice caps and glaciers. There are many potential tier 3 sites, but they are not optimally distributed. As a result, some ecosystem types may have more potential tier 3 sites than are needed for GCOS/GTOS purposes, particularly if a rough global balance is to be preserved. Other ecosystem types may have too few sites, or none at all and thus GCOS/GTOS will need to work with funding organizations to enhance and balance the network.

Tier 4: For these points, spatial representativeness is the highest priority. Because the measurement site is small and access is infrequent, they can be located wherever necessary to ensure representativeness. With the order of 10,000 sites globally, the question on optimum sampling design will require a careful consideration (see section on implementation of tier 4 below) A few of these points may be established research stations, but all should be subjected to the prevailing local land management. The land management should not be altered during the monitoring period. It may also be appropriate to continuously add sites so that impacts of the GCOS/GTOS designation can be estimated.

The locations of tier 4 sites should be based on statistical considerations. It is impractical to prescribe one statistical design for all countries. Hence, individual participating nations would be responsible for locating the sites, and may choose either a systematic or a stratified-random approach (or both, for different variables or different systems). This latter approach requires an *a priori* location specification, but permits rejection of the site and resampling out of the same population if the site is inaccessible or if sampling at the site would compromise national interests.

The main problem with tier 4 is that it is new, and cannot be assembled from pre-existing systems. This makes it apparently expensive and technically untested. The question must be addressed whether tier 4 can be dispensed with, greatly reduced, or phased in without undermining the validity of the entire plan. A detailed discussion of this issue is provided in the sections below.

Tier 5: For the most part, these continuous fields are monitored from space. The frequency of measurement varies depending on the parameter from sub-daily to once in several years. Satellite observations are area averages (for areas <102 m to >107 m, depending on the sensor and variable), while ground observations are point values. Some variables require surface observations, even for tier 5. These are mostly compilations of existing data sets which took many years or decades to produce, e.g., soil maps, topographic maps, etc. It is virtually certain that all future tier 5 data sets will be obtained through satellite observations.

The implementation of tier 5 requires international collaboration, both in the space and ground components, to produce the required data sets. The preparation of data products from satellite measurements must be based on a long-term programme of data acquisition, archiving, product generation, and quality control. Discussions are now underway in CEOS to set up such a system. For data sets compiled from ground observations (e.g., soils) significant efforts are needed to bring together data from many countries and convert these into homogeneous global data products. International organizations (e.g., the UN) and research programmes (IGBP, WCRP) play very important roles in this regard.

It is important to note that the tier structure is a classification system to aid implementation, not a rigid formula for implementation. All the tiers are necessary, but not all the variables are represented at all tiers. For example, the hydrosphere will have few variables at tier 4, principally because the characteristic time scale of hydrological processes tends to be too short to benefit from infrequent sampling. The key tiers for early implementation are 2, 3 and 5, because they are served by existing structures.

GCOS/GTOS must simultaneously have a top-down and bottom-up approach to site selection. The bottom-up approach can be implemented by publicising the existence and benefits of GCOS/GTOS, and inviting sites (and existing networks of sites) to apply for membership. The GTOS would then screen the applicants for suitability. The guidelines are spelled out in the GTOS Planning Group Report (ICSU *et al.,* 1996). Briefly, they are:

- Each participating country should have at least one per biome;
- They should be capable of collecting, documenting and making available the appropriate data;
- Sites in under-represented environmental systems have priority over already-represented systems;
- Reasonable permanence is required.
- All else being equal:
- Sites where research is also carried out are preferred;
- Long-established sites are preferred;
- Existing sites are preferred over sites which need to be established;
- National support for the site is preferred to dependence on external funding;
- Accessible, practical sites are preferred.

The bottom-up approach would not fill gaps where no or insufficient sites exist, or where the sites are not aware of the needs of GCOS/GTOS. A complementary top-down approach is therefore required to fill gaps in ecosystem types where no sites have been identified. If insufficient candidates are found through reviews of existing sites, an active process may be required to upgrade or establish sites in that type. The above described tier observing system can be built largely out of existing national and international observation systems, research centres and stations, with modest additions of stations and sites where representation is inadequate, and a major effort towards methodological consistency and data management. An exception is tier 4 which, for the most part, cannot be assembled from pre-existing systems.

Role of tier 4

Tier 4 serves two primary purposes, only the first of which is strictly speaking a monitoring function, but both of which are necessary for an operational system: repeated measurements, for purposes of change detection; and one-time measurements, for purposes assessing the state of the system and model parameterisation.

Tier 4 has the unique role of providing accurate and spatially-resolved data on variables which at present cannot be remotely sensed. An example is the soil carbon content which is important because it is the largest biospheric carbon pool, is subject to change, and influences other factors such as the soil water holding capacity. It cannot be observed from space. Tier 4 can also act as the calibration and validation points for indirect remotely-sensed variables. Tier 3 can also provide these data, but may have insufficient sites to calibrate or validate all the ecosystem classes. It is important to separate the unique role from the additional roles, because they have different sampling requirements.

Table 7.1 summarizes the variables that are unlikely to be available with useful accuracy and resolution in the foreseeable future without tier 4 and those whose accuracy will likely be seriously affected. Furthermore, the GTOS also has several important non-climatic requirements from tier 4, including land use inputs, disturbance regime and soil chemistry (pH, nitrate, phosphate, bases, acidity, e.g.). It is thus evident that functions met by tier 4 are a critically important component of the global observing system. The benefits of enriching the land surface data go beyond the needs of GCOS and GTOS, into issues such as natural resource management at a regional or local scale. Tier 4 can deliver national-level information and national involvement in the global programmes.

Table 7.1. Impacts of excluding tier 4 from the sampling hierarchy.

UNLIKELY TO BE AVAILABLE	ACCURACY LIKELY TO BE SERIOUSLY COMPROMISED
	Biomass - above ground Biomass - below ground
Necromass	Roughness – surface
Soil carbon	Vegetation structure
Soil total nitrogen	Land use

Soil phosphorus	Soil bulk density
Soil texture	Soil surface state
Rooting depth	Precipitation
Ground water storage fluxes.	Ice sheet mass balance Permafrost - active layer Permafrost - thermal state.

Sampling design for tier 4

Various options can be envisioned for the location of tier 4 sites: systematic (e.g., gridded), stratified random and targets of opportunity, among others. Each scheme has implications in terms of cost, political feasibility and statistical analysis. Table 7.2 provides an analysis of the financial, political and statistical sensitivities of the issue.

Table 7.2. Implications of different tier 4 sampling patterns.

	SYSTEMATIC	STRATIFIED RANDOM	TARGETS OF OPPORTUNITY
Financial	Expensive, because some sites will be hard to access.	Less expensive because more efficient and resampling can eliminate most expensive sites	Marginal cost only.
Political.	Issues of national sovereignty	Resampling can eliminate sensitive sites	No problem, but large parts of the world may be under-sampled.
Statistical	Simple and easy to interpret, unbiased now and in the future.	Statistically efficient with an information-rich stratifier; can be unbiased but sensitive to changes in the stratification.	Biased and difficult to extrapolate

Tier 4 need not have a single sampling scheme for all variables and all places. For instance, where the purpose of the observation is calibration and validation of a remotely-sensed variable, the target-of-opportunity approach is acceptable. For statistical change detection of a variable not indirectly measurable, the scheme must be stratified or systematic. A systematic scheme in one country remains compatible with a stratified scheme in another, if they are designed to the same accuracy specifications.

Implementation strategy for tier 4

Among all the tiers, tier 4 is the least established at the present with only a few countries having monitoring programmes at this level. The implementation strategy is therefore particularly important in view of the new resources required. Some possibilities are considered here. While there are costs associated with analysing and storing any collected data, reducing the number of variables in tier 4 is not a useful strategy, since the costs involved in sampling have largely to do with accessing the sites, not the time spent at an individual site. There may even be a case for increasing the at-site data collection in order to be able to share the sampling effort with a wider range of clients. For example, could GTOS geo-referenced socio-economic data be collected this way? The main cost-reducing options are thus fewer sample sites, use of targets of opportunity, and phased implementation.

Fewer samples

There are two issues which need to be distinguished, accuracy and spatial resolution. The debate on tier 4 initially concentrated on the number of sites needed to validate a land cover product with a given number of classes, to a given level of precision and confidence for each class (i.e., discrete variables). However, most of the variables which depend on tier 4 are continuous values, not categories. The determination of an adequate sample size for these is more complicated, since it requires a knowledge of their statistical distribution, which is largely lacking, and fluctuates from variable to variable. For a completely unbiased and efficient sampling scheme (stratified random, for instance) and a normally-distributed variable with a coefficient of variation of 30%, an accuracy of &plusnm;10% with 95% confidence would need 36 samples, &plusnm;5 % would need 144 samples, and &plusnm;0.5% would need 14,400 samples. In practice, most of the variables in question are log normally distributed and then only once they have been stratified, so the sample number needs to be multiplied by the number of strata if each is to meet the accuracy criteria, or by some area- or value-weighted number for a given global accuracy. If only a global estimate is needed, the sample number is greatly reduced; perhaps by 75% (to allow for increased coefficient of variation as disparate classes are lumped). If regionalised estimates are needed, the requirement goes up in rough proportion to the number of regions.

Although a rigorous analysis has not been performed, it seems that the original estimate of the order of 5,000-10,000 sites for tier 4 remains valid. However, where the tier 4 sites are simply required to calibrate or validate a remote-sensing algorithm, the required sample numbers are much smaller, and the sample location requirements are much less rigorous. Typically, more than 30 samples each are required for calibration and validation of a continuous, linear model if the errors are normally distributed, the model is reasonably predictive (accounting for >75% of the variance), and the sample points cover the full range of variation. If the number of points needed can be reduced to 500 - 1,000, then tier 4 can be substituted by tier 3, but all the problems associated with a biased sample scheme remain. Such reduction would also not provide adequate information on variables listed in Table 7.1.

Targets of opportunity

By piggy-backing on other activities, the costs of sampling can in theory be reduced to the marginal costs of the additional effort needed to collect the GCOS/GTOS data. An example is the Soil and Terrain Data (SOTER) Project which aims to improve global soil data products. If the vegetation component were slightly enhanced and geo-location specifications were tightened to &plusnm;10 m, many GCOS/GTOS requirements for surface climate-related observations would be met.

There are two main drawbacks with using targets of opportunity: the sample locations are likely to be biased, biasing the values in an unknown way; and the chances of being able to revisit the point at the same low cost are small. This approach could be useful for calibration and validation of indirect algorithms and for one-time parameterisations, but is not suitable for change detection except in the sense of archiving a current state, which future generations may find useful. At a minimum, the data system should make provision for the recording of tier 4 - type data from activities outside of GCOS/GTOS, and should actively pursue their acquisition from the original collectors.

Initial implementation

All of the tier 4 variables have relatively slow rates of change, which allows them to be infrequently collected. Thus only 10-20% of the target sample needs to be collected in a given year. Alternatively, or additionally, each tier 3 station could be tasked with collecting one or two tier 4 data points per year, in an *a priori* determined location. This approach has the added advantage of a closer link between the tiers at the regional level.

Recommendations for implementation of tier 4 sites

- Publish a brochure explaining and publicising the hierarchical system;
- Publish and distribute a methods handbook for tier 4 data and actively encourage the placement of target-of-opportunity tier 4 data in public domain databases;
- Phase in the implementation of tier 4 by making it a tier 3 responsibility. Each tier 3 site would appoint one or more dedicated tier 4 observers, who will simultaneously do infield training of tier 3 personnel and collect tier 4 data.

7.3 Management of the Tier Sampling Scheme

The TOPC has concluded that the tier sampling scheme should be a joint responsibility of both GCOS and GTOS, but that a single observing system should take prime responsibility for the overall management. The general management structure outlined in the GTOS Planning Group Report (part 1, page 15) (ICSU *et al*., 1996) is appropriate, but in its initial implementation it should focus on establishing an effective secretariat for this purpose and developing strong links to national implementing agencies and networks.

The steps in an initial operating strategy for managing the system should be:
- Make the Terrestrial Ecosystem Monitoring Sites (TEMS) database more comprehensive by asking regional and national experts to check and populate it;
- Charge the GTOS secretariat, in conjunction with discipline and system experts, to develop a "methods manual" (see comment below), reporting procedures and a training programme. Training exercises should be in-field (not central), and should double as data-collection exercises;
- Establish the communication and distributed database functions of GCOS/GTOS so that they are ready to handle the data flow;
- Begin a dialogue with existing site networks (either international or national) to produce a draft of workable data exchange rules and procedures and to refine the potential site database;
- Conduct an initial tier 3 selection according to the procedures described above;
- Identify under-sampled regions and ecosystem types;

- Hold an international meeting of site and network managers, plus representatives of organizations to establish or upgrade sites in under-sampled regions. Its purpose would be to establish and ratify the rules and methods of data collection, data sharing and quality control and to establish agreement on their participation in a network.

For each variable, standardization should be primarily achieved by specifying the quantity measured, necessary accuracy, measurement frequency, and spatial resolution. Standard methods can be encouraged by publishing manuals and providing training, but these are not obligatory. Full descriptions of the methods used at the site should be provided to the Secretariat at the time that a site joins the network, and updated when necessary. Variables with a significant bias due to the method used should be subject to expert review and cross-calibration exercises.

The first and most important line of quality control is the point of data collection. Data items not accompanied by time, exact location (±100 m or less) and method should be rejected. On entering a GCOS/GTOS data system, data should, as a minimum, be passed through a “smart” filter to detect gross errors and inconsistencies, and then be checked for reasonableness by a discipline expert.

8. Conclusion and Summary

The objective of the TOPC Plan is to provide a rationale for the structure and implementation of the initial observing system. It describes the minimum set of terrestrial variables that are required to assess the impacts of, predict, and detect climate change. Annex I to the document contains a detailed description of each of the variables. While it has taken considerable work to arrive at a consensus on this set of variables, it is recognized that these are a beginning. Future meetings of the TOPC will consider other variables and will prioritize this list further. The Plan recognizes that a comprehensive observing system must address the critical variables by making measurements with sufficient and adequate precision, spatial and temporal resolution, and with long-term continuity. The data must be compiled and collated in a fashion that is useful to the users. Ultimately, the products that are produced by GTOS and others must include ones that are in a form that can be easily utilized by policy- and decision-makers. For much of the land and climate system, such comprehensive observations, databases and associated products are not available.

In spite of the fact that a considerable amount of work needs to be done before a comprehensive observation system can be completely implemented for the terrestrial components of the GCOS or the climate portion of the GTOS, a number of actions can be taken to begin implementing some of the required observations. It is clear that with limited resources the TOPC will also need to prioritise implementation actions at a future meeting. Those observations which can be made from space offer the best hope of globally consistent data sets, and consequently research to increase the number and quality of observations that can be made from space is highly encouraged. At the same time, these data must be made readily available to countries that do not have a programme of space-based observations.

The major issue facing GTOS and GCOS to implement a set of climate-related terrestrial observations is to obtain sufficient resources. While the majority of the required observations are already being made at a number of sites, it is clear that for a comprehensive global observing system there will need to be some additional sites established, particularly in the Southern Hemisphere. In addition, other selected sites will need some additional equipment and upgrading. Both GTOS and GCOS central offices are under-staffed and are in the need of additional personnel. These resources must ultimately come from national efforts; the success of these programmes depends on receiving commitments from operational and research funding agencies and national governments.

Since climate affects all nations, it is important to have the participation of all nations. Thus, GCOS and GTOS have made a commitment to fully involve all nations in the programme. In the case of developing countries, the GCOS/GTOS will, in partnership with other programmes, actively support capacity building and training in both making observations and in developing techniques to fully utilize the data and products for national needs.

Annex I Details of Recommended Variables

BIOPHYSICAL PROPERTIES OF VEGETATION

Biomass - above-ground
Biomass - below-ground
Leaf area index (LAI)
Net primary productivity (NPP)
Net ecosystem productivity (NEP)
Necromass
Plant tissue nitrogen and phosphorus content
Roughness - surface
Spectral vegetation greenness index
Stomatal conductance - maximum
Vegetation structure

BIOGEOCHEMISTRY

Biogeochemical transport from land to oceans
Biomass - peak leaf of nitrogen-fixing plants
Dissolved organic C, N, and P in water (rivers and lakes)
Dry deposition of nitrate and sulphate
Emissions of CO2, NOX and SOX from combustion of fossil fuels
Fertiliser use N and P
Rainfall chemistry
Volcanic sulphate aerosols

LAND COVER/LAND USE AND DISTURBANCE

Fire area
Land cover
Land use

SOIL PROPERTIES

Rooting depth - 95%
Soil cation exchange capacity
Soil moisture
Soil total carbon
Soil total nitrogen
Soil phosphorus - available
Soil phosphorus - total
Soil bulk density
Soil particle size distribution
Soil pH
Soil surface state

HYDROLOGY

Biogeochemical transport from land to oceans
Evapotranspiration
Ground water storage fluxes
Precipitation - accumulated (solid and liquid)
Relative humidity (atmospheric water content near the surface)
Surface water flow - discharge
Surface water storage fluxes

CRYOSPHERIC PROPERTIES
Firn temperature (ice sheets, ice caps, glaciers)
Glaciers and ice caps
Ice sheet mass balance
Ice sheet geometry
Lake and river freeze-up and break-up (timing)
Permafrost - active layer
Permafrost - thermal state
Sea ice concentration/extent
Sea ice motion
Sea ice thickness
Snow cover area
Snow depth
Snow water equivalent (SWE)

RADIATION (AND RELATED VARIABLES)

Aerosols
Albedo
Cloud cover
Radiation - fraction of photosynthetically active radiation (FPAR)
Radiation - incoming short-wave
Radiation - outgoing long-wave
Radiation - reflected short-wave
Temperature - air

TRACE GASES

Carbon dioxide flux (CO2)
Methane flux (CH4)

ANCILLARY VARIABLES

Topography
Wind velocity

Annex II Details on Cryospheric Variables

Table 1. Snow cover data requirements and priorities for system monitoring and climate change monitoring(Crane, 1993).

DATA CHARACTERISTICS				DATA APPLICATIONS		
Parameters	Coverage	Duration	Frequency	Global Climate Monitoring	Earth System Models	Process Models
Snow cover extent	H/R	> 10 Years	Daily/Weekly	1	1	1
Snow water equivalent	H/R	> 10 Years	Daily/Weekly	2	1	1
Snow depth	H/R	> 10 Years	Daily/Weekly	1	2	2
Precipitation amount	H/R	> 10 Years	Daily/Weekly	2	1	1
Precipitation	H/R	> 10 Years	Daily/Weekly	2	1	1
Canopy (vegetarian)	H/R	> 10 Years	Daily/Weekly	1	2	2
Albedo	H/R	> 10 Years	Daily/Weekly	2	1	2
Temperature	H/R	> 10 Years	Daily/Weekly	5	3	1
Melt (runoff)	H/R	> 10 Years	Daily/Weekly	5	3	1

H = Hemisphere R = Regional Ranking: 1 (high) to 5 (low).

Table 2. Sea ice data requirements and priorities for system modelling and climate change monitoring (Crane, 1993).

DATA CHARACTERISTICS				DATA APPLICATIONS		
Parameters	Coverage	Duration	Frequency	Global Climate Monitoring	Earth System Models	Process Models
Concentration	H/R	10 Years	Weekly/Monthly	1	1	1
Thickness	R/P	10 Years	Monthly/Seasonl	1	1	1
Met obs	R	10 Years	Daily	1	1	1
Surface radiation	R	5 Years	Hourly/Daily	1	1	1
Albedo	H/R	10 Years	Weekly	2	1	1

Snow depth	R/P	5 Years	Weekly	2	2	1
Extent	H/R	10 Years	Weekly/Monthly	1	1	5
Leads/Polynyi	R	5 Years	Weekly	4	2	1
Ice temperature	H/R	5 Years	Weekly/Monthly	3	2	2
Ice type	H/R	10 Years	Weekly/Monthly	2	5	1
Ice motion	H/R	5 Years	Weekly	5	2	2
Melt ponds	R	5 Years	Daily/Weekly	3	4	2
Flow size distribution	H?	5 Years	Weekly	5	5	2
Ridge statistics	R	5 Years	Weekly	5	5	2

H= Hemisphere R= Regional P= Point Ranking: 1 (high) to 5 (low).

Table 3. Ice sheet and glacier data requirements and priorities for system modelling and climate change monitoring (Crane, 1993).
Notes: H, M, L = High, Moderate, and Low priority.
* For permafrost thickness and temperature, the demarcation between "shallow" and "deep" is taken as the local depth of zero annual amplitude.

DATA CHARACTERISTICS				DATA APPLICATIONS		
Parameters	Coverage	Duration	Frequency	Global Climate Monitoring	Earth System Models	Process Models
Snow Accumulation	GL/A	>10 Years	Annually	2	2	1
Ice extent	G	>10 Years	Annually	1	5	5
Ice thickness	G	>10 Years	Annually	1	5	1
Ice sheet DEM	GL/A	>10 Years	Decadally	1	5	1
Ice velocity/surge activity	G	>10 Years	Annually	2	5	2
Iceberg production	GL/A	>10 Years	Annually	2	5	3
Mass balance	G	>10 Years	Annually	1	5	5
Land ice fraction	G.5 x.5	>10 Years	Long-term mean	5	3	5

GL = Greenland A = Antarctica G + Global Ranking: 2 (high) to 5 (low).

Table 4. Permafrost data requirements and priorities for modelling and change detection.

PARAMETERS	APPLICATIONS				
	Process Understanding	Engineering Design	GCM Validation	Change Detection	Impact Evaluation
GEOMETRY					
Permafrost extent	M	H	H	H	M
Permafrost thickness (shallow)	H	H	H	H	H
Permafrost thickness (deep)	M	M	L	H	L
Active layer thickness	H	H	M	H	H
Ground ice extent	H	H	M	M	H
Lateral/vertical displacement	H	H	L	H	H
THERMAL STATE					
Temperature (shallow*)	H	H	H	H	H
Temperature (deep*)	M	M	M	H	L
PROPERTIES (SOIL/ROCK)					
Moisture content (water/ice)	H	H	M	H	H
Bulk density	H	H	H	L	L
Texture	H	H	L	M	M
Chemistry (water/ice)	M	M	L	M	M
Trace gases	H	L	H	M	M
Site description: Location, geology, vegetation, geotechnical properties.					
Metadata: Techniques, equipment, precision, post-processing, ownership, etc.					

Annex III Literature Cited

Alcamo, J. (ed.), 1994: *IMAGE 2.0: Integrated Modelling of Global Climate Change*. Kluwer Academic Publishers, Dordrecht, the Netherlands, 321 p.

Ambach, W., 1993: Effects of climatic perturbations on the equilibrium-line altitude, West Greenland. *Glaciology*, 39, 5-9.

Arnell, N., B. Bates, H. Lang, J.J. Magnuson and P. Mulholland, 1996: Hydrology and freshwater ecology. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contributions of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* R.T. Watson,M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.), Cambridge University Press, Cambridge, UK, 325-363.

Baldocchi, D.D., B.B. Hicks and T.P. Meyers, 1988: Measuring biosphere atmosphere exchanges of biologically- related gases with micrometeorlogical methods. *Ecology*, 69, 1131-1340.

Barry, R.G., 1985: The cryosphere and climate change. In: *Detection of Co-induced Climatic Change,* M.C. MacCracken and F.M. Luther (eds.), DOE/ER-0235, U.S. Dept. of Energy, Washington, DC.

Barry, R.G., 1986: The sea ice database. In: *The Geophysics of Sea Ice,* N. Untersteiner (ed.), Plenum, New York, NY.

Barry, R.G. and R.L. Armstrong, 1987: Snow cover data management; the role of WDC-A for Glaciology. *Hydrological Science*, 32, 281-295.

Barry, R.G., 1990: Cryospheric products from the DMSP SSM/I: Status and research applications. *Global and Planetary Change*, 4, 231-234.

Barry, R.G., 1993: Climate change in the mountains. In: *The State of the World's Mountains*, P.B. Stone (ed.), Zed Books, London, UK.

Barry, R.G. and A.M. Brennan, 1993: Towards a permafrost information system. In: *Permafrost, Sixth International Conference Proceedings, Vol. 1*. South China University of Technology Press, Wushan Guangzhou, China.

Barry, R.G. and J.A. Maslanik, 1994: Monitoring lake freeze-up, break-up as a climatic index. In: *Snow Watch '92 Glaciology Data Report, GD-25,* R.G. Barry, B.E. Goodison and E.F. LeDrew (eds.), WDC-A for Glaciology, University of Colorado, Boulder, CO.

Barry, R.G., J. Brown and A. Heginbottom, 1995: Workshop on Permafrost Data and Information, Oslo, Norway. *Glaciology Data Report, GD-28,* WDC-A for Glaciology, University of Colorado, Boulder, CO.

Baumgartner, A. and E. Reichel, 1975: *The World Water Balance*. R. Oldenberg, Vienna, Austria.

Baumgartner, M.F. and A. Rango, 1991: Snow cover mapping using microwave imager processing systems. *Nordic Hydrology*, 22, 193-210.

Berner, E. and R. Berner, 1987: *The Global Water Cycle*. Prentice and Hall Inc., Princeton, NJ.

Beven, K.J. and M.J. Kirkby, 1979: A physically-based, variable contributing area model of basin hydrology. *Hydrological Services Bulletin*, 24, 1, 43-69.

Beven, K.J. and M.J. Kirkby, N. Schofield and A.F. Tagg, 1984: Testing a physically-based flood forecasting model (TOPCMODEL) for three UK catchments. *Journal of Hydrology,* 69, 119-143.

Bonan, G.B., 1991: Atmosphere-biosphere exchange of carbon dioxide in boreal forests. *Geophysical Research*, 96, 7301-7312.

Bonan, G.B., 1993a: Physiological derivation of the observed relationship between net primary production and mean annual air temperature. *Tellus, Ser. B*, 45, 397-408.

Bonan, G.B., 1993b: Importance of leaf area index and forest type when estimating photosynthesis in boreal forests. *Remote Sensing of Environment*, 43, 303-314.

Bonan, G.B., 1995: Land-atmosphere interactions for climate system models. Coupling biophysical, biogeochemical, and ecosystem dynamical processes. *Remote Sensing of Environment*, 51, 57-73.

Botkin, D.B., J.F. Janak, and J.R. Wallis, 1972: Some ecological consequences of a computer model of forest growth. *Ecology*, 60, 849-872.

Bourke, R.H. and A.S. McLaren, 1992: Contour mapping of Arctic Basin ice draft and roughness parameters. *Geophysical Research*, 97, 17715-17728.

Braithwaite, R.J. and Olesen, O.B., 1990: Increased ablation at the margin of the Greenland Ice Sheet under a greenhouse-effect climate. *Annals of Glaciology*, 14, 20-22.

Braithwaite, R.J. 1993: Is the Greenland Ice Sheet getting thicker? *Climatic Change*, 23, 379-381.

Brown, S., J. Sathaye, M. Cannell, & P. Kauppi,1996: Management of forests for mitigation of greenhouse gas emissions. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contributions of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* R.T.Watson, M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.), Cambridge University Press, Cambridge, UK, 773-797.

Brutsaert, W., 1984: *Evaporation into the Atmosphere*. D. Reidel Publishing Company, Dordrecht, Netherlands.

Brutsaert, W., T. Schmugge, P. Sellers and F. Hall, 1988: Large-scale experimental technology with remote sensing in land surface hydrology and meteorology. *EOS* (May 3), 561.

Bugmann, H.K.M. and A.M. Solomon, 1996: The use of a European forest model in North America: A study of ecosystem response to climate gradients. *Journal of Biogeography*, 22, 477- 484.

Carroll, T.R., 1991: Operational airborne and satellite snow cover products of the National Operational Hydrologic Remote Sensing Centre. In: *Proceedings of the 47th Annual Eastern Snow Conference*, Bangor, ME.

Chang, A.T.C., J.L. Foster & D.K. Hall, 1987: Nimbus-7 SMMR derived global snow cover parameters. *Annals of Glaciology*, 9, 39-44.

Chang, A.T.C., J.L. Foster, D.K. Hall, H.W. Powell & U.L. Chien, 1990: Nimbus-7 SMMR derived global snow depth data set. The Pilot Land Data System, NASA/Goddard Space Flight Centre, Greenbelt, MD.

Chapman, W.L. & J.E. Walsh, 1993: Recent variations of sea ice and air temperature in high latitudes. *Bulletin of American Meteorological Society*, 74, 33-47.

Chen, J.M. & T.A. Black, 1992: Defining leaf area index for non-flat leaves. *Plant, Cell and Environment*, 15, 421- 429.

Chen, J.M. & J. Cihlar, 1995a: Plant canopy gap-size analysis theory for improving optical measurements of leaf- area index. *Applied Optics*, 34, 27, 6211-6222.

Chen, J.M. & J. Cihlar, 1995b: Algorithms for retrieving LAI and FPAR of boreal conifer forests using Landsat TM images. *Digest of 17th Canadian Symposium on Remote Sensing*, Saskatoon, Canada.

Clark, P.U., D.R. MacAyeal, J.T. Andrews & P.J. Bartlein, 1995: Ice sheets play an important role in climate change. *EOS*, July 4, 265.

Collingham, Y.C., M.O. Hill & B. Huntley, 1997: The migration of sessile organisms: A simulation model with measureable parameters. *J. Vegetation Sci.* (in press).

Crane, R.G. (ed.), 1993: Workshop on Cryospheric Data Rescue and Access. In: *Glaciological Data*, Report GD25. World Data Centre-A for Glaciology, Boulder, CO.

Dickinson, R.E. 1983: Land surface processes and climate-surface albedos and energy balance. *Advances in Geophysics*, 25, 305-353.

Dickinson, R.E., A. Henderson-Sellers, C. Rosenzweig & P.J. Sellers, 1991: Evapotranspiration models with canopy resistance for use in climate models: A review. *Agricultural and Forest Meteorology*, 54, 373-388.

Dickinson, R.E., 1995: Land processes in climate models. *Remote Sensing of Environment*, 51, 27-38.

Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler & J. Wisneiwski. 1994: Carbon pools and flux of global forest ecosystems. *Science*, 263, 185-190.

Doake, C.S.M. & D.G. Vaughan, 1991: Rapid disintegration of the Wordie Ice Shelf in response to atmospheric warming. *Nature*, 350, 328-330.

Dolph, J., D. Marks & G.A. King, 1992: Sensitivity of the regional water balance in the Columbia River Basin to climate variability: Application of a spatially distributed water balance model. In: *Watershed Management: Balancing Sustainability and Environmental Change*, R.J. Naiman (ed.), Springer-Verlag, New York, NY.

Drewry, D., 1983: *Antarctica, Glaciological and Geophysical Folio.* Scott Polar Research Institute, Cambridge, UK.

Dunne, T. & L.B. Leopold, 1978: *Water in Environmental Planning*. W.H. Freeman and Co., New York, NY.

Duus, A.L., 1992: Estimation and analysis of snow cover in the Snowy Mountains between 1900 and 1991. *Australian Meteorological Magazine*, 40, 195-204.

Eagleson, P.S. 1986: The emergence of global-scale hydrology. *Water Resources Research*, 22, 9, 6-14.

Eidenshink, J.C. & J.L. Faundeen, 1994: The 1 km AVHRR global data set: First stages in implementation. *International Journal of Remote Sensing*, 15, 17, 3443-3462.

Emanuel, W.R., H.H. Shugart & M.P. Stevenson, 1985a: Climate change and the broad-scale distribution of terrestrial ecosystem complexes. *Climatic Change*, 7, 29-43.

Emanuel, W.R., H.H. Shugart & M.P. Stevenson, 1985b: Climate change and the broad-scale distribution of terrestrial ecosystem complexes: Response to comment. *Climatic Change*, 7, 457- 460.

Fahnestock, M., R. Bindschadler, R. Kwok & K. Jezek, 1993: Greenland Ice Sheet surface properties and ice dynamics from ERS-1 SAR. *Science*, 262, 1530-1534.

Famiglietti, J.S., E.F. Wood, M. Sivapalan & D.J. Thongs, 1992: A catchment scale water balance model for FIFE. *Journal of Geophysical Research*, 97, 18997-19007.

Farnsworth, R. & E. Thompson, 1982: Mean monthly, seasonal and annual pan evaporation for the United States. *NOAA Technical Report NWS 34*, U.S. Department of Commerce, Washington, DC.

Fitzharris, B.B., ***et al*****.,** 1996: The cryosphere: changes and their impacts. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).* R.T. Watson, M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.), Cambridge University Press, Cambridge, UK.

Fohn, P.M., 1990: Schnee und lawinen. In: *Schnee, Eis und Wasser der Alpen in einer warmeren Atmosphere*. Mitteilungen 108, VAW/ETH, Zurich, Switzerland.

Foster, J.L., 1989: The significance of the date of snow disappearance on the Arctic tundra as a possible indicator of climate change. *Arctic Alpine Research*, 21, 60-70.

Foster, J.L., J.W. Winchester & E.G. Dutton, 1992: The date of snow disappearance in the Arctic tundra as determined from satellite, meteorological station and radiometric *in situ* observations. *Transactions Geoscience Remote Sensing*, 13, 225-231.

Fung, I.Y., C.J. Tucker & K. Prentice, 1987: Application of AVHRR vegetation index to study atmospheric-biosphere exchange of CO2. *Geophysical Research*, 92, 2999-3015.

GCOS-13, 1995: *GCOS Data and Information Management Plan*, WMO/TD-No. 677, Geneva, Switzerland.

GCOS-14, 1995: *Plan for the Global Climate Observing System (GCOS)*, WMO/TD-No. 681, Geneva, Switzerland.

GCOS-15, 1995: *GCOS Plan for Space-based Observations*, WMO/TD-No. 684, Geneva, Switzerland.

GCOS-17, 1995: *Report of the GCOS Atmospheric Observation Panel, Second Session, Tokyo, Japan*, WMO/TD- No. 696, Geneva, Switzerland.

GCOS-21, 1995: *GCOS/GTOS Plan for Terrestrial Climate-related Observations, Version 1.0*, WMO/TD-No. 721, Geneva, Switzerland.

Gilichinsky, D.A., 1986: *Sezonnaya kriolitozona zapadnoy Sibiri* (Seasonal Cryolithozones of western Siberia). Nauka, Moscow, Russian Federation.

Gleick, P.H. 1987: Regional hydrologic consequences of increases in atmospheric CO2 and other trace gases. *Climatic Change*, 10, 137-161.

Gloersen, P. & W.J. Campbell, 1991: Recent variations in Arctic and Antarctic sea ice covers. *Nature*, 352, 33-36.

Gloersen P., W.J. Campbell, D.J. Cavalieri, J.C. Comiso, C.L. Parkinson & H.J. Zwally, 1992: Arctic and Antarctic sea ice, 1978-1987: Satellite passive-microwave observations and analysis. NASA SDP-511, NASA, Washington, DC.

Goldammer, J.G., 1990: Fire in the tropical biota. In: *Ecosystem Processes and Global Challenges*, J.G. Goldammer (ed.), Springer-Verlag, Berlin, Germany.

Goldstein, R.M., H. Englehardt, B. Lamb & R.M. Frolich, 1993: Satellite radar interferometry for monitoring ice sheet motion, application to an Antarctic ice stream. *Science*, 262, 1525-1530.

Goodison, B.E. & A. Walker, 1993: Data needs for detection of climatic change: Some challenges. In: *Snow Watch '92, Glaciology Data Report GD-25*, R.G. Barry, B.E. Goodison and E.F. LeDrew (eds.), WDC-A for Glaciology, University of Colorado, Boulder, CO.

Goward, S.N., C.J. Tucker & D. Dye, 1985: North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Vegetation*, 64, 3-14.

Goward, S.N. & D. Dye, 1987: Evaluating North American net primary productivity with satellite observations. *Advances in Space Research*, 7 (11), 165-174.

Goward, S.N. & D. Dye, 1995: Global biospheric monitoring with remote sensing. In: *The Use of Remote Sensing in Modelling Forest Productivity at Scales from the Stand to Global*, H.L.

Gholtz, K. Nakane & H. Shimoda (eds.), Kluwer Academic Publishers, New York, NY.

Groisman, P.Ya. & D.R. Easterling, 1994: Variability and trends of total precipitation and snow pack over the United States and Canada. *Climate*, 7, 184-205.

Groisman, P.Ya., T.R. Karl, R.W. Knight & G.L. Stenchikov, 1994a: Changes of snow cover, temperature and radiative heat balance over the Northern Hemisphere. *Climate*, 7, 1633-1656.

Groisman, P.Ya., T.R. Karl & R.W. Knight, 1994b: Observed impact of snow cover on the heat balance and the rise of continental temperatures in spring. *Science*, 263, 198-200.

Gutzler, D.S. & R.D. Rosen, 1992: Interannual variability of wintertime snow cover across the Northern Hemisphere. *Climate*, 5, 1441-1447.

Haeberli, W., 1990: Glacier and permafrost signals of twentieth century warming. *Annals of Glaciology*, 14, 99-101.

Haeberli, W., G.D. Cheng, A.P. Gorbunov & S.A. Harris, 1993: Mountain permafrost and climatic change. *Permafrost and Periglacial Processes*, 4, 165-174.

Haeberli, W., 1995: Glacier fluctuations and climate change detection - operational elements of a worldwide monitoring strategy. *WMO Bulletin* 44 (1), 23-31.

Hall, F.G., J.R. Townshend &E.T. Engman, 1995: Status of remote sensing algorithms for estimation of land surface state parameters. *Remote Sensing of Environment*, 51, 138-156.

Halpert, M.S., G.D. Bell, V.E. Kousky & C.F. Ropelewski, 1994: *Fifth Annual Climate Assessment (1993)*, Climate Analysis Centre, NOAA, US Dept. of Commerce, Camp Springs, MD.

Haxeltine, A., I.C. Prentice, & I.D. Cresswell, 1996: A coupled carbon and water flux model to predict vegetation structure. *Journal of Vegetation Science*, 7, 5, 651-666.

Holdridge, L.R. 1967: *Life Zone Ecology*, Tropical Science Center, San Jose, Costa Rica.

Hornberger, G.M., K.J. Beven, B.J. Cosby & D.E. Sappington, 1985: Shenandoah watershed study: Calibration of a topography based, variable contributing area hydrological model to a small forested catchment. *Water Resources Research*, 21, 1841-1850.

Houghton, J.T., G.J. Jenkins & J.J. Ephramums (eds.), 1990: *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, UK.

Huete, A.R. & H.Q. Liu, 1994: An error and sensitivity analysis of the atmospheric- and soilcorrecting variants of the NDVI for the MODIS-EOS. *IEEE Transactions on Geoscience and Remote Sensing*, 32, 897-904.

IAHS(ICSI)/UNEP/UNESCO, 1994: *Glacier Mass Balance Bulletin No. 3 (1992-1993),* World Glacier Monitoring Service, WGMS/ETH, Zurich, Switzerland.

ICSU/UNEP/FAO/UNESCO/WMO, 1996: *Global Terrestrial Observing System (GTOS): Turning a sound concept into a practical reality*, UNEP/EAP.TR.95-08.

James, M.E. and S.M.V. Kalluri, 1994: The pathfinder AVHRR land data set: An improved coarse resolution data set for terrestrial monitoring. *International Journal of Remote Sensing*, 15 (17), 3347-3364.

Karl, T.R., P.Ya. Groisman, R.W. Knight & R.R. Heim, Jr., 1993: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *Climatology*, 6, 1327-1344.

Kaczmarek, Z., *et al*., (eds.) 1996: *Water Resources Management in the Face of Climatic/Hydrologic Uncertainties*, Kluwer Academic, Dordrecht, Netherlands, 395 pp.

Kelly, C.A., J. Rudd, V. St. Louis & T. Moore, 1994: Turning attention to reservoir surfaces; a neglected area in greenhouse studies. *EOS,* July 19, 332-333.

Kerr, A. & D. Sugden, 1994: The sensitivity of the south Chilean snowline to climatic change. *Climatic Change*, 28, 255-272.

King, G.A., & R.P. Neilson, 1992: The transient response of vegetation to climate change: A potential source of CO2 to the atmosphere. *Water, Air and Soil Pollution,* 64, 365-383.

King, G.A., A.M. Solomon, G. Koerper & D.L. Phillips, 1997: WINDS: A spatially-explicit model of tree migration by wind (*ms submitted to Ecological Applications*).

Kirschbaum, M., A. Fischlin, M.G.R. Cannell, R.V.O. Cruz, W. Galinski & W.P. Cramer, 1996: Climate change impacts on forests. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific- Technical Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* R.T. Watson, M.C. Zinyowera, R.H. Moss and D.J. Dokken, (eds.), Cambridge University Press, Cambridge, UK, 95-129.

Kittel, T. & M.B. Coughnor, 1987: Prediction of regional and local ecological change from global climate model results. In: *Monitoring Climate for Effects of Increasing Greenhouse Gas Concentrations,* R. Pielke and T.G.F. Kittel (eds.), CIRA, Colorado State University, Boulder, **CO.**

Korzun, V.I., 1978: World water balance and water resources of the earth. *UNESCO Studies and Reports in Hydrology, Series No. 25*, UNESCO, Paris, France.

Koster, E.A. & M.E. Nieuwenhuijzen, 1992: Permafrost response to climatic change. *Catena Supplement*, 32, 37-58.

Kuusisto, E., 1993: Lake ice observations in Finland in the l9th and 20th century: Any message for the 21st? In: *Snow Watch ‘92 Glaciological Data Report GD-25,* R.G. Barry, B.E. Goodison and E.F. LeDrew (eds.), WDC-A for Glaciology, University of Colorado, Boulder, CO.

Lachenbruch, A.H. & B.V. Marshall, 1986: Changing climate: Geothermal evidence from permafrost in thc Alaskan Arctic. *Science,* 234, 689-696.

Leemans, R. & W.P. Cramer, 1990: *The IIASA database for mean monthly values of* *temperature, precipitation, and cloudiness of a global terrestrial grid*. Number WP-41 in IIASAWorking Paper. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Leemans, R., A. van Amstel, C. Battjes, E. Kreileman & S. Toot. 1997: The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environmental Change* (in press).

Lettau, H., K. Lettau & L.C.B. Molion, 1979: Amazonia's hydrological cycle and the role of atmospheric recycling in assessing deforestation effects. *Monthly Weather Review*, 107, 227-237.

Lettenmaier, D.P. & D.P. Sheer, 1991: Climate sensitivity of California water resources. *Water Resources Planning and Management*, 117, 1, 108-125.

Li, Z.,& L. Garand, 1994: Estimation of surface albedo from space: A parameterization for global application. *Journal of Geophysical Research*, 99, 8335-8350.

Li, Z. & L. Moreau, 1996: A new approach for remote sensing of canopy-absorbed photosynthetically active radiation. Part 1: Total surface absorption. *Remote Sensing of Environment*, 55, 3, 175-191.

Li, Z., L. Moreau, A. Arking, 1997: On solar energy disposition. A perspective from observation and modelling. *Bull. Amer. Meteor. Soc.*, 78, 53-70.

Lieth, H. & R.H. Whittaker, 1975: *Primary Productivity of the Biosphere*. Springer-Verlag, New York, NY.

L'Vovich, M.I., 1979: *World Water Resources and Their Future*. American Geophysical Union, Washington, DC.

MacAyeal, D.R., 1992: Irregular oscillations of the West Antarctic Ice Sheet. *Nature*, 359, 29-32.

Manabe, S. & A.J. Broccoli, 1985: The influence of continental ice sheets on the climate of an ice age. *Journal of Geophysical Research*, 90, 2167.

McClung, D.M. & R.L. Armstrong, 1993: Temperate glacier response time from field data. *Glaciology*, 39, 323-326.

McLaren, A.S., J.E. Walsh, R.H. Bourke, R.L. Weaver & W. Wittman, 1992: Variability of sea-ice thickness over the North Pole from 1979-1990. *Nature*, 358, 224-226.

McLaren, A.S., R.H. Bourke, J.E. Walsh & R.L. Weaver, 1994: Variability in sea-ice thickness over the North Pole from 1958 to 1992. In: *Polar Oceans and Their Role in Shaping the Global Environment*. Geophysical Monographs No. 85, American Geophysical Union, Washington, DC.

Meier, M.F., 1984: Contribution of small glaciers to global sea level rise. *Science*, 226, 1418- 1421.

Melillo, J.M., I.C. Prentice, G.D. Farquhar, E.-D. Schulze & O.E. Sala , 1996: Terrestrial biotic responses to environmental change and feedbacks to climate. In: *Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.), Cambridge University Press, Cambridge, UK.

Milly, P.C.D., 1994: Climate, soil water storage and the average annual water balance. *Water Resources Research*, 30, 2143-2156.

Mohnl, H., 1991: Fluctuations of snow parameters in the mountainous regions of Austria within the last 90 years. *Mitteil. Hydrogr. Dienst., No. 65/66*, Vienna, Austria.

Monteith, J.L. & M.H. Unsworth, 1990: *Principles of Environmental Physics*. Edward Arnold, London, UK.

Moreau, L. & Z. Li, 1996: A new approach for remote sensing of canopy-absorbed photosynthetically active radiation. Part 2: Proportion of canopy absorption. *Remote Sensing of Environment*, 55, 3, 192-204.

Mote, T.L., M.R. Anderson, K.C. Kuivinen & C.M. Rowe, 1993: Passive microwave-derived spatial and temporal variations of summer melt on the Greenland Ice Sheet. *Annals of Glaciology*, 17, 233-238.

Myneni, R.B. & D.L. Williams, 1994: On the relationship between FPAR and NDVI. *Remote Sensing of Environment*, 49, 200-211.

Nace, R. 1971: *Scientific Framework of World Water Balance*. UNESCO Technical papers in Hydrology, No. 7, Paris, France.

Neilson, R.P., 1995: A model for predicting continental scale vegetation distribution and water balance. *Ecological Applications,* 5, 362-385.

Nelson, F.E., A.H. Lachenbruch, M.K. Woo, E.A. Koster, T.E. Osterkamp, M. Gavrilova &G.D. Cheng, 1994: Permafrost and changing climate. In: *Permafrost, Sixth International Conference Proceedings. Vol. 2,* South China University of Technology Press, Wushan, Guangzhou, China.

Newman, W.S. & R. Fairbridge, 1986: The management of sea level rise. *Nature*, 320, 319- 321.

Oerlemans, J., 1994: Quantifying global warming from the retreat of glaciers. *Science*, 264, 243-245.

Ohmura, A., & H. Gilgen, 1991: *Global Energy Balance Archive (GEBA)*. World Climate Program - Water Project A7, Rep.2: The GEBA Database, Interactive Application, Retrieving Data. Zurich, Verlag der Fachvereine, 60 pp.

Ohmura, A. & N. Reeh, 1991: New precipitation and accumulation maps for Greenland. *Glaciology*, 37, 140-148.

Oliver, H.R., 1983: The availability of evaporation data in space and time for use in water balance computations. In: *New Approaches in Water Balance Computations*. IAHS Publication, Number 148.

Olson, J. S., J. Watts & L. Allison, 1983: *Carbon in Live Vegetation of Major World Ecosystems*. W-7405-ENG-26, US. Department of Energy, Oak Ridge, TN.

Overton, W.S., D. White & D.L. Stevens, Jr., 1990: *Design Report for EMAP, Environmental Monitoring and Assessment Programme*. U.S. Environmental Protection Agency, EPA/600/3- 91/053, Washington, DC.

Parkinson, C.L., J. Comiso, H.J. Zwally, D.J. Cavalieri, P. Gloersen & W.J. Campbell, 1987: *Arctic Sea Ice, 1973- 76*. NASA SP-489, NASA, Washington, DC.

Parkinson, C.L. & D.J. Cavalieri, 1989: Arctic sea ice 1973-1987: Seasonal, regional and interannual variability. *Geophysical Research*, 94 (C10), 14199-14223.

Parkinson, C.L., 1991: Interannual variability of the spatial distribution of sea ice in the north polar region. *Geophysical Research*, 96 (C3), 4791-4801.

Pinter, P.L., Jr., 1993: Solar angle independence in the relationship between absorbed PAR and remotely-sensed data for alfalfa. *Remote Sensing of Environment*, 46, 19-25.

Prentice, K.C. & I.Y. Fung, 1990: The sensitivity of terrestrial carbon storage to climate change. *Nature*, 346, 48-51.

Prentice, I. C. & A. M. Solomon, 1990. Vegetation models and global change. In: *Global Changes of the Past*, R. S. Bradley (ed.), OIES, UCAR, Boulder, CO, 365-383.

Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud & A.M Solomon, 1992: A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography*, 19, 117-134.

Prentice, I.C., M.T. Sykes, & W. Cramer, 1993a: A simulation model for the transient effects of climate change on forest landscapes. *Ecological Modelling*, 65, 51-70.

Prentice, I.C., M.T. Sykes, M. Lautenschlager, S.P. Harrison, O. Denissenko & P.J. Bartlein, 1993b: Modelling global vegetation patterns and terrestrial carbon storage at the last glacial maximum. *Global Ecology and Biogeography Letters*, 3, 67-76.

Prince, S.D., 1991a: A model of regional primary production for use with coarse-resolution satellite data. *International Journal of Remote Sensing*, 12, 1313-1330.

Prince, S.D., 1991b: Satellite remote sensing of primary production: Comparison of results for Sahelian grasslands 1981-1988. *International Journal of Remote Sensing*, 12, 1301-1311.

Prince, S.D., C.O. Justice and B. Moore, 1994: *Monitoring and Modelling of Terrestrial Net and Gross Production*. IGBP DIS/GAIM Report No. 1, Paris, France.

Raich, J.W., E.B. Rastetter, J.M. Melillo, D.W. Kicklighter, P.A. Steudler, B.J. Peterson, A.L.Grace, B. Moore & C.J. Vorosmarty, 1991: Potential net primary productivity in South America: Application of a global model. *Ecological Applications*, 1, 4399-5566.

Rastetter, E.B., M.G. Ryan, G.R. Shaver, J.M. Melillo, K.J. Nadelhoffer, J.E. Hobbie & J.D. Aber, 1991: A general biogeochemical model describing the responses of the C and N cycles in terrestrial ecosystems to changes in CO2, climate and N deposition. *Tree Physiology*, 9, 101-126.

Revelle, R.R. & P. Waggoner, 1983: Effects of carbon dioxide induced climate change on water supplies in the western United States. In: *Climate Change*, National Academy Press, Washington, DC.

Rhodes, J., S. Chen, A. Guetter & K. Georgakakos, 1994: Large-scale aspects of the United States hydrological cycle. *Bulletin of the American Meteorological Society*, 17, 1589-1610.

Robinson, D.A., M. Wilson, G. Kukla & A. Henderson-Sellers, 1983: Observations of surface albedo and its variation for climate models. In: *Proceedings of the Seventeenth International Symposium on Remote Sensing of Environment*. Ann Arbour, MI.

Robinson, D.A., 1993: Hemispheric snow cover from satellites. *Annals of Glaciology*, 17, 367-371.

Rohrer, M.B., L.N. Braun & H. Lang, 1994: Long-term records of snow cover water equivalent in the Swiss Alps. *Nordic Hydrology*, 25, 53-64.

Royer, A., K. Goita, F. Beaudu & J. Cihlar, 1995: Dynamique et productivité, primairie nette de la forêt boréale à partir de l'indice de végétation global AVHRR-NOAA. *Soumis au Colloque Inter. Photosynthese et détection, 28-31 août 1995*, Montpellier, France.

Running, S.W. & R.R. Nemani, 1988: Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. *Remote Sensing of Environment*, 24, 347-367.

Running, S.W., R.R. Nemani, D.L. Pierce & M.A. Spanner, 1989: Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. *Ecology*, 70, 1090-1101.

Running, S.W. & R.E. Hunt, Jr., 1995: Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In: *Scaling Processes between Leaf and Landscape Levels*, J.R. Ehleringer and C. Field (eds.), Academic Press, San Diego, CA, 141-158.

Runyon, J., R.H. Waring, S.N. Goward & J.M. Welles, 1993: Environmental limits on net primary production and light-use efficiency across the Oregon transect. *Ecological Applications*, 4, 226-237.

Sahagian, D.L., F.W. Schwartz & D.K. Jacobs, 1994: Direct anthropogenic contributions to sea level rise in the twentieth century. *Nature*, 367, 54.

Schimel, D., I.G. Enting, M. Heimann, T.M.L. Wigley, D. Raynaud, D. Alves & U. Siegenthaler, 1995: CO2 and the carbon cycle. In: Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios, J.T. Houghton, L.G. Meira Filho, J. Bruce, Hoesung Lee, B.A. Callander, E. Haites, N. Harris and K. Maskell (eds.), Cambridge University Press, Cambridge, UK, 35-71.

Sedjo R.A. & A.M. Solomon, 1989: Climate and forests. In: *Greenhouse Warming: Abatement and Adaptation*, N.J. Rosenberg, W.E. Easterling, P.R. Crosson and J. Darmstadter (eds.), *Resources for the Future*, Washington, D.C.,105-119.

Sellers, P.J., Y. Mintz, Y.C. Sud & A. Dalcher, 1986: A simple biosphere model (SiB) for use within general circulation models. *Atmospheric Science*, 43, 505-531.

Sellers, P.J., 1989: Vegetation-canopy spectral reflectance and biophysical processes. In: *Theory and Applications of Remote Sensing*, G. Asrar (ed.), John Wiley and Sons, New York, NY.

Sellers, P.J., S.O. Los, C.J. Tucker, C.O. Justice, D.A. Dazlich, G.J. Collatz & D.A. Randall, 1994: A global 1 by 1 NDVI data set for climate studies, part 2: The adjustment of the NDVI and generation of global fields of terrestrial biophysical parameters. *International Journal of Remote Sensing*, 17, 3519-3546.

Sellers, P.J., B.W. Meeson, F.G. Hall, G. Asrar, R.E. Murphy, R.A. Schiffer, F.P. Bretherton, R.E. Dickinson, R.G. Ellingson, C.B. Field, K.H. Huemmrich, C.O. Justice, J.M. Melack, N.T. Roulet, D.S. Schimel & P.D. Try, 1995: Remote sensing of the land surface for studies of global change: Model-algorithm-experiments. *Remote Sensing of Environment*, 51, 3-26.

Shugart, H.H., 1984: *A Theory of Forest Dynamics*. Springer-Verlag, New York, NY.

Shukla, J., C. Nobre & P. Sellers, 1990: Amazon deforestation and climate change. *Science*, 247, 1322-1325. Shuttleworth, W.J., 1993: Evaporation. In: *Handbook of Hydrology*, D. Maidment (ed.), McGraw-Hill, New York, NY.

Skinner, W.R., 1988: The break-up and freeze-up of lake and sea ice in northern Canada. *Canada Centre Climate Report, No. 86-8*, Atmospheric Environment Service Canada, Downsview, Ontario, Canada.

Skinner, W.R., 1993: Lake ice conditions as a cryospheric indicator for detecting climate variability in Canada. In: *Snow Watch '92 Glaciology Data Report GD-25*, R.G. Barry, B.E. Goodison and E.F. LeDrew (eds.), WDC-A for Glaciology, University of Colorado, Boulder, CO.

Slack, J.R. & J.M. Landwehr, 1992: Hydro-Climatic Data Network (HCDN): *A U.S. geological survey streamflow data set for the United States for the study of climate variations 1874-1988,* Open-File Report 92-129. U.S. Geological Survey, Reston, VA.

Smith, T.M., R. Leemans & H.H. Shugart, 1992: Sensitivity of terrestrial carbon storage to CO2 induced climate change: Comparison of four scenarios based on general circulation models. *Climatic Change*, 21, 367-384.

Smith, T.M. & H.H. Shugart, 1993: The transient response of terrestrial carbon storage to a perturbed climate. *Nature*, 361, 523-526.

Solomon, A.M. 1986: Transient response of forests to CO2 induced climate change: Simulation modelling experiments in eastern North America. *Oceonologica*, 68, 567-579.

Solomon, A.M. & P.J. Bartlein, 1992: Past and future climate change: Response by mixed deciduous-coniferous forest ecosystems in northern Michigan. *Canadian Journal of Forest Research*, 22, 1727-1738.

Solomon A.M., I.C. Prentice, R. Leemans & W.P. Cramer, 1993: The interaction of climate and land use in future terrestrial carbon storage and release. *Water, Air and Soil Pollution*, 70, 595.

Solomon, A.M., N.H. Ravindranath, R.B. Stewart, M. Weber & S. Nilsson, 1996: Wood production under changing climate and land use. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contributions of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, R.T. Watson, M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.), Cambridge University Press, Cambridge, UK, 487-510.

Solomon, A.M., 1996: Natural migration rates of trees: Global terrestrial carbon cycle implications. In: *Past and future rapid environmental changes: The spatial and evolutionary responses of terrestrial biota*, B. Huntley, W.P. Cramer, A.V. Morgan, H.C. Prentice and J.R.M. Allen (eds.), Springer-Verlag, NY, 455-468.

Sonka, S.T., S. Changnon & S. Hofing, 1992: How agribusiness uses climate predictions: Implications for climate research and provision of predictions. *Bulletin of the American Meteorological Society*, 73, 1999-2008.

Staylor, W.F. & A.C. Wilber, 1990: Global surface albedos estimated from ERBE data. *Proc. 7th AMS Conf. Atmos. Rad.*, July 23-27, 1990, San Francisco, CA, 231-236.

Tans, P.P., I.Y. Fung & T. Takahashi, 1990: Observational constraints on the global CO2 budgets. *Science*, 247, 1431-1438.

Thomas, H.E., 1959: Reservoirs to match our climatic fluctuations. *Bulletin of the American Meteorological Society*, 40, 5, 240-249.

Thornwaite, C.W., 1948: An approach towards a rational classification of climate. *Geographic Review*, 38, 55-89.

Tucker, C.J., J.R. Townshend & T.E. Goff, 1985: African land cover classification using satellite data. *Science*, 227, 369-374.

Van Cleve, K., L.A. Oliver, R. Schlentner, L.A. Viereck & C.T. Dyrness, 1983: Productivity and nutrient cycling in taiga forest ecosystems. *Canadian Forest Research*, 13, 703-720.

Van der Veen, C.J., 1991: State of balance of the cryosphere. *Reviews of Geophysics*, 29, 433- 455.

Van der Waal, R.S.W. & J. Oerlemans, 1994: An energy balance model for the Greenland Ice Sheet. *Global Planetary Change*, 9, 115-131.

VEMAP Members, 1995: Vegetation/ecosystem modelling and analysis project: Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO2 doubling. *Global Biogeochemical Cycles*, 9, 4, 407-437.

Wadhams, P., 1995: Sea ice morphology. In: *The Physics of Ice-covered Seas*. NATO Advanced Study Institute, Savonlinna, Finland.

Wahr, J., H. DaZhong & A. Turpin, 1995: Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic earth. *Geophysics Research Letters*, 22, 977-980.

Walsh, J.E. & C.M. Johnson, 1979: An analysis of Arctic sea ice fluctuations. *Physical Oceonography*, 9, 580-591.

Walsh, J.E. & R.G. Barry, 1990: Cryospheric data for studies of global change. In: *Symposium on Global Change Systems*. American Meteorological Society, Boston, MA.

Waring, R. & Schlesinger, 1984: *Forest Ecosystems: Concepts and Management*. Elsevier, N.Y.

Watson, R.T., *et al*., 1996: Technical summary: Impacts, adaptations, and mitigation options. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific- Technical Analyses. Contributions of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),* R.T. Watson, M.C. Zinyowera, R.H. Moss and D.J. Dokken (eds.), Cambridge University Press, Cambridge, UK, 19-53.

Wilson, M.F. & A. Henderson-Sellers, 1985: A global archive of land cover and soil data for use in general circulation climate models, *Journal of Climatology*, 5, 2, 119-143.

WMO, 1988: *Technical Regulations Volume III - Hydrology*. WMO, No. 49, Geneva, Switzerland.

WMO, 1990: *Global Precipitation Climatology Project. Implementation and Data Management Plan*. WMO, No. 367, Geneva, Switzerland.

Wolock, D.M., D.J. McCabe, G.D. Tasker & M.E. Moss, 1993: Effects of climate change on water resources in Delaware River Basin. *Water Resources Bulletin*, 29, 475-486.

Woodward, F.I., 1987: *Climate and Plant Distribution*. Cambridge University Press, Cambridge, UK.

Woodward, F.I., T.M. Smith & W.R. Emanuel, 1996: A global land primary productivity and phytogeography model. *Global Biogeochemical Cycles,* 9, 471-490.

Zwally, H.J., 1989: Growth of the Greenland Ice Sheet: Interpretation. *Science*, 246, 1589-1591.

Annex IV Abbreviations

AARI Arctic and Antarctic Research Institute
ACSYS Arctic Climate System Study
AMSR Advanced Microwave Scanning Radiometer
ANPP Above Ground Net Primary Productivity
APAR Absorbed Photosynthetically Active Radiation
ARCS Abracos
ARGOS Data Collection and Position Location System
ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR Advanced Very High Resolution Radiometer
BAHC Biospheric Aspects of the Hydrological Cycle (within IGBP)
BGC Biogeochemical Global Climate (models)
BNF Biological Nitrogen Fixation
BNPP Below Ground Net Primary Productivity
BOREAS Boreal Ecosystems Atmosphere Study
CALM Circumarctic Active Layer Monitoring
CEC Cation Exchange Capacity
CEOS Committee on Earth Observation Satellites
CGIAR Consultative Group on International Agricultural Research
CIAT International Center for Tropical Agriculture
CIESIN Consortium for International Earth Science Information Network
CMDL Climate Monitoring and Diagnostic Laboratory
DAAC Distributed Active Archive Centre
DEBITS Deposition of Biogeochemically Important Trace Species
DIS Data and Information System
DMSP Defense Meteorological Satellite Programme
DWD Deutscher Wetterdienst
EMAP Environmental Monitoring and Assessment Program
ENSO El Niño/Southern Oscillation
ENVISAT European Space Agency Environmental Satellite
EOS Earth Observing System
EROS Earth Resources Observation Systems
ERS European Remote Sensing Satellite
ESMR Electrically Scanning Microwave Radiometer
ET Evapotranspiration
FAO Food and Agriculture Organization of the United Nations
FAGS Federation of Astronomical and Geophysical Services
FCCC Framework Convention on Climate Change
FPAR The Fraction of PAR Absorbed by the Plant Canopy
FRIEND Flow Regimes from International Experiments and Network Data
GAW Global Atmosphere Watch
GCM General Circulation Model
GCOS Global Climate Observing System
GDSIDB Global Digital Sea-Ice Data Bank
GEMS Global Environmental Monitoring System
GEWEX Global Energy and Water Cycle Experiment
GHG Greenhouse Gas
GHOST Global Hierarchical Observing Strategy

GIAM Global Integrated Assessment Models
GOES Geostationary Operational Environmental Satellite
GOOS Global Ocean Observing System
GPCC Global Precipitation Climatology Centre
GPCP Global Precipitation Climatology Project
GPS Global Positioning System
GRDC Global Runoff Data Centre
GRID Global Resource Information Database (GEMS)
GTOS Global Terrestrial Observing System
GTS Global Telecommunications System
HAPEXSahel
Hydrological Atmospheric Pilot Experiment
HCDN Hydro-Climatic Data Network
HRV High Resolution Visible
HWR Hydrology and Water Resources Programme (WMO)
IAHS International Association of Hydrological Sciences
ICSI International Commission on Snow and Ice
ICSU International Council of Scientific Unions
IGAC International Global Atmospheric Chemistry Programme
IGBP International Geosphere-Biosphere Programme
IGBP-DIS International Geosphere-Biosphere Programme-Data and Information System
IHDP International Human Dimensions Programme
IOC Intergovernmental Oceanographic Commission
IOS Initial Operational System
IPA International Permafrost Association
IPAR Incident Photosynthetically Active Radiation (at the top of the plant canopy)
IPCC Intergovernmental Panel on Climate Change
IRRI International Rice Research Institute
ISLSCP International Satellite Land Surface Climatology Project
ITEX International Tundra Experiment
JDIMP Joint Data and Information Management Panel
JSTC Joint Scientific and Technical Committee (GCOS)
LAI Leaf Area Index
LOICZ Land Ocean Interactions in the Coastal Zone
LTER Long-Term Ecological Research
LUCC Land Use and Cover Change Project (within IGBP)
MAB Man and the Biosphere Programme
MERIS Medium Resolution Imaging Spectrometer
MODIS Moderate Resolution Imaging Spectroradiometer
MPMR Multifrequency Passive Microwave Radiometer
N/A Not Applicable
NASA National Aeronautics and Space Administration
NCDC National Climatic Data Center
NDVI Normalized Difference Vegetation Index
NEP Net Ecosystem Productivity
NESDIS National Environmental Satellite Data Information Service
NIC US National Ice Centre
NIR Near Infra-Red
NOAA National Oceanic and Atmospheric Administration

NPP Net Primary Productivity
NSIDC National Snow and Ice Data Centre
NWP Numerical Weather Prediction
PAR Photosynthetically Active Radiation
PFT Plant Functional Type
PSD Particle Size Distribution
R and D Research and Development
SAR Synthetic Aperture Radar
SCAR Scientific Committee on Antarctic Research
SIGRID Format for the Archival of Sea-Ice Data in Digital Form
SMMR Scanning Multifrequency Microwave Radiometer
SOP Space-based Observation Panel
SOTER Soil and Terrain Data
SPOT Satellite Probatoire d'Observation de la Terre
SSM/I Special Sensor Microwave Imager
SVAT Soil-Vegetation-Atmosphere Transfer
SWE Snow Water Equivalent
TBD To Be Determined
TEMS Terrestrial Ecosystem Monitoring Sites
TOPC Terrestrial Observation Panel for Climate
ULS Upward-Looking Sonars
UN United Nations
UNEP United Nations Environment Programme
UNESCO United Nations Educational, Scientific and Cultural Organization
USGS United States Geological Survey
WCRP World Climate Research Programme
WDC World Data Centre
WHYCOS World Hydrological Cycle Observing System
WMO World Meteorological Organization
WWW World Weather Watch