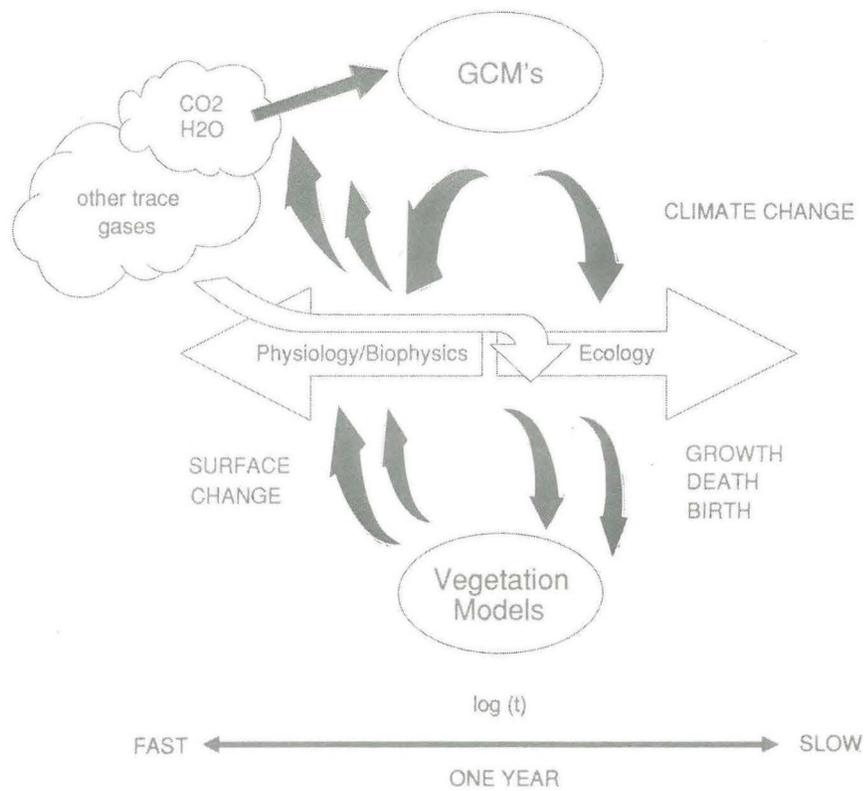


GLOBAL I G B P CHANGE

REPORT No. 10



The Land-Atmosphere Interface

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Report of a Combined Modelling
Workshop of IGBP Coordinating Panels 3, 4, and 5
Brussels, Belgium
8-11 June, 1989

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The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)
Stockholm, 1990

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The international planning for the IGBP is supported from ICSU, the Andrew W. Mellon Foundation, UNEP, Unesco, CEC, Shell Netherlands and national contributions.

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Printed by Graphic System AB, Stockholm, Sweden

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1. Introduction

The International Geosphere-Biosphere Programme requires the coordination and integration of information among and between diverse scientific disciplines. Modelling provides a primary means by which such a synthesis can be obtained. Comprehensive system models that integrate existing knowledge of how component parts of the system function together are necessary to understand climate change and predict the effects of that change on the biosphere.

Figure 1, originally developed for the U.S. Earth System Sciences Committee (ESSC), illustrates a conceptual architecture for a comprehensive system model capable of predicting global changes on time scales of decades to centuries. The model does not yet exist, though prototypes for nearly all of the model's components do, with varying degrees of credibility. The individual boxes in Fig. 1, such as "Terrestrial Ecosystems" identify subsystems. Each roughly corresponds to individual discipline-based models.

Identifying the information that must pass in each direction across the interfaces between subsystems and from external forcing functions (Fig. 1) is important. If the breakdown into subsystems is logically appropriate, the data flow across an interface should be substantially less than that circulating within the boxes. Furthermore, replacing the interfaces by direct measurements provides the possibility of isolating subsystem component models for individual testing and evaluation, a key step in improving confidence in the performance of the model as a whole. The information transfers implied by the arrows should not be confused with the effects of changes in one subsystem on another.

The complexity of comprehensive coupled systems, illustrated by the ESSC design (Fig. 1), provides a guide for the IGBP in developing an appropriate conceptual design for addressing the problems of global change. Clearly some of the boxes in the ESSC design are the focus of the World Climate Research Programme (WCRP) or other on-going programmes. A task of the IGBP is to determine the priority subset of model subsystems which best describe the changing global system together with the appropriate forcing functions. A second task is to identify those elements required to fill the boxes with substance. A third is to integrate the IGBP efforts with those of the WCRP and others to develop a comprehensive coupled-system model of global change.

Linking those pieces to provide a reliable description of the functioning of the entire Earth system and its relationship to human activities is the central task of the IGBP in the coming decades. This task presents enormous technical and organizational challenges. Particularly difficult is the establishment of reliability of the resulting description by means of appropriate measurements and theory.

This report is based upon discussions during a joint meeting between the IGBP Coordinating Panels CP-3 (Biospheric Aspects of the Hydrological Cycle), CP-4 (Effects of Climatic Change on Terrestrial Ecosystems) and CP-5 (Global Analysis, Interpretation and Modeling). The objectives of the meeting were to identify research areas of common interest to the three coordinating panels, to develop a strategy to address these joint issues, and to discuss what actions can be taken by IGBP to explore how different modelling approaches (including those of WCRP) may be synthesized into a system (Fig. 1).

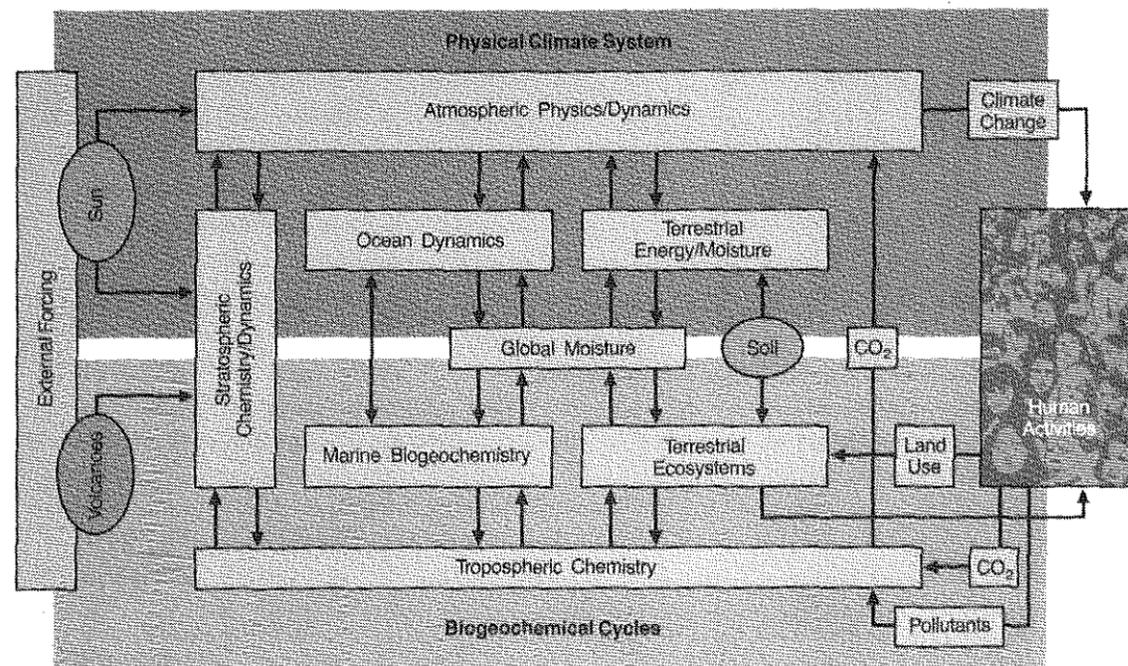


Figure 1. Conceptual model of Earth system processes operating on timescales of decades to centuries (ESSC 1988).

Many aspects of the issues being addressed by Coordinating Panels 3, 4, and 5 overlap at basic research levels. CP-3 addressing the fundamental role of vegetation in the interaction between biotic systems and climate through the hydrologic cycle must integrate efforts closely with the effects of changes in the hydrologic system on terrestrial ecosystems (CP-4) through, for instance, the transport of nutrients by runoff water and changes in ecosystem properties which influence water flux.

The primary focus of CP-5, global analysis, interpretation, and modelling, requires bringing hydrologic, atmospheric, and terrestrial data and models together into one system. Development of global geosphere-biosphere models requires an extension of global climate models to include the transfer of chemical compounds and key chemical and biological reactions and transformations. To understand the interconnecting cycles and to extend the results of local and regional process studies and observations to greater spatial and temporal scales, it is necessary to provide a theoretical basis.

Atmospheric, hydrologic, and terrestrial system models do not operate on the same time and space scales. Therein lies one of the major challenges facing the IGBP. Information transfer between systems must resolve apparent scaling incongruities. The processes which may be crucial to a hydrologic model may be treated as an average quantity for input to terrestrial models and may not provide an adequate description of the input given the dynamics of a changing system.

These types of problems can be addressed by decomposing the climate system into a spatial and temporal scale meaningful to hydrologic and terrestrial ecosystem processes. Soil and vegetation characteristics which control water, energy, and biogeochemical fluxes from the land-surface to the atmosphere must be

aggregated in a meaningful way for use in climate models. These models will be referred to as Soil-Vegetation-Atmosphere-Transfer models (SVAT). Regional level models, both hydrological and terrestrial, must be developed for significant areas of the globe. These in turn require the development of integrated global data sets and monitoring systems.

The results of the joint meeting are presented in Sections 2, 3 and 4 in which the working groups consider the basic modelling needs required for linking the atmosphere with the land surface for predicting and monitoring global change are discussed in Section 2, the interactions between terrestrial and hydrologic systems and the requirements to link the two in global change studies are covered in Section 3 and the coupling of biogeochemical cycles between the terrestrial ecosystem, marine system, and the atmosphere; Section 4. Section 5 contains the recommendations that emerged from the joint meeting.

2. Modelling the Land-Atmosphere Interface

2.1 Introduction and Issues

Existing atmospheric general circulation models (GCMs), in order to become more useful for global change studies, require significant improvement in several key areas; improved treatment of cloud-radiation processes, coupling to realistic oceanic models, and more realistic treatment of land-surface processes. The latter involves an improved treatment of land-surface properties such as topography, wind stress, albedo and hydrological properties, role of vegetation and soil on water flux, and the interactive responses of these to climatic forcing. These improvements are also important for predicting the impact of change on specific ecosystems and on biogeochemical cycles.

The relationships between land surface and climate involve the establishment of appropriately scaled surface parameters of H_2O , CO_2 , and energy fluxes based on models of ecosystems that can be fed directly upward into GCMs and, conversely, establishing atmospheric parameters appropriate for calculating ecosystems response (the downward linkage). Climate parameters may also be used in a non-interactive way to establish first order responses of the ecosystems to climate change. The parameters required for these two purposes may or may not be the same.

An obstacle to the reliable coupling of land-surface models to atmospheric models is the difference in temporal and spatial scales which characterize the two kinds of models. Existing GCMs currently represent atmospheric circulation features at grid scales of about $100 \times 100 \text{ km}^2$ and time scales of decades down to hours (Fig. 2a). Biological models, on the other hand, represent processes from cellular to ecosystem level with characteristic scales which generally operate at finer spatial resolution than climate models. For these models, it is necessary to calculate temperature at a particular point on the Earth. This "scaling" problem has been widely recognized, and remains a key issue for IGBP studies.

In principle, there are three ways of dealing with the scales issue. The first would involve running of the GCMs at greater spatial resolution. There is some hope for improvement in this direction, although this will be seriously constrained by computer-power. A second possibility is to run nested regional models of substantially higher resolution for limited regions of the Earth's surface. The third approach is to disaggregate the climatic information of the GCM at grid resolution into sub-grid scale information using some empirical, statistical relationships derived from knowledge of the real climate

system. Even with nested models, it might be necessary to resort to the third approach.

Models of leaf surfaces at a very small spatial scale can be used to explore the mechanisms of stomatal response to changing environmental conditions. While those models could (in theory) be scaled up to produce an indication of the biophysical performance of plant canopies by direct simulation of the thousands of individual leaves in the plant canopy, in practice the combination of measurement requirements and the interactions among leaves and between leaves and the environment make this approach impossible.

Rather than attempting to scale up from a single leaf, functional relations are used to obtain an estimate of H_2O , CO_2 , and energy fluxes at the scale of a plant canopy. This approach has been applied at somewhat longer time and larger space scales (e.g., S. Running's SVAT models, see Running, 1987). These models assume a particular vegetation structure and at least some of the parameters are expected to change if the structure changes. However, SVAT models are not designed to simulate structural or species changes of the canopy. Inclusion of dynamic canopy change will depend upon development of a sub-model which specifically simulates changes to canopy structure.

One set of models that do change the canopy (as well as the structure and composition of the vegetation) are the "patch" models (small spatial-scale models such as are described in the CP-4 Woods Hole report (IGBP 1990 and Prentice *et al.* 1989). Preliminary tests indicate that the interaction of the SVAT-like models with patch models seems feasible. The SVAT models could compute production of photosynthate, while the patch models allocate this photosynthate to produce canopy structure changes.

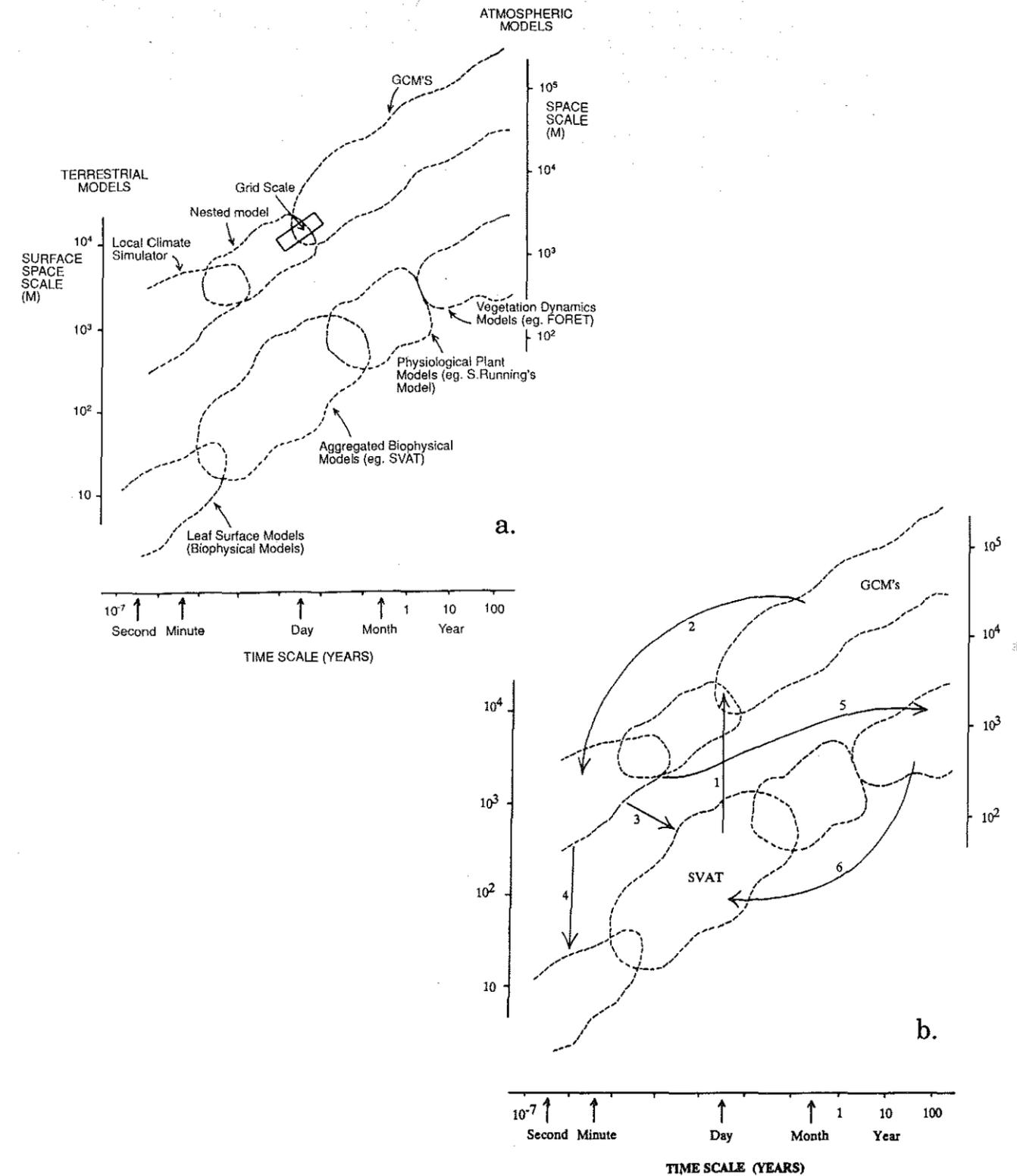


Figure 2. Space-time scaling of atmospheric and biospheric models. a) Comparison of spatial and temporal scales applicable to various atmospheric and biospheric models commonly used. b) Interface between atmospheric processes and biospheric process represented in respective model formulations.

Figure 2a and b illustrate a nested hierarchy of vegetation models at different time and space scales that emphasize different mechanisms. The transition between those different models requires internal consistency between model assumptions, phenomena, etc. and can be a daunting scientific problem. Nevertheless, progress in this area is promising.

A natural interface exists between the GCM grid scale and a fast SVAT model with the leaf-surface properties scaled up in space to match the GCM grid scale (Arrow 1, Fig. 2b). Such a linkage allows the surface to have some of the responses expected from a plant canopy of a given structure. To model interactions with the plant processes which result in vegetative cover, the response to the GCMs must be "translated" into climate/weather variables appropriate in scale to the vegetation models (Arrow 2, Fig. 2b). We envisage that this will most likely be done in a statistical fashion using what will be termed a "local climate simulator".

Changes in the atmosphere could work directly on the canopy (Arrow 3, Fig. 2b), operate on fundamental biophysical mechanisms (Arrow 4, Fig. 2b) or change the vegetation structure by affecting ecosystem processes (Arrow 5, Fig. 2b). Changes in structure could feed back on canopy processes of energy and water fluxes by altering boundary layer conditions, albedo or gas exchange rates (Arrow 6, Fig. 2b). We know from past experience that integrating models of different space/time domains can be difficult, but possible if the key processes at the interface are appropriately represented.

2.2 Short- and Medium-Term Modelling Targets

"Translation" between the scale of general circulation models and the finer scale ecosystem models will require cooperation

between diverse disciplines within the scientific community. Global and ecosystem processes operate at different scales and integration across those scales is not a simple, additive coupling. Thus, models which describe, simulate or predict ecosystem or global climate (circulation) behaviour require specific linkage, which will ensure that data flow between the models contains specific information at the appropriate scale. These problems can be addressed through several activities that should be fostered within the IGBP core projects.

2.2.1 Linking vegetation to SVAT models

SVAT models translate land-surface information into boundary conditions for a GCM. Some existing SVAT models, including SiB (the Simple Biosphere model of Sellers *et al.* 1986), or the BATS model (Wilson *et al.* 1987), have a large number of parameters, too many to be specified reliably. However, relatively few vegetation characteristics (e.g., Leaf Area Index (LAI) and root characteristics) crucially determine the surface properties sensed by the atmosphere.

Recommendation:

SVAT models must be developed which are simple enough to be run using the minimum set of surface characteristics.

Establishment of the link between vegetation and SVAT models is essential to a realistic "upward" coupling of the atmosphere and land surface in atmospheric models. An important part of the effort will be to derive functional relationships for SVAT models between surface resistances and vegetation properties. Such relationships should be mechanistically based as far as possible, but may be calibrated using the type of experiments discussed below.

Surface characteristics should be chosen such that it is possible to specify them either

observationally (from satellite measurements) or from the output of a global ecosystem model.

2.2.2 Developing local climate simulators

GCMs can, in principle, provide scenarios with spatial and temporal distributions of climatological variables such as surface temperature, precipitation, evaporation, and soil moisture. A prototype is available for limited environments (Running 1987). However, the GCMs are not developed to a stage that could provide reliable temporal frequency distributions for these variables. Nor can GCMs provide the spatial distributions of these variables over heterogeneous terrain.

Recommendation:

The most urgent requirement in making the "downward" linkage from atmosphere to ecosystem is the development of models that can translate the large-scale predictions of GCMs into spatially much finer-scale inputs for ecosystem and hydrological models.

These models would take GCM grid-point output and generate spatio-temporal distributions of the relevant atmospheric variables within the area, taking into account its particular terrain (transferring the even, average regional drizzle into rainstorms in space and time). The problem could be approached in a simple way from weather patterns and frequency distributions related to planetary scale atmospheric variability such as ENSO in the tropics. Then, the frequency of extreme events could be changed and used to drive ecosystems models.

A more sophisticated approach involves adapting existing techniques used in translating the output of weather prediction models into local forecasts. The problem is one of translating the variables (such as geopotential height) used in numerical models

into maximum/minimum temperature, cloudiness, probabilities of precipitation, severe storm probabilities, etc. that are used to characterize weather for the general public. This translation may be accomplished by a correlation table established empirically between selected model variables and local weather station records.

Similar translation tables need to be established for interpreting the output of climate simulations in GCMs in terms of local climatological statistics. Research is needed to develop techniques for generalizing such tables for locations for where detailed weather records do not exist, and for using the output from meteorological radar to establish statistics for the spatial extent, intensity and duration of precipitation. Present climate models do not reliably simulate regional climates, so the output of such translations should not be expected to reproduce existing local climates. However, they would have important applications for sensitivity studies and climate change impact analyses.

2.2.3 Developing global models of ecosystem dynamics

"Ecosystem dynamics" refers to the processes by which ecosystems react to environmental changes through changes in composition and structure (see also IGBP 1990). Two key aspects of the development of a global ecosystem dynamics model are incorporated in the following recommendations.

Recommendation:

A generic model, or models, must be developed to simulate ecosystem behaviour at the "patch" scale (c. 10000 m² in forests or <100 m² in non-forest).

The construction of generic models can build on existing models but requires:

- the development of very fast, population-based growth and demography algorithms;
- simultaneous representation of the dynamics of light, water and nutrients within ecosystems; and
- representation of the responses of different functional types of plants to environmental and resource gradients.

Recommendation:

Given the existence of such "patch" scale models, the next requirement is to develop a spatial modelling framework to link patches through large-scale transport processes including dispersal, spread of fire and pest outbreaks, and spatial redistribution of water and nutrients.

This second aspect requires the identification of ingenuity in parameterization and characteristic spatial scales of each transport process.

Recommendation:

Determine the procedures for validating global models of ecosystem dynamics (see below, section 2.3).

2.2.4 Linking ecosystem models and hydrological models

This is a two-way process because hydrological and ecosystem models cannot be separated at the scale of the globe. Continental-scale hydrological models (see Section 3) must be built in such a way that they can take data on key vegetation characteristics from ecosystem models constructed for the same scale. Global ecosystem models must also incorporate hydrological processes. The most

important process, the partitioning of incoming precipitation into evaporation, runoff and stored soil water, can be handled by incorporating a one-dimensional surface hydrology model into a patch-scale ecosystem model. This is required for adequate simulation of ecosystem dynamics in water-limited systems (e.g., savannas), and in systems where water storage and overall production may be low (e.g., the Amazon).

Recommendation:

Regional ecosystem models which incorporate the hydrological processes that are output from hydrologic models must be developed.

2.3 Data and Validation Requirements

Validation of models implies determining the accuracy by which the processes in nature are described by these models. As a measure for the quality of a model the accuracy of the resulting fluxes is in many cases an adequate criterion. These fluxes can be validated at different scales. The experiments and data described in this section provide a framework to validate SVAT-type models and the underlying hydrological models.

Recommendation:

Develop internationally coordinated global data bases of "fixed" surface characteristics.

Surface characteristics are urgently required as boundary conditions for global ecological and hydrological models. The fine spatial scale of surface processes demands a resolution of at least 10 km, or finer. The most important "fixed" characteristics needed at this resolution are elevation and physical soil characteristics. It may be impossible to obtain all the required soil characteristics directly.

Recommendation:

Validate satellite-derived measurements and improve algorithms.

Improvements in the coupling of GCMs to the land surface require statistical summation (to c. 100 km scale) of satellite-based data on the present land cover. These data are only very roughly specified in current models. At a much finer scale, the same type of information is also required for the proposed global ecosystem model and hydrologic models, as primary data validation, as boundary conditions, and as an "initial condition" in applications of such a model to projecting ecosystem change into the future.

Spectral radiances measured at satellite altitude are transmitted to Earth as relative digital values. Calibration data are either transmitted separately or must be derived from auxiliary information. We assume that it is possible to establish absolute radiance values at the top of the atmosphere. In order to translate these radiance values into information needed for modelling purposes, such as albedo: surface temperature, soil moisture in the uppermost layer, energy and water vapour fluxes, vegetation index and LAI and/or biomass production, a number of steps are necessary which involve data transformation procedures (algorithms). These steps include:

- corrections for the influences of atmospheric trace gases and aerosols on the signal;
- spectral interpolations or extrapolations by means of atmospheric radiation transfer models;
- corrections for the solar zenith angle and the angle under which the surface is viewed;

- geometric corrections and resampling into geographic coordinates;
- application of SVAT-type models to bridge from observable quantities to the derived biological quantities;
- correction for the emissivity of the surface.

The validation of the satellite data is therefore primarily a validation of generally applicable algorithms. "Validation" in this sense is defined as a procedure by which error bars can be applied to the products of satellite radiance measurements. Validation can only be done if independent measurements are available that are representative for the area instantaneously viewed by the sensor. Since the homogeneous areas for which ground measurements can be made are very often as small as 100 x 100 meters, the validation procedure must start with high-resolution images such as those currently obtained by LANDSAT and SPOT to identify surface heterogeneity and the scaling up to larger site levels as suggested in Fig. 3. Because radiances are averaged by the sensor, the result will be different for sensors with different horizontal resolution. The averaging procedure has therefore to be studied in detail and standardized for global application. These problems are being addressed by IGBP-WG1 on Data and Information Systems.

Recommendation:

Perform regional field experiments to relate conventional and satellite observations to SVAT and mesoscale models.

Field experiments must be made under various environmental conditions to validate model behaviour under average and extreme conditions. The experiments must be designed to provide data sets for validation of the performance of models in heterogeneous areas.

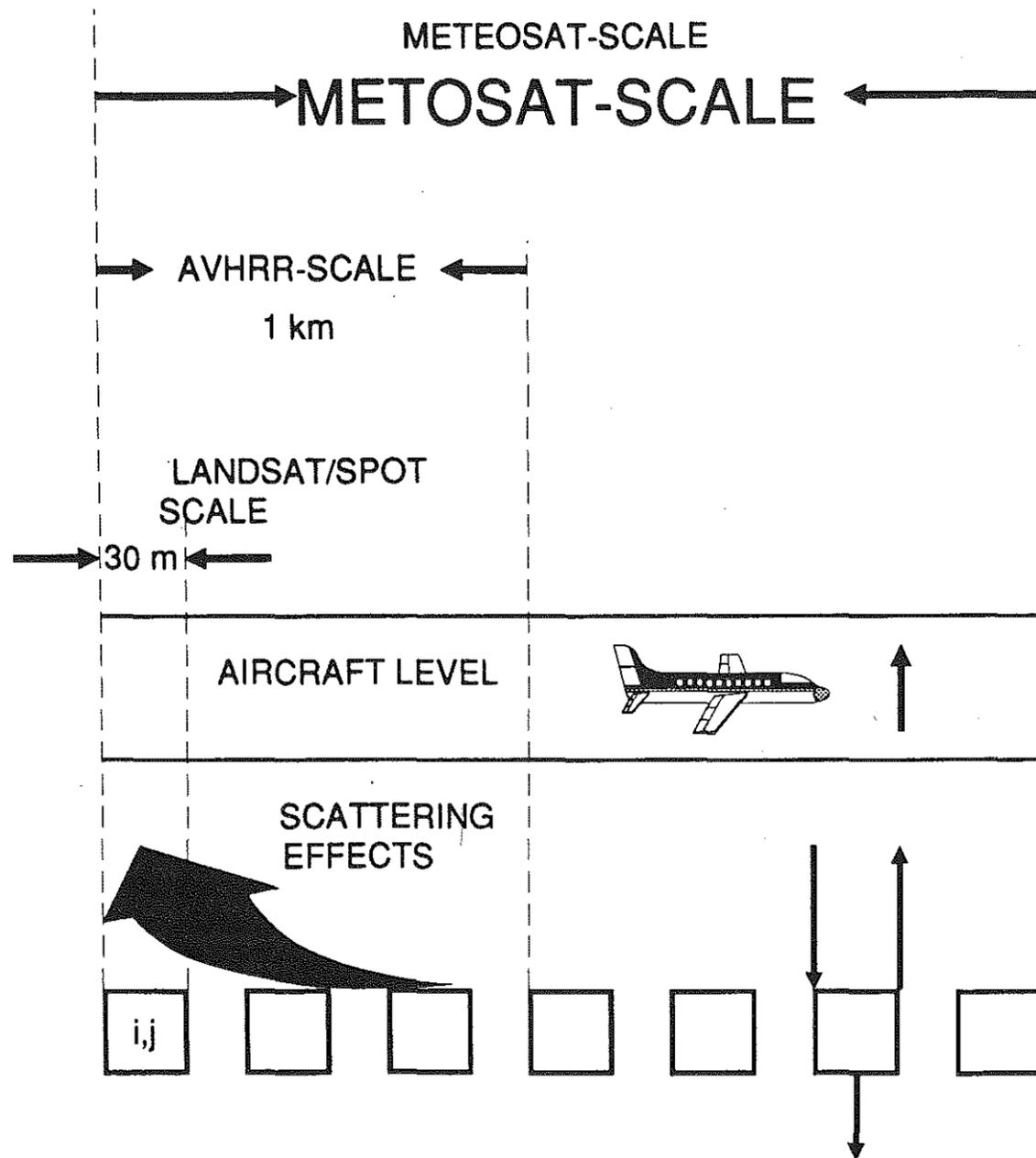


Figure 3. Scaling up from small scale tests to radiance measurements at different altitudes and different fields of view. Across spatial scales from small to large.

Global modelling of the interactions between the soil, hydrology, vegetation and the atmosphere require data for the operation of the models and, on a continuous basis, to update conditions that change due to external forcing. It will be difficult to verify model prediction of change at the global and decade scales empirically. However, the accuracy of subsystems ("modules") of these models can be determined by experiments designed to test key processes.

Following necessary information can be obtained with some effort from spaceborne measurements and from existing surface-based networks: Derivation of the net radiative flux at the surface that drives the heat fluxes between the surface and the atmosphere requires surface albedo and temperature, global radiation at the surface, and atmospheric structure. Vegetation changes that occur on seasonal, interannual and decadal scales, may be quantified from spectral-reflectance-derived vegetation indices. Measures of spatial and temporal variability of precipitation events can be derived, with knowledge of cloudiness that modulate the thermal and radiative regime at the surface. Surface temperatures and their diurnal amplitude provide information about the soil moisture and are required by some biosphere models.

In this regard, field measurements are needed: 1) to validate the derivation of model-relevant information from satellite measurements; 2) for the calibration of surface-vegetation-atmosphere transfer models including the underlying regional hydrological models; 3) to validate the accuracy of the interfaces between different submodels; 4) to determine how changes in an ecosystem during extreme climatic events are reflected in the models and the observational data.

Field experiments for process studies, the validation of models and relating space-borne measurements to ground-level data should be

planned by a joint WCRP-IGBP group on land-surface experiments.

Recommendation:

Conduct field experiments in major ecosystems and in different climatic regimes.

Because various ecosystems react differently to climate forcing, it is necessary that experiments be carried out for major ecosystems in different climatic regimes. Some of these regimes have already been defined by the WCRP. The IGBP must add an ecosystem component to that list. All these experiments have to be organized over spatial extents which are compatible with the size of atmospheric GCMs (i.e., c. 100 km), and which encompass enough spatial variability of surface and sub-surface conditions so as to provide meaningful information for realistic climatic conditions. Within the context already defined as HAPEX (Hydrologic Atmospheric Pilot Experiments), sub-areas of a typical size of 10 km with good spatial homogeneity of surface conditions, should be used as validation sites for satellite remote sensing, as for instance in the ISLSCP series of experiments.

The following are major areas for which experiments are either presently being conducted or are proposed for the near future:

- Kurst, USSR, dedicated to a mid-latitude agricultural area (ongoing).
- Heihe-river basin, PRC, at the fringe between a major desert and a vegetational area (starting 1990).
- Niger, semi-arid savanna (planned for 1992).
- Boreal forest, USA-Canada (1993).
- Castilla-La Mancha, Spain, Mediterranean steppe - marginal land-use area, (1994) with a precursor pilot experiment (1991) and continuing background measurements and satellite observation from (1990) on.

- Northern Australia (1991 or later). There will also most probably be an experiment in Northern Australia covering a gradient from humid tropical woodlands to semi-arid savannas.

Experiments in the tropical rain forest and the tundra are regarded as of high priority. For these and other areas which may be identified as important, no time frame is yet defined.

Past experiments include a large hydrological experiment HAPEX-MOBILHY in France, an ISLSCP-type experiment (10 x 10 km) both in the USA (FIFE, 1987 and 1989) and the Federal Republic of Germany (LOTREX-HIBE, 1988/89). The CEC funded small-scale experiments in La Crau (France), Greenland and Ibecetene (Niger), all in 1987/88. The results of these experiments have to be combined and evaluated jointly with the results expected from the on-going experiments.

2.4 Long-Term Monitoring of Global Change

If the IGBP is to provide information about global change that is useful to governments and other decision makers, we must develop the capability to document unequivocally the significant global changes that actually occur over the coming decades. This means identifying a minimal subset of the variables in the comprehensive system models that define the state of the system on timescales of decades, and establishing a measurement and validation system to monitor this subset on a global scale.

Some major state variables of the comprehensive system can already be identified with confidence (e.g., temperature, precipitation, albedo, vegetation parameters, element transport, groundwater, and river

runoff, etc.). In these cases, the issue is to establish the observational network systems, data management and analysis activity that result in continuing, coordinated global data bases. To do this reliably requires a major international effort extending far beyond the capabilities of individual scientists or laboratories. The feasibility of such a network is being investigated by IGBP-WG1. Global modelling can play a key role in evaluating system trade-offs and in assimilating the data into internally consistent state descriptions. Enough is already known for measurement system development to proceed immediately.

Recommendation:

An IGBP working group should be established to identify a minimum subset of variables in a comprehensive system model that defines the state of the system on time scales of decades. This working group should consequently suggest a specific measurement and validation system to monitor this set of variables on a global scale. This activity should become part of the implementation for an IGBP project on modelling (CP-5).

3. Ecosystem-Hydrology Interactions: Biological Activities Important in Hydrological Modelling and Vice-Versa

3.1. Introduction

General Circulation Models (GCMs) reconstruct the atmospheric component of the hydrological cycle through simulation of the large-scale weather systems. Evapotranspiration and precipitation are the usual atmospheric components. At the land surface, the hydrologic cycle is represented by storage of water as soil moisture and snow cover, and by runoff. Modelling provides the

opportunity for describing and quantifying future changes in land-surface hydrology, which will provide a basis to project the amount of available water. As with other surface ecosystem models it is necessary to improve the information to and from the GCMs through SVAT and local climate simulator models.

The incorporation of land-surface hydrological processes in GCMs is currently inadequate. Hydrologic processes must be accounted for in development of SVAT models. The role of vegetation and the time and space characteristics of precipitation are particularly weak. Vegetation is the major mediator of water flux from the land surface to the atmosphere. Frequency, intensity and spatial distribution characteristics of precipitation must be specified in order to drive models of ecosystem dynamics (i.e., the local climate simulator).

Vegetation is crucial in determining the partitioning of surface-water fluxes and energy fluxes into latent and sensible energy. It does this by accessing soil water through its root systems, intercepting and re-evaporating a fraction of incident precipitation, offering resistance to the flow of water from the soil through stomatal control, and by partially determining surface albedo and roughness.

Large-scale patterns of climate are influenced by the regional variability of surface hydrological processes. Alteration of the vegetation cover affects both global atmospheric composition and the energy and regional water balance, especially evapotranspiration and runoff. Since the hydrological fluxes in a drainage basin are dependent upon the supply of radiant energy, changes in radiation balance will significantly affect the rates of evapotranspiration and alter the water-balance components. It is therefore important to assess the response of

evapotranspiration to changes in both net radiation and vegetation.

The dynamics of, and the synergism among, soils, vegetation and the atmosphere on the small scale and their integrated effects on the macro- or grid-scale is not yet understood. Properties of the land surface together with atmospheric forcing create non-linear responses in hydrologic systems at spatial scales smaller than the scale of GCMs. Precipitation variability and variability in the land surface (e.g., the texture and structure of the soil, the vegetation type and density and geomorphological parameters), create important problems in understanding the hydrologic cycle at regional and global scales. There is an urgent need:

- to study the regional distribution of energy, moisture and momentum sinks and sources over the land surface,
- to determine the seasonal variability of source/sink behaviour,
- to determine the role of the biosphere in controlling these fluxes at various scales,
- to explore (by experiments and models) whether our understanding of surface hydrology involving vegetation on the small scale can be rigorously integrated over space to describe interactions appropriate to the scales of global models, and
- to determine whether such processes can be quantified by remote sensing, individually and as integrated effects.

3.2 Hydrological Modelling: Short- and Medium-Term Targets

A nested hierarchy of hydrological simulation models is needed to meet the aims of IGBP, from the global GCM-grid scale down to the scale of a local drainage basin or sub-basin. Existing hydrological models have dealt with a limited spatial scale ranging from the

agricultural plot, via the drainage basin, to the groundwater aquifer unit. They operate at short time scales (hourly/daily time steps), and require location-specific input information. Generic models, capable of simulating long-term (annual to decade) water fluxes at regional scales do not exist. As with ecosystem models, spatial scale is a major problem in integrating existing hydrological and atmospheric models. In the short and medium term, priority should be given to the development of mechanistic generic hydrological models (GHMs).

A mechanistic GHM could be used to investigate the sensitivity of different parts of the hydrological cycle to changes in external boundary conditions. It could also be used to examine the transient response of the hydrological cycle as a whole to rapid changes in external forcing. Such analyses will make it possible to address questions about the nature and speed of the hydrological response to possible future changes in climate. In addition, a GHM could be used to project regional hydrological outputs as a result of natural or man-made changes. It is, therefore, potentially useful in studies on the effects of regional irrigation schemes, land-use changes, or the construction of large dams.

Vegetation is a key component of the GHM. It controls the partitioning of water to the atmosphere through transpiration and groundwater flow through root uptake and interception. Coupling of the hydrologic cycle and vegetation will be possible with GHMs by prescribing various scenarios of climate or anthropogenic changes in the vegetation. Ultimately, the GHM could be interactively coupled to a generic vegetation model (cf. Prentice *et al.* 1989), which would allow changes in climate (derived from GCM simulations) to be translated into changes in regional vegetation, which would in turn affect regional hydrology. These changes in regional hydrology would have feedback effects

on the vegetation and, through SVAT models, back to GCMs.

We identify below first the critical processes which need to be included in a mechanistic GHM, defining the main partitioning, storage and transfer functions to which the water input will be subject, and secondly the climatic input needed as a forcing function to drive the model. A number of fundamental deficiencies in available data and current modelling methods are identified.

3.3 Critical Process for Inclusion in a Generic Hydrological Model (GHM)

Some of the processes to be included in the proposed GHM must be determined empirically at various scales. Other processes may or must be modelled.

3.3.1 Interception-Evaporation

Canopy and surface-litter interception provide a fundamental partitioning point for the fate of precipitation into physically controlled evaporation and physiologically controlled transpiration. This partition also controls the time retention of precipitation, 1-10 hours for evaporation but 1-50 days for transpiration. Interception capacity could be defined proportional to the satellite-derived Normalized Difference Vegetation Index (NDVI) as outlined in Section 3.4.3. Simple canopy evaporation formulae, such as the Penman equation, can be used to calculate evaporation of intercepted water.

3.3.2 Transpiration

A recent international conference at Penn State University (USA-NSF 1990) concluded that regional transpiration can adequately be calculated by the Penman-Monteith equation. This equation requires net radiation and

vapour-pressure deficit as meteorological driving variables. Windspeed under normal conditions of atmospheric turbulence can be assumed constant for these purposes. The primary physiological control is represented by the surface resistance term, which is calculated as a complex function of solar radiation, air temperature, vapour-pressure deficit and soil water supply. Although the functional controls of stomata are highly non-linear, the basic formulae can represent broad classes of plant types for continental-scale purposes. Scaling the transpiration rate by leaf area index (LAI), derived from satellite NDVI, will provide an important sensitivity of the model to vegetation dynamics. The greatest potential for error in calculating transpiration will occur during soil water deficits when stomatal closure is triggered. The definition of soil available water and its depletion rate will be quite difficult to parameterize on continent scales. Differences in the $^{18}\text{O}/^{16}\text{O}$ isotope ratio of the evaporation and transpiration components offers interesting possibilities for validation.

3.3.3 Soil processes

The partitioning of water at the land surface into a surface runoff component and an infiltration component is determined by the state of the vegetation and soil and the nature of the precipitation event. The overall water-holding capacity of the soil is determined by soil texture, fabric and structure (which determine total pore space) and by the presence and amount of organic material. Soil infiltration rates during a given precipitation event are determined by the overall water-holding capacity, by the effects of antecedent conditions on the amount of water within the soil, and by physical characteristics of the soil surface such as the degree of crusting or compaction (in turn influenced by litter and therefore vegetation). Water movement within the soil is controlled by the internal structure of the soil and the presence of impermeable pans.

We need to develop models which incorporate infiltration within the soil layer, intra-soil water retention, infiltration below the root zone, subsurface runoff both along the surface of impermeable horizons and within the deep regolith, and upward capillary movement due to evaporation from the soil surface.

3.3.4 Groundwater transfers

Groundwater is an important component of the hydrological cycle, because it integrates over relatively large spatial and long temporal scales and can therefore buffer the hydrological system against rapid change. There are fundamental differences in groundwater behaviour, specifically in the location and timing of recharge and discharge, under humid and arid conditions. Groundwater simulation models are theoretically well-developed. However, existing groundwater models are often complex and have heavy data requirements. There is a need to develop more generic groundwater models, capable of simulating 1) changes in groundwater recharge caused by climatic or vegetation changes in the recharge zone; 2) changes in long-term groundwater storages; 3) groundwater transfers along preferred pathways; and 4) changes in human consumption of groundwater relative to scenarios of future climatic or social changes.

At the continental scale, groundwater movement is controlled by lithological and structural factors (e.g., rock porosity and permeability, the presence of fissures and faults), and by subsurface "topography" (which may bear little relation to the surface topography). Groundwater recharge and discharge are controlled primarily by climatic factors and the nature of the vegetation cover, although topography and the geomorphic structure of the land surface influence the size and location of the recharge/discharge areas.

3.4 Identification of the Hydrological System to be Modelled

The land system subject to precipitation controls the behaviour of water input to the land. Three subsystems should be distinguished:

- landscape attributes;
- attributes of the subsurface system;
- vegetation.

3.4.1 Landscape attributes that modulate hydrological and biological processes

The generation of surface-water storages and transfers requires the incorporation of realistic, though generalised, surface topography. This information will also be necessary for improving information exchange with GCMs. Topographic data exist as digital elevation grids at a global scale (e.g., U.S. Navy topographic data base). The spatial resolution varies from continent to continent, from 1.5' by 1.5' at best (for Australia) to 10' by 10' at worst. Such gridded topographic data are too coarse to generate a realistic hydrological network, which requires additional information to establish local base levels. Local base level can be generated by digitising streamlines and sinks (which include lakes, swamps and wetlands). International aviation charts provide the most complete global coverage at a scale of 1:1 million. While the digitization of local base levels is not a trivial task, it could be achieved in a short time (1-2 years) at relatively small cost. Digitizing the streamlines at this scale will improve the surface-fitting algorithm, giving a maximum possible resolution of digital elevation grid of 2.5 by 2.5 km. We suggest that this activity be given high priority. The GRID programme of UNEP could provide a logical vehicle for such a task.

Slope and aspect are important components in computing radiation receipts and potential

evapotranspiration. However, a digital elevation grid of at least 12" is required to generate realistic values of slope and aspect. This level of resolution is unattainable in the foreseeable future, unless there are new developments in remote sensing radar and major international survey programmes. The distribution of different slopes and aspects within a grid must therefore be generated probabilistically. A programme to sample selected target catchments at a range of spatial scales including very high resolution digital elevation data (100 by 100 m) would provide a test of the probability distributions used.

3.4.2 Attributes of the subsurface system that modulate hydrological processes

Subsurface water movement is governed by fundamental material properties such as porosity, permeability, transmissivity, plant available moisture, depth and structure. These fundamental properties vary non-systematically between subsurface strata. Such data are available at local scales in some continents, but are not routinely available at a continental to global scale. While it is possible to identify in conceptual or modelling terms the required inputs to a generic hydrological model, the data do not exist in the required form at the level of spatial resolution required. These properties can be inferred from map sources such as geological and soils maps, but such sources only provide information about a limited part of the subsurface system. A substantial part of the regolith remains undescribed, because it falls outside of traditional classifications of the subsurface. For a general hydrological model, the horizontal stratification of the below-surface component of the hydrological system must be based on functional properties. Boundaries should be delineated by major changes in fundamental properties. The need for a total regolith survey of the fundamental properties is critical, and without active leadership by appropriate international

organisations the necessary data will not be available for modelling climate change and its potential impacts. The UNEP-GRID programme may provide the catalyst for such a development.

Even for those parts of the subsurface system that are described and mapped, the derivation of fundamental hydrological properties from described properties is a non-trivial task. Soil maps typically provide information on soil type and depth, and qualitative estimates of texture, soil temperature regime and soil water regime. They do not provide data on water-holding capacity, rooting-zone depth or other fundamental hydrological properties such as porosity, transmissivity or erodability. Such data may be estimated from soils maps but only in a qualitative or semiquantitative way.

The map source data of the upper functional hydrological layers (approximately, the soil) at global scales is at 1:5 million (FAO-Unesco World Soil Map), a scale vastly inferior to that available for topographic data. A global terrain and soils data base is currently being developed by ISRIC (SOTER) at a scale of 1:1 million.

Delineating groundwater basins is a difficult task. Hydrogeological maps and groundwater observation series with sufficient detail are not available for various regions and are badly needed. Information on the storage capacity of the source areas of runoff components and on the time (storage) constants can be obtained from a continuous long-term analysis of historical hydrographs, using a conceptual hydrological model combined with a water-balance procedure.

3.4.3 Vegetation attributes important for hydrological modelling

A dynamic, continental-scale, mechanistic hydrology model will require definition of the cover and biological activity of vegetation

similar to that required by the terrestrial ecosystem (see Section 2). For instance, a satellite derived leaf area index would be important in defining canopy interception capacity, the major source of partitioning between physically controlled evaporation and physiologically controlled transpiration. The seasonal leaf area turnover to litter will help define the litter surface-interception capacity and the surface-infiltration capacity. In addition, we suggest that the seasonally dynamic rooting depth may be better inferred from the satellite NDVI than from soil maps. However, a problem with this is that NDVI must be translated into LAI, and the relationship is different for plants with structurally different canopies. Bi-directional reflectance models may help in solving this problem.

3.5 Climate Data Requirements for a GHM

The main variables required to describe the forcing functions in the hydrological cycle are:

- 1) *Precipitation*. In many parts of the world the rainfall network is not adequately developed and instrumentation far from unified. Daily values are generally available, although simulation should be based on precipitation events. There is a need to develop effective methods to identify the spatial variability of rainfall distribution, based on the combined use of ground observation and remote sensing (see also Section 2.3). WMO and FAO should be approached to obtain updated information on recent achievements suitable for modelling purposes. Hopefully, difference between rainfall and snowfall regionally can be identified by using temperature measurements. Inadequate methods exist for the assessment of fog-drip and horizontal precipitation, which in some regions contribute significantly to the total precipitation.

2) *Potential Evaporation*. Potential evaporation data are a necessary model input for any regional or continent simulation. Calculated values would be best for regional estimates. However, in some parts of the world where the necessary meteorological observations are not available (i.e., solar radiation data are lacking) direct measurement may be temporarily adequate for the regional analyses. Unified types of instrumentation, preferably class A pans, are recommended for such a purpose.

The following data are most important for the calculation of potential evaporation:

- air temperature - mean daily maxima and minima records;
- humidity - an important input for the calculation of potential evaporation, but available instruments are not accurate. Attention should be given to the development of improved measuring methods; in the meantime, values based on dew point data measurements have to be used;
- solar radiation - a crucial input, but the present observation network is inadequate. Remote sensing methods should be exploited;
- wind speed - a less important input, but becomes important when values in excess of 200 km/day (average 2.3 m/s) are reached. Improved instrumentation is desirable.

3.6 Hydrological Model Testing and Validation

GHMs must be tested against data in order to place confidence limits on projections of future hydrological changes. Modern observational data on changes in various components of the hydrological cycle can be used for testing. River discharge measurements, which are collected on a regular basis on a fairly wide network, could be used. An international

effort would be required to coordinate data collection and to develop a readily accessible computerised runoff data base. Changes in the other elements of the hydrological cycle (e.g., lake levels, snowpack extent, extent of continental glaciers) are not as regularly monitored. Satellite observations could be used to monitor some of these (e.g., lake levels by radar altimetry). Currently, the HAPEX of WCRP is designed to validate hydrological models at the catchment scale.

An alternative approach to testing GHMs is to use palaeohydrological data. Quaternary palaeohydrological data show how individual elements of the system have actually responded to known changes in global boundary conditions. Thus, palaeohydrological data provide a powerful means of testing simulation models. The approach here is analogous to the use of Quaternary palaeoclimatic and palaeohydrological data to test general circulation models (e.g., COHMAP Members, 1988). Recent advances in palaeohydrology have produced a battery of techniques for reconstructing Late Quaternary changes in the hydrological cycle, including changes in lake levels, river discharges, groundwater recharge, glaciers and ice sheets, the extent of permafrost, and soil and biospheric moisture. It should be possible to make quantitative estimates of changes in the different components of the hydrological cycle.

3.7 General Recommendations

There is a need for a hierarchy of mechanistic hydrological models, ranging in scale from river-basin models up to global models. Considerable effort is already being invested in the development of small-scale models.

Recommendation:

The development of mechanistic continental- to global-scale hydrologic models which incorporate vegetation variables parameterized

from spatially explicit regional level vegetation models must be given high priority.

We believe that the development and testing of continental to global-scale models is likely to be hampered by lack of data on fundamental, hydrologically-relevant properties of the land surface and regolith. These data are also important to modelling efforts at the local to regional scale.

Recommendation:

High priority must be given to:

- *the development of a global topographic data base which specifically includes local base level information;*
- *the development of data bases on fundamental hydrological properties of the regolith and bedrock;*
- *the development of a consistent, integrated surface meteorological data base.*

It is not necessary to set up new meteorological stations, but an international effort must be made to maintain existing meteorological networks, to ensure standardization of measurement techniques, to coordinate data collection, and to develop methods for disseminating meteorological data more efficiently.

Recommendation:

Support Global Runoff Data Bank Development.

The Federal Republic of Germany has begun to collect and archive data on a computerized base in the Global Runoff Data Bank as charged and supervised by the WCRP. The IGBP should strongly support this effort and recommend that a joint WCRP-IGBP group be established to advise the data-bank group with respect to the required output and to

inform the scientific community about available products

Recommendation:

There is a need for hydrological models at landscape to regional scales to use, or translate to, the same variables and parameters as those used in the SVAT and Local Climate Simulator models which are used for ecosystem modelling (Section 2).

Recommendation:

Encourage the development of data bases of Late Quaternary palaeohydrological changes (e.g., lake-level changes, groundwater regimes, river discharge, glacier and ice sheet fluctuations, extent of permafrost) for testing general hydrological and vegetation models.

4. Biogeochemical Cycles and Element Transfers Relevant to Global Change

4.1 Introduction and Issues

During the workshop, a subgroup of participants was assigned to assess the state of knowledge of a number of biogeochemical issues that seemed to be of global importance.

Major changes to the Earth system have and are taking place in major biogeochemical cycles of H, C, N, O, P, and S. Examples include acid deposition; atmospheric increases in CO₂, N₂O, CH₄; stratospheric decreases in ozone; and tropospheric increases of ozone. Localized land-use changes are now having major impacts on major biogeochemical cycles via redistribution of key nutrients by processes of fertilization, harvest, and recycling of residue; e.g., development of wetland rice agriculture, biomass burning,

forest deforestation, cropping selection, expansion of animal husbandry. Landscape changes are also affecting relocation of nutrients within, and export out of watersheds.

These are observed changes. Some of the predicted global changes associated with climate change, land use change and further alteration of atmospheric composition are likely to magnify most of the biogeochemical processes already observed and possibly stimulate some processes not yet of concern. Planning efforts by the IGBP on biogeochemical processes must take into account both presently recognized issues and attempt to foresee new issues that may emerge in the decades to centuries ahead.

A research effort consisting of process studies, field research, modelling, and monitoring on the ground and from space is needed to develop an understanding of fundamental controls of processes and estimation of their rates. Ultimately, this understanding must be translated to predictive capacity.

This section does not attempt to design such a programme but seeks to highlight major issues and attempts to cover gaps that might not otherwise be identified by Coordinating Panels with responsibility for specific global zones, e.g., ocean, atmosphere, and terrestrial biota. The issues addressed below are in some cases well known from earlier and current activities of SCOPE and other organizations; This section merely up-dates the status of knowledge of them. Other cases may truly be new considerations. Certain issues are not discussed here since they are dealt with in greater detail by other IGBP Coordinating Panels. Specifically, the biogenic trace gas issues are being reviewed by the IAMAP/CACGP project (IGAC) and the SCOPE project on trace gas emissions. The recommendations from these two projects will be fused into a single research plan which defines the IGBP Core Project dealing with

interactions between the atmospheric chemistry and the biosphere. The final section of this report makes recommendations for how these issues might be addressed through core project organization by IGBP.

4.2 Major Biogenic Elements

4.2.1 Carbon - The global cycle

The important reservoirs of the carbon cycle, on time scales of up to 10^9 years, are the atmosphere, the ocean (including the marine biota) and terrestrial biota and soils. By far the largest of these is the ocean (40,000 GT); the remaining reservoirs atmosphere (700 GT), terrestrial biosphere (600 GT) and soils (1200-1500 GT) are of comparable magnitude. The following discussion is organised by considering these three reservoirs. The man-made CO_2 increase is superimposed on a complex global natural cycle, which exhibits its own natural fluctuations, so that for studying the anthropogenic change it is indispensable to consider also the natural carbon cycling and its variability.

The Ocean

Atmosphere and ocean are linked by air-sea gas exchange, which is controlled by the turbulence conditions near the interface. The way in which gas transfer depends on wind speed and other conditions is not adequately understood and requires further field and laboratory studies. It should be possible in the future to compute gas exchange fluxes with high spatial and temporal resolution, based on synoptic global wind fields obtained from satellite data. For this purpose, measurements of oceanic and atmospheric pCO_2 are needed. Surface water pCO_2 varies in time and space. It would be highly desirable to have a monitoring system for this property.

The ocean circulation determines to a large degree the oceanic uptake of anthropogenic CO_2 , especially its vertical component, and the

coupling to the deep ocean, which represents the major ocean carbon reservoirs. Uptake of CO_2 has been studied in the past mainly by means of simple models which are calibrated by means of tracers, such as ^{14}C and transient tracers like tritium. Such models have serious shortcomings. They cannot reproduce in a realistic way the spatial variability of vertical ocean mixing. And, perhaps more important for global atmospheric CO_2 , they cannot be used for studying feedbacks between climatic change, ocean circulation and the carbon cycle. These questions must be addressed using 3-D ocean circulation models or even coupled 3-D atmosphere-ocean models. The further development of these research tools is therefore of first priority.

Existing 3-D ocean models allow detailed studies of the role of biological, chemical and physical processes on CO_2 uptake. They have serious problems, with respect to vertical water exchange processes. Simulations of the present state and prediction of future trends without inclusion of feedbacks are not yet more realistic than those of adequately calibrated simple models. However, they can be applied to study climate feedback processes. This is particularly important in view of the increasing evidence of a strong sensitivity of the deep ocean circulation to relatively small changes in atmospheric forcing. A whole hierarchy of ocean models, to be used according to the specific problems addressed, is and will remain necessary. A special challenge is the development of models of intermediate complexity that include dynamics.

Radioactive isotopes (like ^{14}C) and transient tracers are an important basis for verifying the performance of 3-D models. Their distribution provides an integrated picture of the processes that are responsible for the uptake of man-made CO_2 . The progressive penetration of transient tracers (CFCs, bomb-produced ^{14}C and tritium, etc.) into the ocean represents a unique observational

opportunity. The marine biota play a very crucial role in determining the CO_2 chemistry of the surface waters, by providing a biological pump transporting carbon and nutrients to deep waters in particulate form. The atmospheric CO_2 concentration is directly controlled by the surface ocean water composition and thus by the interplay of biological, chemical and physical processes. In large areas, marine productivity is limited by nutrients. Thus, the cycles of C, N, P and O are directly linked by biological processes.

The modelling of marine biological processes in the context of the global carbon and nutrient cycles is still in an early stage and requires much work. Bioproductivity is rather heterogeneous in space and time and depends in a highly non-linear way on nutrients, light, stratification, etc. as well as on ecosystem composition and competition. Models of marine ecosystem dynamics must be developed to describe how it will react to changing climate or ocean circulation. They must have appropriate degree of complexity (e.g., number of trophic levels) to be tractable in a global 3-D ocean model. This is the necessary framework for achieving required high temporal and spatial resolution.

The Joint Global Ocean Flux Study (JGOFS) is a field programme that will obtain detailed results on fluxes of carbon (and nutrients) due to biological activity. Satellites are providing data on chlorophyll concentrations that should be linked in the future with biological productivity, based on surface observations. These only begin to provide the information required to understand the impacts of global change on biogenic element cycling.

Human activities are resulting in a large amount of phosphorus being delivered via rivers to coastal waters. It is not known whether this results in globally significant amounts of organic carbon being sequestered by enhanced sedimentation, thus providing a sink counteracting the CO_2 increase. It is

necessary to distinguish between anthropogenic perturbations and natural fluxes to solve this problem. Natural fluxes are large in coastal areas. It is also necessary to distinguish between increased productivity and (not necessarily increased) sedimentation rate. A similar process of unclear significance is the possibly increased river transport of dissolved and particulate carbon to the sea and its fate in the ocean.

Ice cores are providing valuable information on past variations of the atmospheric composition, of CO₂, CH₄ and N₂O. This data may provide information on pre-industrial levels of these gases and their variability. The observation that CO₂ fluctuations during the last 160,000 years are highly correlated with climate fluctuations, and in particular that CO₂ increased parallel to the temperature increase from glacial to post-glacial time, has enormously stimulated the research on the natural carbon cycle. Deep-sea sediment studies have yielded isotopic and other data on changes in the oceanic carbon cycle. These palaeoclimatic observations have thus contributed in an essential way to the present understanding, and they continue to play an important role in research on global change.

The Land Biota and Soils

CO₂ emissions due to deforestation and land use are known only with large uncertainties. Based on satellite data, it should be possible to get reasonably good estimates of the changes in carbon storage resulting from deforestation. In addition to the satellite pictures, ground-based data and ecosystem succession models are required.

The atmospheric CO₂ increase may be counteracted by CO₂ fertilization, i.e., growth stimulation by elevated CO₂ concentration. On the other hand, there may be feedbacks from climatic change to the biological carbon cycle, such as increased soil respiration due to warming or a changed net fixation of carbon.

A difficult step is the translation of laboratory results to the ecosystem level. Field measurements as well as work on ecosystem models are necessary.

The Atmosphere

There is a relatively large network of CO₂ monitoring stations, which is certainly sufficient to document the global concentration increase. Atmospheric transport models can be used to infer exchange fluxes between the surface and the atmosphere from atmospheric CO₂ and other data. This includes the natural air-sea and atmosphere-vegetation exchange as well as tropical deforestation. For these applications, more monitoring stations in the interior of continents would be desirable. The atmospheric transport models require as an input global data such as satellite-based vegetation index and oceanic wind fields. But the limited spatial resolution of these data means that differentiation between oceanic and terrestrial sources/sinks may not be possible. Stable carbon isotope measurements are important to add the spatial component, since biospheric CO₂ is clearly labelled by low ¹³C/¹²C ratios, in contrast to CO₂ of oceanic origin. Research topics which should be pursued in the effort to clarify these relationships include ENSO-related CO₂ variations, due to land-biospheric changes and/or variation in ocean surface waters, and changing seasonal CO₂ amplitude suggesting an effect of CO₂ fertilization.

4.2.2 Biogeochemical cycles of N and P

Nitrogen and phosphorus are involved in biological and abiotic transformations. Both are increasingly affected by human activities. A large body of knowledge and ongoing studies exist on the transformations of N and P, and the following only lists those areas which are incompletely understood and of relevance to the global change issue.

Nitrogen

A major portion of the environmental N flux is anthropogenic and related to the use of N fertilisers in agriculture, or to animal production. Nitrogen availability to crops is linked to the global CO₂ production through the decomposition of organic materials including soil organic matter from which N is mineralized, and through the manufacture of N fertilisers with fossil energy. The relative importance of the two links varies with regions and cropping systems and needs to be quantified. This can partly be done with existing information. New research is also required. The effects of agriculture, forestry and land clearing in the mobilisation of N in the environment have been quantified for some regions. Groundwater contamination is well documented for Europe, but the introduction of N into ground- and surface-waters is incompletely documented for other regions. The large scale shipping of fertilisers, food and feed plays an important role in the changed distribution of N discharges into the environment.

The potential for eutrophication of surface waters, including coastal seas, needs to be considered, and management strategies must be studied. This is particularly important for population centres in less developed regions, where controls on discharges are often minimal, and where traditional recycling methods have been abandoned. Of particular interest are the interactions and relative importance of N and P for the eutrophication of surface waters. The control of N on eutrophication may have a different time scale than that of P, and the relative roles of the two elements need to be examined with respect to the potential CO₂ sink that eutrophying coastal seas represent.

Terrestrial N fluxes in many tropical ecosystems are incompletely understood.

Examples are:

- N losses and their effects on water quality from rice production areas;
- N losses and their impact from slash-burn agriculture, which not only liberates N to the atmosphere during burning, but also leads to massive N mineralisation during the period of organic matter degradation.

A major area of interest is the accretion of N in bush fallow or other aggrading systems, such as re-establishing forests. The actual effectiveness of native legumes and other N fixers in unmanaged aggrading ecosystems is barely known, and needs to be studied.

Phosphorus

Most long distance transport of P is anthropogenic. Shipping of fertiliser P and of feeds cause major accumulations of P in consumer regions. At the same time, many animal feeds are produced in tropical regions, where P availability is severely limited. This situation leads to a global imbalance of P distribution with eutrophication and disposal problems in some regions and deficiencies in others. The quantities of P involved in this redistribution process should be relatively easy to quantify. These should be set in relation to the P supplying potential of tropical producer regions, and to the capacity for P sorption in the accumulator regions. Similar patterns of redistribution may exist on a local scale, and will need to be addressed.

The potential of soils or sediments to sorbe or scavenge P from the environment is incompletely understood. Eutrophication of surface waters may lead to immobilisation of P in sedimenting detritus. Thus, P is linked to the CO₂ sink function of waters. The reversibility of P sorption to soils and sediments is a main issue that needs to be quantified. This is important for agricultural

production, which depends on limited P supplies, but also for the effective disposal of P in the main accumulator regions.

Insufficient information is available on the redistribution of P in landscapes. Increasing erosion and sedimentation, and increased surface flow of water and particulates as a result of agricultural activities leads to significant redistribution of P in landscapes. There is some evidence that vegetation structure, such as riparian belts, and patterns of mixed agriculture have a major effect on the distribution of P in landscapes, but much more information is required.

The quantification of the role of diffuse P sources in the environment is insufficient, particularly since rates of P releases from natural weathering are not known for many regions. The role of fires in the liberation and redistribution of P needs further work, particularly in view of the importance of fires in P deficient tropical forests. And as mentioned above, the interactions of N and P, and their relative importance in limiting ecosystem productivity and eutrophication require closer study.

The parts of the study of biogeochemical cycles that involve trace gases (NO, N₂O, CH₄, CO, etc.) will be covered by the IGBP Core Project, IGAC.

4.3 Erosion and Deposition as Phenomena of Global Change

Transport of mineral matter by fluvial and aeolian processes is a natural phenomenon. Over scales of eons and continents, weathering, erosion and sedimentation are roughly counterbalanced by tectonic and volcanic processes that renew the land and compress the sediments. Over scales of millenia and landscapes, weathering rates may roughly match erosion rates so that the

solum at a position on the landscape is more or less in equilibrium. But at time scales of years, changes in rainfall intensity, drought periodicity and in plant cover can accelerate or decelerate erosion, changing the balance with weathering rates. Solum depth and quality will be altered, transported materials will accumulate faster or slower in basins of arid or semi-arid landscapes, in river channels and in off-shore sedimentation zones, thereby altering structure and function of these ecosystems.

Aspects of global change - climate and land use particularly - will directly and indirectly change rates of erosion and deposition of soil and regolith materials (Goudie 1982, 1989). These land surface processes will change as a function of new weather patterns, vegetation cover and position on slopes and hydrological gradients, all of which will be functions of geographic location. For example, conversion from tropical forest to cropping systems will accelerate erosion of top soil downslope and into riverine systems. Desertification or increasing fire frequency will accelerate wind-driven denudation and subsequent dust deposition downwind. Rising sea levels will alter patterns and positions of sedimentation along shorelines and in the mouths of rivers.

4.3.1 Controlling factors

Erosion, and hence, sediment delivery has been expressed generally and in more detailed, empirical form. Erosion per unit area is expressed at one level of generality with this simple equation:

$$A = RK(LS)(VM)$$

where:

- A = soil loss per unit area
- R = rainfall factor
- K = soil erodability factor
- LS = slope length factor
- VM = vegetative mechanical factor.

Of course each of these parameters will be, in turn, functions of other aspects of climate,

geological substrate, history, regional geomorphology, fire frequency and land use.

This equation is particularly designed for fluvial erosion; analogous models exist for eolian erosion. On the opposite end of the process, geomorphological models, both terrestrial and marine, exist for deposition and sedimentation.

Changes in climate, land use and vegetation via chemical composition of the atmosphere will undoubtedly influence rates of sediment production and deposition, both fluvial and eolian. This heuristic view illustrates how regions that become effectively drier through increases in temperature will probably have less plant cover and will be more susceptible to fluvial and eolian transport through high intensity storms or strong winds. Regions that become more moist may undergo less erosion so that soil mantles become effectively deeper. Outcomes will depend on the relative importance of factors indicated in the simple equation. Semi-quantitative expressions of how sediment delivery may change with changing precipitation regimes and land cover conditions can be expressed. For example, average precipitation amounts might remain the same, but changes in frequency distributions of precipitation rates could make big differences in erosion and deposition. Erodibility could similarly be affected by the regularity or frequency distribution of precipitation, land use, fire frequency or many other factors susceptible to change. Effectiveness of precipitation will be, of course, partly a function of temperature (Chorley *et al.* 1989). Time lags will also complicate predictions of change (Chorley *et al.* 1989).

4.3.2 Implications

Erosion and deposition processes are likely to be altered in rate and kind by anticipated changes in climate and land use. These

alterations are likely to be significant for terrestrial, aquatic and marine ecosystems in large parts of the globe. Perhaps the most obvious implications are for soil processes and how they might alter productivity of natural and agricultural vegetation, but also for biogeochemical processes such as trace gas efflux or dissolved and particulate transport (Reiners 1983). Also of special concern, however, is dust transport, another manifestation of erosion (Morales 1979, Pewe 1981). Besides being important as a transport mode of essential nutrients and mineral soil components, dust particles can effectively scatter light at short wave-lengths, much of it upward. Soil dust may significantly affect the input of solar radiation globally including the sea surface, thereby modifying sea surface temperature, a vital factor in climate. Dust loading may also effectively decrease photosynthetically active radiation (PAR) as well as surface temperature. Thus, if global change in some regions were to increase the movement and long distance transport of dust, it might act as a negative feedback to the anticipated increases in global temperature and, in general, moisture caused by increases in CO₂.

Processes underlying the phenomena described here are generally understood and process models at various degree of generality exist in the several disciplines involved. They are amenable to systematic study and predictive modeling on large scales (but see less hopeful note in Wasson *et al.* 1988). Inputs and outputs to and from these models will be important to other global change models and many of the processes are observable by remote sensing methods (e.g., Ackerman 1989).

4.4 Minor Elements

There are a number of elements, mostly transitional metals, which are either required for life in small amounts, or by their

similarity to essential elements, act as toxins. These include Fe, Mn, Co, Mo, Zn, Ni, Cu, Cd, Pb, Hg, As, Sn and others.

Biologically "essential" elements may be rate-limiting under some circumstances so that local or regional increases in the major biogenic elements (C, H, N, O, P, and S) would not produce the predicted ecosystem response because of trace element limitation. For example, it appears that nitrogen is limiting to phytoplankton growth in the short-term in most parts of the oceans but that phosphorus is limiting everywhere in the long term. The factor underlying this disparity may be molybdenum. Molybdenum is the crucial metal in the enzyme for nitrogen-fixation nitrogenase. If phosphorus is locally available in space and time, molybdenum availability may be the rate limiting factor inhibiting nitrogen-fixation so that nitrogen is, at least temporarily, limiting.

This scenario is controversial but illustrates the need to have competence in trace element biogeochemistry in IGBP projects where needed. Presumably, biogeochemistry research plans emanating from CP 1, CP 2 and CP 4 will highlight such needs.

Other elements that usually are at low concentration in soil, aquatic and marine solution media (but abundant in the lithosphere) may be toxic through their chemical analogy to essential elements. Further these may be locally abundant naturally through geochemical anomalies, or, more commonly, through anthropogenic sources. Cadmium, excessive zinc, nickel and lead are often products of mining and smelting. Lead is widely disseminated as a fuel additive and in paint. Arsenic is associated with some fertilizers and certain industrial products.

Most concern for these so-called "trace" or "heavy metal" problems stem from human

activities. They typically are subregional in scale but can involve global economics. The driving economic forces that lead to metal mining and extraction may come from remote areas of the globe. These toxic aspects of trace elements should not be an IGBP concern unless social science programmes emerge in IGBP or tandem with IGBP research plans. In that case, we recommend that a biogeochemical component of toxic elements be allied with those mainly sociologic-economic issues.

4.5 General Recommendations

4.5.1 Global modelling

Virtually every concern for global change, whether it be of climate or UV-radiation, involves biogeochemical cycles. Fortunately, these cycles have received extensive attention through efforts of SCOPE and other organizations in the last one to two decades. Much has been learned about biogeochemical cycles, but much more needs to be understood to construct the global scale models necessary to make predictions on the scale of decades to centuries. One of the pervasive concerns of the group preparing this report is that excellent biogeochemical projects are being planned at the level of oceans, atmosphere and land, but it is not clear how these projects would be integrated across these spheres or how global scale models would be constructed. The logical planning group for this last concern is the recently constituted CP 5. Therefore, the first, perhaps unnecessary, recommendation of this working group is:

Recommendation:

Coordinating Panel 5 adopt responsibility for integration of biogeochemical projects planned by the other Coordinating Panels across spheres of particular interest.

4.5.2 Carbon cycle

More specific issues have to do with continuing problems of estimation for key processes. The carbon cycle remains central for understanding how the planet functions. Topics relating to the carbon cycle are listed below under one recommendation:

Recommendations:

- Continue improvement of estimates of carbon stored in various forms in the ocean and on land (CP 2, CP 4).
- Encourage continued improvement of ocean circulation models (WCRP).
- Continue improvement of estimates of fluxes of carbon through various physical and chemical compartments of the ocean (CP 2, CP 4).
- Continue improvement of understanding of the spatial/temporal variation in rates of biological uptake and release of carbon and the factors underlying these dynamics (CP 2, CP 4).
- Exert special efforts on the role of human activities in near shore areas on nutrient enrichment and consequent effects on biotic incorporation of carbon (coastal zone study needed).
- Foster development of historical data in ice cores and other historical records, and the development of stable isotope discrimination methods for inferring the sources and fates of atmospheric CO₂ (SSC).
- Maintain measurements of CO₂ in the atmosphere at adequate intervals and geographic positions.

4.5.3 Nitrogen and phosphorus

Nitrogen and phosphorus are most frequently the limiting nutrients regulating energy flow and cycling rates of other elements, particularly carbon, in sectors of cycles

dominated by biological processes. We believe that major processes regarding these elements are receiving adequate attention within the Coordinating Panels with the possible exception of the marine sphere. In the recommendations below, only processes that may have been omitted are listed. Many of these are not global in extent or even pervasive within sectors of land or sea. Nevertheless we offer them for consideration as "tactical target" studies.

Research on interactions between nitrogen and phosphorus in the context of episodic events like fires and major storms at the landscape level are badly needed. Such landscape level biogeochemistry is highly recommended (CP 4).

Recommendations:

Massive fluxes of both nitrogen and phosphorus are occurring in regional scales based on trade in agricultural commodities. In general, these are leading to highly eutrophied regions that are influencing groundwater and near shore marine systems. This phenomenon involves world-wide transport but along very discrete pathways. A study involving social scientists and biogeochemists on the extent, distribution and impacts of these phenomena might yield interesting and important results out of proportion to the masses of material involved and expense of the project.

4.5.4 Erosion-deposition

An issue perceived by many observers of global change, but somehow undeveloped in IGBP planning has been the change in mass movement of dissolved and especially particulate substances by erosion and their subsequent redistribution in waterways and near shore areas. The following recommendation is for a new planning effort and is therefore more detailed than for the others.

Recommendation:

Develop a research project on fluvial and eolian erosion and deposition to produce models for predicting change in these phenomena at continental and regional scales.

This project should develop in interaction with research programs on other global phenomena leading to the joint production of coupled models to help predict the interactive influences of climate and land use change.

This project should have strong linkages with the land processes and remote sensing community, and the terrestrial ecosystem (CP 4), land-atmosphere (CP 1), marine-atmosphere (CP 1), hydrology (CP 3) and modelling (CP 5) planning components of IGBP. The general hydrology model proposed in Section 3 would be an essential "driver" and companion effort to this project.

IGBP should ally itself with other organizations having interests in this subject. For example, the International Soil Science Society has and is organizing a number of workshops on impacts of global change on soils, including erosional aspects. The U.S. NASA program EOS (Earth Observation System) includes four hydrology components, each of which could be important to such a project. A symposium on "Coastal geomorphology, littoral drift, climate

development, greenhouse effect, sea level rise and its consequences, erosion and production" is being organized by the Journal of Coastal Research and the Skagen Pit Project of the Scandanavian countries. The ECHIVAL project (European Climate Hydrological Programme on the Interaction of Vegetation, Atmosphere and Land Surfaces) will include an erosional component in its focus on desertification of parts of Spain. Presently available process models for erosion and deposition need to be built into terrestrial and coastal marine ecosystem models. No particularly new technologies or models need to be invented. The task is one of coupling and coordinating these components. Such a project will significantly enrich the predictive powers of other sectors of interest in global change. This proposal is eminently suited to relatively swift implementation.

4.5.6 Minor elements

As stated in the main text on the topic of "minor elements", we do not believe that an IGBP project on this subject is appropriate. We recognize their importance from a "metabolic" and "toxicity" points of view and assume that all IGBP projects involving relevant biogeochemical studies will also recognize this. To the extent deemed necessary, SCOPE may play a key role in providing new information as needed for IGBP projects.

5. Overall Recommendations

A number of issues continue to surface whenever IGBP Coordinating Panels meet. The intent of this workshop was to specifically address those issues which are important to CP-3, CP-4, and CP-5 in the areas where their investigations overlap. The joint issues were clarified. In addition, new issues were raised and many of those overlapped with topics of interest to Coordinating Panels which were not at the Brussels meeting. The recommendations which must be addressed by all participants in the IGBP are presented in this Section together with general comments and recommendations which overlap the activities of CP-3, CP-4, and CP-5.

1. All IGBP Coordinating Panels should interact in terms of their modelling efforts. CP-5 should take overall responsibility.

There is overlap of modelling issues among all the IGBP Coordinating Panels. It is essential that IGBP does not degenerate into a series of disparate, partial modelling efforts which cannot be linked. CP-5 should take overall responsibility for ensuring that there is constant, detailed communication and collaboration. It is also necessary to ensure that the efforts of the Working Groups are integrated into this coordinated effort.

2. IGBP needs to define "global change" for all of its overall objectives.

Definition of exactly what IGBP understands to be "global change" is suggested for each of the overall objectives. This definition will make possible decisions about what needs to be measured and what can be measured for modelling, monitoring and the underlying basic research.

3. Throughout IGBP there is a need for "independent" validation of modelling efforts.

Independent corroboration of models through validation and testing is necessary to establish the credibility of the models to forecast global change. The only alternative, "wait and see", is not acceptable. However, independent validation will require a definite strategy and widespread cooperation based on monitoring and experimentation. The collection of appropriate data will assume great significance. This must be given high priority.

4. CP-3 and CP-4 must ensure that each can use and contribute to projects of importance to both, including:
 - a. Development of "generic" ecosystem model.

As discussed in Section 2, the development of generic ecosystem models is of prime importance. It is presently hindered by a lack of information about the translation of information across scales within the proposed models, a lack of complete understanding of the necessary components needed to address the problems of global change (see two above) and a lack of coherence between extant models of smaller scales. Development is possible and should be given high priority. The first step in this effort is the development of regional models.

- b. Parameterization of SVAT models.

Simple Vegetation Atmosphere Transfer models (Section 2) are needed to create the vital upward link between the atmosphere and terrestrial and hydrological processes (Section 3). The boundary parameters which are appropriate for a SVAT model must be specified with care so that the transfer between terrestrial/hydrological systems and the atmosphere is coherent at all levels.

Without an accurate SVAT model to feed the climate models biogenic feedback to the atmosphere is lost as is the accuracy of information transferred along the loop from the atmosphere to the ecosystem.

c. Development of "local climate simulators"

The local climate simulator (Section 2) represents the other half of the loop downward between the atmosphere and hydrologic and terrestrial ecosystems. These models would provide temporal frequency distributions of climate parameters. A local climate simulator is not currently developed. Its development is paramount for understanding and predicting the effects of climate change on ecosystems. Developing such a model is possible with cooperation between terrestrial, hydrological and atmospheric modellers.

d. Development of general hydrologic models

High priority should be given to developing mechanistic general hydrologic models (GHMs). These models would be used to investigate the response of the system as a whole to changes in external boundary conditions under global change scenarios. Critical processes necessary for the GHMs are identified in Section 3. Development of these models is hampered by a lack of data on fundamental, hydrologically relevant properties of the land surface and regolith.

e. Prioritization, development and accessibility of necessary data sets.

Lack of data was found to be a crucial issue for the development of all the major recommendations of this workshop. Among the major requirements are:

- A better global map of land cover to provide input to all levels of modelling and monitoring (100 km scale).
 - Topographic and bedrock level global data bases for hydrological modelling.
 - Coordinated global data bases of fixed surface parameters needed for monitoring global change (10-km scale).
 - Global data bases of satellite-derived weather data appropriate for input to ecological and hydrological models.
5. IGBP should address biogeochemical cycling and mass-transport issues.

Biogeochemical cycling and mass transport are important aspects of global change, which are of great concern for all IGBP research areas. A combined workshop of representatives from all five CPs is necessary to specify the scope and objective of the IGBP modelling effort in this area.

6. Model inter-comparison workshops are needed for all the appropriate levels of models required for global change studies.

CP-4 has identified the need for a "model intercomparison" workshop in 1993/94 aimed at comparing and integrating various ecosystem modelling approaches. The workshop would use common data sets to test the coherence between models at an appropriate level for global change studies. A similar target may be appropriate for other CPs. Following is a description of the CP-4 model comparison workshop.

The validation of global ecosystem models will require special attention, as it will not be possible to test their predictions directly against observed time-changes of the natural ecosystems. One feasible way of testing the models (if not the only way) will be to check

their ability to reproduce present conditions, especially in regions where strong gradients exist in both the climatic input conditions and the observed distribution of ecosystem composition and structure. Comparisons between models will have to be organized for two or three such regions with all input parameters (climatic and physical) prescribed from observations and key ecosystem-state variables measured as a "target".

As simplified SVAT models will be intimately coupled to ecosystem dynamics models to provide the interaction with the atmospheric climatic system, it will be necessary to organize the intercomparison of ecosystem dynamics models in such a way that the SVAT models should be run simultaneously, using the output from the ecosystem dynamics models, and the fluxes they predict should be checked for consistency against the input climatic conditions.

The intercomparison exercise should also address the question of the influence of subgrid-scale variability of climatic conditions (where subgrid is defined with reference to the grid size of atmospheric GCM) upon the outputs of both the ecosystem dynamics and SVAT models.

The proposed workshop would be held in 1993 or 1994 over a period of 7-10 days. During the workshop scientists would compare the output from different models, using common data sets from a few contrasting ecosystem types. The consequent modifications to and meshing of the various models developed up to that stage would serve as a major step in achieving a global ecosystem modelling capability.

The specifications of the models are in terms of required outputs. They should be able to simulate the response of an ecosystem to present climate fluctuation phenomena, and should be able to reproduce existing ecological

gradients at a sub-GCM grid-cell scale. The ecosystem changes should include both structure and function (including net carbon storage).

The common data sets should include at least three "core" sites, each of which should have a documented perturbation (e.g., a Sahel site, a tundra/taiga site with a millenia response to an earlier warm period, and a third site with a +/- century time-scale perturbation). The sites should preferably cover two GCM grid cell (c. 300x600 km). For each site the required data (at an agreed scale) would include such variables as:

- Map of the landscape units;
- For each unit-type terrain (slope, aspect); soil
 - profile description
 - texture, WHC, chemistry by horizon
- vegetation
 - physiognomic structure (density by size class)
 - composition by plant functional types (PFTs)
 - rooting depths of PFTs
 - potential growth rates, longevities, temperature, water responses of PFTs (the level of detail needs further discussion)
- climate
 - daily weather over three years (including statistics on storm depth and intensity)
 - monthly statistics over 50 (?) years (including a perturbation).

The data sets would be distributed well in advance of the workshop, and processed by the modelling groups. The workshop would begin with a comparison of model results and would then proceed to compare results using successively coarser "samples" of the data sets, and so forth.

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8. Glossary of Acronyms

SOTER	World Soils and Terrain Digital Data Base
BAHC	Biospheric Aspects of the Hydrological Cycle
ECHP	European Climate Hydrological Programme on the Interaction of Vegetation, Atmosphere and Land Surfaces (The ECHIVAL project)
EOS	Earth Observation System
ESSC	U.S. Earth System Sciences Committee
GAIM	Global Analysis, Interpretation and Modelling
GCM	General Circulation Model
GCTE	Effects of Climatic Change on Terrestrial Ecosystems
GHM	Generic Hydrological Model
HAPEX	Hydrologic Atmospheric Pilot Experiments
ICAO	International aviation charts
ICSU	International Council of Scientific Unions
JGOFS	The Joint Global Ocean Flux Study
LAI	Leaf Area Index
NDVI	Normalized Difference Vegetation Index
PAR	Photosynthetically Active Radiation
PFT	Plant Functional Type
SVAT	Soil-Vegetation-Atmosphere-Transfer models
WCRP	World Climate Research Programme

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