Integration of geodetic techniques into a global Earth monitoring system and its implication for Earth system sciences

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Abstract

The increasing vulnerability of infrastructure and human lives particularly in areas of the Megacities as well as the broad acceptance of sustainability as guiding principal for societal development is putting new emphasis on global processes and the associated geophysical variability and global change. In Earth system studies, the need for integrated data sets is increasingly obvious, both for observational studies of system processes and the validation of integrated system models. Though rapidly improving, the current scientific knowledge of the Earth system with respect to the main processes, the key indicators and the major forcing factors is still limited. Therefore, a more or less complete monitoring of the system's state and trends is mandatory if a valuable contribution of global monitoring to environmental security and sustainability is to be expected. Thus, integrated global monitoring is a prerequisite for global environmental management of a sustainable Earth. Specialised global observing systems have already been initiated and partly are implemented (e.g. the G3OS, the Global Terrestrial, Climate and Ocean Observing Systems: GTOS, GCOS, GOOS). However, these systems are largely based on space-born remote sensing techniques, while investment in urgently needed in-situ measurements are smaller and often decreasing. Moreover, the integration of ground-based networks, data archiving and distributing facilities to provide integrated data sets of in-situ observations is still at its infancy. Space geodesy is now capable of monitoring variables of potential value for environmental monitoring systems. Moreover, in some of the existing networks, these techniques provide crucial auxiliary observations. It is therefore of fundamental value to fully integrate geodetic monitoring techniques into a global integrated Earth monitoring system, which is a significant step towards an Earth information system for sustainability. This integration should follow the Global Integrated Observing Strategy.

1 Introduction

The Earth appears to be a highly complex system where chemical, physical and biological processes are interacting in nearly all processes determining the system's state. Moreover, over the last few centuries, mankind has evolved to be a dominating factor shaping the Earth surface. Particularly the rapid growth in the number of human beings combined with the presently nearly unlimited availability of easy-to-exploit energy[1] has brought mankind to the position of being powerful enough to affect crucial system processes and eventually force secular change in the mean conditions of the Earth system. Therefore, human economic, social and psychological conditions are likely to have a significant impact on the future development of the system. In such a highly complex situation, it is difficult to predict in any respect, be it directly related to human affairs or more pertaining to the non-human part of the system. However, what can be said is that the big challenge for mankind in the next century is going to be the management of the human activities in a way increasingly approaching sustainable development.

The environmental debate taking place over the last thirty-five years can be characterised by a few milestones, which also illustrate a shift in focus over time. One of the early milestones was the ”resource-depletion debate” which is exemplified by the 1972 report of the Club of Rome (Meadows *et al.*, 1972). At that time, the size of the natural resources were seen as the major limitation for the growth of mankind and our economy.

The high social and political risks due to the geographically uneven access to sufficient resources influenced the United Nation's World Commission on Environment and Development in its 1987 report ”Our Common Future” to revitalised and globalised the concept of sustainable development[2] (World Commission on Environment and Development, 1987). This so-called Brundtland report marks a turning point to the ”sustainability debate”, after which the size of available resources were no longer accepted as the only constraint and limitation for economic activities. The normative concept of sustainable development brought ethical considerations into the discussion questioning our rights to deplete natural resources at will. The concept also challenged the basis for our economic theories, which up to then were all based on the assumption of nature being a free gift for humans [3].

The third milestone to be mentioned here is the recognition of another severe limitation to human activity: the capacity

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[1] For a discussion of the impact of the availability of low-cost energy on the recent societal development see Pfister (1995).

[2] The reports states that ”*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*”

[3] For a more detailed discussion of the influence of the concept of sustainable development on the current economic paradigms, see e.g. Ahmad *et al.* (1989).

of the Earth system to maintain a homeostasis favourable for human life under heavy anthropogenic interference with system processes. This limitation may be characterised by the "emission-reduction debate". Under the present level of emissions resulting from production, consumption and transportation, the risk of a change in the system's state to conditions unfavourable for human beings is apparent. Probably most prominent in the scientific and public discussion is the risk of climate change.

In this paper, we will first give a brief review of the sustainability and climate change debate with main emphasis on the relevance of Earth monitoring and Earth system science to progress. An analysis of the potential contribution of Earth sciences on the way towards sustainability is given in Section 3. On the basis of this analysis, the need for an integrated sustainable monitoring of the Earth system is underlined in Section 4. The potential contribution of geodesy to an Earth monitoring system is considered in Section 5. Finally, a possible way to overcome the deficiencies of the present monitoring as well as it interaction with research and assessments is outlined in Section 6. In the conclusions, a need is pointed out for an intergovernmental assessment of the emerging monitoring system as a guidance on the way towards an Earth information system for sustainability.

2 Sustainable development and climate change: a brief review

Currently, the global political dialogue is aiming at securing bearable if not favourable conditions for future generations. A major step was the Earth Summit in Rio de Janeiro, Brazil in 1992, which brought 135 countries and heads of states to Rio. There they signed the Framework Convention on Climate Change, the Framework Convention on Biodiversity, and the Agenda 21, which is a commitment to implement the objectives of the Earth Summit. After this Summit the concept of sustainable development has been widely accepted as the guiding principal for societal development, although its interpretation is not unanimous. The world community presently is in the state of operationalisation of the concept, and the ideas still range widely from dramatic lifestyle changes over simple conservation to "business as usual". In this process, the interdependence of the different dimensions of sustainability and the need for an integrated, interdisciplinary approach to the achievement of sustainable development becomes increasingly obvious.

Agenda 21 [4] clearly emphasises the need for information and a complete monitoring of the Earth system. Chapter 40 of Agenda 21 provides information for decision-making. The first paragraph states: "*40.1. In sustainable development, everyone is a user and provider of information considered in the broad sense. That includes data, information, appropriately packaged experience and knowledge. The need for information arises at all levels, from that of senior decision makers at the national and international levels to the grass-roots and individual levels. The following two programme areas need to be implemented to ensure that decisions are based increasingly on sound information:*

(a) Bridging the data gap;

(b) Improving information availability."

In particular, the need for the development of indicators of the system state is pointed out in paragraph 4 of the same chapter: "*Indicators of sustainable development need to be developed to provide solid bases for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems.*"

Thus, appropriate tools for the assessment of impacts due to human activities need to be developed as a prerequisite for determining the sustainability of these activities. It is the responsibility of the scientific community to provide such tools and to carry out the necessary assessments. In many national and international research funding programs, this is well reflected. The last decade has seen many activities aiming at the definition of geo-indicators [5]. However, research and monitoring is still not focussing sufficiently on identifying variables of indicative value and providing observations of the full set of these key variables.

A major thread for a sustainable development arises from potential climate changes, which in part are the consequences of a non-sustainable use of fossil energy resources. Recognising the potential risk for an anthropogenic climate change and the huge social and economic consequences of anticipated impacts, the WMO and UN in 1988 institutionalised the Intergovernmental Panel on Climate Change (IPCC), which in its 1990 Assessment of Climate Change and the 1992 Supplement (see references in Houghton *et al.*, 1996) provided an initial basis both for decision-making and research development. In 1996, the Second Assessment of the IPCC (Houghton *et al.*, 1996) summarised the current status with little indication that the risk of anthropogenically induced climate change had been reduced. Several countries initiated national committees to work out means to reduce the impacts of an anticipated global warming. Nevertheless, the scientific community is far from providing the required assessments of measures to the political decision-makers, as was well documented by the recent discussion of the agreement for CO_2-reduction, where no clear scientific statement on the contribution of forests in the Carbon cycle could be given.

[4] See gopher://gopher.un.org:70/00/conf/unced/English/ for the full text in English.

[5] For just one example, see the statement which originated at the International Workshop on Geological Indicators of Rapid Environmental Change, held on July 11–17, 1994, in Corner Brook and Gros Morne National Park, Newfoundland, Canada as published in Episodes, no1 & 2, 1994, p.2, where it is stated: *In order to assess the state of any environment, reliable indicators are needed, just as doctors use blood pressure and body temperature as simple, inexpensive guides to human health. Even if causes cannot be determined, we must be able to detect change and warn of dangerous conditions.*

3 Sustainable development: contributions of Earth sciences

As mentioned above, the problem of sustainability has a strong ethical and social component. However, once it is defined and accepted as a basic principle for human activity, sustainability acquires a crucial scientific component. The quest for sustainability puts the scientific community in a position comparable to the physician being ask to design a therapy that will keep a human being in a healthy state or that will restore healthiness in case of illness. Under this principle, any on-going or planned action needs to be assessed in terms of sustainability. This assessment can only be carried out on the basis of a profound knowledge of the Earth system, its processes, and its dominating factors. The contribution of science to sustainable development can be separated into at least two basic topics:

(1) to monitor the Earth system in order to give an indication of the system's state and trend; in this respect it is important to keep in mind that the key variables are still not clearly identified;

(2) to develop higher integrated Earth system models, which are required for the assessment of potential impacts of actions planned to bring the world society on a course towards sustainable development.

A basic prerequisite for the assessment of impacts is a system model designed to simulate the consequences of certain measures. Currently, the most advanced models represent subsystems in terms of the interactions, processes, regions and system components included. Thus, the physical general circulation models (GCM) simulate the circulation in atmosphere and ocean, but do not consider the interaction between chemical constituents and the circulation, i.e. so-called emission scenarios are used to force the circulation model. On the other hand, chemical transport model assume the circulation as given and simulate the distribution of the chemical constituents due to sources and sinks. Most of these models do not account for the biosphere and its interaction with the non-biological system components. Models of the biosphere are basically modelling the carbon transport in the biosphere or the population dynamics as a consequence of environmental conditions. In most of the models used in the study of climate change and the potential impact of the anticipated warming, the solid Earth is only represented as a passive boundary condition not taking part in the dynamics.

The need for higher integrated models is widely recognised. However, the presently available data sets of relevant observations are not sufficient for validation of any higher integrated model.

The recognition of the scientific dimension of climate change and sustainable development has stimulated an ongoing discussion of whether the scientific approach still widely used in studies of global change can ever contribute valuably to the problem of sustainability. This approach, which is best termed as the reductionist's approach, breaks down research into specialised disciplines and studies small, strongly reduced, and highly simplified subsytems of the Earth. An increasing number of scientists are criticising this approach as inappropriate and requesting a more wholistic approach embedded in a system viewpoint.

However, helpful methodological developments to overcome the deficiencies of the reductionist's approach were not to be seen until recently, when first a group at the University of Bern (see Pfister, 1995) used a syndrome description to describe phenomena associated with our energy use. The concept of syndromes is known from medicine and is further elaborated in a recent article by Schellnhuber *et al.* (1997). These authors lay the methodolocial and mathematical basis for an analysis of global change taking into account our limited knowledge of the system and the large uncertainties associated with observations of key variables. This approach, which assigns a high weight to the spatial characteristics of global change, may well be apt to overcome the problems of the current scientific approach in global change research.

It is important to note here that in the context of most classical discussions of global climate change and activities to mitigate the impact of future changes, emphasis is on the effect of Greenhouse gas emissions on the global temperature while the effect of many other anthropogenic interactions are widely neglected. Consequently, most measures also concentrate on the reduction of these emissions. This seems to reflect a rather simplicistic view of the Earth system, which assumes that a few switches (e.g. CO_2 emission) are sufficient to gain control over major processes and, ultimately, the system's state.

However, looking at the complexity of the Earth system, it must be questioned whether this strongly reduced "control panel" is sufficient for a sustainable management of the Earth. It may be worthwhile to compare this Earth system control panel to similar panels required to control technical processes. As an example, we may imagine the control panel of a large modern airplane. To control the relatively simple and well-understood process of flying an airplane, a large number of variables have to be monitored continuously at many locations within the system to ensure that changes in the system's state are detected early enough to allow taking measures counteracting undesired changes. In addition to the numerous displays, the control panel has a number of red lights, which flash whenever critical situations occur. Moreover, there are switches to initiate well-defined and controllable emergency actions if the displays and red lights warrant them. Nevertheless, a small risk remains that specific combinations of conditions might result in a serious accident.

Considering the control panel of the Earth system as sketched in Figure 1, we have to state that only a few variables of the system are monitored, most of them, however, spatially incomplete and many with a rather recent start. Despite the well established fact that the Earth is a bio-geochemical system, only a few chemical variables are monitored, most of them with insufficient geographical distribution. Some physical variables related to the thermodynamic state of the system are collected in near-global networks. Geophysical and geodetic variables are increasingly monitored. Considering the power acquired by mankind, astonishingly few variables related to human activities are monitored and available at the ”control panel”. Political decisions to control economic activities most often are still reduced to one variable, the gross national product, which is taken to be indicative for the health of a national economy[6]. Nevertheless, the key variables and the ”red lights” of the system remain largely unknown. Moreover, only a few switches to affect the system's state are available, and their long-term effects are poorly understood.

From this comparison, it is clear that the ”flight” of the Earth system carries some potentially much higher risks than in a modern airplane. In particular, one might be justified in asking whether current scientific input into the process of political decision-making is based on firm ground. Assessments of the current situation and potential risks like the IPCC assessments do not clearly and openly state the limitation of our monitoring system, modelling capabilities and impact assessment tools. In most assessments, quantitative knowledge is preferred over qualitative knowledge.

An important question in the current global change debate is whether science, with its limited ability to model the Earth system, is able to provide significant quantitative results as input for the decision process. Examples of such an input are the projection of global warming and sea level rise due to predefined emission scenarios (see, e.g. chapters 6 and 7 in Houghton *et al.*, 1996). In public, these projections are interpreted to indicate that it is sufficient to reduce industrial CO_2 emission by a certain amount to ensure that global warming will not result in economically devastating consequences (see Houghton *et al.*, 1996, for a detailed discussion). However, it must be questioned whether these projections provide a firm and scientifically justified basis for such a conclusion which is then used as the basis for international decisions and action plans.

In such a situation, where detailed quantitative constraints for impacts and consequences of proposed actions are difficult to attain, it may be more sensible to consider qualitative knowledge with a high priority. Here, we refer to results obtained from observational and modelling studies not directly convertible into numbers applicable in the course of decisions. A rather simplified example is a patient with considerable risk of a heart attack. It is impossible to provide quantitative information to this patient stating how many stress-free or stress-reduced hours, or how large a reduction in smoking is required, to avoid the event of an heart-attack. It is, however, possible to provide the qualitative input that a stress-reduction, sensible food, and less smoking reduces the risk of an heart-attack. This qualitative result is deduced on the basis of observational studies as well as a broad understanding of the nature of the problem and the physiology of a human being. Similarly, physiological studies of the Earth system based on models as well as integrated data sets may provide qualitative results more important for designing the best therapy to achieve sustainability than quantitative projections based on the current levels of understanding.

Many published examples (see e.g. Schellnhuber and von Bloh, 1993; Rahmstorf, 1995) demonstrate the likely effect of perturbations on systems that are in a state of a dynamical equilibrium (homeostasis). This effect is not a gradual nearly linear response to external forcing or perturbations but more likely a rapid transition to a different state whenever thresholds are exceeded.

For the Earth system, there may be many thresholds for numerous different external and internal perturbations. Exceeding such thresholds may be responsible for the accretion and disintegration of the large ice sheets, and they may be the cause of rapid climate fluctuations believed to be documented in ice cores (Greenland Ice-core Project (GRIP) Members, 1993) and also found in observational data of the last 100 years (Ellsaesser *et al.*, 1986). We do not know any of these thresholds of the complex Earth system. However, we know that we have been changing the Earth's surface to a great extend (for an impressive documentation of the changes, see Turner II *et al.*, 1990). The qualitative knowledge of the Earth system combined with the abundant documentation of our effective interference suggest the conclusion that we may well be close to thresholds separating us from severe risks. The danger of hidden risks awaiting us has been raised in many publications (e.g. Broeker, 1987), however, the scientific community has not succeeded in popularising this point in the social and political process of decision-making.

Moreover, present monitoring activities, including data archiving and information production routines are not adequate to allow for the timely detection of any severe rapid trends in the Earth system. The basic uncertainty in our knowledge concerning the interannual to decadal variability of the system as pointed out in the recent IPCC assessment (Houghton *et al.*, 1996), is a major obstacle in providing such information.

4 The need for sustainable integrated monitoring of the Earth system

As outlined in the previous section, sufficient monitoring of the Earth system is one of the cornerstones required to approach and secure the sustainability of mankind's existence and to control interference with the system's processes. The last decade has seen the emergence of many global or regional programmes and activities directed towards monitoring of the environment (Figure 2). Monitoring the Earth system presently is strongly subdivided and organised according to disciplines and subsystems. A major disadvantage of this lack of integration is the nearly complete absence of the integrated data sets required for the study of system processes. Consequently, science programmes or

[6]There is, however, considerable research going on to define a more diverse set of variables to measure “well-being” in the context of the sustainable development debate.

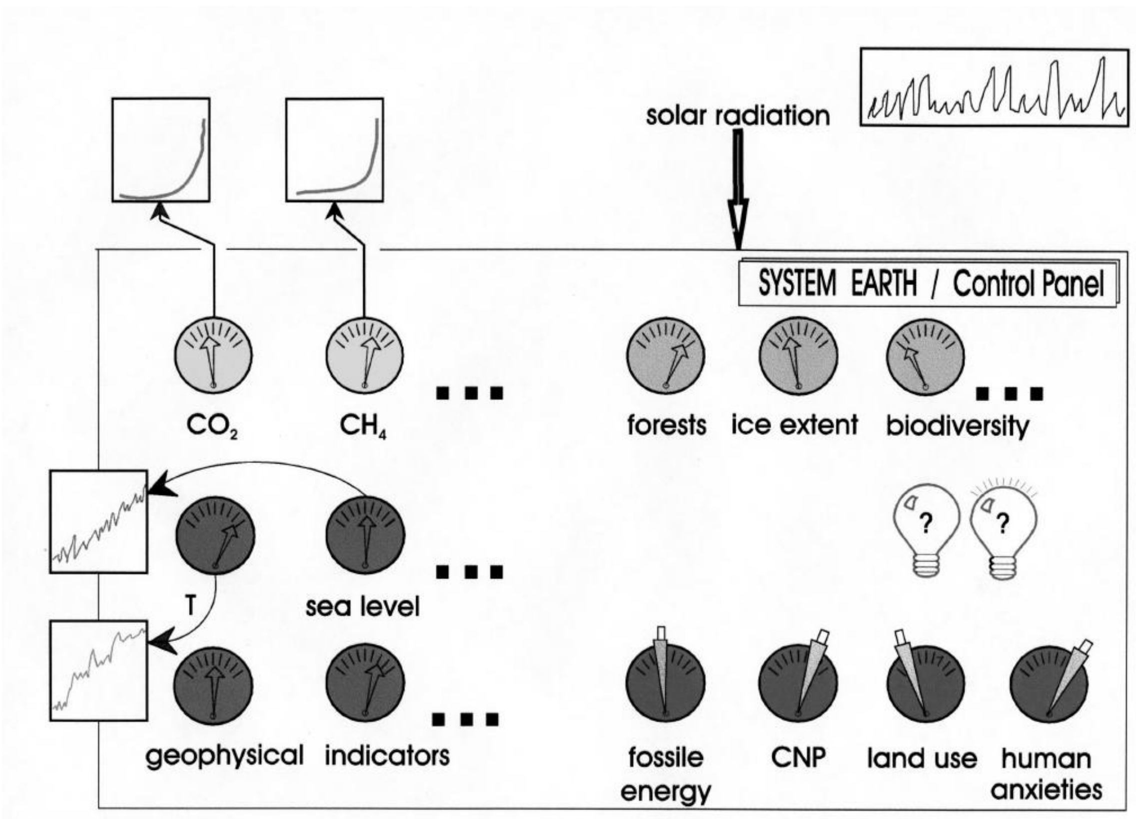

Figure 1: Sketch of the Earth system's control panel.

The "control panel" currently used in science for the Earth system is astonishingly simple, with only a few chemical, biological and physical monitoring parameters, far less parameters pertaining to the state within the antroposphere, and still less control switches. The red lights still remain unknown.

projects aiming at a better understanding of system processes are forced to build up such integrated databases first. An Integrated Global Observing Strategy (IGOS) is drafted only in the remote sensing community, and the three Global Observing Systems (G3OS) are developed according to this strategy. In research, several large programmes like the International Geosphere-Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP) are looking at specific aspects of the global system, while other programmes (such as the International Lithosphere Programme, ILP) still concentrate on subsystems. Assessment is partly organised on a global level, but smaller national and even non-governmental institutes contribute significantly to the assessment of the state of the Earth system.0 Policy-makers crucially depend on the results of these assessments. Thus, these assessments are the interface between both monitoring and research and those determining the course of global development. The direction of funding is largely determined by decision makers and depends on the priorities resulting from the assessment. It should be noted that the assessment presently still draws mainly on the results of the research programmes and not on operational monitoring.

Currently, the monitoring system is characterised by a number of sub-networks with spatial and temporal heterogeneities and with little coordination and cooperation across disciplinary boundaries (see Figure 2). The ground-based component consists of meteorological, hydrological, oceanographical, geophysical, geodetic and chemical networks, with the number of operational stations varying in time. Additionally, a significant amount of data is collected in campaign-type measurements at varying time intervals and locations.

All these sub-networks produce data sets which are inhomogeneous due to spatial and temporal heterogeneities in the station distribution, and due to variations in the observation procedures including the sensors and recording equipment. Problems due to these inhomogeneities are exemplified in Ellsaesser *et al.* (1986) using the station temperature observations at land and sea sites. For a sustainable monitoring, the problem of long-term homogeneity is a crucial one.

Over the last two decades, a strong space-borne component has been introduced into the monitoring. The nearly complete coverage of most of the remote sensing satellites has greatly improved monitoring and opened new doors to understanding system processes. However, in terms of sustainable monitoring, the limited life time of the satellites and sensors, and the high costs of most of the missions, are severe limitations likely to introduce temporal heterogeneities into the data sets. In many cases, only sin-

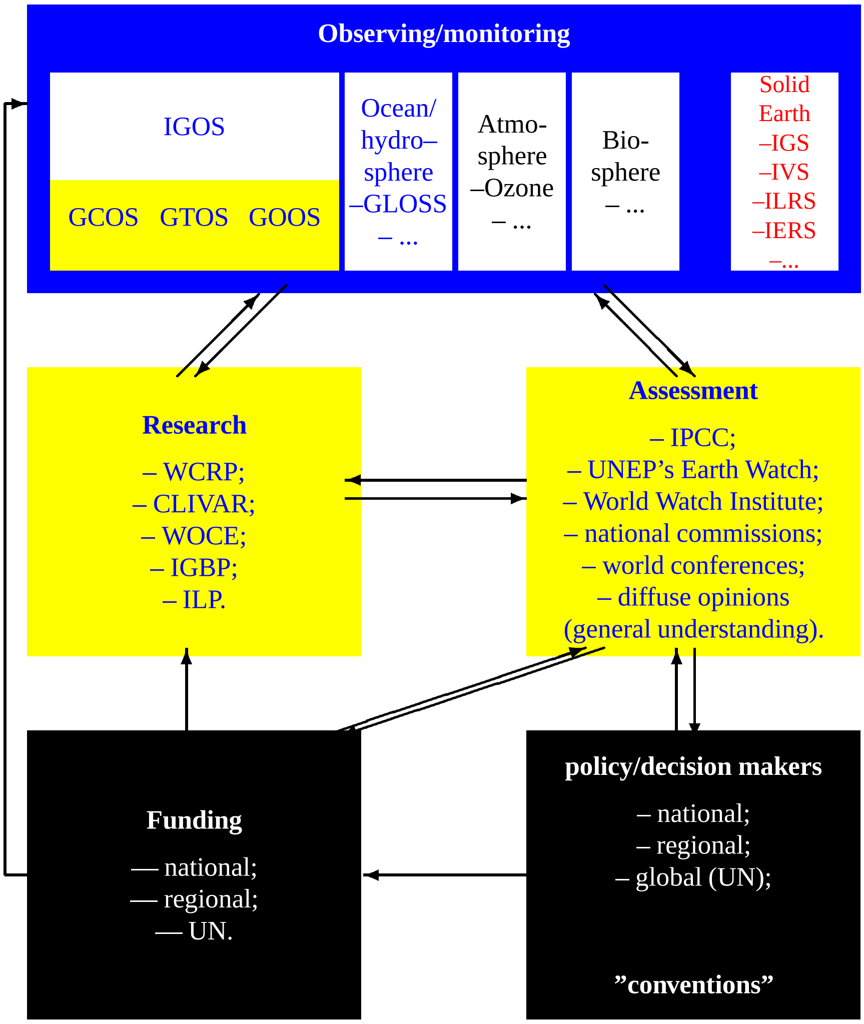

Figure 2: Present monitoring of the Earth in relation to research programmes and system assessment. For a discussion of the figure, see text in Section 4.

gle sensors exist, and the danger of processing errors and miss-interpretation is high (as demonstrated by the error in TOPEX/Poseidon processing, see Nerem *et al.*, 1997).

Particularly within Earth monitoring based on remote sensing, progress has been made recently towards an IGOS (see, e.g., Williams and Townshend, 1998). Within the framework of the emerging global observing systems (see, e.g., Dahl, 1998), much has been done over the last two years to develop the IGOS. A document has been drafted by the key players in global observation, and this document forms a valuable basis for the discussion in the present paper. The most recent draft is available on http://www.unep.ch/earthw/igosstr.htm. The drivers for IGOS are the scale of the issues (global climate change, sustainable development) to be addressed; the cost of space components for remote sensing of the Earth environment; the logistics especially for in-situ data; and the need for data integration from multiple sources for products of use to decision makers, science, and society at large. For key variables of the Earth system, IGOS attempts to provide long-term continuity, adequate data archives and accessibility, consistency of data records, and the ancillary data required for data quality assessment.

These principles of IGOS provide the framework for a coherent response of the monitoring system to the integrated user requirements. Under IGOS, an operational system guaranteeing the long-term continuity of observations to support scientific research can be achieved. IGOS intends to build upon existing strategies for international observation programs, focusing on the identification of areas where the existing systems can be improved, where duplication of observations can be reduced and gaps in observations and data sets can be identified. Moreover, IGOS facilitates improved high-level product developments, and capacity building in developing countries. Thus, if effectively implemented, IGOS appears to be the strategy for providing the observational basis for a future Earth information system. A key issue identified in IGOS is the need to transform many observational activities from their research states into operational monitoring.

In summary, comprehensive monitoring of the Earth system is a crucial prerequisite which needs to be established within the research community and transformed into operational activities. Taking into account the nature of the task at hand, the necessary properties of a sustainable monitoring include
— long-term stability,
— operational mode,
— homogeneity in time,
— multi-parameter sites,
— global coverage and participation, and
— integrated observation and data sets.

5 Geodesy's potential contribution to Earth system monitoring

The present capabilities of space-geodetic techniques are described in detail in several of the publications in this issue. Based on these analyses, the basic contribution of geodesy, and particularly of space geodesy, to Earth system monitoring, can be identified as

- the maintenance of stable reference frames for all position-related information (both terrestrial and celestial);
- the monitoring of the kinematics of the Earth's surface, including deformations;
- the monitoring of the Earth's rotation and its variation in time;
- the observation of variations in the Earth's gravity as a measure of mass movements as well as a quantity required to observe other parameters such as sea surface topography;
- the monitoring of other environmental parameters (e.g. GPS-MET);
- the provision of observing techniques, particularly satellite-borne ones.

Presently, geodesy is realising these contributions with

- global geodetic networks;
- services built upon these networks;
- dedicated satellite missions.

Within space-geodetic observation techniques, over the last decade, a very rapid development has occurred leading to unprecedented possibilities to measure positions (see, e.g., Plag *et al.*, 1998). Several space-geodetic methods including Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI) and the Global Positioning System (GPS), have reached maturity where the transition from research to operational states appears to be feasible. These techniques have the potential to provide for reliable monitoring of key parameters describing the Earth's system, such as surface displacements and deformations, earth orientation, integrated precipitable water vapour content of the atmosphere (IPWC), and electron density in the ionosphere.

Currently, permanent infrastructure potentially valuable for space-geodetic measurements has been and is being installed increasingly for several purposes. Most prominent are networks of permanent GPS sites continuously recording data of several or all visible satellites (denoted here as CGPS sites). Most of these networks originally were established for dedicated purposes, such as differential GPS networks for navigation systems, high precision networks for global reference purposes (i.e. the IGS[7]) and as regional densifications of the global network (e.g. the EUREF[8]), or for geodynamical investigations, pilot-project type networks to derive meteorological information from the GPS data (e.g. the SuomiNet in USA[9]), as well as small station nets for high-precision multi-parameter local studies. Recently, a trend is surfacing towards multi-purpose use of some of these networks.

Some of these nets are operational and often supported or operated by governmental institutions, while others are more associated with research and, as such, operated by university groups or research institutes. Some of the installations are complying to standards for space-geodetic sites and only data storage and availability restricts the possible general scientific or broader use of the recorded observations. Other sites meanwhile do not meet these standards and would require upgrading in order to be of value in geodetic monitoring. The absence of overall coordination in the development and use of these networks represents an unnecessary economic waste. Under the present circumstances there is certainly a loss of potential primary and secondary benefits both in terms of science and economy. Developing an integrated observing strategy would lay the basis for the implementation of a multi-purpose coordinated network of observing stations including those established for commercial purposes. For space-geodetic networks, this strategy currently is not available or being developed. However, as described in the previous section, in other areas of Earth monitoring progress has been made recently towards an IGOS. To develop an acceptable way to bring the space-geodetic networks in accord with IGOS could ensure the quality and availability of the collected space-geodetic data required for monitoring and scientific exploitation.

Examples where operational infrastructure provides data that is of high relevance for science can be found within meteorology, where sites operated particularly at airports (where local conditions are required for safety purposes)

[7]see http://http://igscb.jpl.nasa.gov/index.html
[8]see http://www.oma.be/KSB-ORB/EUREF/eurefhome.html
[9]see http://www.unidata.ucar.edu/SuomiNet/SuomiNet.html

not only provide the basis for regional weather forecasts but also result in long meteorological time series which are now the observational basis for climate studies at time scales up to several decades.

Another example is tide gauges, which are often operated to ensure the safety of ship traffic. This operational monitoring resulted in a database central in studying climate variability over the last 100 years. Analyses of this database provided crucial constraints for models of the cryosphere-ocean interaction and the assessment of the impact of future global change.

To enable maximum scientific exploitation of the data being collected at space-geodetic sites established to serve both scientific and commercial purposes, the installation has to comply to specified standards. Moreover, data collection, processing, and storage has to provide for data integrity, homogeneity in time, and accessibility. Providing for multi-purpose use of the data will help to avoid overlaps in installation. The current development within CGPS is clearly in danger of having established a number of different, partially overlapping, networks. Instead of having an increasing number of CGPS sites for dedicated purposes, a future scenario could (and should) be a multi-purpose CGPS network as an integral part of the general infrastructure of society. Such a network would collect and provide real-time data for navigation purposes, near real-time environmental parameters such as IPWV, electron density, and surface displacements used e.g. as input for forecasts of relevant environmental conditions and possibly hazard warnings, and post-time data for scientific studies. Operated over a longer time period, such an infrastructure would create an environmental database as a legacy for future generations of scientists in the same way as we today partly live on the databases from infrastructure established by far-sighted people more than a hundred years ago.

A multi-purpose CGPS network preferably would be established on a global basis. To secure operation over a longer time period, a clear international dedication and national support would be required. However, for a step-by-step implementation, regional approaches are very valuable. Therefore, the strategy for such a network needs to allow for a modular structure.

In the on-going discussion within IAG to step towards an Integrated Global Geodetic Observing System (IGGOS, see e.g. Beutler *et al.*, 1999), a multi-purpose CGPS network could be a path-finder in the same way as IGS was a path-finder for services based upon single space-geodetic techniques. The strategy developed for a multi-purpose CGPS network naturally would also have to account for multi-sensor sites, and thus foster the integration of techniques.

6 Towards sustainable integrated global Earth monitoring

Any monitoring system can be considered as composed of three different networks which can be visualised as a tri-

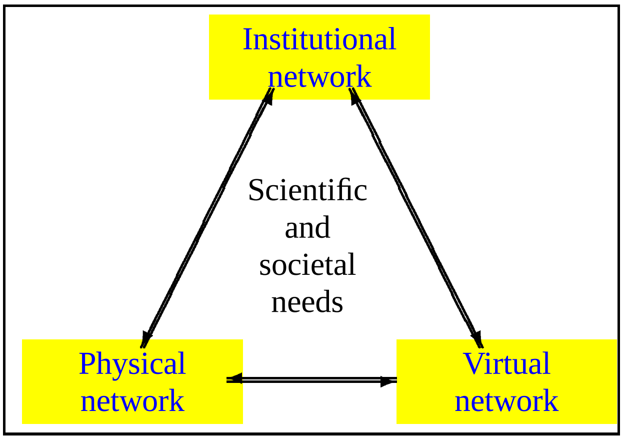

Figure 3: The Network Triangle.

An operational monitoring network should respond to well defined scientific and/or societal needs. Thus, the design of the virtual network should correspond to user requirements derived from these needs. Within the institutional network, the owners of the physical and virtual network have to be linked with the users to provide for the necessary resources and the mandate for maintenance of the network. The physical network needs to comply with the specifications resulting from the virtual network. Thus, the success of the network depends equally on three main aspects, namely, the design of the virtual network, the performance of the physical network, and the efficiency of the institutional structure.

angle with each corner of equal importance for the performance and success of the system (Fig. 3). This triangle should be centred around the needs of the users of the system, which may be scientists or society at large. On one corner of the triangle, the design of a *virtual network*, including its objectives, needs to be such that the products correspond to scientific or societal needs. Thus, the first step in developing the virtual network should be the identification of the user's requirements, that is, the design process should be user-driven. The *physical network*, including the single stations, the communication tools, the data processing and the analysis, has to meet the specifications resulting from the virtual network and, particularly, the objectives of the network. Quality control of performance and products and the long-term consistency of the operation are integral parts of the design of the virtual network. Finally, the *institutional network* has to ensure the political and financial support of the activities. Thus, this network has to include the ”owners” of the (physical) infrastructure as well as the ”owners” of the services linked to the virtual network, and it has to obtain the necessary long-term mandate from the users. In the case of environmental monitoring, where both the users and the owners might be governmental bodies, a mandate from the relevant political level may be required to support and ensure long-term activities. A given physical network can be associated with a number of virtual networks making use of the same data in different ways and for different applications.

First of all, the design of a virtual network has to be based on a thorough analysis of the ”market”. As a result, this analysis should identify all potential users (including future ones) of the network and their needs for specific products. A description of the user requirements should clearly specify the required properties of the products in terms of availability, integrity, continuity, consistency, precision and accuracy. The design of the virtual network has to be such as to provide for these properties. This design process will also result in a set of specifications for the performance of the physical network and the quality of the observations provided by this network as well as the communication tools to be used.

The design of a virtual network also depends on the associated institutional network (see below). Thus, the design can be modular or uniform, hierarchical and top-down or more democratic and bottom up. For a network owned by a single institution or an organisation, a hierarchical structure with clear competence for decisions and delegation of work may be appropriate and most efficient. However, in its physical implementation, for regional or global network it is hard to imagine a physical implementation which is not bottom-to-top and to a large extent depending on voluntary contributions of the participants. Such a structure is characterised by relatively high fluctuation of contributors and support, inconsistencies in observations, meta-information, and, eventually, products, relatively high probability of errors, unequal and time-dependent performance levels of different contributors, and a slow and/or insufficient response of contributors to requests from the network. The design of the virtual network has to account for these deficiencies. In particular, the necessity of comprehensive network monitoring and quality control is obvious. Therefore, regional to global monitoring networks should integrate these elements as part of the design of the virtual network.

Within a future global monitoring system, the physical network should be a multi-purpose infrastructure, i.e. there should be more applications for the infrastructure instead of an ever increasing number of sites. Synergy should be exploited as much as possible through co-location.

Over the last two decades, space-geodetic techniques have seen a research state of very rapid development both in terms of accuracy, applicability and availability. Consequently, much of the development has been stimulated by ad-hoc responses to emerging needs and new potentials and capabilities. Within IAG, CSTG has provide some coordination (see e.g., Beutler *et al.*, 1999), but very little was and possibly could have been done to bring forward a clear or even integrated strategy for building networks. Mainly, space-geodetic networks developed in the broader IAG-context were and still are science-driven.

Stimulated by the success of the IGS, science-driven space-geodetic networks are currently in a phase of reorganisation leading to the establishment of several mono-technique services. Similar to the IGS, these new services focus on fostering the specific technique, the quality and availability of the data products, and partly the co-location with other techniques. All of the services connected to the networks are based on voluntary contributions by the participants. They are mostly supported with scientific recognition by IAG and/or IAG commissions. The contributions to the networks depend to a large extent on the good-will of the participants and the availability of budgets of single individuals and their institutions.

It is interesting to note that many of these networks have demonstrated an extreme ability to survive for a long time and to develop a long-term stability. Nevertheless, the establishment of an environmental monitoring systems providing near real-time applications with considerable consequences in case of failure to meet the specifications, might require a different approach.

As stated above, meteorological and some hydrological observations are the very few examples of governmentally-driven observational networks, which have been operational for several decades if not centuries. Only recently, the growing recognition of the likelihood of human-induced climate change and the associated potential hazards as well as the necessity to approach a sustainable development of the global human society on a limited and vulnerable planet has led to the establishment of a rapidly growing number of operational global or regional monitoring systems. All these systems are institutionalised in a different way than the voluntary science-driven networks prevailing in geodesy.

In Figure 4 the structure of a virtual network for an Earth information system is sketched. In such a system, integrated monitoring is an important part resulting in an integrated database. Analysis and modelling draw on this database and aim for both the detection of syndromes and the establishment of an integrated system model. The system is fully driven by the users' need for key variables and assessment of consequences.

7 Conclusions

The emerging IGOS as the umbrella for the G3OS is a very promising development. A basic recognition of IGOS is the need to transform observations presently largely carried out under research programs into operational activities with a long-term perspective.

The integration of space-geodetic networks into a IGGOS is a timely step, which should, in the end, lead to operational monitoring. This should be oriented along the IGOS and integrated into the larger context of a future Global Integrated Earth Monitoring System (GIEMS) as one prerequisite of an Earth information system.

Though IGOS is providing a framework for such an urgently needed GIEMS, it may not be sufficient to promote the integration and adoption over all the disciplines involved in Earth system monitoring and research. In particular, the need for integrating the data sets to enable the production of data products and information useful for both Earth system science and policy makers may require other means to foster the rapid approach towards a user-oriented GIEMS.

Considering the mutual impact of the IPCC on policy makers and the direction of global change research, it may be wise to use a similar instrument to promote integration

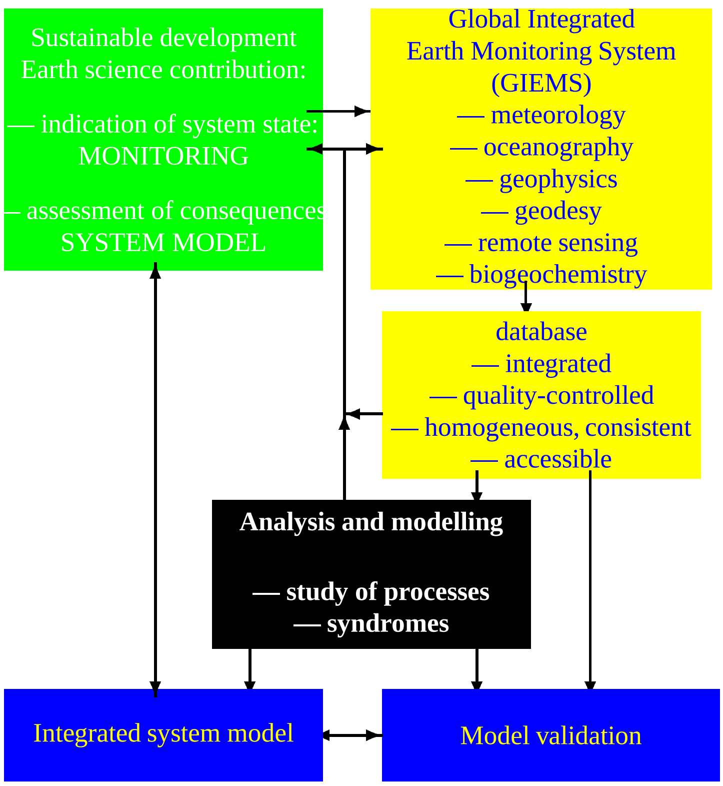

Figure 4: Sketch of a possible integration of monitoring into an Earth information system for sustainability. For a discussion, see text. The contribution of geodesy to the monitoring could be utilised by the IGGOS proposed in Beutler *et al.* (1999).

within Earth monitoring. Therefore, it should be considered to establish an Intergovernmental Panel on Global Monitoring (IPGM). Such a panel would assess the efficiency and quality of Earth system monitoring, specify the user requirements for data products and information, identify gaps in data sets and the dissemination of data sets and information (Figure 5).

This panel could be suggested to IUGG and from there to the United Nations. IAG could take a leading role in initiating this procedure.

While the space or remote-sensing segment of the G3OS appears to be well-developed, there is a clear deficiency in the organisation of the ground-based component leading to a severe lack of in-situ data. The need for an interdisciplinary ground-based observing system is obvious. The Global Geophysical Observing System (GGOS) proposed to the IUGG in 1995 and again in 1999 could provide the means for this organisation.

At the 1995-IUGG meeting in Boulder, the necessity for GGOS was discussed in several plenary sessions and subsequently has been promoted at many occasions. GGOS aims to facilitate (through enhanced communications and co-ordination) the growth of global geophysical observing system real-time networks. In particular, it will promote the co-location of multivariate observing stations for scientific synergy, as well as economy, across all IUGG disciplines and Associations. It derives its motivation from the global nature of the geophysical sciences, technological advances in sensing and telecommunication systems, and the societal imperatives for environmental sustainability and stewardship articulated in Agenda 21. Integral components of GGOS include cultivating the growth of monitoring services, facilitating data dissemination and data quality standards, and fostering interplay between numerical and statistical modelling with data network design, assessment, and utilisation. To be fully successful, GGOS needs to structure a hierarchical approach (national, regional, and global), and to engage research scientists from both the more-developed and the less-developed countries. The IGGOS would not only provide observations to the GGOS but would be a utility for all other parts of the GIEMS.

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References

Ahmad, Y. J., El Serafy, S., and Lutz, E., editors (1989). *Environmental Accounting for Sustainable Developement*. The World Bank, Washington, D.C. 100 pages.

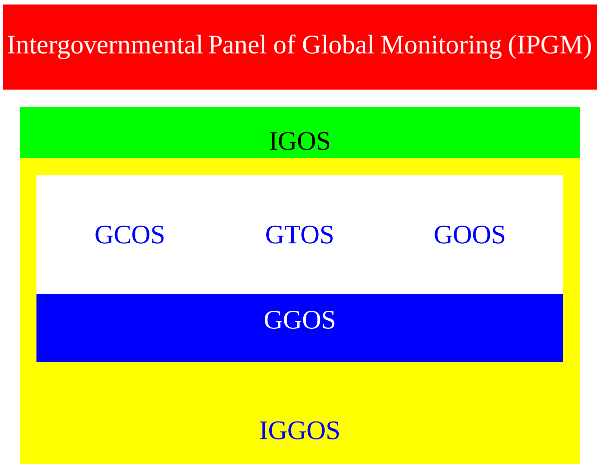

Figure 5: Towards a comprehensive monitoring system. A comprehensive monitoring system would collect all the different networks under a common integrated observing strategy, i.e. IGOS. A solid basis of in-situ data for the three emerging global observing systems GCOS, GTOS and GOOS, which are still strongly focusing on remote sensing, could be provided by a ground-based observing system, the GGOS. The IGGOS would contribute important observations and at the same time be a utility for the other components. Progress of the development in the monitoring should be assessed at a high level, preferably through an IPGM.

Beutler, G., Drewes, H., Reigber, C., and Rummel, R. (1999). Space techniques and their contribution within iag at present and in future. *CSTG Bulletin*, **14**, this issue.

Broeker, W. S. (1987). Unpleasant surprises in the greenhouse? *Nature*, **328**, 123–126.

Dahl, A. L. (1998). IGOS from the perspective of the Global Observing Systems and their sponsors. In *Proceedings for the 27-th Int. Symp. on Remote Sensing of Environment: Information for Sustainability, June 8-12, 1998, Tromsø, Norway*, pages 92–94. Norwegian Space Centre.

Ellsaesser, H. W., MacCracken, M. C., Walton, J. J., and Grotch, S. L. (1986). Global climatic trends as revealed by the recorded data. *Rev. Geophys.*, **24(4)**, 745–792.

Greenland Ice-core Project (GRIP) Members (1993). Climate instability during the last interglacial period recorded in the GRIP ice core. *Nature*, **364**, 203–207.

Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K., editors (1996). *Climate Change 1995 - The Science of Climate Change*. Cambridge University Press.

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens, W. W. I. (1972). *The Limits to Growth*. Universe Books, New York.

Nerem, S. M., Rachlin, K. E., and Beckley, B. D. (1997). Characterization of global mean sea level variations observed by TOPEX/POSEIDON using empirical orthogonal functions. *Surveys Geophys.*, **18**, 293–302.

Pfister, C. (1995). Das "‘1950er Syndrom"’: Die umweltgeschichtliche Epochenschwelle zwischen Industriegesellschaft und Konsumgesellschaft. In C. Pfister, editor, *Das 1950er Syndrom*, pages 51–96. Haupt, Bern. Publikation der Akademischen Kommission der Universität Bern.

Plag, H.-P., Ambrosius, B., Baker, T. F., Beutler, G., Bianco, G., Blewitt, G., Boucher, C., Davis, J. L., Degnan, J. J., Johansson, J. M., Kahle, H.-G., Kumkova, I., Marson, I., Mueller, S., Pavlis, E. C., Pearlman, M. R., Richter, B., Spakman, W., Tatevian, S. K., Tomasi, P., Wilson, P., and Zerbini, S. (1998). Scientific objectives of current and future WEGENER activities. *Tectonophysics*, **294**, 177–223.

Rahmstorf, S. (1995). Bifurcation of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. *Nature*, **378**, 145–149.

Schellnhuber, H.-J. and von Bloh, W. (1993). Homöostasie und Katastrophe: Ein geophysiologischer Zugang zur Klimaentwicklung. In H.-J. Schellnhuber and H. Sterr, editors, *Klimaänderung und Küste: Einblick ins Treibhaus*, pages 11–27. Springer-Verlag Berlin Heidelberg New York.

Schellnhuber, H. J., Block, A., Cassel-Gintz, M., Kropp, J., Lammel, G., Lass, W., Lienenkamp, R., Loose, C., Lüdeke, M. K. B., Moldenhauer, O., Petschel-Held, G., Plöchl, M., and Reusswig, F. (1997). Syndromes of global change. *GAIA*, **6**(1), 19.

Turner II, B. L., Clark, W. C., Kates, R. W., Richards, J. F., Mathews, J. T., and Meyer, W. B., editors (1990). *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years*. University Press, Cambridge. 713 pages.

Williams, D. and Townshend, J. R. G. (1998). The concept of an Integrated Global Observing Strategy. In *Proceedings for the 27-th Int. Symp. on Remote Sensing of Environment: Information for Sustainability, June 8-12, 1998, Tromsø, Norway*, pages 95–98. Norwegian Space Centre.

World Commission on Environment and Development (1987). *Our Common Future*. Oxford University Press, Oxford.