Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle (IGCP 565 Project)

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ABSTRACT

Geodetic observations of the Earth's gravity field, shape, and rotation and their changes in time (the three fundamental areas of geodesy) capture the signals of variation in the entire fluid envelope of the solid Earth, including the terrestrial water storage. Therefore, the Global Geodetic Observing System (GGOS) has the capability to monitor mass transport particularly in the global water cycle. The IGCP 565 Project aims to utilize this potential and to develop GGOS into a monitoring system for the hydrological cycle on global to regional scales. Key scientific issues addressed are: (1) Development of an integrated dynamic model for the predictions of the geodetic signals of daily to interannual surface mass changes; (2) Inversion algorithms for integrated geodetic observations for surface mass changes; (3) Assimilation of observed surface mass changes in hydrological models; and (4) Development of products relevant for regional water management. The project supports capacity building in space-geodetic data processing, modeling of the hydrological cycle, and interpretation of the observations in terms of terrestrial water storage. A focus is on products for regional water management, particularly in developing countries. Coordination of the research and capacity building is provided through a series of five annual workshops.

Keywords: Monitoring of the Global Water Cycle, Global Geodetic Observing System, Earth Observation, Regional Water Management, Capacity Building

1. INTRODUCTION

Water is essential to life on Earth, which is a unique, living planet due to the abundance and vigorous cycling of water throughout the global water cycle. Water is central to human welfare, progress and sustainable economic growth. Clean, fresh water is arguably the most important resource to human society, as it controls our ability to produce sufficient food to support the human population. In many areas of the world, current demands exceed the supply (as indicated by the water scarcity index, see Oki & Kanae, 2006) and water has to be transported over great distances. This situation is expected to become more severe over the next several decades (see, e.g., EEA, 1999; Lawford et al., 2004; Bernasconi et al., 2005; Oki & Kanae, 2006; United Nations, 2006). However, the water crisis is largely a crisis of governance (United Nations, 2006), brought about by water management obstacles such as sector fragmentation, poverty, corruption, stagnated budgets, declining levels of development assistance and investment in the water sector, inadequate institutions and limited stakeholder participation. The lack of detailed knowledge of the water cycle from local to global scales is contributing and enforcing this crisis.

Usable water resources reside in lakes, streams, artificial reservoirs, and groundwater. Of these, groundwater represents the greatest volume. In many areas, groundwater is easily accessible through wells. However, in semiarid to arid regions, where the stress on water resources is most acute, aquifers do not recharge at a significant rate relative to the rate of withdrawal. Utilization of such water resources has to be considered as “mining” of a non-renewable resource. Consequently, water tables drop, and the aquifers have limited lifetimes before depletion. Lake levels also change, both due to natural and anthropogenic causes including surface water diversion for irrigation, and modify the available water resources. The discharge of rivers into the global oceans constitutes an important input to the chemistry of coastal water and ecosystem function, which is highly modulated by water use throughout the drainage basin. Knowledge of the changing mass distribution due to water withdrawal and/or changes in precipitation, evaporation, and runoff is therefore a fundamental input to any responsible water management. However, *in situ* observations are limited, particularly in many developing countries.

The global hydrological cycle operates on a continuum of temporal and spatial scales. Its variability which regulates flood, drought, and disease hazards is being continuously transformed by climate change, erosion, pollution, agriculture, and civil engineering practices. The most visible impact expected from climate warming includes changes in the distribution of precipitation and evaporation, and the exacerbation of extreme hydrological events, floods, and droughts. Understanding the water cycle, quantifying the mass redistribution, and developing predictive capabilities are therefore mandatory prerequisites for understanding global change processes. Despite its fundamental role for mankind, and despite the challenges through increasingly limited availability of water for human activities, knowledge of key quantities of the hydrological cycle is still associated with large uncertainties, and urgent questions cannot be answered. Although progress has been made over the last few years to better understand some aspects of the water cycle (some of which directly result from the availability of geodetic observations, see U.S. Climate Change Research Program, 2007), the research questions identified by the U.S. Climate Change Research Program (Box 1) remain to a large extent unanswered, primarily due to the fact that key scales of the water cycle vary by 18 orders of magnitude from water molecules (10^{-10} m) to global planetary scales (10^7 m, see, e.g., Dooge, 2004), and the relevant processes take place in the atmosphere, the ocean, on the Earth's surface, and below. Particularly the latter ones are difficult to access with *in situ* observation techniques or to model. Although the dynamic nature of groundwater is not readily apparent, groundwater flow and storage are continually changing in response to human and climatic stresses (Alley et al., 2002). Groundwater physics is better understood at small length scales, while larger scales still pose significant challenges (Anderson, 2007). Although much attention has been focused on both the theory and measurement of fluxes between surface water bodies and groundwater, there are still many difficulties in obtaining accurate estimates of the spatial and temporal distribution of these fluxes (National Research Council, 2004). Accurate soil water content observations are still restricted to very small spatial scales (~10^{-3} m^3 or less, Topp & Ferré, 2002). Observations of water fluxes in the soil require highly specialized equipment with many limitations and high costs

Strategic Research Questions

5.1 What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

5.2 How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

5.3 What are the key uncertainties in seasonal to interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

5.4 What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

5.5 How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

BOX 1: Strategic research question related to the global water cycle. From http://www.usgcrp.gov/usgcrp/ProgramElements/water.htm.

hampering widespread applications. There are no standard procedures for measuring recharge of groundwater from precipitation (National Research Council, 2004). Therefore, Earth observations can improve the knowledge base and thus help to mitigate the emerging water crisis.

In part, the problems in measurements can be attributed to the diffuse nature and spatially large extent of most groundwater discharge and recharge areas (National Research Council, 2004). It is therefore highly desirable to develop observation methods to measure in an integral way large-scale variations in soil water content and fluxes into the soil and groundwater. Moreover, assimilation of these observations into terrestrial water storage models can be expected to enhance the predictive capabilities of these models.

Geodetic observations relate to the Earth's gravity field, shape, and rotation and their changes in time (the three fundamental areas of geodesy). At time scales from weeks to decades, hydrological loading of the Earth's surface dominates non-secular variation in each of these areas of geodesy. Thus, geodesy naturally provides integral constraints on the water cycle at multiple spatial and temporal scales. Space-geodetic sensors capture the signals of variation in the entire fluid envelope of the solid Earth, including the terrestrial water storage. Space-geodetic observations of surface mass variability are inherently strong at regional to global scales, and could be an important complement to traditional *in situ* measurements of terrestrial water storage.

The geodetic observations are sensitive to changes in the total vertical column of the terrestrial water storage, including the subsurface component. The subsurface component of the terrestrial water storage consists of unsaturated water in the vadose zone and saturated groundwater below the water table. The unsaturated soil moisture plays a crucial role in the water cycle: it is in this zone where precipitation is partitioned into runoff and net infiltration.

Together with the water stored in the soil column, the fluxes between surface, vadose zone, and groundwater determine the soil water balance. The quantification of these fluxes necessitates the establishment of a soil water balance. While various methods are in use to do so, all of them have difficulties in determining groundwater recharge. They all rely on local, small-scale soil water content observations, and water budget closure to date has not been fully successful. For land management and policy making, the most relevant spatial scales are on larger scales of up to several 100 km. Moreover, the most important information is not the vertical distribution of the water content but rather the total water variations in soil moisture and groundwater. Space-geodetic observations are sensitive to these variations and can provide the critical link needed to further quantify and reduce uncertainties in water budget changes. Therefore, space-geodetic observations present a promising avenue to ameliorate observation techniques for subsurface water content and to reduce the data gap caused by the limitations of current subsurface observational capabilities.

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) has the capability to monitor mass transport in the Earth system and particularly the global water cycle. Crucial to this application are the gravity satellite missions that measure the temporal variability of the Earth's gravity field. The Gravity Recovery and Climate Experiment (GRACE) mission has demonstrated the great potential of such missions, but the continuity of the satellite missions is not secured. Moreover, the utilization of the full suite of the geodetic observations is hampered by model insufficiencies, inconsistencies, and a lack of integration of the different space-geodetic techniques. As a consequence, the dissemination of products into practical water management has not taken place.

In the International Geoscience Programme (IGCP) 565 Project, our goal is to develop GGOS into a monitoring system for the hydrological cycle on global to regional scales (for more information, see http://geodesy.unr.edu/igcp565). The intergovernmental and international frames of the Group on Earth Observation (GEO) and GGOS, respectively, are utilized with the goal to ensure sufficient satellite gravity missions, particularly with participation of emerging space agencies in Africa and Asia. Ongoing and planned research projects address the combination of space-geodetic observations, particularly Global Positioning System (GPS) and GRACE-type observations, in order to exploit their individual strengths and mitigate their weaknesses; improve the geophysical models for the processing of the observations; enhance the extraction of highly accurate information on changes in terrestrial water storage; prepare the assimilation of the observations in integrated predictive models of the hydrological cycle; and focus on the interpretation of the space-geodetic observations in terms of regional groundwater and soil moisture changes. Through cooperation with research institutions in developing countries, the project supports capacity building in the field of space-geodetic data processing, modeling of the hydrological cycle, and interpretation of the observations in terms of terrestrial water storage. Through interaction with water management authorities particularly in developing countries, the practical use of the products for regional water management will be promoted. Coordination of the research and capacity building is being provided through a series of five annual workshops.

2. METHODOLOGY

2.1 Objectives and Goals

The research carried out in the frame of the IGCP 565 Project has the main objectives to: explore and develop the components of GGOS that are most relevant for monitoring the water cycle; make the observations available for assimilation in predictive models of the global water cycle; interpret the observations in terms of changes in terrestrial water storage; develop products and algorithms that will allow regional water management to fully utilize the potential of the geodetic techniques for monitoring the regional terrestrial hydrosphere; and assess the extent and way in which the projected climate change might affect the hydrological cycle and the availability of water to society in the various regions.

2.2 Geodetic Observations of the Global Water Cycle

For the development of an observational strategy, we separate the water cycle into a slow and a fast branch. The 'fast branch' consists of precipitation (liquid and solid), evapotranspiration, clouds, and water vapor. The dynamics of the elements in this branch can vary significantly within a day. The 'slow branch' consists of changes in soil moisture, groundwater, snow and ice, freeze-thaw states, ocean dynamics, salinity and volume, and river discharge. The elements in this branch change on much longer time scales. From the perspective of an observing system with two corresponding branches, it is the slow branch where geodetic observations can best contribute (Lawford et al., 2004).

At time scales from sub-daily to decades, the largest mass redistributions on the surface of the solid Earth occur in the water cycle. Exchanges of mass between the major reservoirs of the water cycle, i.e. the atmosphere, ocean, continents, and glaciers and ice sheets, are linked to each other through conservation of mass. The mass redistributions load and deform the solid Earth. Any of these mass movements changes the Earth's gravitational field primarily due to the mass redistribution, and, secondarily, due to deformations of the solid Earth. Through associated changes in the angular momentum and the moments of inertia of atmosphere, ocean, terrestrial hydrosphere, and solid Earth, the redistribution of mass in the fluid envelope also affects the rotation of the Earth (Figure 1). Any of these changes will in turn impact the mass distribution in the ocean and thus create additional loads and induce variations in the geodetic parameters. Therefore, the geodetic loading signals of atmosphere, ocean, and terrestrial hydrosphere are inherently linked together (Blewitt & Clarke, 2003), and an integrated gravitationally consistent modeling approach is required in order to predict these geodetic signals with high accuracy. Moreover, variations in groundwater level lead to surface displacements and local gravity changes.

The current gravity mission GRACE is producing the best-ever estimates of subcontinental-scale variation in terrestrial hydrology over several years (e.g., Tapley et al., 2004; Rowlands et al., 2005; Crowley et al., 2006), and is also providing the best estimates of present-day changes in the large ice sheets (e.g., Velicogna & Wahr, 2006). However, the integration of the three areas of geodesy is still in an initial stage, with the main focus on a combination of GPS and GRACE observations for the inversion of surface mass changes or associated surface deformations (e.g., Davis, et al., 2004; Kusche & Schrama, 2005; Wu et al., 2006). Moreover, the inversion of geodetic observations for surface mass changes is hampered by model inconsistencies, which limit the full exploitation of the geodetic observations (Plag et al., 2007).

Exploring the linkage between the signals in gravity, shape and rotation of the Earth, GRACE can be used to validate new methods using GPS data on Earth's shape to produce estimates of decadal-scale variation in continental-scale water storage. Unlike GRACE, high-quality GPS data now spans >10 years, and the global GPS network with ever increasing spatial resolution and accuracy provides longer term stability toward studies of global climate change and its effect on terrestrial water storage. Moreover, by combining the geodetic observations with hydrological

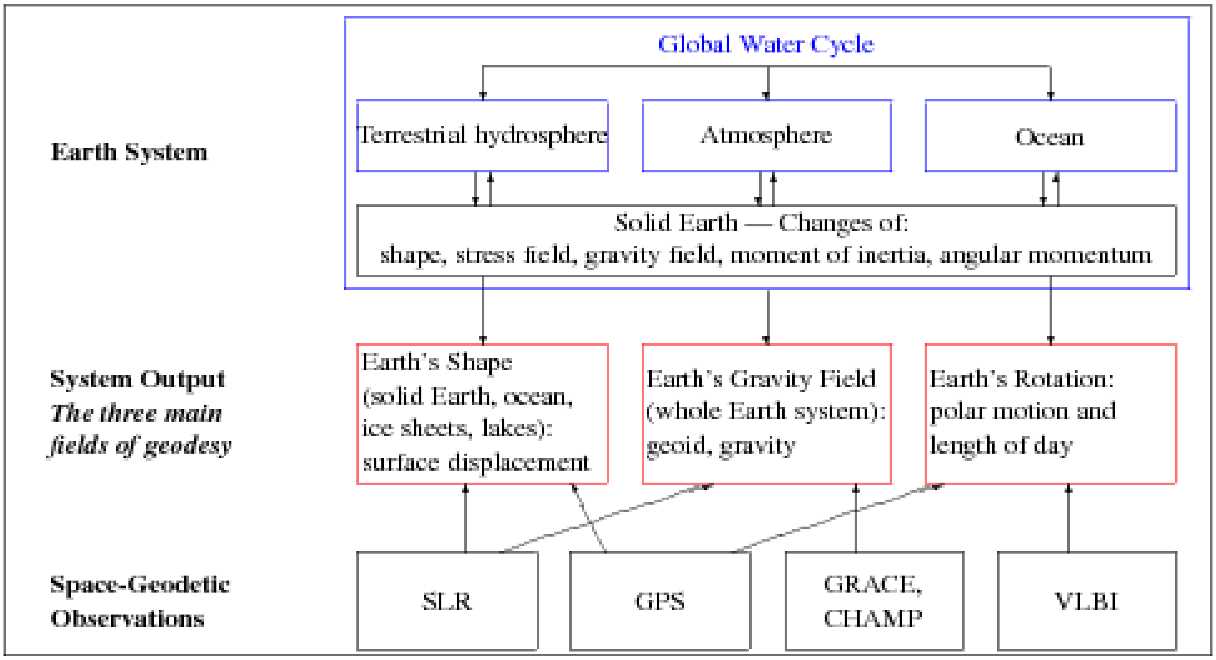

Figure 1: Sensitivity of geodetic observations to mass-redistribution in the global water cycle. Mass redistribution in the ocean, atmosphere, and terrestrial water storage loads and deforms the solid Earth. Both, the water mass redistribution and the solid Earth deformations change the gravity field of the Earth system, and they affect the Earth's rotation. The changes in the solid Earth in turn impact the mass distribution in the ocean and, to a lesser extent, the atmosphere and the terrestrial hydrosphere. Space-geodetic observations of Earth's shape, gravity field and rotation are inherently linked to each other and to mass redistribution in the fluid envelope of the solid Earth.

models, the geodetic techniques are the basis for a mass transport monitoring system. In order to fully exploit the geodetic potential, a number of science issues need to be addressed. These issues are discussed below.

2.3 The Open Science Issues

The key scientific issues addressed in the frame of the IGCP 565 Project in order to reach the objectives presented above are:
(1) *The development of an integrated dynamic model for the predictions of the geodetic signals of daily to interannual surface mass changes*: these surface mass changes are mainly relocation of water mass in the ocean, atmosphere, and terrestrial hydrosphere. The main source of current model inaccuracies is in the surface mass models and the modeling approach, which does not sufficiently account for the mass conservation in the global water cycle and the gravitational and mechanical interactions between water mass redistribution and solid Earth deformations (see Plag et al., 2008, and the references therein). Moreover, the surface mass-induced deformations and gravity signals are not sufficiently taken into account in space-geodetic analysis, leading to biases in the geodetic reference frame (Herring et al., 2008) and surface mass estimates (Kusche and Schrama, 2006; Wu et al., 2006).
(2) *Inversion algorithms for combined geodetic observations for surface mass changes*: currently, most inversions for surface mass changes are based on one technique (e.g. Blewitt et al., 2001 for GPS; Crowley et al., 2006; Velicogna and Wahr, 2005 for GRACE), while combined analyses

exploring the strengths and mitigating the weaknesses of the individual techniques are just starting to emerge (e.g. Kusche and Schrama, 2005; Wu et al., 2006; Gross et al., 2008). Cross-validation of techniques is not explored and increase in resolution through multi-technique combinations has not been assessed. Inversion algorithms that routinely utilize multi-technique data are not available and need to be developed in order to make water-cycle related space-geodetic products continuously available. The goal of these algorithms is the determination of surface mass changes equivalent to 1 mm water column with spatial and temporal resolutions of 100 km and 10 days, respectively.

(3) *Integration/assimilation of observed surface mass changes in hydrological models*: models of the global water cycle are increasingly gaining in complexity, accuracy, and predictive capabilities. Most of these models are based on meteorological observations and coupled atmosphere ocean models. Examples are the Land Dynamics (LaD) World Model (Milly and Shmakin, 2002), the hydrological components of the reanalysis models of the European Center for Medium Range Weather Forecast (ECMWF) and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR), and the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004). Comparisons of the terrestrial water storage predicted by these models show significant intermodel differences. Therefore, utilizing the geodetic observations of surface mass in model validation is expected to resolve some of these differences. Assimilation of the geodetic products in these models will likely help improve the accuracy and cross-model consistency.

(4) *Development of products relevant for regional water management*: for practical applications, estimates of changes in surface mass are not directly usable. Together with water management experts, it will be necessary to develop specific products serving the users' needs in this field. Science questions to be addressed include the relation between the surface mass changes and hydrological parameters such as changes in regional aquifers, surface water storage, and soil moisture. The goal is to develop groundwater hydrology and terrestrial surface-groundwater modeling based on space-geodetic observations of GRACE- and GPS-type.

2.4 The Global Geodetic Observing System

The international cooperation fostered by IAG has led to the establishment of the IAG Services that provide increasingly valuable observations and products not only to scientists but also for a wide range of non-scientific applications. With the recent developments in geodesy, Earth observations, and societal needs in mind, IAG has established GGOS as the umbrella for all IAG Services (e.g., Plag et al., 2008; Plag & Pearlman, 2008). Today, GGOS is a full component of IAG and the permanent observing system of IAG (see, e.g., http://www.iag-ggos.org).

GGOS as an organization provides the interface for the IAG Services and Commissions to the outside world, particularly the main programs in Earth observations and Earth science. GGOS is actively involved in GEO. GGOS constitutes a unique interface for many users to the IAG Services. GGOS adds to the three main fields of geodesy a new quality and dimension in the context of Earth system research by combining them into one observing system having utmost accuracy and operating in a well-defined and reproducible global terrestrial frame. The observing system, in order to meet its objectives, has to combine the highest measurement precision with spatial and temporal consistency and stability that is maintained over decades. The research needed to achieve these goals influences the agenda of the IAG Commissions and the GGOS Working Groups.

GGOS as an observing system utilizes the existing and future infrastructure provided by the IAG Services (Figure 2). It aims to provide consistent observations of the Earth's time-variable shape, gravitational field, and rotation. GGOS provides on a global scale, and in one coordinate system, the spatial and temporal changes of the shape of the solid Earth, oceans, ice covers, and land surfaces. In other words, it delivers a global picture of the surface kinematics of our planet. In addition, it provides estimates of mass anomalies, mass transport, and mass exchange in the Earth system. Surface kinematics and mass transport together are the key to global mass balance determination, and an important contribution to the understanding of the energy and mass budget of our planet (e.g., Rummel et al., 2005; Drewes, 2006). Moreover, the system provides the observations that are needed to determine and maintain a terrestrial reference frame of increasing accuracy and temporal stability (Beutler et al., 2005). For this purpose, GGOS exploits (and tries to extend) the unique constellation of satellite missions relevant to this goal that are in orbit now or planned for the next two decades, by integrating them into one measurement system. The backbone of this integration are the existing global ground networks of tracking stations for the space-geodetic techniques Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS). GGOS is integrating these tracking networks with terrestrial gravity networks. GGOS also complements the space segment and global ground networks by airborne and terrestrial campaigns that serve the purpose of calibration and validation, regional densification, and refinement. Furthermore, through the analysis of the dense web of microwave radiation connecting the GNSS satellites with Low Earth Orbiters (LEO) and with the Earth's surface, a powerful new technique emerges for probing the atmosphere's composition. Assimilation of these observations into models of weather, climate, oceans, hydrology, ice, and solid Earth processes have and will continue to fundamentally enhance the understanding of the role of surface changes and mass transport in the dynamics of our planet.

Developing the geodetic observing system into a mass transport and dynamics observing system is a main motivation for the work of GGOS. Developing an observing system capable to meet the demanding user requirements by measuring variations in the Earth's shape, gravity field, and rotation with an accuracy and consistency of 0.1 to 1 ppb, with high spatial and temporal resolution, and increasingly low time latency, is a very demanding task. Accommodating the transition of new technologies as they evolve in parallel to maintaining an operational system is part of this challenge. Another challenge is associated with the integration of the three fields of geodesy into a system providing information on mass transport, surface deformations, and dynamics of the Earth. The Earth system is a complex system with physical, chemical, and biological processes interacting on spatial scales from micrometers to global and temporal scales from seconds to billions of years. Therefore, addressing this challenge requires a “whole Earth'” approach harnessing the expertise of all fields of Earth science.

Yet another challenge for geodesy arises from recent developments in global Earth observation with the establishment of GEO as culmination point. The challenge is to appropriately integrate GGOS as an organization into the international context of Earth observation and society, and to develop GGOS as an observing system in accordance with the strategies and methodologies of the global observing systems for the mutual benefit of all. Earth observation and society at large

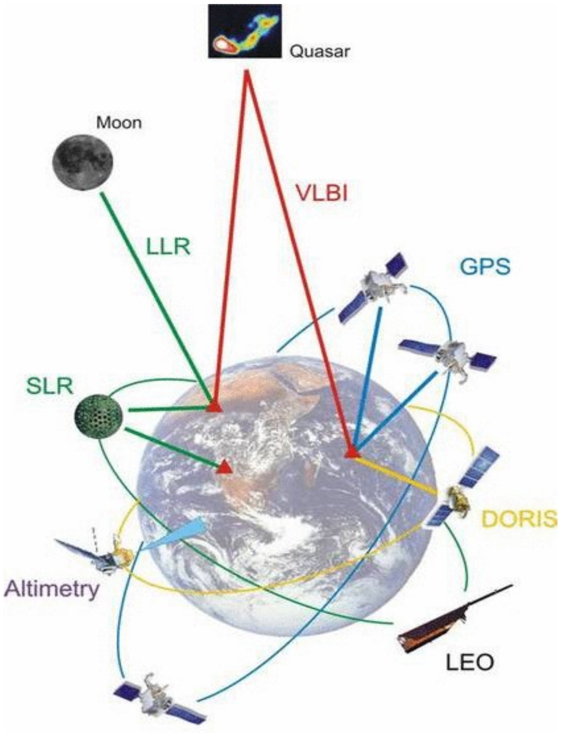

Figure 2: Infrastructure contributing to GGOS. The combined infrastructure allows the determination and maintenance of the global geodetic reference frames, and the determination of Earth's gravity field and rotation. The ground networks and navigation satellites (currently in particular GPS) are crucial in positioning, with applications to all SBAs. In particular, they allow the monitoring of volcanoes, earthquakes, tectonically active regions and landslide-prone areas. The *Low Earth Orbit* (LEO) satellites monitor sea level, ice sheets, water storage on land, atmospheric water content, high-resolution surface motion, and variations in the Earth' gravity field. The latter are caused, to a large extent, by regional and global mass transport in the hydrological cycle.

will benefit from the availability of geodetic observations and products, and GGOS will benefit from an improved visibility and acknowledgment of the valuable service it provides. In order to facilitate the contribution of GGOS to the Global Earth Observation System of Systems (GEOSS), IAG is a Participating Organization in GEO and is represented there by GGOS, which is also a contributing system to the GEOSS. The IGCP 565 Project has an important role in facilitating coordination between GGOS as it relates to the global water cycle, relevant research projects, and activities in the frame of the Societal Benefit Area (SBA) Water of GEO.

2.5 Related Activities

The observation system for the water cycle is the focus of several Tasks of the GEO Work Plan, each address different aspects of the cycle. Most importantly, Task WA-07-02 focuses on the remote-sensing part of the monitoring system for water quantity, and Task WA-06-05 addresses the *in situ* component (for more information, see the Task Sheets available at ftp://ftp.wmo.int/Projects/GEO/TaskSheets/).

Water-related issues are also covered by the GEO Community of Practice (CoP) for Water, which is linked to the Integrated Global Observing Strategy (IGOS) Theme on Integrated Global Water Cycle Observations (IGWCO). The IGWCO Theme has provided a description of the basic elements of an integrated observing system for the global water cycle (see Lawford et al., 2004). The geodetic contributions, particularly the one from gravity satellite missions like GRACE, are identified as crucial for regional to global scale variations in the water cycle.

Other relevant programs are the Global Energy and Water Cycle Experiment (GEWEX, see http://www.gewex.org) and the Climate Variability and Predictability (CLIVAR) project (see http://www.clivar.org) of the World Climate Research Programme (WCRP). GGOS and the

IGCP 565 Project utilize existing links between the project leaders and key actors of these programs and projects in order to explore and utilize synergies and coordinate the activities.

On the applied side, a number of international programs and organizations are potential partners in the development of products serving improved water resource management. An example is the International Water Management Institute (IWMI, http://www.iwmi.org), which "*concentrates on water and related land management challenges faced by poor rural communities,*" and the Global Water Partnership (GWP, http://www.gwpforum.org/), which is a comprehensive partnership among all those involved in water management and which "actively identifies critical knowledge needs at global, regional and national levels, helps design programs for meeting these needs, and serves as a mechanism for alliance building and information exchange on integrated water resources management." In the frame of the IGCP 565 Project, links to these organizations, and particularly their relevant regional bodies are being established in order to gain their support for the applied aspect of the work carried out in the project.

2.5 The IGCP 565 Workshop Series

A main activity of the IGCP 565 Project is the organization of a series of five annual workshops starting in 2008. The workshops aim to facilitate coordination of the research and capacity building within the frame of the IGCP 565 Project. The first workshop focuses on a review of the current status of research and technology with respect to the extraction of hydrological signals from geodetic observations with the goal to identify current gaps, challenges and obstacles. The second workshop will focus on future satellite gravity missions, while the third workshop will address issues related to data processing, technique integration, modeling, and interpretation. The last two workshops will be devoted to hydrological applications, particularly in developing countries, and they will bring in end users from the wide area of regional water management. The results of these workshops will be documented in workshop reports and published in appropriate journals. The results are expected to promote improved understanding of mass redistribution in the water cycle, in particular, changes in groundwater; better exploitation of the space-geodetic observations for hydrology; and societal benefits through an improved knowledge basis for regional water management.

3 CURENT AND ANTICIPATED RESULTS

3.1 Scientific Results

Although GRACE has provided the best estimates of changes in water storage on land and in ice sheets on sub-continental scales, and GPS observations have provided quantitative estimates of the seasonal changes in hemispheric water storage (for references, see below), the current water mass changes derived from space-geodetic observations are hampered by a number of short-comings. The on-going research (see http://geodesy.unr.edu/igcp565/ for a list of research projects) addresses these short-comings and is expected to significantly improve the accuracy, spatial resolution, and temporal coverage of water mass changes determined from space-geodetic observations. The dynamic reference Earth model for surface loads (Plag et al., 2007), which is being developed, will provide better insight in the fluxes between the various reservoirs of the water cycle. Validation based on and assimilation of the space-geodetic observations in water cycle models is expected to reduce inter-model differences and to improve the predictive capabilities of these models.

The project activities are expected to results in improved understanding of the global water cycle particularly on global to regional spatial scales and from sub-monthly to decadal time scales. The research projects are improving quantitative estimates of fluxes between the reservoirs in the water cycle, improvements of models of the global water cycle and the interaction of surface mass loads and the solid Earth's shape, gravity field, and rotation. Currently, the insufficiently modeled geodetic signals of surface loading on the solid Earth reduce the accuracy of geodetic products and hamper many scientific applications of the geodetic observations. The improved models of the geodetic signals of water mass redistribution developed in the project help to quantify the mass redistributions and their interactions with the solid Earth. This leads to a general improvement of geodetic products (reference frame, time series of Earth rotation, gravity field, and surface displacement changes) and thus enables research in other areas such as geodynamics and geohazards. The integrated and self-consistent model also correctly describes the contributions of the different components of the global water cycle (atmosphere, ocean, terrestrial hydrosphere). A better understanding of the relation between geodetic observations and changes in the terrestrial hydrosphere will improve the knowledge about decadal changes in the terrestrial hydrosphere on regional to global scale and thus enable global change research.

3.2 Results in Applied Sciences and Technology

A major anticipated result of the activities is the continuous monitoring of the global water cycle with gravity satellite mission. This includes both the immediate need for planning a follow-on mission for GRACE as well as the development of improved future missions with higher accuracy and spatial resolution. A continuation of GRACE-like missions is a fundamental prerequisite for a geodetic monitoring of the global water cycle. A major effort needs to be made to ensure subsequent missions when the current GRACE mission stops operation potentially as early as 2010. While on longer time scales, new and improved gravity missions are considered, the immediate need for continuation may be best met by a second GRACE-type mission. Such a mission could be deployed in close cooperation with one of the emerging space agencies in Africa or Asia. Moreover, in the frame of a virtual constellation for water cycle monitoring, additional gravity missions could be considered, thereby increasing spatial resolution considerably. The IGCP 565 Project is therefore exploring within GEO the various options for an appropriate path to ensure continuous gravity missions.

The current success of the GRACE mission and initial combined GPS and GRACE analyses shows that there is the capability to use the geodetic techniques for a remote sensing of the terrestrial hydrosphere. This capability has a great potential for further development, and major progress is attainable over the next few years. In further developing the understanding of the signals of regional hydrological loading in the regionally and globally inherently strong space-geodetic records, a major transition of the hydrological monitoring system on these spatial scales can be enabled. In combination with improved hydrological models, the expected improved gravity missions integrated with ever-growing GPS (and in the future GNSS) station networks, and the ensuing increase in accuracy and spatial resolution of the water-related information, will empower regional water resource management in a way and to an order of magnitude unattainable without geodetic sensing of the terrestrial hydrosphere.

Improved models and algorithms for the combination of space-geodetic observations in the inversion for surface mass changes will result in higher accuracy, spatial resolution, and extension of the time window accessible through space-geodetic observations. The surface mass changes determined from space-geodetic observations are supporting and will further improve the validation of the water cycle components of meteorological and climate models and help to reconcile the current inter-model difference. Moreover, the improved models of surface mass changes and their fingerprint in the geodetic observations provide a basis for the development of products that support regional water management. In this way, the full suite of space-geodetic observations will be made available for practical applications.

3.3 Terrestrial Water Storage From Space-Geodetic Observation

Particularly the combination of space-geodetic techniques has enabled significant progress in quantifying and understanding the processes in the Earth's interior and fluid envelope that are shaping the Earth's surface. The observations collected by the global geodetic networks have provided an increasingly detailed picture of the kinematics of points on the Earth's surface and the temporal variations in the Earth's shape. Among other applications, the observations have been used to determine improved models of the secular horizontal velocity field, to derive seasonal variations in the terrestrial hydrosphere, to study seasonal loading, to invert for mass motion, and to improve the modeling of the seasonal term in polar motion (see Plag et al., 2008, and the reference therein). Improvements in gravity field models obtained over the last three decades have gone hand-in-hand with improvements in the reference frames and Earth orientation observations. The innovative sensor technologies used in recent gravity field missions have already enabled a dramatic improvement of the gravity field during the last decade. Gravity field models from GRACE have benefited the space geodetic analysis of the DORIS tracking data, the orbits of ocean radar altimetry satellites, and laser altimeters (for references, see Plag et al., 2008).

The integration of all the satellite missions with other space-geodetic techniques into a consistent reference frame creates new opportunities to determine and study the mass transport in the Earth system in a globally consistent way (e.g., Kusche & Schrama, 2005; Wu et al., 2006; Gross, 2006) or to derive information on changes in reservoirs of the water cycle (e.g., the large ice sheets, see Velicogna & Wahr, 2005; Velicogna & Wahr, 2006). Analysis of the data delivered by GRACE yields a direct measure of mass flux with high spatial resolution of ~500 km on the Earth's surface (e.g., Wahr et al., 2004; Davis et al., 2004; Tapley et al., 2004; Crowley et al., 2006; Rodell et al., 2006), and sub-monthly temporal resolution (Luthcke et al.,2006). Combining these mass changes with advanced models of land water storage such as GLDAS (Rodell et al., 2004) rapidly improves the quantitative knowledge of the water cycle and provides new data sets for climate change studies (Troch et al., 2007).

However, inversion of single-technique observations for water storage changes are impacted by technique-specific weaknesses. In the case of GRACE, in addition to the accuracy of the satellite-to-satellite microwave ranging system, the accelerometers on each satellite, the GPS receivers, and a number of in-flight corrections (center-of-mass trims, for example), the result is also affected by non-instrumental ‘corrections’, such as an accurate removal of the energetic short period aliasing of the GRACE signal due to tides in the oceans, solid Earth, and atmosphere, and aliasing due to sub-monthly mass redistribution in the atmosphere, oceans, and over land. These aliasing effects (Stammer et al., 2000; Tierney et al., 2000; Thompson et al., 2004) are spread all over the globe because of the nature of the monthly or sub-monthly gravity field estimation. Separation of contributions from individual reservoirs (atmosphere, ocean, ice sheets, river basins, etc.) poses a significant problem too, and comparison with independent estimates of water storage changes reveal discrepancies. For example, Troch et al., (2007) found disagreements for the Colorado River basin between GRACE-based estimates of the timing of wet periods and those resulting from coupled atmosphere-terrestrial water balance. This may be partly due to an incomplete spatial separation of the different contributions to gravity changes. There are many potential sources of error in the final result, and any reasonable external validation would increase the confidence of external users in GRACE results. In addition, GRACE is insensitive to degree-1 changes, which are a significant component in seasonal variations. In the case of surface displacements observed with GPS, reference frame instabilities bias the hydrological signal, while implicit spatial filtering removes part of it, and discrepancies are found between different analyses (see, e.g., Wu et al., 2006). Incomplete modeling of the effect of mass redistribution in the global water cycle further hampers space-geodetic analyses and affects in particular the degree-1 term (e.g., Lavallée et al., 2006; Plag et al., 2007), thus demonstrating the level to which these effects are captured by geodetic observations. An integrated approach to the analysis and interpretation of space-geodetic observations will mitigate these technique-specific problems.

3.4 Current Use of Geodetic Observations for Land Water Storage Modeling

Over the last decade, a number of models providing information on terrestrial water storage variations have become available. The reanalysis of meteorological observations carried out by major meteorological centers (e.g., NCEP and ECMWF) provide land water storage as output, although with different spatial and temporal resolutions and different separation of reservoirs of the water storage system. More advanced Land Surface Models (LDMs) have been developed, which provide soil moisture, surface and subsurface runoff, snow cover, and, in some cases, plant canopy water storage. Examples are the GLDAS and LaD models.

GLDAS "*is a global, high-resolution, offline (uncoupled to the atmosphere) terrestrial modeling system that incorporates satellite- and ground-based observations in order to produce optimal fields of land surface states and fluxes in near-real time*" (Rodell et al., 2004). GLDAS incorporates several LDMs (including MOSAIC, CLM, NOAH, and VIC, see Rodell et al., 2004, for details and references) and several forcing data sets (including NCEP and ECMWF operational model and reanalysis outputs, as well as forcing fields derived from observations, see Rodell et al., 2004, for details). Output variables include among others soil moisture in each soil layer, snow depth and water equivalent, plant canopy water storage, surface and subsurface runoff, surface evaporation and canopy transpiration, snowmelt, snowfall, and rainfall.

LaDWorld is a series of retrospective simulations of global continental water and energy balances, created by forcing the LaD model (Milly & Shmakin, 2002) with estimated historical atmospheric conditions. Simulated variables include snow water equivalent, soil water, shallow groundwater, soil temperature, evapotranspiration, runoff and streamflow, radiation, and sensible and latent heat fluxes.

Both the GLDAS and LaD models continue to undergo development. The development benefits from collaborations with non-hydrologists whose studies of Earth-system dynamics both require and yield information on global hydrological processes. The IGCP 565 Project exploits these benefits in a direct link between the land hydrology modeling and space-geodetic communities.

Assimilation of space-geodetic observations in these land water storage models is currently restricted to GRACE. Moreover, the assimilation is not done on the observation level or the level of the geodetic parameters (gravity field variations). For GLDAS, assimilation is currently based on water equivalents. This requires a preprocessing of GRACE observations which extracts the water storage variations from the gravity field variations observed by GRACE. With respect to spatial scales, variations for large river basins can be extracted (Troch et al., 2007). In practice, GRACE estimates of water storage on river-basin levels are assimilated for large basins.

3.5 Integration of Space-Geodetic Observations

We are considering three aspects of the integration of the space-geodetic observations: (1) forward modeling, (2) inversion, and (3) validation. Current forward modeling is mostly done separately for surface displacement and gravity changes on the one side and Earth rotation on the other side. In most cases, the loading signals of atmospheric, terrestrial, and oceanic loading are computed separately without ensuring mass conservation in the water cycle and gravitational consistency of the mass redistribution. The numerical models for prediction of load-induced surface displacements and gravity changes are based on the same theory used for solid Earth tides, ocean-tidal loading, and post-glacial rebound (see, e.g., Farrell, 1972; Peltier, 1974; Dahlen, 1976). For surface loading, numerous studies have shown that the main uncertainties of the predictions result from uncertainties in the load model (e.g., Vandam et al., 2003; Blewitt & Clarke, 2003), hence the sensitivity of geodetic observations to variations in the load. Earth rotation models are normally based on a linearized angular momentum balance and, again, the main uncertainty of the predictions results from uncertainties in the forcing (e.g., Plag, 1997, Aoyama, 2005). Our forward model for the surface-mass induced response of the solid Earth makes use of an integrated model of the mass redistribution in the atmosphere, ocean, and on land. This model ensures mass conservation and, particularly in the ocean, a mass redistribution that is gravitationally consistent. The surface mass distribution is described in terms of the three stress components on the surface of the solid Earth and the incremental gravity field due to mass variations. Together with angular momentum changes in the atmosphere and ocean, these quantities drive the deformation and rotational perturbations of a solid Earth module in a modular Earth system model (see, e.g., Jüttner & Plag, 1999), which produces predictions of Earth rotation perturbations, surface displacements, and gravity field variations.

The inversion model used here was first published by Blewitt & Clarke, 2003 and is based on the same theory as the forward models. The inversion makes use of base functions specifically designed to account for the different response and impact of ocean and terrestrial water load changes. Much of the progress with respect to inversion is published in the literature and is given in the references (in particular, Gross et al., 2004; Clarke et al., 2005; Lavallée et al., 2006). We emphasize a recent progress in the base functions for the representation of the surface loads which led to significantly better accuracy and consistency (Clarke et al., 2007).

For the integration of the three geodetic fields as a tool to study the terrestrial hydrosphere, it is first essential to validate each technique through intercomparison with the other methods (to assess internal consistency and precision) and through comparison with surface loading (forward) models (external consistency and accuracy). The complexity of this task is apparent from Figure 1 and the discussion above. However, recent consistency studies between gravity, Earth rotation, and surface displacements based on comparison of temporal variations in the degree-2 term determined from the different space-geodetic techniques reveal a promising degree of agreement (Gross et al., 2008). The conclusions from this study are that GRACE measurements agree closest with current models of the surface mass load, with correlations as large as 0.96, and time series variances explained as large as 70%. Earth rotation measurements also agree quite well with surface mass load models. GPS measurements of the Earth's shape agree reasonably well with surface mass models, though they appear to be noisier than GRACE and Earth rotation measurements. Correlations as large as 0.85 were observed, with as much as 64% of the variance explained. Most likely, the current limiting factor for the mass inferred from GPS observations is the incomplete modeling of hydrological loading in the reference frame determination (Lavallée et al., 2006; Plag et al., 2007).

4. DISCUSSION

As discussed above, on regional to global scales, the mass transports observed by GGOS are already improving the database concerning the motion of water through the hydrological cycle, and future combined analysis of the variations in Earth's gravity field, shape and rotation will help to reduce the uncertainties. But the project activities also have significant organizational and societal impacts.

4.1 Institutional Impact Results and Capacity Building

GGOS is based on the best effort of institutions of many countries (on the order of 100). However, active representation of institutions from developing countries is limited and the IGCP 565 Project aims to increase integration of these institutions into GGOS with particular focus on the activities related to the monitoring of the global water cycle. The IGCP 565 Project also provides a formal frame for improved international cooperation of the GEO and GGOS activities aiming at improved monitoring of the global water cycle. Moreover, it fosters links between ongoing water-cycle related international programs and the relevant GEO Tasks.

The project has a strong focus on knowledge transfer to developing countries in several areas. The anticipated participation of one or more emerging space agencies in Africa and/or Asia in a follow-on GRACE-like mission would lead to significant technology transfer to these agencies. Integration of institutions in developing countries in data processing and interpretation, particularly in the frame of GGOS, facilitates knowledge transfer to these institutions and supports capacity building with respect to research. Developing products for applications in developing countries stimulates capacity building in the utilization of Earth observation products for societal applications. The project is fully aligned with the goals of GEO with respect to data sharing, knowledge and technology transfer in Earth observation, and capacity building in applications utilizing Earth observation products.

4.2 Societal Impact

The societal significance of the work carried out in the project is underlined by the fact that the Earth Observation Summits (EOS) identified "*Improving water resource management through better understanding of the water cycle*" as one of the nine SBAs of Earth Observations (see Appendix 4 in GEO, 2005). Subsequently, the GEO members have initiated several water-related tasks in the GEO Work Plans, to which the project activities contribute.

The societal benefit of improved knowledge about the water cycle has been emphasized by many. Improving water resource management is a crucial challenge for the global society. As pointed out above, this implies better information through improved monitoring, capacity building, and delivery of the “right” data and information products to those responsible for water management. Capacity building in developing countries, both through the series of workshops as well as joint research projects, facilitates technology transfer related to geodetic monitoring of the water cycle. Crosscutting activities bringing together water managers, data providers and researchers, promote a broader use of the space-geodetic products for practical applications in the field of regional water management, including flood predictions and drought monitoring. Through feedback from users to providers, the project fosters the availability of useful products for water resource management. Through the involvement of several international organizations and the coordination with additional relevant international programs, the project aims to provide a focal point with respect to monitoring the global water cycle bringing together research, observation, and user communities.

CONCLUSIONS

Although we do not expect that full utilization of the space-geodetic observations will provide ultimate answers to the research questions reported in Box 1, based on the results available to date, we anticipate that these observations will provide important constraints on terrestrial water storage variations if they are utilized in an integrated, gravitationally, and geophysically consistent way. Considering the debilitating effect of the observational gap with respect to subsurface water changes on land water storage models, the potential of the combined space-geodetic observations cannot be ignored. However, in order to fully exploit this potential a number of science issues, including those listed in Section 2.3, need to be addressed. The research projects associated with the IGCP 565 Project are well posed to achieve this goal.

As argued above, only the integrated space-geodetic observations can ensure consistency of the inferred mass redistribution forcing the variations in Earth's shape, gravity field, and rotation. Therefore, the full potential of these observations as constraints for mass redistribution in the water cycle requires an integrated approach and a state model that ensures gravitational and geophysical consistency. In terms of improved constraints for regional water storage models, we distinguish between three different levels of geodetic products:

- Level 0: geodetic observations, i.e., GRACE, GPS, SLR, and VLBI observations: these observations require rather complex algorithms for the processing and therefore are difficult to use directly as constraints in terrestrial water storage models.
- Level 1: geodetic parameters, i.e., gravity field variations, surface displacements, and Earth rotation changes: these parameters can be directly related to mass redistribution in the water cycle by the theory of our forward and inversion models. Individual parameters have different sensitivities at given spatial and temporal scales, and integrating these parameters reduces weaknesses and explores strengths.
- Level 2: water mass changes, i.e., mass redistribution from inversion: the result of the inversion depends on the model assumptions and approaches, and there are problems with aliasing, resolution, and the separation of processes and regions.

We believe that the most appropriate approach for constraining water-mass redistribution is by assimilating the geodetic parameters (level 1) directly into the water cycle models. The theory linking mass redistribution to the geodetic parameters is available and to a large extent validated.

Therefore, developing and validating a state model for the assimilation of the geodetic parameters into water cycle models such as GLDAS is feasible, based on our forward and inversion models. The space-geodetic parameters would add an independent, observation-based, long-term stable, and globally consistent constraint to the terrestrial water storage models. At least for surface displacements and Earth rotation, the geodetic parameters could be made available with high temporal resolution and low latency and thus support near-real time models.

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