Challenges and Opportunities in Water Cycle Research: WCRP Contributions

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Abstract

The state of knowledge and outstanding challenges and opportunities in global water cycle observations, research and modeling are briefly reviewed to set the stage for the reasons behind the new thrusts promoted by the World Climate Research Programme (WCRP) as Grand Science Questions (GSQs) to be addressed on a 5 to 10 year time frame. A number of GSQs are being brought forward within the WCRP under guidance of the Joint Scientific Committee (JSC) and those focused on water are led by GEWEX, the Global Energy and Water cycle Experiment. Here we describe what are some imperatives and opportunities for major advancements in observations, understanding, modeling, and product development for water resources and climate that will enable a wide range of climate services and inform decisions on water resources management and practices.

1. Introduction

Driven mainly by solar heating, water is evaporated from ocean and land surfaces, transported by winds, and condensed to form clouds and precipitation which falls to land and oceans. Precipitation over land may be stored temporarily as snow or soil moisture, while excess rainfall runs off and either forms streams and rivers, which discharge the freshwater into the oceans, or infiltrates into the soil and percolates to depths to re-charge the underground aquifers thereby completing the global water cycle (Trenberth et al 2007; Fig. 1). Associated with this water cycle, energy, salt within the oceans, and nutrients and minerals over land are all transported and redistributed within the Earth climate system. Moreover, water is vital for human existence and is irreplaceable. It is more than a natural resource that we exploit and often take for granted. Water plays a crucial role in Earth’s climate, functioning of ecosystems and environment.

Many studies on the global water cycle deal with only specific aspects (see the review by Trenberth et al. 2007a, and other chapters in this monograph). Reliable data on the surface water budget are often available only over certain regions. Relatively few studies (e.g., Trenberth et al. 2007, 2011; Oki and Kanae 2006) have attempted to provide a synthesized, quantitative view of the global water cycle, and our quantitative knowledge of the various components and their variability of the global water cycle is still fairly limited because of a lack of reliable data for surface evapotranspiration, oceanic precipitation, terrestrial runoff, and several other fields. Regional closure of the water cycle over many large river basins has been attempted by Vinukollu et al. (2011) and Sahoo et al. (2011) using satellite data but, unless adjusted, they do not adequately close the water budget, and the imbalances highlight the outstanding observational and modeling limitations.

Satellite based observations provide global coverage but may lack continuous coverage in time and generally require some kind of algorithm to produce a geophysical product that inevitably has limitations, so the result must be verified against other independent measurements such in situ observations. However, as the number of analyzed fields grows with ever increasing satellite data products, it is vital for these to be properly evaluated and documented for their strengths and weaknesses along with quantifying their uncertainties. Some of the satellite-based observations limitations may be overcome with in situ observations because they measure directly the quantity desired, but it is likely a spot measurement and its representativeness and calibration may not be sufficient to capture the spatial characteristics, unless a sufficiently large number of such measurements are obtained. Building and maintaining such large measurement networks have been challenging, especially over the developing regions of the world where such measurements are needed most. Blended or hybrid satellite and in situ products are also growing in number and attempt to capitalize on the strengths of each. Some are produced in a model framework and may involve data assimilation. Nevertheless, with multiple products synthesized in the framework of the overall water cycle, it is possible to make use of physical constraints inherent in a closed water budget, and physical models to help refine all components that are not well observed, by taking their uncertainty into account.

2. The WCRP

The World Climate Research Programme (WCRP) mission is to facilitate analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society. The two overarching objectives of the WCRP are:

1) **to determine the predictability of climate**; and
2) **to determine the effect of human activities on climate.**

Progress in understanding climate system variability and change makes it possible to address its predictability and to use this predictive knowledge in developing adaptation and mitigation strategies. Such strategies assist the global communities in responding to the impacts of climate variability and change on major social and economic sectors including food security, energy and transport, environment, health and water resources (Asrar et al. 2012a). The main foci of WCRP research are:

- Observing changes in the components of the Earth system (atmosphere, oceans, land and cryosphere) and in the interfaces among these components;
- Improving our knowledge and understanding of global and regional climate variability and change, and of the mechanisms responsible for this change;
- Assessing and attributing significant trends in global and regional climates;
- Developing and improving numerical models that are capable of simulating and assessing the climate system for a wide range of space and time scales;
- Investigating the sensitivity of the climate system to natural and human-induced forcing and estimating the changes resulting from specific disturbing influences.

The WCRP is sponsored by the World Meteorological Organization (WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

WCRP is organized as a network of core and co-sponsored projects, working groups and cross-cutting initiatives. The current core projects of WCRP are:

- **Climate and Cryosphere (CliC):** The principal goal of CliC is to assess and quantify the impacts of climatic variability and change on components of the cryosphere and their consequences for the climate system, and to determine the stability of the global cryosphere.
- **Climate Variability and Predictability (CLIVAR):** CLIVAR’s mission is to observe, simulate, and predict the Earth’s climate system with a focus on ocean-atmosphere interactions in order to better understand climate variability, predictability and change.

- **Global Energy and Water Cycle Experiment (GEWEX):** GEWEX focuses on the atmospheric, terrestrial, radiative, hydrological and coupled processes and interactions that determine the global and regional hydrological cycle, radiation and energy transitions and their involvement in global changes such as increases in greenhouse gases.
- **Stratospheric Processes And their Role in Climate (SPARC):** SPARC has as its principal focus research on the significant role played by stratospheric processes in the Earth's climate, with a particular emphasis on the interaction between chemistry and climate.

There are also several working groups or councils on modeling and data that coordinate climate observations, modeling and prediction activities across the entire WCRP. The coordination of research among the physical, biogeochemical, socio-economic dimension of global change research is achieved through Earth System Science Partnership (ESSP) which will be soon succeeded by a new initiative entitled "Future Earth: research for global sustainability" http://www.icsu.org/future-earth.

The Joint Scientific Committee of the WCRP is considering several scientific Grand Challenges that emerged from the consultation with the global scientific community at a recent WCRP Open Science Conference to be the major foci for the WCRP activities during the next decade (Asrar et al. 2012b). They include:

- Provision of skilful future climate information on regional scales
- Regional Sea-Level Rise
- Cryosphere response to climate change
- Improved understanding of the interactions of clouds, aerosols, precipitation, and radiation and their contributions to climate sensitivity
- Past and future changes in water availability
- Science underpinning the prediction and attribution of extreme events.

Although global water cycle is affected by and affects all of these, we focus only on the last two challenges that involve water and the hydrological cycle for this monograph.

3. The global water budget and hydrological cycle

As the climate changes partly from human activities, the water cycle is also changing (Trenberth 2011). Moreover demand for water continues to increase owing to growing population, enhanced agricultural and industrial development, and other human activities such as transformation of landscape and construction of dams and reservoirs, so that very little of the land surface is not changed. This affects the disposition of water when it hits the ground: how much runs off, and how much find its way to rivers or infiltrates into the soil and percolates to depths to replenish the underground water reservoirs.

The adverse impact of such activities is not confined to quantity and distribution of water, but also increasingly affects water quality. Water is used in various ways: such as through irrigation or by consumption in other human activities; reservoirs and artificial lakes are used to store water, while dams and other structures are used to control water flows in rivers. Water is heated and cooled and, as a strong solvent, it is polluted in many areas.

Many physical scientists have tended to ignore the latter aspects and deal mainly with the climate system either in its "natural" state or as changed by human activities by mainly accounting for increased greenhouse gases and changing atmospheric particulates (IPCC 2007). Even in this somewhat simplified framework, it has been challenging to simulate the hydrological cycle. For example, global reanalyses of most existing observations have substantial shortcomings in representing the hydrological cycle (Trenberth et al. 2011). Such shortcomings arise because, while observations are assimilated to ensure a realistic representation of atmosphere and some Earth surface processes, the analysis increment ensures that water is not conserved and sources of moisture for precipitation may come from the increment and not evapotranspiration. Models generally have a lifetime of water in the atmosphere that is too short, and this affects their ability to transport water vapor onto land while they tend to recycle moisture locally more than observed.

The main impacts of a warmer climate on global water cycle include the following:

- With warming, higher atmospheric temperatures increase the water holding capacity of the atmosphere by about 7% per degree Celsius.
- Over the ocean where there is ample water supply, the relative humidity remains about the same and hence the observed moisture goes up at about this rate: an increase in total column water vapor of about 4% since the 1970s (Trenberth et al 2007b).
- Over land the response depends on the moisture supply.
- With more heat in the earth system the evaporation is enhanced resulting in more precipitation. The rate of increase is estimated to be about 2% per degree Celsius warming (Trenberth 2011).
- Locally this means increased potential evapotranspiration, and in dry areas this means drying and more intense and longer lasting droughts.
- Larger warming over land versus the ocean further changes monsoons.
- Precipitation occurs mainly from convergence of atmospheric moisture into the weather system producing the precipitation, and hence increased water vapor leads to more intense rains and snows, and potentially to more intense storms.
- More precipitation occurs as rain rather than snow.
- However, higher temperatures in winter over continents favor higher snowfalls.
- Snow pack melts quicker and sooner, leading to less snow pack in the spring.
- These conditions lead to earlier runoff and changes in peak streamflow.

Hence there is a risk of more extremes, and thus both floods and droughts.

The pattern of observed changes, so far, indicates wetter conditions in higher latitudes across Eurasia, east of the Rockies in North America, and in Argentina, but drier conditions across much of the tropics and subtropics (IPCC 2007; Dai et al. 2009; Trenberth 2011; Dai 2011), and this pattern is referred to as “The rich get rich and the poor get poorer” syndrome (the wet areas get wetter while the arid areas get drier). This pattern is projected to continue into the future (IPCC 2007), including an increase in probability of the water-related extremes (IPCC 2012).

Over land there is a strong negative correlation between precipitation and temperature throughout the tropics and over continents in summer, but a positive correlation in the extratropics in winter (Trenberth and Shea 2005). The latter arises from the baroclinic storms that advect warm moist air ahead of and into the storm. The former arises from the nature of the atmospheric circulation interactions with land. In cyclonic conditions increased cloud and rain provides more soil moisture and thus partitions the decreased surface energy more into latent energy (higher evaporation) instead of sensible heat (lower temperatures). Anticyclonic conditions favor sunshine (more available energy), less rain and soil moisture, and the larger surface energy raises temperatures instead of evaporating moisture. The result is more likely either hot and dry or cool and wet conditions, but not the other options.

On global land, there is large variability in precipitation from year to year and decade to decade associated especially with El Niño-Southern Oscillation (ENSO) but there has been an increase overall in land precipitation (Fig. 2). The two wettest years are 2010 and 2011. In particular, major flooding in Pakistan, Australia, and Colombia was associated with record high sea surface temperatures (SSTs) in the second half of 2010 into 2011 (Trenberth 2012) and led to a dramatic drop in sea level of about 5 mm (Fig. 3). The prospects for more intense precipitation but longer dry spells leads to the increased risk of flooding and drought, which pose major challenges for the society at large and those who have to manage water resources for food, fiber and energy production, and human consumption and leisure. We therefore view observing, understanding, modeling and predicting the global water cycle as a grand science challenge.

4. Grand Challenges

A Grand Challenge should inspire the community to want to be involved; it needs to be specific and focused while identifying barriers and ways to advance the science, and it must capture the imaginations of agencies, program managers, and the public. It should also provide a vehicle to encourage the different WCRP panels to interact in pursuing a common goal. It must provide a way forward that is tractable, perhaps via new observations (e.g., from satellites), computer and model advancements, and ideas. It must matter, as shown by answers to questions on possible benefits and impacts and links to food, water, health, energy, biodiversity, and so on.

The GEWEX Science Steering Group (SSG) has identified four such Grand Challenge Questions (GSQs). Three of these challenges deal with water and two of them are combined into a more general water resource GSQ for WCRP that also encompass scientific activities coordinated by the CliC, CLIVAR and SPARC projects. The third GSQ in GEWEX is part of a WCRP-wide theme of extremes. The following section describes the GSQs.

4.1 GSQ on water resources

How can we better understand and predict precipitation variability and changes, and how do changes in land surface and hydrology influence past and future changes in water availability and security?

These questions focus on the exploitation of improved data sets of precipitation, soil moisture, evapotranspiration, and related variables such as water storage and sea surface salinity expected in the next 5 to 10 years. These will allow us to close the water budget over land and provide improved information for products related to water availability and quality for decision makers and for initializing climate predictions from seasons to years in advance. The improvements will come from ongoing and planned satellite missions (see below) as well as greater use of in situ observations; their evaluation and analysis to document mean, variability, patterns, extremes and probability density functions; their use to confront models in new ways and to improve our understanding of atmospheric and land surface processes that in turn feed into improved simulations of precipitation; and new techniques of data assimilation and forecasts that can lead to improved predictions of the hydrological cycle across scales, from catchments to regional to global, including hydrogeological aspects of ground water recharge. In particular need of attention is the use of realistic land-surface complexity with all anthropogenic effects taken into account, instead of a fictitious natural environment. This encompasses all aspects of global change, including water management, land-use and land-cover change, and urbanization. The ecosystem response to climate variability and responsive vegetation must be included, as must cryospheric changes such as dynamics of permafrost, thawing and changes in mountain glaciers. These results should all lead to improved understanding and prediction of precipitation and water variability, enhance the evaluation of the vulnerability of water systems, especially to extremes, which are vital for considerations of water security and can be used to increase resilience through good management and governance.

The 21st century poses formidable challenges for the sustainable management of water resources at all levels, from the local, regional to the global scale. Water is a basic requirement for life and effective water management is needed to provide some of society's most basic needs. However, demand for water resources is increasing, due to population growth and economic development, while water resources are under pressure globally from over-abstraction and pollution. This is increasingly leading to competition for water, at local, regional and international levels. Environmental change is adding additional pressures. Anthropogenic influences are changing land and water systems, redefining the state of drainage basins and the rivers and groundwater aquifers that supply the bulk of renewable freshwater supply to society. Widespread land use changes, associated with population increases, urbanization, agricultural intensification and industrialization, are changing hydrological systems in complex ways, and on many of the world's major rivers, water management is changing flows, often with severe effects on downstream users, aquatic ecosystems and freshwater discharges to the world's seas and oceans. Superposed on these pressures, expected climate change and climate variability can combine to create extreme and perhaps unprecedented conditions which have high impact consequences for human populations, economic assets and critical physical infrastructure. This unique combination of pressures has exposed weaknesses in current water governance and management. It has increased the awareness of uncertainties, the complexity of the systems to be managed, and the need for profound changes in policy and management paradigms, as well as governance systems.

WCRP has a unique role to play in developing the new scientific understanding and modeling and prediction tools needed for a new era of global water management. WCRP mainly through GEWEX and based on significant contributions from CLIVAR and CliC projects is well poised to motivate a new generation of land surface and global hydrological models, building on recent developments in earth observations, that represent the dynamics of major managed water systems. The modeling activities have an equally important role in motivating a new generation of weather-resolving climate models that are capable of simulating and potentially predicting the basic modes of variability, whether arising from sea surface temperature and ocean, land surface moisture, sea ice, or other sources that are known to drive global precipitation variability and extremes on seasonal to decadal time scales. Such prediction systems are increasingly necessary to address regional impacts of climate change.

The vast majority of water comes from precipitation – either directly, or indirectly through runoff from distant locations. From a climate perspective, it is therefore an imperative to understand the natural variability of precipitation in the system, as well as its susceptibility to change from external forcings. Because of its inherently intermittent nature, it is a major challenge to determine precipitation amounts reliably with a few instantaneous observations of rates such as from available satellites. Improved observations and analysis products related to precipitation and the entire hydrological cycle, and their use in evaluating and improving weather, climate and hydrological models is important and tractable over the next 5 to 10 years.

The specific questions that will be addressed over the next 5-10 years include:

- ***How well can precipitation be described by various observing systems, and what basic measurement deficiencies and model assumptions determine the uncertainty estimates at various space and time scales?*** Despite significant improvements in many observing systems during the past two decades, the uncertainty in precipitation estimates lies not only in the measurement error itself, but in the space/time interpolation of a naturally discontinuous and intermittent field and/or in the assumptions needed to convert a physical measurement from remote sensing into a precipitation amount. Critical water source regions often reside in complex terrain where sampling issues, remote sensing artifacts, and limitations are compounded. The errors are not static but instead depend on the nature of the precipitation itself. Focusing on the large scale environment responsible for the precipitation therefore holds hope to build not only better rainfall products, but characterizing the uncertainties in a verifiable manner as well. Regional hydroclimate projects provide detailed understanding that translate the large-scale information into usable information for decision makers.

- ***How do changes in climate affect the characteristics (distribution, amount, intensity, frequency, duration, type) of precipitation – with particular emphasis on extremes of droughts and floods?*** Increased temperatures, and associated increases in lower tropospheric water vapor, by making more water vapor available to storms, will very likely increase the intensity of rains and snows, increasing risk of severe floods. Changes in seasonality, shifts in monsoons, changes in snow-melt and runoff, and so on are also part of this question which is elaborated on in the "extremes" science question.
- ***How do models become better and how much confidence do we have in global and regional climate predictions of precipitation?*** A challenge to the earth system science community is to develop improved global models. Scientists are beginning to run global climate models at sub 10 km resolution, resolving meso-scale weather including the most extreme tropical storms. These need to be coupled to the ocean and land, and will require a new generation of parameterizations that better reflect what processes are and are not resolved in such models. These models can potentially revolutionize our ability to correct long-standing model biases, minimize the need for downscaling, and provide predictions of regional impacts and changes in extremes from months to decades ahead. There is great need to quantify the uncertainty in precipitation projections and predictions, especially at regional scales. Starting with improved uncertainties in the climate observations of precipitation, new and improved diagnostics must be developed to test the robustness of model predictions in different regimes. Knowing the uncertainties is critical if predictions of the mean precipitation and its distribution are to be used in local planning efforts.
- ***How do changes in the land surface and hydrology influence past and future changes in water availability and security?*** While the land surface has small heat capacity, and heat moves slowly via conduction, the water flow and storage vary enormously. Land has a wide variety of features, topography, vegetation cover, and soil types and consists of a mixture of natural and managed systems. Land plays a vital role in carbon and water cycles, and ecosystems functions and services. Of particular need of attention is use of realistic land surface complexity in hydrological models with all anthropogenic effects included instead of a fictitious natural environment. This includes all aspects of global change including water management, land-use and land-cover change and urbanization, and their feedbacks to the climate system. There is a need to address terrestrial water storage changes and close the water budget over land through exploitation of new datasets, data assimilation, improved physical and biogeochemical understanding and modeling skill across scales, from catchments to regional to global with links to the entire hydrological cycle.
- ***How do changes in climate affect terrestrial ecosystems, hydrological processes, water resources and water quality, especially water temperature?*** The ecosystem response to climate variability and responsive vegetation must be included but is mostly neglected in today's climate models. Cryospheric changes such as permafrost thawing, changes in the extent, duration and depth of seasonal snowpacks,

and changes in mountain glaciers must also be included. Feedbacks, tipping points, and extremes are of particular concern to all economic sectors and regions, globally. The scientific knowledge of water cycle should enhance the evaluation of the vulnerability of water systems, especially to extremes, which is vital for considerations of water and food security and can be used to increase their resilience through good management practices and governance.

- ***How can new observations lead to improvements in water management?***

Over the last few decades, in situ observations of land surface hydrologic variables, such as streamflow, rainfall and snow have generally been in decline. Regional estimation of evapotranspiration remains a significant challenge. At the same time, new observation methods, such as weather radars, flux towers, and satellite sensors have led to different types of measurements, and challenges for their incorporation in the hydrologic models used for hydrologic prediction and water management. One example is soil moisture, which in most models essentially acts as a buffer between the land forcings (mostly precipitation and evapotranspiration) and runoff, and whose characteristics are defined by the internal model parameterizations that control runoff production. Sustained measurements of soil moisture are critically important to understanding, modelling and prediction of the water cycle.

- ***How can better climate models contribute to improvements in water management?*** Regional precipitation predictions remain a challenge at all timescales from seasonal forecasting out to centennial climate change. However, there are limited regions with forecast skill on seasonal timescales, associated mainly with ENSO, and broad scale, zonally-averaged precipitation changes associated with climate change appear to be detectable. The challenge now is to maximise the skill and reliability of predictions of regional rainfall changes on all timescales, for all regions around the world. This requires better understanding and model simulation of the teleconnections and drivers of regional climate such as changes in the oceans and cryosphere that are relevant to regional precipitation. Subsequent improved climate prediction systems and better dissemination of climate prediction information must be developed to deliver the envisioned information and their ultimate benefit to society.

Prospects for advancements are excellent on this GSQ because of new observations already underway and those planned for the ensuing decades, and the growing interest in climate predictions on all timescales. Key areas of development include:

1. A new Global Precipitation Mission as detailed at http://pmm.nasa.gov/GPM. *"Through improved measurements of precipitation globally, the GPM mission will help to advance our understanding of Earth's water and energy cycle, improve forecasting of extreme events that cause natural hazards and disasters, and extend current capabilities in using accurate and timely information of precipitation to directly benefit society."* The joint US National Aeronautics and Space Administration (NASA)/Japan Aerospace Exploration Agency (JAXA) mission's Core Observatory is scheduled for launch in 2014. Most of the world's major space agencies will participate in this mission through the contribution of constellation satellites to obtain the desired revisit times to roughly 3 hrs, over the entire Earth.
2. Closely related missions such CloudSat (a NASA mission with components from the Canadian Space Agency to measure clouds and light precipitation), and EarthCARE a European Space Agency (ESA) mission (http://www.esa.int/esaLP/SEM75KTWLUG_LPearthcare_0.html) to advance our understanding of the role that clouds and aerosols play in the climate system), due for launch late 2015, that will make important contributions to the global precipitation estimates.

3. New satellite sensors such as Soil Moisture and Ocean Salinity (SMOS) (an ESA mission to map soil moisture and sea surface salinity), Aquarius (a NASA/Space Agency of Argentina mission to improve sea surface salinity),and future Soil Moisture Active Passive (SMAP) data (a NASA mission dedicated to measuring soil moisture and the freeze/thaw cycle), produce or will produce estimates of near-surface soil moisture that can be used to diagnose or update model estimates, and Gravity Recovery and Climate Experiment (GRACE) (a joint NASA/German Aerospace Center (DLR) mission to map gravity anomalies and thus detect changes in water storage), now provides a nearly decade-long record of total water storage, albeit at coarse spatial resolutions. The GRACE follow on mission is intended to enhance the spatial resolution of such measurements, and provide continuity of measurements over the future decade. The planned Surface Water and Ocean Topography (SWOT) mission will provide observations of lake and reservoir surface area and levels, from which changes in storage of over 7000 km^3 of the estimated 8000 km^3 of reservoir storage globally will be available at one to two week intervals. In addition in situ observations from buoys and ARGO floats will help close the water and energy budgets over the oceans.
4. A dedicated snow hydrology mission such as ESA's Cold Regions Hydrology High-Resolution Observatory (CoReH2O) will enable better understanding of the role snow hydrology plays in the regional/global water cycle, especially in mountainous regions of the globe that depend mainly on snow as a source of fresh water for human consumption, food production and industrial activities (e.g., California, Tibetan Plateau, La Plata Basin, etc.).
5. Improvements in communication and data exchange policies to help create higher resolution global surface maps of precipitation and soil moisture based upon both local very dense networks of high-resolution measurements as well as surface radar networks where these are available. Significant gains are expected from high resolution gridded products being developed by GEWEX and other projects based on in-situ data as well as inventories of long-term in-situ precipitation time series focused on engagement of these data into validation, error estimation and intercomparison efforts. The use of improved error statistics to develop new blending algorithms and fusion techniques capable of bringing together precipitation measurements with distinct error characteristics (e.g. gauges, radar, satellites and models) into a consistent physical framework. Advances in data assimilation techniques that allow more precipitation information to be incorporated into Numerical Weather Prediction models.
6. Estimates of fluxes of moisture from surface are improving through the use of flux tower and other observations over land, feeding into improve estimates of evapotranspiration as part of the GEWEX Landflux and ocean flux projects.
7. The production of an Integrated Water and Energy product by the GEWEX Data Assessment Panel (GDAP) can be used to explore linkages between hydrology and energy variables in the Earth System which in turn provides a much improved basis for evaluating models on all aspects of the water cycle. Advanced diagnostic methods that use the observed variables and their covariability to diagnose not only problems in the model output, but also assess model processes and potential improvements to these processes in order to better represent the observed climate behavior.
8. Incorporation of more realistic land surface hydrology into land surface models, including water management, land management and land-use and land-cover change, as well as improved process representation (including cryospheric processes). The envisioned new information is expected to be revolutionary in terms of the management of trans-boundary rivers, but current climate models have no

mechanisms for use of this information, since most do not represent the effects of water management.

9. New methods must be developed to address water system vulnerability, particularly to extremes. Quantification of the uncertainty in each of the elements of the global water-balance, including the managed aspects, in a consistent manner is required. Further there is a need to communicate uncertainties, manage expectations, address the needs of water management under uncertainty (e.g., building resilience).
10. Several other developments in modeling are progressing and advances appear likely. These include development of improved precipitation downscaling methods, particularly for mountainous and arid regions; evaluation of the hydrologic dynamics of land surface models with newly available data; prediction of stream temperature as a diagnostic tool in land surface models; improving freshwater fluxes to the world's seas and oceans; and including the known climate feedbacks in off-line land-surface change assessments. Water demand models and assessments to land surface and hydrological models must be linked at the global scale.
11. Demonstration of the usefulness of GEWEX, and Global Climate Observing System (GCOS) and WCRP coordinated data products is required along with new tools and provision of derived information for water resources management. The new tools include cross-scale modeling, ensemble hydrological prediction, data assimilation, and data analysis and visualization.

There are multiple benefits and the results are critically important for society. In addition to greatly improved knowledge about land water resources and ocean salinity, and the causes of their variations, much improved models will allow better predictions of the variability and change on all time scales from seasonal to centennial and from global to continental to basin scales. Predictions, with quantified uncertainties provide invaluable information for water managers and users, including decision makers at many levels associated with food and water security. These developments would naturally serve to push WCRP research and development priorities, as users provide feedback on weaknesses and further needs for information.

The information provided also feeds into the development of a "Global Drought Information System". Such a system would provide a user anywhere in the world access to information on our current understanding of drought in that region (e.g., role of ENSO, Pacific Decadal Oscillation, global warming, etc), the history of drought in that region (with access to various data, time series, indices, etc), current conditions (monitoring results), the results of near real time attribution (our understanding of the current conditions), and regularly updated forecasts from months to years in advance (with consistent estimates of uncertainties).

The system would naturally build on the various investments being made in observations (including reanalysis), drought research, and modeling and forecasting capabilities (e.g., the various national and international Multi-Model Ensemble (MME) efforts such as the WMO lead center for long range forecasts: http://www.wmolc.org). The system would be built hand-in-hand with the user community, and would have to be sustainable and refreshable as new datasets, better understanding and better modeling capabilities become available. It would naturally serve to push WCRP research and development priorities, as users provide feedback on weaknesses and further needs (analogous to how the weather community is continuously being pushed for better weather forecasts). These are the envisioned products and information to be provided by the network of organizations and centers through Global Framework for Climate Services (GFCS) and Future Earth (WMO 2011; Asrar et al. 2012a).

4.2 *GSQ on water extremes*

How does a warming world affect climate extremes, especially droughts, floods, and heat waves, and how do land area processes, in particular, contribute?

A warming world is expected to alter the occurrence and magnitude of extremes such as droughts, heavy rainfalls and floods, as well as the geographic distribution of rain and snow. Such changes are related to an acceleration of the hydrologic cycle and circulation changes, and include the direct impact of warmer conditions on atmospheric water vapor amounts, rainfall intensity, and snow-to-rain occurrence. How well are models able to handle extremes and how can we improve their capability? New improved and updated data sets at high frequency (e.g., hourly) are needed to properly characterize many of these facets of Earth's climate and to allow for assessment against comparable model data sets. New research activities are needed to promote analyses quantifying which changes are consistent with our expectations and how we can best contribute to improving their prediction in a future climate. Confronting models with new observationally-based products will lead to new metrics of performance and highlight shortcomings and developmental needs that will focus field experiments, process studies, numerical experimentation, and model development. New applications should be developed for improved tracking and warning systems, and assessing changes in risk of drought, floods, river flow, storms, coastal sea level surges, and ocean waves.

There is major concern that the occurrence, character and intensity of extremes will change in the future as the climate changes due to human activities, and this will have enormous consequences for society and the environment. Yet addressing changing extremes satisfactorily is a daunting task and it will be difficult to keep up with society's expectations. As noted above, huge improvements in near-global spatial and temporal coverage for precipitation, soil moisture and other hydrological variables provide opportunities for new datasets, products, improved models, and model applications, making it an opportune time to fully address extremes.

The climate system does not neatly package such extremes. Extremes may be highly localized in time and in space. Drought in one region frequently means heavy precipitation not that far away. The worst extremes are generally compound events which often are consequences of a chain-of-events that may be related at the global scale despite their regional implications. Flooding may be accentuated due to saturated soils from previous storms and/or from snowmelt. Furthermore, coastal flooding may involve storm surge effects, local precipitation and remote snowmelt signals.

Because of its importance, there are many efforts focusing at least in part on extremes within WCRP. One focus is on drought although there is certainly interest in other hydrometeorological extremes and related issues, such as statistical analyses. WCRP, mainly through CLIVAR, also addresses tropical and extratropical cyclones and associated marine storms as well as extreme sea level variability and change that is connected to storm surges. GEWEX with its focus on the water cycle and on land surface processes with strong observational capabilities from global to local and with numerous links with society is a natural 'home' for addressing many types of extremes. The question is what is missing and what can be done within GEWEX to move ahead? The main GEWEX focal point is to increase efforts on hydrometeorological extremes including drought, heat waves, cold outbreaks, floods, storms, and heavy precipitation events including hazardous winter snowfalls and hail.

The specific questions that will be addressed over the next 5-10 years include:

- **What are the short-term, mid-term and strategic requirements for the existing observing systems and datasets, and which observations are needed to accurately quantify trends in the intensity and frequency of extremes on different space/time**

scales? Despite a continuous improvement in most observing systems, high frequency information (e.g., hourly precipitation) required to properly assess extremes is often not made available and shared. New satellite observations and the synthesis of all observations will help and may free up some data. Metrics for quantifying extremes need to be assessed and new ones should be introduced to improve diagnostics of extremes and scale them to different areas. It is necessary to determine for which regions (national observing systems) the requirements are close to be satisfied and where they are not. There is an urgent need for research on design, development and maintaining optimum observing systems, the regular analysis of their adequacy/inadequacy for future investments in such systems.

- **How can models be improved in their simulation and predictions or projections of the magnitude and frequency of extremes?** Current models have difficulty in simulating the hydrologic cycle and they typically have problems handling the diurnal cycle. Model resolution is insufficient in most cases to simulate many of the extremes of interest, including floods with scales of a few kilometers and even drought whose worst-affected areas are typically in areas only of order a few hundred kilometers or less. Model parameterizations addressing precipitation, convection and clouds are insufficient for accurate simulation and timing of many extreme events. Models need to be confronted with the new observational products in innovative analyses and with new diagnostics and metrics of performance. This includes numerical weather prediction and climate models. There are conceptual difficulties in validating model results against observations, first of all associated with (but not limited to) co-location in space and grid cell data versus point measurements. Many observational products are developed independent of models so that gridding projections and associated error characteristics are often different from model-derived data products thus making their direct inter-comparisons very difficult if not impossible. Focused investments by space agencies (e.g., ESA and NASA) to make the observational products consistent and intercomparable is quite timely. Such efforts facilitate research on observations and make intercomparisons with models much easier, and enhance the use of observations by the modeling community.
- **How can the phenomena responsible for extremes be better simulated in models?** Many phenomena that are responsible for extremes are not well simulated in models; some because of resolution (such as tropical storms and highly localized precipitation events), but also others that are resolved (such as blocking anticyclones). As well as statistical analyses, studies should examine the phenomena responsible for extremes, whether and how well they are depicted in models, and how to overcome incompatible resolution requirements. Developmental needs should be used to focus field programs, process studies, and numerical experimentation.
- **How can we promote development of applications for improved tracking and warning systems arising from extremes?** It is essential to develop ways to better assess changes in risk of drought, floods, river flow, storms, coastal sea level surges, and ocean waves. Such information has the greatest benefit to society for management of risks associated with these events to reduce their adverse impacts. In most cases, such applications will be done in conjunction with the CLIVAR and CliC projects and made available through networks sponsored by GFCS and other regional climate information systems.

Prospects for advancements are excellent on this question because of new observations, research, modeling and prediction activities already underway and planned. A number of specific, short and near-term activities are envisioned that will move this GSQ ahead. Key areas of development include:

1. Utilization of the new global and regional datasets outlined above and from improved data assessment (within the GEWEX Data Assessment Panel) to better characterize extremes on different spatial scales and, with the WCRP Modeling Council, promote evaluations of model results, potentially with one or more workshops in 2014-15.

2. Ensure strong involvement in the Global Drought Information System. This focuses on one particular type of extreme but the effort may also act as a prototype for dealing with all types of extremes in the future. In particular, GEWEX and CLIVAR will develop trackable actions on monitoring and quantification of the global distribution of droughts and their trends using observational information, model development, land area factors governing drought, and societal interactions.
3. Facilitate a number of intercomparison projects aimed at comparison of characteristics of extremes in different data sets (in-situ, reanalyses and satellites), and revealed by different models.
4. Initiate a parallel activity centered on capabilities of statistical methodologies to deal with the complexity of extremes, including their clustering in space and time and with sparse and regionally unevenly distributed data.
5. Initiate multi-methods activities and encourage documentation and data inventory centered on a few mega-extreme events (for example, catastrophic flooding, droughts, unusual storm patterns) to enable further analysis with observations and models, ensure that all their aspects are comprehensively addressed, and with special attention on assessing their likelihood in the future. This activity may be facilitated by bringing teams together and should build in flexibility with adaptable approaches as one learns by doing. It has the advantage that the results are immediately relevant.
6. Examine cold season extremes such as snowstorms, rain-on-snow episodes, freezing precipitation and prolonged cold weather events with CliC and other international and national research programs/projects.

There are multiple benefits and the results are important for society.

Drought has devastating consequences whenever and wherever it occurs. Water resources can be strained and adverse effects occur in agriculture. Heat waves are often but not always linked with drought. Health effects can be profound. Prolonged cold weather episodes are a critical feature of mid- and sub-polar latitudes in winter. They are disruptive and costly. Isolated extreme rainfalls as well as continuous periods of heavy and moderate precipitation occur everywhere with numerous impacts including flooding, devastation of ecosystems, and havoc in urban regions. Storms in different parts of the world are the means by which precipitation, often linked with strong winds, occur, and changes in their paths, intensity and frequency have enormous consequences, sometimes devastating. Warming conditions imply that regions accustomed to receiving snow should experience more rain, and changing times of runoff and peak streamflow, with large consequences for ecosystems, hydrologic risks and water resources.

These examples highlight the importance of progress in the area of climate extremes, both in terms of their observations and analysis, and in terms of improved modeling and prediction. In summary, WCRP through GEWEX, CLIVAR and CliC and its seamless modeling framework across space and time scales (e.g., Working Groups on Coupled Modeling and Numerical Experimentation (WGCM and WGNE)) will focus great attention on extremes, including research on detection and attributions of causes and consequences of such events over the next 5-10 years. By doing so, it will be carrying out its very natural role of addressing the estimation, modeling, understanding and future projection of extremes with a particular focus over land.

5. Conclusions

The successful implementation of WCRP Grand Science Challenges and associated science questions described in this chapter depend significantly on GEWEX Imperatives: observations and data sets, their analysis, process studies, model development and exploitation, applications, technology transfer to operationalize results, and research capacity development and training of the next generation of scientists. They involve all of the GEWEX panels, and will benefit greatly from strong interactions with other WCRP projects such as CLIVAR and CliC and other sister global change research programs such as the International Geosphere-Biosphere Programme (IGBP), International Human Dimensions (IHDP), etc.

Closure of the observed regional and global water budget over the past decade has progressed significantly, but remains a major challenge thus it continues to be a science imperative for the research community to better observe and understand all aspects of the water cycle in order to improve models that can predict reliably its future variability and change as a major source of information for decision makers for water resources, food production, and management of risks associated with extreme events. Many potential products could be invaluable to water resource managers on several time horizons, extending well beyond the one week weather scale to seasonal, inter-annual and decadal predictions, and climate change projections.

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Figure legends

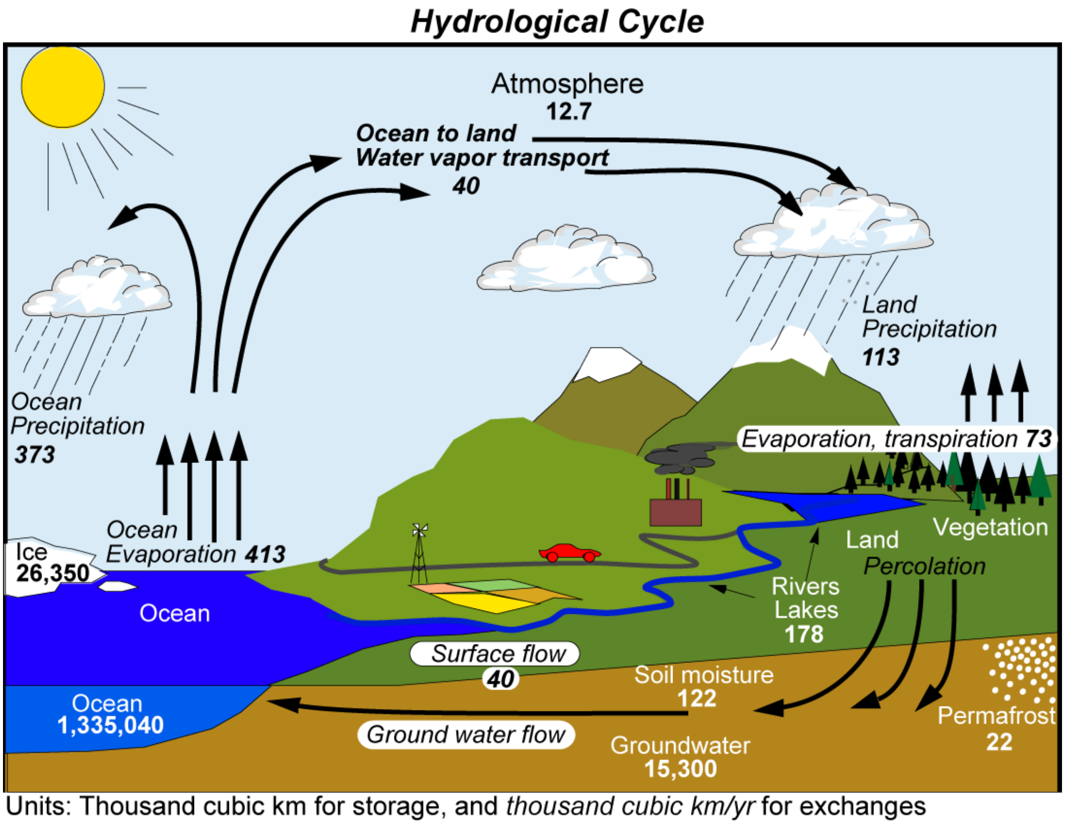

Fig. 1. The global annual mean Earth's water cycle for the 1990s. The arrows indicate the schematic flow of water substance in various forms. From Trenberth et al. (2007).

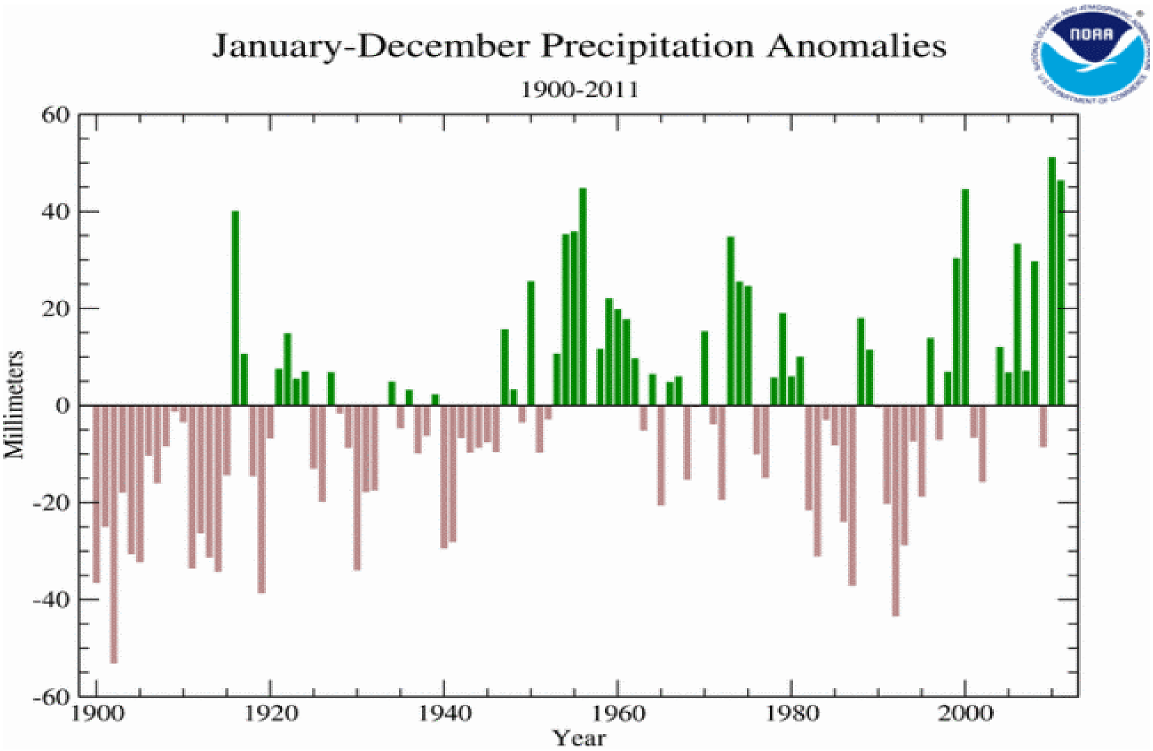

Fig. 2 Annual mean anomalies in global land precipitation from 1900 to 2011 in mm; from NOAA. http://www.ncdc.noaa.gov/sotc/global/2011/13

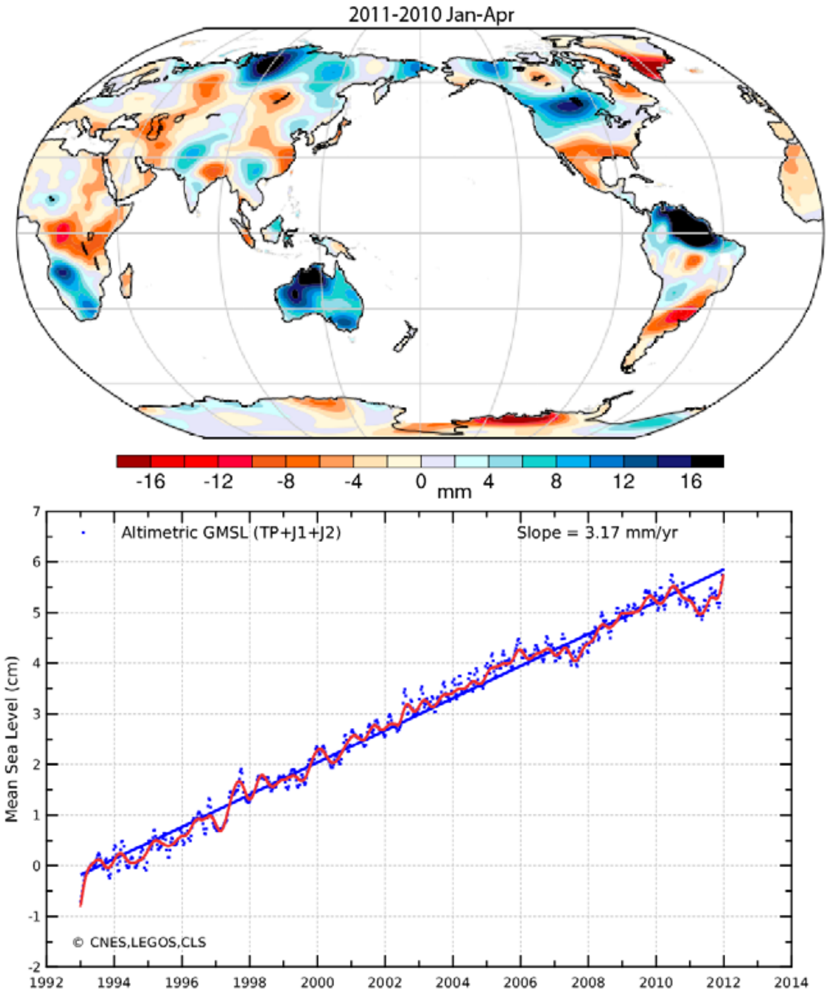

Fig. 3. (top) Differences between GRACE microgravity estimates of changes in mass on land in mm of land water equivalent from January to April 2011 vs 2010. (bottom) AVISO (http://www.aviso.oceanobs.com/msl) estimates of global sea level anomalies based upon satellite altimetry. The inverse barometer and postglacial rebound adjustments have been applied. The dots show 2-month values and the red line shows the 6-month smoothed changes. Courtesy CNES, LEGOS, CLS.