GEWEX
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Global Energy and Water Exchanges
Project of the World Climate Research Programme

GEWEX Plans for 2013 and Beyond

GEWEX Science Questions

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Preface

The World Climate Research Programme (WCRP) under the guidance of the Joint Scientific Committee (JSC) has adopted six Grand Challenges to be addressed in a 5-10 year time frame. The Global Energy and Water Exchanges (GEWEX) Project is the lead project for the challenges that are focused on water. Four overarching GEWEX Science Questions (GSQs), identified by the GEWEX Scientific Steering Group, are being brought forward within GEWEX. This document describes these and the associated opportunities for major advancements in observations, understanding, modeling, and product development for water resources, climate extremes, and other aspects of climate that will enable a wide range of climate services and inform decisions on water resource management and practices.

Introduction

The mission of the World Climate Research Programme (WCRP) 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 WCRP are to determine the predictability of climate and the effect of human activities on climate.

The **Global Energy and Water Exchanges (GEWEX)** Project is one of four core projects under WCRP and its focus is 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 gasses. GEWEX was previously known as the Global Energy and Water Cycle Experiment, but was recently renamed and retains the same acronym. The other WCRP projects are the Climate Variability and Predictability Project (CLIVAR), the Climate and Cryosphere Project (CliC), and the Stratospheric Processes And their Role in Climate Project (SPARC). These projects may also change their names to better reflect their evolving roles based upon the WCRP Grand Challenges described below.

Grand Challenges

The Joint Scientific Committee (JSC) of WCRP developed six scientific Grand Challenges after consultations with the global scientific community during the WCRP Open Science Conference in October 2011. The major foci of the Grand Challenges that will lead WCRP activities during the next decade include:

1. **Actionable regional climate information**
2. **Regional sea-level rise**
3. **Cryosphere in a changing climate**
4. **Cloud and climate sensitivity**
5. **Changes in water resources**
6. **Prediction and attribution of extreme events**

GEWEX has been asked to take the lead on the last two of these, but also plays a major role in the first and fourth, and a lesser role in the others.

The primary goal of the Grand Challenges is to inspire the community to become involved. They are specific and focused while identifying barriers and ways to advance the science, and they should capture the imaginations of funding agencies, science program managers, and the public. The Grand Challenges are meant to provide a vehicle to encourage the different WCRP components to interact in pursuing common goals. They also provide a way forward that is tractable, perhaps via new observations (e.g., from satellites), computer and model advancements, or ideas. Funding for some challenges has been secured, but others require agencies to step up to fund them. They must matter, as shown by answers to questions on possible benefits to society, by providing the science-based information to address impacts of climate variability and change to food, water, health, energy, biodiversity, and so on.

GEWEX

GEWEX is made up of four main projects.

- GDAP: GEWEX Data and Assessments Panel, focused on global data sets and their assessment
- GASS: Global Atmosphere System Study, focused on atmospheric processes and their parameterization
- GLASS: Global Land-Atmosphere System Study, focused on land surface modeling and processes
- GHP: GEWEX Hydroclimatology Panel, focused on regional hydroclimate projects

GEWEX Science Questions

The GEWEX Science Steering Group (SSG) has identified four GEWEX Science Questions (GSQs). These were developed in parallel with or slightly before the Grand Challenges, but are fully compatible. The GSQs emerged from in-depth discussions and subsequent circulation to all GEWEX Panel members for comment. They were then posted on the GEWEX website for open commentary. They have also been presented to the WCRP Joint Scientific Committee and the outcome is presented here. Three of the GSQs are concerned with water and two of them have been combined into a more general water resource Grand Challenge for WCRP, which also encompasses the scientific activities coordinated by the CliC, CLIVAR, and SPARC projects. The third GSQ is part of a WCRP-wide theme of extremes. The final GSQ relates to energy and processes.

The GEWEX Science Questions are related to the following research areas:

1. **Observations and Predictions of Precipitation**
2. **Global Water Resource Systems**
3. **Changes in Extremes**
4. **Water and Energy Cycles and Processes**

GSQ #1

GEWEX Science Question 1: **Observations and Predictions of Precipitation**

How can we better understand and predict precipitation variability and changes?

This question focuses on the exploitation of improved data sets of precipitation as well as related variables, such as soil moisture, water storage, and sea surface salinity expected in the coming five years. These improvements will come from ongoing and planned satellite missions 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. These results should all lead to improved understanding and prediction of precipitation variability and related climate services.

Context

The 21st Century poses extreme challenges for the sustainable management of water resources at all levels from the local to the global scale. Water is a basic requirement for life and the vast majority of water comes from precipitation–either directly, or indirectly through runoff from distant locations. From a climate perspective, it is therefore 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 just from available satellites with a few instantaneous observations of rates. Improved observations, modeling, and analysis products related to precipitation and the entire hydrological cycle, and their use in evaluating and improving weather, climate, and hydrological models, are important and tractable over the next 5-10 years.

GEWEX has a unique role to play in exploiting the internationally diverse set of satellite, in situ, and model resources to foster a global approach to mapping precipitation and its uncertainty at scales from local to global with resolutions of hours to decades and longer. Its unique vantage point of treating precipitation not as a stand-alone quantity but a component within the water and energy fabric, where precipitation is naturally connected via the hydrological cycle to runoff, stream flow, evaporation, water vapor, clouds, and radiative fluxes, allows GEWEX to gain insights that would be difficult to achieve from a single variable perspective. CLIVAR has an equally important role, along with GEWEX, 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 and ocean temperature, 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 specific questions that will be addressed over the next 5-10 years are:

How accurately 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 a continuous improvement in observing systems, the uncertainty in precipitation estimates lies not only in the measurement error itself, but also 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. Neither of these errors is 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 also to characterize the uncertainties in a verifiable manner. Regional hydroclimate projects provide detailed understanding that translates the large-scale information into usable information at decision- making scales.

How do changes in climate affect the characteristics (e.g., distribution, amount, intensity, frequency, duration, type) of precipitation, with particular emphasis on extremes of droughts and floods? Increased temperatures, and associated increases in lower troposphere water vapor, make more water vapor available to storms, and will very likely increase the intensity of rains and snows, thus increasing the risk of severe floods. Changes in seasonality, shifts in monsoons, changes in snowmelt and runoff are also part of this question, which is elaborated on in the “extremes” science question, GSQ3.

How much confidence do we have in global and regional climate predictions of precipitation? Regional precipitation predictions and projections 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 El Niño Southern Oscillation (ENSO), and broad scale, zonally-averaged precipitation changes associated with climate change appear to be detectable. Scientists are beginning to run global climate models at sub-10 km resolution, resolving mesoscale 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 is and is not resolved. 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 maximize the skill and reliability and quantify the uncertainty of precipitation projections and predictions at regional scales. 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. 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 mean precipitation and its distribution are to be used in local planning efforts.

Prospects for advancements are excellent on this question because of new observations already underway and planned. Key areas of development include:

1. A new Global Precipitation Mission (GMP) 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 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 used to reduce revisit times to roughly 3 hours. [GDAP]
2. Closely related missions such as 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 in late 2015] will make important contributions to the global precipitation estimates. [GDAP, GASS]
3. Additional data sets from missions such as the Soil Moisture and Ocean Salinity (SMOS) mission (an ESA mission to map soil moisture and sea surface salinity) and Aquarius (a NASA and Argentina Space Agency mission to improve sea surface salinity), in addition to in situ observations from buoys and Argo floats, will help close the water and energy budgets over the oceans. [GLASS, GHP, GDAP]
4. Surface observations of soil moisture, ground water, and hydrology (see GSQ 2), in addition to space-based observations including the recently available 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] data, SMOS data, and data from the future Soil Moisture Active Passive (SMAP) satellite (a NASA mission dedicated to measuring soil moisture and the freeze/thaw cycle), will help constrain precipitation estimates over land, as well as close the water budget to add confidence in all these observations at global scales. [GHP, GDAP, GLASS]
5. Improvements in communication and data exchange policies will help create higher resolution global surface maps based upon both local very dense networks of high-resolution precipitation measurements and surface radar networks where these are available. Significant gains are expected from high-resolution gridded products based on in situ data as well as inventories of long-term in situ precipitation time series focused on the engagement of these data in validation, error estimation, and intercomparison efforts. All GEWEX Regional Hydroclimate Projects (RHPs) have collected precipitation data from a network of surface stations, and many have created gridded precipitation data sets from these, making them well placed to be testing grounds for new remotely sensed precipitation data sets. [GDAP, GHP]

6. The production of an Integrated Water and Energy product that can be used to explore linkages between hydrology and energy variables in the Earth system will in turn provide a much improved basis for evaluating models on all aspects of the water cycle. Advanced diagnostic methods that use the observed variables and their co-variability will enable not only diagnosis of problems in the model output, but also assessment of model processes and potential improvements to these processes in order to better represent the observed climate behavior. [GDAP, GASS]
7. In turn, model development and especially development of precipitation parameterizations (cumulus convection and microphysics) will be enabled. [GASS, GLASS]
8. The use of improved error statistics will enable development of 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. [GHP, GLASS]
9. Advances in data assimilation techniques will allow more precipitation information to be incorporated into numerical weather prediction (NWP) models. [GASS, GLASS]

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

As well as greatly improved knowledge about land and water resources, ocean salinity, and the causes of their variations, much improved models will allow better predictions on all time scales 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.

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 with access to information on our current understanding of drought in that region [e.g., the role of ENSO, the Pacific Decadal Oscillation (PDO), global warming], the history of drought in that region (with access to various data, time series, and indices), current conditions (monitoring results), the results of near real-time attribution (our understanding of the current conditions), and forecasts (with consistent estimates of uncertainties). The system would naturally build on the various investments we are making in observations including reanalysis of all data, drought research, and modeling/forecasting capabilities [e.g., the various national and international Multi-Model Ensemble (MME) efforts]. The system would be built hand-in-hand with the user community, and would have to be sustainable and refreshable as new data sets, 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 the Global Framework for Climate Services (GFCS).

GSQ #2

GEWEX Science Question 2: **Global Water Resource Systems**

How do changes in land surface and hydrology influence past and future changes in water availability and security?

There is a need to address terrestrial water storage changes and close the water budget over land through exploitation of new data sets, data assimilation, and improved physical understanding and modeling skill across scales, from catchments to regional to global with links to the entire hydrological cycle, including ground water. 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 change, and urbanization. Water quality and especially water temperature, both of which are greatly affected by industrial and power plant use, are of immediate concern, to be followed by nutrients. The ecosystem response to climate variability and responsive vegetation must be included, as must cryospheric changes such as permafrost thawing and changes in mountain glaciers. Feedbacks, tipping points, and extremes are of particular concern. The results should 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.

Context

The 21st Century poses extreme challenges for the sustainable management of water resources at all levels from the local 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 further 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 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. Added to these pressures, expected climate change and the concomitant increase of extreme events will 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.

GEWEX has a unique role to play in developing the new scientific understanding and modeling tools needed for a new era of global water management. GEWEX is well poised to motivate a new generation of land surface and global hydrological models, building on recent developments in Earth observations, which represent the dynamics of managed waters. At the same time, many closely related activities are occurring in the International Geosphere-Biosphere Programme (IGBP) where biogeochemical and ecological aspects, as well as land use and land cover change issues, are dealt with in detail. The integrated Land-Ecosystem-Atmosphere Processes Study (iLEAPS) and the International Land Model Benchmarking (ILAMB) projects under IGBP are especially relevant. Fully integrated Earth system models will be the ultimate tool to provide synthesis and predictions.

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

How do changes in 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, water storage varies enormously and water flows from one place to another. Land has a wide variety of features, slopes, vegetation, and soils and is a mixture of natural and managed systems. Land plays a vital role in carbon and water cycles, and ecosystems. In particular need of attention is use of realistic land surface complexity with all anthropogenic effects included instead of a fictitious natural environment. This includes all aspects of global change including water management, land use 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 data sets, data assimilation, improved physical 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 and changes in mountain glaciers must also be included. Feedbacks, tipping points, and extremes are of particular concern. The results should enhance the evaluation of the vulnerability of water systems, especially to extremes, which is vital for considerations of water security and can be used to increase their resilience through good management 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 stream flow, have generally been in decline. At the same time, new observation methods such as weather radars 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.

Prospects for advancements are excellent for this question because of new observations already underway and planned. Key areas of development include:

1. New satellite sensors such as SMOS, Aquarius, and future SMAP data produce or will produce estimates of near-surface soil moisture that can be used to diagnose or update model estimates. GRACE 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 1-2 week intervals. In addition, in situ observations from buoys and Argo floats will help close the water and energy budgets over the oceans. [GHP, GLASS, GDAP]
2. More realistic land-surface hydrology will be incorporated into land-surface models, including water management, land management, and land use change, as well as improved process representation (including cryospheric processes). The new information coming available 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. [GLASS, GHP]
3. New methods must be developed to address system vulnerability, particularly to extremes. Quantification of the uncertainty in a consistent manner in each of the elements of the global water-balance, including the managed aspects, is required. Further, there is a need to communicate uncertainties, manage expectations, and address management under uncertainty (e.g., building resilience). [GHP]
4. 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 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. [GASS, GLASS, GHP]
5. Demonstration of the usefulness of GEWEX data products, as well as new tools such as cross-scale modeling, ensemble hydrological prediction, data assimilation, and data provision in water resource management, is required. [GHP, GLASS]
6. A dedicated snow hydrology mission, such as the ESA 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). [GHP, CliC]

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

As well as greatly improved knowledge about land and water resources, and the causes of their variations, much improved models will allow better predictions on all times scales 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.

GSQ #3

GEWEX Science Question 3: **Changes in 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 our climate and to allow for assessment against comparable model data sets. New 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 programs, 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.

Context

There is great concern that the occurrence, character and intensity of extremes will change in the future, as the climate changes due to human influences, 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 in GSQ 1 and 2, huge improvements in near-global spatial and temporal coverage for precipitation, soil moisture and other hydrological variables provide opportunities for new data sets, products, improved models, and model applications, making now 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. 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. Effects of persistence are a critical aspect of drought.

Because of its importance, there are many efforts within WCRP focusing at least in part on extremes. 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 fluctuations 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 data sets, 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 or subhourly 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 being satisfied and where they are not. There is an urgent need for research on the design, development and maintenance of optimum observing systems, and 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 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 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 independently of models so that gridding projections and associated error characteristics are often different from model-derived data products, thus making their direct intercomparisons very difficult if not impossible. Focused investments by the 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. There is a great need for more scientists to work on improving models.

How can the phenomena responsible for extremes be better simulated in models? Many of the phenomena responsible for extremes are not well simulated in models. This is partly due to resolution issues (e.g., tropical storms and highly localized precipitation events), however there can also be problems with phenomena that have been resolved (e.g., blocking anticyclones). Statistical analyses studies should be used to examine these phenomena, including 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. In most cases, such applications will be done in conjunction with the CLIVAR and CliC projects.

Prospects for advancements are excellent on this question because of new observations and other 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 data sets outlined in GSQ 1 and 2 and from GDAP to better characterize extremes on different spatial scales and, with the WCRP Modeling Council, promote evaluations of model results and development and improvement of models through detailed analysis of the performance of the physical parameterizations, potentially with one or more workshops in 2014-15. [GASS, GDAP, GHP, GLASS]
2. Ensure strong involvement in the Global Drought Information System. This activity has been discussed under GSQ1 and it focuses on one particular type of extreme, but this effort may also act as a prototype for dealing with all types of extremes in the future. In particular, develop [together for CLIVAR] tractable actions on monitoring and quantification of the global distribution of droughts and its trends using observational information, model development, land area factors governing drought, and societal interactions. [GDAP, GHP, GLASS]
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. [GASS, GDAP, GHP, GLASS]
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. [GDAP, GHP, GLASS]

5. Initiate multi-tool activities and encourage documentation and data inventory centered on a few mega-extreme events (e.g., 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. [GHP, GASS, GDAP, GLASS]
6. Evaluate and benchmark models and exploit data assimilation to improve calibration with respect to extremes as opposed to average conditions. Knowing model performance is essential for making good use of models and also for improving them. [GLASS, GASS]
7. Examine cold season extremes such as snowstorms, rain-on-snow episodes, freezing precipitation and prolonged cold weather events with CliC via a workshop. [GASS, GDAP, GHP]

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 for drinking water, agriculture, energy production and the aquatic environment. 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 stream flow, with large consequences for ecosystems, hydrologic issues 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, GEWEX will focus a great deal of attention on extremes over the next several 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.

GSQ #4
GEWEX Science Question 4: **Water and Energy Cycles and Processes**

How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?

This question includes goals of improved consistency between net solar and infrared radiation and sensible and latent heat fluxes at the surface to reveal processes that in turn must be replicated in climate models, at multiple scales. This question relates also to uncertainties introduced by incomplete understanding of cloud-aerosol-precipitation interactions and their feedbacks to the climate system. Only through a better understanding of the uncertainties in observations and models will it be possible to discriminate natural variability from longer-term trends of key variables such as temperature and precipitation. Possibilities of new satellite-based measurements, combined with observations at the surface and in the ocean, should enable improved reconciliation between observed changes in the radiative imbalance at the top-of-atmosphere (TOA) and the inventory of changes in energy throughout the Earth system. Upgraded GEWEX data sets, global reanalyses of atmosphere and ocean, and improved modeling together with advanced diagnostics being planned throughout the GEWEX Panels play key roles in advancing this topic. The result is improved tools and products for climate services.

Context

Part of this question relates to the energy imbalance at the top-of-atmosphere and at the surface, how it is changing over time, and how it is manifested in terms of warming signs. The global mean temperature is but one, albeit widely used, indicator. Even in a steadily warming climate, it is known that natural variability can overwhelm rising global mean temperatures for periods of up to 17 years. An ongoing accounting of where heat goes and its manifestations is a great need and has implications for interpreting the recent past and immediate future. How much warming has gone into melting Arctic sea ice, Greenland, Antarctica, and glaciers? How much has gone into the oceans and where and what depth, and is it likely to return to the surface to influence climate patterns (e.g., via El Niño) or is it mixed into the abyss? How much can strong heating events penetrate into the deep ocean or how long can heat be stored in the mixed layer? How much can perturbations in global radiative forcing affect the efficiency of the atmospheric thermal engine? On regional scales, how much change in temperature and precipitation is due to circulation changes and how much is due to energy flux changes at the surface and TOA?

GEWEX can play an important role in triggering the development of new data products, in increasing the understanding of the observed changes and their attribution, and in detailing the uncertainty from global to local scale. Evaluation and improving models through close scrutiny of these aspects is greatly needed. This effort is essential for correctly transferring climate information to stakeholders in several sectors encompassing financial and risks assessment.

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

Can we balance the energy budget at the top-of-atmosphere? How is the energy balance changing over time and how is it manifested in terms of changes in ocean heat content, sea ice, land ice, and other storage on Earth? The potential exists to monitor TOA radiation at the $0.2 Wm^{-2}$ level needed to monitor the Earth's energy, but can we do an inventory of changes in heat that matches TOA imbalance continually over time?

Can we balance the energy budget at the surface of the Earth? Currently it appears that best estimates of all individual components fail to balance by a significant amount. This has major implications for our observing and modeling capabilities. Possibly the observations are insufficient and error bars are too large to be meaningful. Or there are major errors in how quantities such as downwelling radiation are computed, which may have implications for all climate models which use similar methods. The implied error is huge and of major concern.

Can we further track the changes over time? The changes are known better than the absolute amounts as the instruments from space are often more stable than they are accurate. However, accounting for changes in ocean heat content, melting ice, warming land and atmosphere, reveals large discrepancies that have major implications for understanding global warming.

Can we relate the changes in surface energy budget with atmospheric-oceanic processes and long-term variability? How strongly are these changes affecting atmosphere/ocean general circulation? Improved knowledge of the movement and storage of heat and energy within the climate system has implications for future projects and predictions.

Can we improve confidence in feedbacks associated with cloud-aerosol-precipitation interactions in the climate system? This topic addresses how the interactions between clouds, greenhouse gasses, and aerosols affect temperature and precipitation in a changing climate, and determine the climate sensitivity. It aims at integrating expertise from theory, modeling (process, cloud-resolving to large-scale modeling), observations, and weather prediction.

Prospects for advancements are excellent on this question because of new observations and model development already underway and planned. Key areas of development include:

1. New prospects exist to better monitor TOA radiation, possibly using a proposed (but not approved) Earth's Radiation Imbalance System (ERIS) of small radiometers deployed on Iridium satellites with prospects of global 2 hourly sampling at about 600 km resolution. [GDAP]
2. New observations from EarthCARE on clouds and aerosols, combined with CloudSat, CALIPSO, and other observations from space, provide valuable new information and insights. [GDAP, GASS]

3. Argo is in place in the ocean and methods are being improved to analyze ocean heat content, with prospects for extending Argo to depths below 2000 m depth (the current limit). [CLIVAR]
4. GRACE (and its follow-on) measurements of microgravity changes provide prospects for assessing the mass of the ocean and changing glacial ice and water around the world as a major component of sea level change and on land. [GLASS, GDAP, GHP, CLIVAR]
5. All aspects of the hydrological cycle, both on land and over the oceans are expected to be substantially improved in terms of observations, analyses, assessments and modeling, as detailed in GSQ 1, 2 and 3. [GDAP, GLASS, GHP]
6. New very high-resolution products will be relevant for analyzing the heterogeneity of surface fluxes and providing improved estimates of the surface energy budget. [GDAP, GHP, CLIVAR]
7. Atmospheric reanalyses are improving to the point where the changes in energy within the atmosphere are reasonably in hand with prospects for much improved surface fluxes. Ocean reanalyses are improving and with prospects of better defining ocean changes over time. [GDAP]
8. New products on surface fluxes are coming available and will be fully assessed. [GDAP]
9. Modeling activities such as CMIP5 and CORDEX provide new data sets and ways to examine current modeling capabilities and downscaling methods. Confronting models with the observationally based data sets is a first step to improving model veracity. [GHP, GLASS, GASS]
10. Diagnostic studies provide ways to probe in depth empirical relationships. For instance, the role of the land surface and drought in amplifying major climate perturbations, such as heat waves, are being pursued. Global and regional scale interactions of the atmosphere with the ocean, cryosphere, biosphere, vegetation and other land surface aspects are being developed. [GLASS, GHP]
11. Several initiatives led by the Working Group on Coupled Modeling (WGCM), and by GASS within GEWEX, target enhanced activities in several areas related to clouds and climate sensitivity. They include exploiting the Coupled Model Intercomparison Project Phase 5 (CMIP5), the Cloud Feedback Model Intercomparison Project (CFMIP) and other MIPs, CORDEX, leveraging the observational and paleo-records, and fostering new parameterizations, analyses, and projects leading to improved and more reliable models. This topic is the subject of a Grand Challenge. [WGCM, GASS, CLIVAR]

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

The first and foremost benefit is much improved knowledge and understanding of the climate system that is translated into improved climate assessments and more reliable climate models. The latter are the primary tools for synthesizing the observations, performing attribution of what is happening and why, and in making predictions and projections on all space and time scales. This activity underpins all aspects of improved climate services.

An improved quantification of energy budget at the Earth’s surface will improve knowledge about the radiation and latent and sensible heat components, which in turn are of paramount importance for computing impact parameters in food security sector and in water management. Information on downwelling radiation is valuable for many applications in the renewable energy sector.

Conclusions

The successful implementation of the WCRP Grand Challenges and associated science questions described here depend significantly upon the GEWEX Imperatives: observations and data sets, their analyses, process studies, model development and exploitation, applications, technology transfer to operational 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, SPARC, and CliC, and other sister global change research programs such as the IGBP and the International Human Dimensions Programme (IHDP).