GEWEX Plans for 2013 and Beyond

Pan-GEWEX Meeting, University of Washington, Seattle, August 2010

GEWEX Imperatives

GEWEX Plans for 2013 and Beyond

4 January 2010

GEWEX: Global and regional Energy and Water EXchanges

This document describes the framework proposed for the new GEWEX, post-2013, in response to the WCRP visioning plans to revamp its projects and activities.

Mission Statement

To measure and predict global and regional energy and water variations, trends, and extremes (such as heat waves, floods and droughts), through improved observations and modeling of land, atmosphere, and their interactions; thereby providing the scientific underpinnings of climate services.

Imperatives

Datasets: Foster development of climate data records of atmosphere, water, land, and energy-related quantities, including metadata and uncertainty estimates.

Analysis: Describe and analyze observed variations, trends and extremes (such as heat waves, floods, and droughts) in water and energy-related quantities.

Processes: Develop approaches to improve process-level understanding of energy and water cycles in support of improved land and atmosphere models.

Modeling: Improve global and regional simulations and predictions of precipitation, clouds, and land hydrology, and thus the entire climate system, through accelerated development of models of the land and atmosphere.

Applications: Attribute causes of variability, trends, and extremes, and determine the predictability of energy and water cycles on global and regional bases in collaboration with the wider WCRP community.

Technology transfer: Develop new observations, models, diagnostic tools, and methods, data management, and other research products for multiple uses and transition to operational applications in partnership with climate and hydro-meteorological service providers.

Capacity building: Promote and foster capacity building through training of scientists and outreach to the user community.

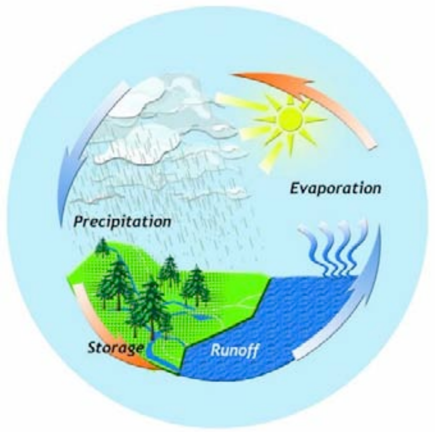
Vision Statement

Water and energy are fundamental for life on Earth. Fresh water is a major pressure point for society owing to increasing demand and vagaries of climate. Extremes of droughts, heat waves and wild fires as well as floods, heavy rains and intense storms increasingly threaten to cause havoc as the climate changes. Other challenges exist on how clouds affect energy and climate. Better observations and analysis of these phenomena, and improving our ability to model and predict them will contribute to increasing information needed by society and decision makers for future planning.

Introduction

The **Global Energy and Water Cycle Experiment (GEWEX)** is an integrated program of research, observations, and science activities ultimately leading to the prediction of global and regional climate change. It is a core project of the World Climate Research Programme (WCRP). The International GEWEX Project Office (IGPO) is hosted by the United States and located in Silver Spring, MD, and the GEWEX web site is at http://www.gewex.org. The appendix provides a list of acronyms.

The WCRP has been carrying out what is called a visioning exercise with a view to revamping the structure and activities of the WCRP with a particular view toward the role of climate research in support of climate services. The timeline is to sunset the current projects and launch new ones in 2013, guided by the Joint Scientific Committee of the WCRP. In particular, the guidance has suggested that core projects would be retained but with revised responsibilities to facilitate climate system research at the interface of the physical Earth system components. The suggested four new core projects should be: 1) Ocean-atmosphere (c.f. CLIVAR); 2) Land-atmosphere (c.f. GEWEX); 3) Cryosphere (c.f. CliC); and 4) Stratosphere-troposphere (c.f. SPARC). Then within each core project there should be a common set of basic "themes" including 1) Observations and analysis; 2) Model development, evaluation, and experiments; 3) Processes and understanding; 4) Applications and services; and 5) Capacity building. Coordination across projects on these themes would be via WCRP Modeling and Observations Councils.



In preparation for the forthcoming changes, the GEWEX Scientific Steering Group (SSG) met in January 2010 in New Delhi and began formulating plans for the future via a new mission statement, a set of Imperatives (things that must be done), and a set of frontier challenges for the future. The draft set of these was published in the May 2010 GEWEX newsletter as a basis for the more extensive discussions at the pan-GEWEX meeting in Seattle in August 2010. The final set of Imperatives, given here, have been approved by the SSG.

In January 2010 the SSG discussed why the three GEWEX panels existing at that time: the GEWEX Radiation Panel (GRP), the GEWEX Modeling and Prediction Panel (GMPP), and Coordinated Energy and Water Cycle Observations Project (CEOP) should be together under the GEWEX umbrella. The arguments were strong and convincing that we should continue with similar components in any future GEWEX. Figure 1 illustrates the points from the standpoint of the hydrological cycle, featuring radiation, atmospheric processes and land surface hydrology and processes. The original motivation for these being together is that they correspond to the "fast" processes in the climate system, and this still applies. Here the term "fast" relates to the atmospheric and land surface processes compared with the "slow" components associated with the ocean and the cryosphere. However, since then, there has been further evolution of the panels, as noted below.

However, key questions were "how much science falls under land-atmosphere?" and "what about those that do not?" The approach endorsed by the SSG is that while the future GEWEX should indeed be the place where land-atmosphere interactions are featured, it should be much more. In particular, it should retain the global energy and water cycle as a core focus while further highlighting regional aspects. It should indeed also feature hydrological and land surface processes and modeling, and interactions with the atmosphere. However, it should further retain a strong atmospheric component related to the water and energy cycles, and hence scientific issues related to radiation, clouds, convection, precipitation, boundary layers, surface fluxes, runoff, and human influences which should also be included in terms of observations, process understanding and modeling.

The mission statement and set of Imperatives given above were approved by the SSG and they summarize the plans for the new GEWEX. Further below, each Imperative is described in more detail as to the rationale and what it encompasses, the scientific background and challenges, and the strategic plan on how to move ahead in GEWEX. This includes the lead within GEWEX, the other parts of WCRP and other organizations for which there should be strong linkages and involvement, and the main actions and outcomes expected, along with deliverables and a rough timeline.

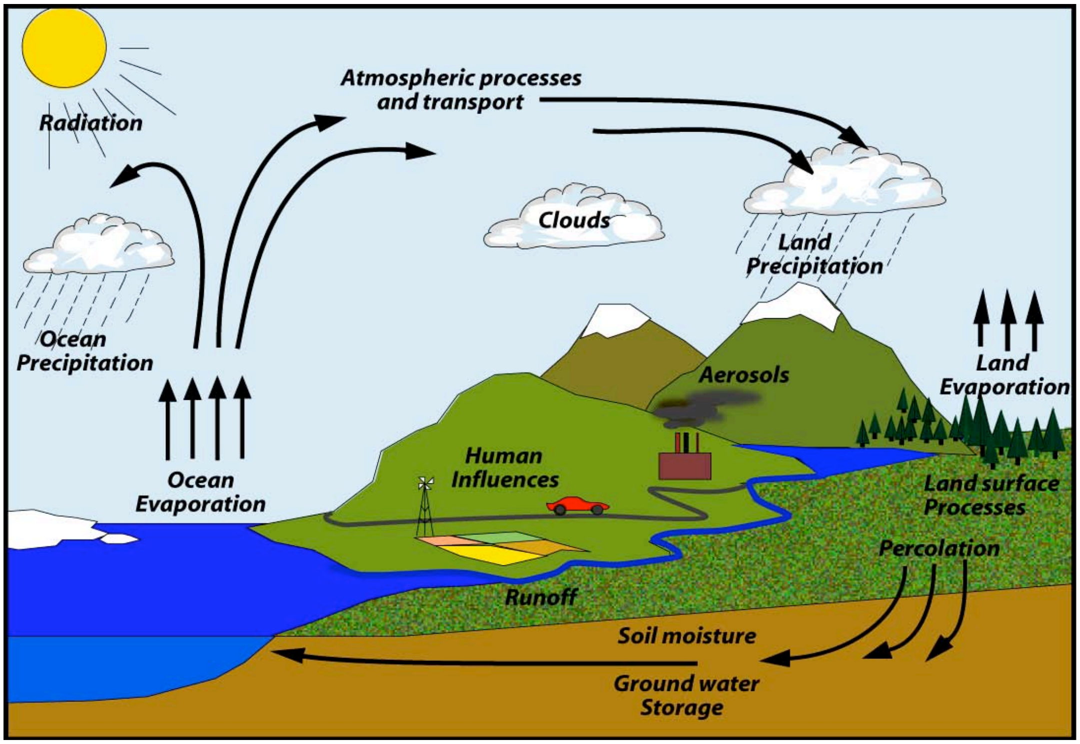


Fig. 1 depicts the hydrological cycle schematically and thus the driving by radiation and energy, the atmospheric dynamics that move water and energy around and produce clouds which block the sun, the complex land surface complete with human influences and the interactions with the atmosphere, and the surface and below surface processes that complete the water cycle (adapted from Trenberth et al., 2007).

A New Name

While the old GEWEX name (the Global Energy and Water cycle Experiment) was liked by many for its uniqueness (e.g., in a Google search) and name recognition, the "EX" part is clearly obsolete. Accordingly, a new name post-2013 was suggested to be: *"Global and Regional Energy and Water" (GREW).* However, there were strong sentiments expressed for the old acronym ***GEWEX*** and a suggestion for an alternative name has won out (for now): "***Global and regional Energy and Water Exchanges.***"

A vision statement has been added to the mission statement and list of Imperatives, as given above. In addition to the Imperatives, there are a number of challenges that are perhaps a bit further off onto the future that we call frontiers. A partial and very preliminary list is given below.

Frontiers

The frontiers are to be developed further. At present they include:

- Understanding and modeling:

    - Anthropogenic influences on land and water use, including urbanization
    - Effects of climate variability and change on land surface properties and processes
    - Anthropogenic aerosols
- Improved representation of hydrological processes in land surface schemes, including groundwater
- Assimilation of local and regional data for multiple purposes, including to constrain global model parameterizations
- Extremes in water cycle effects on, for example, ecosystems, land forms, food systems, human health, etc.
- Linkages with biogeochemical processes, including modeling of water quality and other non-physical variables
- Geo-engineering
- Urban issues

Recent Developments

There are a number of evolutionary changes occurring within GEWEX already that help set the stage for the new post-2013 phase. In part these come from natural evolution as personnel change, projects mature, and new directions are set that recognize the developments outside of GEWEX.

GEWEX Datasets. The original GEWEX datasets were developed under the auspices of the GEWEX Radiation Panel (GRP) although several originated before GEWEX began. GRP continues, but is looking for a name change as it does a lot more than radiation. It does deal with all of the global satellite data related to energy and water and their synthesis into products, and is currently leading and promoting reprocessing of the datasets with a goal of creating climate data records of sufficient quality to be useful for examining trends. Some of the datasets are well known and already used extensively, but scientists are confident that they can be made much better and more consistent with each other, and with better estimates of uncertainties. In general GRP is working well toward the new goals and has produced simulators, that take into account the sampling and characteristics (such as thresholds) of the observations to enable intercomparisons of satellite products with model data. Interactions of GRP with other parts of GEWEX were fostered by the pan-GEWEX meeting, and the GEWEX datasets have potential for great use in evaluating and improving models on issues such as clouds and indirect effects of aerosols, precipitation frequency, intensity and amount, and in providing the context for the RHPs.

Land Surface and Hydrological Science. Major changes have occurred and are underway in the realm of the regional hydrological projects (Fig. 2) during and following the pan-GEWEX meeting. In part these came about naturally from the evolution of the program, and given an extra nudge by the change in leadership. The following provides a brief background context for the changes underway.
In the 1990s a panel set up to provide coordination and oversight was the GEWEX Hydrometeorological Panel (GHP). Then to take advantage of many new satellite and other observations the **Coordinated Enhanced Observing Period (CEOP)** was begun in 1995 and continued into the second phase of GEWEX for 2001-2006. This activity, which also developed extensive data management activities, led to some similar panels to those in GHP and some duplication of effort. Accordingly, this first CEOP activity was combined with GHP and evolved to become the **Coordinated Energy and Water Cycle Observations Project** with the same acronym**, CEOP**, in 2007-2008. The initial observing period grew to become a move to produce a 10 year dataset and archive especially set up for the regional projects. However, other developments had already occurred in observations and data management, which suggested that the activity should be wrapped up and refocused, even as it is utilized and hopefully becomes part of the

heritage of GEWEX. In particular, the development of the many flux towers around the globe provide alternatives to the CEOP reference sites for local studies of energy, water and biogeochemistry.

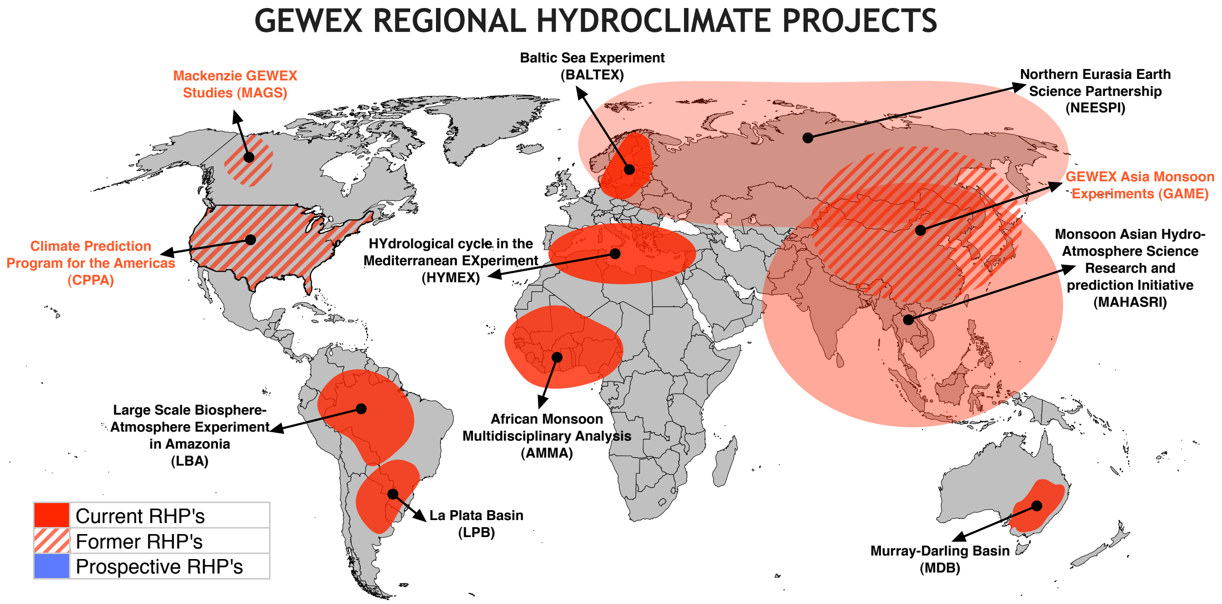


Fig. 2. Former and current RHPs. These provide detailed local observations and modeling which need to be placed in a larger setting, but which can help elucidate important processes.

CEOP developed an impressive and extensive program, including the Regional Hydroclimate Projects (RHPs), associated modeling and data base development, and the Hydrologic Applications Project (HAP). CEOP remains at the core of the GEWEX mission, includes more than a thousand researchers, and provides important regional data, modeling and a valuable end-user interface.

Accordingly, the community began what might be called a “back to basics” movement, with recognition of the need to reinvigorate and refocus the regional hydrological projects which would foster the next generation of hydrologically realistic land surface schemes. Thus a new **GEWEX Hydroclimatology Panel** (GHP: note the change in the name from the first version) has been formed to replace CEOP. GHP will be the home for hydrologic science and modeling within WCRP and there is considerable scope for developments in this area, e.g., in seasonal forecasting, the detection and attribution of hydrologic change, and the development and analysis of climate projections and their implications for water resources. Challenges remain in dealing with monsoons and to help coordinate the multitude of national initiatives in this area. There are also opportunities for linkage with GLASS in bringing disciplines together in the development of next generation Land Surface Models as well as increasing interactions with CORDEX. Changes in the management structure are likely to accompany the new consolidation of efforts as GHP realizes its considerable potential.

A new RHP was approved at the Pan-GEWEX Meeting: the HyMeX project, which involves some 20 countries centered around the Mediterranean Sea. Moves are underway to develop a new North American RHP. One possibility, called the Terrestrial Regional North American hydroClimate Experiment (TRACE), will hold a workshop set for April 2011 in the Washington, D.C., area.

Modeling. The need to address the future structure of GEWEX and GEWEX modeling post-2013 has led to some fundamental changes arising from the pan-GEWEX meeting. The GMPP layer between GCSS, GABLS and GLASS has been removed and instead GCSS/GABLS will be combined and, along with GLASS, will report to and take advice from the SSG directly. As a result, GCSS/GABLS will undergo some reorganization that will also pave the way for the post-2013 transition. The GCSS is abandoning its Working Group structure and instead will operate through projects. Those can be initiated by any member of the community. A Science Steering Committee (SSC), which will form the GCSS/GABLS Panel, will be responsible for the successful running of the program. This includes the approval of proposals as well as engagement with the community to explore new opportunities. The GABLS activities will be fully integrated into this structure through GABLS-specific projects as well as GABLS membership on the SSC. The GCSS and GABLS brand names will be maintained.

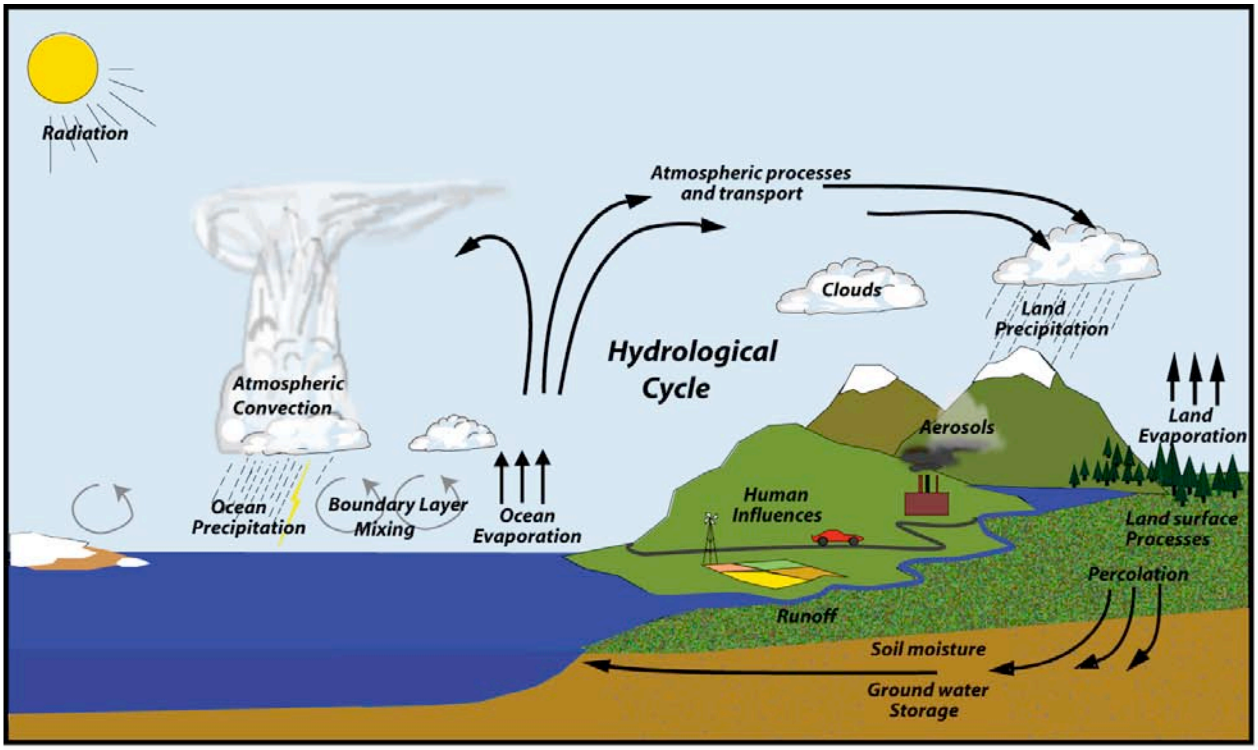
There has also been an accepted proposal for a **Framework for Atmospheric Model Enhancement (FAME)** with a mission*: Improving the representation of physical and dynamical processes in the troposphere in models for all purposes and especially weather and climate services.* This recognizes the complementary nature of SPARC in dealing with the stratosphere and troposphere-stratospheric interactions. The main focus of FAME is the improvement of the representation of clouds and precipitation in atmospheric models, which can only be achieved by improving our understanding of the intricate coupling of physical and dynamical processes associated with clouds and precipitation at various scales. FAME is seen as a natural extension to the existing GCSS/GABLS panel described above. This should maintain continuity, provide close links to the land and limited area modeling communities and ensure FAME's natural focus on the energy and water cycles.

These activities were originally grouped together to provide a focus on relatively "fast processes" as compared with those involving the ocean or cryosphere. Extensive land surface modeling continues in GLASS, and the hydrological and regional modeling continues within GHP. The way in which all of these fit together and a schematic of the processes involved is given in Fig. 3. FAME could make a major contribution to a potential cross-WCRP effort on atmospheric model development. Questions include how FAME goes forward, whether as a panel or working group.

***Extremes*.** The 2010 northern summer record breaking flooding in Pakistan, India and China, and heat-waves and wildfires in Russia highlight the extremes of the hydrological cycle of drought and floods that are changing from human activities. Further flooding extremes have continued in the southern summer of 2010-11 in Australia.

Dealing with extremes in WCRP is a cross-cutting activity that involves all projects although GEWEX plays a leading role. A WCRP extremes workshop involving some 132 people from 32 countries at UNESCO was held in late September 2010. Breakout groups were held on issues of 1) data requirements and availability (such as the need for hourly precipitation data to properly characterize extremes); 2) representation of extremes in models, including scaling and spatial issues (how station data relate to grid squares, comparing apples to apples); and 3) methodologies for estimating extremes across areas and disciplines, including statistical methods. Continuing issues are sorting out the human changes in extremes and how to best communicate with the general public on such technical attribution issues.

A goal is: *To provide much improved observational datasets and model capabilities on variability and extremes, especially those that have high impacts on society and the environment, and develop a climate information system that include predictions and assessments of future changes in risk from extremes.* Some proposed activities include (i) Dataset development with high temporal resolution (sub-daily) that can be used to assess changes in extremes of all sorts, including especially those with high impacts on humans and the environment, such as drought, heat waves, floods, and storms. Promote sustained observing systems to allow predictions of seasonal to decadal time scales. (ii) Provide a focus for evaluating models with regard to how well they replicate extremes, including developing better methods for comparing model grid point values with observations. (iii) Determine the main phenomena responsible for extremes, such as blocking anticyclones, tropical storms, tornadoes, polar lows, and snow storms, and evaluate models from the standpoint of their ability to reproduce statistics of these, and how they vary and change. (iv) Improve understanding of the relevant physical processes and ways to improve them in models. (v) Develop robust statistical methods for assessing extremes and their uncertainties and make tools available for wide-spread use and ensure that archives of model projections include sufficient high frequency data to assess pdfs and extremes. (vi) Develop a CMIP5 focused activity on analysis of extremes. (vii) Build a community of climate scientists and statisticians working together.



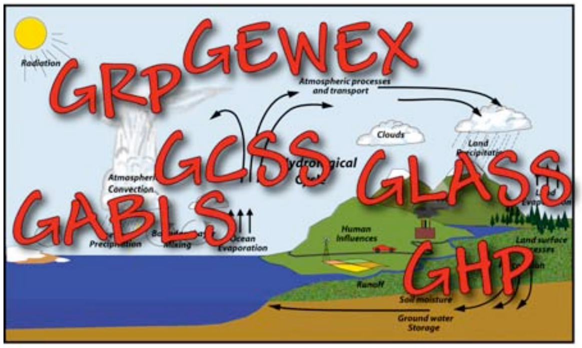


Fig. 3. Schematic of the main processes of importance in the energy and hydrological cycles, many of which are not fully resolved by global climate models and thus have to be parameterized. Radiation is affected by clouds and aerosols. Surface fluxes of heat and moisture are mixed in the atmospheric boundary layer and feed convection and clouds that are in turn affected by aerosols and lead to precipitation. Land surface processes are highly heterogeneous and affect surface hydrology, soil moisture, ground water, and river flows. Human influences affect the atmospheric composition and land use. Domains of GEWEX panels are given in the icon at left.

The GEWEX Imperatives

Preamble: *Water is unique in its role on Earth. Not only does it provide the necessary sustenance to support life, but it also acts as an energy storage and transport mechanism as it changes phase from solid to liquid and vapor. Together with water in the atmosphere, the surface reservoirs of water are continually exchanging mass. Water evaporates from the ocean and land surfaces, is transported by the atmosphere, forms clouds and returns to the surface as precipitation. Rainfall on land can return to the sea via rivers or be stored in lakes and aquifers. Snowfall on land can accumulate over the cold season and later melt and flow into rivers or build up into or act to maintain large ice masses (glaciers, ice caps and ice sheets), which can eventually melt as well.*

In the following, the new GEWEX Imperatives are outlined. For each Imperative, a rationale and motivation for the Imperative is provided, followed by the scientific background that describes the state of the art briefly. Then the strategic approach is outlined to address the Imperative, including the actions, the expected outcomes, deliverables with a rough timeline, and links to other activities within GEWEX, the WCRP and elsewhere. While the plans are looking forward for 15 years beyond 2013, the main focus is on the first 5 year period from 2013 to 2018, after which a comprehensive conference, workshop and assessment will likely take place to set the stage for the next five years.

The document is prepared by relatively small groups of scientists (listed in an appendix) on behalf of all of the GEWEX community, bearing in mind the discussions at and beyond the Pan-GEWEX Meeting. The document is intended for presentation to the JSC in April 2011 and open evaluation and commentary before being finalized.

1. Datasets: Foster development of climate data records of atmosphere, water, land, and energy-related quantities, including metadata and uncertainty estimates.

1.1 Rationale

The Earth's Energy budget (Fig. 1.1) is deeply affected by the water cycle. Without water in the atmosphere, the Earth would be inhospitably cold. Water vapor absorbs both visible and infrared radiation. The relatively strong absorption in the infrared makes water vapor the most important greenhouse gas, surpassing even CO_2 in absolute terms. Yet, this same water vapor causes the Earth's atmosphere to continually lose energy while the surface gains the excess heat. The intricate balance is restored by evaporative cooling at the surface and the subsequent heating in the atmosphere from the condensation of water vapor. The process of condensation, however, further complicates the energy exchanges by creating clouds that modify the radiative energy balance through the simultaneous reflection of solar radiation and absorption and emission of infra-red radiation. The Data Imperative is designed to estimate these various stores and exchanges of water and energy on global and regional scales needed to document the observed changes and confront the models.

The processes themselves occur at many space and time scales ranging from multi-decadal variability, forcing due to the 11-year solar cycles down to the scales of individual cumulus clouds. El Niño variations, for example, occur over broad areas of the Pacific ocean on a 2-7 year time cycle, while the regulation of local tropical Sea Surface Temperatures (SST) appear to be related to feedbacks between evaporation, clouds and solar radiation on much smaller time scales of days to weeks. The Data Imperative focuses on all of the scales necessary to validate climate models down to the cloud scales needed to verify process understanding.

The Data Imperative thus focuses on answering the following specific questions:

- How can we better measure and characterize the state and the variations of the climate using global observations?
- What are the observed changes in radiative forcing that can be associated with climate variability?
- How do the interactions of radiation with changes of the internal state of the climate (a.k.a. radiative feedbacks) relate to climate variability?
- How does the water cycle and associated internal water exchange and transport processes in the Earth system (a.k.a. water feedbacks) relate to climate variability?

1.2 Scientific Background

The main source of global information about the climate system comes from the analysis of satellite remote sensing data which requires detailed models of the interaction of radiation with the atmosphere and the Earth's surface, including the effects of vegetation, as a function of wavelength, polarization state and observing geometry. The GEWEX Radiation Panel, while originally constituted to understand the short- and long-wave energy balance of the Earth System, used that expertise in radiation and remote sensing to also put together global water and energy budget data sets of Surface Radiation (SRB), Clouds (ISCCP), and Precipitation (GPCP) (Fig. 1.2). Over time, these were further expanded to include Aerosols (GACP) and to complete the surface flux and forcing terms (SeaFLux and LandFlux). Where beneficial, these data sets use in situ observations not only to validate the global products, but also to enhance them as in the case of GPCP that blends satellite and in situ products into a globally coherent estimate of precipitation. These products represent the legacy of the GEWEX radiation panel and are considered the standard in many applications. These GEWEX data products can be tied directly to the Earth's energy budget diagram shown in Fig. 1.1.

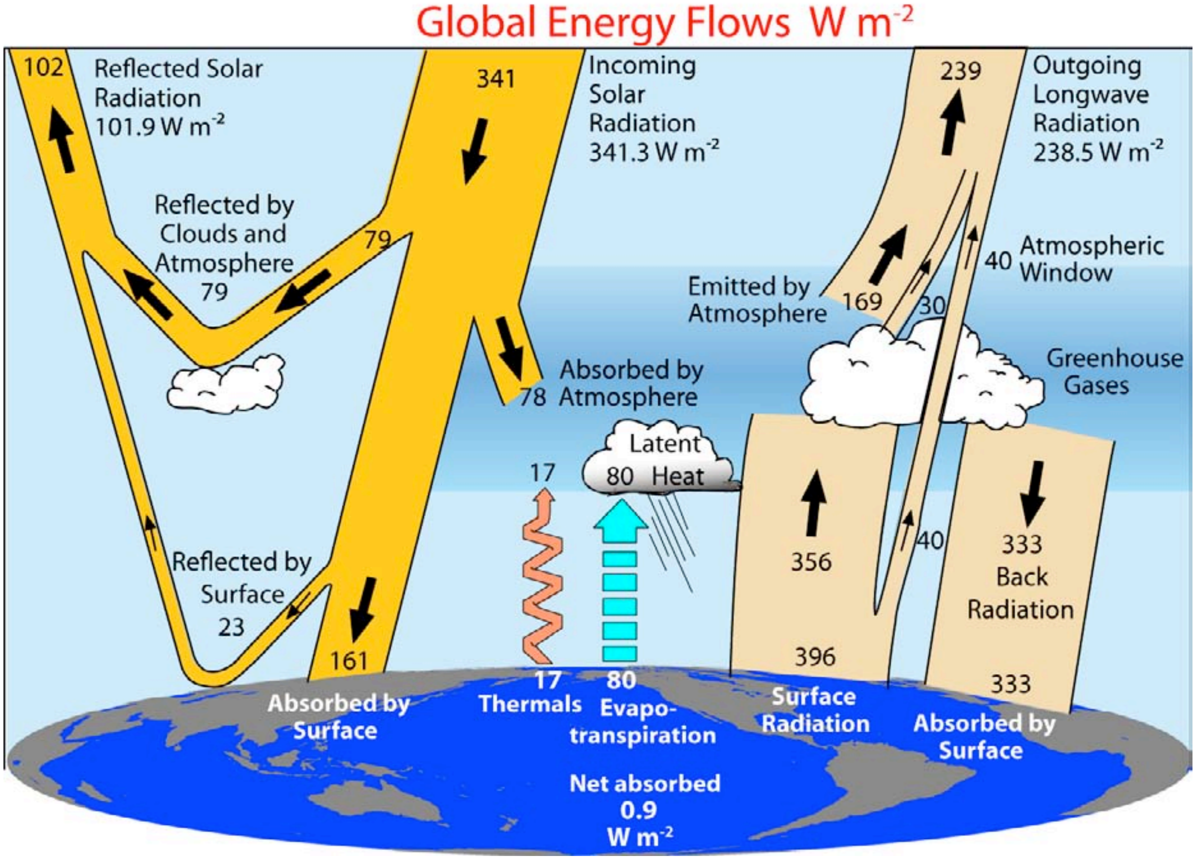


Fig. 1.1. The Earth's energy budget from *Trenberth et al.* (2009).

In the first phase of GRP, the focus was on developing individual products to monitor global water and energy fluxes shown in Fig. 1. Algorithm development for many of these products was a key activity of the radiation panel. As time series grew longer, new challenges emerged. Algorithm stability needed to be revisited as subtle trends emerged. Some of these trends were related to cross-talk among variables in the retrieval algorithms themselves. Some were associated with changes in satellites and instruments, drifts in orbit (in altitude and time) and calibration. Reprocessing these records with the benefit of new technology and lessons learned enables improved and more continuous products. With the radiative terms of the Earth system in place, GRP now plans to produce a first version of a “Unified” Global Water and Energy product. This unified product integrates the individual GRP products listed above into a single product with equal space and time grids and consistent ancillary data and assumptions applied across the data product suite.

GRP will undertake an assessment of the state of the Water and Energy budgets from the Unified Global Water and Energy product. This assessment, which is intended to document the state of our knowledge given the present observational capabilities, is meant to be the first in a periodic re-evaluation of the state of the Water and Energy observing system. The assessment will consist of selected closure tests utilizing physical constraints on the global scale; analysis of temporal variability in the fluxes and states; attribution of changes to observed forcings; estimation of uncertainties, and a maturity index of various components based upon ongoing assessments of individual components of the budget. Importantly, all these challenges are met using different data sources, which allow the possibility to inter-compare budget assessments and sensitivity estimates obtained from satellite and in situ data. It is the baseline against which future refinements can be judged.

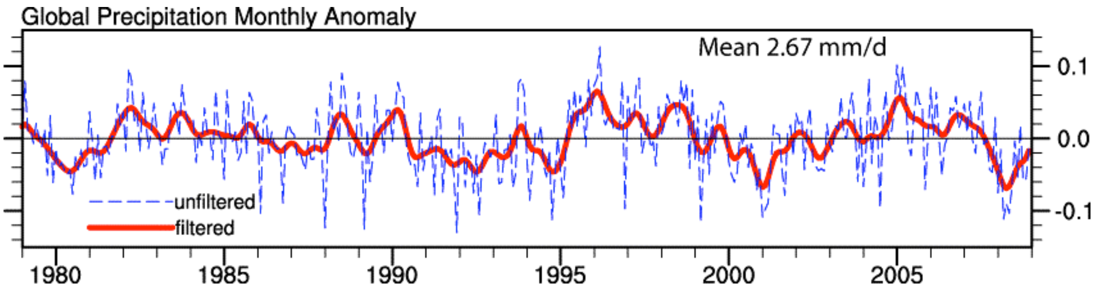


Fig 1.2. GPCP v2.1 monthly global anomalies about the annual mean of 2.67 mm/day, plus the smoothed values to show interannual variability.

1.3 Strategic Plan

The GEWEX products consist of a combination of satellite and in situ products. A key function of the "Data" activity is to monitor and advise agencies regarding the current and future data availability. The "Data" activities thus include:

- Periodic reviews of Space- and Meteorological agency plans for current and future satellite programs to ensure that long-term measurements needed for climate records of water and energy variables are maintained. This includes a review of calibration accuracy/stability requirements for current and planned instruments.
- Review of the activities of Space- and Meteorological Agencies as well as Archiving Centres to ensure the proper archiving of long-term satellite and in situ records of all types of climate variables together with metadata (wherever available). Ensure that data quality control is performed and that original data archives with the highest available resolution are made freely available to the users.

GEWEX data products need to be constantly monitored in order to ensure that climate records remain as accurate as possible. Once data have been collected and processed, global data sets from satellite and in situ sources must constantly be assessed, characterized, improved, and distributed. Data related activities therefore must ensure that:

- Periodic assessments of all climate products being used to ensure the best possible characterizations of global water and energy variables. Assessments are particularly relevant when new data products become available that can shed light on the longer-term climate data records.
- Assessments, comparisons to independent in situ observations, as well as water and energy budget closure studies be used to assess the quality of the global data sets to define standardized error metrics and to provide both quantitative and qualitative error estimates for all the products. This will help to identify those areas of the water and energy budget associated with the largest uncertainties that require increased focus in the future.
- Improvements in algorithms or data quality are incorporated into the global data sets in a timely manner by supporting the periodic reprocessing of global climate data sets.
- Data are distributed freely and without restrictions. The data distribution and meta-data needs must be continuously evaluated and improved as necessary.

GEWEX data products are global in nature but of sufficient time and space resolution to be fully applicable to regional scales. Synergies will be exploited between the globally homogeneous products and those produced by GHP from its Regional Hydrometeorological Projects (RHPs) in order to:

- Provide the regional data sets targeting specific regional mechanisms driving water and energy transformations.
- Provide high resolution additional validation data against which to judge the global products.
- Provide the global context in which the regional hydrometeorological studies must fit.

The GEWEX data are of sufficient spatial and temporal resolution to allow models to validate not only against single variables, but to explore the relationship among variables, thus helping to properly attribute changes and to understand their mechanisms. To help foster this new area of process related research, the Data Imperative will create specialized products as well as tools to enable better comparisons between observations and models. Successful tools have been the ISCCP simulator that allows models to compare their cloud fields directly to ISCCP and thus verify if the observed clouds are being produced. Similar simulators have been created for CloudSat and TRMM. Interaction with global and regional reanalysis activities will increase the understanding of model vs. observation uncertainties and their magnitude compared to climate variability. Reanalysis also supports the characterization of the spatial and temporal representativeness and stability of observational products from different sources. Specialized products and tools required for these efforts need a great deal of interaction with the modeling community. This will be accomplished through:

- Supporting workshops on advanced model diagnostics at the intersection of data products and modeling studies
- Supporting activities aimed at understanding of uncertainties in long-term in situ observations records, including problems of data homogenization
- Supporting the development of new radiative transfer codes to improve modeling and understanding of forcings in the climate system. This effort includes assessment of new potential satellite and in situ observing systems that would help close budgets or refine understanding

Leads: GRP, GHP; **Partners**: SCOPE-CM, CEOS, WOAP, GCOS, WCRP projects, GEO

2. Analysis: Describe and analyze observed variations, trends, and extremes (such as heat waves, floods, and droughts) in water and energy-related quantities.

2.1 Rationale

The observational data sets developed within GEWEX and elsewhere provide useful information for multiple purposes only after analysis of some kind. There is a huge diversity in the nature of the analyses into statistical parameters, time series, patterns, gridded fields, diagnoses of processes, and highly derived quantities to convert the data into information. It is important to also understand the uncertainties in any analysis. As well as providing information on variations, trends and extremes, the data sets help improve the understanding of climate processes related to energy and water cycles at all relevant scales and on feedback mechanisms. The complementary nature of the datasets enables multivariate analyses and this is a major strength of the GEWEX approach. One of the greatest sources of uncertainty in current climate models still arises from the inability of the coarse resolution to simulate clouds and their radiative and water feedbacks, as well as depict intense storms and the associated extreme precipitation. An analysis of the correlated climate state variables, such as temperature and precipitation, or precipitation and soil moisture, using the GEWEX and other data sets can advance our understanding of the underlying processes and feedback mechanisms and the influence on surface conditions at short to multi-decadal time scales. Fig. 2.1 illustrates the challenges from the standpoint of global precipitation amount by revealing the disparities among reanalysis estimates and the spurious trends associated with the changing observing system.

Key uncertainties in observed changes in climate and their effects and causes in the IPCC AR4 include limited data coverage in some regions, and analyses and monitoring of extreme events. Of special importance are the phenomena and events that have a high potential to adversely impact society. Extreme climate events, such as heat waves, floods and droughts have disastrous impacts on environmental, economic, and social conditions, resulting in fatalities and monetary losses and can affect the economic stability of regions. In addition to improved monitoring and information for these events, an improved understanding of extremes and their role in global climate change is needed. Of special concern are the frequency and intensity of extreme precipitation events and associated floods, the spatial extent, severity, and duration of droughts, and the variability of monsoon systems and their changes in a modified climate. GEWEX data sets can be used to discern the major phenomena responsible for extremes, such as

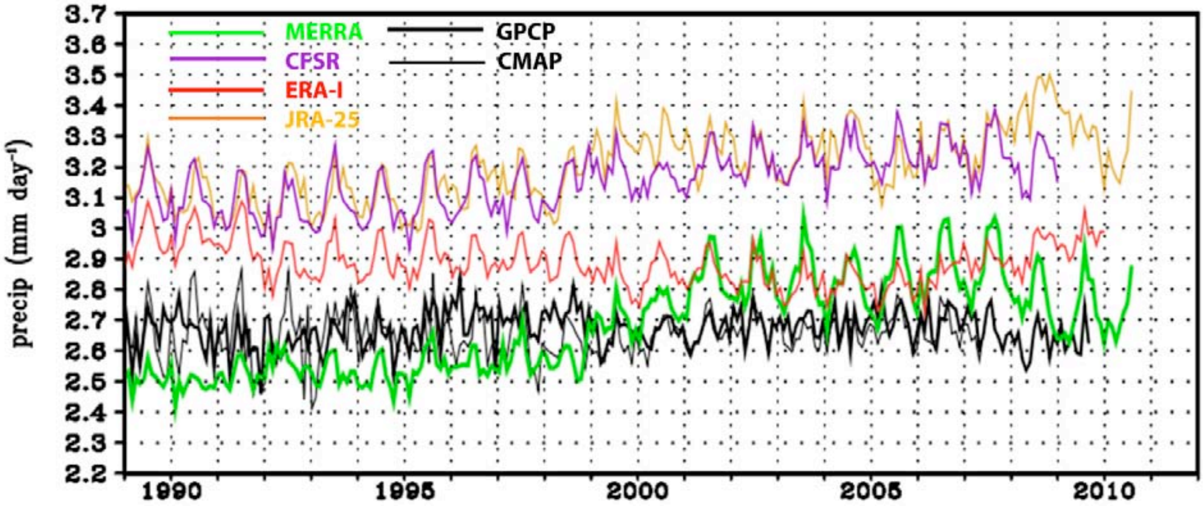


Fig. 2.1 shows time series of global precipitation from 1989 to 2010 as estimated from two observational analyses (GPCP and CMAP) and four reanalyses, in mm/day

blocking anticyclones, tropical storms, tornadoes, polar lows, and extratropical snow storms. Improved data sets are needed, in particular with respect to higher spatial and temporal resolution.

Data analysis is essential to turn the observational evidence provided by the data sets into information useful for society; i.e., the analysis results must be used to improve decisions and predictive capabilities that enable society to be prepared for transient climate variability including extremes. Existing water management practices often cannot satisfactorily cope with current climate variability let alone the impacts of future climate change on water supply, agriculture, energy, and aquatic ecosystems.

The Analysis Imperative thus focuses on answering the following specific questions, among others:

- Are GEWEX data sets internally consistent with each other, do they satisfy physical constraints, and do they support findings on energy and water budgets from other sources on global and regional scales?
- Are the low frequency variations and trends real and how much are they contaminated by inhomogeneities?
- Are the data suitable for documenting extremes and co-variability among extremes (such as floods in one area related to drought in another), and how can they be improved?
- What are the requirements for a new generation of data sets and models to be capable of describing and predicting extremes and long term changes in the frequency and intensity of extremes?
- How can we improve methodologies to better quantify and predict extremes considering the non-stationarity of hydrological variables, and especially extremes of floods and droughts, associated with climate and global change?
- What products are most useful as information for climate services?

2.2 Scientific Background

The IPCC AR-4 started the process of examining consistency of findings across observations. One striking example is the change of the freshwater balance of the Atlantic Ocean over the past four decades. The observed freshening in the North Atlantic accompanied by an increase in salinity south of 25°N implies an increase in the moisture transport in the atmosphere from the subtropics to higher latitudes, and is in line with observed increases in precipitation over the northern oceans and adjacent land areas, and runoff into the oceans (Fig. 2.2). GEWEX data sets covering the global energy and water budgets play an important role in bringing water budget closure on global and regional scales. Globally gridded reanalysis data may also serve as part of an energy and water cycle validation of climate model results.

Many innovative ways have been devised to process observations and determine patterns of variability and change, as well as providing insights into the phenomena involved. However, trends are especially challenging to deal with owing to the need for calibrated continuous homogeneous observations over long periods of time. The human influence on climate ensures that non-stationarity exists in all statistics and the past is no longer a good guide to the future. Validation of model results and assessing past trends is complicated by the lack of reliable climate data records.

As reported in the AR4, during recent decades, extreme events (precipitation, flooding, heat waves, dry and wet spells, droughts, cyclone activity, extreme winds, marine storminess) have changed in intensity and frequency. However, observed and projected changes in the extremes are strongly localized and differ significantly from region to region. According to the IPCC AR4 the intensity of precipitation and heat-related extremes will further increase under anthropogenic climate change. Despite considerable progress in understanding climate and weather extremes, their estimation is still highly inaccurate. Large uncertainties result from the insufficient quality and sampling of observational data and from inadequate resolution of model simulations. This makes it difficult to apply advanced statistical methodologies to estimate climate extremes. Furthermore, advanced statistical methodologies for estimation of extremes themselves have not yet been exploited to the full extent and require validation and improvement. Effective comparisons and cross-validation of extremes between estimates derived from observational point data and model gridded outputs is therefore very difficult. These complications limit the use of models for understanding driving mechanisms and the assessment of extremes predictability.

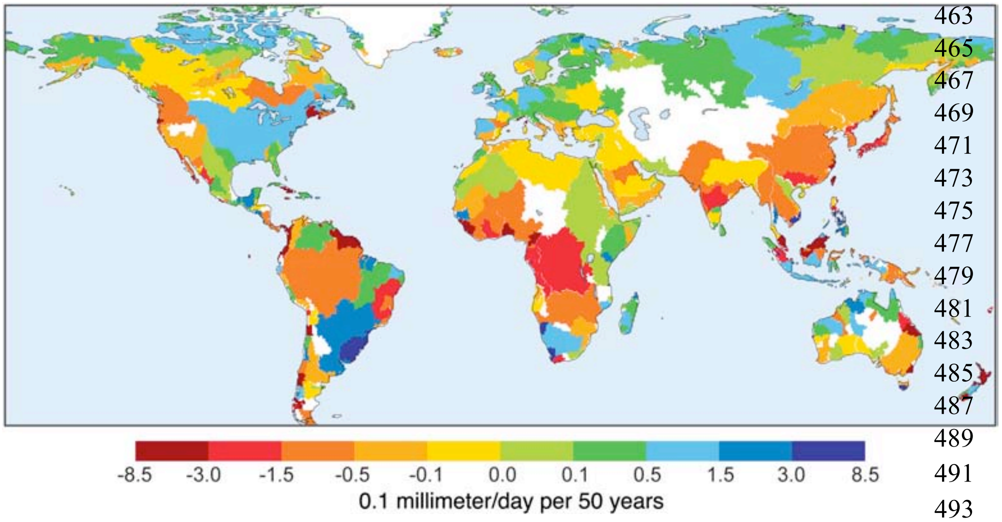


Fig 2.2. Linear runoff trends from 1948 to 2004 based on annual (water year) discharge estimated from available gauge records and reconstructed river flow as given by the river basins. From Dai et al. (2009, *J. Climate*, **22**, 2773-2791.)

2.3 Strategic Plan

The GEWEX Data Analysis Imperative is closely connected to the Datasets Imperative, i.e., data analysis is the mean to perform assessments of the currently existing and shortly upcoming data sets. In general, the Analysis Imperative needs to:

- Describe the geographical and seasonal characteristics of key water and energy cycle variables especially over land areas. This should include a characterization of the entire probability distribution function of variables and especially the characteristics of precipitation (frequency, intensity, amount, type, duration).
- Document the variability and trends, and their uncertainties.
- Stimulate analysis and evaluation of the water and energy budgets and their closure over global, regional and catchment scales.
- Document the results and define the needs for improved global and regional data sets to close moisture and energy budgets.
- Encourage the compilation of comprehensive multi-variable datasets that document the many critical aspects of the water and energy cycles, and especially extremes.
- Specify the attributes that models must have in order to account for extremes.
- Communicate the needs to the observations community to create a plan for improvement of data sets and to construct trial data sets that can be used to assess improvements.
- Support product integration, including data assimilation into hydrological models and integrated model/observational studies. Data assimilation into hydrological models is a means for assessment but results depend very much on the model and catchment used.

Concerning the analysis and monitoring of changes in extreme events and, in particular precipitation, there is a need to develop an optimal strategy for improving the estimation of climate and weather extremes from observations and to improve their projection for future climates. Specific actions of the Analysis Imperative shall include:

- Review and assess the existing metrics of extreme weather and climate events and identify their strengths and weaknesses.
- Carry out a critical assessment of the variety of methods for climate extremes estimation along with uncertainties, involving experience from different research areas and utilizing the statistics community.
- Unravel the means and chains-of-events that lead to extremes in different regions and assess the degree to which these are universal.
- Determine the phenomena responsible for extremes and thus the ability of models to be able to replicate them properly.
- Assess the reliability of representation of different extremes in different data types and model simulations. This needs to include an assessment of the synergy between different extremes, e.g., precipitation, temperature and flooding, and of the impacts of extremes on the environment.
- Assess the degree to which extremes have been affected by land-surface changes.
- Identification of critical gaps in quantitative estimation of climate and weather extremes in data and model experiments, particularly spatial aspects of extreme events and the nature of “compound” events.

This should then lead to:

- A definition of requirements for data types, sampling and resolution for extremes that needs to be communicated to in situ network operators and shall influence the planning of satellite agencies future missions. The long term goal for such data sets must be to achieve long term data sets with higher spatio-temporal resolution that enables better statistical analysis (e.g., of frequency and intensity of precipitation extremes).
- Development of new statistical methods for planning for extremes.
- Develop new generation methodologies for quantification and prediction of extremes.
- Develop and exploit methods of dealing with non-stationarity of hydrological variables, and especially extremes of floods and droughts, associated with climate and global change.
- Apply similar methods to model output and support model development, focused on extremes, and definitions consistent with observations (upscaling and downscaling).

Particular initiatives may include:

- Spin up a new joint GRP-modeling-GHP effort in advanced diagnostics.
- Contribute to building a comprehensive end-to-end pan-WCRP initiative on climate extremes such as heat waves, floods and droughts, addressing the compound nature of extreme events, their ubiquity and risk coping issues.
- Assist with information to reduce vulnerability and enable planning for adaptation to and coping with changes.
- Perform a regional study on climate change impact assessment and adaptation with HAP, LMWG, CMIP5, Extremes, RHPs, Cold, HE, SRS, Monsoon, DMWG.

Leads: GHP, GRP; **Partners:** CLIVAR, CAS, IHDP (Global Water System Project, GWSP), UNESCO (International Hydrological Programme, IHP), Hydrological community, IRDR (Integrated Research on Disaster Risk)

3. Processes: Develop diagnostic approaches to improve process-level understanding of energy and water cycles in support of improved land and atmosphere models.

3.1 Rationale

The physical processes represented in a dynamical climate model are introduced based upon a combination of theory and empirical evidence. Some processes are well resolved by the size of the grid in the model (i.e., the model resolution), some are not at all, and many are partially resolved. A good example is clouds. Because the unresolved scales move around or influence water and energy in various ways and rectify the larger scales, it is essential that their effects are represented via process of parametric representation of the unresolved processes (parameterization). As the resolution is increased, more processes are explicitly resolved, requiring a scale dependency to be built in to the parameterization. Fundamental questions remain about whether it is even possible to parameterize some processes and whether there is a sufficient separation of scales to make the parameterization well posed. In any event, whatever is done has to be verified and robust across space and time scales. A module of a climate model, such as for the atmosphere, is typically assembled with all the relevant processes included, but how they interact when assembled is often unpredictable. Hence detailed evaluations are required.

Improvement in weather and climate system simulation and prediction requires an accurate and detailed assessment of the land, atmosphere, and ocean components at the process-level that combines observations with diagnostics of model behavior. Hence it is essential to synthesize model (and module) development efforts with the observations such that the accuracy and understanding of the processes governing the key components (e.g., land surface and atmospheric water and energy budgets, clouds and precipitation, and boundary layer evolution) can be quantified.

3.2 Scientific Background

Model diagnostics tend to vary by discipline, as well as resolution and application. Observations themselves, on the other hand, are becoming more abundant in time and space, and with improved accuracy particularly with recent advances in global remote sensing. In order to fully evaluate the physics that underpin models of all scales, special diagnostics tailored to specific processes must be developed.

Diagnostics of stand-alone modules or model components are more straightforward, but there has been difficulty in establishing metrics for coupled systems (e.g., land-atmosphere) that quantify the strength of the interactions. GLACE, for example, was successful in identifying how strongly soil moisture was coherent with precipitation at the model resolution scale of order 100 km, but other than a relative ranking of strength was unable to provide quantitative metrics or understanding of the governing processes *nor their accuracies*. To achieve these goals, regional and local-scale models and diagnostics that resolve said processes at the scale they can be observed need to be developed. This remains a difficult task, as the complexity of land-atmosphere interactions (Fig. 3.1) has proven difficult to capture in a single observable diagnostic . To this end, the local coupled (LoCo) initiative from GLASS has gained momentum in recent years in developing a suite of diagnostics that can be applied to both models and observations while explicitly focusing on process-level quantities.

For atmospheric processes, advanced diagnostics should be developed for clouds and precipitation, using satellite estimates, aircraft measurements from field campaigns, as well as ground based measurements for comparisons with models. As well as using retrieval algorithms, simulators of satellite observations to account for instrument characteristics (especially thresholds) (e.g., from ISCCP, TRMM, Cloudsat, and Calipso) may be required to further the evaluations. Such diagnostics should go beyond the comparison of mean of seasonal and diurnal cycle of total rain, and should include, for instance, rain and cloud types.

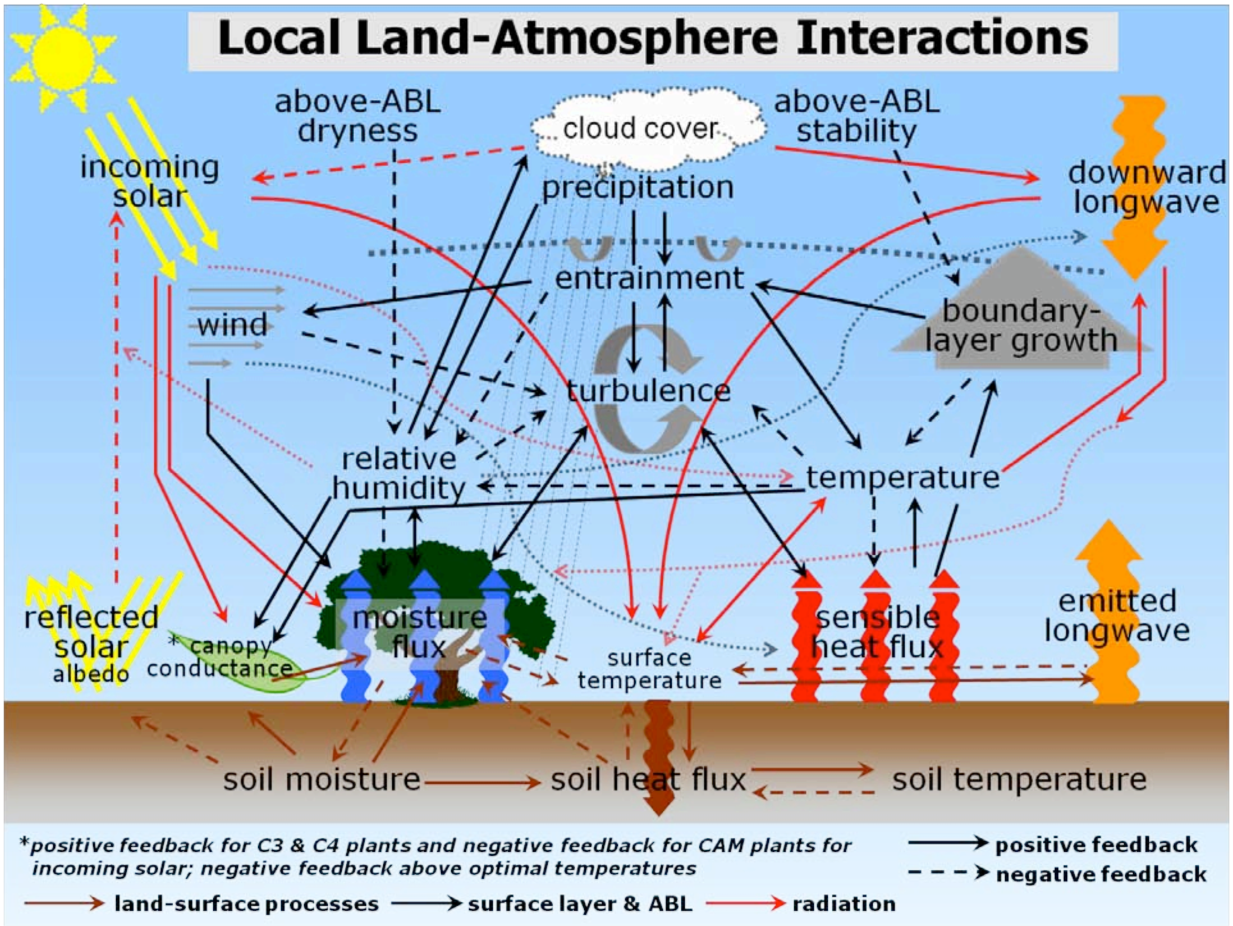


Fig. 3.1. Schematic of the complex interactions between the land surface, atmospheric boundary layer (ABL) and radiation via many variables (temperature, relative humidity, wind and associated turbulence, cloud cover, etc). Adapted from Ek and Holtslag (2004 J *Hydromet.*, **5**, 86-99), courtesy Mike Ek and Kevin Trenberth.

Examples are rain probability distributions (PDF), providing information on frequency of occurrence and intensity of light, moderate, heavy to extremely heavy rains; cloud profiles to delineate their vertical structure; radiative and latent heating profiles at various temporal scales, i.e., diurnal, intra-seasonal, seasonal, and interannual (ENSO) time scales. These diagnostics will be useful in identifying problems in model formulations of shallow to deep clouds, liquid and solid phase rain, during different stages of the convection cycle. For climate change modeling studies, aerosol-cloud microphysics, and possible impacts of aerosols on the water cycle are important (Fig. 3.2). Validation diagnostics should include aerosol types, properties, horizontal and vertical distribution and their evolution over time, and co-variability with physical variables (especially water vapor and clouds). The objective is that model aerosol radiative forcing and response can be tested against observations in different regions.

3.3 Strategic Plan

Process studies will include field programs with varying levels of complexity, generally in collaboration with other groups. These may provide a basis for new ongoing observations. A number of actions are planned:

- Field campaigns and RHPs (e.g., AMMA; see Fig. 2 on page 6) augmented by remote sensing provide a starting point for process-based model comparisons and improved parameterizations.

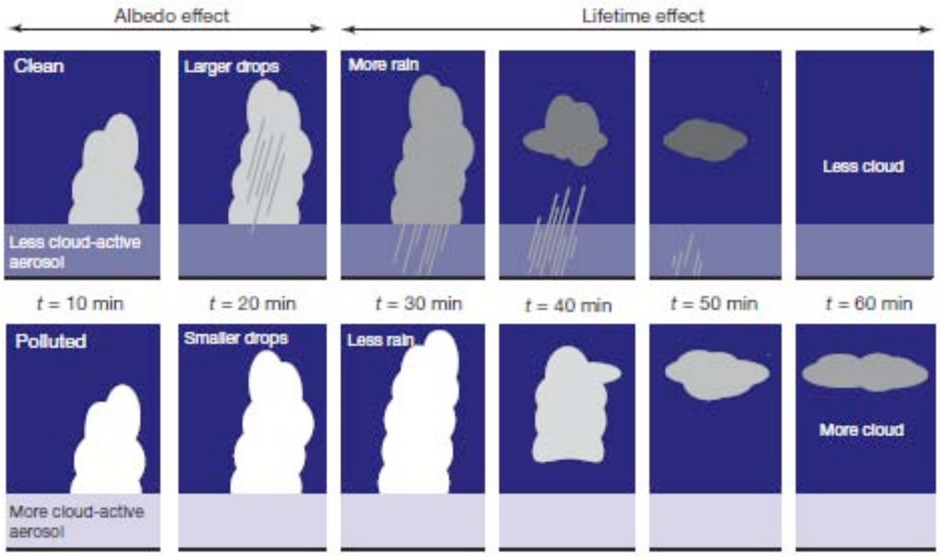


Fig. 3.2. The time line for cloud development in clean and polluted environments, and the effects on precipitation and cloud lifetime are illustrated (from Stevens and Feingold 2009; *Nature,* **461***, 607-613*). Clouds also interact strongly with radiation through their lifetime and optical thickness.

- Investigate alternative representations of sub-grid processes in land surface schemes;
- Develop improved understanding of climate variability and change on land surface properties, including soils, vegetation and hydrological processes, and an associated modeling capability;
- Investigate the scope for development of next generation land surface models with improved representation of subsurface hydrology, including groundwater processes; identify suitable areas for their evaluation.
- Develop more modular Land Surface Models and components for use in Earth system models.
- Develop one-dimensional and two-dimensional PDFs for cloud and precipitation processes.
- Construct radiative and latent heating profiles to test validity of cloud and microphysical parameterization in cloud resolving models and climate models, against a wide range of rainfall products.
- Develop diagnostics using satellite simulators, to validate model atmospheric microphysical processes directly against different type of satellite radiance observations, particularly the A-train.
- Utilize models in data assimilation to help diagnose the models and to provide estimates of climatologies, such as terrestrial water resources.
- Carry out diagnostic and empirical studies using reanalyses to explore both the real world processes and the model depiction of them, especially with regard to precipitation.
- Explore feedbacks and the interactions among different processes, and build confidence in their replication in models.
- Explore improved ways of coupling land and atmosphere modules.
- Spin-up activities in advanced diagnostics through a joint pan-GEWEX workshop (GRP, GLASS, GHP, and others).
- Develop metrics to aid benchmarking activities for both un-coupled and coupled modeling activities.
- With the current and expected increasing complexity of land models in terms of various hydrologic and vegetation treatments, model optimization (i.e., parameter estimation approaches) will continue to be relevant to GLASS efforts (through Model Data Fusion).

Leads: All parts of GEWEX will be involved in this activity with the leads taken by GCSS/GABLS, GLASS, GHP, and/or GRP. The partners will include: CLIVAR, CliC, SPARC, WGCM, WGNE, CAS.

4. Modeling: Improve global and regional simulations and predictions of precipitation, clouds, and land hydrology, and thus the entire climate system, through accelerated development of models of the land and atmosphere.

4.1 Rationale

Global and regional models are key tools for the analysis and prediction of weather and climate. While there are large communities who utilize and analyze these models, there are far fewer scientists involved in their development – particularly in the areas of core atmospheric and land processes. This Imperative therefore makes a specific point of targeting model development with a goal of improved weather and climate prediction on the global and regional scales.

Key components of these models include the atmosphere, land, ocean and cryosphere. The fast processes in the climate system happen for the most part in the atmosphere and on land and these aspects and expertise are brought together within GEWEX to tackle the development of the land and atmosphere components. The focus will therefore be on improving the core components of the atmosphere and land, including the boundary layer, convection, clouds, radiation, vegetation, snow, surface hydrology and surface fluxes, rather than increasing the complexity of the earth system. Also, the focus is on the troposphere and interactions with the surface, as the stratosphere and its interactions with the troposphere are covered by SPARC. Ocean model development will be covered within CLIVAR, land-ice modeling is in CliC, and iLEAPS deals with developments of terrestrial biogeochemical cycles. Coordination among these efforts is facilitated by the WCRP Modeling Council.

GLASS, GCSS/GABLS and GHP do not specifically develop models themselves but act as a facilitating group who support model development within operational centers and academic institutions. The group will focus the attention of model developers within operational centers and academic institutions on specific problems and help the community to progress. This key role has been acknowledged in the operational centers as an important component in the model development strategies. However, it does mean that making specific targets for model improvements are not appropriate and instead specific scientific problems are outlined that will serve to organize projects around.

4.2 Scientific Background

Climate models continue to struggle to reproduce many aspects of current climate and fail to agree on the responses of many key variables to climate change. For example Fig. 4.1 shows the IPCC plot of projected precipitation changes in December-January-February, and June-July-August under the A1B scenario; and it shows the degree to which models agree. The biases in current climate and the variability across models in their response to climate change are strongly influenced by the physical parameterizations in the models which represent sub-grid scale processes and their interactions (Fig. 3, above).

GCSS, GABLS and GLASS have a strong reputation for bringing together observations and detailed process models to support those who develop and improve the parameterizations used for weather and climate simulations and predictions. Owing to the limited computational resources within weather and climate models, there will remain a need for the parameterization of sub-grid process of the atmosphere and land.

Hence we need to continue a focus on the following scientific challenges:

- Measurable improvements in both weather forecasts and simulations of recent climate which can be attributed to parameterization developments facilitated through GLASS, GCSS/GABLS and GHP projects.

- Increased confidence in prediction of regional weather extremes and the response in the frequency of these due to climate change.
- Improved representation of the boundary layer, clouds and convection in models robust across all scales of resolution, including grid-lengths of less than 10 km.
- Improved understanding of how the representation of land and atmospheric sub-grid scale processes affect the prediction of climate change by these models.
- Improved understanding of the role of clouds and their feedbacks in climate change.
- How clouds and precipitation react to and affect large-scale circulation features of the atmosphere, especially tropical sub-seasonal variability, such as the Madden-Julian Oscillation.
- A high-quality estimate of the land surface state and fluxes from about the 1960s to the present (perhaps using reanalyses), that serve as verification for process evaluation at a range of spatial and temporal scales.
- A diagnostic framework for assessing land-atmosphere interactions in models and observations at a range of spatial and temporal scales.
- Ensuring the role of the hydrological cycle and the role of clouds on the radiation balance of the earth remains a focus of weather and climate models as Earth system modeling becomes increasingly complex.

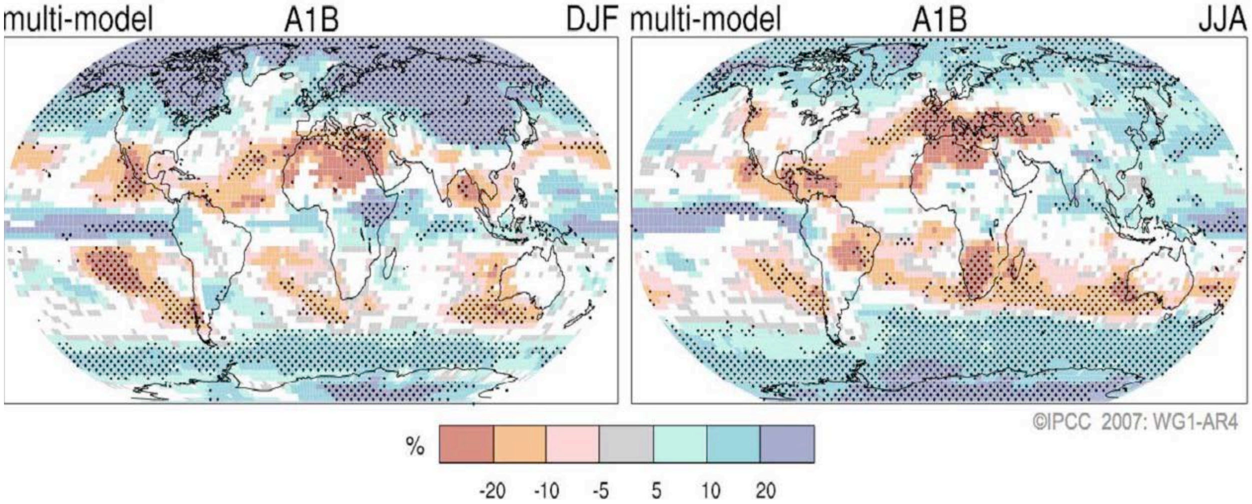


Fig. 4.1. Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. From IPCC 2007.

4.3 Strategic Plan

Within the WCRP, models are developed and used for many purposes, including simulation of the past (paleo and the instrumental record), numerical experimentation, attribution studies especially those focused on sorting out the human contribution to climate change, data assimilation, analysis and reanalysis of multivariate data, initialized predictions of El Niño and other seasonal to interannual to decadal variations, and projections into the future on decadal to centennial time scales. Predictability studies can help determine the utility of the models. Comprehensive diagnostic studies and validation of models helps to provide documentation of performance and shortcomings, and clues on how to improve models. WCRP has sponsored model intercomparison projects (MIPs) as a particularly valuable way forward by designing certain specified numerical experimentation structure for all groups that enable the processes, feedbacks, strengths and weaknesses to be exposed. Traditionally GLASS, GABLS and GCSS have a strong history in evaluating multiple models by a systematic comparison of standardized simulations with observations, and these have given rise to a wide range of model improvements in many modeling centers.

Development of sophisticated land models needs awareness of their role in the entire climate system. Progress in land model development is seriously hindered by the lack of a reliable estimate of the climatology and the typical spread of many fundamental state variables and fluxes, such as evaporation, soil moisture, and terrestrial carbon content is unduly large. Questions that arise include: what are the feedbacks of land model changes on the development of the PBL, convection, the atmospheric energy balance[1]? Where the GLACE experiments gave a fair picture of a specific feedback (soil moisture – precipitation) at a particular time/spatial scale (continental, seasonal) in state of the art models, many of comparably important interactions in different physical domains or different spatial/temporal scales need to be systematically explored (e.g., stable boundary layer with surface energy budget, triggering of convection due to local surface anomalies, snow interactions with atmospheric temperature, to mention a few). With the current and expected increasing complexity of land models in terms of various hydrologic and vegetation treatments, model optimization (i.e., parameter estimation approaches) will continue to be relevant to GLASS efforts (through Model Data Fusion).

GEWEX scientists will play a strong supporting role in all of these activities and take the lead in some. GCSS/GABLS exercises have usually brought together the modelers of a given process representing many models to perform tests of their models under controlled settings that expose the differences. These model simulations can be compared with observations and the results of much finer process-resolving models to understand the causes for differences and potentially identify pathways towards improved process representation in weather and climate models. GEWEX is likely to take the lead on several aspects, including the following objectives:

General actions include:

- Support improved estimate and representation of land states and surface fluxes in models, the interactions with the overlying atmosphere, and maximize utilized fraction of inherent predictability.
- Facilitate the improvement in the representation of the atmospheric energy and water cycles in global and regional models.
- Encourage the exploitation of short-range and seasonal forecasts as a method for identifying and improving climate model biases.
- Highlight the importance of investing in model development activities to ensure improvement in the prediction of water and energy cycle variability on all time scales.
- Act as a focal point for land and troposphere model improvement activities within WCRP (recognizing the complementary role for SPARC with regard to the stratosphere).
- Strengthen collaboration between model developers – particularly those working on the development of weather and climate models.
- Support the evaluation of processes related to the water and energy cycle in earth system models.
- Develop archives to support model development and intercomparison.
- Confront regional climate models with observations and information from process models.
- Exploit observations and process studies to support model development.
- Support the comparison and development of process models which are used to underpin the development of weather and climate models.

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[1] Similar arguments hold for the development of many earth system components, e.g., carbon models where links to the hydrological constraints need to be included.

Cloud and Boundary Layer Modeling (GCSS/GABLS):

- Organize comparisons of models and their components to provide process level information that can be used to inform the development of atmospheric parameterization schemes.
- Continue efforts to ensure that the model comparisons utilize the best available observational data and allow for development of process models, as well as weather and climate prediction models.
- Improve collaboration with SPARC on tropospheric-stratospheric interactions and to improve the representation of impacts of convection on transport across the tropical tropopause layer.
- New efforts will consider the development of radiation parameterizations, especially with a view to the role for clouds on radiative transfer.
- Work with YOTC data and the MJO taskforce to consider the interaction of parameterizations with larger scale dynamics and planetary waves.
- Increased efforts to improve fog in weather and climate models through detailed process studies.

Land Surface Modeling (GLASS):

- Coordinate the construction of a global land reanalysis system. Building on ongoing and preparatory activities in Landflux, GSWP3, GLDAS and operational weather centers, by 2018 a combination of land surface model simulations, satellite based data sets, and statistically extrapolated in situ observations need to be integrated into a semi-operational land reanalysis product. The scientific development of reliable error estimates, weighting schemes and error attribution models will be promoted. This objective will be advanced through the organization of workshops and product intercomparison experiments; proposal of new diagnostics; creation of links between existing networks; promotion of the use of data sets for trend analyses and model development; and coordination of the use of datasets for CMIP5 model evaluation.
- Develop a framework for evaluation of land-atmosphere feedbacks. This should include the development of more quantitative estimates of uncertainty in the land condition and how this uncertainty propagates through to the atmosphere (e.g., PBL, convection, water and energy). By 2018, an experimental protocol and infrastructure should be devised by WCRP that allows this systematic exploration of such feedbacks. A starting point of this is the Land Information System (LIS) infrastructure with eventual capabilities of combining multiple model components, running it at various locations and resolutions, allowing single-column, limited area and global simulations, and using a standardized verification package using a range of observations according to a clear evaluation protocol. This objective will be advanced by promotion of development of land-atmosphere interaction diagnostics, development of funding proposals for feedback studies in a range of climate zones and time/spatial scales, and organization of workshops and review papers.
- Organize coordinated intercomparison experiments for a range of model components. With the introduction of new components in state of the art land models, new intercomparison experiments are needed especially with regard to: groundwater hydrology; surface water treatment (snow, river routing, lakes, irrigation, and dynamic wetlands); vegetation phenology and links between carbon and water; and Land Data Assimilation systems (follow-up the PILDAS initiative).
- Evaluation of these components will also have to be considered in their interactive (coupled) context with the PBL. Also inherent in this theme is an assessment of parameter estimation and uncertainty. Developing more quantitative measures of uncertainty in the land parameters and states will enable more robust evaluation of data assimilation systems. Advances will occur through the organization of intercomparison experiments; promotion of submission of dedicated research proposals; and advice on metrics and benchmarks.

Hydrological Modeling (GHP): There has been considerable modeling within CEOP/GHP of two kinds:

- Regional Hydroclimate Project modeling, which can range from detailed hydrologic models over catchments or river basins, to regional climate modeling such as now given by CORDEX.
- Global and intercontinental transferability. This includes the MAC: Multi-model Analysis for CEOP.

Global models in GCSS/GABLS and GLASS should enable interactions with RHPs to provide local expertise and datasets for validation etc, in the context of global processes. GHP with the regional expertise gained through RHPs will perform MIPs over these regions and evaluate the process interactions produced by the models and give guidance to model developers. With application models (including hydrological models) it will also evaluate the land/atmosphere coupled models from a user perspective.

Deliverables:

- Improved parameterizations and model components, and ultimately models.
- Diagnostic tools and multi-model output from comparisons of weather and climate models with observations and process models.
- Papers of multi-model comparisons which can be used as benchmark runs for those working on model development.
- Papers describing benchmarking cases for land and atmosphere models.

Links to Other Activities:

Leads: GLASS, GCSS/GABLS and GHP; **Partners**: WGNE, WGSIP, WGCM, iLEAPS, YOTC

- Many activities are carried out in conjunction with either WGNE, WGCM, or both, especially with regard to model evaluation, improvement and MIPs.
- WGCM and WGSIP MIPs provide key “top-down” information on what are the common problems in current climate models.
- WGNE annually highlight weather and climate forecasting problems within operational center’s models and are a joint parent body of GCSS and GABLS.
- GEWEX radiation panel provide useful diagnostic tools and datasets.
- Field campaigns (e.g., AMMA) can provide the starting point for process based model comparisons.

5. *Applications:* Attribute causes of variability, trends and extremes, and determine the predictability of energy and water cycles on global and regional bases in collaboration with the wider WCRP community.

5.1 Rationale

The climate community has long been engaged in attribution studies that attempt to identify causality of the variability and trends in long-term hydroclimatic observations. From an atmospheric perspective, the causes may be assigned to the systematic influences of other parts of the climate system, such as anomalies in sea surface temperatures (El Niño is a good example). From the climate system perspective, a particularly vigorous activity has been assessing the effects on the climate system of external "forcings." Natural forcings include variations in the sun's output, changes in atmospheric composition, especially from volcanoes and, on a longer time scale, the effects of the orbital sun-Earth changes that are thought to be the pacemaker for large glacial and interglacial changes. In the latter half of the 20th century, however, human influences on climate have become large enough to be outside the range of natural variability, leading to large and systematic trends and non-stationary statistics. The main global influences arise through changes in the composition of the atmosphere, especially increases in greenhouse gases and changes in particulates (aerosol), while land-use changes are important locally. In either case, climate models are the main tools for attribution. GEWEX contributes to improvements in climate models and earth observation data and will participate in numerical experimentation related to detection and attribution studies, as well as the predictability and prediction of future trends and variations. Moreover, GEWEX scientists play a leading role in analysis of changes that affect energy and water cycles, including integrated regional hydroclimate observations and modeling.

A key area of application of improved understanding of energy and water cycles is in water management. Water resource systems are designed to provide buffering against natural variability, e.g., the Biblical seven lean and seven fat years of Joseph. These designs are essentially all based on an assumption that observed historical times series (e.g., of river discharge) are statistically stationary, an assumption that is increasingly untenable for reasons outlined above. Similarly, flood defenses are generally designed to protect against flood risk defined using historical streamflow and/or precipitation data. While deficiencies in stationary statistics have become increasingly evident to water managers, new methods have yet to evolve. Information about the direction, if not the magnitude of future changes in the climatic forcings to the land surface system almost certainly will have to be extracted from global and/or regional climate models. As GEWEX evolves post-2013, much more attention will need to be given to assessment of the ability of these models to provide the requisite information for hydrologic prediction and water management, and in particular for the extremes of floods and droughts.

5.2 Scientific Background

How precipitation and its extremes change as the climate warms are critical issues for GEWEX. There is a direct influence of global warming on changes in precipitation. Increased heating leads to greater evaporation and thus surface drying, thereby increasing intensity and duration of drought. However, the water holding capacity of air increases by about 7% per 1°C warming, which leads to increased water vapor in the atmosphere. Hence storms, whether individual thunderstorms, extratropical rain or snow storms, or tropical cyclones and hurricanes, supplied by increased moisture, produce more intense precipitation events that are widely observed to be occurring, even in places where total precipitation is decreasing. In turn, this transition is expected to increase the risk of flooding. With modest changes in winds, patterns of precipitation do not change much but result in dry areas becoming drier (generally throughout the subtropics) and wet areas becoming wetter, especially in mid to high latitudes. Hydrological responses to changes in precipitation and evaporation are complex, and vary between regions and catchment types. Under some circumstances, the hydrological system can amplify changes to the driving climate variables (primarily precipitation). For example, in many mountainous regions, because more precipitation occurs as rain instead of snow with warming, and snow melts earlier, there is increased runoff and risk of flooding in early spring, but increased risk of drought in deep summer, especially over interior continental areas. However, with more precipitation per unit of upward motion in the atmosphere, the atmospheric circulation weakens, causing monsoons to falter. In the tropics and subtropics, strong patterns of precipitation are dominated by shifts as sea surface temperatures change; El Niño is a good example. The eruption of Mount Pinatubo in 1991 led to an unprecedented drop in land precipitation and runoff, and widespread drought as precipitation shifted from land to oceans and evaporation faltered, providing lessons for possible geoengineering. In most models, precipitation occurs prematurely, too often, and with insufficient intensity, resulting in recycling that is too large and a lifetime of moisture in the atmosphere that is too short. These biases in turn affect runoff and soil moisture. Understanding the profound consequences of climate change on water and the model capabilities and shortcomings is especially important for water managers.

Understanding natural variability in the climate system, as related in particular to moisture fluxes over land, is especially critical to GEWEX applications activities in flood and water resources management. Flood risk management and the design of flood protection systems are almost exclusively based on the observed historical record of extreme precipitation and flood events despite the fact that most credible scenarios of climate change point to increased risk of extremes. Guidance is urgently needed in this area; floods are one of the world’s most damaging and dangerous natural hazards, with major populations and assets at risk. Similarly, the water systems developed in the 20th century to provide reliable and clean water for the world’s major cities were based on estimates of the inter-seasonal and inter-annual variability derived from observations of the water sources (primarily streamflow) that supplied these water systems. Early representations of natural variability associated with these water sources used simple stochastic models (e.g., shuffled deck experiments). Through the 1970s, when the era of large dam construction ended in the U.S. and much of the developed world, reservoir reliability methods based on stochastic modeling of records of river discharge were an area of active research in hydrology. These methods continue to form the basis for most reservoir system planning and operations studies. Essentially all are based on assumptions of statistical stationarity, and have little or no consideration of causality, i.e., links to representations of variability and trends in the climate system. At seasonal time scales, there has in recent decades been some link of river forecast methods to climate teleconnections, e.g., forecasts conditional on ENSO state in regions, such as northeastern Brazil, where there is a strong ENSO signal. There has been much less work that links the evolving capability to predict variability in the climate system at seasonal to decadal signals to water resources applications. This is in part because the models often are not convincingly able to reconstruct past trends, and because of spatial scale mismatches with hydrological applications requirements.

5.3 Strategic Plan

A major Climate Modeling Intercomparison Project, CMIP-5, is underway and results will be used for the IPCC AR5 assessment. Extensive archives from many models will be made available for analyses of past century and future projections under different emissions scenarios. A number of initialized predictions will also become available, as well as more specialized experiments designed to illuminate aspects of attribution. Many scientists, including those associated with GEWEX, will tap into this rich archive and participate in evaluating the model results and their implications for the future. It is expected that a number of projects will focus on evaluating the performance of models in energy and water-related variables.

Particular elements of this Imperative are to a) evaluate the ability of coupled land-atmosphere models to reproduce observed trends in land surface hydrological variables; b) evaluate coupled model predictions of hydrologic extremes with respect to their potential use for risk-based design (e.g., of dam spillways), as well as the ability of models to reproduce observed characteristics of drought, such as space-time variations on soil moisture deficits; and c) evaluate the predictability of hydrologic extremes (floods and droughts) using coupled models over a range of lead times from days to months or longer. These are challenges that require integration of the atmospheric, land surface and hydrological communities at the scale of major river systems, and can best be addressed by building on the strengths of the GEWEX Regional Hydroclimate Projects. Each of these is elaborated, along with deliverables, below.

5.3.1 Evaluate Ability of Models to Reproduce Observed Trends in Land Surface Variables

GEWEX should coordinate evaluations of the ability of coupled models to reproduce observed trends, both in experiments that constrain coupled model boundary conditions (for regional models) and in "free wheeling" experiments using coupled global and regional models constrained only by prescribed global emissions. Under such conditions, are the models able to reproduce important observed hydrologic trends, such as reduced mountain snowpack and earlier snowmelt runoff in the western U.S. (Fig. 5.1), observed increases in Eurasian Arctic river discharge, reduction in northern hemisphere snow cover extent, and others?

<u>Deliverables</u>**:** Sorting out the role of natural variability from climate change signals and from effects due to land-use change is a key challenge. A primary deliverable could be a compendium of trends in key land surface variables for which there is a sufficient observational basis to identify long term (multiple decades to century) trends. This could include, for instance, precipitation, streamflow, snow cover extent, soil freezing depths, and lake freeze-up and thaw dates. Care would need to be taken to assure consistency of spatial resolution with that of coupled models, e.g., river discharge most likely would need to be for relatively large rivers. A companion deliverable could be a paper or set of papers comparing modeled trends with observed, perhaps both directly from climate model historical runs and regional model output, e.g., from the WCRP COordinated Regional Downscaling Experiment (CORDEX) studies.

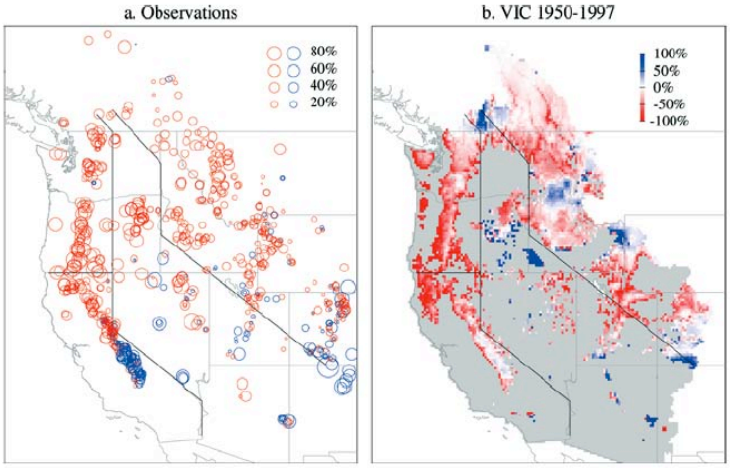

Fig. 5.1. Observed (from manual snow course data, left panel) and modeled trends (right panel) in snow water equivalent in the western U.S. (from Mote et al. 2005: *Bull. Amer. Meteor. Soc.*, **86**, 39-49). Can coupled models reproduce the observed trends as do hydrological models when forced with observed precipitation and temperature at the land surface?

5.3.2 Evaluate Utility of Coupled Model Predictions for Reconstruction of Flood and Drought Risk

The ability of coupled models (either weather forecast analysis fields or climate model historical output) to reproduce observed flood and drought events is not well known except in the most general sense. There is no guidance available to the practitioner community concerning changes to extreme floods, and little information on the performance of coupled models for more frequent flood events. From a hydrological standpoint, the space-time variability of droughts, for instance, can be characterized using methods such as severity-area-duration analysis (see Fig. 5.2). To date, however, such methods have not been used in a diagnostic sense to evaluate the ability of models to reproduce droughts. Furthermore, while there is some indication that climate model precipitation has too little long-term persistence relative to observations (see Lettenmaier and Wood, *GEWEX News*, May 2009), the implications of these biases for simulated droughts have yet to be investigated. As for floods, little work has been done to evaluate the ability of global or regional climate models to reproduce observed flood characteristics (e.g., frequency distributions).

Deliverables: GEWEX could sponsor a set of workshops aimed at diagnosis of climate model output with respect to its ability to reproduce flood and drought characteristics. For floods (and perhaps droughts as well) it is likely that one key issue will be access to archived output at appropriate temporal resolution, and for variables of interest (runoff, soil moisture, groundwater). Most archives of climate output (e.g., CMIP-3) are limited for most models, to monthly output, and regional climate model output archives (in particular, for the CORDEX studies) have not yet reached the level of standardization achieved in the CMIP archives, the result of which is the frustrating absence of key hydrological variables in the archives. Hence, one basic deliverable should be standardized archive protocols for land surface variables for both global and regional models that could support diagnoses like those suggested above. For those models for which appropriate archives exist, GEWEX could sponsor a project, consisting of a workshop or workshops followed by journal publications that analyze and interpret the ability of the models to reproduce observed flood and drought characteristics.

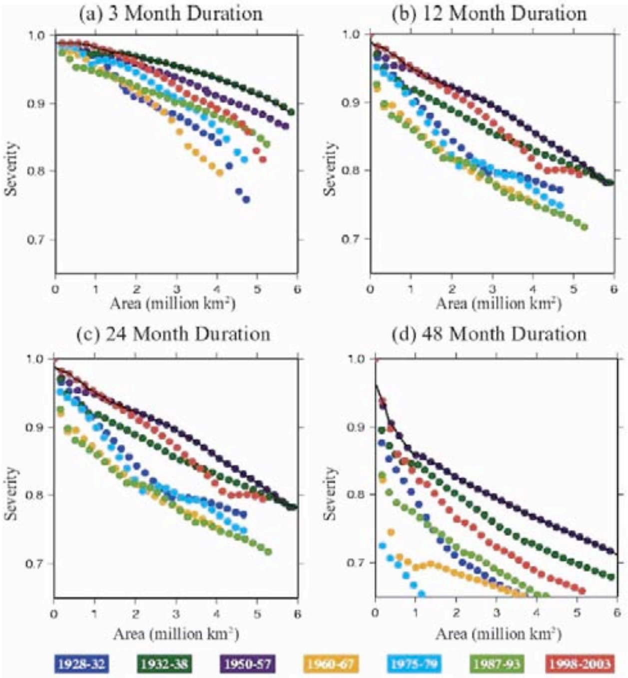

Fig. 5.2. Severity-Area-Duration results for continental U.S., based on analysis of off-line simulations of soil moisture. Plots show average severity (as average cumulative probability over the given area) vs. area for a range of durations. From Andreadis et al., 2005: *J. HydroMet.*, **6**, 985-1001.

5.3.3 Evaluate Predictability of Hydrologic Extremes from Days to Seasons Using Coupled Models

Considerably more effort has been made to utilize weather and climate model output for real-time short (hours to days), medium (days to weeks), and seasons (weeks to months) hydrological prediction than for unconditional hydrological estimation (e.g., of flood and drought frequency). HEPEX, the Hydrological Ensemble Prediction Experiment, has focused on short and medium time scales. Seasonal hydrological prediction has been undertaken in various contexts, and some methods, such as conditional resampling (known in the hydrological community as Ensemble Streamflow Prediction, or ESP) are now applied operationally. Nonetheless, key science issues remain to be addressed. These include: 1) understanding the relative skill of long-range weather and climate forecasts as compared with skill attributable to persistence in hydrological initial conditions, and the factors controlling this tradeoff; 2) the value of ensemble and multimodel ensemble methods in hydrological applications; and 3) particulars related to use of multiple ensembles and relating the ensemble range to quantitative prediction errors. Furthermore, while most hydrological prediction implicitly is directed towards hydrological extremes (when the value of accurate forecasts is highest), nonetheless a more explicit focus on evaluation of the factors affecting forecast skill under extreme conditions is warranted.

Deliverables: A key requirement of essentially all methods that use coupled models for ensemble forecasting of hydrological extremes is access to a climatology sufficient for estimation of the probabilistic characteristics of the ensembles. This information often is not readily available (especially for operational forecasts), or the number of ensembles archived is too small. GEWEX could help to coordinate, in collaboration with programs like HEPEX, perhaps extended to longer lead times, archiving of the ensembles. GEWEX could also work with HEPEX to develop a proposal for a “next generation” intercomparison of hydrological forecasts made using coupled model output. Finally, GEWEX could encourage efforts to evaluate the feasibility of direct (possibly post-processed) hydrological output of coupled models, in contrast to off-line runs of hydrological models using downscaled forcings from weather and climate models, as is being done by HEPEX.

6. Technology Transfer: Develop diagnostic tools and methods, new observations, models, data management, and other research products for multiple uses and transition to operational applications in partnership with climate and hydro-meteorological service providers.

6.1 Rationale

Technology transfer is the process of sharing of skills, knowledge, technologies, and facilities among scientists, governments and other institutions to ensure that scientific and technological developments are accessible to a wider range of users. GEWEX is comprised of a large body of international scientists that can carry out scientific studies: data set development and analysis, model development, and assessment, and demonstration applications. In turn these provide information for users on approaches for improving models, better utilization of data, new tools for comparing satellite and model data, assessment of model skill, and synthesis activities that draw on the experience of a broad diverse set of scientists. An essential aspect of this Imperative is to transfer knowledge, methods, tools, and models developed through GEWEX Research Imperatives to operations, as well as to outside users. The sharing of technological information may come through education and training (see Imperative 7).

GEWEX has a well established legacy of development of global datasets, providing results from regional field programs with observations and products, establishing new methods of processing data and displaying results, improving models, and demonstrating the usefulness of these developments through applications focused on all manner of aspects of the water and energy cycles.

There is a need for international climate service providers, including government agencies, international agencies like UNESCO and GEO, NGOs and the private sector, to improve their understanding of the variability and trends in the water and energy cycles at the regional and global scales, and improve their modeling and predictive capabilities in order to provide improved services. Research provides the way forward.

Space agencies are providing an ever increasing amount of satellite-based data, such as near-global precipitation and soil moisture products, and there is a great need to help transition data products to operational uses and to demonstrate how the data and products can be applied to user problems. GEWEX research can help assess the utility of such data for water and energy cycle applications.

Historically, hydrologic design of water supply, addressing irrigation demands, flood protection and similar long-life water projects, use long-term data to determine capacity/size and assess reliability of the systems. But with climate change, the past is no longer a good guide to the future. The challenge is to help users understand the scope of the climatevariability and change on water resources design, to test approaches for assessing design reliability under projected climate change, and to compute the sensitivity of the terrestrial hydrologic system to climate and global change signals. The availability of climate model projections, often downscaled to finer spatial and temporal scales, has the potential for operational agencies, NGOs and private sector companies to assess the adequacy of existing water infrastructure for dealing with projected changes in extreme events (floods and droughts).

In addition, the use of climate-service data in hydrological forecasting is advancing and the use of seasonal to multi-decadal climate information for decision making is significant and growing. For example there is a growing demand for drought monitoring and forecasting, understanding the impacts of El Niño-Southern Oscillation (ENSO) and other climate patterns and teleconnections on regional seasonal climate and its impacts on large-scale hydrologic impacts such as flooding.

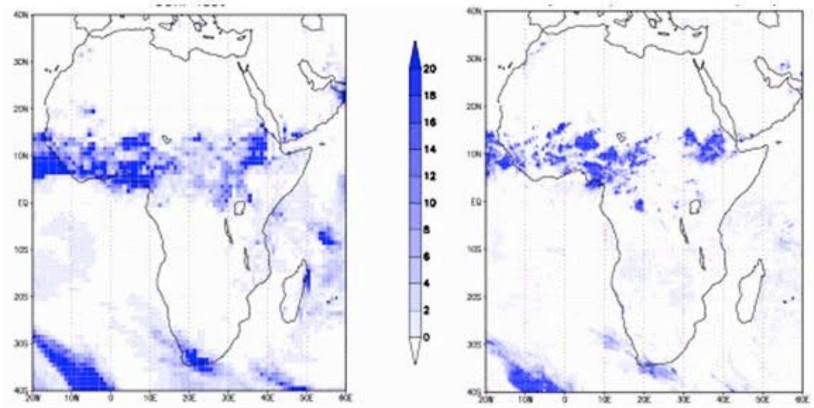

Fig. 6.1. Daily estimated precipitation for July 31, 2006. Left: from NOAA’s Global Forecast System (GFS); right: from TRMM 3B42RT product, accumulated from 3-hourly overpasses. Note the excess drizzle in the model result (Compiled by E. Wood).

6.2 Scientific Background

Perhaps the most visible GEWEX accomplishments to date have been the GEWEX global datasets based extensively on satellite data. These have had widespread use for many purposes, mostly related to water and energy cycle research. A number of surface “reference sites” with specific observations have also been established and the data are available, and networks, such as the Baseline Surface Radiation Network (BSRN), have been fostered and developed. Similarly, extensive work has been carried out on developing a prototype data management scheme that is proving invaluable in GEOSS, for instance.

A number of very useful tools have been developed to better enable observations from space to be compared with models (e.g., Fig. 6.1). Special tools, developed in association with the GEWEX Radiation Panel, such as simulators for ISCCP, Cloudsat and TRMM data, incorporate the characteristics and limitations of the observations including the sampling in space and time and thresholds of sensors. There is additional interest in simulating radiance observations that are related to the water and energy budget variables, and developing generalized tools for assessing the quality of radiative transfer computations. These range from fast models used in climate applications to detailed 3-Dimensional models needed to account for cloud inhomogeneity or surface vegetation effects. These tools enable increased understanding of the statistical uncertainty in satellite geophysical products and the skill in weather and climate model forecasts and projections, which will allow users to use these products effectively in data sparse regions. Mechanisms such as workshops, forums and demonstration applications are foundations for successful research to operations transfer. As an example, a forum has been established for determining the accuracy of radiation codes for use in models and other applications.

Land data assimilation systems have been developed where a number of land surface models provide monitoring information for water and energy cycle related needs; for example drought monitoring. By necessity these systems require inputs from some combination of in situ meteorological networks, satellite observations, and forecast model outputs. Alternatively, satellite observations from the various space agencies offer decadal-long data records of land states such as soil moisture (e.g., from the AMSE-E sensor and more recently from ESA’s SMOS satellite), snow cover, and evapotranspiration (e.g., at <100 m resolution from LandSat and ASTER; 1–2 *km* from MODIS and geostationary systems like GOES and MSG; and 5 to 25 km from sensors on-NASA TERRA and AQUA platforms). It is desirable to transfer these research developments and demonstration applications to operational agencies and users.

As an example, the potential of current soil moisture remote sensing to monitoring drought is also being done through land surface models forced with high quality meteorological data (in the case of Fig. 6.2 by NCEP’s Noah model). The comparison in Fig 6.2 is very good, giving confidence that the remote

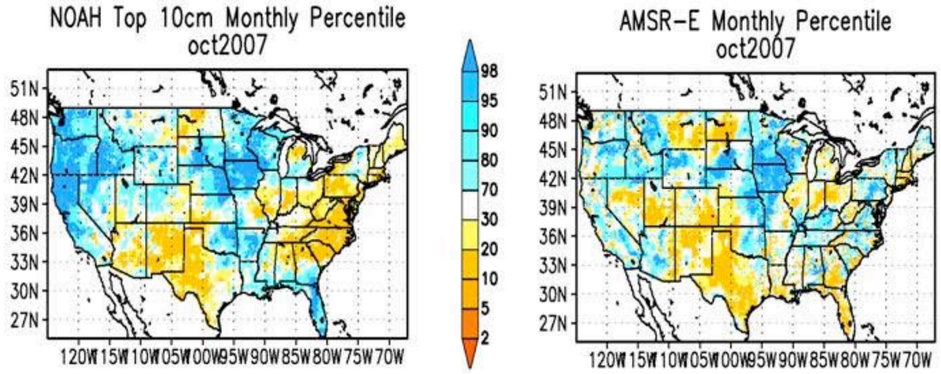

Fig. 6.2. Estimated drought index as the percentile value of the estimated soil moisture based on a long data record for October 2007. Left: Noah Land surface model estimate; right: AMSR-E based (from Sheffield et al., 2011).

sensing drought index approach can be transferred to regions like Africa with sparse data networks that may not support estimates via land surface models.

A sustained GEWEX research focus is the development and assessment of seasonal climate forecasts, for which the GEWEX modeling panels have the lead (see Imperative 4), and hydrological forecasts, led by GHP's Hydrological Application Project (HAP). In addition, HAP has begun to develop and test approaches for making climate change projections, based on CMIP4 model intercomparison runs, useful for applications through bias correcting and downscaling approaches. The results of research and demonstration applications (cf. Imperative 5) are critically needed by the operational agencies and user community so they can carry out climate change assessments related to sustainable water resources, water-related hazards, agriculture and other water and energy cycle sectors.

6.3 Strategic Plan

There is broad interest by governmental and international agencies (e.g., UNESCO, US AID, GEO) and hydrological service providers to have improved global monitoring of the water cycle at regional to global scales. The needs range from assessing water availability, agricultural food security, flood disaster monitoring, and so forth. The challenge is to help users obtain information on water cycle monitoring (e.g., in GLDAS) and synthesize the experiences in regional to global water cycle monitoring. This will demonstrate the "value" of such monitoring systems and show hydrologic service users how new and anticipated satellite data can be useful for their needs. Effective transition of GEWEX Research-to-Operations will require a sustained effort by GEWEX leadership and scientists as well as having receptive recipients to receive the transferred technology. Objectives include the following.

Data Set Developments:

- Develop and transfer approaches for assessing the skill of satellite-based water and energy cycle products that are needed for operational applications. As examples, the development of satellite based flood and drought monitoring using current and anticipated satellite data such as the Soil Moisture Ocean Salinity (SMOS) data; the Global Precipitation Mission (GPM) data (expected launch 2012), Soil Moisture Active Passive (SMAP) (expected launch 2014) and other systems, recently launched or anticipated over the next decade.
- Develop tools to access, utilize and assess data from large data archives (e.g., NASA satellite DAACs; EUMETSAT SAFs; atmospheric reanalysis model archives (ERA-interim, MERRA, CFSR); and in situ water and meteorological archives that are appropriate and useful for operational users and decision makers. This activity would build on similar tools already developed by the research

community, and requires an understanding of how such tools would be used by the operational and user community.

- Simulators and radiative transfer codes are continuously being developed by the scientific community including members of the GRP. GRP will catalogue these tools and resources for the broader community along with brief descriptions of the tools intended purpose and strengths. Assessments will be undertaken if the current suite of tools and resources grows to the level that users require guidance about the individual products.

Model Developments:

- The challenge is to quantify the skill of seasonal climate forecasts when used for hydrological prediction, including assessment of procedures for bias correcting and downscaling the seasonal forecasts, and to get the hydrological service providers to use and evaluate procedures being developed by GEWEX scientists. The action is to transfer the technology of hydrologic seasonal forecasting (models and methods) to operational centers. GEWEX's traditional requirement of having operational meteorological (and hydrological) services participate in the RHPs needs to be reinvigorated to develop a pathway for transition. As an example, collaborative GEWEX-operational agency RHP demonstration projects can serve as a "poster child" for other operational groups.
- Develop products and tools (including bias correction and downscaling methods) to demonstrate the predictive skill in rainfall and temperature from current seasonal forecast models using their hindcast data sets. As with the transfer of data products, current tools evolved from the GEWEX research community and need to be made appropriate for the operational community. GEWEX will work with related programs (e.g., the Hydrological Ensemble Prediction Experiment, HEPEX) that have user groups along with research groups addressing these issues.
- Transfer of global water cycle monitoring models and methods. One key scientific issue is how to go from global to regional scales and vice-versa, and to link modeling with observations. While this is an effort within other Imperatives (c.f. Imperatives 4 and 5), it is important to deliver regional expertise in terms of modeling and observations of parts of the water cycle, from event scales (drought, heavy precipitation, and flood) to seasonal and decadal variability to operational agencies, user groups, and various decision makers.
- Tools and procedures are required to synthesize the hydrological impacts from projected climate change and to develop an international benchmark of hydrological climate change impacts to assess uncertainty in AR5 projections useful for operational adaptation plans. While Imperative 5 discussed the need to develop and assess issues, such as data non-stationarity in assessing water-related hazard risks (e.g., floods and droughts) and water resource performance (e.g., water supply reliability), tools and procedures will be developed to translate those research and demonstration results to operational guidelines to help agencies understand and cope with anticipated climate change. This will be done using a range of water cycle assessment models forced by downscaled model outputs or high spatial resolution AR5 time-slice data, calibrated against historical records of hydrological impacts such as droughts and floods. In addition, GEWEX scientists will evaluate regional climate models within CORDEX using the expertise of the RHP scientists. Water resources, agriculture, food production, and other areas should provide metrics which can be used to evaluate the performance of climate models for providing useful climate information.

Statistical Developments: GEWEX should also foster advanced statistical tools. There are many mathematical ideas that need development into computationally practical schemes. They should deal with data inaccuracies which pure mathematicians often do not deal with and only geo-scientists can judge the "meaningfulness" of the results. The task is to foster such studies to stimulate development. Some specific examples related to advances of statistical methodologies for extreme event statistics have not yet been exploited to the full extent and this precludes accurate quantitative estimation of probabilities of risks of climate-associated natural disasters, making risk management actions highly uncertain and not regionally oriented. In order to overcome these shortcomings, efforts are needed to:

- Build a community of climate scientists and statisticians working together, cross-pollinating the ideas of each other and speaking the same terminology language; develop robust statistical methods for assessing extremes and their uncertainties; and make tools available for wide-spread use.
- Ensure that archives of model projections include sufficient high frequency data to assess the required statistical metrics (higher order statistical moments and probability density functions) required for accurate regional assessment of risks of extreme events and planning adequate risk management actions.
- Initiate a close co-operation and consolidate a task force of the observational, modeling and statistical communities to improve estimation of probabilities of compound extreme events and their potential prediction, taking into account that particularly compound extremes result in most disastrous economic and human losses and require specific actions to manage their risks.

Links to Other Activities: The GEWEX Capacity Building Imperative (Imperative 7) will be an essential element, but GEWEX must work with ESSP programs, inter-governmental programs and agencies like UNESCO, WMO, and GEO, as well as NGOs, for success in meeting many goals of this Imperative. On seasonal hydrologic prediction, it is essential to work with the GEWEX modeling panels, the GHP/HAP WG, and the RHP basin coordinators.

Partners: pan-WCRP, IGBP, ESSP and especially links to the Global Water System Project (GWSP), UNESCO/IHP, GEO and hydro-meteorological and climate services. Quantify the performance of the models in conjunction with EU-WATCH and ILAMB projects.

7. *Capacity Building:* Promote and foster capacity building through training of scientists and outreach to the user community.

7.1 Rationale

Capacity building has been an objective of global programs and their regional projects for many years. Within climate and hydrology programs, capacity building involves increasing the capacity of society in general and the research community in particular to deal with environmental issues. Capacity building occurs through training programs and outreach by targeting groups that do not have an adequate science and technology capability to take advantage of new research findings to participate in independent research, or to adapt new technologies. It also applies to the need to transfer the technologies developed by a generation that is moving towards retirement to those who will be able to build on these technologies and move them to the next level in support of global information systems.

7.2 Background

GEWEX has undertaken a number of capacity building activities since its inception, particularly through its RHPs and through the CEOP (and now the GHP). RHPs with active capacity building activities (currently or in the recent past) include AMMA (African Monsoon Multidisciplinary Analysis Project), BALTEX (Baltic Sea Experiment), CPPA (Climate Prediction Program for the Americas), LPB (La Plata Basin), MAHASRI (Monsoon Asian Hydro-Atmosphere Scientific Research and prediction Initiative), and NEESPI (Northern Eurasian Earth Science Partnership Initiative).

The relevant activities of the RHPs and other GHP groups fall into the following three general classes of capacity building that may also be appropriate for other parts of GEWEX, namely provision of:

- Scientific materials, knowledge and methodologies to young scientists in developed countries who benefit from GEWEX expertise and experimental products. This also includes the involvement of young scientists in research projects with senior scientists who can serve as mentors
- Scientific materials, knowledge and methodologies to scientists (especially young scientists) and other specialists in developing countries who can benefit from GEWEX expertise and experimental products
- New experimental data products, new observational systems, advanced data management systems, integrative assessments of science knowledge, and related infrastructure and user interactions that provide operational service providers, policy makers, resource and environmental managers, decision makers, and stakeholders with the understanding and techniques needed to do their jobs better.

Although the formats for these capacity building activities take place in different forms, they all have proven to be successful for certain communities and will be continued in the future.

7.2.1 Educational Approaches

Science Conferences and Meetings: These are important opportunities to bring young scientists into environments where they can interact with senior scientists in presenting results or discussing plans for future research programs thereby building confidence in their research methodologies, results, and scientific assessments. Recent activities included the GEWEX/iLEAPS Science Conference for young scientists in Melbourne, Australia, in August 2009, the Pan-GEWEX Meeting in Seattle in August 2010, and the September 2010 WCRP-UNESCO (GEWEX/CLIVAR/IHP) Workshop on Metrics and Methodologies of Estimation of Extreme Climate and Events in Paris. MAHASRI invites scientists from Asian developing countries to AOGS meetings, while BALTEX has organized international conferences every 3 years since 1995 that provide travel support for young scientists mainly from specific target countries. Most RHPs hold annual investigator meetings which serve a similar function.

Workshops: These focus on specific issues and are used to engage young scientists and senior scientists in interactions that benefit both groups. During the past 2 years RHPs held workshops in South America (LPB) (Fig. 7.1), west Africa (AMMA), southeast Asia (MAHASRI) and Russia, Former Soviet Union countries, and Alaska (NEESPI).

Directed training activities: Events such as summer schools and field schools, training programs and courses enable scientists and/or practitioners to make better use of GEWEX technologies and data services, and conduct independent research. During the past two years summer schools and other training programs were held in Russia (NEESPI), Europe (BALTEX), and southeast Asia (MAHASRI in collaboration with the Disaster Prevention Research Institute in Japan). Training is very efficient in circumstances where a group of people need to learn certain skills to operate data systems or provide services in support of GEWEX research. Training also develops young scientists so they can obtain accreditation and be better prepared to undertake their own independent research. For example, the MAHASRI project has provided training programs for the operation of data systems, data acquisition, data management and analysis in southeast Asia. A new research initiative, SATREPS (Science And Technology Research Partnership for Sustainable development), initiated in 2009 in Thailand and Indonesia will also entail capacity building activities. Other related activities include the Ev-K2-CNR project that enables young scientists to study climate change related to processes in high altitude areas and effects on fragile ecosystems, by participating in UNEP and HKKH Partnership (www.hkkhpartnership.org) projects. NEESPI practices long-term visits (up to six months) of early career scientists to leading institutions of the United States and Russia. AMMA organized several Summer Schools, including a recent one in Dakar, Senegal on climate change and water resources.

Not all training programs are formally structured. During field missions in Nepal, Pakistan, and Uganda, Ev-K2-CNR’s European researchers commonly involve local technicians and young scientists in “on-the-job” training related to the management and maintenance of sophisticated environmental monitoring systems. Institutional seminars and courses are also organized in various research fields on topics from environmental monitoring, to sampling procedures, to protection of natural resources. Training is a natural outcome of GEWEX research because many RHP scientists occupy academic positions and are involved in training students as part of their on-going responsibilities. In AMMA, co-supervision of graduate students and theses between universities in developing countries and developed countries has been very successful. In West Africa, France has been working to promote shared supervision. Students spend part time in their country and part time in France; register in universities in both countries and graduate with one diploma signed jointly by the two countries. Efforts to reach high school students were pursued by CPPA through the NOAA “Teachers in the Field” program when the North American Monsoon Experiment (NAME) sponsored two teachers to participate in its field campaign and communicate their learning experiences back to their classes.

7.2.2 Development of Observational Capabilities

To complete its field campaigns, GEWEX needs to establish strong ties with the National Hydro-Meteorological Services (NHMS) because they often play a critical role in providing observations and on occasion field support for RHP field campaigns. In several cases GEWEX has enabled NHMS to strengthen their observational networks and services. AMMA, which assisted in building capacity in the national weather services in western Africa by finding support for enhanced observational programs, has initiated a number of small-scale observatories through collaborative research projects. In Niger and Senegal two -high density rain gauge networks have been running for several years. MAHASRI has installed new hydrometeorological instruments at sites in Asian countries, including China (Tibet), Thailand, Vietnam, Cambodia, Lao, Bangladesh, India and Indonesia in partnership with a number of the projects participating in AMY. In the Americas, the CPPA NAME project worked with the Mexican Weather Service to strengthen observational capabilities along the northwest coast of Mexico.

Fig 7.1. Participants at a recent LPB Workshop held in Itaipú Technological Park, Foz do Iguaçu, Paraná State, Brazil.

7.2.3 Direct Interaction with Decision Makers and Stake Holders

GEWEX also interacts with users to assess their needs. In addition to the feedback received from capacity building activities some stakeholder interactions have been initiated in some projects. Knowledge has been summarized in many forms: lectures, blogs, web sites and publications. NEESPI has produced three books and has another in preparation. These books accumulate and disseminate information about environmental changes, existing gaps, and the latest research advances in the appropriate areas of the NEESPI domain. BALTEX has initiated several activities to help creating awareness for measures to adapt to climate change, based on a publication ["*Assessment of Climate Change for the Baltic Sea Basin*" (BACC)], which has also been used by the Helsinki Commission/HELCOM (www.helcom.fi), see Fig 7.2. Actions include a one-day conference "*Adapting to climate change – Case studies from the Baltic Sea Region*" scheduled for May 2011 targeted for regional decision makers organized within BSSSC (www.bsssc.com).

The GEWEX GHP/Extremes Drought Research Initiative (DRI) is also preparing a book for professionals on drought to inform resource managers of the most recent findings of Canadian drought research and organizing a public lecture series. DRI also held a series of workshops in 2010 for its users and stakeholders in each of three Canadian Prairie provinces featuring a table top exercise where users provided feedback on various experimental products that could be used in drought management.

7.2.4. Data Services and Infrastructure in Developing Countries

One of the greatest challenges for scientists in developing countries is knowing where and how to access data. To assist scientists in developing countries in Eurasia with their research, NEESPI has prepared and will release national in situ data sets for Kazkhstan, Belarus, Uzbekistan and thematic data sets including snow depth and structure and borehole permafrost observations. On a larger scale, GHP maintains a data system to facilitate the analysis of data for model development on a global basis. These data are freely available to anyone who registers as a user. In Asia, these services are complemented by the University of Tokyo's Data Integration and Analysis System (DIAS).

In addition, a new Data Analysis and Exploring System for Hydrology of the NEESPI domain has been implemented at University of New Hampshire–Durham which provides unrestricted web-based access to data products (http://neespi.sr.unh.edu/maps/), making it a useful tool for hydrological assessments within Northern Eurasia. This system is mirrored at the Siberian Center for Environmental Research and Training, Tomsk, Russia (http://www.scert.ru/).

The Ev-K2-CNR project focuses on the transfer of knowledge and technologies, use of tools, multidisciplinary approaches, and reinforcement of institutional networking at local, national, and regional levels. Several RHPs such as AMMA, have envisioned the creation of databases and the use of technological infrastructure to support the research and decision making. Maintenance of these data bases and dissemination of the information about their accessibility are two on-going challenges.

Fig. 7.2. A panel discussion held at the International BACC Conference, May 2006, in Gothenburg, Sweden, providing for science – stakeholder interaction and GEWEX/BALTEX outreach. Panel members included scientists, members of EU and national parliaments, HELCOM representatives and journalists.

7.3 Strategic Plan

There are increasing expectations and requirements for capacity building. The majority of GHP capacity building activities are focused at the regional scale and are often supported through regional agencies other than those providing the primary funding for the RHP projects. In the future, GEWEX is likely to find that its capacity building effort will have more impact if it is coordinated between regions and some common messages are provided in each region. GEWEX capacity building activities need to be focused and supportive of its overall goals while at the same time supporting WCRP and its broader goals. In the post 2013 era GEWEX will pursue capacity building efforts to:

- Ensure that younger scientists entering careers in the climate and hydrological sciences in both the developing and the developed nations are aware of the advances, technologies and opportunities that GEWEX has developed and are mentored in mobilizing the capabilities, data systems and funding sources needed to take full advantage of the GEWEX heritage and to contribute to new developments and advances in coupled land atmosphere modeling and measurement.

- Assist developing countries to adapt the new technologies needed to participate in data analysis and prediction systems for the efficient management of their resources. This will involve the transfer of technologies and knowledge needed to access global data systems and to implement the technologies locally that are needed to improve the efficiencies of NHMS and water resource management and related environmental agencies.

Some RHPs are already preparing for the future. Ev-K2-CNR capacity building activities will be strengthened by its more active involvement in UNEP projects, which together will assist in enhancing institutional capacities in developing countries to implement the science-policy interface to better support management of mountain ecosystems and natural resources. Within this context, special efforts in training and technology transfer will be given to issues concerning water quality and energy and water cycle processes, and their responses to climate change. These activities will raise awareness on the effects of climate change in mountain regions and allow local researchers to become more autonomous in the implementation of long-term environmental monitoring programs.

To date, the main barriers and gaps experienced in GEWEX capacity building activities relate to lack of resources for capacity building and training workshops. Also, data sharing remains an issue for some countries and research groups.

7.4 Links to Other Activities

Leads: GHP; **Partners**, ESSP, START, GEO

There are a number of organizations with mandates to do capacity building in areas of interest to GEWEX. In particular, the ESSP provides links to many relevant activities. Through its RHPs, GEWEX has made links with regional programs, including the regional components of international programs. For example, at the project level, links exist between GEWEX activities and APN- and IAI-funded research.

START, another natural partner for GEWEX in Capacity Building, is the global change **S**ys**T**em for **A**nalysis, **R**esearch and **T**raining, a non-governmental research organization that assists developing countries in building the expertise and knowledge needed to explore the drivers of and solutions to global and regional environmental change. Their goal is to reduce vulnerability through informed decision-making. To achieve this goal they administer several capacity building programs. GEWEX has had success in working on specific initiatives with START although much more could be done, especially if projects were planned at the strategic level.

GEWEX also contributes to the water-related capacity building efforts in the Group of Earth Observations (GEO) work plan. GEO maintains an active capacity building activity as part of its efforts to build and use the Global Earth Observing System of System (GEOSS). GEWEX, through its linkages with the IGWCO Community of Practice has contributed to these efforts in the area of water. Specific collaborations have occurred in Asia with the Asian Water Cycle Initiative, the African Water Cycle Coordination Initiative and in Latin and Caribbean Americas with CIEHLYC (Spanish for Centre of Hydrologic and Spatial Information for Latin America and the Caribbean). Given the common interests, it is appropriate for GEWEX to build an alliance with GEO Water and to work on some collaborative initiatives related to capacity building.

Linkages with other partners will be developed for the mutual benefit of GEWEX and the other partners. Specific groups where stronger links will be developed in the future include WMO, UNESCO (IHP), the Global Water System Project (GWSP) and IRI among others.

Credits

The main teams that developed the initial drafts of the Imperatives are given below. However, many others also provided input via comments and suggestions, and the document is a community effort. Kevin Trenberth assembled, edited, and reviewed all contributions with help from the IGPO.

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ACRONYMS

ABL: Atmospheric Boundary Layer
ACPC: Aerosols, Clouds, Precipitation and Climate Initiative (iLEAPS/GEWEX/IGAC)
A.K.A.: also known as
AMMA: African Monsoon Multidisciplinary Analysis Project
AMSR: Advanced Microwave Scanning Radiometer
AMY: Asian Monsoon Years
AOGS: Asia Oceania Geosciences Society
APN: Asian Pacific Network
AR4: IPCC Assessment Report 4
AR5: IPCC Assessment Report 5, due in 2013
ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer
BACC: BALTEX Assessment of Climate Change for the Baltic Sea Basin
BALTEX: Baltic Sea Experiment
BSRN: Baseline Surface Radiation Network
BSSSC: Baltic Sea States Subregional Co-operation
CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation.
CAS: WMO Commission for Atmospheric Sciences
CEOP: Coordinated Energy and Water Cycle Observations Project
CEOP also previously: Coordinated Enhanced Observing Period
CEOS: Committee on Earth Observation Satellites
CFS: Climate Forecast System
CFSR: NCEP-NOAA CFS Reanalysis
CIEHLYC: Community for spatial and hydrological information in Latin America and the Caribbean
CLIVAR Climate Variability and Predictability Project (WCRP core project)
CLiC: Climate and Cryosphere Project (WCRP core project)
CMAP: NOAA Climate Prediction Center (CPC) Merged Analysis of Precipitation
CMIP: Climate Model Intercomparison Project
CORDEX: COordinated Regional climate Downscaling EXperiment
CPPA: Climate Prediction Program for the Americas
CSE: Continental Scale Experiment
DAAC: Distributed Active Archive Centers
DIAS: Dynamic Information Architecture System
DMWG: Data Management Working Group
DRI: Drought Research Initiative
ECMWF: European Centre for Medium Range Weather Forecasts
ENSO: El Niño-Southern Oscillation
ERA-I: ECMWF Interim Reanalysis
ESP: Ensemble Streamflow Prediction
ESSP: Earth System Science Partnership
Ev-K2-CNR: Everest-K2 National Research Council
FAME: Framework for Atmospheric Model Enhancement
GABLS: GEWEX Atmospheric Boundary Layer Study
GACP: Global Aerosol Climatology Project
GCOS: Global Climate Observing System
GCIP: GEWEX Continental Scale International Project
GCSS: GEWEX Cloud System Study
GEO: Group on Earth Observations
GEOSS: Global Earth Observing System of Systems
GEWEX: Global Energy and Water Cycle Experiment (WCRP core project)
GFS: Global Forecast System
GHP: GEWEX Hydroclimatology Panel (previously GEWEX Hydrometeorology Panel)

GLACE: Global Land Atmospheric Coupling Experiment
GLASS: Global Land Atmosphere System Study
GLDAS: Global Land Data Assimilation System
GMPP: GEWEX Modeling and Prediction Panel
GOES: Geostationary Operational Environmental Satellites
GPCP: Global Precipitation Climatology Project
GPM: Global Precipitation Mission
GRP: GEWEX Radiation Panel
GSWP3: Global Soil Wetness Project 3
GWSP: Global Water System Project
HAP: Hydrological Application Project
HE: High Elevation Working Group
HELCOM: Helsinki Commission – Baltic Marine Environment Protection Commission
HEPEX: Hydrological Ensemble Prediction Experiment
HKKH: Hindu Kush-Karakoram-Himalaya region
HyMeX: HYdrological cycle in the Mediterranean Experiment
IAI: Inter Americas Institute
IGAC: International Global Atmospheric Chemistry
IGBP: International Geosphere-Biosphere Programme
IGPO: International GEWEX Project Office
IGWCO:- Integrated Global Water Cycle Observations Community of Practice
IHDP: International Human Dimension Programme on Global Environmental Change
IHP: International Hydrology Programme
ILAMB: International Land Model Benchmarking
iLEAPS: Integrated Land Ecosystem-Atmospheric Processes Study
IPCC: Intergovernmental Panel on Climate Change
IRDR: Integrated Research on Disaster Risk
IRI: International Research Institute
ISCCP: International Satellite Cloud Climatology Project
JAMSTEC: Japan Agency for Marine-Earth Science and Technology
JRA-25: Japanese Meteorological Agency 25 year reanalysis
JSC: WMO/ICSU/IOC Joint Scientific Committee (for WCRP)
LBA: Large-scale Biosphere Atmosphere Experiment in Amazonia
LIS: Land Information System
LMWG: Land Model Working Group
LOCO: LOcal COupled Modelling Working Group in GLASS
LPB: La Plata Basin
MAC: Multi-model Analysis for CEOP
MAGS: Mackenzie GEWEX Study
MAHASRI: Monsoon Asian Hydro-Atmospheric Science Research and prediction Initiative
MERRA: Modern Era Retrospective-Analysis for Research and Applications
MDB: Murray Darling Basin
MIP: Model intercomparison Project
MODIS: Moderate Resolution Imaging Spectroradiometer
MSG: Meteosat Second Generation
NAME: North American Monsoon Experiment
NASA: National Aeronautics and Space Administration
NCEP: National Center for Environmental Prediction
NEESPI: Northern Eurasian Earth Science Partnership Initiative
NHMS: National Hydro-Meteorological Service
NGO: Non Governmental Organization
NOAA: National Oceanic and Atmospheric Administration
PBL: Planetary Boundary Layer

PDF: Probability Density Function
RHP: Regional Hydroclimate Project
SAF: Satellite Application Facility
SATREPS: Science And Technology Research Partnership for Sustainable development
SCOPE-CM: Sustained, Co-Ordinated Processing of Environmental Satellite Data for Climate Monitoring
SMAP: Soil Moisture Active Passive
SMOS: Soil Moisture Ocean Salinity
SPARC: Stratospheric Processes And their Role in Climate ((WCRP core project)
SSC: Science Steering Committee
SSG: Scientific Steering Group
SST: Sea Surface Temperature
START: **S**ys**T**em for **A**nalysis, **R**esearch and **T**raining
TRACE: Terrestrial Regional North American hydroClimate Experiment
TRMM: Tropical Rainfall Measuring Mission
UNEP: United Nations Environmental Programme
UNESCO: United Nations Education, Scientific and Cultural Organization
USAID: U.S. Agency for International Development
WATCH: EU Integrated Project on Water and Global Change
WCRP: World Climate Research Programme
WGCM: Working Group on Coupled Modelling
WGNE: Working Group on Numerical Experimentation (Joint WCRP, WMO (CAS))
WGSIP: Working Group on Seasonal to Interannual Prediction
WMO: World Meteorological Organization
YOTC: Year Of Tropical Convection