GEWEX Hydrology

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Abstract The Global Energy and Water Cycle Experiment (GEWEX), of the World Climate Research Programme (WCRP) was initiated in 1988 and has coordinated the activities of the Continental Scale Experiments (CSEs), which are now known as Regional Hydroclimate Projects (RHPs) and other land surface research through the GEWEX Hydrometeorology Panel (GHP). The GHP was established in 1995 to contribute to the WCRP objective of "developing the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of man's influence on climate". More specifically, the GHP contributed to the GEWEX objectives such as "determining the hydrological cycle and energy fluxes, modelling the global hydrological cycle and its impact, developing a capability to predict variations in global and regional hydrological processes and fostering the development of observing techniques, data management and assimilation systems". GHP activities included diagnosis, simulation and prediction of regional water balances by various process and modelling studies aimed at understanding and predicting the variability of the global water cycle, with an emphasis on regional coupled land–atmosphere processes. GHP efforts were central to providing a scientific basis for assessing critical science issues such as the consequences of climate change for the intensification of the global hydrological cycle and its potential impacts on regional water resources. This paper discusses the more relevant scientific issues relating to hydrology addressed by the GHP in collaboration with the international science community, in particular the IAHS Predictions in Ungauged Basins (PUB) initiative. GHP activities have now been formally merged with the Coordinated Enhanced Observation Period (CEOP) I and II activities to form a new body, called the Coordinated Energy and water-cycle Observations Project (CEOP), which will continue to foster large-scale hydroclimate research. Within GHP and now within CEOP the Water Resources Applications Project (WRAP) was established in 2000 to facilitate the broader use of GEWEX products in water resource applications and initially promoted dialogue between the GEWEX community and the water resources community. With members from each of the RHPs, IAHS, UNESCO programmes, and the World Meteorological Organization (WMO), this group provided a wide range of expertise related to water management. WRAP relied on the development of physically-based hydrology and "application" or decision support models, and the coupling of these models with regional climate models. Application studies require a capability to downscale large area (model grid square) precipitation forecasts and observed averages, statistical analyses of the relationships between SST anomalies and seasonal streamflow, and analysis of the value and utility of seasonal forecasts in water management decisions. WRAP is now evolving toward a Hydrologic Applications Project (HAP) which was defined in October 2006 together with the "Roadmap" for the remainder of the Second Phase of GEWEX (2006–2012). This paper summarises the achievements to date of GEWEX pertaining to hydrology and gives an indication of the planned hydrological focus of the project over the next five years. It also discusses the more relevant scientific issues relating to IAHS hydrological issues to be addressed by CEOP, including the IAHS Predictions in Ungauged Basins (PUB) initiative.

INTRODUCTION

In the late 1980s, a number of global projects were underway when the space agencies and the World Climate Research Programme (WCRP) and IAHS became interested in supporting the newly proposed GEWEX (Global Energy and Water cycle EXperiment). When GEWEX commenced in 1988 with a focus on global products and data, it was recognised that the developing global data sets needed to be evaluated not only for short time and spatial scales, but also at regional scales, for many annual cycles. For example, significant improvements were being made to land surface models as a result of intensive regional land surface experiments being carried out by the GEWEX International Satellite Land Surface Climatology Project (ISLSCP) and the Biospheric Aspects of the Hydrologic Cycle (BAHC) initiative under the International Geosphere-Biosphere Programme (IGBP). ISLSCP carried out intensive field campaigns focused on relatively homogeneous areas covering a 10 000 km^2 area (then approximately the area of a climate model grid square) and involved intensive observational periods for (generally) two to four week periods several times a year. As a result of the convergence of GEWEX and IAHS interests for an extension of these ISLSCP studies to a regional climatological testbed, the concept of a continental scale hydrological experiment was developed in 1990. Regional water and energy budgets on the continental scale became a central theme for the proposed regional experiment based on the hypothesis that water and energy budgets over a large basin would not be as sensitive to random errors as they are at a point or for a small basin, but they could still be examined in a meaningful way because there was an increasing likelihood of closing continental-scale water and energy budgets within acceptable limits using newly available data sets and models.

In 1990, the GEWEX Scientific Steering Group (SSG) approved the development of a scientific plan for a continental-scale project. In addition to testing GEWEX global products, this study was intended to assist GEWEX in modelling the hydrological cycle. Initially a group of international experts recommended the Mississippi River basin as a focus area and then worked with others to draw up a science plan for the GEWEX Continental-scale International Project (GCIP). However, as planning progressed, it became evident that not all processes important to global climate occurred in the Mississippi River basin (e.g. permafrost, tropical forests, etc.). In addition, a number of country representatives indicated that they could make stronger national contributions to GEWEX if they studied a basin that fell within their national boundaries. In 1992, it was agreed that proposals for additional continental experiments in other regions would be considered, provided that they satisfied mutually agreed criteria. As a result of developments since that time, five mature continental-scale experiments and three relatively new experiments now cover ten large land areas, with further areas in cold regions being proposed. Together, they have and are still accumulating many years of unique data, research results and experience.

The GEWEX SSG established the GEWEX Hydrometeorology Panel (GHP) in 1995 to coordinate the wide range of interests and activities involved in these continental-scale experiments. ISLSCP, the Global Runoff Data Centre (GRDC), and the Global Precipitation Climatology Centre (GPCC) activities were also included as part of this Panel's responsibilities. The overall GHP mission was to "demonstrate the capability to predict changes in water resources and soil moisture at time scales up to seasonal and interannual as a component of the WCRP's prediction goals for the climate system". To this end, it maintained an overview of research in the CSEs and influences the priorities of each CSE. The GHP also initiated, synthesised, reviewed and recommended joint activities that promoted a common research agenda in each of the CSEs and integrated the results from the individual CSEs to fulfil the expectations for GEWEX and the WCRP. The GHP further promoted and coordinated interactions with the other GEWEX Panels, namely the GEWEX Radiation Panel (GRP) and the GEWEX Modelling and Prediction Panel (GMPP). The GHP developed numerous summaries and reports to GEWEX, WCRP and the public on a range of scientific activities (refer to http://www.gewex.org).

GEWEX REGIONAL HYDROCLIMATE PROJECTS

As GEWEX developed and planning progressed, a consensus emerged that other climatic areas needed to be included for a global coverage of the important processes. As a result several experiments were developed to cover large land areas. GEWEX continental-scale experiments have included:

- MAGS (MAcKenzie GEWEX Study),
- GCIP/GAPP/CPPA (GEWEX Continental-scale International Project/GEWEX Americas Prediction Project/Climate Prediction Program for the Americas),
- LBA (Large-scale Biosphere Atmosphere experiment in Amazonia),
- LPB (La Plata Basin),
- BALTEX (BALTic sea EXperiment),
- GAME/MAHASRI (GEWEX Asian Monsoon Experiment/Monsoon Atmospheric Hydrologic Study Research Initiative),
- MDB (Murray-Darling Basin),
- AMMA (African Monsoon Multidisciplinary Analysis)
- NEESPI (Northern Eurasia Earth Science Partnership Initiative).

These CSEs have had different start and end dates. For example, AMMA was approved as a CSE beginning in 2005 and MAGS, which began in 1994, ended in 2005. The newest CSE, NEESPI, has now been proposed and accepted by the GEWEX SSG in 2007. Also, as of 2007, the CSEs became known as Regional Hydroclimate Projects (RHP).

The RHP areas are outlined in Fig. 1 and include two areas, LPB and AMMA that are collaborative experiments with WCRP's longer-term Climate Variability (CLIVAR) programme. The AMMA initiative is a collaborative regional study being

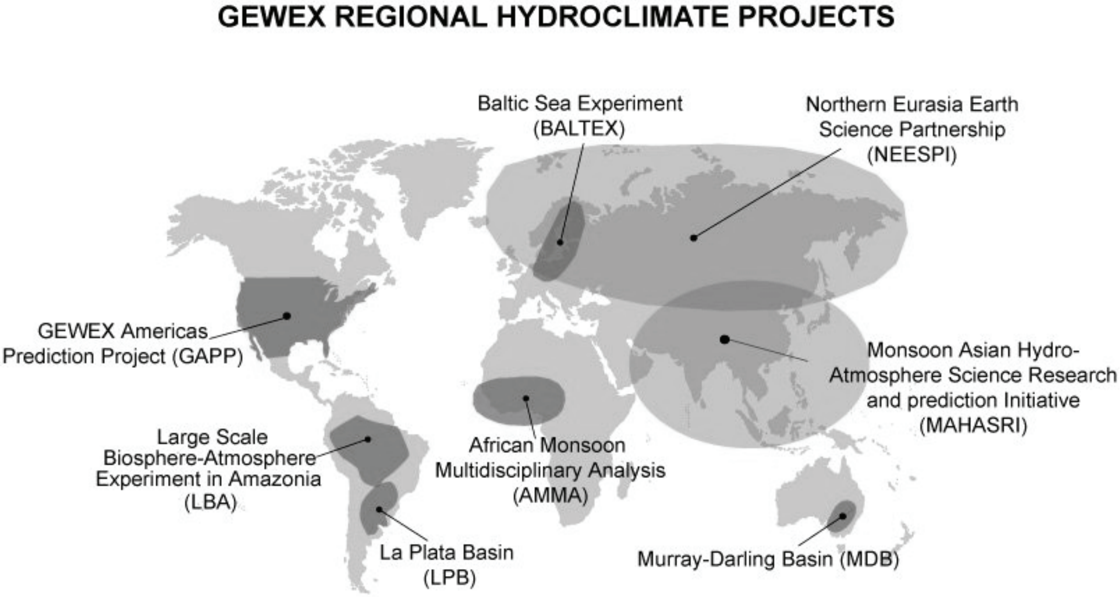

Fig. 1 Regional Hydroclimate Projects (RHPs).

coordinated by France and Benin under the auspices of GEWEX and CLIVAR, and the LPB is recognized as a joint GEWEX/CLIVAR/VAMOS activity. One area, NEESPI, is a multidisciplinary Earth System Science Partnership (ESSP) project and besides being recognized as a GEWEX RHP, NEESPI is also recognized as a project under the CLImate and the Cryosphere (CliC) project and the IGBP.

With the maturation of the RHPs and their data sets, the GHP placed a new emphasis on collaborative research linking them. Free and open data exchanges were found to be essential for the success of these activities. Accordingly, a data committee was established in 1998 and new initiatives were launched in 1998 to carry out Water and Energy Budget Studies (WEBS) and a Water Resource Applications Project (WRAP) in 1999. In addition, GHP adopted the following eight-step strategy for advancing its collective efforts:

1. Develop a consensus on the best surface characterization fields available for use by GHP.
2. Establish access to this information for special case studies.
3. Study regional climates and develop statements of progress by the RHPs and by the GHP.
4. Develop a strategy for examining the processes, data sets and remote sensing capabilities relevant to the RHPs and other regions. This should result in clearer priorities for future research and data collection activities.
5. Carry out a demonstration projects off-line with uncoupled hydrological and surface models and with these models coupled to an atmospheric model.
6. Select a specific observational period in one RHP as the basis for validation-transferability studies among the RHPs.
7. Produce summary statements regarding the influence of land on large scales for each of the RHPs.

8. Prepare a summer school on regional climate and water and publish a GHP overview article (see Lawford *et al*., 2004).

Projects within the RHPs serve as the regional building blocks for the global initiatives being led by the GHP. Each of the RHPs deals with a range of observational and scientific issues. Individually, they are unique because of the large number of diverse nations involved, the range of environmental and socio-economic conditions existing in each basin, and the degree of involvement of the operational services in the experiment. Table 1 summarizes the major features of each basin/area including the nations and regions involved. Each mature RHP has a science plan and documented research results that can be found on their web site. Additional details are provided on the early RHPs in Lawford *et al*., 2004.

Table 1 Summary of the countries and unique features of each of the RHPs.

RHP	Lead country	Other countries	Unique aspects
BALTEX	Germany	Sweden, Finland, Russia, Poland	Involves an oceanographic component over the Baltic Sea
GAME / MAHASRI	Japan	China, Thailand, Korea, Sri Lanka, Bangladesh, Nepal, India, Russia, (Mongolia)	Transect of study areas from tropical areas to the Arctic
GCIP / GAPP / CPPA	USA	Mexico	Involves well instrumented mid-latitude regions, land surface processes and water resource applications
LBA	Brazil	Colombia, Peru, Bolivia, Venezuela, Ecuador, EU, USA	Addresses role of tropical rain forests and the consequences of tropical deforestation for regional and global climate
LPB	Argentina	Uruguay, Brazil, USA	Looks at the moisture fluxes into La Plata Basin and its implications for runoff and flooding
MAGS	Canada		Freshwater inputs to the Arctic Ocean; cold region processes
MDB	Australia		Studies largely semi-arid region with high evaporation rates
AMMA	Europe	African countries, USA	Studies the effects of easterly waves, SSTs soil moisture and Saharan dust on the West Africa Monsoon
NEESPI	USA & Russia	Europe, China, Mongolia, Japan	Studies the effects of climate variability and change on the ecology of the region

HYDROLOGICAL TRANSFERABILITY STUDIES

Predictability of models

The WCRP strategy, the Coordinated Observation and Prediction of the Earth System (COPES) has made the topic of predictability and climate prediction its central focus for the 2005–2015 period. Predictability studies provide the scientific basis for the development of prediction systems by identifying the processes, areas, seasons and global circulation regimes in which predictive skill exists at longer (seasonal) time scales. The successful application of regional (and global) Land Surface Models

(LSMs) is dependent upon effectively representing the critical land–atmosphere processes in models. Land surface processes that contribute to persistent atmospheric conditions are being quantified and appropriately represented in coupled land–atmosphere models. These processes include vegetation (type, density, seasonal distribution), soil moisture (influences the partitioning of both the incoming solar radiation into sensible and latent energy and precipitation arriving at the surface into infiltration and runoff) and cold season processes (ground freezing, snow formation, accumulation and melt, winter surface albedo and ice formation). A number of special observing periods in support of process studies have been carried out by the RHPs. GHP predictability studies have helped to assess the sensitivity of models to anomalies of different sizes, determined whether errors in initial states have long-term effects on predictions, and established what feedbacks can account for the autocorrelations that are observed in soil moisture and other water cycle variables.

The assessment of the closure of water budgets has made it clear that neither models nor data by themselves are adequate for accurately simulating water budget components. This limitation has motivated the development of better assimilation and prediction systems including modelling systems that accommodate the horizontal movement of surface water through streamflow. Models are also used for process studies, to develop data assimilation products in a consistent framework and to produce experimental predictions. GHP studies have relied on global models, regional meso-scale models, land surface schemes and distributed and lumped hydrological models. Regional meso-scale models are being run as independent climate models using re-analysis data sets for boundary conditions, and are being nested in global models in prediction mode with considerable success.

Meso-scale model development activities have relied on the intercomparison of models, and on observations for establishing parameter values within models and for assessing model performance. By participating in the WCRP Project for the Inter-comparison of Land Surface Schemes (PILPS), modellers have identified many weaknesses in the way different land surface schemes handle individual water budget components such as runoff and evapotranspiration (Lohmann *et al*., 1998). Surface schemes from three of the six CSEs (VIC and Eta from GAPP, CLASS from MAGS, IBIS from BALTEX) participated in these intercomparisons. PILPS-2c was the first PILPS study to look at basins and was followed by PILPS-2e with a focus on cold season hydrology (Bowling *et al*., 2003). Koster *et al*. (2004) have shown that soil moisture also influences the predictability of precipitation over some land areas. This indicates that short-term climate forecasts (monthly and seasonal) from models are also dependent on accurate soil moisture and precipitation estimates.

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Large-scale hydrological modelling

Both lumped and distributed hydrological models have been used in GHP to explore the partitioning of precipitation into runoff and infiltration. Errors in model outputs arise not only from uncertainties in the values of the input variables (particularly precipitation), but they can also result from problems in model structure and parameter estimates. Distributed hydrological models (e.g. Variable Infiltration Capacity (VIC) model) are attractive because they facilitate the use of high resolution distributed forcing data produced by radar and satellites and utilize high resolution distributed hydrological parameters derived from satellite data or other sources (Wood *et al*., 1997; Mitchell *et al*., 2004; Sheffield *et al*., 2006). They also often have grids that are easier to interface with climate models, an ultimate GHP goal. In addition, these models allow for the explicit representation of the lateral movement of water through the elements of the basin (Lohmann, 1998).

Data assimilation

Data assimilation is an important tool for both climate studies and numerical weather prediction and can now provide estimates of key hydrological parameters for the application of models at basin scales. The development of data assimilation systems that can assimilate specialised data sets have been important for BALTEX, GAPP and LBA. Although these new atmospheric data sets pose challenges for data assimilation, their inclusion in initial fields produces significant improvements in the forecasts. A regional Land Data Assimilation System (LDAS) (Mitchell *et al*., 2004) developed through GAPP allows a number of different land schemes to be used in uncoupled and coupled modes including the NOAH, CLM, VIC and MOSAIC land models. Through collaboration with NCEP, NASA has extending this system to cover the globe as a high resolution (0.125 degree) Global Land Data Assimilation System (GLDAS) (Rodell *et al*., 2004). The goal of GLDAS is to produce optimal output fields of land surface states and fluxes by making use of advanced observing systems. Errors in land surface forcing and parameterisation tend to accumulate in modelled land stores of water and energy, leading to incorrect surface water and energy partitioning. Incorporating primarily precipitation and radiation reduces the biases in atmospheric model derived forcing and using data assimilation techniques land surface observations, such as soil temperature and moisture and snow depth/cover, can provide more realistic simulated storages. For the hydrologist, land data assimilation now provides a way of integrating all the available information of the energy and water balance into a system which gives gridded hydrological variables at scales commensurate with basin modelling.

Model Parameter Experiment (MOPEX)

MOPEX is an international project aimed at developing enhanced techniques for *a priori* estimation of parameters in hydrological models and in land surface parameterisation schemes connected to atmospheric models. The MOPEX science strategy involves: database creation, *a priori* parameter estimation methodology development, parameter refinement or calibration, and the demonstration of parameter transferability. A comprehensive MOPEX database has been developed that contains historical hydrometeorological data and land surface characteristics data for many hydrological basins in the USA and in other countries. This database is being continuously expanded to include basins from various hydroclimatic regimes throughout the world. MOPEX research has largely been driven by a series of international workshops that have brought interested hydrologists and land surface modellers together to exchange knowledge and experience in developing and applying parameter estimation techniques. With its focus on parameter estimation, MOPEX plays an important role in the international context of other initiatives such as GEWEX, PILPS and PUB.

The application of hydrological models worldwide requires their application to a wide range of hydroclimatic regimes and an understanding of how changes in different basins are reflected as changes in the model parameters or in its structure. Current model structure requires that at least some key parameters are adjusted (calibrated) according to the fit of the model predictions to observations of the response variable of interest, usually streamflow. However, these measurements are not always available and where available, they may be very sparse. Thus, other approaches are needed to derive *a priori* (before calibration) parameter estimates. Current procedures for *a priori* parameter estimation are often based on relationships between model parameters and basin characteristics – that is, soils, vegetation, topography, climate, geology, etc. These developed relationships have not been fully validated through rigorous testing using retrospective hydrometeorological data and corresponding land surface characteristics, and gaps still exist in our understanding of the links between model parameters and land surface characteristics. It is also not clear how heterogeneity associated with spatial land surface properties affects those characteristics at the scale of a basin or a grid cell. Consequently, there is a considerable degree of uncertainty associated with the parameters derived using current procedures, which is propagated into the model predictions and into the subsequent water resources decision making processes.

Recent publications have covered the last three MOPEX Workshops. Sixteen papers from the MOPEX-3 Workshop held as part of the IUGG in Sapporo in July 2003 have been published as a special MOPEX issue of the *Journal of Hydrology* (2006, 320(1–2)). Based on 26 papers from the MOPEX-4 (Paris, July 2004) and MOPEX-5 Workshops (Brazil, April 2005) an IAHS Red Book has been published dealing with the current parameter estimation issues (Andreassian *et al.*, 2006). This publication includes a CD of the MOPEX US data sets of 348 basins used in the Workshops. Full reports of these Workshops including the active discussion sessions and the presentations are available on the MOPEX web page: http://www.seas.ucla.edu/~thogue/MOPEX.

The work of MOPEX will continue contributing to the improved understanding of *a priori* and *a posteriori* (calibrated) model parameters for hydrological and land surface models. This will be implemented through workshops with different foci, and an increased interaction with other initiatives such as HEPEX, and other working groups, such as the PUB Top-down Modelling and Uncertainty working groups.

Transferability of hydrological models

While MOPEX has essentially been addressing the model parameter estimation issues at the same time it encompasses the application of different hydrological models to different climate regimes and thus hydrological predictability, an essential ingredient of PUB. Specific studies have yet to be undertaken within GEWEX and this is an area which can benefit from PUB and the developing HAP (see below).

SEASONAL HYDROLOGICAL PREDICTION

Water Resources Applications Project (WRAP)

The GEWEX Water Resources Applications Project (WRAP) was established in 2000 to facilitate broader use of GEWEX products in water resource applications. The group promoted dialogue between the GEWEX community and the water resources community. With members from each of the CSEs, IAHS, the International Hydrology Programme (IHP) of the United Nations Educational Scientific and Cultural Organization (UNESCO), the World Water Assessment Programme (WWAP), and the World Meteorological Organization (WMO), this group provided a wide range of expertise related to water management. WRAP relied on the development of physically-based hydrology and "application" or decision support models, and the coupling of these models with regional climate models. Application studies require a capability to downscale large area (model grid square) precipitation forecasts and observed averages, statistical analyses of the relationships between SST anomalies and seasonal streamflow, and analysis of the value and utility of seasonal forecasts in water management decisions. In future studies the hydrological and applications modelling community are expected to provide valuable guidance for climate modellers by identifying the degree of complexity required for input data and outputs in seasonal to interannual prediction studies.

A number of the RHPs have conducted regional workshops and needs assessment studies to determine the needs for information to support water resource management. In 2002, a workshop organized by WRAP in collaboration with the International Conference on Water and Environmental Research found that water managers would like to see more projects demonstrating the use of GEWEX products in decision making. WRAP explored how the concerns raised at that meeting about forecast accuracies and uncertainties can be addressed through GEWEX initiatives. WRAP also supported applications activities related to the Integrated Global Observing Strategy (IGOS) Partnership Water Cycle theme and the Global Water System Project (GWSP). MDB, AMMA, BALTEX and GAPP projects have been, or continue to be, involving water agencies and trials in projects that include the preparation, tailoring, and delivery of forecast and assimilation products from the operational NWP centres to support routine water management.

Hydrological Ensemble Prediction Experiment (HEPEX)

Following the strong message from the WRAP deliberations on the need to address forecast accuracies and uncertainties, HEPEX was launched in March 2004 at a meeting hosted by the European Centre for Medium-Range Weather Forecasts (ECMWF), in Reading, UK. HEPEX (http://hydis8.eng.uci.edu/hepex/) is an international effort that brings together hydrological and meteorological communities to develop advanced probabilistic hydrological forecast techniques that use emerging weather and climate ensemble forecasts, such as those being developed by GEWEX. Ensemble prediction is a basic approach to account for uncertainty in predictions for complex systems. Because hydrological systems are highly nonlinear, uncertainty in seasonal hydrological predictions depends not only on uncertainty in seasonal input forecasts but on uncertainty and variability of inputs at all time scales, starting with the basic model computational time step, up to seasonal. Uncertainty in hydrological predictions depends also on a wide range of spatial scales of input forecast uncertainty beginning at the spatial scale of the smallest sub-basin. This requires an integrated approach to weather, climate and hydrological forecasting that is beyond the scope of what GEWEX can achieve alone. It also requires connections with hydrological forecast users that GEWEX is not in a very strong position to develop and maintain. Therefore, HEPEX, through collaboration with scientists and water resource managers involved in various aspects of weather, climate and hydrological forecasting, including those involved in GEWEX, is an important affiliation for GEWEX.

The overarching goal for HEPEX is "to develop and test procedures to produce reliable hydrological ensemble forecasts, and to demonstrate their utility in decision making related to the water, environmental and emergency management sectors". Increasingly, users of hydrological forecasts want quantitative estimates of forecast uncertainty rather than only an approximation of the single most probable scenario. In response, operational agencies are beginning to employ ensemble forecast techniques for hydrological predictions. Ensemble forecast systems provide an estimate of the most probable future scenario, and also offer a wide range of possible outcomes that account for all sources of forecast uncertainty. These sources include precipitation and other meteorological inputs, estimates of boundary/initial hydrological conditions, the hydrological forecast models, and model parameters.

At a second workshop held at NCAR in 2005, HEPEX participants discussed the potential benefits that a probabilistic approach to hydrological prediction could bring to the end users, formulated a series of scientific research questions and tasks needed to move HEPEX forward in addressing its overall goal. The latter included a series of coordinated testbed demonstration projects. The testbeds are collections of data and models for specific basins or sub-basins, where relevant meteorological and hydrological data has been archived. In these testbeds, it is expected that different forecast approaches and tools can be demonstrated and intercompared. The development of these tools and their demonstration in the testbed basins are central activities for the implementation phase of HEPEX, along with intercomparison of various hydrological prediction methods and linkages to users. A third workshop was held in Stresa, Italy, in June 2007, to review progress of the test bed projects and to develop plans for the future. The outcome of this workshop will be reported at the HEPEX web site.

Hydrologic Applications Project (HAP)

In 2006, WRAP was replaced by the Hydrologic Applications Project to better reflect GEWEX's Phase II strategic direction to foster close cooperation with the hydrological research community to launch projects dealing with hydrological seasonal forecasting. In particular, GEWEX will work closely with HEPEX to launch pilot projects in collaboration with Regional Hydroclimate Project (RHP) (formerly the CSE) scientists to demonstrate how ensemble forecasts from atmospheric models can be used with hydrological models to provide improved hydrological seasonal forecasts.

HAP will oversee and manage GEWEX's involvement with HEPEX, to provide direction from a GEWEX perspective to HEPEX activities and to will work closely together to organize joint projects of common interest.

Thus, HAP was formulated with the emerging goals being:

1. developing procedures for assessing current hydrological conditions (nowcasting) through application of GEWEX supported data products, including remote sensing;
2. developing and testing of reliable, skilful hydrological ensemble forecast procedures based on seasonal climate model forecasts; and
3. demonstrating that the procedures can be applied at scales useful for water resources through testbed sites and demonstration projects.

Hence an important research focus of HAP is to assist GEWEX in "demonstrating skill in predicting variability in water resources and soil moisture on a seasonal to annual basis as an element of WCRP's prediction goals for the climate system". In doing so, HAP will help foster and develop the science behind skilful ensemble hydrological seasonal forecasts and demonstrating their usefulness.

In addition, HAP will work with PUB to demonstrate how remote sensing data, land data assimilation products and hydrological prediction can improve the decisions made by water resource managers. This activity offers GEWEX science and data products to the applications community. GEWEX will also promote strategies to work more closely with the WMO Hydrology and Water Resources Department, operational hydrometeorological services and UNESCO's International Hydrology Programme. These lead to HAP's fourth goal; namely:

4. Working with related projects, such as WISE, HEPEX, PUB, and other GEWEX panels, particularly GMPP.

HAP's goals will result in a set of activities that cross a number of GEWEX panels and projects within the Coordinated Energy and water-cycle Observations Project (see below). For example these range from data products from remote sensing to transferability modelling studies and the WISE activities on extremes. Additionally there are related activities in WCRP that HAP should support including GEWEX's contribution to the Global Water System Project within the Earth System Science Partnership (ESSP) framework; WCRP's new strategy, commonly known as the Coordinated Observation and Prediction of the Earth System (COPES); and the WCRP Task Force on Seasonal Prediction.

WATER AND ENERGY BUDGET STUDY (WEBS)

Through WEBS and other regional studies, GHP continues to develop a better understanding of the regional climate of each RHP, the interactions between each land area and its moisture sources, and the transport mechanisms including large-scale circulation patterns. Evaluations of the ability of model simulations and data assimilation systems to close regional water budgets in different climate and data intensive regimes provide a benchmark for the modelling community. The various RHP areas respond to large-scale forcing on different time scales depending on their latitude, distance from a large ocean, topography, and other factors.

One of the major objectives of the RHPs has been to assess the accuracy to which water and energy budgets could be characterised and "closed" on a continental scale. The current goal of this activity is to develop the best available water and energy budgets for the global land regions associated with the RHPs. For example, Roads *et al.* (2003) developed a GCIP WEBS for the Mississippi River basin from representative models, available observations and various re-analyses. An assessment of these results suggests that the water budget for the Mississippi River basin can be closed to within approximately 15%, whereas, studies of the water balance for the Amazon have suggested that the Amazon Basin is a sink for moisture where precipitation exceeds evaporation (e.g. Marengo, 2005). The observed uncertainty in closing the water balance over the Amazon is approximately 50%, based on estimates of moisture convergence and evaporation from the NCEP Reanalysis products. WEBS uses GEWEX radiation products developed by the GEWEX radiation working groups, including: the International Satellite Cloud Comparison Project (ISCCP) cloud and radiation products, the Global Water Vapour Project (GVAP) water vapour products, the Global Precipitation Climatology Project (GPCP) precipitation products, the Surface Radiation Budget (SRB) radiative fluxes, the NOAA Climate Prediction Center Merged Precipitation and the Climate Research Unit surface air temperature global products, together with products from the current global atmospheric models and land re-analyses. These various products enable an assessment of the current uncertainty in estimating water and energy processes and variables, and how well they can be simulated and ultimately predicted. A comprehensive archive and analyses of global streamflow and runoff is available at the Global Runoff Data Centre (GRDC), although management effects can sometimes be a problem in connecting physical model output with measured streamflow. WEBS is also examining runoff based global products developed by the University of New Hampshire (USA; Fekete *et al.*, 2002). Developing projects from the GMPP, including the Global Land Atmosphere Simulation Systems (GLASS), Global Soil Wetness Project (GSWP), Global and Regional Land Data Assimilation Systems (LDAS), projects are attempting to develop improved land data assimilation, which will further aid the development of comprehensive global syntheses of water and energy budget characteristics.

Using the above global products, WEBS is now focusing on the first GEWEX Phase II objective to "produce consistent research quality data sets complete with error descriptions of the Earth's energy budget and water cycle and their variability and trends on interannual to decadal time scales, and for use in climate systems analysis and model development and validation". From these data sets, WEBS is giving guidance to the Phase II question of "Are the Earth's energy budget and water cycle changing?".

COORDINATED ENHANCED OBSERVING PERIOD (CEOP)

In 1997, GHP developed the concept of a Coordinated Enhanced Observing Period CEOP for the time frame 2002 to 2004, when the RHPs would be fully functioning and the next generation of Earth observing satellites would be producing new measurements of global water and energy cycle variables. Through CEOP, the influence of continental hydroclimatic processes on the predictability of global atmospheric circulation patterns, the role of land in monsoonal systems, and the changes in water resources at time scales up to seasonal, will be studied (Koike, 2004). Through the involvement of the Committee on Earth Observing Satellites (CEOS) and its members (particularly the Space Agencies), extensive archives of satellite remote sensing data and products are becoming more accessible. A number of major Numerical Weather Prediction (NWP) global models and regional models are now providing three-dimensional model output fields, which are being archived at the Max Plank Institute (MPI), associated with the BALTEX project. Each of the RHPs is also supplying data from a total of 36 global reference sites to the CEOP data centre at University Corporation for Atmospheric Research (UCAR), supported through GAPP by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautic and Space Administration (NASA). A global data integration system at the University of Tokyo (established as part of the CEOP Asian Monsoon Project) will archive remote sensing data. Data integration is also being carried out by the Global Land Data Assimilation System infrastructure being developed at NASA Goddard and NCEP. The implementation of CEOP relies upon a Scientific Steering Group, an Advisory Committee and working groups dealing with Water and Energy Budget Simulation and Prediction (WESP), monsoon systems, hydrological studies in ungauged basins (PUB), satellite data and data management interests and concerns. Some countries, such as the USA and Japan, have national CEOP working groups. In addition to its own programme objectives, CEOP will undertake validation activities that support various CEOS objectives including a new CEOS/CEOP project initiated by the Working Group on Information Systems and Services (WGISS). CEOP has continued beyond 2004 and more detail on CEOP plans and activities are on the CEOP website at http://www.gewex.org/ceop.htm/. The Phase II science plan calls for an enhanced observational activity at high latitudes in collaboration with ClIC and IPY, more studies in semi-arid areas and in high altitude regions, and research into the role of aerosols in monsoon systems.

Coordinated Energy and water cycle Observations Project (CEOP)

CEOP, which began as a discussion item at the second GHP meeting in 1995, subsequently became the CEOP Working Group of GHP. It was then moved from GHP in 2001 to what the WCRP designated it then as “an element of WCRP initiated by GEWEX”. CEOP continued to be strongly supported by GHP and many GHP science activities soon became actively entrained within CEOP, in part through the CEOP data management and modelling activities, and in part through cross linkages of some of the RHPs and GHP science working groups within the CEOP Monsoon Panel and the Water and Energy Simulation and Prediction Panel (WESP) Again, these focused science activities are designed to take advantage of this unique international cooperation developed by CEOP.

Initially CEOP was a pilot experiment, designed to intensively study a limited time period, 1 July 2001–31 December 2004, a period when many RHPs would likely have corresponding intensive observation periods to complement CEOP and a time when many of the new Earth observing satellites would be providing a wealth of new information about the Earth. With the demonstrated uniqueness of CEOP Phase 1 and advent of

CEOP Phase 2, which will extend the time period of enhanced observations and enhance the science agenda, it is clear that CEOP will contribute to the scientific objectives of GEWEX and integrated data management activities of WCRP on a much longer term. As a result, GEWEX, in full agreement with the GHP, and with CEOP, has decided to merge GHP and CEOP to form a new entity, tentatively designated the Coordinated Energy and water cycle Observations Project (CEOP). This formal merger is meant to enhance the efforts of both GHP and the original CEOP and will not lose sight of any of the GHP strategic goals or any of the ongoing GHP science work since the same scientists and more are already working on closely related projects and goals in CEOP.

WHAT HAS HYDROLOGY GAINED FROM GEWEX?

Data sets

In addition to the RHP reference sites described under CEOP, some of which have hydro-meteorological data from basins within the archived atmospheric model footprint (200 × 200 km), some GEWEX projects have *in situ* data and products that are useful for global water cycle and hydrological research. Model outputs for some regions are now down to scales of 10 km or lower and are more useful for hydrologists working at the basin scale. ISLSCP provides support through the generation of global data sets of up to 17 years (1982–1999) of some 47 different data types and 230 parameters (including 29 vegetation, 39 hydrology, topography and soils) at broader scales of ¼ to 1 degree. GRDC developed a global monthly climatology of runoff, which is being used as the basis for many global water balance studies. GPCC, which contributes precipitation products to Global Precipitation Climatology Project studies, also develops global products by merging remote sensing and *in situ* data at scales down to ¼ degree.

Each RHP has its own active data collection and management programme focused on priority regional scientific issues. As the GHP began to initiate studies along specific themes, it became evident that a more effective means for sharing data sets among RHPs was needed. To achieve this goal, a data committee was established with representation from each RHP. It has developed protocols for data exchanges, reviewed data policies and facilitated the preparation of selected data sets to support theme priorities. Annual and multi-year data sets from the RHPs have allowed modellers to evaluate their models in a variety of climate zones over the full annual cycle. A description of each of the currently available RHP data sets is given in Roads *et al.* (2006).

A number of the RHPs are providing multi-year data sets from special networks and extensive shorter period data sets from field campaigns for satellite product development. GHP data sets are used to assess the uncertainties in data products derived from new satellites in the pre-launch and post-launch phases. Within GAME, LBA and GAPP data activities have led to the development and refinement of satellite algorithms for soil moisture (AMSR) and precipitation (TRMM).

The previously discussed collection of MOPEX data sets developed to support *a priori* parameter estimation for hydrological models is an initiative supported by GEWEX. GLDAS enables the integration of the energy forcing and the water balance into a convenient gridded format for basin modelling.

Process understanding at different scales

Starting with the ISLSCP field programmes evolving to the regional and more specific RPH studies, a better understanding of the key hydrological processes in different climatological regimes has been achieved. Through projects such as GLASS and MOPEX, the intercomparison of modelling approaches has shown where specific models/approaches can be improved resulting in better estimates of the hydrological variables and some understanding of the errors involved. However, this question is as yet unresolved and is an area where it is hoped PUB will make some progress.

Global hydrological products

As part of GLASS Phase 2 of the Global Soil Wetness Project (GSWP-2), this activity has produced the first global 1-degree daily Multi-Model-Analysis (MMA) of 52 land surface variables and fluxes for the 10-year period 1986–1995. Generally, the MMA is superior to the individual models and is as good as or better than the *in situ* soil moisture observations (Dirmeyer *et al*., 2006).

In 2001, the Earth System Science Partnership (ESSP) chose water as one of its four focus areas and started planning the Global Water System Project (GWSP). GWSP promotes research to improve the knowledge of the interactions of the Global Water System (GWS) with the environment over a range of time and space scales. In this context, the GWS is defined as the totality of natural processes, biogeochemical and ecological interactions, human engineering and policy interventions, and domestic and industrial use and recycling. GWS is seen as both a driver of environmental change and a recipient of the impacts of different external changes. As this initiative views the global water cycle as the essential coupler between all of its components, it is only natural that there will be strong links with GEWEX in areas of hydrological modelling and water cycle data sets.

GEWEX PLANS TO 2012

Based on an analysis of GEWEX strengths and the gaps in scientific understanding that need to be addressed, the GEWEX has developed a series of actions (a "roadmap") for each of the GEWEX objectives for the period 2007–2012. In particular, the roadmap identifies both interim and final deliverables, and milestones it plans to achieve as GEWEX moves toward the realization of its heritage through scientific insights, analysis tools, models and data products for the benefit of the WCRP, the agencies that sponsor GEWEX, the global environmental community, and other GEWEX stakeholders including IAHS.

Objective 1 *Produce consistent research quality data sets complete with error descriptions of the Earth's energy budget and water cycle and their variability and trends on interannual to decadal time scales, for use in climate system analysis and model development and validation.*

Work related to this objective builds upon the global products derived primarily from satellite data by the GEWEX panels, and includes particular items of hydrological interest such as modelled soil wetness. During the second phase of GEWEX, scientists will rely on data from new satellites and make more extensive use of data assimilation systems. This will require a more coordinated approach to the testing and use of new satellite products and in deriving relationships between the on-going products and new data products from research satellites. As part of this objective GEWEX will place a higher priority on producing reprocessed data sets that will address a broader range of climate analysis.

Objective 2 *Enhance the understanding of and quantify how energy and water cycle processes contribute to climate feedbacks.*

The second GEWEX objective will be addressed by both process and modelling studies that will target specific problems related to cloud and land surface feedbacks, often with the cross-cuts of specific priorities such as monsoons and extremes. GEWEX will assess the factors that contribute to different climate phenomena and processes. Included in this list will be the diurnal cycle, precipitation processes, and floods and droughts. In addition, the processes that strengthen, maintain and weaken monsoons will be understood and simulated under current and projected climate changes.

Objective 3 *Improve the predictive capability for key water and energy cycle variables and feedbacks through improved parameterizations to better represent hydro-meteorological processes, and determine the geographical and seasonal characteristics of their predictability over land areas.*

GEWEX has worked towards improving seasonal predictions from its inception and is committed to contributing to the improvement of prediction systems by advancing our physical understanding of the underlying processes, developing and testing experimental products, improving parameterizations, and facilitating their transfer to operations. During Phase II, GEWEX plans to study the contributions of land–atmosphere and cloud processes on atmospheric predictability for: (1) precipitation, and (2) monsoon intensity. Results from model studies such as the Global Land Atmospheric Coupling Experiment have suggested that there are critical land areas ("hot spots") where surface wetness has a very significant influence on the predictability of seasonal precipitation at lead times of one to three months (Koster *et al.*, 2000). GEWEX Predictability studies also address the WCRP objective of determining the predictability of climate.

Objective 4 *Undertake joint activities with operational hydrometeorological services, related Earth System Science Partnership projects such as the Global Water System Project and hydrological research programmes to demonstrate the value of GEWEX research, data sets and tools for assessing the consequences of climate predictions and global change.*

This objective will be the focus of the previously described GEWEX HAP working in conjunction with PUB and HEPEX to demonstrate how remote sensing data, land data assimilation products, and hydrological prediction can improve the decisions made by water resource managers. These advances will benefit operations through the development of better prediction systems for hydrological prediction services. GEWEX will also promote strategies to work more closely with the GWSP, WMO's Hydrology and Water Resources Department, operational hydrometeorological services, and UNESCO's

International Hydrology Programme. In order to achieve these objectives, a new approach to hydrometeorological research in support of the water resources sector is needed. An important element of this new approach will be the strategy of focusing GEWEX efforts on collaboration with hydrological research programmes and operational services with the mandate to provide predictive and informational services to users in the water resources sector.

SUMMARY AND FUTURE ACTIVITIES

GHP was a coordinated effort that addressed issues related to water and climate over land and applied its new scientific understanding to analysis and prediction questions in many regions. GHP made many contributions to international environmental programmes enabling GEWEX and WCRP to work towards their own prediction goals. GHP also has contributed to the integration of WCRP's programmes such as joint GEWEX (GHP)/CLIVAR initiatives, the study of fully coupled land–ocean–atmosphere system at seasonal time scales.

GHP has interacted with international and regional organisations and programmes to improve hydrometeorological predictions and applications. In particular, GHP has facilitated the linkages of RHPs and the major NWP organizations. Space Agencies have also benefited from access to unique RHP data sets for validation of their satellite products. CEOP has provided a framework within which the data sets for integrated projects can be developed and enhanced. Together with the GHP data sets, these provide hydrometeorological data which are useful to PUB. GEWEX has also contributed to the development of the water cycle theme within the IGOS Partnership. Although many global programmes have international participation, few have shown as broad a multinational base of scientific leadership and financial investment as GHP and CEOP.

As the merged GHP and CEOP – the new CEOP – contribute to the second phase of GEWEX, it is shifting its emphasis from analysis to prediction. This shift will allow individual RHPs to contribute more effectively to the GEWEX mission of "demonstrating a capability to predict changes in water resources and soil moisture on time scales up to seasonal and interannual as an integral part of a climate prediction system". The new CEOP will see better coordination within GEWEX and the further exploration of the wide range of new observing capabilities that will be available with the new satellite systems being launched during the first few years of the 21st century.

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REFERENCES

Andréassian, V., Hall, A., Chahinian, N. & Schaake, J. (eds) (2006) *Large Sample Basin Experiments for Hydrological Model Parameterization*. IAHS Publ. 307. Wallingford, UK, IAHS Press.

Bowling, L. C., Lettenmaier, D. P., Nijssen, B., Graham, L. P., Clark, D., El Maayar, M., Essery, R., Goers, S., Gusev, Y., Habets, F., van den Hurk, B., Jin, J., Kahan, D., Lohmann, D., Ma, X., Mahanama, S., Mocko, D., Nasonova, O., Niu, G-Y., Samuelsson, P., Shmakin, A., Takata, K., Verseghy, D., Viterbo, P., Xia, Y., Xue, Y. & Yang, Z.-L. (2003) Simulation of high-latitude hydrological processes in the Torne-Kalix basin: PILPS phase 2(e) – 1: Experiment description and summary intercomparisons. G*lobal and Planetary Change* **38**(1-2), 1–30.

Dirmeyer, P. A., Gao, X., Zhao, M., Guo, Z., Oki, T. & Hanasaki, N. (2006) The Second Global Soil Wetness Project (GSWP-2): Multi-model analysis and implications for our perception of the land surface. *Bull. Am. Met. Soc.* **87**, 1381–1397, October. doi:10.1175

Koike, T. (2004) The Coordinated Enhanced Observing Period – An initial step for integrated global water cycle observation. *WMO Bulletin* **53**(2), 115–121.

Fekete, B. M., Vorosmarty, C. J. & Grabs, W. (2002) High-resolution fields of global runoff combining observed river discharge and simulated water balances. *Global Biogeochem. Cycles* **16**(3), 1042.

Koster, R. D., Suarez, M. J. & Heiser, M. (2000) Variance and predictability of precipitation at seasonal-to-interannual timescales. *J. Hydromet.* **1**, 26–46.

Koster, R. D., Dirmeyer, P. A., Guo, Z.-C,. Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C.-H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y. & Yamada, T. (2004) Regions of strong coupling between soil moisture and precipitation. *Science* **305**, 1138–1140.

Lawford, R. G., Stewart, R., Roads, J., Isemer, H.-J., Manton, M., Marengo, J., Yasunari, T., Benedict, S., Koike, T. & Williams, S. (2004) Advancing global- and continental-scale hydrometeorology: contributions of the GEWEX Hydrometeorology Panel (GHP). *Bull. Am. Met. Soc.* **85**(12), 1917–1930.

Lohmann, D., Lettenmaier, D. P., Liang, X., Wood, E. F., Boone A,, Chang, S., Chen, F., Dai, Y., Desborough, C., Dickinson, R. E., Duan, Q., Ek, M., Gusev, Y. M., Irannejad, P., Koster, R., Mitchell, K. E., Nasonova, O. N., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y., Shmakin, A. B., Verseghy, D., Warrach, K., Wetzel, P., Xue, Y., Yang, Z.-L. & Zeng, Q.-C. (1998) The Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS): Phase 2c, Red-Arkansas River basin experiment. 3. Spatial and temporal analysis of water fluxes. *Global Planet. Change* **19**, 161–176.

Marengo, J. A. (2005) Characteristics and spatio-temporal variability of the Amazon River basin water budget. *Climate Dynamics* **24**(1), 11–22.

Mitchell, K. E., Lohmann, D., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Cosgrove, B. A., Sheffield, J., Duan, Q., Luo, L., Higgins, R. W., Pinker, R. T., Tarpley, J. D., Lettenmaier, D. P., Marshall, C. H., Entin, J. K., Pan, M., Shi, W., Koren, V., Meng, J., Ramsay, B. H. & Bailey, A. A. (2004) The multi-institution North American Land Data Assimilation System (NLDAS): utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res*. **109**(D7), doi:D07S90 10.1029/2003JD003823 09.

Roads, J., Lawford, R., Bainto, E., Berbery, E., Chen, S., Fekete, B., Gallo, K., Grundstein, A., Higgins, W., Kanamitsu, M., Krajewski, W., Lakshmi, V., Leathers, D., Lettenmaier, D., Luo, L., Maurer, E., Meyers, T., Miller, D., Mitchell, K., Mote, T., Pinker, R., Reichler, T., Robinson, D., Robock, A., Smith, J., Srinivasan, G., Verdin, K., Vinnikov, K., Vonder Haar, T., Vorosmarty, C., Williams, S. & Yarosh, E. (2003) GCIP Water and Energy Budget Synthesis (WEBS). *J. Geophys. Res*. **108** (D18), doi:10.1029/2002JD002583.

Roads, J., Isemer, H.-J., Takahashi, K., Yasunari, T., Williams, S., Huang, J., Loehrer, S., Marango, J., Horta, L. M., Dias, M. A. F. S., Berbery, E. H., Meitin, J., Crawford, B. & Szeto, K. (2006) Data sets from the continental-scale experiments. *GEWEX Newsletter*. **16**(3), 3–5.

Rodell, M., Houser, P. R., Jambor, U., Gottschalk, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entrin, J. K., Walker, J. P., Lohmann, D. & Toll, D. (2004) The Global Land Data Assimilation System. *Bull. Am. Met. Soc.* **85**(3), 381–394.

Sheffield, J., Goteti, G. & Wood, E. F. (2006) Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modelling. *J. Climate* **19**(13), 3088–3111.

Wood, E. F., Lettenmaier, D. P., Liang, X., Nijssen, B. & Wetzel, S. W. (1997) Hydrological modeling of continental-scale basins. *Ann. Rev. Earth Planet. Sci.* **25**, 279–300.