ADVANCING GLOBAL- AND CONTINENTAL-SCALE HYDROMETEOROLOGY

Contributions of GEWEX Hydrometeorology Panel

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This article introduces the GEWEX Hydrometeorology Panel, describes the participating continental-scale experiments, outlines its current activities and priorities, and identifies new areas of science to which atmospheric scientists and hydrologists are invited to contribute.

The GHP* (refer to appendix for acronym expansions) was formed in 1995 to coordinate the activities of the CSEs and related global initiatives. Many of the GHP activities had their roots in projects that began in the late 1980s. At that time the space agencies and the WCRP became interested in supporting the newly proposed GEWEX.

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When GEWEX commenced in 1990 with a focus on global products and data, its lead scientists recognized that the global datasets needed to be evaluated at regional scales. At the same time significant improvements were being made to land surface models as a result of intensive regional experiments being carried out by the ISLSCP and BAHC initiative under the IGBP. In particular, ISLSCP carried out intensive field campaigns that focused on relatively homogeneous areas of 10,000 km^2 (approximately the size of a climate model grid square) and involved intensive observational periods for (generally) 2–4 weeks several times a year. However, there was also a growing recognition by the climate community of the need for continental-scale land surface studies. The concept of a continental-scale hydrologic experiment was developed in 1990 as a result of the convergence of GEWEX interests for a regional test bed, the need to scale up ISLSCP intensive studies to larger geographical areas, and the de-

*Information about the GHP can be found online at http://ecpc.ucsd.edu/projects/ghp/.

sire of IAHS to involve hydrology more actively in climate research. The proposed regional experiment was 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 watershed and therefore they could be examined in a meaningful way because there was an increasing likelihood of closing continental-scale water and energy budgets to acceptable limits using the newly available datasets and models.

In 1990, 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 GCIP. As planning progressed, however, a consensus emerged that areas with other important processes, such as permafrost and tropical forests, should also be studied. In addition, a number of countries could make stronger national contributions to GEWEX if they studied a basin that included their national territories. As a result, five mature continental-scale experiments and two relatively new experiments were developed to cover 10 large land areas. Together, they have accumulated many years of unique data, research results, and experience.

GEWEX established the GHP in 1995 to coordinate the wide range of interests and activities involved in these continental-scale experiments. The GHP also takes responsibility for coordinating the activities of the ISLSCP, GRDC, and GPCC. The overall GHP mission is 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 World Climate Research Programme's prediction goals for the climate system." To this end, it maintains an overview of research in the CSEs and influences the priorities of each CSE. The GHP also initiates, synthesizes, reviews, and recommends joint activities that promote a common research agenda in each of the CSEs and integrates the results from the individual CSEs. The GHP further promotes and coordinates interactions with the GRP and GMPP. The GHP has developed numerous summaries and reports to GEWEX, WCRP, and the public on the role of macroscale hydrometeorological processes in the climate system and in water resources planning.

GHP members, appointed by the GEWEX SSG, include international scientific experts and the principal contacts for each of the CSEs. The GHP reviews proposals for new CSEs and makes recommendations to the GEWEX SSG based on an evaluation of their ability to meet the following criteria:

1) regional data collection activities,
2) a substantial land surface modeling effort,
3) linkages with a NWP center,
4) free and open data exchange, and
5) linkages with resource management agencies (generally water resources) that would use results from the experiment.

The mature experiments, including GAPP in the United States (which extends GCIP in both space and time), BALTEX, GAME, LBA, and MAGS, comply with the criteria listed above. These CSE areas are outlined in Fig. 1, along with MDB. The latest approved CSE, LPB, along with the AMMA initiative are collaborative experiments with WCRP's CLIVAR program. It should be noted that GAPP and GAME are also developing strong ties with CLIVAR.

With the maturation of the CSEs and their datasets, GHP has placed a new emphasis on collaborative research linking the individual CSEs. New initiatives, including WEBS (1998) and WRAP (1999), were launched. The requirements for free and open data exchange to support these activities led to the formation of a data committee in 1998. The eight-step GHP strategy is to

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 CSEs and by the GHP;
4) develop a strategy for examining the processes, datasets, and remote sensing capabilities relevant to the CSEs and other regions (This should result in clearer priorities for future research and data collection activities.);
5) carry out demonstration projects offline with uncoupled hydrological–land surface models and with these models coupled to an atmospheric model;
6) select a specific observational period in one CSE as the basis for validation transferability studies among the CSEs;
7) produce summary statements regarding the influence of land on large scales for each of the CSEs; and
8) prepare a summer school on regional climate and water resources and publish a GHP overview article.

The following sections provide additional highlights of GHP and CSE activities.

CSEs. CSEs serve as the regional building blocks for the global initiatives led by the GHP. Each of the CSEs deals with a range of observational and scientific issues and unique environmental and socioeconomic conditions (see Table 1). The number of nations participating in some CSEs (e.g., BALTEX and GAME) has posed major coordination and logistics challenges.

A science plan and documented research results can be found at each of the CSE Web sites found in the following paragraphs. Table 2 provides a summary of their chief geographical characteristics. Highlights from each CSE are summarized below.

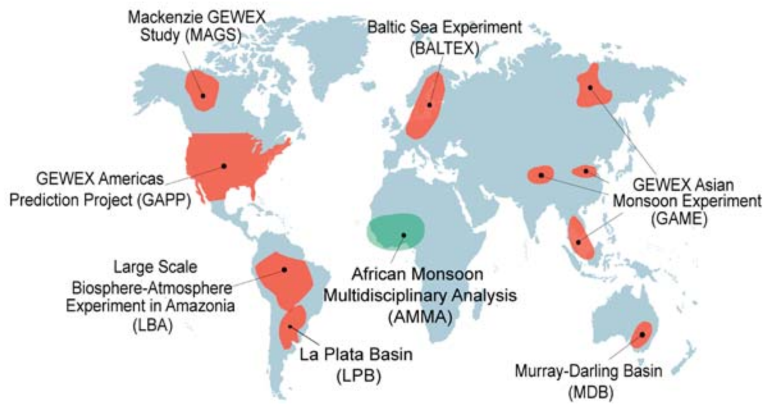

Fig. 1. Continental-scale areas included in the GEWEX Hydrometeorology Program.

BALTEX. The BALTEX project (Raschke et al. 2001, and online at www.gkss.de/baltex/) has been studying the entire drainage basin of the Baltic Sea, including the sea itself, since 1994. The basin, which involves land in 14 nations, is in the transition zone between maritime and continental climates. The atmosphere/land surface/ocean model coupling and the development of regional climate models is a particular focus in BALTEX, and two different regional coupled model systems have been established (e.g., Hagedorn et al. 1999; Döscher et al. 2002; Jacob et al. 2001) and are currently being validated and improved. BALTEX is unique for its strong marine research component comprising both modeling activities (e.g., Lehmann et al. 2002) and field experiments (e.g., Launiainen and Vihma 2001). Data evaluation and analysis of enhanced observing periods, including PIDCAP (August–October 1995) and BRIDGE (October 1999 to February 2002) is ongoing. BALTEX is currently defining enlarged objectives for its second phase (2003–12), including issues of climate and climate impact research, as well as water quality issues.

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

	Lead country	Other countries	Unique aspects
BALTEX	Germany	Denmark, Sweden, Finland, Russia, Poland, Belarus, Estonia, Latvia, Lithuania, the Netherlands, Austria, United Kingdom	Involves an oceanographic component over the Baltic Sea
GAME	Japan	China, Korea, Thailand, Malaysia, India, Nepal, Sri Lanka, Russia, Mongolia	Transect of study areas from tropics to the Arctic
GAPP	United States	Mexico	Involves well-instrumented midlatitude regions, land surface processes, and water resource applications
LBA	Brazil	Colombia, Peru, Bolivia, Venezuela, Ecuador, European Union, United States	Addresses role of tropical rain forests and the consequences of tropical deforestation for regional and global climate
LPB	Brazil, Argentina	United States, Uruguay, Paraguay, Chile, Bolivia, Organization of American States	Addresses the role of low-level jets and land cover changes in a humid basin
MAGS	Canada		Freshwater inputs to the Arctic Ocean; cold region processes
MDB	Australia		Hydrologic regimes in semi-arid areas

Table 2. Some physical characteristics of the CSEs (from GHP Web site and other sources).

	AREA (10^6 X km^2)	DISCHARGE (10^3 m^3)	CLIMATE
BALTEX	2.0	470	Continental but modified by the Atlantic Ocean
GAME-HUAIHE	0.1	30	Continental
GAME-LENA	2.49	na	Continental-Arctic
GAME-THAILAND	0.16	37	Tropical
GAME-TIBET	na	na	Continental-High Elevation
GAPP/GCIP	3.2 (GCIP)	570	Continental
LBA	6.2	6,300	Tropical
LPB	3.3	820	Extratropical Humid Basin
MAGS	1.8	300	Continental-Arctic
MDB	1.0	na	Continental-Semiarid
AMMA	na	na	Continental-Semiarid

GAME. The GAME (information online at www.hyarc.nagoya-u.ac.jp/game/) initiative is being undertaken in four large areas in eastern Asia, three of which are strongly influenced by the summer occurrence of the Asia–Australian monsoon. Moisture and energy fluxes in humid environments over rice paddy fields and forests are being studied in the Chao Phraya River basin in Thailand. The important role of vegetation and land use in the seasonal cycles of energy and water and their changes, such as deforestation, have been documented through these experiments (e.g., Tanaka et al. 2003; Toda et al. 2002). Observational programs in HUBEX in China have focused on a better understanding of energy and hydrological processes in cloud and precipitation systems along the Meiyu front and their interactions with land surface processes. GAME research on the Tibetan Plateau, a flat plain located at or above 3500 m elevation and intersected by an east–west mountain chain, examines the effects of this elevated thermal source on the monsoons. In cooperation with Chinese TIPEX, two observational networks have been deployed on the plateau, which are supplemented by special field campaigns, automatic weather stations, and a 3D Doppler radar system. The GAME Lena River basin study area, with a focus on taiga and tundra regions in Siberia, provides intensive observations of circumpolar Arctic processes. Research themes for studies in this area involve seasonal and interannual variations in one-dimensional water and energy fluxes over different landscapes, water balances in tundra watersheds, and the distribution and effects of ground properties and vegetation (Ohta et al. 2001).

The GAME experiment has been enhanced by similar initiatives taking place in China (TIPEX, SCSMEX, and KORMEX). The GAME reanalysis data for the IOP 1998 has been released, and new aspects of the energy and water cycle processes in the Asian monsoon region are being clarified using this dataset (e.g., Ueda et al. 2004). The scientific results of GAME are documented in a special issue of the *Journal of the Meteorological Society of Japan* (Yasunari 2001).

GAPP. After extensive planning (Schaake 1993; WMO 1992) and pilot projects in 1993 and 1994, GCIP, the forerunner of GAPP (online at www.ogp.noaa.gov/mpe/gapp/), was fully implemented in 1995 in the Mississippi River basin. A major component of this research was directed toward understanding the regional and local-scale hydrometeorological processes during different seasons, and their role in understanding and closing regional energy and water budgets for the basin.

GCIP undertook systematic studies throughout the basin to determine hydrologic balances over a wide range of regional climates. The basin was divided into four LSAs (IGPO 1993), each with its own regional and seasonal scientific focus. Soil moisture processes were studied in the Southwest, cold season processes in the north-central, precipitation and streamflow regimes in the East, and the annual cycle in the Northwest. These areas were studied sequentially moving from the Southwest (1995–97), to the north-central (1996–98), East (1997–99), and Northwest (1998–2001). GCIP relied mainly on data from existing meteorological and hydrological networks across the Mississippi River basin, including the unique research datasets from the

ARM CART facility. GCIP benefited from the strong interactions between the research component of the program and NOAA/NCEP's OHD. The strategies and successes of GCIP are detailed in NRC (1998), and overview articles by Coughlan and Avissar (1996) and Lawford (1999).

GAPP was initiated in 2001 as an extension to GCIP. GAPP extends the area of study to the Pacific coast and into the northern parts of Mexico. GAPP places more emphasis on monthly to seasonal prediction issues and provides a basis for studying orography and precipitation and the role of land in the monsoonal circulations associated with the Gulfs of Mexico and California. GAPP is partnering with CLIVAR in NAME, which addresses the role of monsoon systems and remote forcing on summer precipitation patterns in the United States (Higgins et al. 1998).

LBA. LBA (online at http://lba.cptec.inpe.br/lba) studies the natural variability of energy and water budgets over the Amazon River basin and examines the effects of rapid deforestation on these budgets. LBA is an international project led by Brazil and involves active participation by, and support from, other Amazon countries, the United States, and the European Union. LBA is highly interdisciplinary and links hydroclimatological research to the project's broad ecological research goals. LBA relies upon the measurement of key parameters in selected areas over long periods (3–5 yr) that is supplemented by intensive observing periods during the wet (WET) and dry (DRY) seasons. Data from an LBA-WET AMC (wet season of 1999) and the LBA-DRY to LBA-WET AMC (September–October 2002), which took place in Rondonia, Brazil, have been used to determine the diurnal cycle in different circulation and rainfall regimes, the effects of land surface change on the planetary boundary layer and rainfall, and the effects of aerosols from biomass burning on the physics of rainfall and the onset of rainfall (Marengo 2004a). Data from SALLJEX, which took place under the auspices of LBA and the VAMOS program in the wet season of 2003, are being used to document the characteristics of the low-level flow from the Amazon basin to southern Brazil and northern Argentina.

Results from LBA have led to improved weather and climate prediction capabilities at CPTEC in Brazil. The project is contributing to sustainable development goals through studies of the transferability of models and techniques to the Sao Francisco River basin in northwest Brazil.

MAGS. The goal of MAGS (online at www.msc.ec.gc.ca/_toc/gewex_e.html) is to assess the role of the Mackenzie River basin in the climate system, including its freshwater flux contribution to the Arctic Ocean. The basin is very sensitive to climate change, as indicated by the warming of 2°C per decade that has been observed there since the mid-1970s (Cao et al. 2001). The role of northern lakes and their freeze–thaw cycle and permafrost in regional water balances are also being explored. These local processes must be studied in the context of more remote processes because the large-scale circulation and synoptic storms play critical roles in determining the moisture fluxes into the basin (Stewart et al. 1998; Rouse et al. 2003). Important land surface processes operating in the basin include snowfall interception by boreal forest canopies, blowing snow, snowpack evolution, snowmelt, spring breakup, lake processes, permafrost melt, runoff processes, and evapotranspiration. The paucity of operational data being collected in the basin, particularly north of 60°N, has been a major challenge in implementing MAGS.

MDB. The MDB (online at www.bom.gov.au/bmrc/csr/gewex/) project examines water and energy budgets in a semiarid catchment where the potential evaporation rate is more than twice that of the precipitation rate and the interannual variability of precipitation is very large. Irrigation is a major factor in the basin's water budget. Information from MDB is being used locally to help in the management of groundwater and basin salinity.

LPB. LPB, which was approved in January 2004, will examine a highly productive La Plata River basin (information online at www.joss.ucar.edu/platin/) where the SALLJ transports moisture from the Atlantic Ocean and the Amazon River basin into the basin on a year-round basis (Berbery and Collini 2000). Precipitation patterns are strongly dependent upon adjacent ocean SST anomalies. The project will consider the roles of the Andes Mountains, low-level jets, and the Pantanel on regional water budgets.

Emerging study area. AMMA. The AMMA (online at http://medias.obs-mip.fr/amma/index.en.html) project consists of intensive study areas in two contrasting parts of the rain regime over southwest Africa, including two CATCH sites, the dry Niamey site in Niger and the relatively more humid site in the Oueme basin in Benin. The local and remote causes for long-term trends in precipitation patterns over these regions are being examined and modeled. Both AMMA and the newly approved LPB initiative support the goals of the second phase of GEWEX through their strong linkages with CLIVAR.

REGIONAL CLIMATE SYSTEMS. Each CSE represents a particular climate regime and interacts with the global climate system in a unique way. Figure 2 shows the range of climate regimes covered by the experimental areas. The characteristic climates range from dry polar conditions to wet or arid tropical conditions and span most of the larger land climate regimes. In spite of the differences among the basins, the large-scale teleconnection patterns of climate anomalies suggest that these CSE areas do not operate independently. For example, SST anomalies over the equatorial Pacific and Atlantic Oceans lead to large changes in the precipitation regime over the Amazon as a result of changes in the Walker circulation. These circulation changes influence other areas, such as the precipitation regimes in the Mississippi River basin, and the southern GAME and MDB study areas. Anomalies in the extratropical CSEs also appear to be connected with sea surface temperature anomalies in the North Pacific Ocean. It has been shown that many aspects of regional climate in northern Europe, including the BALTEX region, vary in concert with the NAO. Through WEBS and other regional studies, GHP continues to develop a better understanding of the regional climate of each CSE, the interactions between each land area and its moisture sources, and the transport mechanisms, including dominant 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 provides a benchmark for the modeling community.

Local processes also have a large influence, particularly during the summer and the transition months. For example, Stewart et al. (2002) analyzed the record-low-flow year of 1994/95 on the Mackenzie River and found that a number of surface and atmospheric factors, including below-average atmospheric convection over the basin, combined in a mutually reinforcing way to produce this low-flow year. Droughts over the Mississippi River basin also have been associated with lower-than-average moisture convergence over the basin, particularly those related to reductions in the strength of the low-level jet from the Gulf of Mexico (Dirmeyer and Brubaker 1999). As noted earlier, this nocturnal summer low-level jet dominates moisture fluxes into the Mississippi River basin and accounts for much of the east–west gradient in precipitation that occurs across the basin and the well-known nighttime precipitation maximum that occurs in the central part of the basin. A low-level jet also acts as a conveyer belt for moisture leaving Amazonia and entering the La Plata basin. This jet operates all year round, but is most intense during the austral summer (Liebmann and Marengo 2001). Ohta et al. (2001) have shown that the taiga forest and permafrost exert an important influence on the seasonal cycle of surface energy and water budget of Siberia. GHP has facilitated many of these interbasin comparisons of important processes by bringing together experts from different countries to develop common approaches to their analysis.

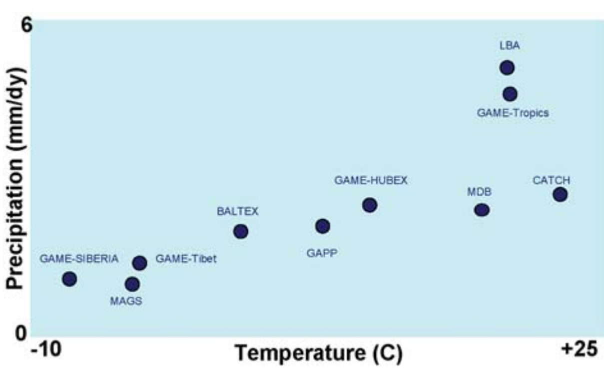

FIG. 2. Range of the mean annual temperature and mean annual accumulated precipitation characterizing each of the CSEs (Roads 2002).

LAND SURFACE PROCESS UNDERSTANDING. The success of regional (and global) land surface models depends upon effectively representing the critical land–atmosphere interactions in models. Many research activities within the CSEs have been directed at improving our understanding of key land surface processes that appear to contribute to predictability. A number of special observing periods in support of process studies have been carried out by the CSEs (Table 3).

Vegetation. Growing season moisture fluxes to the atmosphere through transpiration can be as large as 300–500 W m^{-2} in the midlatitudes (Baldocchi and Meyers 1999). Plant type influences the magnitude and seasonal distribution of transpiration, while plant density also affects the amount of transpiration and the surface albedo (Baldocchi and Meyers 1999). These moisture inputs can lead to increased low-level instability and convective precipitation in continental areas (Xue et al. 1996). Modeling studies indicate that the scale and patterns of hetereogeneity in vegetation distribution influence local cloud and precipitation patterns (Avissar and Liu 1996) and seasonal climate (Lu et al. 2001). GHP is placing increasing emphasis on the development of dynamic vegetation models that incorporate plant phenology.

Soil moisture. Viterbo and Betts (1999) showed that the 1993 Mississippi floods were intensified by earlier pre-

TABLE 3. GHP Enhanced Observing Periods and Web Sites for accessing the special data sets.	
Continental Scale Experiment **Special Data Periods (IOPs)**	**Web site for accessing data**
AMMA (CATCH)	www.lthe.hmg.inpg.fr/catch/database.htm
BALTEX	www.gkss.de/baltex/data.html
PIDCAP (Aug – Oct 95)	www.gkss.de/baltex/data.html
BRIDGE (Oct 99 – Feb 02)	www.gkss.de/baltex/data.html
GAME	http://gain-hub.mri-jma.go.jp/
HUBEX (May-Aug 98)	http://gain-hub.mri-jma.go.jp/hubex/Hubex_data.html
Tibet (summers 98, 99)	http://gain-hub.mri-jma.go.jp/Tibet_data.html
Tropics (summers 98, 99)	http://gain-hub.mri-jma.go.jp/Tropics_data.html
Siberia (May-Sep 98, 99)	http://gain-hub.mri-jma.go.jp/siberia/Siberia_data.html
KORMEX (Summer 98)	http://gain-hub.mri-jma.go.jp/kormex/Kormex_data.html
GAPP	www.joss.ucar.edu/gapp/
GCIP LSA-SW (Apr-Sep 95,96)	www.joss.ucar.edu/gapp/project/gcip
GCIP LSA-N (Oct 96-May 98)	www.joss.ucar.edu/gapp/project/gcip
GCIP LSA-E (Oct 97-Sep 99)	www.joss.ucar.edu/gapp/project/gcip
GCIP LSA-NW (Apr 99 – Mar 01)	www.joss.ucar.edu/gapp/project/gcip
NAME (prop. May 04-Sep 04)	www.joss.ucar.edu/name/dm/name_dm_index_html
LBA	http://lba.cptec.inpe.br/lba/lbadis/lbadis.htm
TRMM-LBA (Nov 98- Feb 99)	http://lba.cptec.inpe.br/lba/lbadis/lbadis.htm
LBA DRY AMC (Jan-Feb 99)	http://lba.cptec.inpe.br/lba/lbadis/lbadis.htm
LBA DRY-WET AMC (Sep-Oct 02)	http://lba.cptec.inpe.br/lba/lbadis/lbadis.htm
SALLJEX (Dec 02-Feb 03)	http://lba.cptec.inpe.br/lba/lbadis/lbadis.htm
MAGS	www.usask.ca/geography/MAGS/lo_Data_e.htm
CAGES: 1998-1999	www.usask.ca/geography/MAGS/lo_Data_e.htm
MDB	www.bom.gov.au/bmrc/csr/gewex

cipitation events. The saturated soils, in turn, supplied moisture to produce precipitation downwind from the area of the initial rain. Land surface models have the difficult task of representing soil wetness in the upper few centimeters, where the water leaves the soil and enters the atmosphere, as well as the movement of moisture in the deeper soil layers. The soil moisture term in climate models is important because it accumulates errors from inaccurate precipitation inputs. Finescale heterogeneity in soil texture and hydraulic properties add to the complexity of the parameterizations in these models. Studies have shown that even soil moisture measurements must undergo extensive calibration to account for this heterogeneity before they are used to validate regional and global climate models.

Cold season processes. Cold season processes are important for GAME, MAGS, BALTEX, and GAPP. Datasets have been developed to facilitate research on ground freezing; snow formation, accumulation, and melt; winter surface albedo; and ice formation. These new unique cold season datasets include temperature profiles in the soil throughout the annual cycle, freezing and thawing patterns, permafrost distribution, snow cover and its heterogeneity, and surface ponding. Advances have included better representation of multilayer snowpacks in land surface models (Yang et al. 1997), parameterizations based on vegetation and their associated subgrid-scale variability (Liston et al. 1999), the heterogeneity of albedo in shallow snow cover (Kunkel et al. 1999), frozen ground processes (Koren et al. 1999), and vegetation greenup in permafrost regimes (Ohta 2001). Increased understanding of these processes has led to the improvement of a number of land surface models and improved simulations and predictions of surface temperatures in winter.

MODELS AND DATA ASSIMILATION.

Uncoupled and coupled models. Neither models nor data by themselves are adequate for accurately simulating water budget components (Ropelewski and Yarosh 1998). This limitation has motivated the development of better assimilation and prediction systems, including modeling 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 mesoscale models, land surface schemes, and distributed and lumped hydrologic models. Regional mesoscale models are being run as independent climate models, using reanalysis datasets for boundary conditions, and are being nested in global models in a prediction mode with considerable success.

Mesoscale model development activities have relied on the intercomparison of models and on observations for establishing parameter values within models and for assessing model performance (Jacob et al. 2001). By participating in PILPS (Wood et al. 1998; Lohmann et al. 1998) and PIRCS (Tackle et al. 1999), modelers have identified many weaknesses in the way different land surface and atmospheric schemes handle individual water budget components, such as runoff and evapotranspiration.

Land surface scheme improvements have been shown to lead to better predictions of precipitation. The proper representation of soil moisture in models for precipitation and flood prediction was important at both ECMWF and NCEP, especially in studies involving GCMs (Vieterbo and Betts 1999). More accurate representations of snow processes have also improved temperature and precipitation simulations and forecasts. Further work is needed to understand how future improvements could arise from a better representation of energy balance processes.

Large-scale hydrologic modeling. Both lumped and distributed hydrologic models have been used in GHP to explore the partitioning of rain into runoff and infiltration. Errors in model outputs arise not only from uncertainties in the values of the input variables (e.g., precipitation), but they can also result from problems in model structure and parameter estimates. Distributed hydrologic models (e.g., 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 hydrologic parameters derived from satellite data or other sources (Wood et al. 1997). 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 areal sub-elements of the basin.

Data assimilation. Data assimilation is an important tool for both climate studies and numerical weather prediction. The development of systems that can assimilate specialized datasets has been important for BALTEX, GAPP, and LBA. For example, within BALTEX water vapor fields derived from GPS (Emardsen et al. 1998) are being incorporated into prediction systems. Although these new atmospheric datasets pose challenges for data assimilation, their inclusion in initial fields produces significant improvements in the forecasts. A regional LDAS (Mitchell et al. 1999), 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 is extending this system to cover the globe (Houser et al. 2001). The Eta Model has also been upgraded to assimilate precipitation gauge data and radiances from the GOES. This modeling system recently has been used by NCEP to produce a 32-km resolution regional reanalysis over North America for a 25-yr period.

WEBS. One of the major objectives of the CSEs has been to assess the accuracy with which water and energy budgets could be characterized and "closed" on a continental scale. Results from a WEBS for the Mississippi River basin (Roads 2002, Roads et al. 2003) suggest that the water budget for the Mississippi River basin can be closed to within approximately 15%. Studies by J. A. Marengo (2004b), Costa and Foley (1999), and Matsuyama (1992) suggest that the Amazon basin is a sink for moisture where precipitation exceeds evaporation. A more global study, using reanalysis products reported in Roads (2002) and Roads et al. (2002), showed that the annual mean percentage error in closing the budgets (as measured by the difference between estimated runoff and moisture convergence to the runoff) is coincidentally small in some basins/regions, such as the Mississippi River basin (20%), Lena River basin (4%), BALTEX (3%), Tibet (16%), and GAME Tropics (6%), despite large errors, which cancel, in individual terms (like precipitation and evaporation). The closure is less over the Mackenzie (76%), GAME HUBEX (84%), Amazon (46%), and CATCH (in the AMMA region)(116%), where the errors can be as large as the associated runoff.

WEBS is continuing in the individual CSEs, as well as other GEWEX projects, and will make use of overlapping and updated GEWEX products such as the ISCCP cloud and radiation products, GVaP water vapor products, GPCP precipitation products, and SRB radiative fluxes. Datasets from other GEWEX projects will aid future GHP WEBS. A comprehensive archive and analyses of global streamflow and runoff data have become available at GRDC. Emerging projects in GMPP are developing improved land surface simulations and data assimilation, which will further aid in GHP's research.

WRAP. The GEWEX WRAP (established in 1999) promotes interaction between the GEWEX and water resources communities. GEWEX has produced many products that could assist water resource managers with more efficient water use. WRAP members have a wide range of expertise related to water management and represent many international water programs, as well as the CSEs. WRAP relies on physically based hydrology and "application" or decision support models, and the coupling of these models with regional climate models. Some applications studies require downscaling 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 hydrologic and applications modeling communities are expected to identify the degree of complexity required for input data and outputs in seasonal and interannual prediction studies.

A number of the CSEs are carrying out regional workshops and studies to determine the information requirements of water resource managers. One workshop showed that water managers would like to see more projects demonstrating the use of GEWEX products in decision making. WRAP will explore how the concerns about forecast accuracies and uncertainties can be addressed through GEWEX initiatives. Currently, the MDB and GAPP projects involve water agencies and include trial delivery of tailored forecast and assimilation products from NWP centers for routine water management. Future WRAP activity will focus on building better hydrologic prediction capabilities through collaboration with IAHS PUB. In addition, WRAP, through GAPP and MDB, is supporting studies of the Red–Arkansas, San Pedro, and Murrumbidgee basins in the UNESCO/WMO HELP program. In the future WRAP will also actively contribute to the GWSP of the ESSP.

CEOP. In 1997, GHP developed the concept of a CEOP for the time frame of 2002–04, when the CSEs would be fully functioning and the next generation of Earth Observation Satellites would be producing new measurements of global water and energy cycle variables. CEOP has been accepted as an independent WCRP project, although GHP still provides leadership for the implementation of CEOP and facilitates research to address CEOP science goals (IGPO 2001). 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 up to seasonal time scales are being studied.

Through the involvement of the 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 NWP global models are now providing three-dimensional model output fields, which are being archived at MPI, associated with the BALTEX project. Each of the CSEs is also supplying data from a total of 36 global reference sites (Fig. 3) to the CEOP data center at UCAR. A global data-integration system at the University of Tokyo will archive remote sensing data. Data integration is also being carried out by the GLDAS infrastructure being developed at NASA Goddard and NCEP. (For more detail on CEOP plans, visit the CEOP Web site at www.gewex.org/ceop.htm/.)

GHP DATASETS. In addition to the CSE reference sites, individual GHP projects and centers have in situ data and products that are useful for global water cycle research. ISLSCP provides support through the generation of global datasets. 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 GPCP studies, also develops global products. In addition, BALTEX has developed a GPS for analyzing three-dimensional water vapor fields (Emardsen et al. 1998), as well as a precipitation dataset covering much of the BALTEX region, integrating Doppler radar and in situ gauge data (Koistinen and Michelson 2002). In collaboration with the FAA, GCIP facilitated the development of a water vapor sensor mounted on commercial aircraft (Fleming 1996) and has produced 5-yr datasets for the Mississippi River basin of hourly radar rain amounts (at 4-km resolution) and shortwave radiation from satellite data.

Each CSE has its own active data collection and management program 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 datasets among CSEs was

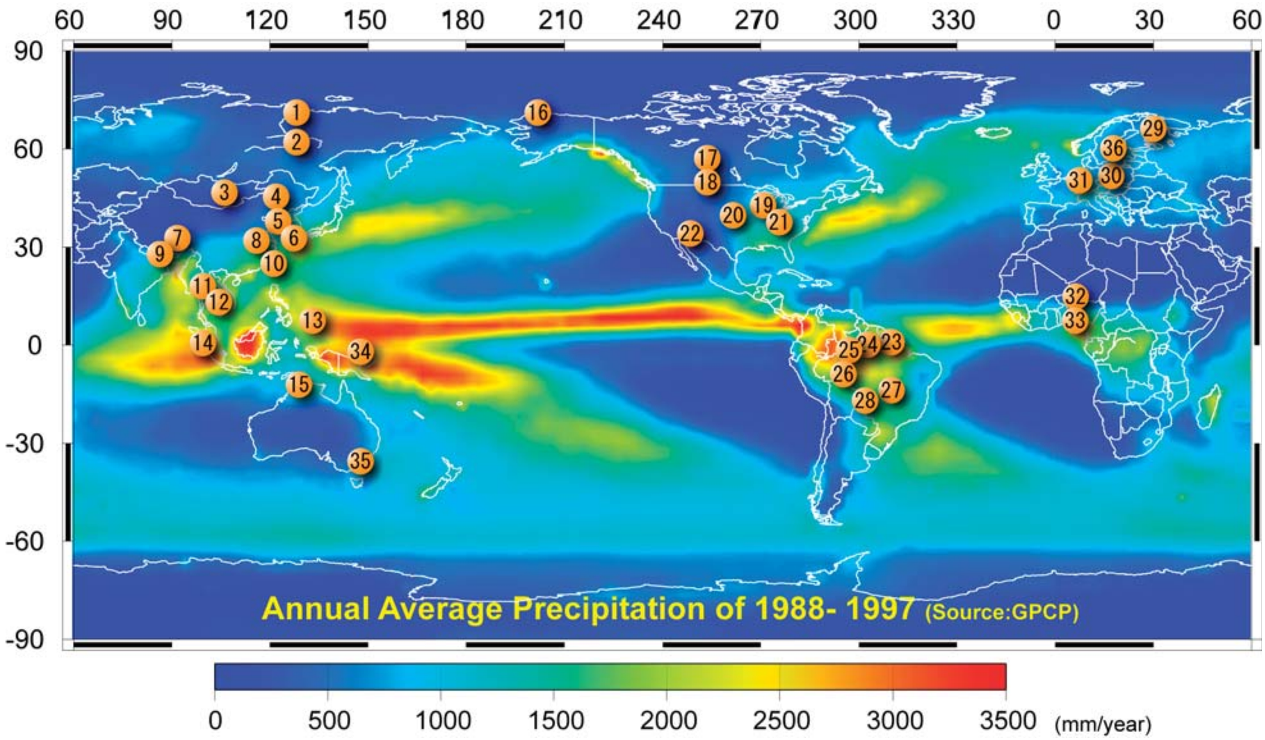

Fig. 3. CEOP reference sites.

needed. A data committee now works toward this goal by developing protocols for data collection and exchanges and developing a common data policy.

A number of the CSEs are providing multiyear datasets from special networks and extensive shorter-period datasets from field campaigns for satellite product development. GHP datasets are used to assess the uncertainties in data products derived from new satellites. CSE data and their analyses have led to the development and refinement of satellite algorithms for soil moisture and precipitation. Datasets are also being developed to support "a priori" parameter estimation for land surface and hydrologic models.

EMERGING ISSUES. As GHP matures, more cross-cutting themes will emerge. Some of these new themes are described below. In addition, extreme events will be another theme considered by the GHP in the future.

Predictability studies. Predictability studies identify the processes, areas, seasons, and global circulation regimes in which predictive skill exists at longer (seasonal) time scales. Land surface processes that contribute to persistent atmospheric conditions are being quantified and appropriately represented in coupled land–atmosphere models. To date, 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. In the United States, for example, studies of the low-frequency variability of soil moisture by Oglesby et al. (2002) have shown that the influences of land surface processes and remote ocean temperature effects are hard to separate, due to their interdependencies. In LBA, CPTEC is studying seasonal forecasts in the Amazon basin. Validation and predictability assessments for the basin are made using global datasets such as ISCCP, GVaP, and GPCP products. As datasets become available, CPTEC plans to extend these studies to other parts of the world and to coordinate predictability studies with other CSEs in collaboration with CLIVAR and WRAP studies.

Orographic precipitation. The effects of mountains on regional hydroclimate and water supply are an increasingly important focus for a number of CSEs. Geography determines the distribution of precipitation and snowpacks in many parts of the world. The rate and timing of the melt of snowpacks and glaciers often determine the availability of water throughout the summer on the surrounding lowlands. Furthermore, the influence of mountains, such as the

Tibetan Plateau and the western Cordillera in the western United States, on the overall atmospheric circulation through barrier and elevated heat and moisture source effects needs to be better understood. Datasets from GAME-Tibet and GAPP are expected to contribute to the required studies. In addition, modeling studies to assess the importance of model resolution in simulating precipitation processes in complex terrain and to correct for the influences of elevation and aspect are being initiated.

GHP's FUTURE. In summary, the GHP is applying its new scientific understanding to analysis and prediction questions being developed in many regions. GHP has made many contributions to international environmental programs and has, therefore, advanced the ability of GEWEX and WCRP to reach their own prediction goals. GHP also has contributed to the integration of WCRP's programs. GHP has facilitated the linkages between the hydrologic and meteorological science communities and between NWP organizations and hydrologic forecast services. Although many global programs have international participation, few can claim as much success in having as broad a multinational base of scientific leadership and financial investment as GHP.

As GHP contributes to the second phase of GEWEX, it is shifting its emphasis from analysis to prediction. This shift will allow individual CSEs to contribute more effectively to the GHP 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." It will also require CSEs to develop more uniformity to ensure stronger contributions to the global themes of GHP and GEWEX. CEOP contributions also will enable GHP to explore the wide range of innovative observing capabilities that will be available with the new satellite systems being launched during the first few years of the twenty-first century.

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APPENDIX: LIST OF ACRONYMS

AMC	Atmosphere Mesoscale Campaign
AMMA	African Monsoon Multidisciplinary Analysis
ARM	Atmospheric Radiation Measurement
BAHC	Biological Aspects of the Hydrological Cycle
BALTEX	Baltic Sea Experiment
BRIDGE	the Main BALTEX Experiment
CART	Cloud and Radiation Testbed
CATCH	Coupling of the Tropical Atmosphere and Hydrological Cycle
CEOP	Coordinated Enhanced Observing Period
CEOS	Committee on Earth Observing Satellites
CliC	Climate in Cold Regions
CLIVAR	Climate Variability
CLM	Common Land Model
CPTEC	Centro de Previsao de Tempo e Estudos Climaticos (Brazil)
CSE	Continental Scale Experiment
ECMWF	European Centre for Medium-Range Weather Forecasts
ESSP	Earth Science System Partnership
FAA	Federal Aviation Administration
GAME	GEWEX Asian Monsoon Experiment
GAPP	GEWEX Americas Prediction Project
GCIP	GEWEX Continental Scale International Project
GCM	Global climate model
GEWEX	Global Energy and Water Cycle Experiment
GHP	GEWEX Hydrometeorology Panel
GLDAS	Global Land Data Assimilation System
GMPP	GEWEX Modeling and Prediction Panel
GOES	Geostationary Operational Environmental Satellite
GPCC	Global Precipitation Climatology Center
GPCP	Global Precipitation Climatology Project
GPS	Global positioning system
GRDC	Global Runoff Data Center
GRP	GEWEX Radiation Panel
GVaP	Global Water Vapor Project
GWSP	Global Water System Project
HELP	Hydrology for Environment, Life and Policy
HUBEX	Huaihe Basin Experiment
IAHS	International Association of Hydrological Sciences
IGBP	International Geosphere–Biosphere Programme
IGPO	International GEWEX Project Office
IOP	Intensive observing period
ISCCP	International Satellite Cloud Climatology Project

ISLSCP	International Satellite Land Surface Climatology Project
KORMEX	Korean Monsoon Experiment
LBA	Large Scale Biosphere–Atmosphere Experiment in Amazonia
LDAS	Land Data Assimilation System
LPB	La Plata Basin
LSA	Large-scale area
MAGS	Mackenzie GEWEX Study
MDB	Murray Darling Basin
MOSAIC	A NASA land surface scheme
MPI	Max Planck Institute for Meteorology
NAME	North American Monsoon Experiment
NAO	North American Oscillation
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWP	Numerical weather prediction
OHD	Office of Hydrologic Development
PIDCAP	Pilot Study for Intensive Data Collection and Analysis of Precipitation
PILPS	Project for the Intercomparison of Land Surface Schemes
PIRCS	Project for the Intercomparison of Regional Climate Simulations
PUB	Project on Ungauged Basins
SALLJ	South America Low-Level Jet
SALLJEX	South America Low-Level Jet Experiment
SCSMEX	South China Sea Monsoon Experiment
SRB	Surface radiation budget
SSG	Scientific Steering Group
SST	Sea surface temperature
TIPEX	Tibetan Plateau Experiment (Chinese)
UCAR	University Corporation for Atmospheric Research
UNESCO	United Nations Educational, Scientific and Cultural Organization
VAMOS	Variability of Americas Monsoon System
VIC	Variable Infiltration Capacity (model)
WCRP	World Climate Research Programme
WEBS	Water and Energy Budget Study
WMO	World Meteorological Organization
WRAP	Water Resources Applications Project

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