GEWEX Contributions to Large-Scale Hydrometeorology

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ABSTRACT

This paper describes how the articles in this special issue support the Global Energy and Water Cycle Experiment (GEWEX) priorities with a specific focus on the advancement of hydrometeorological sciences. It explores how hydrometeorological research has been used to improve process understanding and forecast models, provide datasets for model validation, and support water resource applications. In particular, in this collection of papers, the water balance is considered at both global and watershed scales. In this process the limitations of reanalysis products and inputs to hydrologic models are identified. Some of these limitations arise from the lack of understanding of orographic processes and the best way to incorporate them into models. Several modeling studies reported in this special issue address different aspects of the role of topography in land–atmosphere interaction over mountain systems including the mountains in Asia and North America. Other land processes are considered as well including soil and vegetation processes. A limitation in these modeling studies arises from issues related to model initialization and validation data. One precipitation paper in this collection considers the information on extreme precipitation events that can be extracted from these data while another reports on a new algorithm for observing light rain and drizzle events. As phase II of GEWEX progresses, more emphasis will be placed on the use of GEWEX products to explore climate science questions related to the global energy and water cycle and its applications. Some areas of opportunity for future GEWEX activities include the development of high-resolution integrated products, flux estimates from satellites, and open processes (or test beds) for product improvement.

1. Introduction

The Global Energy and Water Cycle Experiment (GEWEX) was initiated in 1988 as a core project of the World Climate Research Program (WCRP). The early vision of the GEWEX program anticipated at least two phases that could build upon the initial activities related to clouds and radiation. The first phase (1988–2002) was directed toward producing tools to analyze satellite data. The second phase (2003–12) focuses on the application of these tools to climate research. Figure 1 provides a schematic summary of the GEWEX time line. Given this background and the subsequent development of its research program, the GEWEX mission could be defined functionally as the development and application of planetary Earth science, observations and models to climate and hydrology. In fulfilling this mission, GEWEX addresses its central science objectives dealing with global energy and water budgets and has developed more than 40 coordinated projects and activities that exploit global datasets and products, cli-

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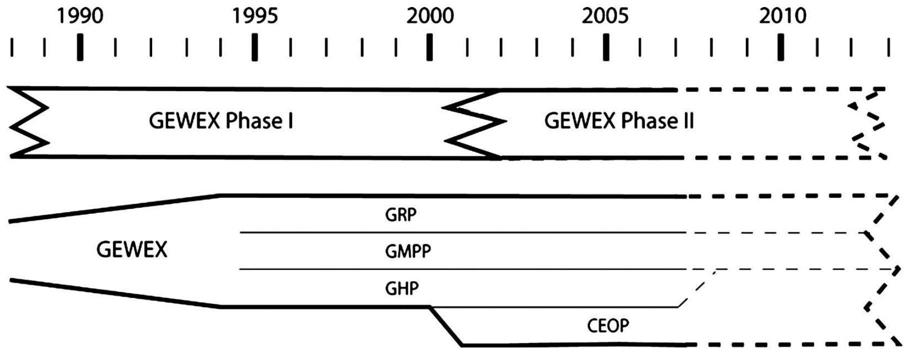

FIG. 1. Schematic showing the timeline associated with phases I and II of the GEWEX project. Also shown is the time history of the main components of GEWEX. The dashed lines for 2007 and beyond indicate that the plans for this period may be subject to change.

mate system analyses, model development, predictability studies, field campaigns, process studies, and applications. Details about the GEWEX objectives and activities are available online (see www.gewex.org).

In developing its data and modeling systems, GEWEX frequently works within the framework of national operational services and research agencies. For example, each of the continental-scale experiments (CSEs) works closely with either a numerical weather prediction (NWP) center and/or a hydrologic service center. GEWEX hydrometeorological studies frequently use satellite data to map water and energy cycle variables, to independently evaluate the performance and accuracy of models, and to assist in the validation of new sensors. At least 14 GEWEX projects are directed at hydrometeorological processes and modeling. Other GEWEX projects focus on the development and testing of new global products or on the development of the scientific underpinnings for new missions and improved forecast systems. Many of the functional interactions within GEWEX are summarized in Fig. 2.

This GEWEX special issue of the *Journal of Hydrometeorology* documents some of the most recent scientific contributions to GEWEX objectives and to our understanding of the large-scale hydrometeorological system. Precipitation is considered in the first section because of its role as the driver for land surface hydrology and for determining the distribution of the world's renewable water resources. It is also a critical contributor to the global water cycle through its removal of water from the atmosphere and to the global energy cycle through its latent heat release. Land–atmosphere interactions on different scales, which are discussed in the second section of this special issue, determine the surface component of water and energy budgets over land surfaces, influence the predictability of precipitation, and affect the contributions of land use practices to global change. For example, the state of the surface as represented by soil moisture is critical in determining the heat and moisture fluxes to the atmosphere. Papers in the third section of this special issue deal with global and regional water budgets, which are also an integrating theme of GEWEX. This summary paper is intended to provide the reader with a broader perspective and understanding of GEWEX as well as a context for the detailed papers that follow.

GEWEX is organized into three research domains: modeling and prediction studies, hydrometeorology, and the analysis of global energy and water cycle variability (Sorooshian et al. 2005). Modeling activities are undertaken under the guidance of the GEWEX Modeling and Prediction Panel (GMPP), which develops and tests new parameterizations for land and cloud processes and model evaluation, as well as by the GEWEX Hydrometeorology Panel (GHP), which oversees GEWEX field campaigns and continental-scale studies. The GEWEX CSEs, coordinated by the GHP, have strongly supported the development of regional meteorology and hydrology (see Lawford et al. 2004). Both GMPP and GHP play a central role in understanding land surface processes and their improved representation in land surface parameterizations. GHP also initiated the Coordinated Enhanced Observing Period (Koike 2004), which brings together in situ and satellite data and model output to address critical science issues related to Water and Energy Simulation and Prediction (WESP). Land surface datasets from satellites and models are also featured in the International Satellite Land Surface Climatology Project (ISLSCP) Initiative II datasets that were previously overseen by GHP. The third domain of research, analysis of global energy and water cycle variability, is overseen by the GEWEX Radiation Panel (GRP), which focuses on the development of satellite data products and their physical inter-

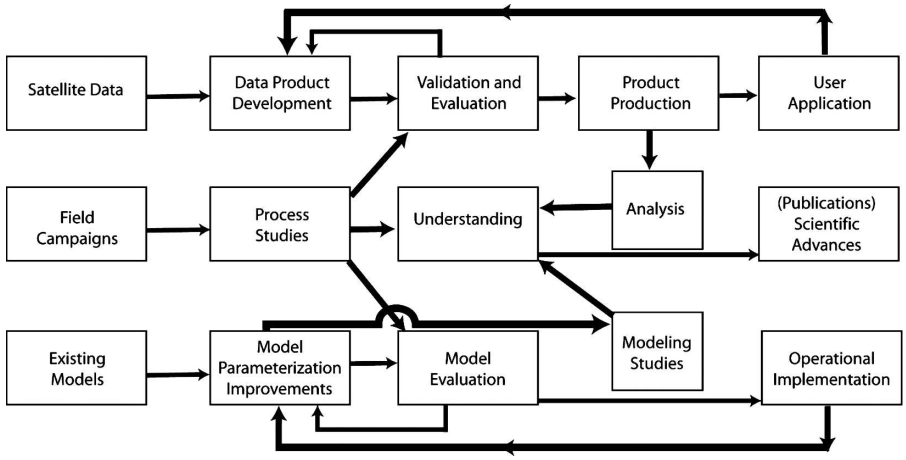

FIG. 2. Schematic showing the interactions between data, analysis, and modeling activities within the GEWEX project.

pretation. GRP activities have supported GEWEX efforts to produce datasets that are useful in representing precipitation, radiation, and clouds.

2. Precipitation: The primary forcing for land surface hydrology

a. *Precipitation measurement and analysis*

Precipitation is arguably the most widely measured water cycle variable, but it is still poorly predicted. GEWEX has a strong interest in precipitation products for a number of reasons. Precipitation is needed to force hydrologic models and to initialize weather and climate models. The assimilation of precipitation into weather prediction and climate models can make a significant contribution to their ability to predict. Using a regional climate model, Nunes and Roads (2007) showed that a regional climate simulation using humidity adjustments to force model precipitation closer to observed precipitation had a positive influence on simulated surface water and energy budget terms. Precipitation, near-surface temperature, runoff, upward shortwave, and downward short- and longwave radiation fluxes had regional seasonal cycles closer to observed values than a control experiment.

In 1986, just prior to the initiation of GEWEX phase I, the Global Precipitation Climatology Project (GPCP) was launched to support WCRP programs by producing precipitation maps on a global basis using the ability of satellites to provide global coverage. Initially these products, which were produced by combining data from a global network of rain gauge stations and geostationary satellite infrared and passive microwave observations, were available at $2.5° \times 2.5°$ and monthly resolution (Huffman et al. 1997; Adler et al. 2003). A product with similar characteristics and data sources but utilizing a different approach, known as the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), was developed by Xie and Arkin (1997). Both of these products have been available since the early 1990s and the strengths of each product are well documented (Adler et al. 2003; Yin et al. 2004).

While these products were very useful for climate applications, the hydrology community pointed out that they were not adequate for most hydrologic applications because they need much higher time and space resolutions. The GPCP responded by developing and implementing products with near global coverage and much finer spatial and temporal resolution, that is, $1° \times 1°$ and daily scales (Huffman et al. 2001). Even this resolution is not adequate for many purposes, and so the GPCP has begun experimental production of a product on $0.25° \times 0.25°$ and 3-hourly scales. These data have been used to analyze the seasonal and interannual variability in tropical and midlatitude precipitation and to assess limitations in the data product related to inhomogeneities in input datasets, artifacts in the resulting analyses, records that are too short to identify trends and too heterogeneous to permit budget calculations, and problems with high-latitude and orographic precipitation. At the same time, satellite systems that provide high-resolution, high-quality data [e.g., Tropical Rainfall Measuring Mission (TRMM) and the National Aeronautics and Space Administration (NASA) Earth Observing System series of satellites] have offered new opportunities for more accurate precipitation estimates.

GEWEX also maintains close relations with the Global Precipitation Climatology Center (GPCC), which provides the surface measurement component of GPCP. The GPCC has developed and implemented an operational collection and quality control procedure as part of the World Meteorological Organization (WMO) synoptic network and produces analyses of monthly precipitation used in the global merged GPCP and CMAP products as well as a new provisional monthly anomaly product available soon after the end of each month.

Some recent GPCP precipitation products (Gebremichael et al. 2003, 2005) and other products generated by high-resolution satellites have been assessed using the GPCC gauge-only products. Product validation is also taking place for regional precipitation products through collaboration between the International Precipitation Working Group (IPWG) and the GPCP. The validation sites for Australia and the United States can be found online (see http://www.bom.gov.au/bmrc/SatRainVal/sat_val_aus.html for Australia and http://www.cpc.ncep.noaa.gov/products/janowiak/us_web.shtml for the United States).

Precipitation maps based on the TRMM satellite data have advanced scientific understanding of the earth's energy and water cycles. Through its Large-scale Biosphere–Atmosphere Experiment in Amazonia, GEWEX helped to validate the TRMM measurements over the Amazon River Basin. More broadly, GEWEX is working with IPWG and the Integrated Global Water Cycle Observations (IGWCO) theme of the Integrated Global Observing Strategy Partnership (IGOS-P) on a project being led by IPWG to develop an integrated precipitation product that would build on existing capabilities (e.g., GPCP products) but incorporate the higher-resolution satellite observations (e.g., TRMM) and new products such as the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) (Sorooshian et al. 2000), and the CPC Morphing (CMORPH; Joyce et al. 2004) techniques, which are of great interest to the hydrological community. GEWEX also is promoting science that will provide background understanding needed to interpret data from the approved Soil Moisture and Ocean Salinity (SMOS) and Global Precipitation Measurement (Arkin et al. 2007) missions, as well as swath altimetry for inland water applications, for example, the Water Elevation Recovery (WaTER) mission concept (Alsdorf and Lettenmaier 2003).

While satellites and gauges have been the primary sources of observations for GEWEX, there is a growing realization that weather radars provide a vast amount of useful data for applications on regional scales. GEWEX has made extensive use of radar data for the land areas covered by the Baltic Sea Experiment (BALTEX) and the GEWEX Americas Prediction Project (GAPP), where sophisticated surface radar systems provide nearly continuous spatial coverage. However, these data often have unknown errors, especially in drizzle and snow situations, where reflectivities are very low and are not well suited to climate applications because of quality control issues and short record lengths. Kogan et al. (2007) have conducted a study using Observing System Simulation Experiments to show that the accuracy of the values of cloud liquid water can be significantly improved by using Doppler radar rather than single frequency radar. According to these experiments, both the Doppler velocity and the Doppler spectrum provide information that enables better drizzle flux retrievals. In addition, the Advanced Microwave Sounding Unit B (AMSU-B) channels at frequencies above 150 GHz promise to offer data that will help to address the light snow measurement problem because these wavelengths are sensitive to small ice particles.

b. Precipitation extremes

GEWEX precipitation products provide a broad view of the water cycle that includes oceans as well as land areas including the effects of El Niño events on precipitation. Gu et al. (2007) have shown that in the Tropics over 37% of the spatial extent of rainfall extremes over the oceans are explained by sea surface temperature variations associated with ENSO events. In particular, El Niño events are associated with rainfall deficiencies over the oceans. Other precipitation studies have explored the interaction between precipitation patterns and the timing of El Niño events (Curtis et al. 2004). In this special issue, Curtis et al. (2007) describe precipitation extremes during ENSO events using the low-resolution GPCP product and much higher resolution TRMM data. Although the GPCP product is useful for monitoring dry extremes that tend to extend over periods of months, Curtis et al. (2007) found that the higher-resolution TRMM data were needed to identify wet events that emerge on a daily or even an hourly time scale. In tropical areas, El Niño events lead to an increase in the number of dry extremes over land while the number of wet extremes decreased. On the other hand, the La Niña events lead to more very wet events while there was no change in the number of dry extremes under these conditions.

Rainfall prediction on medium and longer time scales poses a major challenge for the hydrometeorological community. The connections between the ENSO signal and precipitation anomalies have been extensively documented (Ropelewski and Halpert 1987, 1989). However, in spite of these correlations for specific events, the development of numerical models that can reliably simulate regional precipitation anomalies has proven to be an immense challenge. It is important to define the areas with high predictability of precipitation because it will be easiest to achieve skill in seasonal predictions in these areas and in turn derive the societal benefits that accurate seasonal forecasts promise to provide. Koster et al. (2000) have assessed the effects of soil moisture on the predictability of seasonal precipitation over the continents and found that soil moisture effects exceed those of SST contributions in some areas during the summer months. These effects are discussed in more detail in the following section.

3. The response of surface hydrology

Land–atmosphere interactions vary according to the wetness of the surface. Surface layer soil moisture determines the partitioning of the incoming shortwave radiation into latent and sensible heat and ground heat flux. It also controls the partitioning of rainfall into infiltration and runoff. Evapotranspiration (equivalent to the latent heat flux) is also influenced by vegetation type and amount of cover, profile soil moisture, radiation, and atmospheric moisture demand (ambient air temperature, vapor pressure deficit, and wind speed). Based on his assessment of soil moisture effects on precipitation predictability, Koster et al. (2004) postulated that areas with average precipitation frequency tend to have different characteristics in terms of their contributions to the predictability of seasonal climate than areas with very frequent or infrequent precipitation.

a. *Observational issues*

Errors and uncertainties in numerical prediction models result from poorly specified initial conditions, inaccurate boundary conditions, inadequate parameterizations, and inefficient model structure. For weather prediction, in particular, it is essential to define the initial conditions as accurately as possible because even small errors in initial conditions grow rapidly to produce large forecast errors. Furthermore, the dynamic atmosphere is very efficient in rapidly distributing initialization errors from an individual location to the entire globe. For longer time scales (e.g., seasonal) the prediction of the evolving boundary conditions (e.g., sea surface temperature, soil moisture, vegetation) become more important.

Through the GEWEX Continental-scale International Project (GCIP) and its follow-on project, GAPP, a number of regional land surface and atmospheric products have been developed to support the forecast systems at NOAA/National Centers for Environmental Prediction (NCEP). In particular, the snow cover fields derived from Advanced Very High Resolution Radiometer (AVHRR) data and the solar radiation fields derived from Geostationary Operational Environmental Satellite (GOES) data improved NCEP forecast products by providing more accurate and comprehensive initial conditions for forecast model runs. Other advances have been made at the European Centre for Medium-Range Weather Forecasts (ECMWF), the Japanese Meteorological Agency (JMA), and the German Meteorological Office (GMO) as a result of the use of data products developed through GEWEX research for model initialization and development (Chahine et al. 2005).

Reliable monitoring of surface energy and water fluxes is required to diagnose predictions of coupled land–atmosphere models. Measurements of subsurface (soil moisture and groundwater) conditions may also have an impact on long-term surface–atmosphere forcings in some cases. New technologies, such as those used by the Gravity Recovery and Climate Experiment (GRACE) to measure gravity anomalies, show promise for the monitoring of subsurface waters (Tapley et al. 2004). Ramillien et al. (2005) and Rodell et al. (2004a) have shown some preliminary results regarding the use of GRACE data for estimating evapotranspiration and land water storage. GRACE may also contribute to the development of land surface parameterizations required in land–atmosphere models. Other land surface atmospheric boundary layer modeling systems have been developed that rely on GOES radiation and radiometric surface temperatures to provide routine continental-scale surface energy balance estimates and a potential metric for root-zone soil moisture conditions (Diak et al. 2004). This approach offers fully independent datasets for validating surface energy budgets estimates in NWP models.

b. *Development of process understanding*

GEWEX has conducted field campaigns and established reference sites that have been intended to improve understanding of hydrometeorological processes. Among these are the ISLSCP Boreal Ecosystems–Atmosphere Study (BOREAS), the GEWEX Asian Monsoon Experiment (GAME) Tibetan Plateau Experiment, and the Baltic Sea Experiment (BALTEX)—all of which provided important data that have been used to understand important land surface processes such as soil moisture, vegetation cover, and clouds. BOREAS (Sellers et al. 1997) and more recently

GAME-Siberia developed datasets that have helped in improving the parameterization of vegetation processes (Ohta et al. 1999; Tanaka et al. 2002, Betts 2004). More recently Coordinated Enhanced Observing Period (CEOP) reference sites (Lawford et al. 2006) have contributed to land surface studies. Other studies undertaken through GAPP and through other regional experiments have explored the possibility of direct soil moisture measurement using the wavelengths being considered for soil moisture sensors on spaceborne missions (Wigneron et al. 2001; Morland et al. 2003; Jackson et al. 2002).

GEWEX hydrometeorological research has contributed to better weather and climate prediction through improved model parameterizations based on process studies and observations. These new insights are based on targeted observations and analysis, and the results are formulated in ways that allow them to be represented in models. Better model parameterizations of soil freeze–thaw processes are one example. In this special issue Zhang et al. (2007) describe how they have used new insights about soil freezing to develop a model for frozen soils that brings together the water flow and heat transfer processes during the freezing process. They report that during freezing the upward ground heat transfer results from heat produced by freezing water and advection along a temperature gradient. Their model has been validated using GCIP data from Rosemount, Minnesota, and GAME data from the Tibetan Plateau.

The results of process studies often must be up-scaled in order to be useful in models. A common issue in so doing involves techniques to effectively represent the effects of surface heterogeneity, which are always present at the spatial scale where coupled land–atmosphere models are applied. Various approaches have been used to understand this variability and heterogeneity at the subgrid scale and to represent it at grid scales in models. Chen et al. (2007) in this issue use a finite-element surface model and MODFLOW to provide a distributed modeling platform for assessing groundwater fluxes under natural conditions and with groundwater extractions for irrigation. Frequently this problem is addressed by partitioning the heterogeneous surface features into different classes (e.g., land cover tiles) without necessarily accounting for how these classes are distributed within the grid square. Other potential approaches such as the incorporation of nonlinear mathematics (fractals and chaos theory) to represent heterogeneous processes within traditional modeling frameworks remain to be developed to the point where they would be suitable to incorporate into land–atmosphere models. Soils are characterized by large heterogeneity in three dimensions over spatial scales ranging from pore size to hill slope and landform scales. Nonlinearities in soil hydraulic properties can affect horizontal water fluxes, the vertical turbulent latent heat flux, and the movement of water in the soil matrix. Mohanty and Zhu (2007) have shown that soil heterogeneity can be addressed by using both vertical and horizontal parameterizations of soil hydraulic properties. Their results show that fractal dimension and domain size allow for larger heterogeneity effects on the coefficients for hydraulic parameters. These effects are important for the interpretation of satellite data and for modeling subsurface flows.

Another example of the process of using physical understanding in model development is described by Zeng and Wang (2007) in this issue. They have focused on the changes that occur in a deciduous canopy as the autumn season progresses and the foliage on the trees disappears. They found that their Community Land Model produced much better simulations of wintertime sensible and latent heat fluxes when this defoliation process was represented as a convergence of the model's canopy roughness length and displacement height to bare soil values.

c. *Model improvement and data assimilation*

Given the important feedbacks from the surface to the atmosphere and their effects on the predictability of precipitation, it is imperative that the effects of soil moisture and vegetation on these feedbacks be understood and accurately represented in climate and weather models. Soil moisture has a precise meaning to those who take in situ measurements but the term is often used more generically in discussions among modelers and remote sensing experts. A more general term, soil wetness, has been introduced to address the need to represent the moisture content in the soil and vegetation at the surface for the purposes of computing evapotranspiration in models. GEWEX has addressed the "soil wetness" feedbacks by using both uncoupled and coupled models. The Global Soil Wetness Project (GSWP) was an uncoupled model study that has simulated soil wetness conditions for the period 1986–95 using a range of land surface models and prescribed atmospheric forcings (Dirmeyer et al. 2006). The Global Land Atmospheric Coupling Experiment (GLACE), another GEWEX experiment, used a coupled model to isolate the primary factors that control the land surface feedbacks (Koster et al. 2006).

Using models to synthesize data has proven to be a useful way to bring together in situ and satellite data for analysis and model initialization. There is a constant need to incorporate better physical understanding of complex hydrological processes into the models used for data assimilation. Although data assimilation systems are an effective way to interpolate or integrate observations, they can introduce errors and uncertainties into final products making it difficult to isolate the uncertainties that arise from observational errors. GEWEX relies on regional and global land data assimilation systems at both forecast centers and satellite laboratories to produce maps of land surface variables. Collaboration between modeling, observation, and validation groups is needed for a complete description of the analysis errors. Some global product groups do not use data assimilation systems because they feel that current assimilation methods are not sufficiently accurate and prefer other nonlinear methods.

At seasonal prediction time scales, boundary conditions such as sea surface temperatures, soil moisture, and vegetation cover are generally much more important than the initial atmospheric conditions. The contributions of surface conditions such as surface moisture and vegetation vigor provide "memory" in the climate system that can contribute to a system's predictability. The North American Land Data Assimilation System (NLDAS) is one approach for obtaining better surface conditions for prediction models (Mitchell et al. 2004). This system uses inputs of current weather conditions as well as boundary condition information to compute a number of variables that are not directly measured (e.g., leaf temperature, soil moisture at depth). A generalization of this system is now being applied globally (GLDAS; Rodell et al. 2004b). However, limitations remain due to the uncertainties introduced by the satellite data that are assimilated as well as limitations in our knowledge that are reflected in the quality of the physical parameterizations incorporated into land–atmosphere models.

Yang et al. (2007) documented the effect of the temporal resolution of updated soil moisture boundary conditions on the simulation of precipitation in the NCEP Eta Regional Climate Model. To do this, they looked at two climate regimes: a wet regime that occurred over the midwestern United States in 1993 and a very dry regime that occurred over the same area in 1988. The results showed that when the input to the model resolves the diurnal cycle in soil moisture, it produces more realistic precipitation, especially in very wet and very dry conditions when the modeled precipitation tends to be significantly different from the observed precipitation.

As data sources and products become more complex and demands for higher resolution increase, data assimilation systems will need to provide downscaled products for regional and local applications. NCEP is developing a land data assimilation system on a very high resolution grid to provide initialization datasets for single and ensemble forecasts over North and Central America. Work is underway at the Goddard Space Flight Center (GSFC) to reduce resolutions in a version of the global land data assimilation system to 1 km through the Land Information System (LIS) project. There is a constant need to acquire data from parts of the world where observations are sparse in order to validate these products. LIS is the main system supporting the new GEWEX Local Coupled (LoCo) Project.

4. Surface energy and water budgets

A central goal of GEWEX is to develop a better characterization of the major components of the energy and water balance at global and regional scales. Analysis of water and energy budgets has relied on satellites and in situ data, as well as reanalysis models. In this special issue, Trenberth et al. (2007) provide comprehensive estimates of the water budget based on the 40-yr ECMWF Re-Analysis (ERA-40) data as well as other datasets. They identify geographical areas where ERA-40 overestimates evaporation and precipitation and describe the limitations in the ERA-40 reanalysis products.

In the GEWEX Water and Energy Budget Studies (WEBS), GPCP data have been used as a basis for comparing reanalysis data and other model outputs (Roads et al. 2003). Observational studies of the energy and water budget currently require the use of both satellite products and model outputs because GEWEX is only beginning to develop some of the satellite-based surface flux products needed over land (e.g., evaporation). Several methods have been developed that provide evaporation estimates from GRACE (Rodell et al. 2004a), from operational satellites such as the Moderate Resolution Imaging Spectroradiometer (MODIS; Nishida et al. 2003) and GOES (Diak et al. 2004). The use of remote sensing to derive better vegetation properties (Tian et al. 2004) also contributes to the derivation of more reliable values of evapotranspiration from models. There is also a potential for assimilating remote sensing–based products for improving predictive capabilities of weather forecasting and hydrologic models (Drusch 2007; Crow et al. 2005).

Within GEWEX, water budgets have been analyzed at many different scales. Roads et al. (2003) focused on the Mississippi River basin using regional models and reanalysis products. Roads et al. (2002) applied similar techniques to intercompare the same variables for all of the primary CSEs. These and other studies show, not surprisingly, that water budgets can be closed with more certainty in areas with high density observations than they can in areas with sparse observations. The CEOP is a science and dataset development project initiated by GEWEX that has placed substantial emphasis on the development of water and energy budgets using integrated datasets. CEOP phase I (2002–04) brought together the observational capabilities of 35 reference sites, 11 NWP centers, data assimilation centers, and a number of space agencies (Koike 2004). Data centers have been established at the National Center for Atmospheric Research (NCAR) in the United States, the University of Tokyo in Japan, and the Max Planck Institute for Meteorology in Germany for reference site data, satellite data, and model output data, respectively. Data management and visualization tools have been developed to ensure efficient data assurance and facilitate the use of the data by the research community (Koike 2004). During phase II of CEOP (2005–10) the emphasis is shifting from the development of data systems to the utilization of these systems and datasets for research into water and energy budgets.

Seasonal and diurnal processes (e.g., low-level jet, monsoon circulation) exert important controls on continental and regional moisture fluxes over a range of time scales. The North American low-level jet is a seasonal and intermittent process that is responsible for the majority of moisture flux into the central Mississippi River basin from the Gulf of Mexico. Another low-level jet phenomenon is present in the vicinity of the Andes Mountains in South America where moist air from the Amazon Basin is transported into the La Plata Basin (Berbery and Barros 2002). In this special issue Wu et al. (2007) describe the role of another major orographic feature, the Tibetan Plateau, on the regional water and energy budget. The high altitude and large mass of the Tibetan Plateau makes it unique in terms of its energy inputs to the upper atmosphere. During the summer months the slopes of the plateau warm and air moves upward over the plateau. As a result of the convergence and the ascending motion there is a net flow inward toward the plateau during the summer months. This effect is not present in the cooler winter months but switches on when the weather is sufficiently warm. The regional circulation induced by the plateau helps to create the South Asian high pressure system and accounts for the sharp cold-season to warm-season transition that is observed in this area (Wu et al. 2007). In the winter months the plateau acts as a weak energy sink and its effect on the overlying circulation is much less dramatic.

Kim and Kang (2007) also report here on a modeling study of the role of the Sierra Nevada on the regional water cycle. In the Sierra Nevada the thermal effects on the flow are less dramatic than in the Tibetan Plateau, particularly in the winter months when the ridge of mountains primarily functions as a mechanical barrier to the flow. In assessing this effect they used the Froude number to characterize the flow because it is a function of the wind speed and the degree of mechanical mixing of the air. Flows tend to be more stable under higher Froude numbers and show more variability close to and downwind from the mountain range when the Froude number is lower. A full assessment of the relative importance of thermal and mechanical contributions of orographic systems still needs to be carried out for all major mountain ranges.

GEWEX has assessed various limitations in the ability of land surface and coupled land–atmosphere models to simulate energy and water budgets of both the land surface and atmosphere and has attempted to improve them. A critical limitation is the general lack of capability to simulate multiscale rain-producing processes in climate models. Two possible approaches offer improvements: 1) increase the resolution to better resolve surface features and the moisture flux processes; and 2) improve process understanding in order to better represent the physical processes in models. In addition to the difficulties in simulating precipitation, models also have difficulty simulating the diurnal cycle. Li et al. (2007) applied a high-resolution model to the water balance over the upper Rio Grande River basin. They show the high-resolution variability of moisture convergence and divergence patterns over the basin terrain as well as the ability of the model to represent the appropriate relationships between precipitation, evaporation, and atmospheric moisture fluxes at seasonal to interannual time scales. However, the results indicate that even for high-resolution models with explicit cloud physics, challenges remain in simulating precipitation over highly variable terrain. Even though computer capabilities are now sufficient to enable models to run at high resolutions, these models also must have improved model physics if their full contribution is to be realized. GEWEX process studies are addressing these modeling issues, first by improving our understanding of the physics, and then by incorporating that understanding into improved process parameterizations for use in models.

5. Climate and water resource applications

a. Climate

GEWEX addresses three aspects of anthropogenic climate change including increasing concentrations of greenhouse gases in the atmosphere, and changing land use and other changes in the movement and storage of surface water. Taylor et al. (2002) and Zhang et al. (1996) have both demonstrated that land cover changes can have significant effects on surface temperature patterns. Through the Global Land–Atmosphere System Study (GLASS), GEWEX has developed plans to study the effects of land use change on surface temperatures and precipitation. Henderson-Sellers et al. (1993) demonstrated that these changes can be very large. Plans are being developed by the GLASS Panel for a more comprehensive study of the potential contributions of land use change to climate variability and change by using six global climate models in a comparison of the preindustrial and the present-day land cover conditions. In the case of changes in storage water, GEWEX supports the activities of the Global Water System Project. Furthermore, GEWEX has played an important role in contributing to the assessment of the atmospheric impacts of greenhouse gases by developing tools such as the Continuous Intercomparison of Radiation Codes for the evaluation of the radiation codes used in climate models.

b. Water resources

Given the growing world population and the finite renewable water resources, there is a need to assess water stress and scarcity, particularly in dry areas. Time series of hydrometric data are needed to assess variability and long-term trends in water availability. However, many hydrometric station sites, installed for short periods during the design phase of water work projects, fail to yield the necessary long-term data records. Water balance models with varying levels of sophistication are applied to calculate supply for regional applications. Furthermore, water resources planning requires information on variability and extremes, as well as average conditions. Overuse of groundwater is becoming an important issue in a number of areas. For example in the Huaihe basin in China, groundwater is being extracted and extensively used to irrigate crops. Chen et al. (2007) report in this issue on a new hydrologic model they have developed to address this problem. The model consists of a surface hydrologic model coupled to the MODFLOW groundwater model. The results are used to track the movement of water among the various natural reservoirs and could be used to monitor the effects of groundwater extraction on these fluxes.

The ability of water managers to address water cycle variability is limited by the generally decreasing investment by nations in in situ monitoring (IAHS 2001). There are significant opportunities for more integrated observational methods, including making greater use of operational assimilated and hydrometeorological products that incorporate in situ and satellite data. With the development of the CSEs and the GHP, the potential for serving a wider user community with interests in hydrological applications of these data are emerging. This new user base includes hydrologic modelers and water resource managers who require precipitation and radiation data to drive their models. These users are also interested in products that synthesize in situ and satellite data inputs. Consultations with this user community have been facilitated by the GEWEX Water Resources Applications Project (WRAP). GEWEX studies carried out with the U.S. Bureau of Reclamation have used LDAS products to advise reservoir operators on tactical management decisions using satellite observations, prediction systems, and a decision support system known as RIVERWARE (Frevert et al. 2006). One important requirement related to these applications involves the use of high-resolution models such as the one described by Li et al. (2007) in this issue to downscale precipitation predictions produced by climate models.

6. Discussion

To continue to advance hydrometeorological research and to effectively support enhanced understanding of climate processes and applications it will be necessary for GEWEX to exploit new observing systems and research approaches. Three of these opportunities are discussed in the following paragraphs.

a. Development of high-resolution integrated products for hydrometeorological studies

As noted in this article, the value of satellite products with higher-resolution, multichannel information from research satellites for monitoring extreme wet events has been shown. However, the full value of these global data products cannot be fully exploited because the high-resolution products have not been integrated with the long-term low-resolution products. Combining satellite data collected at different resolutions and at different view times that rely on different wavelengths is a major challenge. Various techniques for bringing these datasets together have been discussed including data fusion and data assimilation. The methodologies need to be compared to provide a better understanding of the strengths of each approach and to understand how they can be combined to form an optimum product. Basic high-quality in situ datasets for different variables are needed to support these evaluations.

b. Flux estimates from satellites

The estimation of surface fluxes comes mainly from flux towers over land areas, measurements on buoys over the oceans, or from indirect estimates from models or reanalyses. While in situ measurements can be fairly accurate, the costs for obtaining global estimates from a high-density flux network are prohibitive. It is also debatable whether such networks can provide spatially representative fluxes for complex landscapes. For this reason GEWEX is attempting to determine how well fluxes can be estimated by satellite data and, in turn, will be assessing how satellite and in situ datasets can be merged into an optimal product. The GEWEX SeaFlux project has focused on fluxes over the ocean and is dedicated to producing climatological datasets of air–sea fluxes of heat, moisture, and momentum (Curry et al. 2004). Using a set of basic equations and data derived from satellites it produces gridded fields of fluxes over the oceans (Clayson 2006). GEWEX is currently launching a parallel LandFlux Project to estimate radiative, sensible, and latent heat fluxes over land from satellite data. This effort, which will bring together experts from remote sensing and hydrometeorology, will build on earlier efforts to derive evapotranspiration from satellite data (Nishida et al. 2003; Diak et al. 2004) as well as the GEWEX experience in land data assimilation. In fact, preliminary studies indicate potential improvements in land surface modeling using data assimilation techniques with remote sensing (Crow 2003; Crow et al. 2005).

c. *Pathways for transferring research techniques into operations*

GEWEX seeks to find operational homes for its mature products and systems as part of its collaborative efforts with operational services. Once systems and data products reach a certain level of maturity, it is desirable to support them through operational agencies rather than research projects. However, as noted by the National Research Council (2000), there are many difficulties and pitfalls in this process. One of the pervasive obstacles to this transfer is the lack of funding available for operational agencies to take over these new technologies. There have been some successes, such as the U.S. National Environmental Satellite, Data, and Information Service (NESDIS), which operationally produces shortwave radiation (Pinker et al. 2003) and snow cover products that were developed as a result of GCIP research. GEWEX facilitates these transitions by focusing on research and development into new retrievals and analyses that can enhance operational services. Many other successful operational transfers from research to operations have occurred at ECMWF, Centro de Previsao de Tempo e Estudos Climaticos (CPTEC; Brazil) and the Canadian, German, and Japanese meteorological services (Chahine et al. 2005).

7. Summary and conclusions

GEWEX has supported a number of developments in hydrometeorology over the past decade including hydrometeorological process studies, incorporating process understanding into models, and the development of land data assimilation capabilities. These developments have also been used to more accurately close water and energy budgets at regional and global scales. However, as shown by Trenberth et al. (2007), in this special issue limitations exist in the ability of models to reproduce the global distribution of water and energy variables. Examples of these problems include evaporation that is too strong in the Tropics and subtropics, precipitation that is too strong in the monsoon trough and convergence zones, and high-latitude and high-altitude precipitation amounts. Although limitations exist as they point out in the ECMWF reanalysis, very substantial progress has been made in reanalysis products over the past decade, thanks in part to the improvement of land surface schemes. Some of the most recent model developments reported in this issue are those associated with seasonal variation in the representation of vegetative factors that control water and energy exchanges in the summer to winter transition (Zeng and Wang 2007), and representation of the heterogeneity of soil moisture (Mohanty and Zhu 2007) and soil freezing (Zhang et al. 2007).

Modeling studies reported in this special issue have also documented recent advances in understanding the dynamic and thermodynamic influences of mountains. Wu et al. (2007) have shown the importance of thermodynamic effects for the Tibetan Plateau in the summer while Kim and Kang (2007) have shown that dynamic effects in the Sierra Nevada range can be summarized by an index. Li et al. (2007) also found an important role for convergence associated with topographical effects in the hills that are included in their modeling domain.

GEWEX research has advanced the general approach and specific techniques for satellite product development and has been the primary source for many of the long-term satellite datasets used in climate analysis. While these data are useful in general they become more useful in model validation and extreme analysis when scale factors are considered. In this special issue Curtis et al. (2007) have shown that high-resolution data are more useful for detecting extreme wet events while coarse data are adequate for monitoring dry events, which tend to develop on a much longer time scales (and generally a larger space scale). These scale considerations are important for initiatives that try to combine satellite datasets with different time and space scales. Above all, the papers in this special issue emphasize the scientific synergy that has arisen through GEWEX's success in bringing together hydrologists and meteorologists to address climate problems over land, particularly those involving land–atmosphere interactions.

While this issue focuses on progress that has been made by the hydrometeorological component of GEWEX, there are still many challenges that need to be addressed by the GEWEX community, particularly in geographical areas where in situ measurements are sparse and satellite data are underutilized. In the future it is anticipated that more satellite data and products will become available in near–real time enabling GEWEX developments to have a greater impact on both climate and weather research and services. Increased computer power and improved data assimilation tools will provide more opportunities to develop and provide improved and more targeted prediction products to the user community. The research and operational forecast communities will need to work more closely together to ensure this opportunity is fully realized.

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