GEWEX: The Global Energy and Water Cycle Experiment

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Abstract. GEWEX is one of the world's largest global change research programs. Its purpose is to observe and understand the hydrological cycle and energy fluxes in the atmosphere, at land surfaces and in the upper oceans. The goal of the GEWEX Program is to model and ultimately predict variations of the global hydrological regimes and their impact on atmospheric and surface dynamics, as well as changes in regional trends of hydrological processes and water resources and their response to an increase in greenhouse gases.

INTRODUCTION

Understanding the Earth's water cycle is fundamental to the study and prediction of the response of Earth's climate to changes in external forcing. Water (and the associated energy transfer) exerts tremendous effects on the social, political, and industrial aspects of our daily lives, A critical need exists to improve our estimation and understanding of this cycle.

Water in its various phases simultaneously warms and cools the atmosphere, as shown in Figure 1, In general, the atmosphere is a net loser of radiative energy. Clouds and aerosols cool the atmosphere, reflecting and emitting more than they absorb; however, the atmosphere regains some of its infrared energy from precipitation, which redistributes latent heat and reestablishes the atmospheric energy balance. Understanding the intricate cycle of evaporation, precipitation, and cloud formation is among the most intriguing investigations in climate change(1).

In June 1987, a group of scientists met at McGill University in Montreal, Canada, to discuss the prospects for an international program to study the Earth's global energy and water cycles. The World Climate Research Program (WCRP), which organized the meeting, had sought recommendation from the participants for undertaking such a program, The participants concluded that current understanding of the global hydrological cycle is poor, and has been limited by the absence of reliable global data on such vital parameters as precipitation, evaporation, and atmospheric winds. Acquisition of these data is a prerequisite to improved knowledge. Subsequently, space agencies in the United States, Europe, and

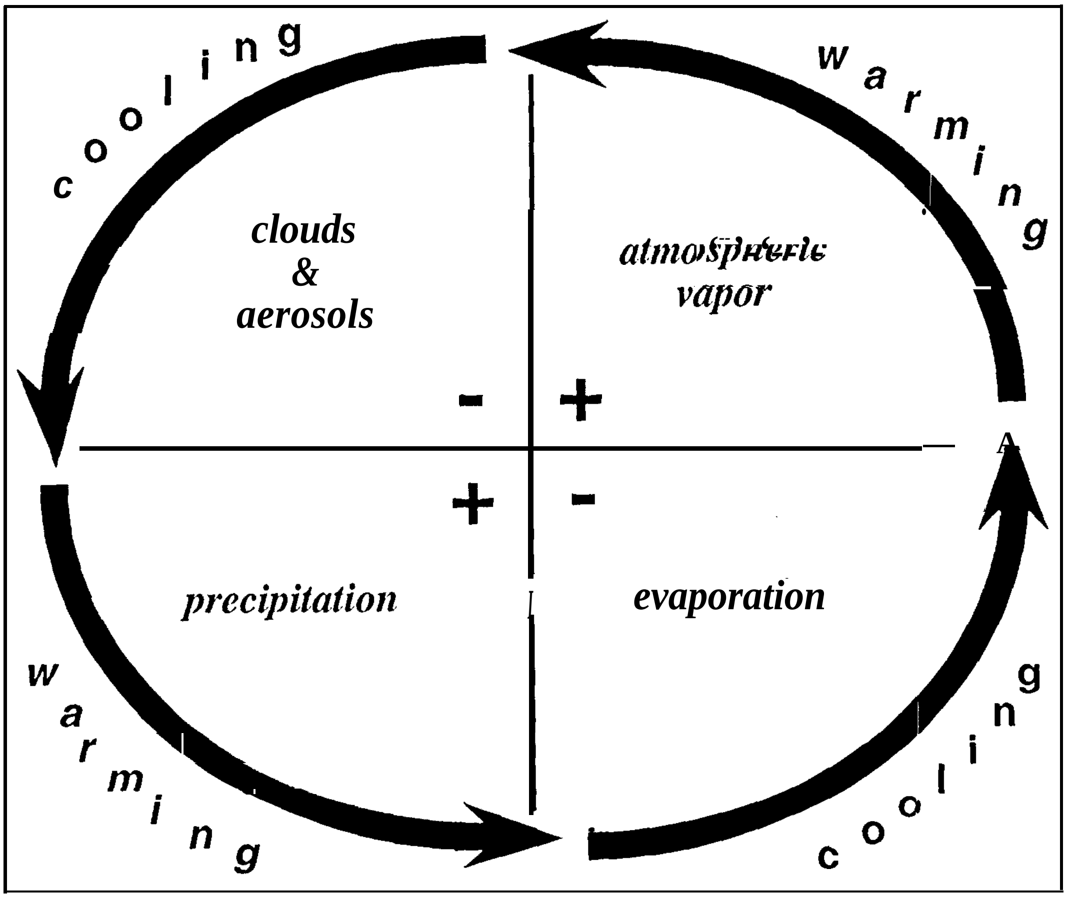

FIGURE 1. The Complex Role of Water in the Climate System

Japan developed plans to launch a series of global remote-sensing satellites in the late 1990s, to monitor a range of essential surface and atmospheric parameters. Thus, the concept of the Global Energy and Water Cycle Experiment (GEWEX) was born (2). The ultimate goals of GEWEX—namely to improve by an order of magnitude the ability to model global precipitation and evaporation, and to provide an accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change-clearly matched those set by the Intergovernmental Panel on Climate Change (IPCC) and by NASA's Mission to Planet Earth. GEWEX incorporates in a single, coordinated program all relevant aspects of the climate system from model development and data assimilation to the deployment and use of pertinent observing systems. The GEWEX Program addresses the following objectives:

- Determine the hydrological cycle and energy fluxes by means of global 'measurements of observable atmospheric and surface properties
- Model the global hydrological cycle and its impact on the atmosphere and ocean

- Develop the ability to predict the va,iations of global and regional hydrological processes and water resources, and their response to environmental change,

High priority was given to improving our currently very poor quantitative estimates of the global hydrological cycle. For example, evaporation minus precipitation (or equivalently the net flow of water from land to oceans, and the net advection of moisture from the marine atmosphere to the terrestrial atmosphere) is known only to within a factor of two. Even more significant, the volume of water in ice and snow, soil moisture, and underground water percolation is known on] y to within a factor of two to four. The regional and temporal distributions of the components of the hydrological budget are even more uncertain than the global averages, Any attempt to understand and predict the hydrological cycle is clearly hampered by such lack of knowledge. Therefore, GEWEX has an additional objective to foster the development of observing techniques and data management and assimilation systems suitable for operational applications to long-range weather forecasts, hydrology, and climate predictions.

IMPLEMENTATION OF GEWEX

The GEWEX Program is organized into three major research areas (see Figure 2)—namely, radiation, cloud systems and precipitation, and hydrometeorology. Each research area incorporates major international scientific projects to implement modeling and process studies, and to develop databases of climatologicall y important variables (see Table 1). The GEWEX implementation strategy consists of four connected thrusts: Modeling, process studies, global observations, and, ultimate] y, predictive capability (see Figure 3). Following the launch of the global Earth observing systems in the latter part of this decade, a major global experiment will be conducted to validate improved climate models. A build-up effort to this global experiment was initiated in 1993, with the support of the National Oceanic and Atmospheric Administration (NOAA), termed the GEWEX Continental-scale International Project (GCIP). GCIP will observe and model the Mississippi River basin, taking advantage of an exceptionally dense meteorological and hydrological measurement network over this region. Several related activities will be conducted in other parts of the world to complement GCIP. The goal is to develop and improve modeling of surface and near-surface processes, and to integrate surface and groundwater processes on the catchment scale into fully interactive global land-atmosphere models.

in a relatively short time, GEWEX gained significant international support. Following recommendations made by the Joint Scientific Committee in 1989, both the Executive Council of the World Meteorological Organization

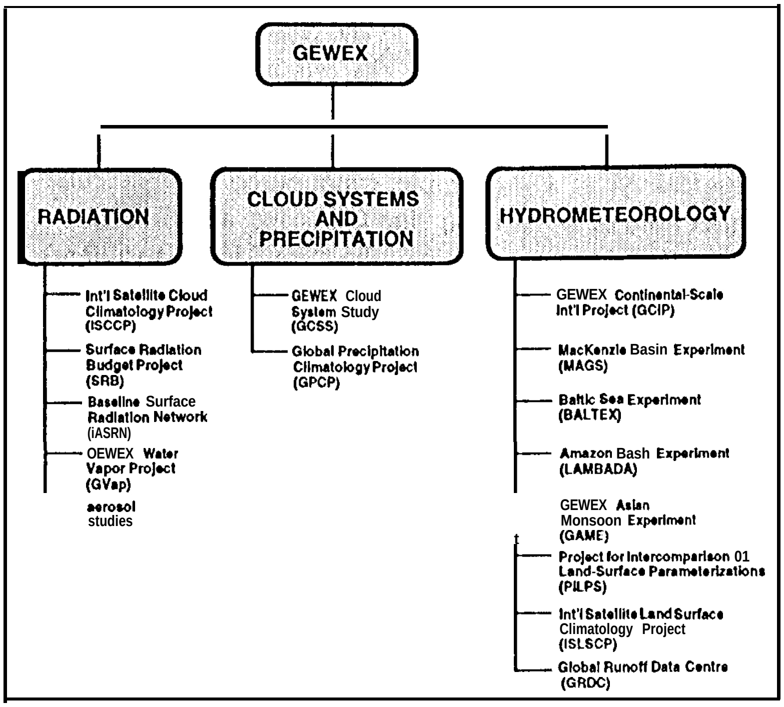

FIGURE 2. GEWEX Program Organization

(WMO) and the Executive Board of the International Council of Scientific Unions (ICSU) have endorsed GEWEX as a core program of the WCRP and as a major contribution to the study of global climate change. The major international space agencies have extended strong support for GEWEX. In the United States, the Committee on Earth and Environmental Sciences (CEES) identified clouds and the hydrological cycle as the highest priority 'issue for research on global change. The International Association of the I hydrological Sciences (IAHS) and the WMO Hydrology and Water Resources Program have established a joint working group on GEWEX to develop scientific initiatives to be undertaken in large-scale hydrology in support of GEWEX. The International GEWEX Program Office (lGPO) resides in Washington, D. C., and coordinates all GEWEX activities.

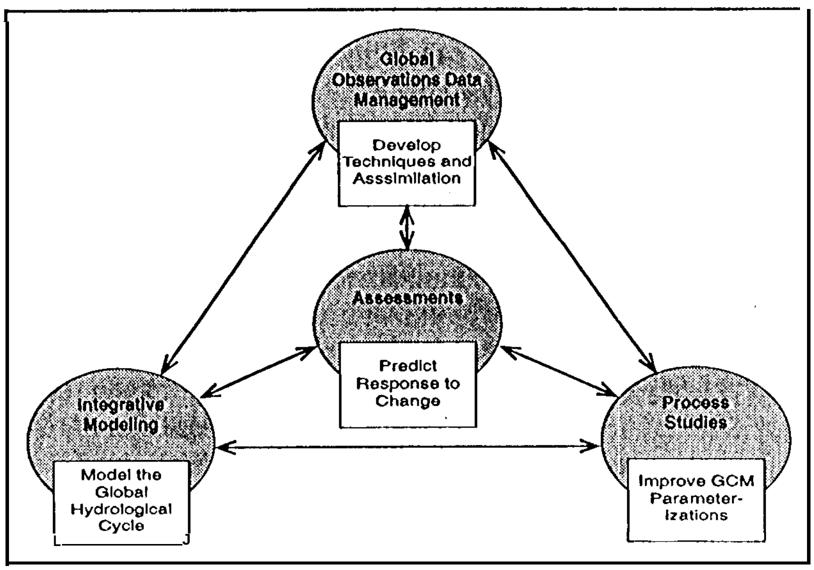

FIGURE 3. GEWEX Program Implementation

TABLE 1. Global Data Needed for GEWEX

Basic Meteorological Parameters	Radiation and Clouds
- Atmospheric temperature	- Solar irradiance
- Atmospheric humidity	- Spectral outgoing longwave radiation
- Ocean surface temperature	- Reflected solar radiation at the top of the atmosphere
- Ocean surface stress	- Net flux at the surface
- Ocean surface topography	- Earth radiation budget
- Surface meteorological observations	- Greenhouse trace gases
	- Aerosols
Tropospheric Wind Vector	- Stratospheric water vapor
- Global Doppler wind lidar	- Cloud amount, type, and heights of base and top
- Upper air winds	
	Land Surface Data
Precipitation	- Surface albedo and roughness
- Global rain radar data	- Skin surface temperature and emissivity
- Rain gauge data	- Vegetation index
- Ocean salinity	- Snow cover, depth and water content
	- Soil moisture
	- Water runoff
	- Topography, soil type

HYDROLOGY AND THE CLIMATE SYSTEM

Water vapor is one of the most variable constituents of the atmosphere, both spatially and temporally. Overall, the greenhouse effect of increased $C0_2$ is more than doubled by the accompanying increase in atmospheric water vapor, but this effect is strong] y dependent on the vertical redistribution. Water vapor is intimately connected to the prediction of cloudiness, which itself strongly regulates the Earth's radiation budget, A better understanding of the vertical and horizontal distribution of water vapor is urgently needed,

Clouds, ice and snow have important influences on the Earth's radiation budget. Recent observational studies show that the global, annual mean effect of clouds is to cool the Earth (3), but we cannot yet assess the cloud--radiation feedback especially under changed climate conditions,

The hydrological cycle is also strongly modulated by the biological characteristics of the Earth's surface. Vegetation is influenced by water and energy, and, in turn, vegetation cover influences the partition of energy and water inputs at the land-atmosphere boundary layer. Thus, the biological and physical aspects of the hydrological cycle are intrinsically and intricately linked, and understanding their functions and interactions is crucial to reducing current uncertainties in the sensitivity of the Earth's climate system to changes in greenhouse gases and land use.

The runoff of water from continents together with precipitation and evaporation at the ocean surface are important determinants of ocean salinity, therefore of ocean vertical mixing rates. The turnover time for the upper ocean is slow, on the order of 50 years, while it is on the order of thousands of years for whole ocean basins and major ice sheets. By contrast, exchange of the total inventory of tropospheric moisture with the ocean and land surface through precipitation and evaporation is fast, on the order of 10 days. These two regimes determine the Earth's climate system, The slow component-consisting of the bulk of the ocean and its deep water circulation, land glaciers, and ice caps—modulates the transient response of the Earth's climate and introduces a delay of 50 years or more. The fast component-consisting of the atmosphere, land surface, and upper ocean—supplies the climate system with momentum, water, and energy, and determines the amplitude and regional patterns of climate change. The focus of GEWEX is on the treatment of the fast component and understanding its complex feedback processes.

GENERAL CIRCULATION MODELING AND GLOBAL OBSERVATIONS

While existing observing and forecasting systems are very useful for predicting atmospheric circulation, they are rather primitive in their ability to predict the phase changes and transport of water in the atmosphere. The problem is more serious when it comes to the capabilities of land hydrology and upper ocean models. Improving current models to the level needed to determine global water and energy fluxes will require not only considerable improvement in the parametric formulation of the physical processes in the models, but also improvement in the observations themselves.

Parametrizing the effect of the water cycle properly remains one of the outstanding problems in climate modeling—a result both of computer limitations and a lack of understanding of the physical processes. This is especially true for the distribution of water vapor, the radiative effects of clouds, and the release of latent heat. Since hydrological processes have fine structure, improved understanding requires higher resolution models and higher resolution data. Unfortunately, several hydrologic] processes in the boundary layer and the surface cannot be observed directly. In addition, measurements are generally made from a variety of surface and space-based platforms with different temporal and spatial scales. Elaborate data assimilation strategies using global or regional atmospheric-surface models will be required. In these strategies, the task of exploiting observational data cannot be divorced from the task of improving models. A build-up phase in climatological data is already underway, starting with best estimates of seven parameters to be compiled and issued by GEWEX:

- Radiation at the top of the atmosphere
- Surface radiation budget
- Cloud amount and radiative properties
- Water vapor
- Rainfall
- Runoff
- Land surface climatology, including "soil wetness,"

GEWEX will exploit four-dimensional data assimilation to provide time and space continuity of data sets. Four-dimensional data assimilation systems will be used for constructing global, complete, and self-consistent descriptions of the state of the atmosphere and the ocean. In these systems, a sophisticated general circulation atmospheric model is used to provide a very short forecast (e.g., 6 hours), and this first guess of the state of the atmosphere is statistically combined with atmospheric data (both ground-based and remotely sensed) observed in a window of ±3 hours, Such analysis/forecast systems have improved very significantly in the last few years, with the result that their output is generally the preferred research tool for many climate studies. These improvements have come both from the use of advanced numerical models of the atmosphere and from sophisticated anal ysis schemes. The use of the model is very important because it provides time continuity, transports information from data-rich to data-poor regions, and gives an estimate of all the characteristics of the atmosphere, including those not directly measured.

Progress in four-dimensional data assimilation has reached the stage where the accuracy of model-derived atmospheric temperature profiles is comparable to or better than that obtained from existing operational satellites. Consequently, further improvements in numerical modeling will require corresponding improvement in the accuracy of atmospheric temperature profiles to about 1 "C. This accuracy could be met in the future by using very high spectral resolution sounders like the Atmospheric Infrared Sounder (AIRS), which will fly on NASA's Earth Observing System (EOS), in conjunction with an advanced microwave sounder.

Knowledge of atmospheric winds is essential for reconstructing the state of the global circulation, especially in the tropics. Whereas the dynamic balance of the atmosphere at middle and high latitudes allows inferring the wind field from the temperature field through the geostrophic relationship, this approach does not apply in the equatorial regions. Direct measurements of wind profiles are necessary. This type of capability is under consideration by NOAA.

Quantitative global precipitation data with sufficient vertical resolution are needed to separate true surface rainfall from precipitation that evaporates or accretes into cloud water before reaching the surface. An active spaceborne rain radar with a multi-frequency passive imaging radiometer is expected to be tested on the NASA/NASDA Tropical Rainfall Measuring Mission (TRMM) in 1996, but a follow-on flight will also be needed.

The vertical distribution of clouds affects the partitioning of heat between the atmosphere and the surface, thereby affecting both the surface radiation budget and the large-scale circulation of the atmosphere through effects on both the horizontal and vertical gradients of heating. In addition, ice clouds detrained from deep convection dominate the water budget of the upper troposphere and affect the longwave emission of the atmosphere through the water vapor feedback mechanism. A millimeter-wave radar would provide information about the vertical structure of clouds and cloudbase altitude, and, with suitable complementary measurements, is a promising method to provide estimates of ice mass. A cloud radar is the highest priority new measurement capability for the GEWEX Program, and is currently under study by several international space agencies.

In addition to the above measurements, GEWEX requires the collection of basic meteorological parameters, Earth radiation budget, and land surface data. For the most part, the required advanced sensor development is already underway at the initiative of the international space agencies. Implementing these new and improved satellite sensors is a prerequisite to successfully completing the GEWEX Program.

GEWEX CONTINENTAL-SCALE INTERNATIONAL PROJECT

Current data are inadequate to test detailed surface and mesoscale algorithms. In particular there is a need to develop surface hydrological models on the appropriate scale to couple them with atmospheric general circulation models. The GEWEX Program supports the development of coupled hydrologic-atmospheric models of continental-scale river catchments encompassing a diversity of terrain and climate conditions and permitting the systematic testing of these models on a long-term basis. The GEWEX Continental-scale International Project (GCIP) will provide the opportunity to compare the detailed performances of the various models under real istic time-dependent conditions, to ascertain their sensitivity y to various possible estimates of forcing fluxes and to determine the degree of similarity with observed hydrological quantities (4), GCIP scientific objectives follow:

- Develop and validate macroscale hydrological models and coupled high-resolution atmospheric-hydrological models
- Develop and validate information retrieval methods for present and future satellite observations
- Provide a capability to translate the effect of increased greenhouse gases into impact assessments on regional water resources and temperature.

The concept would include a program of extensive meteorological and hydrological observations combined with modeling activities. The duration of the project is a minimum of 5 years, in order to monitor seasonal changes and account for long-term variation in soil moisture.

The Mississippi River basin was selected for the project primarily because of the availability in the near future of a new dense network of radar systems (NEXRAD), which will provide accurate precipitation data and a network of meteorological and hydrological stations providing quality meteorological, surface, and subsurface hydrology data. Equivalent data are not available in other large catchments. l-he Mississippi basin is large enough so that the measurements describing the hydrological processes can be incorporated into future global models. in addition, the area encompasses a wide range of soil moisture conditions, vegetation types, and surface topography and contains sufficient conventional observations so that many of the future satellite observations could be simulated using *in situ* data. The area also has readily available, sufficient historical observations. GCIP will collect standard meteorological data, high spatial resolution wind profiler and rain radar data, satellite cloud and radiance data, as well as cloud infrared properties and radiation fluxes, an expanded set of rain-gauge data from private and government operators, streamflow and other relevant hydrological measurements over a period covering several annual cycles of hydrological processes. The project is therefore meant to provide a powerful incentive, as well as the means, to develop the type of multivariate data and information system required in the future for the global observation phase of GEWEX. It is clear that GCIP will develop into a major data collection and processing exercise relying to a considerable extent upon existing operational facilities and procedure, and will constitute a meaningful test of the international EOS Data and information System (EOSDIS) planned by NASA and other organizations.

GCIP is complemented by four other large-scale hydrological studies (see Figure 4), which will be used to develop versions of GCIP coupled atmospheric-hydrologic models for use in other climatic regions: The Mackenzie Basin GEWEX Study

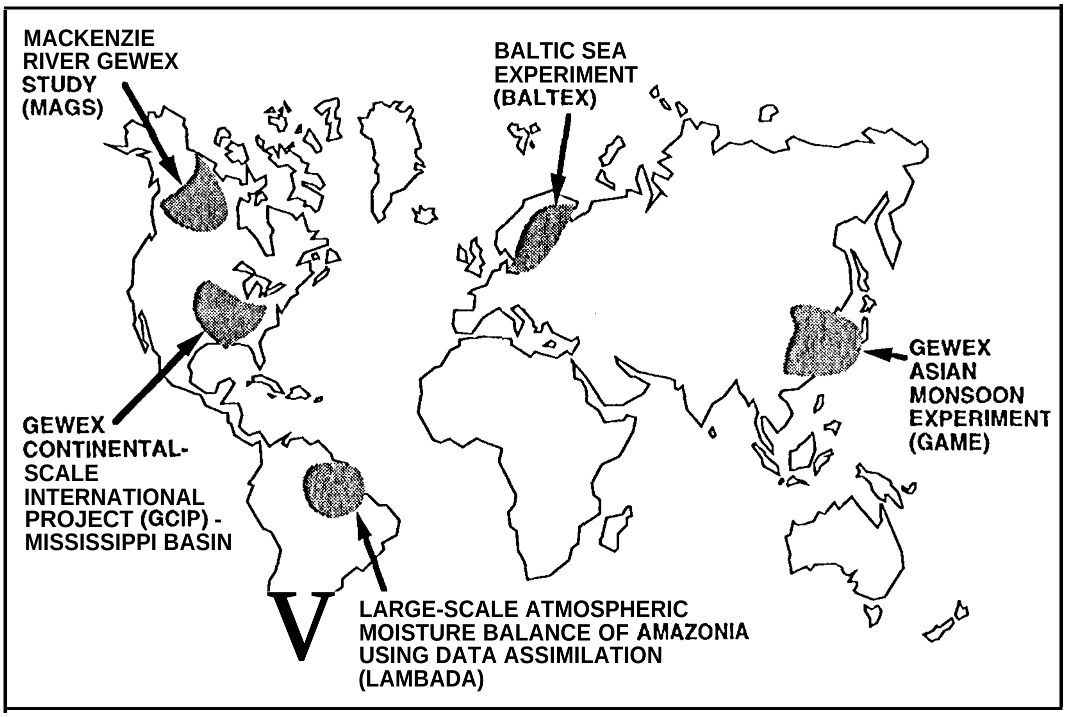

FIGURE 4. GEWEX Large-Scale Hydrological Studies

(MAGS), the Baltic Sea Experiment (BALTEX), the Amazon Basin Experiment (LAMBADA), and the GEWEX Asian Monsoon Experiment (GAME),

SUMMARY

The development of the space component of the GEWEX observing system is a pacing item for the program as well as a prerequisite for undertaking the global-scale study. GEWEX will advocate for the deployment of new sensor systems—such as those on EOS, particularly the advanced sounder—and for a cloud radar and the rain radar system that are deemed essential for closing the energy and hydrology budgets.

The data analysis and assimilation efforts will require new initiatives beyond the existing capabilities of operational weather forecasting centers or theoretical climate modeling institutions. Dedicated climate research and prediction centers will be needed, which combine expertise in data retrieval and data validation with data assimilation and refinement of numerical prediction models. GEWEX will exploit new technological developments in computers and data information systems for model verification and improvement.

TABLE 2. Major Scientific Programs with Links to GEWEX

Program	Sponsoring Organization
Atlantic Climate Change Program (ACCP)	NOAA
Atmospheric Radiation Measurement (ARM) Program	U.S. Department of Energy
Biospheric Aspects of the Hydrological Cycle (BAHC)	IGBP
Climate Variability Program (CLIVAR)	WCRP
Working Group on Numerical Experimentation (WGNE)	Joint Scientific Committee

In all activities planned and underway, collaboration with many other ongoing programs will be essential (see Table 2). Through the GEWEX Program, we will gain confidence in accounting for the physical processes and complex feedbacks in the global hydrological cycle—any one of which could upset climate simulation in important but presently unknown ways.

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