Water and energy cycles: investigating the links

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Introduction

The Earth's climate fluctuates and changes both regionally and globally. Inevitably, this is reflected in the variability and change of Earth's water budget and its complex and dynamic energy balance with the Sun. Processes controlling the transports, transformations and exchanges of heat and water in the climate system are inextricably intertwined over a large range of space- and time-scales from boundary-layer turbulence to global climate change. Recognizing the pressing requirement to better understand and predict these complex processes and their interactions, the World Climate Research Programme (WCRP) launched the Global Energy and Water Cycle Experiment (GEWEX) in 1990. GEWEX leads WCRP's studies of the dynamics and thermodynamics of the atmosphere, the atmosphere's interactions with the Earth's surface (especially over land), and the global water cycle. By virtue of this central role, GEWEX connects with other WCRP projects, including the Climate Variability and Predictability (CLIVAR) project, the Stratospheric Processes and their Role in Climate (SPARC) project, and the Climate and Cryosphere (CliC) project. Furthermore, WCRP's co-sponsors, WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, provide GEWEX access to researchers in both the academic and governmental sectors.

GEWEX: Phases I and II

The first phase of GEWEX (1990-2002) focused on the development of analysis tools and models, using operational and research satellites, regional analyses of continental scale basins, and process studies to support the development of parameterizations of feedback processes (relating to clouds and land) for global climate models.

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During Phase I, more than 1 500 scientists from over 35 countries participated in GEWEX activities and more than 20 special issues of refereed papers were produced.

Understanding the role of water in the climate system is a priority for WCRP and GEWEX. As vapour, water is the Earth's strongest and most plentiful greenhouse gas. Clouds also have an important feedback role in the climate system and, depending on their composition, spatial distribution and altitude, may enhance or diminish climate-change effects. Feedback influences also come from land-surface states determined by soil moisture and vegetation, which controls the partitioning of incoming solar radiation into radiative, sensible, latent (evaporation) and ground-heat fluxes and precipitation into runoff and infiltration. The cycle is closed by evapotranspiration from the land and evaporation from the ocean. Understanding, characterizing and

GEWEX Phases I and II

GEWEX Phase II (2003-2013) emphasizes the full exploitation of the understanding and tools from Phase I (1990-2002), along with increased reliance on upgraded models and assimilation systems and new environmental satellite systems to produce even greater contributions to climate science.

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closing both the global water and energy budgets have been a major focus for GEWEX research.

This agenda has placed GEWEX on the leading edge of science, which is directed at bringing the hydrology, land-surface, and atmospheric science communities together through process studies in order to show the importance of understanding soil moisture/atmosphere and cloud/ radiation interactions and their parameterization within prediction models. Also, by producing or fostering the production of global datasets to validate predictive models, GEWEX is ready to assess whether the global water cycle has been undergoing significant changes in the past two decades. GEWEX has also actively engaged and benefited the water resource community. As shown in **Figure 1**, GEWEX plays a critical role in relating WCRP prediction activities to hydrology programmes, such as those of the International Association of Hydrological Sciences (IAHS).

During Phase I, GEWEX activities included: (a) global dataset development; (b) process studies; and (c) model development support and modelling studies. In order to focus activities and to provide for better coordination, a programmatic structure was adopted in 1995 that set goals for GEWEX activities in three separate areas, namely radiation, hydrometeorology and modelling and prediction. The hydrometeorology activities, coordinated through the GEWEX Hydrometeorology Panel, focused on the coupling of the land and the atmosphere and hydrological processes at the continental and mesoscales. Modelling and related process studies coordinated through the GEWEX Modelling and Prediction Panel (GMPP) addressed clouds, land-atmosphere interactions, and, more recently, boundary-layer processes. The radiation projects, coordinated by the GEWEX Radiation Panel (GRP), developed global data products and scientific understanding related to the global distribution and variability of clouds, water vapour, aerosols, surface radiation and precipitation.

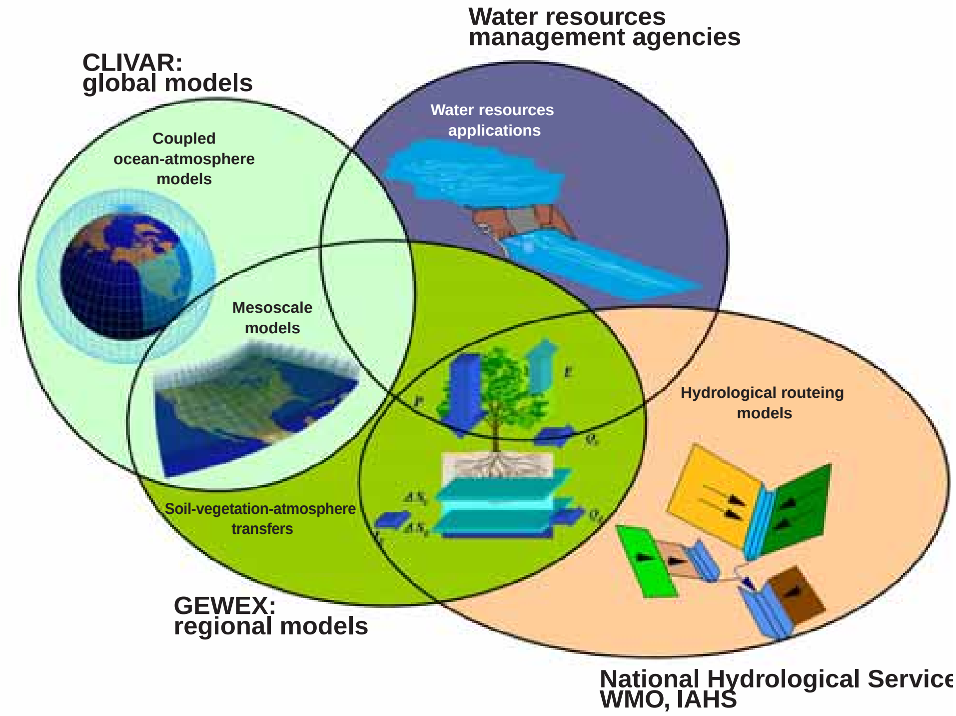

Figure 1 — Role of different international and national programmes and agencies in addressing climate prediction and water-resource management issues. (Figure: S. Sorooshian)

GEWEX Hydrometeorology Panel (GHP)

GHP efforts are directed at demonstrating skill in predicting changes in water resources and soil moisture on time-scales up to seasonal and annual as an integral part of the climate system. It also focuses on building upon distributed process studies in the GEWEX Continental Scale Experiments (CSEs) as well as the Coordinated Enhanced Observing Period (CEOP) effort initiated by the GHP in order to coordinate globally the CSE observations and modelling efforts (Lawford *et al.*, 2004). Coupling of the land-atmosphere (and the Baltic Sea) has been a central strategy for the GEWEX CSEs and five major continental-scale field campaigns have been underway for more than a decade to provide new process understanding and improved model representation in the Amazon, Baltic Sea, Mississippi and MacKenzie River Basins, and four areas in eastern Asia (Thailand, Tibet, Siberia and eastern China). New CSE initiatives have subsequently been developed for basins in Australia, the La Plata Basin of South America, and most recently western Africa. The locations of the CSEs are shown in Figure 2.

Through new hydrometeorological data, models, and analyses, the GHP

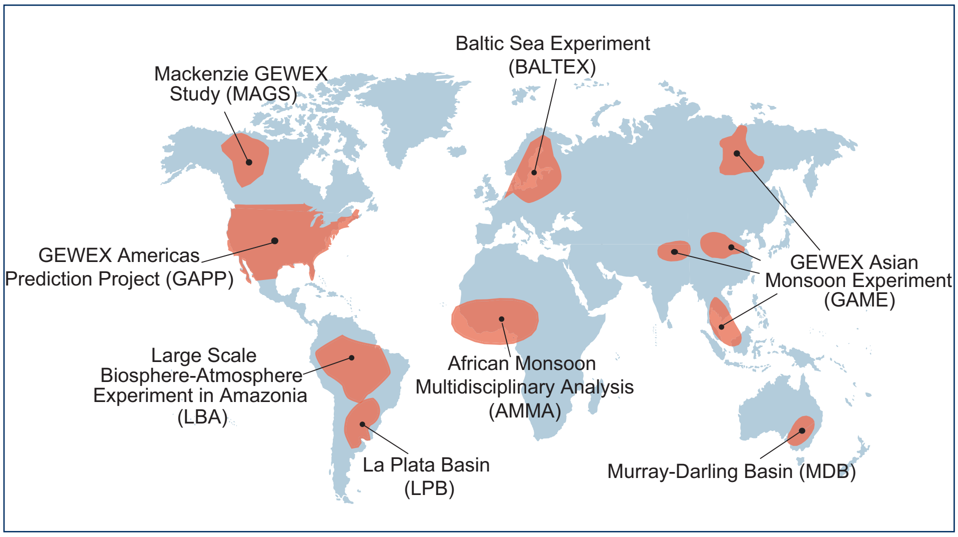

Figure 2 — Continental scale areas included in the GEWEX Hydrometeorology Programme.

has demonstrated the critical importance of land-surface interactions, soil-moisture measurements and the application of regional and global high-resolution precipitation data. Furthermore, major new land-surface scheme upgrades have resulted in improved regional to global prediction capability. The development of this new interdisciplinary relationship of the hydrological and atmospheric sciences with a focus on coupled land surface-atmosphere interactions led to a large number of new research papers and helped to initiate the American Meteorological Society's *Journal of Hydrometeorology*. In brief, regional data and modelling have proved to be very effective in improving the understanding of local processes and led to suggested approaches to improve current regional and global models, which have difficulties simulating diurnal and surface-subsurface hydrological processes.

GEWEX Continental-scale International Project (GCIP)

The GCIP in the Mississippi River Basin was the first international project of its size to bring together the hydrological and meteorological science communities for a common research goal. GCIP was launched in 1995 to take advantage of the extensive meteorological and hydrological networks that existed and were being upgraded there. The motivation for GCIP came from the recognition of the need to close regional water and energy budgets and to improve parameterization of land-atmosphere interactions and land-surface hydrology in climate models. Other basins were soon established as CSEs after the adoption of the GCIP in order to study coupled hydrometeorology over diverse climatic and political regions. The success of the GCIP subsequently resulted in an expansion of activities as part of the GEWEX Americas Prediction Project (GAPP). Studies of the North American Monsoon System in GAPP have promoted closer linkages between GEWEX and CLIVAR in monsoon research.

GEWEX Asian Monsoon Experiment (GAME)

GAME research has been directed at understanding the role of the Asian monsoon in the Earth's climate system and to improve the simulation and seasonal prediction of Asian monsoon patterns and regional water resources. The scientific strategy of GAME includes monitoring by satellites and in situ surface observations, process studies based on the four regional experiments located in distinctive climate regions (tropics, sub-tropics, Tibetan Plateau and Siberia) and modelling of hydrometeorological processes in the climate system.

Baltic Sea Experiment (BALTEX)

BALTEX, which includes the Baltic Sea and its drainage basin, has explored and modelled the mechanisms determining the space and time variability of energy and water budgets over the BALTEX region, which covers roughly 20 per cent of the European continent. The experiment has analysed large seasonal, interannual and regional variations in climate and episodic hydrometeorological events in the basin that have produced flooding in densely populated areas and have led to important ecological changes in the Baltic Sea.

Mackenzie GEWEX Study (MAGS)

MAGS is a multidisciplinary project that is undertaking research to understand and model the response of the energy and water cycle in northern Canada to climate variability and change; to define the impacts of its atmospheric and hydrologic processes and feedbacks on the regional and global climatic systems; and to apply these predictive capabilities to climate, water resources, and environmental issues in the cold regions. MAGS identified sublimation in blowing snow as one of the main causes for the "missing surface water storage."

Furthermore, MAGS scientists quantified evaporative losses from large northern lakes and improved understanding and model representation of runoff processes in the northern regions. Along with GAME-Siberia, MAGS has strengthened the links between GEWEX and CliC.

Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)

The hydrometeorological aspects of LBA have been directed at understanding the role of tropical forests and the consequences of deforestation for regional energy and water budgets. Phase I field experiments, modelling, and analyses showed a 44 per cent imbalance of the water cycle in the Amazon basin. Amongst the many important findings, LBA studies determined the transport of moisture from Amazonia to southern Brazil via the low-level jet east of the Andes and quantified the interannual variability of the Amazon Basin as a source/sink of carbon dioxide and moisture based on an assessment of carbon sequestration in tropical forest environments during ENSO events.

International Satellite Land Surface Climatology Project (ISLSCP)

The ISLSCP initially focused on field experiments but more recently has undertaken the development of interdisciplinary data sets. These field experiments included the First ISLSCP Field Experiment (FIFE) and the Boreal Ecosystems-Atmosphere Study (BOREAS). Subsequently, ISLSCP launched two interdisciplinary data collections to develop co-registered interdisciplinary Earth science land datasets for variables needed by modellers for coupled land atmosphere modelling. The first co-located 1 x 1° observational datasets covered a two-year period and have been used widely in research and education. The second data collection initiative (ISLSCP II) produced datasets at spatial resolution of 1° to 0.5° and 0.25° for the period 1986-1995.

GHP has mounted several global projects that integrate studies and activities in all of the CSEs. These activities include the Water and Energy Budget Sudies (WEBS) and the Waer Resources Applications Project (WRAP). GHP also coordinates GEWEX-related research with global projects, including the Coordinated Enhanced Observing Period (CEOP) and the International Association of Hydrologic Sciences Project for Ungauged Basins, global data centres, including the Global Precipitation Climatology Centre and the Global Runoff Data Centre, and international agencies, including the International Atomic Energy Agency. Its activities help to coordinate and disseminate hydrological results to the international hydrological community.

GEWEX Modelling and Prediction Panel (GMPP)

GMPP contributes to the global modelling of the processes that control the global energy and water budget and demonstrates the value of predicting the variability of this cycle and its response to climate forcing with a particular emphasis on cloud and land-surface process representation. The goal of GMPP research is to demonstrate the capability to predict water storage and runoff over continental regions, as an element of seasonal-to-interannual climate predictability, and to demonstrate the capability to predict the radiation budget and fluxes as an element of decadal-to-centennial climate variability and response to changes in external forcing factors (Chahine, 1997).

Phase I components

The principal Phase I components of GMPP include the GEWEX Cloud Study System and Global Land-Atmosphere System Study with its primary subprojects: the Project for Intercomparison of Land-Surface Parameterization Schemes and the Global Soil Wetness Project. GMPP studies have reduced uncertainties in the understanding and simulation of key water-cycle variables through the application of Phase I observations and land-surface and cloud-process parameterizations derived through regional studies and model intercomparisons.

The GEWEX Atmospheric Boundary Layer Study was formed in 1999 to study how the interactions of the land surface and the boundary cloud layer are mediated through the atmospheric boundary layer.

GEWEX Cloud Study System (GCSS)

The GCSS has carried out studies that support the development of new physically-based cloud parameterizations using cloud-resolving models of different cloud system types for numerical weather prediction and climate models: marine boundary-layer clouds, Cirrus, extra-tropical layer clouds, tropical deep convection and polar clouds. GCSS investigates these cloud types with a combined analysis of a wide range of models: from turbulent-eddy-resolving models to cloud-resolving and regional-scale models to single-column and general circulation models used for weather forecasting and climate in addition to a wide range of in situ, surface, and satellite remote-sensing observations.

Tools for conducting these studies have been gathered on a linked set of Websites, the main one being the GCSS Data Integration for Model Evaluation (DIME) site at http://gcss-dime.giss.nasa.gov. These activities are leading not only to improved cloud parameterizations but also to the implementation of more focused new field experiments and advances in the use of combined sets of surface and satellite-based active sensors.

GCSS study results have supported improved understanding of the effects of the three-dimensional structure of clouds on radiative fluxes, the interaction of clouds with the marine surface and atmospheric boundary layer, the organization and distribution of precipitation in tropical convective complexes, and the character and evolution of Cirrus and polar clouds.

Global Land-Atmosphere System Study (GLASS)

GLASS seeks to improve our understanding of, and capability to simulate, surface processes from the plot scale to the global scale by multi-institutional experiments of both stand-alone land-surface models (LSMs) and coupled land-atmosphere models on both the local (point, plot, and catchment) and large (continental to global) scales. Through multi-model experiments, GLASS confronts the hypothesis under which the LSMs have been developed and thus advance the community's knowledge of their capabilities. The goal of GLASS is to incorporate improved understanding of the physical processes at the land surface into global models and to identify and understand the important components of land-atmosphere interaction.

Project for Land-Surface Parameterization Schemes and Global Soil Wetness Project

Initially through the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) and now through GLASS, the development of improved land-surface models has been coordinated at the process level. Subsequently, the Global Soil Wetness Project (GSWP) carried out intercomparisons of land-surface models on the global scale. More generally, GLASS initiated within the community the transition for land-surface parameterizations bound to an atmospheric model to land-surface models. PILPS and GLASS have led to the accelerated development of LSMs by model and data intercomparisons for different climate regimes.

The evaluation of simulated soil wetness and precipitation predictions in ensembles of models within GSWP and the Global Land Atmosphere Coupling Experiment (GLACE) has raised the awareness of the community to the intrinsic limitation of LSMs to produce observable quantities. For example, coupled LSMs and global climate models (GCMs) have been assessed in terms of their sensitivity to soil moisture and ocean sea-surface temperatures, which can greatly affect their ability to

Energy and water cycles of climate

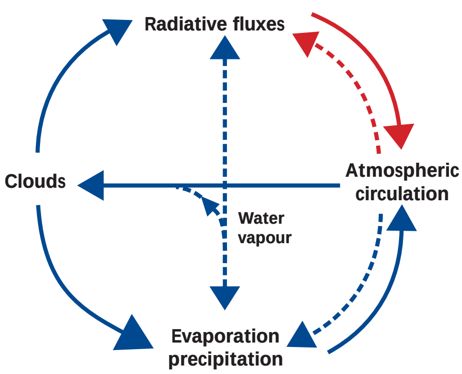

Figure 3 — Dominant atmospheric linkages in the global energy and water budgets

simulate climate predictability. GLASS also developed a critical set of standards for the exchange of forcing data to facilitate modelling studies using land-surface models.

The GMPP facilitates the transfer of knowledge about models and modelling techniques to operations through an annual joint meeting with the WMO Commission for Atmospheric Science/Joint Scientific Committee Working Group on Numerical Experimentation (WGNE).

GEWEX Radiation Panel (GRP)

Efforts of the GRP are directed towards determining the diabatic heating of the atmosphere and surface by radiative, sensible and latent energy exchanges with accuracy sufficient to diagnose the processes influencing variations of the surface and atmosphere from weather to decadal climate scales. GRP projects analyse long-term, global satellite observations that are supported by key, high-quality, long-term, in situ measurements that are used to diagnose the causes of forced and unforced climate variations (Rossow *et al.*, 2005). The GRP studies foster improvements in radiative transfer models used in weather and climate models and in the analysis of satellite- and surface-based remote-sensing observations.

The GRP projects have developed 15-25 year global data products quantifying the variability of radiative fluxes, clouds, water vapour, aerosols, precipitation and turbulent fluxes at the ocean's surface and are working to develop more advanced products. All these data products are available and are being used to study recent climate variations associated with volcanic eruptions and El Niño-Southern Oscillation cycles by quantifying all the

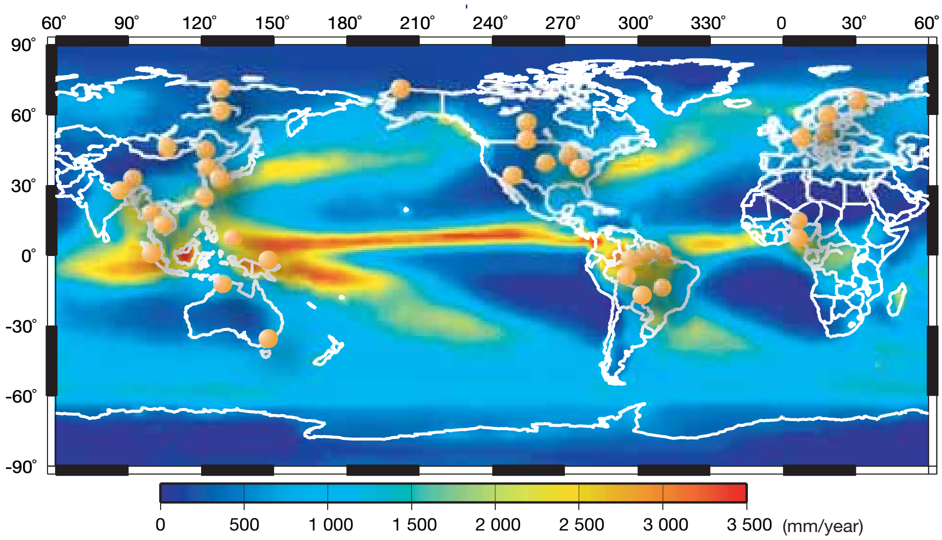

Figure 4 — Annual average precipitation 1988-1997: the Coordinated Enhanced Observing Period (CEOP) aims at developing a global network of pilot joint meteorological-hydrological stations and makes use of the huge amounts of Earth observing satellite data available today. (Source: GEWEX Continental-Scale International Project)

interactions illustrated in Figure 3. A reconstruction by the Surface Radiation Budget project (SRB) of the global radiation budget using GRP and other global data products has achieved a more accurate quantification of the role of clouds in partitioning the planetary radiation budget among the atmosphere, ocean, land, and cryosphere.

The International Satellite Cloud Climatology Project (ISCCP) has pioneered the cross-calibration, analysis and merger of measurements from the international constellation of weather satellites to produce the first global quantitative description of the physical properties of clouds resolving diurnal-to-decadal variations. The Global Precipitation Climatology Project has produced the first globally complete determination of precipitation resolving five-day-to-decadal variations by the analysis and merger of measurements from the international constellation of weather satellites and in situ measurements. The Global Water Vapour Project conducted a pilot study that pioneered the merger of water-vapour measurements from the international constellation of weather satellites and in situ atmospheric soundings to produce a detailed description of the global distribution of atmospheric water-vapour profiles resolving daily-to-decadal variations. The Global Aerosol Climatology Project recently completed a systematic analysis of year-to-year variations of aerosols that is now being merged with an analysis of the associated variations of cloud microphysical properties. In addition, the first comprehensive compilation of in situ ocean surface flux measurements was produced by the SeaFlux project. These efforts have fostered improvements in global satellite-based products, providing turbulent fluxes of heat, water, and momentum resolving daily-to-decadal variations. The global satellite observation analysis projects are supported by reference networks established by GRP and data centres. For example, the development of the Baseline Surface Radiation Network BSRN) has led to reductions in measurement uncertainties of more than a factor of two. The Global Precipitation Climatology Centre (GPCC), a data centre that is linked with GRP precipitation studies, has compiled an extensive collection of surface precipitation gauge data and analyses. Both these initiatives are key elements of the Global Climate Observing System (GCOS).

In preparation for Phase II of GEWEX, the GRP has an ongoing project, known as the Intercomparison of Radiation Codes in Climate Models, to foster significant development of radiative transfer codes in all atmospheric general circulation models and a working group to develop a coordinated approach for the reduction and analysis of combinations of atmospheric profiling instruments (radars, lidars and sodars) from a worldwide network of long-term monitoring sites. In addition, the GRP is working with other GEWEX activities to develop an advanced, comprehensive analysis of the fluxes of energy and water between the land and atmosphere.

Challenges

To achieve its objectives in Phase II (**see box •••**), GEWEX will develop and apply a wide range of modelling tools ranging from global climate models to regional and mesoscale models, and will evaluate downscaling methods suitable for the smaller spatial and temporal scales generally associated with hydrological models used in local water-resource management.

Another primary element of Phase II is the Coordinated Enhanced Observing Period (CEOP). The first phase of this experiment (CEOP I) is described in Koike (2004). CEOP II will focus on the development of a two-year data set of in situ, satellite and model data for the period of 2003-2004 to support

GEWEX Phase II objectives

- Produce consistent research quality data sets complete with error descriptions of the Earth's energy budget and water cycle and their variability and trends on interannual to decadal time scales, and for use in climate system analysis and model development and validation
- Enhance the understanding of how energy and water cycle processes function and quantify their contribution to climate feedbacks
- Determine the geographical and seasonal characteristics of the predictability of key water and energy cycle variables over land areas and through collaborations with the wider WCRP community determine he predictabiity of energy and water cycles on a global basis
- Develop better seasonal predictions of water and energy cycle variability through improved parameterisations encapsulating hydrometeorological processes and feedbacks for atmospheric circulation models
- Undertake joint activities with operational hydrometeorological services and hydrological research programmes to demonstrate the value of new GEWEX prediction capabilities, data sets and tools for assessing the consequences of global change

research objectives in the climate prediction and monsoon system studies. GEWEX also takes the lead on behalf of WCRP in the Integrated Global Water Cycle Observations theme of the Integrated Global Observing Strategy Partnership. In that regard, CEOP has been endorsed as the first element of the new IGWCO theme. GEWEX also will contribute to the Global Water System project within the Earth System Science Partnership (ESSP) framework. In addition, research projects in GEWEX Phase II will be supportive of WCRP's new strategy, commonly known as the Coordinated Observation and Prediction of the Earth System (COPES). Readers wishing to follow the progress of GEWEX or to access the wide range of data and data products available through the GEWEX home page (www.gewex.org).

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