The First 30 years of GEWEX

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Abstract

The Global Energy and Water Cycle EXchanges (GEWEX) project was created more than thirty years ago within the framework of the World Climate Research Programme (WCRP). The aim of this initiative was to address major gaps in our understanding of Earth's energy and water cycles given a lack of information about the basic fluxes and associated reservoirs of these cycles. GEWEX sought to acquire and set standards for climatological data on variables essential for quantifying water and energy fluxes and for closing budgets at the regional and global scales. In so doing, GEWEX activities led to a greatly improved understanding of processes and our ability to predict them. Such understanding was viewed then, as it remains today, essential for advancing weather and climate prediction from global to regional scales. GEWEX has also demonstrated over time the importance of a wider engagement of different communities and the necessity of international collaboration for making progress on understanding and on the monitoring of the changes in the energy and water cycles under ever increasing human pressures.

This paper reflects on the first 30 years of evolution and progress that has occurred within GEWEX. This evolution is presented in terms of three main phases of activity. Progress toward the main goals of GEWEX is highlighted by calling out a few achievements from each phase. A vision of the path forward for the coming decade, including the goals of GEWEX for the future, are also described.

Capsule

Progress on advancing our understanding of and ability to predict Earth's water and energy cycles over the thirty years of the Global Energy and Water Cycle EXchanges (GEWEX) is reviewed.

1.0 Introduction

The presence of water in all three phases is fundamental to the Earth system. Water is essential to the operation of the Earth's heat engine, in the chemical and biological molding of the Earth's surface and, indeed, to life itself. As the key to all climate

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problems is the redistribution and storage of the sun's energy over the Earth's surface and its loss to space; it is through the coupling to energy that water exerts its fundamental influence on the physical climate system and on climate change. The meridional redistribution of heat by the atmospheric transport of water vapor, and by ocean gyres strongly constrains the atmospheric circulation and limits the strength of the winds and shapes the distribution of clouds around Earth. Clouds in turn control the planetary albedo and the amount of solar radiation reaching the surface. The inflow of fresh water at high latitudes seas is a major source of buoyancy, which modulates the deep ocean circulation. The ocean circulation, in turn, determines and modulates the climate of many regions of the world. The scavenging of chemicals by precipitation is a major cleansing process of the environment. For these and many other reasons, a quantitative understanding and clear appreciation of how water cycles through the Earth system are of fundamental importance for understanding environmental change on all scales, from global to local.

A realization emerged from the Global Atmosphere Research Programme (GARP, Bolin, 1969) in the latter part of the 1970s: qualitatively little was known about the global and regional aspects of water and energy budgets and even less was understood about the processes that connect these two major components of the Earth system. The acquisition of climatological data on these basic budgets was viewed then, as it is today, as essential to advance global weather and climate prediction. The existence of this major gap in weather and climate science at that time would not be remedied by the major programs being planned like the World Ocean Circulation Experiment (WOCE, WCRP, 1986) and the Tropical Ocean and Global Atmosphere Project (TOGA, WCRP, 1985) as they mainly addressed slower components of the climate system.

A new joint water and energy initiative germinated at the Memorial Symposium for Prof. Verner Suomi in honor of his retirement (Figure 1). At that conference, partly in response to the presentation of the then-new NASA Earth Observing System (EOS) program by Shelby Tilford promoting satellite measurements for global change research, Verner Suomi, Lennart Bengtsson and Pierre Morel formulated a comprehensive research

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program focused on the ‘fast’ atmospheric and hydrologic processes. This initiative was the Global Energy and Water Cycle Experiment (GEWEX). GEWEX was intended to address gaps in knowledge through the combination of promised new observing systems to augment the existing operational systems and advances to global atmosphere-ocean-land-ice models. This was deemed especially timely, given the potential to exploit technological advances expected to happen with the advent of the emerging NASA’s Earth Observing System (EOS) era (e.g., Dozier, 1994) coupled with the introduction of ever-more powerful computers.

Figure 1 Professors Pierre Morel and Verner Suomi at the University of Wisconsin-Madison, 13 May 1994. Their earlier meeting in 1984 laid the foundation for GEWEX.

GEWEX became a core project of the World Climate Research Programme (WCRP) and its first scientific plan was published in December 1990. As was pointed out by GEWEX first Scientific Steering Group chair Moustafa Chahine: “*By virtue of its breadth, GEWEX is not an ‘experiment’ in the traditional sense; rather, it is an integrated ‘program’ of research, observations, and science activities ultimately leading to prediction of variations in the global and regional hydrological regimes.*” The plan from the outset was to implement this program as a series of phases that reflect evolution and progress on this broad topic.

Today, GEWEX is now over thirty years old and has survived because it continues to address the most basic aspects of Earth system science with a focus on those processes that uniquely establish Earth’s climate. GEWEX also continues to advance the use of

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long-established scientific methods rooted in confronting theory and models with observations. Although the vision of GEWEX has evolved in ways that reflecting advances made, the aspiration of GEWEX has remained broadly similar since its inception:

> *To measure and predict global and regional energy and water variations, trends, and extremes (such as heat waves, floods and droughts), through improved observations and modeling of land, atmosphere and their interactions; thereby providing the scientific underpinnings of climate services.*

Using largely the same methodologies, GEWEX continues to actively engage field-based experimental research, with operational forecasting; involve global modeling centers towards advancing model development expressed through process models, hydrological models, large eddy resolving to the convection permitting climate models of today (refer to sidebars 1 and 2); and exploit observations from Earth orbiting satellites both for basic understanding and for assessing and advancing models and prediction systems.

The purpose of this paper is to reflect on the 30 years of evolution and progress that has occurred within GEWEX. This is presented as three main phases of activity that define GEWEX and its evolution over time. While many projects and achievements of GEWEX have been recorded over its lifetime, this review provides only a narrow selection of examples that are chosen more to motivate discussion of issues broader than the illustration itself hinting at the future directions of GEWEX described in section 5.

2.0 Phase I – The formative period (1990–2002)

The earliest phase of GEWEX intended to "*maximize the use of the operational and research satellite data of the period to address its stated goal*." It laid the groundwork for subsequent phases preparing for the exploitation of the new global observations expected to emerge later in the period. A principal part of the strategy for Phase I was to observe the key energy and water cycle elements globally; to move toward better understanding and improved parameterizations of land surface coupling and cloud processes within mesoscale models through regional process studies; to upscale to global models for

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prediction; and to downscale for local water resource applications. Phase I also inherited a number of important ongoing activities managed by the WCRP Joint Scientific Committee (JSC) Working Group on Radiative Fluxes (WGRF). This working group provided oversight for a number of developing satellite-based global data projects including the surface radiation budget project with the supporting surface radiation networks (the Baseline Surface Radiation Network, BSRN), the International Satellite Cloud Climatology Project (ISCCP) that started in 1984 (e.g., Rossow and Schiffer, 1991), global precipitation climatology activities that became the Global Precipitation Climatology Project (GPCP, Huffman et al., 1997), a general oversight of Earth Radiation budget observations, and the lead in the Global water Vapor Project (GVaP, Randel et al., 1996), among other efforts.

A programmatic structure was adopted part way through the phase defining activities in three separate areas, namely radiation, hydrometeorology, modeling and prediction. These activities were organized under panels. GEWEX Modeling and Prediction Panel (GMPP) consisted of the GEWEX Cloud System Study (GCSS) and the GEWEX Land Atmosphere System Studies (GLASS), the latter being built on the success of the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS). These two project activities later morphed into GEWEX panels. The WGRF of the JSC transitioned into the GEWEX Radiation Panel (GRP) midway through the decade. In some respects, this was a misnomer, as the GRP oversaw much more than just projects on radiation. The GEWEX Hydrometeorology Panel (GHP) was home to the Continental Scale Experiments (CSEs) as well as the International Satellite Land Surface Climatology Project (ISLSCP) and the Global Runoff Data Centre (GRDC).

Activities during Phase I were guided by four main objectives under the following themes:

2.1 Global fluxes of water and energy

Objective: Determine the Earth's hydrological cycle and energy fluxes using global measurements (GRP)

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Most of the activities under this theme involved the stewardship of the global climate data records inherited from the WGRF. ISCCP pioneered the construction of global data using the global constellation of geostationary satellites. It was realized that these data could be more effectively used as a tool to assess global weather and climate models and to study the role of clouds in climate by first simulating the observations directly within the models and then mimicking the ISCCP analysis. This provided a more direct and rigorous means of comparison. The ISCCP simulator developed for this purpose is widely used by most major climate modeling centers since its creation over 20 years ago [e.g., Klein and Jakob (1999) and others]. It laid the foundation for a much wider development of satellite simulators that have become important diagnostic tools in assessing present-day climate models (e.g., Bodas-Salcedo et al., 2011).

The International Satellite Land Surface Climatology Project (ISLSCP) was also initiated during this same period. With the coordination of GEWEX, ISLSCP initially produced a global 1° x 1° land surface dataset for period of 1987-1988 (Sellers et al., 1996). This included boundary conditions, initialized state variables, and near-surface meteorological and radiative forcings needed to drive land-atmosphere models and assess climate models.

2.2 Modeling the global hydrological cycle

Objective: Model the global hydrological cycle and assess its impact on the atmosphere, oceans and land surfaces (GMPP)

Three important elements relating to water and energy exchanges were the focus of this theme: (i) clouds, (ii) the atmospheric boundary layer (ABL) and (iii) land surface processes. It was realized from the outset that advances to land surface models (LSMs) were needed (Sidebar 1) and this would require that LSMs be compared to and assessed against observational data. GEWEX has been instrumental in evolving these land models (Figure SB1) and GLASS continues to promote such improvement using both point observations, from individual station data like that presented in Figure 2, to data collected from the continental scale experiments (CSEs) described below as well as global assessments of LSMs (e.g. Polcher et al. 2000). It was also recognized that model evaluation needed to be done within a common framework such as adopted by PILPS

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(Henderson-Sellers et al., 1993). PILPS was co-sponsored by the World Meteorological Organization's Working Group on Numerical Experimentation (WGNE) and GEWEX. Figure 2 exemplifies the PILPS approach highlighting how analysis of point-like data from the Cabauw site could identify shortcomings in LSM representations of latent heat flux (i.e., evapotranspiration) from the surface compared to the observations (Chen et al., 1997). This was one of the most highly-cited papers in land surface modeling at that time, exposing the weaknesses inherent in the Manabe "bucket" (Manabe, 1969) scheme that was then widely-used (Figure SB1). Increasingly well-constrained experiments then followed, although focused mainly on mid- and high-latitude regions.

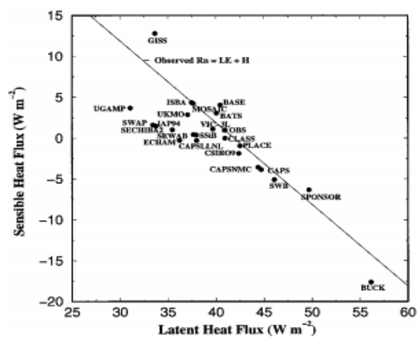

Figure 2 (from Chen et al., 1997) Comparison of LSMs and observations is a philosophy of GLASS that has been sustained from the outset. In this example, annually averaged surface sensible (H) versus latent heat (LE) fluxes (Wm^{-2}) are shown. The observed annual net radiation (Rn) is 41 Wm^{-2} and the line shown is this net radiation value expressed as the sum of the two coordinates with any single point falling on the line being simply the surface energy balance relation Rn=LE+H. Although some models simulate the annual net radiation close to that observed, the components of the balance differ markedly from observations with many models failing to conserve energy.

The Global Soil Wetness Project (GSWP, phase 1), a modeling activity of ISLSCP, also formed at the same time, but with a more global, rather than local, focus on LSM assessment (Dirmeyer et al., 1999). A pilot phase of GSWP created a two-year global dataset of soil moisture, temperature, runoff and surface fluxes by integrating uncoupled land surface schemes using externally specified surface forcings from observations and standardized soil and vegetation distributions (Dirmeyer et al., 1999).

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A far-reaching modeling initiative of Phase I that laid the foundation for developments to come, including those anticipated of the current decade (Sidebar 2), was an initiative that developed around the concerted use of higher-resolution models to advance the parameterization of clouds in global models. This was the underlying motivation of GCSS (GEWEX Cloud System study team, 1993). GCSS aimed to develop better parameterizations of cloud systems for weather and climate models by seeking an improved understanding of cloud physical processes, including convection, leading to a better representation of these models. GCSS was an embodiment of the broader GEWEX methodology. It brought together the observational community and the disparate cloud modeling communities. It seeded the evolution of the convection-permitting regional and global models of today (sidebar 2) and applied their early versions to the development of parameterizations for global prediction systems. In so doing, GCSS transformed parameterizations with a philosophy that continues today in numerical weather prediction (NWP) and climate modeling centers. Although successful, there was a general over-reliance on models in shaping these parameterization developments and not enough emphasis on critical evaluation of them. Consequently, biases inherent to these process models, such as the bias of vertical motion in deep convection (e.g., Varble et al., 2014) or with respect to the microphysics properties of clouds and precipitation (Kay et al., 2018), persist today with important consequences to current climate change projections (e.g., Mülmenstadt et al., 2021). While some progress has occurred in using observations especially through the application of simulators noted above, much more needs to be done to exploit the ever-improving observational capabilities. Recognition of this need led to the formation of the GEWEX Aerosol Precipitation project (GAP, Stier et al., 2022) and the Process Evaluation Study (PROES, Stephens et al., 2015) both created in the latter phases of GEWEX to promote the development of observational-based diagnostic tools for studying important climate processes.

2.3 Regional hydrology and water resources

Objective: Develop the ability to predict variations in global and regional hydrological processes and water resources as well as their responses to environmental change (GHP)

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Although GEWEX provided the stewardship of a number of global data records, it was decided that addressing some of the important goals of GEWEX, including climate impacts on water resources, required a focus that is a scale-up from the traditional catchment-by-catchment studies traditionally adopted by the hydrology science community to regional and continental scales. The concept of continental-scale hydrological experiments was developed (see Lawford et al., 2004 for review) and addressing its hydrological objectives on these scales made it possible to deduce the main water and energy fluxes by combining meteorological, remote sensing and hydrological data using various methods to close the water and energy cycle as they have compatible footprints. What emerged was the formation of the CSEs, the first being the Continental-Scale International Project (GCIP, Coughlan and Avissar, 1996, Lawford 1999) centered around the Mississippi River basin. This basin was chosen because it was considered to be one of the better-instrumented basins in terms of in situ atmospheric and land-based observations. It would also be an ideal place to evaluate and exploit the new remotely-sensed observations coming on-line during that time. Other regional hydrometeorological projects were also developed in parallel, providing ways to explore other regional climate-related features of the water cycle not represented in the Mississippi River basin, such as permafrost and other cold processes (the Mackenzie GEWEX Study, MAGS; the Baltic Sea Experiment, BALTEX), seasonal high intensity rainfall during monsoons (the GEWEX Asian Monsoon Experiment, GAME), and high year-round evapotranspiration fluxes in tropical forests (the Large-Scale Biosphere-Atmosphere Experiment in Amazonia, LBA).

The initial five CSEs that emerged during Phase I are called out in Figure 3a as well as other CSEs that were considered later. Each CSE included explicit connections to hydrological and weather prediction centers and much was achieved during this phase laying the foundations for more to come in subsequent phases. These activities influenced and even accelerated the development of the land components of regional models at that time, including, for example, the Eta model in NOAA (e.g. Black, 1994) used in the NOAA forecast system, in subsequent developments of the Land Data Assimilation System (LDAS, Mitchell et al., 1999), and in regional reanalysis carried out in the early 2000s. NCEP's link to both GCIP and PILPS accelerated the development of the Eta

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model and the sophistication of the representation of land-atmosphere interactions (Ek et al., 2003).

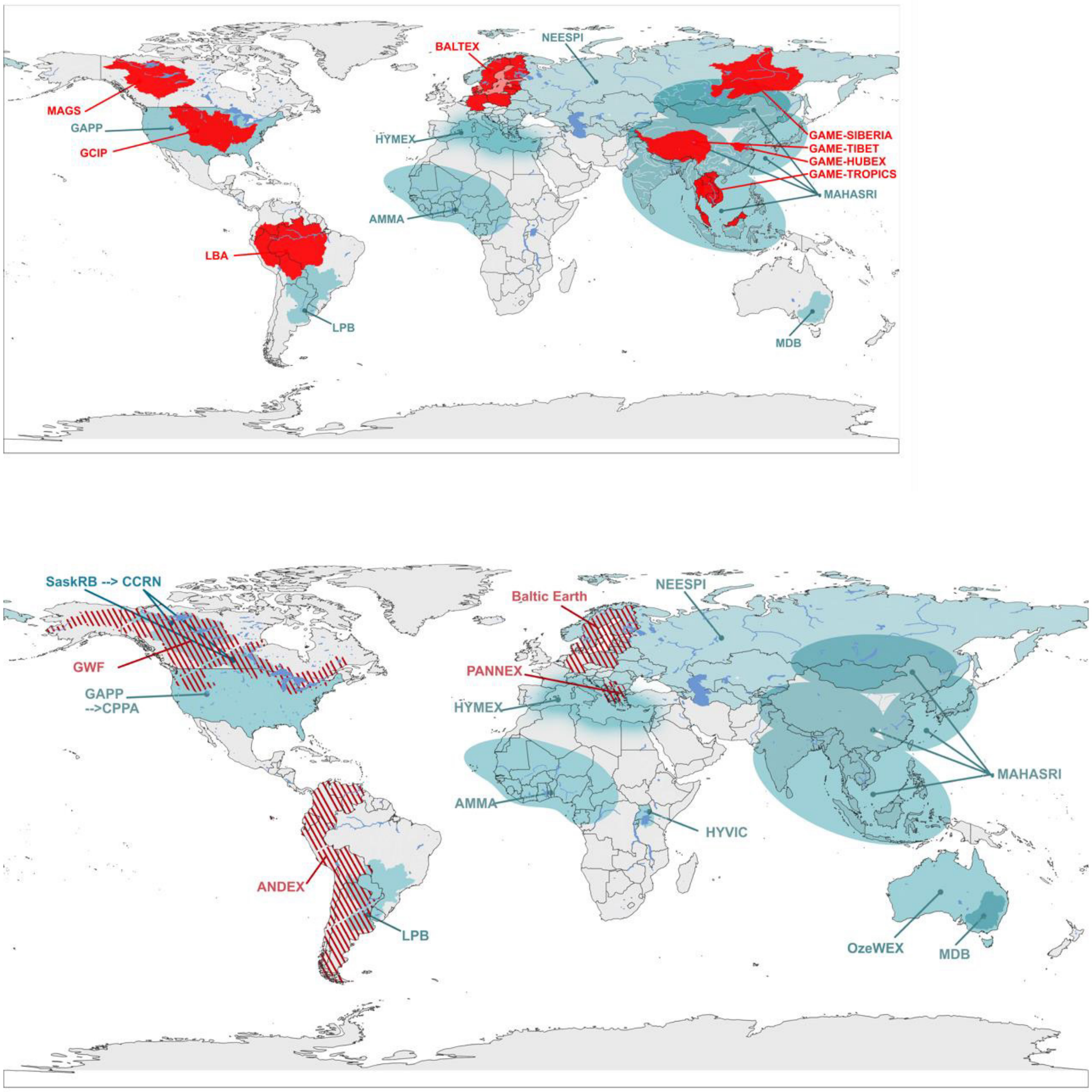

Figure 3 (a) (upper panel) The five original CSE's of GEWEX in red and others that were developed later in phase II in green, and (b) (lower panel) A summary of the RHPs created over the course of GEWEX including the initial 5 CSEs.

2.4 Observing systems

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Objective: Foster the development of observing techniques, data management and assimilation systems for operational application to long-range weather forecasts, hydrology and climate predictions

During Phase I, and before the appearance of the decadal surveys conducted within the USA more than a decade later, the GEWEX community was an important voice in defining gaps in Earth observations, deemed a priority for the science of that community (e.g., Morel and Readings, 1989). These priorities, at that time, aligned in three areas: i) precipitation, ii) clouds and radiation and iii) winds. While some of these priorities have been addressed in part over time with measurements of winds from ESA's Aeolus, cloud vertical structure from CloudSat, measurement of the radiation budget from Clouds and the Earth's Radiant Energy System (CERES), and precipitation provided by Tropical Rainfall Measuring Mission (TRMM) and now the Global Precipitation Mission (GPM), major gaps in our global Earth observing system remain today (e.g., NAS, 2018). Strategies for sustained monitoring of the essential variables of the Earth system also remains a work in progress. Morel and Readings also identified soil moisture as an important but missing global measurement. This gap was subsequently addressed by both the soil moisture and ocean salinity (SMOS) mission of ESA and the soil moisture active passive (SMAP) mission of NASA launched in 2009 and 2015 respectively. GEWEX played important roles in these missions forming the International Soil Moisture Working Group in 2005 and later the development of the International Soil Moisture Network (Dorigo et al., 2011) funded by ESA to serve as a calibration source for these missions.

3.0 Phase II – A period of consolidation (2002–2013)

Phase II was intended to utilize GEWEX *"prediction capabilities, datasets and tools for assessing the consequences of global change"*, particularly as they relate to water resources and the related applications communities. While the original objectives of Phase I remained, the transition from Phase I to Phase II was characterized by a greater emphasis on water resources and on the impact of a changing climate on the water cycle. This phase focused on the full exploitation of the tools developed for Phase I and the understanding that also resulted and benefited from expanding data records, along with

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increased reliance on upgraded models and assimilation systems and new environmental satellite systems that promised even greater contributions to climate science and large-scale hydrology. Notable were the long-awaited EOS satellites of NASA (e.g., Terra, Aqua) that were about to provide important data for the GEWEX community especially with the promise of more definitive precipitation measurements from TRMM, as well as the European Space Agency Environmental Satellite, ENVISAT, launched in 2002 (a precursor to the Sentinels of today), and the Advanced Earth Observation Satellite II (ADEOS II) of the Japan Aerospace Exploration Agency launched in 2002 after ADEOS I failed 10 months after launch in 1996.

Phase II set forth four principal scientific questions related to variability of the water and energy cycles and subsequent change to these cycles. This was a natural progression from Phase I, given that the growing length of data records and the emergence of climate-quality reanalysis that offered the potential to document Earth system change and improve methods to understand it. These questions were:

- Are Earth's energy budget and water cycle changing?
- How do processes contribute to feedbacks and causes of natural variability?
- Can we predict these changes on seasonal to interannual time scales?
- What are the impacts of these changes on water resources?

Assessments were a common theme of phase II. These ranged from the evaluation and analysis of the lengthening observational data records with emphasis on uncertainty quantification, assessment of the degree to which water and energy budgets could be "closed" notably on a continental scale, and assessments of models of varying complexity.

3.1 Evaluation of Earth's energy budget and water cycle datasets

This objective sought to produce consistent research-quality datasets complete with error descriptions of the Earth's energy budget and water cycle necessary for understanding the context of variability and trends on interannual to decadal time scales, for use in climate system analysis and for model development and validation. Consequently, the growing

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emphasis on assessment of data records during this period brought a sharper focus on understanding and quantifying uncertainties attached to the different GEWEX products. Notable were the cloud assessment of Stubenrauch et al. (2013) which continues today in a second phase and the assessment and validation of a 20-plus year record of surface radiation balance (SRB, Zhang et al., 2009). The latter depended heavily on the continued oversight, stewardship and procedures of the BSRN (Ohmura et al., 1998) that has been a flagship data effort of GEWEX (Driemel et al., 2018). The SeaFlux project was also initiated within the GRP with the aim to produce a high-resolution satellite-based dataset of surface turbulent fluxes over the global oceans to complement existing global surface radiation fluxes and precipitation products (Curry et al., 2004). SeaFlux and the SRB assessment were part of a larger concerted effort that revolved around both addressing gaps and quantifying the errors of individual energy and water cycle components that, from the energy balance perspective, were summarized for the first time in Stephens et al. (2012). The importance of the planetary Earth Energy Imbalance (EEI) and challenges associated in quantifying it also began to come into focus (e.g., Trenberth and Fasullo, 2010; and later von Schuckmann et al., 2016). The error characterization of Earth's energy budget that was being constructed during Phase II became an essential ingredient of the more integrative and objective water and energy balance assessments that emerged later in Phase III and highlighted in Sidebar 3.

During Phase II, the first data initiatives of ISLSCP were expanded upon extending the global data archives of the first initiative to 10 years (1986–1995) and included data on vegetation, carbon cycle components, hydrological fluxes and stores, soils and topography, radiation and clouds, near-surface meteorology, snow and sea ice and socioeconomics relating to the water cycle (Hall et al., 2006). The communities that drove the definition of this initiative II data collection were investigators within GEWEX, the International Geosphere/Biosphere Program (IGBP), http://www.igbp.kva.se); and the U.S. Global Change Research Program, (USGCRP) (http://www.usgcrp.gov/).

3.2 *Continental scale water and energy balance closures*

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Roads et al. (2002) presented a preliminary water and energy budget synthesis (WEBS) study of the GCIP Mississippi basin that was initiated during Phase I. This synthesis was for the period 1996–1999 and used the ‘‘best available’’ observations and models of that time. The observations available, however, could not adequately characterize or ‘‘close’’ budgets since the contributions of too many fundamental processes were missing from the observations. Roads et al. (2002) argued for a synthesis of models and observations with models fillings gaps in representing the many complicated atmospheric and near-surface interactions not reflected in the observations. This was the forerunner to more advanced analysis systems that would begin to develop years later (see also Figure 4). A qualitative understanding of the water and energy budgets was then gleaned from this early model and observation synthesis.

The GHP framed its activities around obtaining unique and concentrated observations from the Continental Scale Experiments noted in Figure 3a. Phase II saw more efforts to integrate across the CSEs. There was an emphasis on collaborative research that links the CSE of this phase (Lawford et al., 2004). A selected time period for simultaneous investigations of water and energy cycles was chosen to develop this cross CSE collaboration. This initiative was the Coordinated Enhanced Observing Period (CEOP). The purpose was to provide data from a multitude of sources in a common format to address two main science themes: the simulation and prediction of the water and energy cycles, with a focus on monsoon systems. Monsoons also became an important cross cutting topic pursued jointly by GEWEX and Climate and Ocean: Variability, Predictability and Change (CLIVAR) during this time (refer also the discussion of section 3.4).

3.3 Water resource impacts and the emergence of CORDEX

GEWEX sought to develop more explicit links to water resource applications including stronger links to hydrological forecasting activities. The Water Resources Applications Project (WRAP) established in 2000, for example, connected the GEWEX research community with the water resources community by developing relations between each of

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the CSEs and a number of international hydrology associations and organizations. The Hydrological Ensemble Prediction Experiment (HEPEX) was also created being motivated by a desire to explore ways hydrological forecast activities might take advantage of the progress gained in understanding the atmospheric branch of the water cycle (e.g. Hall et al. 2007). This effort brought the international hydrological and meteorological communities together with a goal to demonstrate how to produce and utilize reliable hydrological ensemble forecasts.

The scope of the CSEs also expanded beyond just the observation of the physical processes associated with the water and energy cycle to connect both to other disciplines and stakeholder interests. Three CSEs that exemplified this expanded reach were the Baltic Sea Experiment (BALTEX), the African Monsoon Multidisciplinary Analyses (AMMA) and CLARIS-LPB. Each in its way had a trans-disciplinary approach to the water cycle. In BALTEX, the understanding of the water cycle and its interaction with the biogeochemical cycles provided a way to perform in-depth assessments of how climate change would modify the ecological and marine system (Reckermann et al., 2012). Over West Africa, AMMA observations of the atmospheric and hydrological processes offered operational services with concrete guidance on how to improve weather and climate forecasting as well as how to improve early warning systems for drought, famines and public health (Polcher et al., 2011). CLARIS-LPB provided a better understanding of the interactions between the water cycle of the La Plata basin, ecology, the food production and the challenges posed by climate change (Boulanger et al., 2016). Along with other RHPs, these three experiments illustrate the greater level of outreach and exposure to local science communities than had been previously achieved, the CSEs also supported the development of regional meteorology and hydrology (Lawford et al., 2004,2007).

Another important outcome of the more trans-disciplinary evolution of the CSEs was the emergence of the Coordinated Regional Downscaling Experiment (CORDEX), which sought to address the need for downscaled climate change predictions and impacts at the scales more immediately relevant to society. AMMA was an especially important source

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of motivation to CORDEX, with the international community being asked to downscale various scenarios so that they could be evaluated with the new knowledge brought by the CSE and disseminated to the scientific community of the region (e.g., Paeth et al. 2011; Nikulin et al., 2012).

3.4 Toward the prediction challenge: Model representation of hydrometeorological processes and feedbacks involving water and energy

A number of activities aimed at various aspects of prediction were initiated during Phase II. Model assessment initiatives were introduced under the GMPP as a step toward developing a process understanding of critical hydrological feedbacks. The GEWEX Atmospheric Boundary Layer Study (GABLS) activity, introduced in 2002, aimed at improving understanding and representation of the atmospheric boundary layer in weather-forecast and climate models on regional to global scales. The Continual Intercomparison of Radiation Codes (CIRC, Oreopoulos and Mlawer, 2010) was another initiative aimed at providing regularly updated reference sources for evaluation of radiative transfer (RT) codes used in global climate models and other atmospheric applications. CIRC called out issues with respect to the treatment of shortwave radiative transfer in schemes used in global models (Pincus et al., 2015). This was a topic that emerged later in the context of the hydrological sensitivity of climate models and the constraint radiation provides on this sensitivity, underscoring again the central importance of coupling energy and water in shaping changes to the hydrological cycle (e.g., DeAngelis et al., 2015).

The North American Monsoon Experiment (NAME) was also created during Phase II. This was a joint CLIVAR and GEWEX process study experiment aimed at determining the sources and limits of predictability of warm season precipitation over North American (Higgins and Gochis, 2007). The NAME strategy revolved around improving understanding of the key physical processes that must be parameterized for more realistic simulations and accurate predictions with coupled ocean–atmosphere–land models. The NAME field experiment highlighted the importance processes associated with lower-atmospheric circulations and their modulations via interactions with the land surface, the

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diurnal cycle, the influence of synoptic conditions and the important role of atmospheric boundary layer all affecting the onset of the North American Monsoon.

The second phase of the Global Soil Wetness Project (GSWP-2) produced the first global gridded multi-model land surface analysis (Dirmeyer et al., 2006) developed from multi-model simulations forced by common "hybrid" observational and reanalysis forcing datasets. This forcing included observed precipitation, radiation and near-surface meteorology interpolated using model fields on finer space-time resolutions not available in the observations but required to force the models. The analysis was presented on a regular 1° x 1° grid and reported for the same 10-year core period of ISLSCP (1986–1995). Figure 4 is a highlight of this analysis showing a multi-model analysis of the hydrological cycle over global land presenting global land means of the water fluxes and soil water stores (box values), as well as the range of interannual variability of these global values for the 10-year period. The horizontal black bars and values represent the ranges of these global mean annual hydrological cycle components and are an indicator of model uncertainty. The fact that there existed such wide variability among LSMs driven by the same forcing data suggests there is still much room for improvement in the modeling of this part of the Earth system.

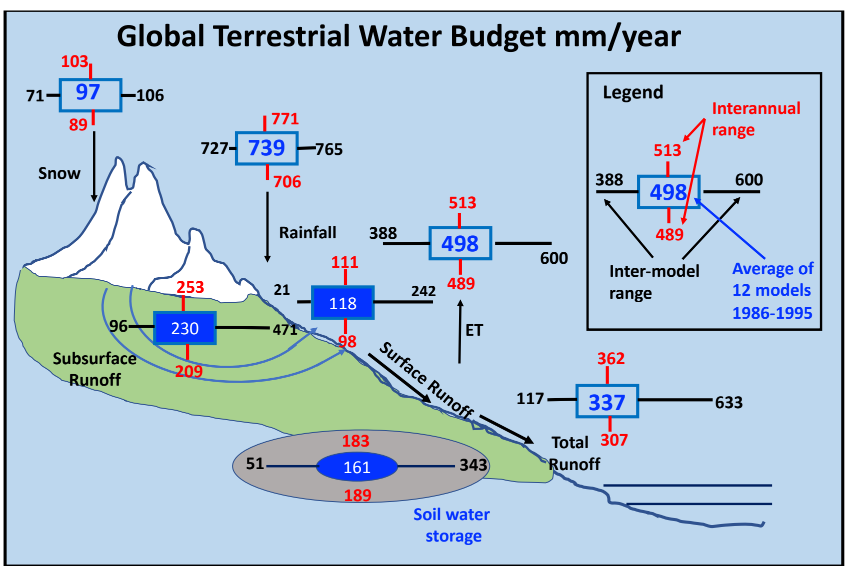

Figure 4 Multi-model mean terrestrial water budget from GSWP-2 data analysis. Both the inter-model spread (values in black) and the inter-annual variability (1986-1995; values in red) are shown for each

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term. Model spread in precipitation terms reflect the distribution of total precipitation over snowfall and liquid precipitation. Variability of the estimates of evapotranspiration (ET), soil moisture storage and runoff from the model ensemble is much larger than the interannual range, reflecting the limitations of understanding of the hydrological partitioning processes (modified from Dirmeyer et al, 2006).

4.0 Phase III – The quantitative understanding of water and energy coupling (2013–2022)

Building both upon the results and experience from Phases I and II, GEWEX reorganized its panels splitting GMPP into two panels, the Global Land/Atmosphere System Study (GLASS) Panel and the GEWEX Atmospheric Systems Study Panel (GASS) and renamed GRP as the GEWEX Data Assessments Panel (GDAP) to reflect more appropriately the activities of that panel. GEWEX formulated its activities during this phase around four main themes, each defined by specific science questions and a number of cross-panel activities began to emerge making connections across panels.

4.1 Observations and predictions of precipitation: How can we better understand and predict precipitation variability and change?

4.1.1 *Observations*

Advances that occurred were a result of the ever improving and expanding global precipitation data records accrued from observations and overseen by GDAP and GHP (Kummerow et al. 2019). Observational developments initiated during this period included the INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes (INTENSE, Blenkinsop et al., 2018). The INTENSE project created (i) a new data record for study of short-duration rainfall extremes (discussed below), (ii) assessments of current global precipitation products for addressing different science questions including those related to precipitation extremes (e.g., Masunaga et al., 2019; Roca, 2019) and (iii) identification of gaps in precipitation observations, such as in regions of high terrain with steps toward addressing these shortcomings. This latter effort was part of a broader cross-cut project initiated by GHP, namely the International

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Network for Alpine Research Catchment Hydrology (INARCH, Pomeroy et al., 2015). Its goal is to understand alpine cold region hydrological processes, improve prediction of these processes and diagnose their sensitivities to global change. The project has accumulated and evaluated crucial data, including precipitation, from 29 experimental research basins in 14 countries covering most continents and mountain regions of the world (e.g., Pomeroy and Marks, 2015). The initial phase of INARCH (2015–2020) saw significant advances in understanding and predictive modeling of the high mountain water cycle (e.g., López-Moreno et al., 2020).

4.1.2 *Modeling and prediction*

The GEWEX strategy to advance precipitation prediction, beyond the obvious and central role observations play, involved coordinating efforts to improve the representation of precipitation-related critical processes in models. GEWEX launched projects to understand and model the local and remote effects of land surface processes and state variables (soil moisture, soil temperature, vegetation water and energy fluxes and snow water equivalent, among other factors, Sidebar 1) on precipitation as well as activities aimed at understanding and simulating the diurnal cycle of precipitation. An important and perhaps defining activity, not only for Phase III, but also one that is expected to shape the science of WCRP in the coming decade, is the desire to simulate the coupled atmosphere, ocean, ice and land Earth system at a resolution of an order of 1 km (hereafter *km-scale* Earth system models and information systems, e.g., Bauer et al., 2021; also Sidebar 2).

While it can be argued that modeling at the km-scale is essential for representing many critical hydrological processes, it should not be misconstrued as also being entirely sufficient for such progress. Modelling on the km-scale introduces a different set of challenges that GEWEX is now beginning to confront. LSMs suitable for km-scale simulations, for example, will have to abandon the hypothesis that evaporation is fed only by local precipitation and include explicit hill slope processes to redistribute water horizontally over continents (e.g., Swenson et al., 2019; Fan et al., 2019; also Sidebar 1). Higher resolution modeling also exposes the need to address important dependencies of

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processes, such as convective initiation and intensity, that are increasingly sensitive to local mechanisms typically obscured in a more coarse, global view. Convective precipitation and storm severity, for example, are sensitive to local factors like topography, the heterogeneity of land surface characteristics including snow cover, vegetation type and soil moisture, as well as human influences resulting from land and water management (e.g., urbanization, irrigation for crop cultivation or forest degradation to create agricultural land) among other factors. Figure 5, from Fujita (1987), suggests such a connection between convective storm intensity, expressed as tornado occurrence between 1930–1985, with areas of agriculture world-wide. Although anecdotal, the tight location of tornadic storms in areas of agriculture hints at connections between storm intensity and soil moisture, a topic of considerable past and ongoing research within GEWEX (e.g. GLACE, Koser etal., 2006) as well as ongoing research today (e.g., Wallace and Minder, 2021).

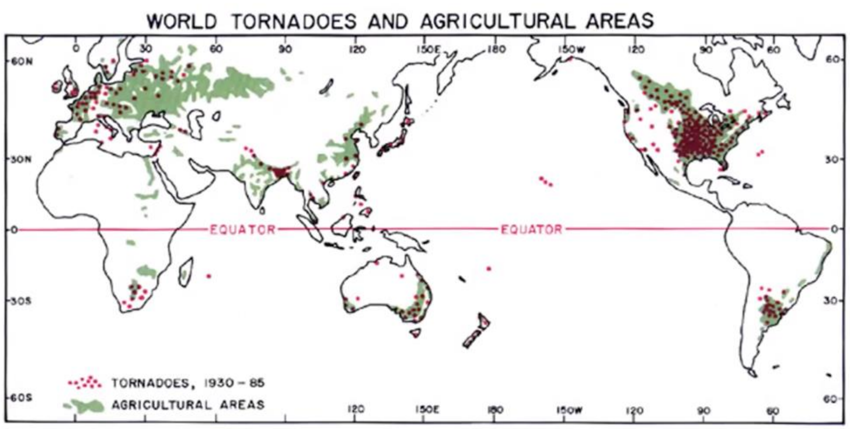

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Figure 5 A hint at the coupling between soil moisture and convection storm intensity underscoring the importance of soil moisture feedbacks on convection. Shown are the occurrences of tornadoes overlying areas of agriculture suggesting a connection between the enhanced soil moisture of these regions and severity of convective storms (from Fujita, 1987).

4.2 Global water resource systems: How do changes in land surface and hydrology influence past and future changes in water availability and security?

The continental scale projects, aimed at addressing questions about water resource systems, evolved further during Phase III. The Regional Hydroclimate Projects (RHPs)

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(Figure 3b) continued to evolve from activities more concerned with geophysical processes to efforts that include effects of human processes on water resource systems, thus preparing GEWEX to be much more societally-relevant in grappling with the challenges of changing water resources in the coming decade. The RHPs became increasingly more trans-disciplinary, addressing explicitly the interactions between climate change and the human management of land and water resources. The Changing Cold Regions Network (CCRN, DeBeer et al., 2021), grew out of earlier activities like MAGS, examined how the rapid warming experienced over the Canadian Rockies and plains interacts with the hydrological processes and the water management of the region. The Hydrological cycle in the Mediterranean Experiment (HyMeX, Drobinski et al., 2014) studied how intense rainfall events, projected to intensify in a warmer climate, influence the hydrology of the region.

Land surface models also morphed into land models (LMs) that capture not only surface, but also sub-surface process interactions (Sidebar 1). During Phase III of GEWEX, observations also advanced with new insights emerging on continental water storage gleaned from a multi-decadal record that emerged from the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2019) (Sidebar 4). Land models that represented only the components of the natural land water and energy cycles evolved to include human water management and usage. One area worth noting is that during the latter two phases of GEWEX, significant advances were made in accounting for land and water use changes and in representing these effects in models. The task of simulating water use, however, is complex. Steps toward accounting for this influence in land surface models are advancing, albeit in simple ways (see, e.g., Nazemi and Wheater, 2015a, 2015b; Blyth et al., 2021, for an overview). For example, the largest consumptive water use is irrigation, which is being progressively added to models (e.g., Blyth et al., 2021). In the coming years, LMs will need evolve such that irrigation also satisfies the water continuity equation. Abstraction points for each demand will also have to be predicted (Zhou et al., 2021). GLASS and GHP continue to lead the community in this direction.

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4.3 Changes in extremes: How does a warming world affect climate extremes, especially droughts, floods and heat waves, and how do land area processes, in particular, contribute?

INTENSE was the first major international effort to focus on global sub-daily rainfall extremes, enabling progress in quantifying observed historical changes and providing some physical understanding of processes necessary for improved regional prediction of change. It delivered a rain-gauge-based data record to study short duration precipitation and its changes. The data have been used in a number of studies, and Fowler et al. (2021) summarize the main findings so far as well as provide suggestions for future directions of research. Evidence from analysis of INTENSE data suggests, for example, that the intensity of long-duration (on the order of a day and longer) heavy precipitation increases at a rate close to the Clausius-Clapeyron (CC) rate (6-7% K^{-1}) for the warming observed during the period defined by the data record whereas the rate of change of sub-daily precipitation often exceed this implied CC rate of change (e.g. Guerreiro et al., 2018). Many uncertainties in understanding the scaling of precipitation either of localized heavy short-duration (hourly and sub-hourly) or only even larger spatial and longer temporal scales remain and mechanistic understanding is still rudimentary. The influences of large-scale circulation versus the more local convective storm-scale dynamics on changes to precipitation extremes, in particular, are also yet-to-be understood (e.g., Stephens et al., 2018).

While the early studies of extremes concentrated on analysis of data records of individual variables, like precipitation, the coordinated joint GEWEX/CLIVAR study of extremes pointed to how extreme events are often linked and effects compound. Floods, wildfires, heatwaves and droughts, for instance, often result from a combination of interacting physical processes across multiple spatial and temporal scales. A more systems-based approach to understanding extremes as compound events is needed, and from a better understanding of compound events, improving projections of potential high-impact events is likely to result with better quantification of risks associated with them (e.g., Zscheischler et al., 2018).

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4.4 Water and energy cycles and processes: How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?

It is well understood that water and energy are intimately coupled, and in most respects this understanding has been the foundational principle of GEWEX. It was also recognized from the outset that quantitative assessment of the uncertainties attached to individual fluxes of water and energy, an emphasis of Phase II, was seminal to any representation of respective budgets and the degree to which closure could be claimed. Many of the GEWEX activities in the earlier phases culminated in Phase III with a joint synthesis of the water and energy budgets, performed either on the regional scale of the HyMeX RHP (e.g., Pellet et al., 2019) or globally as supported under the NASA Energy and Water Cycle Study (NEWS) program and ESA's Water Cycle Multi-mission Observation Strategy (WACMOS) projects (Sidebar 3).

Although major progress on closing Earth's energy budget (sidebar 3) has occurred, at least in the global mean, our ability to define this closure at Earth's surface or establish a closure more regionally remains rudimentary. The adjustments developed so far and used to produce constrained budgets of the form illustrated in Figure SB3 are constructed primarily using Earth's energy imbalance as a global constraint. While we have not yet established ways to define constraints more regionally, progress is occurring. Regional constraints on energy budgets over ocean basins, for example, were introduced in the study of Thomas et al. (2020) in the form of the additional horizontal transports in oceans derived from re-analyses. Furthermore, our lengthening data records on the TOA balance are also now adding new insights about how these budgets change overtime. With the development of advanced tools to diagnose these changes and link them to correlative properties of the Earth system, we are able to identify those processes that shape these changes (e.g. Loeb et al., 2021; Kramer et. al., 2021; Stephens et al., 2022) hinting at important feedbacks within the Earth system.

4.5 Remaining challenges emerging from the Phase III era

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4.5.1 *Hydrology of high terrain*

The Intergovernmental Panel on Climate Change Working Group II (IPCC WG II) Report (2014) notes that the changing nature of precipitation, and changes to the degree of snow and ice melt, are altering hydrological systems and affecting water resources both in terms of quantity and quality. Understanding the sensitivity of hydrological processes to the warming being experienced in high elevation snowy and glacierized headwater catchments is of paramount importance for improving our ability to understand and predict the climate, ecology and water system changes not only within those regions, but also for large portions of the world population dependent on snow melt (Immerzeel et al., 2020). The development of reliable alpine datasets for advancing such understanding combined with developing and testing models continues to define INARCH's goals going forward. Modelling the hydrology of these regions of high mountain terrain, however, remains challenging. Lack of model resolution profoundly limits our ability not only to characterize regional hydrology and predict how water resources are likely to be impacted as Earth warms (Sidebar 2, also section 4.5.3 below) but especially so in regions of high mountain terrain. Figure 6 illustrates this point, showing how better resolving the topography of the Colorado Rockies (Figures 6a and b) improves precipitation simulation in the region (Figures 6c and d, adapted from Rasmussen et al., 2014). The large differences between modeled and observed precipitation apparent for the 36 km resolution model, in part because of the highly smoothed topography at that resolution, are largely eliminated with finer resolution that significantly improves the representation of precipitation both locally and regionally and in both cold and warm seasons. In a more recent study, Müller et al. (2021) use the global discharge from rivers to assess the representation of precipitation in two versions of the Hadley Centre Global Environmental Model, version 3 (HadGEM3) of differing resolutions. They find that not only do models with higher resolution produce more discharge owing to increased precipitation over the more-resolved topography, but that the different estimates of discharge from observations and reanalysis are also dependent on the coarseness of the resolution of the data itself. The more spatially resolved are the data, the greater is the discharge estimated.

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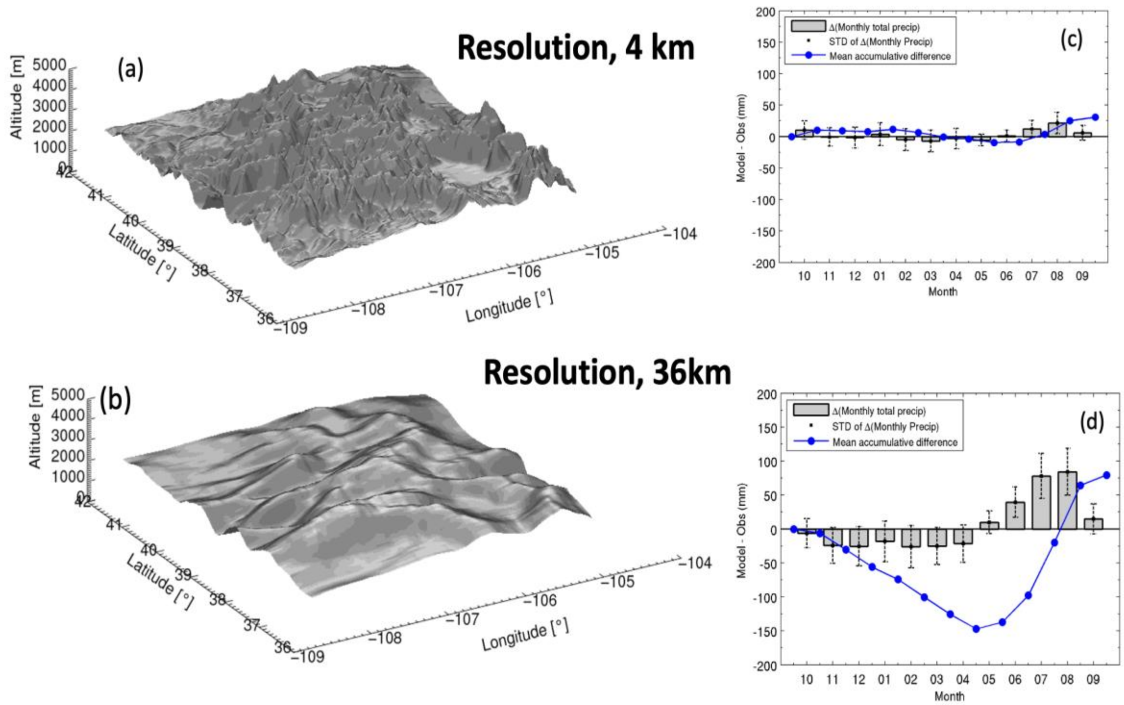

Figure 6 a) and b) The topography of the Colorado Rockies at two different resolutions that define the head waters as described in Rasmussen et al (2014). c) and d) The 8-yr average of the model bias (model minus observations) in monthly total precipitation (bars) and accumulation difference (blue line) over a full year from the c) 4-km (upper) and d) 36km simulations.

Kilometer scale modeling of the Earth system improves our ability to represent hydrological processes in more explicit ways (e.g., Sidebar 2), including prediction of extreme events such as flood and drought in regions with complex topography. Moving the attention of the GEWEX communities to these higher resolutions can be expected to lead to even more important collaborations with the hydrological and agronomic sciences for developing the process knowledge needed to improve climate, weather and hydrological forecasts of phenomena critical for society. The emergence of km-scale modeling, however, comes with new challenges noted above that, in one way or other, are concerned more broadly with how different components of the Earth system couple on these scales.

4.5.2 Earth's energy imbalance (EEI)

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The imbalance between incoming and outgoing radiation at the top of the atmosphere (TOA), referred to as EEI, is a basic measure of the warming of the planet and careful monitoring of it is essential for understanding many aspects of the changing Earth system. Given that absolute accuracy of TOA radiometric measurements is approximately ±4Wm^{-2}, the EEI which needs to be quantified, between 0.5–1 Wm^{-2} (Figure SB3), is small and is challenging to observe from space alone (e.g., Stephens et al., 2012). It is obvious that reliable estimates for long-term global mean EEI from TOA fluxes are not possible and even more challenging from the perspective of surface fluxes presented in Figure SB3. Thus, we are forced to resort to more indirect ways to deduce the EEI. As over 93% of the EEI is stored in the ocean, the global ocean heat content (OHC) provides our strongest global constraint on the EEI and the ability to determine the global ocean heat storage change continues to be essential assessing the state of climate and its future evolution.
A joint GEWEX and CLIVAR workshop was devoted to the topic of EEI and an assessment of our ability to estimate it. Meyssignac et al. (2019) provide an overview of the key outcomes of that workshop noting that none of the techniques available today enable us to estimate the EEI with the perceived required accuracy less than ±0.3 Wm^{-2}, let alone with an aspirational accuracy of ±0.1 Wm^{-2}. Significant improvements in existing observing systems are necessary to achieve this target.

4.5.3 km-scale Earth system modeling and the role of Convection – A prevailing theme of Earth system science in the 2020s

A prevailing theme not only of GEWEX, but one that cuts across WCRP including within its new Lighthouse Activities (LHAs, https://www.wcrp-climate.org/lha-overview) and beyond, is the emphasis on km-scale modeling called out above. Existing climate models have significant shortcomings in simulating local weather and climate because of a lack of resolution. They cannot resolve the detailed structure and lifecycles of systems such as tropical cyclones, depressions and persistent high-pressure systems which are key in the coupling of the energy and water cycle. These systems also drive many of the more costly impacts of climate change, such as coastal inundation, flooding, droughts and wildfires. Present-day global models are also unable to resolve ocean currents that are fundamental to climate variability and regional climate change (Marotzke et al., 2017). Recent studies

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illustrate the potential of the new generation of high-resolution models for revolutionizing the quality of information available for mitigation and adaptation, from global and regional climate impacts, to risks of unprecedented extreme weather and dangerous climate change. A thread common across both GEWEX objectives and these new modeling initiatives is the topic of convection, not only from the context of resolving it with models, but also for its importance to the prediction of precipitation and severe weather. Resolving convection is essential for understanding the future of our water resources and for protection from flash flooding under climate change (Slingo et al., 2022). This comes with the challenge in representing the couplings between the main components of the systems across this range of scales ultimately moving these models to km-scale Earth system models.

5.0 GEWEX in the decade of km-scale Earth system science

As GEWEX moves forward, it does so under a simple vision articulated at the 2018 GEWEX Open Science Conference by Dr. Alan Betts during his keynote address, *"Water, Energy: Life on Earth",* which underscores the very basic challenge of the next phase of GEWEX and beyond: that humanity is deeply embedded in an interconnected physical Earth system. That the Earth system influences humanity in profound ways is well understood, but an appreciation for the wider and profound influences of humanity on the Earth system, and on the hydrological and climate cycles in particular, continues to be realized. The connections between water, energy and life become particularly acute as we strive to bring Earth sciences down to the km-scale (e.g., Slingo et al., 2022), a point further underscored by reference to Figure 7 that also hints at why we expect this connection will become increasingly important as GEWEX moves into the next phase. The figure offers a contrast between the natural water cycle, expressed here as a mean discharge of the Amazon (5000 km^3/yr), the largest river by volume, compared to the volume of global water withdrawn by different sectors of human society. The modification to the continental water cycle occurring from a continually increasing human withdrawal is now larger than the mean discharge of the Amazon river. The impact is more complex to evaluate as not all water abstracted by humans from the

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natural system is consumed. Human water management practices impact river discharge, coastal processes and contribute non-trivially to sea level rise (e.g., Reager et al., 2016).

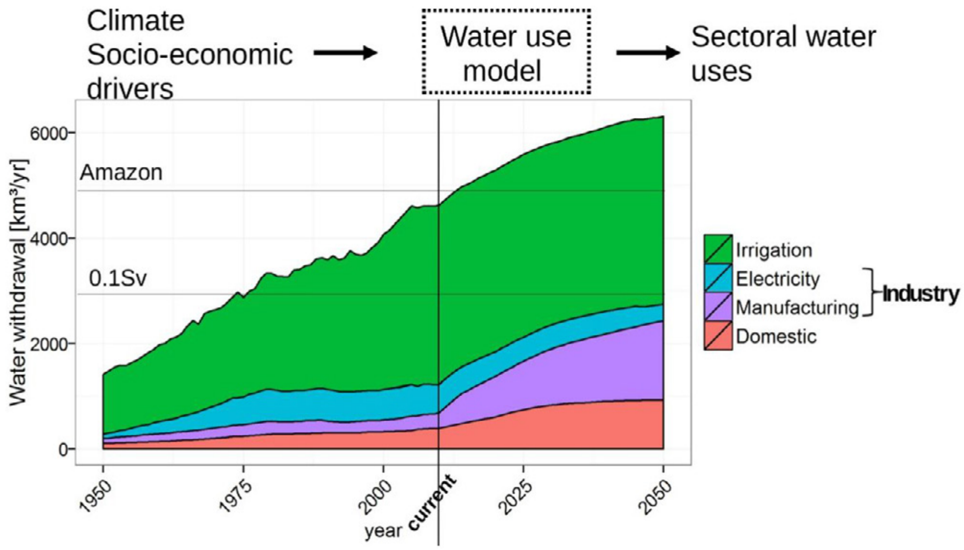

Figure 7 Reconstructed time change of human water withdrawal by different sectors including projections to 2050 compared to an average discharge from the Amazon. The estimates of past consumptions are based on Flörke et al. (2013) while the projections are derived by Wada et al. (2016).

5.1 The GEWEX Phase IV science goals

In recognition of the emerging challenges in understanding how the water cycle is changing in response to these different pressures, and to make progress in addressing the issues central to them, GEWEX Phase IV proposes a focus around three overarching but connected goals. One goal is centrally focused on prediction, another on the critical interactions that define the physical system and the third delves more explicitly into anthropogenic influence on water and energy cycles with special focus on water resources at continental and regional scales.

Goal # 1 (GS1): Determine the extent to which Earth's water cycle can be predicted. This Goal is framed around making quantitative progress on three related areas posed in terms of the following questions:

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1) Reservoirs: What is the rate of expansion of the fast reservoirs (atmosphere and land), what is its spatial character, what factors determine this and to what extent are these changes predictable?

2) Flux exchanges: To what extent are the fluxes of water between Earth's main reservoirs changing and can these changes be predicted, and if so, on what time/space scale?

3) Precipitation Extremes: How will local rainfall and its extremes change under climate change across the regions of the world?

Goal # 2 (GS2): Quantify the inter-relationships between Earth's energy, water and carbon cycles to advance our understanding of the system and our ability to predict it across scales:

1) Forcing-feedback understanding: How can we improve the understanding of climate forcings and feedbacks formed by energy, water and carbon exchanges?

2) ABL process representation: To what extent are the properties of the atmospheric boundary layer (ABL) defined by sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and exchanges between the ABL and the free atmosphere)?

3) Understanding circulation controls: To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?

4) Land-atmosphere interactions: How can we improve the understanding of the role of land surface-atmospheric interactions in the water, energy and carbon budgets across spatiotemporal scales?

Goal # 3 (GS3): Quantify anthropogenic influences on Earth's water cycle and our ability to understand and predict it:

1) Anthropogenic forcing of continental scale water availability: To what extent has the changing greenhouse effect modified the water cycle over different regions and continents?

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2) Water management influences: To what extent do water management practices and land use change (e.g., deforestation and irrigation, among others) modify the water cycle on regional to global scales?

3) Variability and trends of water availability: How do water and land use and climate change affect the variability (including extremes) of the regional and continental water cycles?

6.0 Concluding comments: Prospects for progress

The very first GEWEX newsletter released in spring 1991 contained contributions by both Dr. Moustafa Chahine, the Chair of the GEWEX Scientific Steering Group (SSG), and Professor Pierre Morel, Director of WCRP. While Dr. Chahine outlined the objectives of GEWEX that shaped the program for many years to come and described above, Professor Morel offered the insight that "*A little thought about the problem of climate and climatic variations leads to an understanding that the main difficulty lies with getting the coupling right between the different components of the climate system, the global atmosphere, the world oceans, land and sea ice and the land surface hydrology including snow and vegetation.*"

As WCRP undergoes its reorganization and develops its strategic plan for the coming years via the WCRP Lighthouse Activities, the motivating focus of both WCRP and GEWEX remains true to Morel's insight that the emphasis will be toward developing a more quantitative understanding of climate processes, which are necessary for "*getting the coupling right between the different components of the climate system*." What has sustained the relevance of GEWEX over time is a steadfast focus on the most basic of processes that are fundamental to these couplings, those processes that intimately connect water and energy. These processes are at the core of many pressing Earth's science questions today, shaping Earth's climate and changes to it. A joint focus on the basic processes and on stewardship of and support for sustained observations of essential water and energy variables is the foundation of GEWEX's making it relevant to many of today's Earth science and societal challenges. While GEWEX has provided the means for

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major progress our understanding of key quantities that define, for example, the couplings of water between its main reservoirs (e.g. Stephens et al., 2020) or energy exchanges at Earth's surface remains rudimentary and aspects of it still inadequately observed.

We can anticipate progress over the next 5–10 years on the challenge expressed by Morel because of major opportunities in observations, computing, modeling, artificial intelligence and machine learning (AI/ML) and emerging partnerships.

(i) New observations, both in situ and from space, will reveal new understanding of processes in Earth's energy, water and carbon cycles and identify where progress is still lacking. This will come from the expansion of the Earth observing systems, including the Sentinel program of the ESA, NASA's designated observables iden-tified as priorities for the coming decade (NAS, 2018) and the sustained and enhanced observations from operation observing systems that collectively establish the Program of Record (PoR). One example of where progress can be expected from the PoR comes from the development of the next-generation version of the ISCCP, a coordinated effort across major operational satellite organizations and research communities to create global, high-resolution in space and time data products (on the order of 2 km global, 10–30 minute) on clouds and related information. The creation of a fundamental data record of spectral, spatially and temporally homogenized radiances for this purpose serves as input to many other Earth science applications. The development of smallsats and cubesats, drones and other space and airborne platforms, and advances in space technology associated with these developments (e.g., Stephens et al., 2020), opens a whole new era of observational capabilities.

(ii) The length of existing data records will continue to expand and with the expansion comes unforeseen evolution of the system being realized as new trends. Sea level rise data records have revealed an increase in the rate of sea level rise over time with surprising interannual variations (e.g., Boening et al., 2012) and recent studies of the TOA radiation budget are hinting at an energy imbalance that is also increasing over time

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(Loeb et al., 2021; Stephens et al., 2022, among others), suggesting an acceleration of global warming. These expanding data records will test our understanding of the changing Earth system that will force a re-examination of the contributions of the various man-made changes to the energy and water cycles.

(iii) Evolving modeling techniques and exa-scale computers will enable research and operational simulations at kilometric scales globally and at even higher resolutions regionally with benefits that are only now becoming apparent. This evolution will also reveal that some assumptions necessary for coarser resolutions (such as assumptions inherent to convection parameterization, influences of surface topography and heterogeneities in soil/vegetation and other landscape features that affect hydrological processes) may not be valid. Over continents, these km-scale resolutions will reveal the importance of human management on surface/atmosphere interactions with associated environmental impacts and will thus need to be explicitly represented to gain the full value for society of (sub)kilometric scale predictions. These developments, however, will come with other challenges, including the couplings of the system on these finer scales and in how to represent different natural and anthropogenic processes that emerge on such scales (e.g. section 4.1.2)

(iv) Our enhanced observational capabilities and the promise of more spatially-refined models will require new techniques to confront one with the other and to deduce essential parameters of the system that are not yet directly measured by the current observational systems. With the rapid progress in AI/ML, their applications become more important for GEWEX activities in the physics-inspired AI/ML analysis of huge amounts of data from observations and model output, in the AI/ML integration with modeling (e.g., to replace some of the existing physical parameterizations in Earth system models), and in the AI/ML assistance in data-based scientific discovery and understanding.

(v) Continued close collaboration of the research groups within GEWEX with operational weather and hydrological services, a hallmark of GEWEX throughout the years, serves to better formulate societal needs in terms of environmental monitoring and prediction

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and ensures that the scientific topics proposed serve wiser management of the environment and an adaptation to changing resources. The collaboration of GEWEX with the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) and other programs will facilitate improvements to the coupling of the energy and water cycle with the carbon cycle in models and in Earth system analyses and studies of climate change at decadal to centennial time scales.

7.0 Acknowledgements

To the memory of Moustafa Chahine, The inaugural chair of the science steering committee. GEWEX's achievements over the last 30 years would not have been possible without the scientific community collectively working on the Earth's water and energy cycles. As not all can be thanked here, we especially want to express our gratitude to the many who have contributed to GEWEX over the years and to those who have chaired the Scientific Steering Group before us: Moustafa Chahine, Soroosh Sorooshian, Tom Ackerman, Kevin Trenberth, Howard Wheater and Sonia I. Seneviratne. GEWEX has also benefitted greatly from interactions with other WCRP projects, and other international projects, particularly IGBP and its successor, Future Earth, as well as the UNESCO Intergovernmental Hydrological Programme. The continuous support from NASA of the International GEWEX Project Office has been foundational to the long-term success of GEWEX, as were the GEWEX data services provided by UCAR in the early stages of the project and support of various GEWEX activities by ESA. The research grants from various funding agencies to support GEWEX scientists over the years has also contributed to the long-term success of GEWEX. We also want to acknowledge the valuable comments and insights of one of the anonymous reviewers of the original manuscript. The lead author has been supported as co-chair of the GEWEX science steering committee at the Jet Propulsion Laboratory, California Institute of Technology, under contract 80NM0018D0004 with the National Aeronautics and Space Administration.

8.0 Data Availability

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GEWEX provides the stewardship of many global and regional data sets and data producing networks. The data are publicly available and an overview of these data is provided at https://www.gewex.org/panels/gewex-data-and-analysis-panel/gdap-matured-datasets/

Specific links to important data sets that have been maintained over the many years of GEWEX include:

Matured Datasets

International Satelite Cloud Climatology Project (ISCCP):

https://isccp.giss.nasa.gov

https://www.ncei.noaa.gov/products/international-satellite-cloud-climatology

Global Precipitation Climatology Project (GPCP):

https://disc.gsfc.nasa.gov/datasets/GPCPDAY_3.2/summary?keywords=GPCPDAY_3.2 (latest)

https://www.ncei.noaa.gov/products/global-precipitation-climatology-project (Historical)

Surface Radiation Budget (SRB):

https://asdc.larc.nasa.gov/project/SRB

Regional Hydroclimate Projects:

https://www.gewex.org/panels/gewex-hydroclimatology-panel/regional-hydroclimate-projects-rhps/

Key network centers:

Baseline Surface Radiation Network (BSRN):

https://bsrn.awi.de

Global Precipitation Climatology Centre (GPCP):

http://gpcc.dwd.de/

Global Runoff Date Centre (GRDC)

https://www.bafg.de/GRDC/EN/Home/homepage_node.html

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Appendix A: List of Acronyms

ABL	Atmospheric Boundary Layer
ADEOS II	Advanced Earth Observation Satellite II
AI/ML	Artificial intelligence and machine learning
AMMA	African Monsoon Multidisciplinary Analyses
BALTEX	Baltic Sea Experiment
BSRN	Baseline Surface Radiation Network
CC	Clausius-Clapeyron rate
CCRN	Changing Cold Regions Network
CEOP	Coordinate Enhanced Observing Period
CERES	Clouds and the Earth's Radiant Energy System
CIRC	Continual Intercomparison of Radiation Codes
CLIVAR	Climate and Ocean: Variability, Predictability and Change project
CORDEX	Coordinated Regional Downscaling Experiment
CRM	Cloud Resolving Model
CSE	Continental Scale Experiment
DO	Designated observables
EEI	Earth Energy Imbalance
ENSO	El Niño-Southern Oscillation
ENVISAT	European Space Agency Environmental Satellite
EOS	Earth Observing System
ET	Evapotranspiration
GABLS	GEWEX Atmospheric Boundary Layer Study
GAME	GEWEX Asian Monsoon Experiment
GAP	GEWEX Aerosol Precipitation
GARP	Global Atmosphere Research Programme
GASS	GEWEX Atmospheric Systems Study Panel
GCIP	Continental-Scale International Experiment
GCSS	GEWEX Cloud System Study
GDAP	GEWEX Data Assessment Panel/ GEWEX Data Analysis Panel
GEWEX	Global Energy and Water Cycle Experiment / Global Energy and Water EXchanges project
GHP	GEWEX Hydrometeorology Projects
GLACE	Global Land–Atmosphere Coupling Experiment
GLASS	GEWEX Land Atmosphere System Studies
GMPP	GEWEX Modeling and Prediction Projects
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Mission
GRACE	Gravity Recovery and Climate Experiment
GRP	GEWEX Radiation Project
GSWP	Global Soil Wetness Project
GVaP	Global water Vapor Project
HadGEM3	Hadley Centre Global Environmental Model, version 3
HyMeX	HYdrological cycle in the Mediterranean Experiment
iLEAPS	Integrated Land Ecosystem-Atmosphere Processes Study

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INARCH	International Network for Alpine Research Catchment Hydrology
INTENSE	INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes
IPCC WG II	Intergovernmental Panel on Climate Change Working Group II
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
JSC	Joint Scientific Committee
LAI	Leaf Area Index
LBA	Large-Scale Biosphere-Atmosphere Experiment in Amazonia
LHA	Lighthouse Activities
LSM	Land Surface Model
LWE	Liquid water equivalent
MAGS	Mackenzie GEWEX Study
NEWS	NASA Energy and Water Cycle Study program
NWP	Numerical weather prediction
OHC	Ocean heat content
PILPS	Project for the Intercomparison of Land-Surface Parameterization Schemes
PoR	Programs of Records
PROES	Process Evaluation Study
RHP	GEWEX Regional Hydroclimate Projects
SMOS	Soil Moisture and Ocean Salinity mission
SRB	Surface radiation budget
SSG	Scientific Steering Group
TOA	Top of atmosphere
TOGA	Tropical Ocean and Global Atmosphere Project
TRMM	Tropical Rainfall Measuring Mission
WACMOS	Water Cycle Multi-mission Observation Strategy
WCRP	World Climate Research Programme
WEBS	Water and energy budget synthesis
WGNE	Working Group on Numerical Experimentation
WGRF	Working Group on Radiative Fluxes
WOCE	World Ocean Circulation Experiment

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Sibebar 1: From land surface to land models

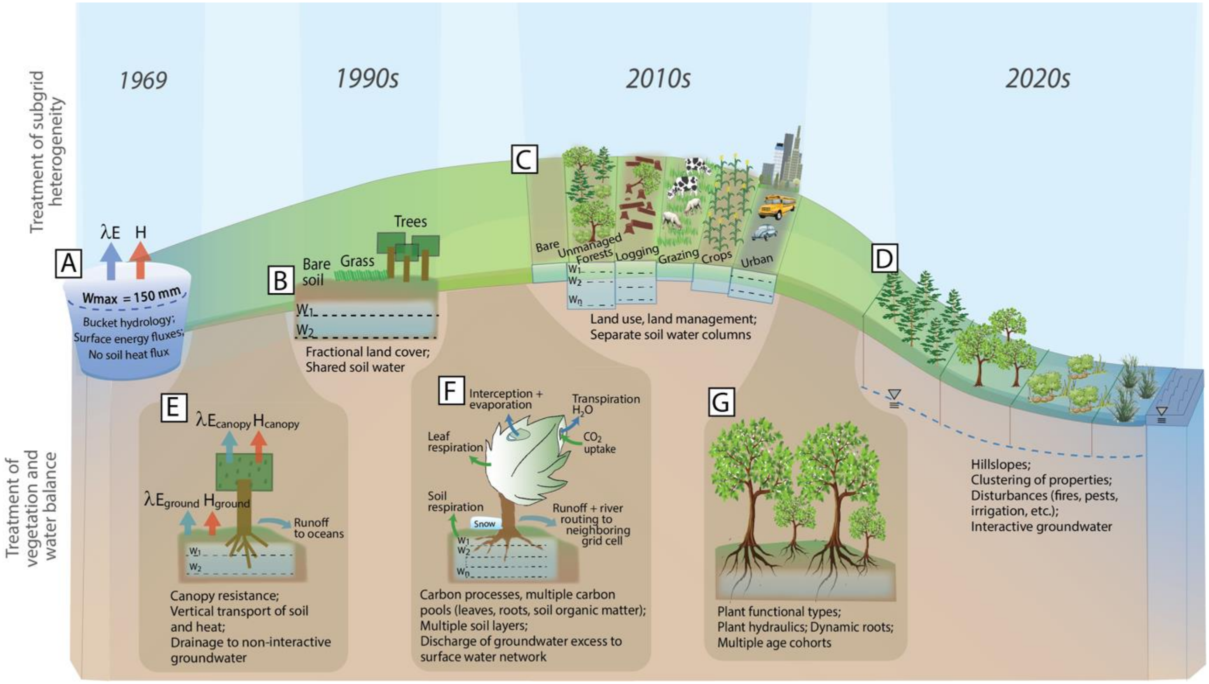

Figure SB1: *The evolution of land model formulations, beginning with the Manabe bucket model in 1969 (A), gradually improving the treatment of water, heat and vegetation, while also including increasingly complex and heterogeneous representations of vegetation and soil processes both above and below the land surface. Dates are approximate. Blue arrows: λE = evaporative flux (where λ = latent heat of vaporization of water, E = evaporation rate). Red arrows: H = sensible heat flux. Green arrows: carbon fluxes.*

Land models are numerical representations of processes within and below the land surface and vegetation canopy. Output of these models include fluxes of water, energy and carbon transferred from the land to the atmosphere. The early bucket model of Manabe (1969) was designed to provide the surface fluxes of latent and sensible heat as boundary conditions for the atmosphere (Element A in Fig. SB1). Initially, treatment of the land was embedded within atmospheric model code. GEWEX facilitated the important work of pulling land-relevant code out of the larger model code, allowing for the broader creation and development of stand-alone land models while still serving as the “surface” for the atmosphere (Polcher et al., 1998). These models have since evolved to account for vertical moisture and heat transport within the soil column and separate

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evaporative terms from the vegetation canopy and the ground (Dickinson et al., 1984; Element E), to inclusion of carbon processes (photosynthesis, transpiration, leaf respiration; e.g., Shevliakova et al., 2009; Element F) and routing of runoff to neighboring grid cells through river routing schemes (e.g., Milly et al., 2014; Ngo-Duc et al., 2007), to finally the complex models at the cutting-edge today, including forest systems with a range of canopy heights and multiple age cohorts, dynamic roots, plant hydraulics and more (Element G).

A synergistic evolution of the treatment of sub-grid heterogeneity (Elements B–D) occurred in parallel to the evolution of more advanced process representation (Elements E–G). Early approaches to heterogeneity occurred by allowing for a few tiles of different surface types, but with access to a shared soil water reservoir (e.g., Koster and Suarez, 1992, 1994; Element B), to treatment of land use and land management in tiles with separate soil moisture reservoirs (de Rosnay and Polcher, 1998; Element C). Recent advances include using machine learning techniques to cluster land properties (e.g., elevation, soil textures, vegetation types) and better represent the hydrological connectivity between these subgrid clusters (Chaney et al., 2018; Element D).

The improved representation of the soil system was central to the evolution conveyed in Figure SB1. Modeling the soil system and its role within the Earth system has been topic of focus of different communities for many decades. The motivation has varied from interests in understanding how soils impact the environment and ecosystem (see Vereecken et al., 2016) to perspectives on both hydrology (e.g., Sood and Smakhtin,

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2015) and climate (e.g., van Looy et al., 2017; Fatichi et al., 2020), with a particular focus on land-atmosphere coupling. The defining roles of water and energy fluxes in coupling the land and atmosphere provide the motivation of both the formation and evolution of GEWEX-GLASS activities (e.g., van den Hurk et al., 2011; Dirmeyer, 2018; Santanello et al., 2018). Soils were initially viewed simply through the lens of the Manabe single layer "bucket" model, which parameterized the available soil moisture by assuming a 15 cm soil moisture holding capacity globally (Element A). Soil heat flow and storage was not accounted for in this simple scheme. Pivotal improvements occurred when Deardorff (1978) introduced a method for simulating soil temperature and moisture in two layers (Element E). Subsequently, analytical equations were replaced by numerical schemes that solve partial differential equations for the conservation of soil water and heat, thus allowing for the coupled heat and water transfer and providing a number of advantages, including the prediction of seasonally frozen soils. This approach also gave the modelers the soil matric potential, which allowed for the proper implementation of root water uptake and plant hydraulic theory, thus offering a more interactive land surface and sub-surface system. Further increases to the number of soil layers (~4 initially and currently up to 20; Element F) were required for appropriate treatment of soil thermal and hydrological lower boundary conditions (Decharme et al., 2013), which proved particularly important in cold regions (Stevens et al., 2007; Slater and Lawrence, 2013; Sapriza-Azuri et al., 2018). The inclusion of groundwater (Yeh and Eltahir, 2005; Maxwell and Miller, 2005) significantly improved simulation of the hydrological cycle. Most Earth system models are still working to add fully interactive groundwater (Element D). For further reviews and vision papers on land model development, see, e.g., Pitman

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(2003), Overgaard et al. (2006), Clark et al. (2015), Fisher and Koven (2020) and Blyth et al. (2021).

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Sidebar 2: From local to global cloud resolving modelling – A GEWEX legacy

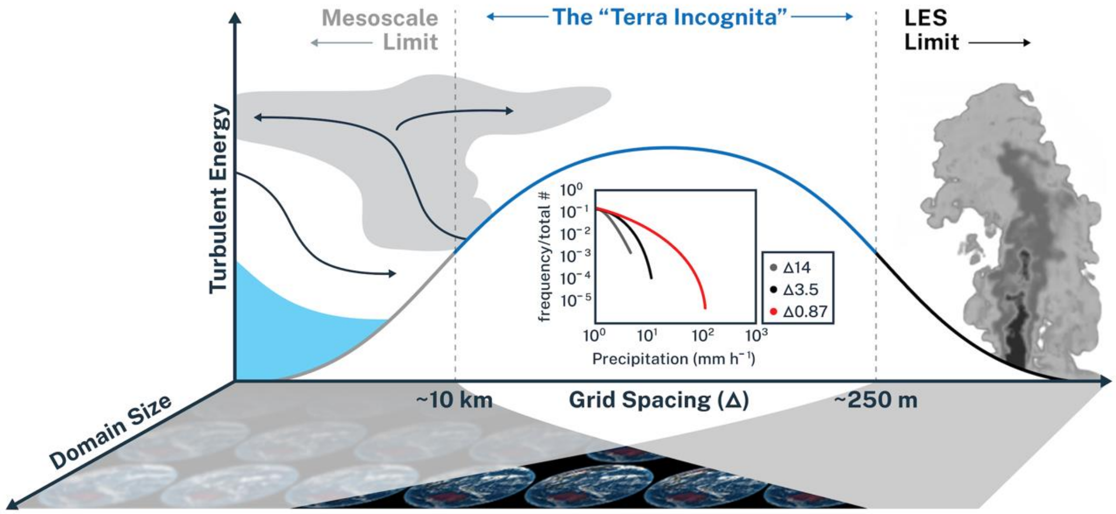

Figure SB2 A schematic of the turbulence energy spectrum (the multi-colored curve) in the vertical plane as a function of the length scale of the turbulent energy. This scale when contrasted against the horizontal grid spacing used to resolve flows defines three regimes in which cloud models have evolved. Cloud models in the mesoscale limit represent mesoscale and large-scale clouds and convection, the large eddy simulation limit in which the turbulence eddies in clouds are resolved are in the LES limit and the middle terra-incognita zone is what we now experience today in which the two developments in the outer limits converge and overlap. The domain size has also expanded over time giving rise the km-scale global cloud models of today. The inset precipitation distributions, characteristic of a model in both the mesoscale and terra-incognita domains, are from the NICAM model of different grid resolutions (in km), after Miyamoto et al., (2013).

Historically, numerical models of the cloudy atmosphere advanced along two separate tracks that today are beginning to merge (Figure SB2) into a common space. The earliest cloud models were of limited domain size and can be placed in the context of the resolved scale of turbulent flow as suggested by Wyngaard (2004). The two broad historical classes of cloud scale modeling fall either under a class of 'mesoscale' cloud models also referred to as cloud resolving models (CRMs) typically set on larger domains (10's-100's km) or a second class referred to as large-eddy simulation (LES) models applied to much smaller domains (of order 1km). What sets these two classes apart,

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according to Wyngaard, can be expressed in terms of the ratio of the energy-containing turbulence scale ℓ and the grid spacing of the model Δ. The early cloud models assumed $\ell/\Delta < 1$ so none of the turbulence is resolved. Traditional LES models, on the other hand, fall into the parameter space $\ell/\Delta > 1$ meaning the energy- and flux-containing turbulence is explicitly resolved by these models. In between where $\ell \sim \Delta$ is the region of 'terra-incognita' which, more and more, is the region we find cloud modelling today made possible by the greater computing capabilities available. Cloud models are also now both being applied globally with grid spacing Δ at the km scale and even smaller (e.g. Miyamoto et al., 2013).

It can be reasonably argued that the modern discipline of cloud physics, and the development of CRMs in the 'mesoscale limit', was greatly shaped by the need to understand how seeding of clouds might affect the precipitation produced by them. There was no obvious simple way to contrast the observed behavior of seeded and unseeded clouds and thus no way to establish causality statistically from the small number of experiments conducted (NRC, 2003). The earliest cloud models thus grew out of a desire to simulate effects of cumulus dynamics on cloud microphysics in order to establish a basis to assert causality in seeding experiments that could not be statistically achieved otherwise. One of the earliest forms of cloud models developed for this purpose was that of Simpson and Wiggert (1968). Although this model was merely one dimensional, what emerged was a deep appreciation of the importance of resolved motions within clouds and on scales of dynamical organization referred to as the mesoscale (e.g. Cotton, 1972) – scales deemed critical to weather modification experiments (e.g. Cotton and Pielke, 1976), thus giving early impetus to the modern cloud resolving models of today.

At the same time when these meso-scale cloud models were beginning to emerge, LES models were also being developed to study the intricacies of atmospheric turbulence. LES was first proposed in 1963 by Smagorinsky to study atmospheric flows and has been used widely to examine, for example, turbulent flows around objects. In a seminal LES study, Deardorff (1972) introduced an LES model to study clear air neutral and unstable boundary layers. This model was the basis for many following studies. For example,

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Sommeria (1976) extended it to produce the very first LES model study of the cumulus-topped boundary layer. Many LES studies of the cloudy boundary layer followed with LES emerging as an important tool for studying low cloud processes (e.g. Teixeira et al. 2021ref).

From the outset GEWEX recognized the important role of these two streams of cloud model activities and developed specific initiatives to exploit both to study the important cloud systems on Earth, to elucidate the most critical processes that need to be represented in global modes and to develop ways to represent them. Early work with these models helped to develop and refine the physics of process models such as that of deep convection and the cloud-topped boundary layer, to serve as a substitute for observations that were not or could not be made as a way to both inform and test physical parameterizations of climate models. They also exposed several global model shortcomings, such as their inability to represent the organization of single convective clouds into larger systems, that are critical elements of Earth's radiation budget, important to climate feedbacks, a basic influence on precipitation extremes, and influential to circulation on all scales.

Through their use in GCSS and more recently GASS, the LES models and CRMs were continuously exposed to field observations (e.g. Siebesma et al., 2003), resulting in continued improvements to them. It soon became clear that these models could produce realistic simulations at the cloud system scale, and later work showed that the organization of clouds into mesoscale systems could emerge when the CRMs or LESs were run on larger domains. This created the exciting prospect to further increase the domain size of these models even on the domain of the whole globe, eventually using them to perform climate simulations. This first led to the implementation of simplified CRMs to replace parametrizations in the so-called super-parametrization approach (Grabowski, 2001) representing the first real shift of models into Wyngaard's terra-incognita regime.

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There is now compelling evidence that the lack of resolution of coarse global models and even coarsely resolved meso-scale cloud models and the inability to explicitly resolve convection specifically is a major obstacle in making the advances needed to confront important Earth science challenges of today (Slingo et al., 2022). The inset example of Figure SB2, taken from the global model study of Miyamoto et al (2013), offers a clear example of the influence of model resolution on the properties of convection and why models are pushing further and further into the domain of the ‘terra-incognita’. Shown is a global composite of the pdf of convective precipitation deduced from model simulations with grid spacings that span the Wyngaard space ranging from mesoscale regimes of Δ=14 km to the regime of terra incognita with Δ=870m. For the coarser simulations of Δ=14km and Δ=3.5km, the extreme precipitation is confined to less than 20 mm h^{-1} in contrast to the Δ=0.87km simulation of intense precipitation of more than 100 mm h^{-1}. This merely underscores just how important resolution is in representing the heaviest and most extreme rainfalls from convective storms.

Today the advantages of global, kilometer-scale (*km-scale*) models and associated information systems is becoming more widely appreciated (e.g. Bauer et al., 2021; Slingo et al. 2022) both for short term weather prediction (Palmer, 2014; Deuben et al., 2020) and regional and global climate prediction (Schär et al., 2019). GEWEX has advanced and continues to advance the agenda of such modelling and does so on a number of fronts, such as through its workshops (e.g., Prein et al.,2017), through the advances to observations of extremes (Fowler et al., 2021) and to the specific advances being made to land models (e.g. Box 1) and also to LES and CRMs. The various activities that focus on modelling Earth on the *km-scale* have also galvanized into a few large international efforts (e.g. Stevens et al., 2019) including those expressed by the new WCRP lighthouse activities that can be expected to shape future activities of GEWEX.

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Sidebar 3: Earth's energy budget

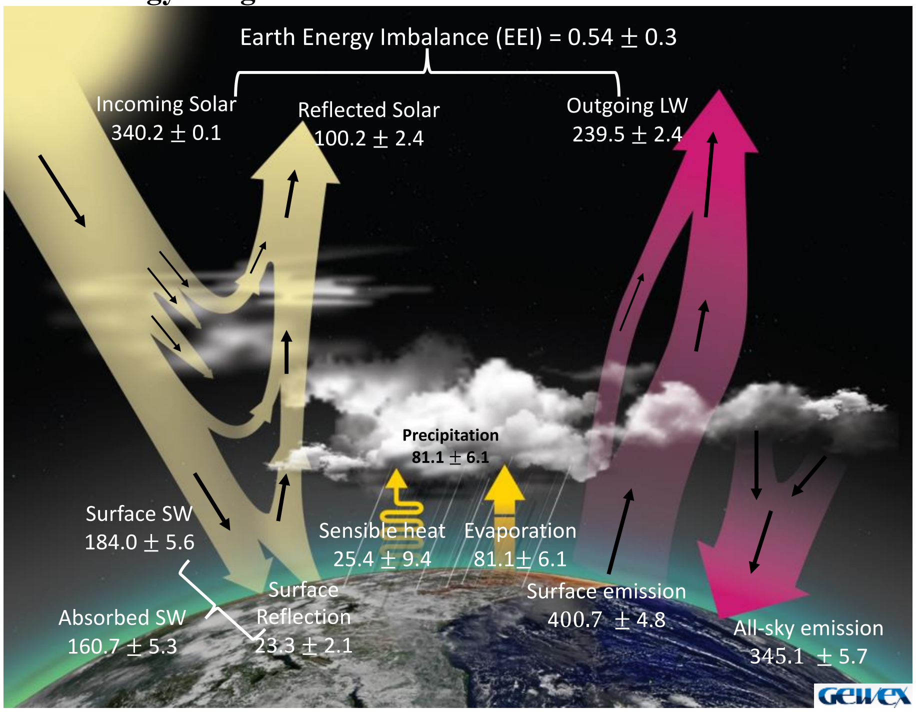

Figure SB3: An update on the mean annual fluxes of the global energy budget (all in Wm^{-2}) for the first decade of the millennium. This budget was achieved using a 'global' optimization described in L'Ecuyer et al (2015) that requires quantitative uncertainties but uses data that produce more consistent set of fluxes.

Quantifying the various ways energy flows through the Earth system has been a foundational activity of GEWEX from the outset and the latest version of the annual global mean depiction is presented in Figure SB3 based on the most up-to-date GEWEX data records. A number of sustained GEWEX activities, like the surface radiation budget project, land and ocean heat flux activities, maintenance of the GPCP precipitation climatology precipitation, TOA radiation budget assessments evolved over time with a focus on defining the uncertainties of the energy components of the budget which are reflected in Figure SB3. The NASA NEWS project produced a synthesis of a vast amount of these global data and provided, for the first time, a careful and more detailed assessment of the joint uncertainties attached to both global energy and water budgets. This provided the basis for a more objective methodology to adjust fluxes to constrain

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jointly closure of the global water and energy budgets, finally moving away from past *ad hoc* flux adjustment methods that had little justification. This coupled, constrained depiction of the energy and water balances and methods developed are described in the joint studies of L'Ecuyer et al. (2015) and Rodell et al (2015) and the global budget portrayed in Figure SB3 uses these same objective methodologies.

It was also recognized within GEWEX that inconsistencies existed in data inputs that were used to determine some of the fluxes that define these global balances. GDAP introduced an effort to address this issue creating an integrated self-consistent range of products (Kummerow et al., 2019) that offer a better and more consistent source of information for determining all fluxes, but particularly those at the Earth's surface. The fluxes expressed in Figure SB3 are based on the use of these newer integrated and more self-consistent GEWEX products.

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Sidebar 4 Continental water storage

A remarkable result derived from observations of continental water storage appears in the visible imprint of human water management on the evolution of regional ecosystems. This imprint is illustrated in Figure SB4b) and the greening of cropland regions in northern India over the past two decades (Figure SB4a). These regions also coincide with the canals built in the early 20th century to support irrigated agriculture and which have raised the water table through their leakage. This comparison underscores an important point that to understand current trends in the continental water cycle one needs take into account both the influence of human water usage and the engineering developed to support it, as well as the influence of the physical climate system.

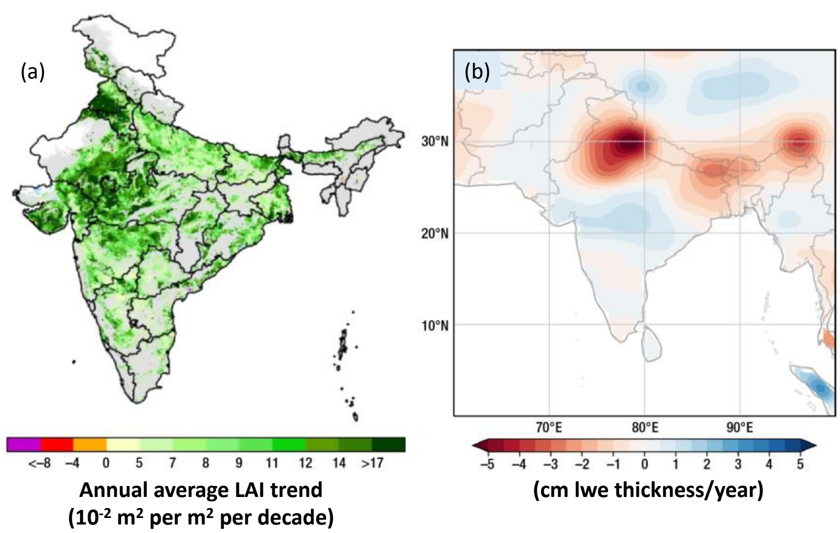

Figure SB4 (a) Trends in annual average MODIS leaf area index (LAI) for 2000–2017 in croplands in India. Statistically significant trends (Mann–Kendall test, p≤0.1) are color-coded. Grey areas show vegetated land with statistically insignificant trends. White areas depict barren lands, permanent ice-covered areas, permanent wetlands and built-up areas. (b) GRACE record length trends (2002–2016) over the Indian subcontinent (in liquid water equivalent (LWE) units in cm per year), showing extensive groundwater depletion in Northwest India (adapted from both Chen et al., 2019 and Stephens et al., 2020).

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