GEWEX NEWS

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SPECIAL CONFERENCE THEME ISSUE

TRENDING NOW WATER

7th International Scientific Conference on the Global Water and Energy Cycle

Preliminary Program (Page 30)

14-17 July 2014
The Hague,
The Netherlands

http://gewex.org/2014conf/home.html

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Commentary

Trending Now: Water

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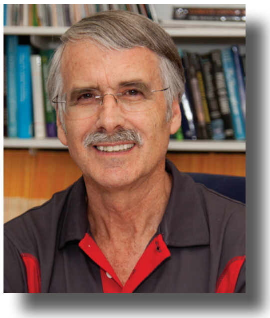


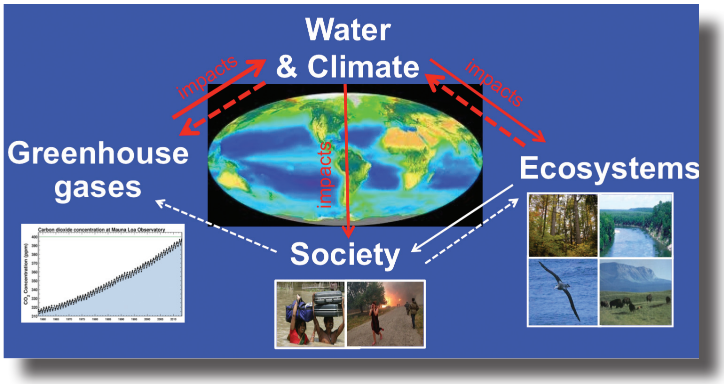
The 7th International Scientific Conference on the Global Water and Energy Cycle is being held in The Hague on 14-17 July 2014. The Conference celebrates 25 years of GEWEX research and sets the stage for the next phase of research addressing the World Climate Research Programme Grand Challenges on water resources, extremes, and climate sensitivity through observations and data sets, their analyses, process studies, model development and exploitation, applications, technology transfer to operational results, and research capacity development and training for the next generation of scientists.

Fresh water cannot be substituted; it is irreplaceable. More than any other natural resource, "water is life." The increasing demand for fresh water and the impacts of climate change on extreme events and water availability highlight why water is of major global concern and is "Trending Now." That is to say, this is not only an important headline in the news—water availability is changing due to increasing demand and climate change. Hence, as the theme for the Conference, it has a double meaning.

In GEWEX, the focus has been on the physical climate system, and indeed this is our mandate. But we are also cognizant of the increasing importance of ensuring that our research is usable and relevant to societal needs. We interact with multidisciplinary scientists as well as users, and decision and policy makers. Major advancements are occurring in observations, understanding, modeling, and product development for water resources, climate extremes, and other aspects of climate that will enable a wide range of climate services and inform decisions on water resource management and practices.

The 7th Conference has 19 distinguished invited speakers to lead topics in the plenary sessions and 66 scientists who volunteered to convene the 23 contributed sessions. The topics have been loosely classified into contributions to the climate system, land, and atmospheric aspects. Several Climate Variability and Predictability Project (CLIVAR) scientists serve on the Conference Program Committee and, in both the plenary and contributed sessions, many topics span the breadth of the GEWEX and CLIVAR domains. These include observations and modeling of extremes of climate, how monsoons vary and change, the global energy and water cycles, processes and phenomena, and modeling of regional and global aspects of climate and the water cycle. The plenary sessions all feature panel discussions and interactions with the audience. The poster sessions are expected to be the focus of a tremendous amount of profitable interactions among the Conference participants.

More specifically, topics in the Conference will include: (i) understanding, modeling, and predicting all aspects of the water and energy cycles and the climate system as a whole; (ii) land-surface feedbacks, including effects of land and water management; (iii) hydrological impacts and prediction; (iv) process studies involving clouds, rainfall, water vapor, aerosols, atmospheric dynamics, radiation, and land-atmosphere interactions; (v) observations and GEWEX data sets, including satellite observations; and (vi) phenomena such as monsoons, storms, convective cloud systems, the Madden-Julian Oscillation, surface fluxes, the boundary layer, and their impacts on society. The Chair of the International Geosphere Biosphere Project Scientific Committee, Dr. James Syvitski, is the guest speaker at the banquet, and he will no doubt place our science in a broader context.



The recently adopted GEWEX Vision is as follows: water and energy are fundamental for life on Earth. Fresh water is a major pressure point for society owing to increasing demand and vagaries of climate. Extremes of droughts, heat waves and wild fires, as well as floods, heavy rains and intense storms increasingly threaten to cause havoc as the climate changes. Other challenges exist on how clouds and aerosols affect energy and climate. Better observations and analysis of these phenomena, and improving our ability to model and predict them, will contribute to the information needed by society and decision makers for future planning.

The articles in this newsletter issue highlight the challenges ahead in dealing with "trending water" and provide the wisdom from established scientists and leaders in the field. However, we especially look forward to welcoming new students, post docs, and early career scientists into the GEWEX and WCRP communities. We need their new ideas on how to broach and resolve long-standing problems that will lead to better information systems on water and climate variations and change. I look forward to an exciting Conference and hope to see you there.

The Food/Water/Climate Nexus

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In 2010-2012 about 850 million (or 15 percent) of the world population were chronically undernourished (United Nations Food and Agriculture Organization, FAO 2012: The State of Food Insecurity in the World). In fact this number has dropped from 1000 million in 1990 as a result of increasing agricultural production (between 2 and 4 percent per annum) over the last 50 years—although since 2008 this increase may have stalled. More than 40 percent of the increase in food production has come from irrigated areas, which have doubled in size, primarily in Asia (FAO Statistical Year Book 2013). The rest has come from increasing yields through improved fertilizer input and technology. These trends are not uniform across the world, with much higher growth in Asia compared to Africa. These dramatic improvements in food production have come at an environmental price. Groundwater levels have dropped over most of the major irrigated regions (Wada et al., 2010; Rodell et al., 2009), high nutrient use has created a web of pollution affecting the environment and human health, and there are continuing pressures on forest and natural regions.

In the last decade we have seen considerable climate variability, with a succession of floods and droughts across the world (e.g., in China, India, Pakistan and Australia, North America, Russia and Europe). We have also seen storms of unprecedented intensity, such as Hurricane Katrina and Cyclone Haiyan, and the recent severe storms in the UK, the latter leading to flooding not seen for 100 years. All of these events have put pressure on food regionally and globally, with food prices doubling over the last decade. This apparent increase in variability may just be a consequence of natural variability, although as Trenberth (2012) comments: *all weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be*.

Water availability is a growing constraint in areas where a high proportion of renewable water resources is already being used. Water scarcity increasingly constrains irrigated agriculture, particularly in the most highly water-stressed regions. Many important food production regions depend on groundwater, while declining aquifer levels and the extraction of non-renewable groundwater presents a growing risk to regional food production. About one-fifth of the world's population already live in countries with water scarcity (defined by areas where annual water supplies drop below 1,000 m^3 per person per year). This scarcity of water extends in a band from southern U.S. to North Africa, the Middle East, Pakistan, India and northern China.

In the coming decades, climate change may bring further risks and unpredictability to food supply—from high temperatures, increased evaporation, shifts in rainfall patterns and the frequency and duration of extreme weather events. Water availability and its distribution are likely to be profoundly affected. While warming may extend the frontiers of agriculture in higher latitude areas (in both the northern and southern hemispheres), it is anticipated that key agricultural systems will have to cope with new temperature, humidity and water stresses. These pressures are on top of an already difficult situation with potentially a further 2 billion people to feed by 2050 and the increasing aspiration of people to consume more food and food of higher quality. There is already little scope for the easy expansion of agricultural land. At present, more than 1.5 billion hectares (about 12 percent of the world's land area) is used for crop production. Although considerable amounts of land are potentially suitable for agriculture, much of this land is covered by forests, protected for environmental or cultural reasons or used for urban settlements. This all makes the need to manage land and water use even more urgent.

Our uncertainty in predictions of future water resources comes from many sources, in particular, the uncertain responses of the global economy and the political system, the continuing uncertainties in climate models and the uncertainties in the impact models (which translate climate and the socio-economic scenarios into predictions of future water availability and scarcity). In the last five years, climate and sectoral impact scientists have come together to explore more thoroughly these uncertainties and provide a blueprint of reducing them in the future. The Water Model Intercomparison Project (WaterMIP) compared 11 global land surface and hydrology models and highlighted the very large range of outputs. The simulated range in global runoff was 45 percent of the mean value (290 to 457 mm per annum), with an even larger variability in individual basins, in particular in semi-arid regions (Haddeland et al., 2011). The GEWEX sponsored LandFlux Project has focused on global evaporation by comparing 12 monthly mean land-surface heat flux products, including satellite-based estimates, products of reanalyses and land-surface models. A substantial variability is found with a spread of approximately 20 W/m^2 and a global average of approximately 45 W/m^2. The seasonality was generally well captured by all products; however there are large differences in the partitioning of fluxes between sensible and latent heat (Jiménez et al 2011).

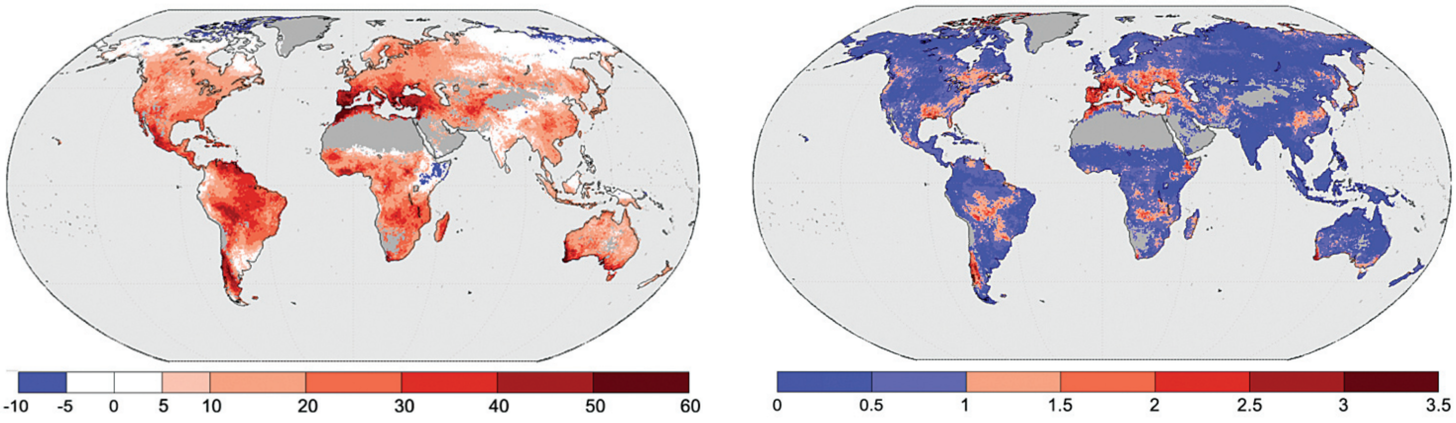
In the last year the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) has built upon these initiatives, producing a comprehensive analysis of the uncertainties arising from the combination of climate models and impact models (Warszawski et al., 2013). This major international effort has examined the predictions and uncertainties in six sectors (water availability, river flooding, coastal flooding, agriculture, ecosystems, and energy demands) using a coherent set of climatic and socio-economic scenarios. In total the study used over 30 impact models, five GCMs and four representative concentration pathway (RCP) scenarios. The results of the ISI-MIP provide a unique and systematic overview of the state of the art of climate impact research across sectors.

To assess future water scarcity ISI-MIP used 11 global hydrological models (GHMs) driven offline by five climate models. Schewe et al. (2013) shows that climate change is likely to exacerbate regional and global water scarcity. The ensemble average of the models suggests that a global warming of 2°C above present (approximately 2.7°C above pre-industrial) will severely deplete the water resources for an additional 15 percent of the global population and will increase the number of people living under absolute water scarcity (less than 500 m^3 per capita per year) by another 40 percent (according to some models, more than 100 percent), compared with the effect of population growth alone. For some of these impacts, the steepest increase is seen between present day and 2°C temperature rise, whereas indicators of very severe impacts increase unabated beyond 2°C. At the same time, the study highlights large uncertainties associated with these estimates, with both global climate models and GHMs contributing to the spread. GHM uncertainty is particularly dominant in many regions affected by declining water resources.

A similar model ensemble is used by Wada et al. (2013) to assess the effect of climate change on irrigation water demand (IWD). The ensemble suggests an increasing trend in future IWD, but the increase varies substantially depending upon the degree of global warming. Under the highest greenhouse gas emission scenario (RCP 8.5; Riahi et al., 2011), IWD will considerably increase during the summer in the Northern Hemisphere (more than 20 percent by 2100), and the present peak IWD is projected to shift one month or more over regions where 80 percent or more of the global irrigated areas exist and 4 billion people currently live. Again uncertainties arising from GHMs and global climate models (GCMs) are large, with GHM uncertainty dominating throughout the century but GCM uncertainty increasing substantially from the midcentury, indicating that in the near term the choice of GHM outweighs the uncertainty arising from the choice of GCM and associated emission scenario.

The studies mentioned above considered only the long-term average condition and did not consider potential changes in interannual and seasonal variability. But, it is often the extreme events, floods and droughts that have the greatest impact on water, food production and livelihoods. Prudhomme et al. (2013) used the ISI-MIP framework to assess future droughts. Drought severity was defined as the fraction of land under runoff deficit (runoff less than a drought threshold) and is a measure of the time-integrated effect of several interlinked processes and stores, including precipitation, evaporation and soil moisture storage. Results from the ensemble of linked global climate and hydrology models show a likely increase in the global severity of drought at the end of the 21st Century, with systematically greater increases for the RCPs describing the stronger radiative forcings. Under RCP8.5, droughts exceeding 40 percent of the non-arid parts of the land area are projected to increase by nearly half of the simulations. This increase in drought severity has a strong signal-to-noise ratio at the global scale and regionally (see figure below). Southern Europe, Middle East, Southeastern United States, Chile and South West Australia are identified as possible hotspots for future water security issues. Again the uncertainty due to the hydrology models is greater than that from GCMs. In particular, the inclusion of a hydrology model that accounts for the dynamic response of plants to carbon dioxide and climate has a dramatically different prediction from those that do not. This demonstrates that different representations of terrestrial water cycle processes in global hydrology models are responsible for a much larger uncertainty in the response of hydrological drought to climate change than previously thought. When assessing the impact of climate change on hydrology it is therefore critical to consider a diverse range of models to better capture the uncertainty associated with the models. These studies also illustrate that there is considerable potential for improved water resource simulations through hydrological model development.

WaterMIP, LandFlux and ISI-MIP studies graphically illustrate that there is still much left to do to understand the climate/water/food nexus, and that there are considerable uncertainties in our projections of water scarcity in the 21st Century. However, a clear picture is emerging of increasing water scarcity and the limitation of food production by water and climate. That we need to improve the representation of climate



Percentage change in the occurrence of days under drought conditions for the period 2070–2099 relative to 1976–2005, based on a multi-model ensemble (MME) experiment under RCP8.5 from five global climate models and seven global impact models. MME Mean annual change (left) and associated signal to-noise ratio (right; Prudhomme et al., 2013).

in models is a given and has been an objective of World Climate Research Programme and GEWEX research strategies since their inception. It is also clear that we need to better understand the causes and impacts of climate variability and this forms a central part of the new GEWEX science questions. Perhaps the novel aspects that these studies have thrown into relief are the urgent need to improve our impact models and the need to understand and model the interactions between the components. For example, on the physical side it seems essential to understand and include the effects of carbon dioxide fertilization (where higher ambient carbon dioxide concentrations in the atmosphere literally "fertilize" plant growth), both on our agricultural and water security projections. Linked to this is how vegetation, land cover and land use will change in a changing climate and how this will impact water resources. Even more challenging will be the link to political, social, economic and technological changes.

In the mid 20th Century few people would have predicted that with a doubling of world population it would still be possible to feed the majority of the world and that undernourishment would actually be declining. There is, however, no place for complacency. There are indications that food production is levelling off, which may be partly a result of the climate instability we have experienced in the last few years. The increases in food production have also come with environmental costs, including a general depletion of groundwater, increasing environmental pollution, and loss of forests. Feeding another two billion people by 2050 will require very careful management of our environment and deep understanding of the interactions between the different components of our Earth system.

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Impacts of Human Activities on Continental Water Cycles

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In the era of the Anthropocene (Crutzen, 2002), where human impacts on natural processes are large and widespread, it no longer makes sense to study only natural hydrological cycles (Oki and Kanae, 2006). Anthropogenic effects on the water cycle over land were thought to be small (in part because the global land area is small in comparison with the oceans, and populations were small) until the recent era (Gleick et al., 2013). Today it is clear that anthropogenic activities, such as land use and land cover change, irrigation, groundwater withdrawals, and reservoir storage, influence sea level. This has been observed using in situ observations (Gornitz et al., 1997; Chao et al., 2008; Konikow, 2011), satellite observations (Rodell et al., 2009; Moiwo et al., 2012), and modeling studies (Lettenmaier and Milly, 2009; Wada et al., 2010; Pokhrel et al., 2012), even though uncertainties are large (Konikow, 2013; Pokhrel et al., 2013).

Apart from the human influence on greenhouse gases, changes in land use and land cover (Anderson-Teixeira et al., 2012), and interventions on water cycle components (Oki et al., 2013), such as irrigation (Rosnay et al., 2003; Guimberteau et al., 2012), have a large impact on ecosystem climate regulation. Globally, 18 percent of total cropland (2.73×10^6 km^3) is equipped with irrigation facilities and estimated to evapotranspirate an additional 1530 km^3 of water annually (Hanasaki et al., 2010). This amount corresponds to approximately two percent of the total evapotranspiration from land; however, irrigation can have regional impacts on the prediction of global air temperature and precipitation (Puma and Cook, 2010). Wada et al. (2013) estimated that human water consumption alone increased the frequency of global hydrological drought (the occurrence of anomalously low streamflow) by 27 (±6) percent. The intensification of drought frequency is most severe over Asia (35 ± 7 percent), but also substantial over North America (25 ± 6 percent) and Europe (20 ± 5 percent). Integrated land surface models that consider biogeochemical cycles and anthropogenic interventions explicitly need to be developed and implemented in order to provide more realistic climatic predictions and impact assessments, and to support the design of practical adaptation measures.

Recently, a comprehensive assessment was conducted to investigate the impacts of anthropogenic interventions (e.g., man-made reservoirs, water withdrawals, and water consumption) on the global terrestrial water balance (Haddeland et al., 2013). Based on a large number of simulations using eight

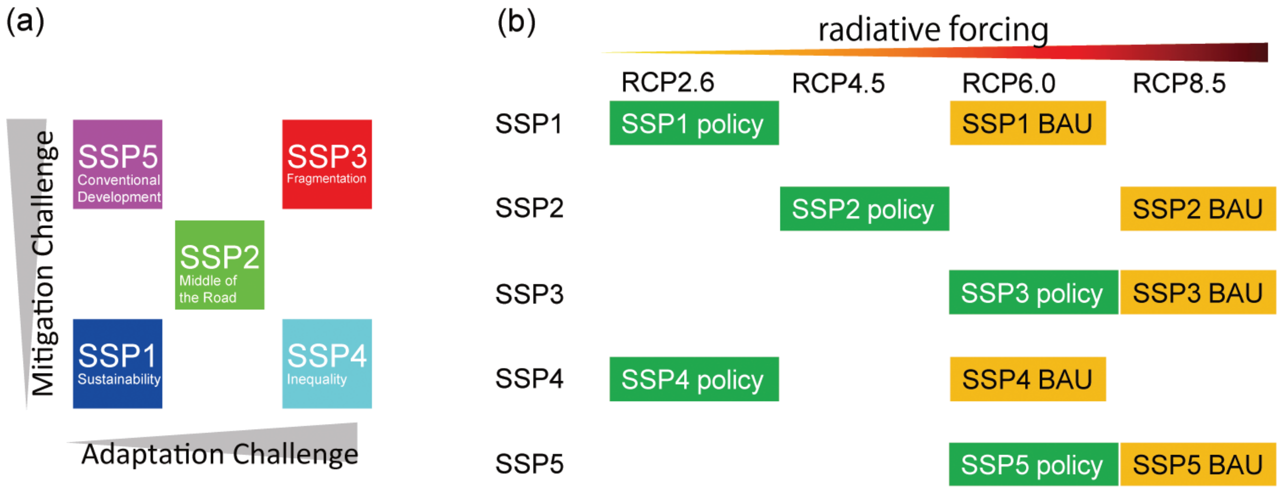

Figure 1. Scenarios used in Hanasaki et al. (2013a,b). (a) Socio-economic scenarios termed SSPs. Five scenarios are located in a conceptual space of mitigation and adaptation challenge. (b) Scenario matrix or combination of socio-economic and radiative forcing scenarios. Since radiative forcing would be affected by the future climate policy, the radiative forcing varies within each socio-economic scenario. Policy for effective climate policy and BAU for Business as usual or no policy. Figures from Hanasaki et al. (2013a).

global circulation models (GCMs) and seven global hydrological models, the assessment concluded that these impacts on the long-term global terrestrial water balance are small. However, they are far from negligible in several large river basins in Asia and the western United States where cropland is largely irrigated. The effect of current anthropogenic interventions on the mean annual runoff in those rivers was estimated to be larger than the projected changes for a 2-3 K increase in global mean temperature.

A detailed global water scarcity assessment was conducted for the 21st Century (Hanasaki et al., 2013a,b) and is one of the first examples of a climate change impact study that is fully compatible with the new global change scenario proposed by Moss et al. (2010). They used a global hydrological model termed H08 (Hanasaki et al., 2008a,b) that included sub-models for major human activities, such as water extraction and reservoir operation. The latest radiative forcing and socio-economic scenarios, namely Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) and Shared Socio-economic Pathways (SSPs; O'Neill et al., 2012), which were developed by community efforts, were applied. RCPs consist of four scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). The numbers indicate the increase in radiative forcing by the end of 21st Century compared to the pre-industrial level. SSPs consist of five scenarios (SSP1-SSP5) depicting considerably different views of the world. A brief description for each scenario is shown in Figure 1(a) above and the Table on the right.

Water availability and use were estimated globally for the combination of SSPs and RCPs shown in Figure 1(b). Figure 2 shows water scarcity in the present and the middle of the 21st Century. Water scarcity is assessed using an index called the Cumulative Abstraction to Demand ratio (CAD; Hanasaki et al., 2008b), which shows whether sufficient volume of water is available when it is needed. It ranges between zero (water is lacking throughout the study period) and one (water is sufficient throughout the study period). Water scarcity is alleviated if CAD increases. Under the SSP3 scenario (Fragmented world), large parts of the world are shown in dark red, which indicates that water scarcity has considerably worsened globally and that water is less available when it is needed. In con-

Five SSP Scenarios and Views of the World

(After O'Neill et al., 2012 and Hanasaki et al., 2013a)

Scenario	Views of the World
SSP1	Sustainability: it represents a sustainable world where it is easy to mitigate and adapt to climate change because of the rapid development of low-income countries, reduced inequality, rapid technology development, and a high level of awareness regarding environmental degradation.
SSP2	Middle of the Road: it represents conditions where the socio-economic trends of recent decades continue. Reductions in resource use and energy intensity are achieved at historic rates.
SSP3	Fragmentation: it represents conditions where it is difficult to mitigate and adapt to climate change because of extreme poverty and a rapidly growing population. There is serious degradation of the environment and technological change in the energy sector is slow. Because of the limited coordination between regions, use of local energy resources is enhanced.
SSP4	Inequality: it represents a highly unequal world both within and across countries.
SSP5	Conventional Development: it represents a situation where it is easy to adapt owing to robust economic growth, but difficult to mitigate the effects of climate change because the energy system is dominated by fossil fuels.

trast, under the SSP1 scenario (Sustainable world), most of the regions except Africa are shown in white, which indicates that water scarcity doesn't change significantly from the present level. Here, CAD in Africa is decreased under every scenario. The difference in these two scenarios is partly attributed to the influence of climate change (i.e., difference in RCP used) and largely to drastic increase in water use due to population and economic growth and technological change (i.e., difference in SSP used). Among the five global scenarios, only the SSP1 scenario stabilized the level of water scarcity at the present level, except for Africa, but the other scenarios worsened the water scarcity for the vast area of the world.

Natural flooding can be simulated physically as a fraction of an inundated area using a detailed global elevation map (Yamazaki, 2011), but in reality is highly controlled by human activities (e.g., river embankment) that are not well considered in current modeling systems. Simulating inundation area and depth is critically required when climatic hazard information is translated into economic (and possibly human) impact, and will be challenged in the coming years in addition to the coupling of material cycles, such as carbon and other nutrients, associated with hydrological cycles. These developments in hydrological components of modeling will certainly contribute to the future Earth System Models (e.g., Watanabe et al., 2011).

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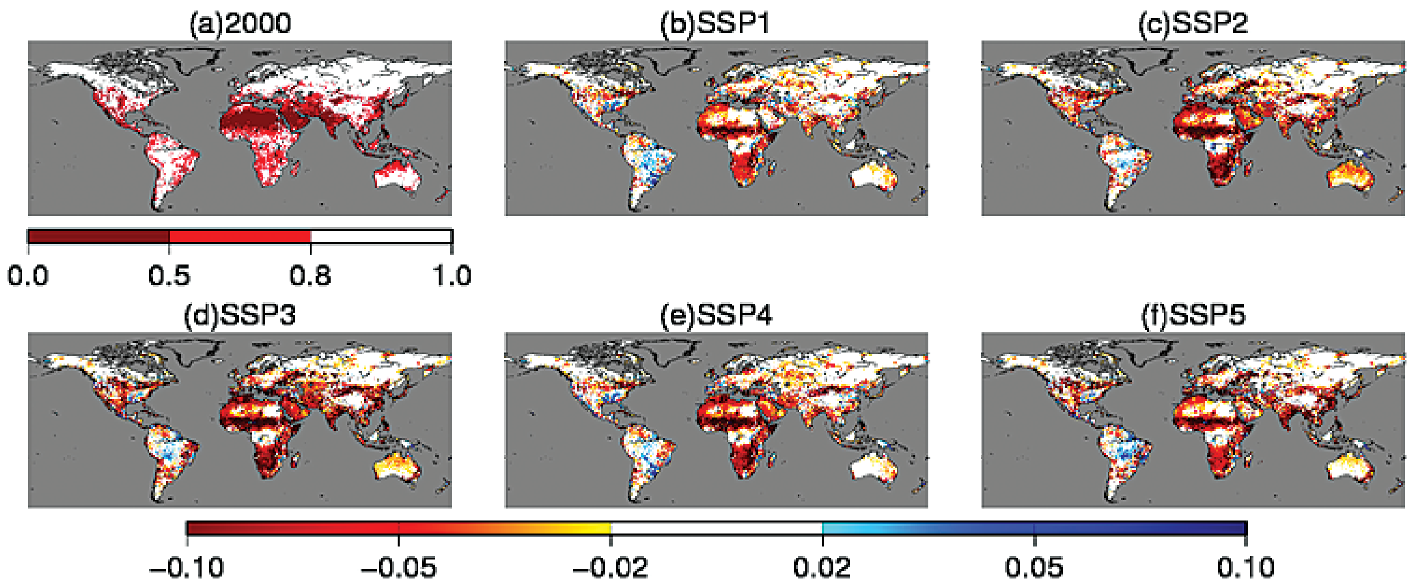

Figure 2. Water scarcity index (Cumulative Abstraction to Demand ratio). (a) CAD in 2000. Dark red shows the regions with high water stress. (b)-(f) The difference in CAD between the middle of 21st century and 2000 for five SSPs. All include climate policy. Red (Blue) color indicates the water scarcity worsened (improved). White indicates the water scarcity level does not change from the present level. Figures after Hanasaki et al. (2013b).

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How Good are our Observations of the Global Water and Energy Budgets?

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Good baseline estimates of the global water and energy budgets form the basis from which we can understand regional impacts of climate change as well as any ongoing trends. Global observations of radiation at the top of the atmosphere (TOA) are reasonably well constrained by direct satellite observations since the Earth Radiation Budget (ERB) instrument launched in October of 1978 aboard the Nimbus-7 satellite. Top of the Atmosphere (TOA) fluxes have generally been balanced within 3-4 Wm^{-2} (Loeb, et al. 2009) which represents the limit of our current observing capabilities. At the Earth's surface, the energy fluxes are not balanced, and instead require sensible and latent heat fluxes from the surface into the atmosphere to restore equilibrium. Unfortunately, neither radiation nor sensible and latent heat fluxes are directly observed at the Earth's surface except for some very limited in situ observations. Global estimates can be derived from satellite observations but require inversion techniques and assumptions that introduce random and systematic errors. The latter often have space-time structures related to how well the atmospheric composition and cloud structures conform to the algorithm assumption. While papers such as Trenberth et al. (2009) and more recently Stephens et al. (2012) have attempted to pull together global estimates of the water and energy fluxes, they have relied on a combination of observations, reanalyses, and sometimes just intuition as to the quality of individual data sets available from the literature. Consequently, their estimates of surface fluxes differ rather substantially. Their values are summarized in the Table at the top of the next page.

As can be seen, the estimate of Stephens et al. (2012), significantly increases both the downwelling shortwave and longwave fluxes at the surface to reflect the latest values in the literature obtained by the CERES team (Kato et al., 2013), as well as the GEWEX Surface Radiation Budget (SRB) product (Stackhouse et al., 2011). The resulting difference is most pronounced in the two sensible heat fluxes, which differ by 30 percent and the latent heat fluxes, which differ by 10 percent. Since the latent heat flux is directly related to evaporation and thus precipitation, the GEWEX Global Precipitation Climatology Project (GPCP) can also be brought to bear on these numbers. The latest estimates from GPCP (Adler et al., 2012) are given as 2.68 ± 0.19 $mmday^{-1}$ for the global mean precipitation which is within the error bars given by the two flux papers, but lower than the mean values, especially in the case of the Stephens et al., (2012) paper which leads to nearly 14 percent more precipitation than reported by GPCP. Moreover, Adler has argued (2013 GEWEX panel meeting) that GPCP is already on the higher end of the currently available precipitation estimates and that some of the arguments used

Radiative fluxes as published by Trenberth et al. (2009) and Stephens et al. (2012)

Paper	SW ↓ [wm^{-2}]	SW ↑ [wm^{-2}]	LW ↓ [wm^{-2}]	LW ↑ [wm^{-2}]	SH [wm^{-2}]	LH [wm^{-2}]	Precip to balance LH [mm day-1]
Trenberth et al.	161	21	333	396	17	80	2.84
Stephens et al.	165±6	23±3	346±9	398±5	24±7	88±10	3.04

by Stephens et al. (2012), to increase the precipitation beyond the current GPCP estimate may not be valid. In short, it appears as if uncertainties in the absolute values of current observations are perhaps larger than each of the closure studies imply. Using globally available satellite and in situ observations, the GEWEX Data and Assessments Panel has made it a priority to better understand these discrepancies and foster the observations needed to close the TOA and surface water and energy budgets through physically derived satellite products and in situ observations.

One issue that must be carefully considered when relying on retrievals of geophysical parameters instead of direct observations is the assumptions that go into each specific retrieval algorithm. At a minimum, the retrieval algorithms should be independent of each other. This avoids any potential risk that output products, either directly or indirectly, consider water and energy budget closure and adjust their solution accordingly. The Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) product (Kato, 2013), for instance, is designed explicitly to balance the energy budgets at the surface except for a term of 0.6 W/m^2 corresponding to the best estimate of the current net absorption into the global oceans. Also important is that products should, to the extent possible, use similar ancillary data. Without such commonality, two ocean or vegetated land areas can actually be quite different and budget calculations can run afoul of non-consistent definitions. Beyond these potential issues with specific products, satellite retrieval of water and surface energy fluxes can have significant errors stemming from the forward radiative transfer calculation used as a basis for the physical inversion (Stephens and Kummerow, 2007). These can be large, and can have regional and temporal patterns that fit neither the classical bias nor random error categories. Instead, the errors can follow changes in atmospheric composition and cloud properties whose characteristics are assumed constant in the forward model.

To shed some light on the apparent inconsistencies at the global scale, we focus here on the water budget of tropical oceanic boxes where products are perceived to be perhaps more reliable. Three tropical (15°S, 15°N) ocean regions, including the Indian Ocean (60°-90°E), the West Pacific (150°-180°E) and Central Pacific (160°-130°W) are examined over the period 1998–2007. Because the budget is regional, not only must latent heat (*E*) balance precipitation (*P*), but *E* - *P* must be balanced by the water vapor divergence ($\Delta \cdot Q$) from the box. Evaporation is obtained from the GEWEX SeaFlux product (Clayson et al., 2014). Satellite data are used to estimate the bulk flux variables in that formulation. SeaFlux uses a neural network version of the Coupled Ocean-Atmosphere Response Experiment (COARE 3.0) bulk parameterization of an air-sea fluxes algorithm (Fairall et al., 2003) to calculate surface turbulent fluxes (Clayson et al., 2014). The resultant 3-hourly 0.25° x 0.25° gridded data set was downloaded from *http://seaflux.org/*.

The Global Precipitation Climatology Project (GPCP) One-Degree Daily Precipitation Data Set Version 1.2 (Huffman et al. 2001, 2012) is one of the most widely available and utilized satellite-gauge merged precipitation products. These data are produced by aggregating satellite and products into monthly composites, blending them with monthly gauge products at that scale and subsequently using any biases between the satellite-only and the satellite-gauge composite to calibrate the gridded daily satellite-based observations. Ocean data are primarily satellite derived, as few gauge data exist in oceanic regions. GPCP data were obtained from *http://precip.gsfc.nasa.gov/*.

The European Centre for Medium-Range Weather Forecasts (ECMWF) European Reanalysis Assessment Interim (ERA-Interim, Dee et al., 2011) is used to compute water vapor divergence. ERA-Interim incorporates observations and satellite data into 12-hourly analysis cycles with a four-dimensional variational assimilation scheme. The forecasts from the analysis cycles are combined with observations to produce an evolving model that observations constrain (Dee et al., 2011). While surface parameters are provided at 3-hourly resolution, pressure level products needed to compute the water vapor divergence are given at 6-hourly intervals. The ERA-Interim full resolution 0.75° x 0.75° gridded data was accessed from *http://apps.ecmwf.int/datasets/*.

The three products are completely independent except for the use of SSMI data by all three products. This commonality is not thought to affect any of the conclusions. Monthly averages (1998-2007) of three tropical regions' atmospheric water budget components are shown in Figures 1-3. SeaFlux *E* and GPCP *P* time series provide the primary elements of atmospheric moisture cycling in these figures. The inclusion of SeaFlux *E* - GPCP *P* and ERA-Interim divergence complete the major components of atmospheric moisture conservation.

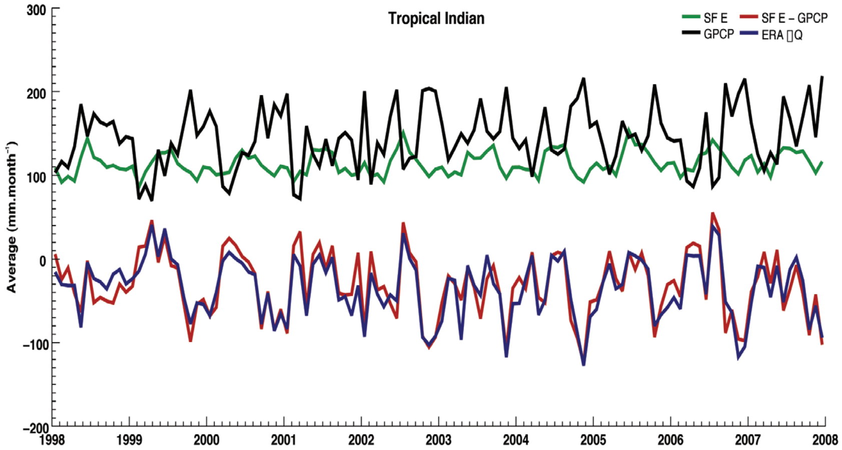

Figure 1. Monthly average time series of SeaFlux (SF E) evaporation and GPCP precipitation, as well as ERA-Interim evaporation and precipitation over the Tropical Indian Ocean (60°-90°E, 15°N-15°S). Observation-based freshwater flux (E - P) and ERA-Interim atmospheric moisture divergence (ΔQ) are shown.

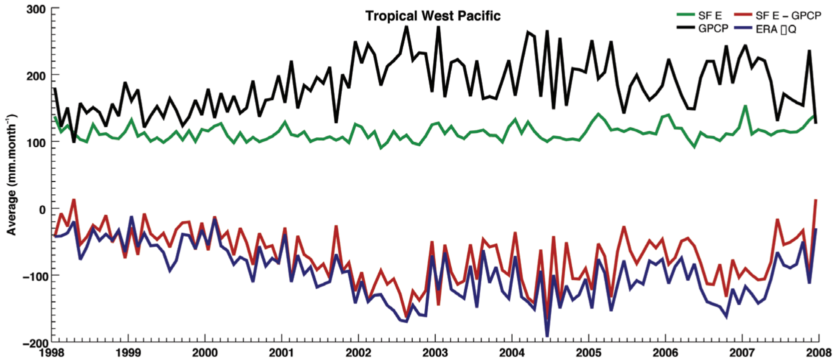

Figure 2. As in Figure 1, but for the Tropical West Pacific (150°-180°E, 15°N-15°S).

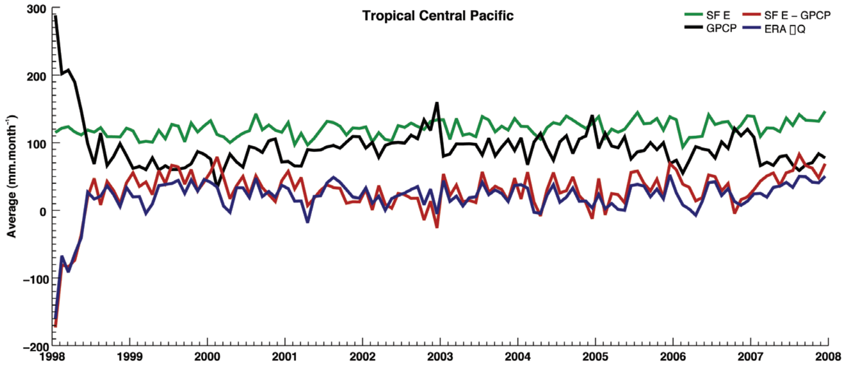

Figure 3. As in Figure 1, but for the Tropical Central Pacific (160°-130°W, 15°N-15°S).

Results

The Tropical Indian region features a very close relationship between *E - P* from observations and ΔQ from ERA-Interim (Figure 1) that is reinforced by a correlation of 89 percent. Over the period 1998–2007, the average difference between *E - P* and ΔQ is 3.4 mm.month^{-1} at the monthly scale, or 3.0 percent of average *E* and *P* values. Monthly averages of *E - P* and ΔQ show little difference over the whole 10-year period, which implies this region's water balance can be closed using two independent data sources.

The Western Pacific behaves differently. While the monthly fluctuations in these time series exhibit considerable consistency between *E - P* and ΔQ, as indicated by a correlation of 93 percent, the increasing trend in the difference between the two measures is apparent in Figure 2, going from fairly good agreement to almost 25 mm.month^{-1}. This trend is not due to satellite drift since it is not observed in the other basins. Instead, it must be a regional error such as the forward model errors described earlier, or a problem with the reanalysis drifting in this region as more observations are added.

The Central Pacific, like the Indian Ocean shows good agreement between *E - P* when compared to ΔQ, suggesting that the atmospheric moisture budget almost achieves closure. An average difference of -8.2 mm.month^{-1} (7.2 percent) is due to the observed fluxes being slightly higher than moisture divergence from ERA-Interim, with the two being highly correlated. However, although there are periods where *E - P* and ΔQ are close, some considerable separations also occur (Figure 3). These separations are associated with periods when GPCP precipitation is lower than 90 mm.month^{-1} but the reanalysis data does not feature equivalent dips in precipitation. El Niño conditions in 1998 do not affect the closure achieved, despite the large increase in precipitation that occurs.

The Indian and Central Pacific, as well as Eastern Pacific and Atlantic Ocean (not shown) lead to rather good closure. The Western Pacific has a pronounced but unexplained trend towards smaller divergences relative to *E - P*. With a large fraction of the global precipitation falling over these equatorial regions that contain the Inter Tropical Convergence Zone (ITCZ), it becomes less likely that the global observations of GPCP, which are anchored by gauge data over land, can be significantly biased as suggested by Stephens et al., (2012).

Yet, trends in the Western Pacific do raise the specter that biases are possible and not fixed in any of these products. Better observations, such as may come from the Global Precipitation Mission (Hou et al., 2014) and more emphasis on climate quality products are still needed to close the budgets from observations alone.

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Different Perspectives in Land Surface-Atmosphere Research

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The upcoming 7th International Scientific Conference on the Global Water and Energy Cycle: *Trending Now: Water*, will provide an excellent forum for the exchange of ideas on research areas related to climate, land surface and the atmosphere; in particular, small and large breakthroughs in model development, observational analyses, applications, and the implications of these. At the same time, a number of outstanding controversies related to the puzzling inconsistencies in scientific results that occur because of opposing viewpoints or perspectives, will drive discussions in the lecture rooms and hallways.

The climate system and its components (e.g., terrestrial hydrology and land surface processes) can be observed and analyzed using many different approaches and perspectives. For example, soil moisture can be seen as a regulator of atmospheric fluxes (e.g., playing a crucial role in extreme events, such as droughts and heat waves) or as a resource of fresh water for various uses. However, a truly integrated perspective on soil moisture would require including all of its functions, processes, interactions, feedbacks, responses and scales, which is impossible. Scientists and the general public have a tendency to reduce an object of study to a constrained conceptual framework. However, interesting questions can arise when we (temporarily) leave our preferred framework and let ourselves become inspired by other perspectives. In discussions among experts from different research areas, confrontations between these frameworks rarely lead to a uniform consensus on the issue of interest, but occasionally trigger new insights or approaches.

Included in the following text are a number of topics related to land surface and climate research that can be approached from very different viewpoints, and for which decades of research have not managed to resolve the controversies stemming from the confrontation among these perspectives. A number of fairly arbitrary examples were selected at different scales without pretending to give the answer to which approach is actually the correct one. Nevertheless, it is the authors' hope that these will trigger the Conference participants to occasionally step out of their own comfort zone, turn the argument upside down, and refresh their viewpoint on issues that they thought were "done and dusted" or were deemed impossible to solve.

What level of complexity is required to reliably predict evapotranspiration?

The following examples show that increased simplicity, as well as increased complexity can lead to improved predictions of the hydrological cycle in land surface models.

The land surface model (LSM) components related to transpiration, and carbon dioxide uptake via photosynthesis, have seen tremendous advancement in the past decades, going from simple bucket schemes representing root extraction to complex multilayer schemes with detailed biophysical process representations (see Figure 1). This increase in complexity is usually justified by the desire to describe the canopy exchange processes more adequately, ultimately accompanied by the claim of improved predictability of the coupled system.

To address the effect of soil water stress on transpiration (and related photosynthesis) in LSMs, a considerable number of scientists attacked the problem using a bottom-up approach where plant physiological findings guide the development of plant-water relationships. With the aim of introducing more mechanistic descriptions of plant water stress, physiologists have often proposed using combined soil-plant hydraulic models to make a connection between leaf and soil water potential (rather than soil moisture content), coupled with parameterizations of chemical signaling from roots to leaves. Although the use of soil water potential, instead of soil moisture content, is still to some degree controversial, recent findings illustrate that the prediction of the shape of the transpiration reduction function under soil drought conditions is indeed improved by including soil-plant hydraulic and chemical signalling (Verhoef and Egea, 2014).

Considerable improvement in LSMs can also be achieved when using a top-down type approach, such as described in Koster and Mahanama (2012). They further explored the idea proposed in Koster and Milly (1997) that complex LSM formulations can be examined with simple surrogate relationships, such as soil moisture–evapotranspiration and soil moisture–runoff relationships that are driven only by hydroclimatic forcings (i.e., no specific soil or plant data are involved). With this approach Koster and Mahanama substantially improved the description of the soil moisture stress term in the evaporation calculation of the complex Catchment LSM (the land component of the earth system model of the NASA/Goddard Space Flight Center), to a large degree mimicking the shape derived from the physiological findings mentioned above, which in turn led to much more reliable hydroclimatic simulations.

What drives the hydrological interaction between land and atmosphere?

A well-known model study by Koster et al. (2004) showed the degree to which precipitation at seasonal time scales is sensitive to altered soil moisture conditions. The main result is a world map showing the areas where this "coupling" is supposed to be strong, at least in the interpretation of how the world looks according to the participating models. The power of the concept of "coupling" was reinforced by an understandable conceptual model of drivers behind this coupling. A sensitivity of evapotranspiration to soil moisture and a sensitivity of precipitation to evapotranspiration are both required for allowing strong interaction between soil moisture and precipitation. These areas are found in transitional climate zones where either evapotranspiration or precipitation are constrained by available energy or water (Seneviratne et al., 2010). This study is also often used as a motivation for the development of better land surface models. Soil moisture in the experiment was modulated, which led to a noticeable precipitation response; therefore, it must be the soil that is to be held responsible for this coupling.

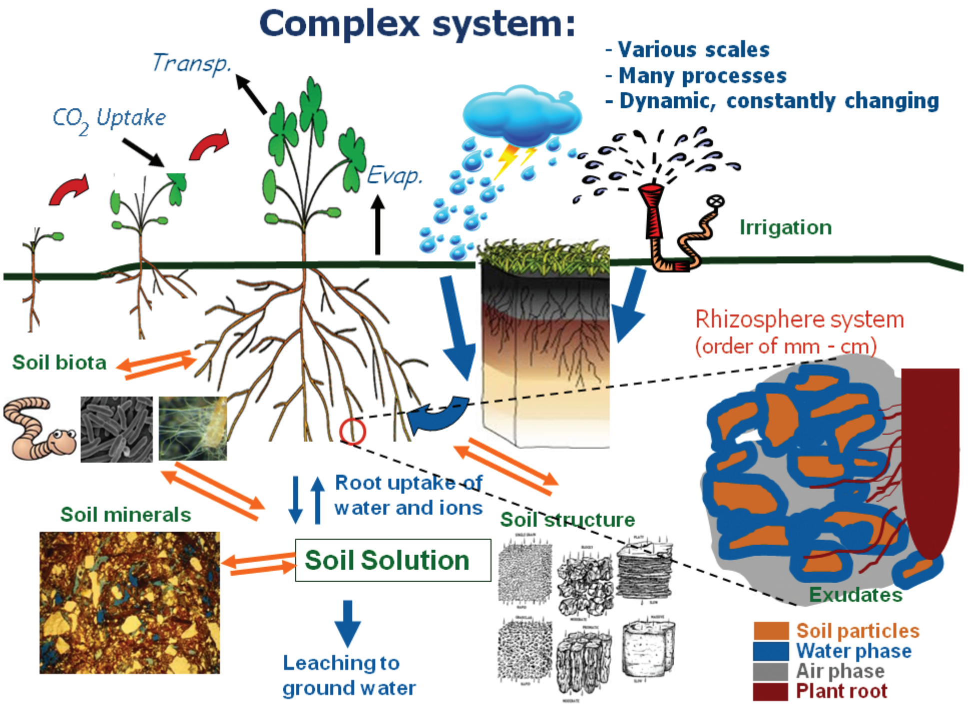

Figure 1: The complex soil-plant-atmosphere system. (Slightly adapted figure courtesy of Ahmad B. Moradi, University of California, Davis)

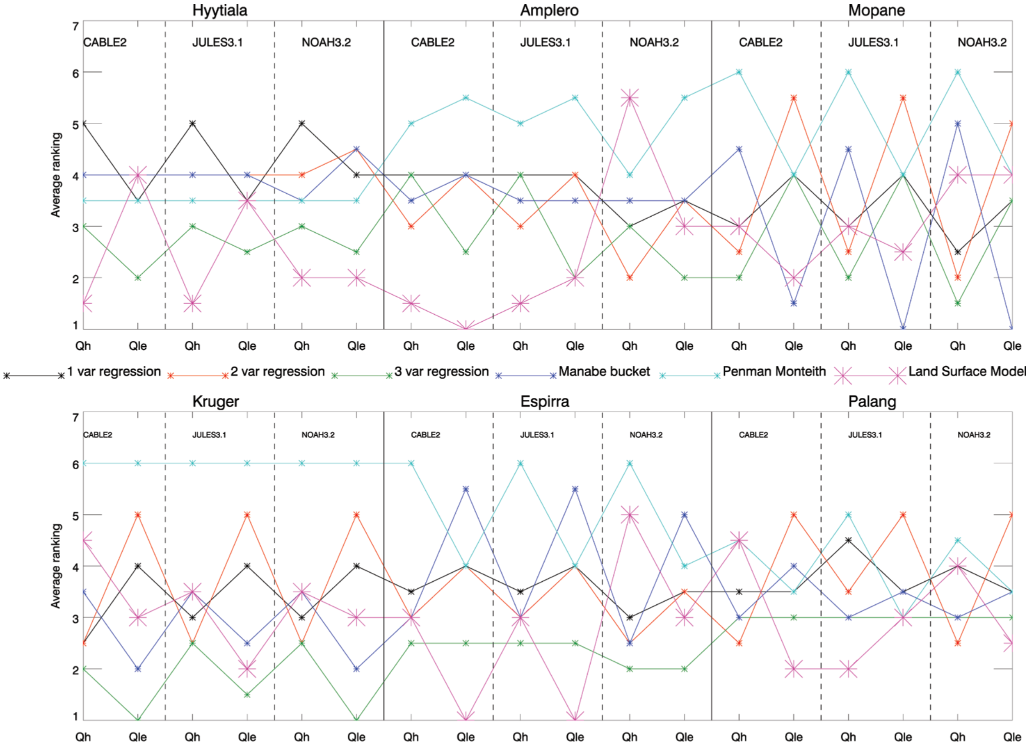

Figure 2: Ranking of an ensemble of methods to calculate fluxes at a large set of FLUXNET sites: various empirical regression models, a simple bucket scheme, a single Penman-Monteith equation, and a complex land surface model (one shown in each panel). Low ranks imply a good score compared to the other methods. Top panels show range of sites with increasing available radiation, bottom sites increase with available water from left to right (source: PLUMBER project, Martin Best and co-authors).

However, later observational and modeling studies have changed this somewhat one-dimensional picture. The exchange of moisture between the land and atmosphere does not occur at spatial scales of hundreds of kilometers as represented in the models described above. Small-scale variability related to clouds, land surface heterogeneity and topographic contrasts all affect the land-atmosphere interaction. Analysis of satellite observations by Taylor et al. (2012) illustrate the importance of small scale variability in surface wetness for the formation and advection of convective systems in the African Sahel. Interestingly, later modeling studies have demonstrated a strong dependence of this so-called coupling strength on the representation of the convection in the models used (e.g. Hohenegger et al., 2009) or on spatial resolution (Demory et al., 2013).

What drives surface fluxes at regional scales?

The concept of "benchmarking" model evaluation studies offers a vivid basis for controversial conclusions about the role of models in explaining and predicting variability in crucial processes, such as land surface fluxes. We tend to build and improve model components for the sake of understanding the drivers that explain the variability of the system—why is the evaporation on day or location x different from its value on day or location y? A physically based model is considered to add more predictive information than statistics based on calibrated responses in the past. These calibrations are only valid within the regime covered by the training data. Since we cannot calibrate on climate conditions that have not yet occurred in our instrumented period, these statistical models per definition have limited skill in an unprecedented future climatic regime.

A number of "benchmarking" projects (see the dedicated session on this theme convened by Martin Best) dare to challenge this assumption. Rather than promote model improvement by organizing multi-model comparison experiments using a set of carefully selected observations, the models are compared to a statistical benchmark—a (out-of-sample) calibrated regression model that describes the variance of the land surface fluxes solely as function of variability in the meteorological forcing. Intriguingly, the physically based models have a very hard time beating these regressions (see Figure 2), especially for limited water climate regimes. The conclusions to be drawn from this depend a lot on the exact setup of the comparison experiment and statistical model. This raises the question of what we gain from using a physically based model when the majority of all explainable variance in the fluxes comes from the forcing. This benchmarking activity is a real eye-opener that will generate considerable challenges to the model development community.

What drives human sensitivity to changes in hydrological variability?

Researchers working on the hydrological cycle are highly motivated by the need for scientific information to support important decisions used to mitigate the adverse effects of climate change on water resources. Water-related extremes are one of the major concerns, both too much water and too little of usable quality. Climate change is altering the hydrological cycle and this has become noticeable by the intensity of extreme events. A good understanding of the degree to which climate and its variability affect the availability of essential water is required and is a major driver behind a considerable volume of research that includes model development, observational programs, building forecasting tools, and tailoring information for a wide range of stakeholders.

But what really drives the vulnerability to inadequate resources of water? Is it the changing climate system? Or is it how the water is used? The increase in damages due to water related extremes (both floods and droughts) cannot be solely ascribed to a change in the intensity and frequency of extreme climate events. Population growth, the value of property, and the occupation of vulnerable geographical areas definitely play a role as well. Scenarios for future water stress in populated areas heavily rely on assumptions about these drivers. Last but not least, the expected consumption pattern of mankind is probably the main source of uncertainty when assessments of future water availability are made (see Figure 3).

A lot of our work is motivated by the desire to improve the representation of future climate conditions. But these climate outlooks or scenarios only tell a part of the relevant story that concerns the many drivers roughly identified as "socio-economic scenarios" or "shared socio-economic pathways," that are often framed as a necessary input to the climate projections rather than as a relevant outcome of future assessments. A scenario framework that takes the water availability or scarcity as a major outcome (such as planned for instance by IIASA Water Futures and Solutions; *see www.iiasa.ac.at/wfas*) deserves more public attention, at least similar to the attention for the well-known Intergovernmental Panel on Climate Change scenarios.

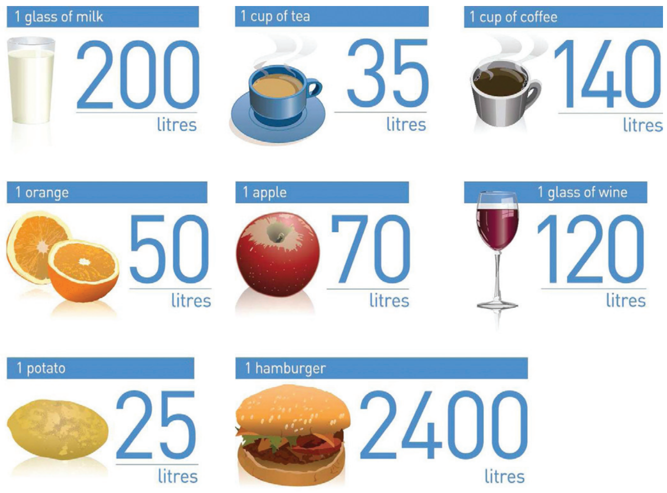

Figure 3. Liters of water needed for the production of indicated products; Source: Science Media Centre, Wellington, New Zealand. http://www.sciencemediacentre.co.nz/2009/09/11/virtual-water-what-is-it-and-what-does-it-mean-for-nz/.

Conclusions

Most climate scientists are trained to increase their knowledge and understanding within a particular area of expertise. They develop better tools and skills to unravel the complexity of the climate system and make gradual progress in better forecasts and more realistic pictures of past, present and future systems. They often operate in a limited research domain, although they are well aware of the existence of other domains and perspectives. They educate people and debate about the significance of climate change using concepts, such as "signal/noise ratios," "verification," "model skill," "improved realism," and "uncertainty levels." However, they never fully agree on many issues within their direct realm of operation or outside it, and their work is rarely presentable as a list of facts that provide guidance on relevance, urgency, risks, significance and uncertainty. Those with different perspectives will inevitably give different guidance on these crucial issues. This is a healthy process by which understanding can mature: repeatedly asking new questions arising from different perspectives to provide illuminating insights leading to new approaches that will ultimately improve mitigation strategies against hydrological phenomena that threaten lives, livelihoods and food security.

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The Cusp of Major Progress in Predicting Land-Atmosphere Interactions

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During the frontier days of the American West, surveyors and real estate speculators enticed settlement and farming of the lands beyond the Mississippi by invoking the notion of Manifest Destiny—that westward expansion by peoples of European origin was divinely ordained and providence would be provided to early settlers. Cyrus Thomas, entomologist and agronomist for the U.S. Geological Survey during western surveys in the early 1870s, is credited with originating the theory that "rain follows the plow." Land speculator Charles Dana Wilber later wrote:

> *God speed the plow…. Suppose (a wave of settlers) 50 miles in width, from Manitoba to Texas, could, acting in concert, turn over the prairie sod, and after deep plowing and receiving the rain and moisture, present a new surface of green growing crops…. No one can question or doubt the inevitable effect of this cooling condensing surface upon the moisture in the atmosphere as it moves over by the Western winds. A reduction of temperature must at once occur, accompanied by the usual phenomena of showers. The chief agency in this transformation is agriculture (Wilber, 1881).*

Similar notions were touted to induce settlement of semi-arid lands in Australia during the late 19th Century (Diamond, 2005). The basic concept that underlies such proclamations was that climate responds to the state of the land surface. The motivation for those statements was grounded more in greed than scientific inquisition, and later droughts in the 1880s and early 1900s in Australia, and during the 1890s and especially 1930s in North America dashed the notion that agriculture could assure for itself a favorable climate. Nevertheless, recent research under the aegis of GEWEX has shown that there is a kernel of truth to those ideas—a kernel that could lead to improved forecasts.

The Current State

Decades later, with the advent of computer models of the atmosphere that represented the surface water and energy cycle over land, numerical experiments could test the idea that climate depends on the land state. Shukla and Mintz (1982) showed that global rainfall patterns in an atmospheric circulation model were very different between saturated versus dry continents. This helped to revive the concept that terrestrial "boundary forcings" to the atmosphere can exert some control on climate. A long period of scientific proving has followed, starting with a growing set of sensitivity studies, gradually evolving into studies of predictability (potentially useful sensitivity) and eventually prediction (actually useful sensitivity).

Two consensus conclusions have been reached within the scientific community studying the impact of the land surface on climate. First, there is indeed sensitivity, predictability and a positive impact on prediction skill in modeling studies. There are even demonstrations of indirect observational evidence, although feedbacks in complex nonlinear systems are difficult to pin down in nature.

Second, these sensitivities, predictabilities, and examples of enhanced prediction skill are elusive and transient. The coupled land-atmosphere processes that result in significant feedbacks vary in space and time. Only certain regions appear to be "hot spots" for land-atmosphere coupling (Koster, 2004) and they seem to migrate with the seasons (Dirmeyer et al., 2009). There is also interannual variability within hot spots (Guo and Dirmeyer, 2013). Vexingly, where these couplings appear to exist, not all weather and climate models are able to capture them (Koster et al., 2011).

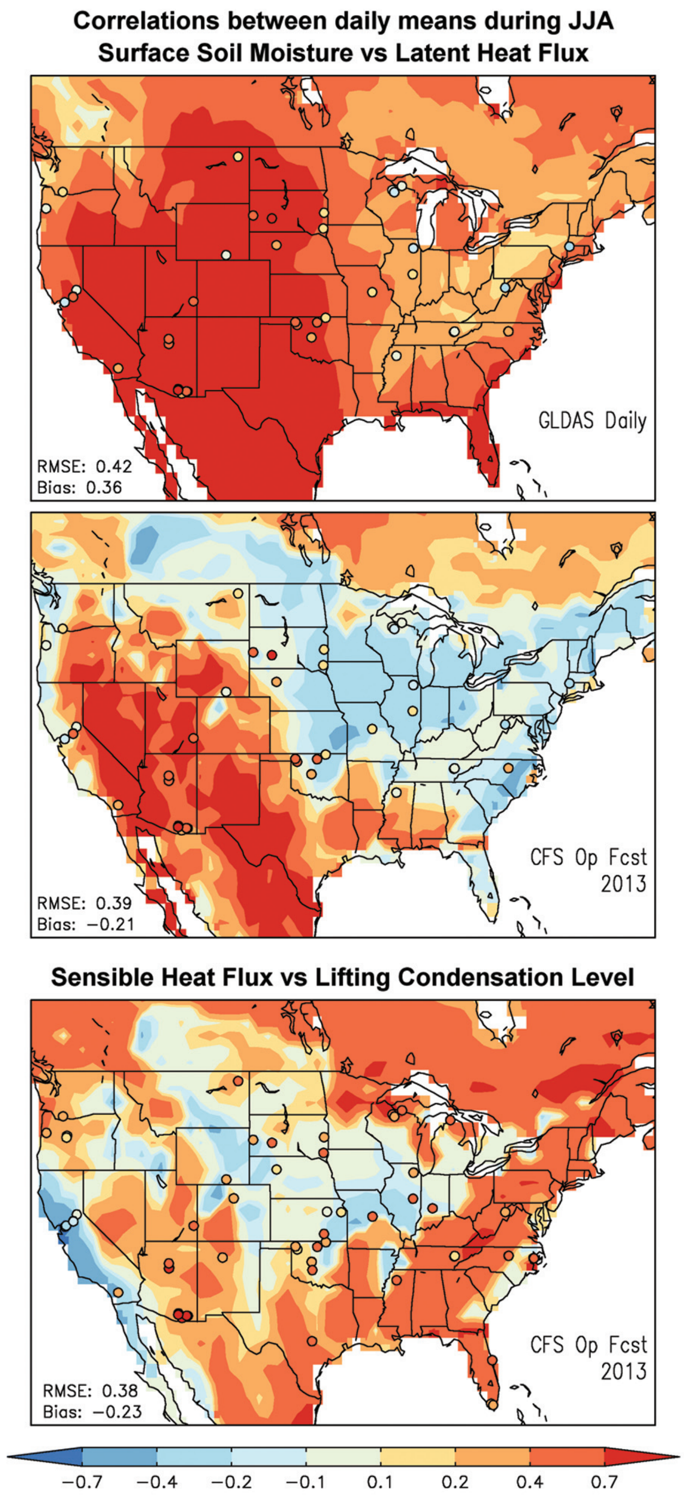
Replacing "Quick Fixes" with Physically Based Model Developmnt

Land surface models have long been used as a means to compensate for errors in atmospheric models. Because land surface models typically have more parameters than can be fully calibrated with observations, developers have justified using them as a means to tune simulated near-surface meteorology.

The European Centre for Medium-Range Weather Forecasts (ECMWF) has long used a data assimilation technique that adjusts soil moisture to minimize errors in near-surface temperature and humidity. Climate models have been particularly prone to positive surface temperature biases caused by excessive surface downwelling radiation. Although the causes of such errors are often attributable to problems in the simulation of clouds and the treatment of aerosols, it has been common to adjust land surface characteristics such as surface albedo or vegetation properties to compensate for the radiation errors.

Treating symptoms gives quick results and is usually easier that addressing the root cause of atmospheric model errors. The band-aid approach is still practiced. Warm biases over many land areas in the reanalysis and reforecasts of the National Oceanic and Atmospheric Administration Coupled Forecast System (CFSRR) prompted extension of the root zone deeper into the soil for the operational forecast model, employing additional evaporative cooling via transpiration to reduce surface temperatures.

Haphazard "corrections" inevitably introduce further errors that can impair the realism of a model's representation of coupled land-atmosphere processes—errors that are becoming obvious as coupling metrics are developed. Replacing "quick fixes" with physically based model development will lead inevitably to broad-based improvements in weather and climate prediction.


Correlations between daily means during JJA
Surface Soil Moisture vs Latent Heat Flux

Sensible Heat Flux vs Lifting Condensation Level

A comparison of the Noah land surface model in the Global Land Data Assimilation System (top) and NCEP Coupled Forecast System operational forecasts from 2013 (middle and bottom) to FLUXNET site estimates (colored circles on maps) for the correlation between daily means during JJA for surface soil moisture versus latent heat flux (top and middle) and for sensible heat flux versus the height of the lifting condensation level (bottom). The figure illustrates the gaps in land-atmosphere coupling behavior between observations and models used for operational weather and climate forecasts.

The problem is that coupled land-atmosphere models used for weather and climate forecasting and research have never been thoroughly validated in terms of their simulation of the coupled processes that provide predictability. A hypothetically perfect land surface model will perform poorly if coupled to an atmospheric model with serious systematic biases or inadequately represented physical processes. Likewise for a deficient land surface scheme paired with an excellent atmospheric model.

The situation is analogous to that in the coupled ocean-atmosphere system, which drives phenomena like El Niño, the Madden-Julian Oscillation and the Atlantic Meridional Overturning Circulation. The first coupled ocean-atmosphere models could not reproduce these phenomena at all. Once sufficient, appropriate observations were collected from existing and newly deployed buoy and satellite platforms, dynamical models were steadily improved, calibrated and validated on those data. The result is that now those phenomena are better understood and increasingly predictable. In many ways, coupled land-atmosphere modeling is where coupled ocean-atmosphere modeling was 15-20 years ago.

Realizing Progress

Only recently have we reached a time when sufficient observational data of high quality and completeness exist such that we can begin to validate (and develop and calibrate) the coupled land-atmosphere processes in models that are key to representing critical feedbacks. In addition to the gold standard co-located meteorology, flux and soil observations of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Program (Ackerman and Stokes, 2003), a growing list of FluxNet (Baldocchi et al., 2001) sites are accumulating long-term records of sub-surface, surface and lower atmospheric measurements. Figure 1 shows how FLUXNET data are beginning to be applied to validate coupled land-atmosphere behavior in models. Efforts are underway to synthesize these data with the nearest neighbor radiosonde observations from the Integrated Global Radiosonde Archive (IGRA; Durre et al., 2006) to provide complete assessments of states and fluxes from a meter or so below the surface through the atmospheric boundary layer. Comparisons of coupled land-atmosphere models to simultaneous point observations throughout the diurnal cycle over months, seasons and years, have never been done, but are now possible.

The GEWEX Global Land Atmosphere System Study (GLASS) has several initiatives aimed at model benchmarking and metrics with an eye towards improved understanding of land-atmosphere coupling processes. (cf. Santanello and Boone, 2013). The Protocol for the Analysis of Land Surface models (PALS; Abramowitz, 2012) includes empirical benchmarks and automated metrics that test uncoupled land surface models against statistical methods over FLUXNET sites. The local-coupled (LoCo) working group is compiling a suite of coupled metrics such as mixing diagrams (Santanello et al., 2009), lifting condensation level (LCL) deficit (Santanello et al., 2011), convective triggering potential and humidity index (Findell and Eltahir, 2003), relative humidity tendency metrics (Ek and Holtslag, 2004), decoupling coefficients (McNaughton and Jarvis, 1991), buoyant condensation level (Tawfik and Dirmeyer, 2014), and triggering feedback strength and amplification feedback strength (Findell et al., 2011). A model test bed project is being formulated based on the Southern Great Plains ARM facility. Also, a joint project is now underway between GLASS and the GEWEX Global Atmospheric System Studies (GASS) Panel called the Diurnal Coupling Experiment (DICE). DICE will compare and benchmark coupled land surface/atmospheric single column models in order to understand the intricate feedbacks across the diurnal cycle. Furthermore, a joint effort between the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP) called the Subseasonal to Seasonal Prediction Project (S2S) will address the timescales where land surface states such as soil moisture have the greatest atmospheric impact.

Feedback Pathways for Land-Atmosphere Models

For a coupled system to exhibit a relevant feedback from component B to component A, three things are necessary. **First**, there must be one or more physical processes that act as pathways through which the feedback can occur. **Second**, there must be a significant correlation or connection from B to A that is distinguishable from random variability or background noise in the system. **Finally**, the variations in the driving element(s) of B must be large enough to generate a meaningfully large response in A; if there is strong sensitivity but weak forcing, the feedback may be inconsequential.

Studies of land-atmosphere coupling have shown several possible feedback pathways can exist from land to atmosphere. For instance, in semi-arid regions there is often a strong correlation chain from soil moisture to surface evaporation and sensible heat flux, surface air temperature, boundary layer growth and eventually precipitation. This occurs in regions where evaporation rates are more limited by moisture availability than energy availability, and where convection in the atmosphere is sensitive to triggering across a typical range of variations in the Bowen ratio. Regions that are very cold, humid, arid, or under strong maritime or baroclinic influence usually display weak land-atmosphere coupling.

Climate models have consistently suggested that in a warming climate, new areas will become moisture stressed, mid- and high-latitude growing seasons will lengthen, and the portion of the continents experiencing subtropical climate conditions will expand. Observational evidence suggests these changes are being detected already. This suggests the area of the globe under ideal land-atmosphere coupling conditions is expanding.

The implications are twofold.

From the perspective of prediction, the potential for land states to contribute skill to weather and climate forecasts will also expand to new regions and seasons.

From the standpoint of mitigation and adaptation, climate may become more sensitive to natural and anthropogenic changes at the land surface, including vegetation cover changes, the effects of water management and urbanization; one more consequence of climate change.

Even though systematic multi-model diagnosis of coupled land-atmosphere models is in its early stages, it is not too early to begin exploiting the predictability in the land surface states for prediction. This should proceed on both research and operational fronts. For operations, a serious thrust should begin now to incorporate state-of-the-art land surface analyses as initial conditions for extended weather and climate forecasts. This has in fact begun in a minor way as products from Land Data Assimilation Systems (LDAS) are being used to initialize operational forecasts (de Rosnay et al., 2012). Despite recent advances in satellite-based monitoring of land surface conditions (e.g. soil moisture, temperature), few actual land surface measurements are assimilated to produce these analyses, and there has been little testing to evaluate the impact of land surface initialization in an operational setting. Projects like the Global Land-Atmosphere Coupling Experiment (GLACE) have shown the potential is there.

On the research side, we must continue to improve the representation of coupled processes in models with a broad effort motivated by prediction, such as was begun for ocean-atmosphere models two decades ago. We finally have sufficient observational data to do this. As models' coupled feedback processes are improved, their capacity to realize predictability as prediction skill will also improve, provided high-quality land surface initial conditions consistent with the land surface model are provided (cf. Koster et al., 2009). Furthermore, innovations must find their way into operational models in a timely fashion, as land-atmosphere feedbacks have obvious consequences for socially important trends such as the increasing frequency of drought around the world. We are poised to make major progress in exploiting the predictability in land-atmosphere feedbacks during the next decade.

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Understanding Hydroclimate Extremes in a Changing Climate: Challenges and Perspectives

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Why are Hydroclimate Extremes Important?

Over the last decade, the scientific community has become increasingly focused on the documentation, diagnostics, mechanisms and modeling of weather and climate extremes. This research agenda is associated with the threat posed by natural hazards resulting from these extremes. As human populations increase and the economic development of many densely populated areas progresses, the risks associated with natural hazards also increase, threatening the lives and livelihoods of the people living in these areas. With the increasing complexity and cost of infrastructure, economic losses resulting from natural hazards have risen dramatically in the past 10 years, often amounting to several-fold higher losses than those incurred prior to infrastructure development. As the needs of the human population increase and climate variability continues to escalate, the interaction between humans and the natural environment will further intensify.

Reducing vulnerability requires changes in the population's level of preparedness for natural hazards. Both the risk of property loss and the vulnerability of the population to life-threatening events can be reduced only by better understanding the nature of climate-related hazards. Therefore, understanding the mechanisms of weather and climate extremes and accurately predicting these extremes are critical challenges.

Hydroclimate extremes, such as very heavy precipitation or anomalously long dry periods (and associated floods and droughts) have major impacts on societies and economies due to the threat they pose to both humans and infrastructure. Although hydroclimate extremes result from many factors that sometimes act together, water is a central component of these extremes via either its excess or scarcity. The major factor underlying hydroclimate extremes is precipitation. Heavy and extreme precipitation results in flooding. Flash floods represent a typical local response to abundant precipitation, whereas river flooding can be associated with more remote events because rivers and their catchment areas often aggregate precipitation over large areas. Among other climate factors that can result in flooding, temperature extremes are important because they can initiate abrupt snow melt, releasing water precipitated during winter in the form of snow.

Droughts are typically considered extremely long dry periods that result in substantial water deficits over large regions. Moreover, very high temperatures in the presence of decreasing soil moisture memory during a drought can intensify these

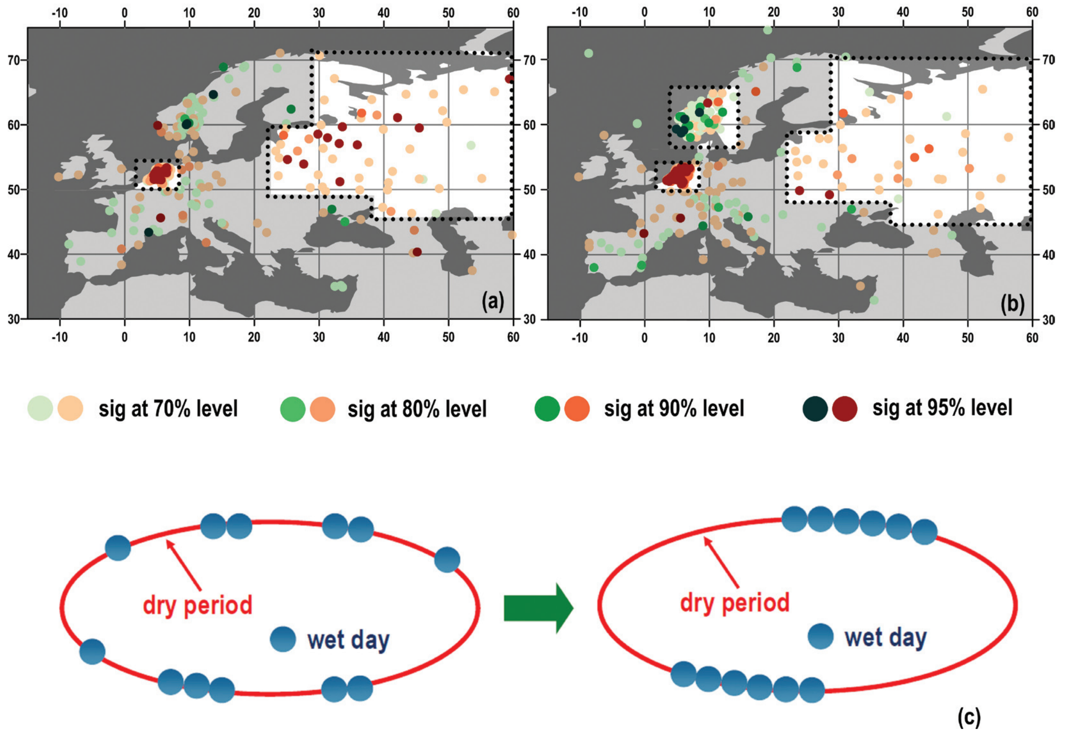

Figure 1. Locations for which linear trends (over 1950–2009) in the duration of wet and dry periods show the same sign including their statistical significance at different levels for the (a) cold and (b) warm seasons. Red circles correspond to the positive trends and green ones indicate negative trends. (c) Hypothetical scheme showing potential lengthening of both wet and dry spells in changing climate with no significant change in the number of wet days. This may be seen as a redistribution of beads on a necklace with a fixed total number of beads. Adapted from Zolina et al. (2013).

deficits, affecting local evapotranspiration and decreasing the soil moisture content and groundwater level. Nevertheless, drought is defined by a lack of precipitation over an extended period. Thus, precipitation extremes form the basis of hydroclimate extremes.

Several issues must be explicitly addressed to improve the quantification and prediction of extreme precipitation. In this short note, I will touch on two of these issues, namely, precipitation timing and the spatiotemporal scaling of precipitation extremes, and attempt to formulate challenges for the GEWEX community that are associated with these problems.

The Problem of Precipitation Timing

Defining precipitation extremes is a difficult task. On one hand, extreme precipitation can be traditionally defined as rainfall events that exceed a given threshold (e.g., the 99.9th or 99.99th percentile; Groisman et al., 1999). Relative precipitation extremes can be quantified based upon the proportion of the total precipitation that occurs during the wettest days (Klein Tank and Koenen, 2003; Zolina et al., 2009; Leander et al., 2014). On the other hand, even very heavy precipitation events may not necessarily result in disastrous flooding. Moreover, hazardous floods may originate from continuous moderate or moderately heavy precipitation. Therefore, in the context of climate change, an increased intensity of precipitation extremes may not necessarily lead to an increased occurrence and intensity of flooding, whereas changes in the temporal structure of precipitation and the lengthening of wet periods may lead to the intensification of flood events. Thus, for an appropriate quantitative description of extreme precipitation patterns and the associated flooding, we must extend our definitions of absolute extremeness and relative extremeness (traditional metrics for extreme precipitation) by considering the duration of wet periods; these revised metrics will enable the necessary analysis of total precipitation extremes that are associated with wet periods rather than individual wet days.

Recent analyses of the durations of wet and dry periods in Europe (Zolina et al., 2010, 2013; Zolina, 2014) demonstrated that both wet and dry periods have become longer (Figure 1a,b) in several large European regions, specifically in Central and Eastern Europe. This effect is not associated with changes in the number of wet days but, rather, with the grouping of wet days into prolonged wet and dry periods, increasing the likelihood of floods and droughts, respectively. This phenomenon is analogous to the redistribution of beads on a necklace with a fixed total number of beads, as schematically illustrated in Figure 1c. However, many areas of Western Europe, particularly along the coast of Scandinavia, are experiencing an increased duration of wet periods at the expense of dry spells as a result of a greater overall number of wet days. Therefore, it is particularly important to include the duration of precipitation along with precipitation intensity and frequency in the analy-

Figure 2. Disastrous flood over the Russian Far East in August-September 2013. The water level of Amur River exceeded 9 meters in some places. Hundreds of villages and towns were inundated.

sis of extreme precipitation events; these three factors form a critical triad for studying rainfall in hydrologic engineering.

Extending the analysis of the durations of wet and dry periods to all areas exposed to flooding and droughts will enable the links between extreme precipitation and hydroclimate hazards to be accurately quantified and will provide insight into the mechanisms underlying these hazards. For example, the record-breaking flood of 2013 over the Russian Far East and northern China was accompanied by human fatalities and unprecedented economic losses (Figure 2). This flood originated from a more than month-long period of moderately heavy precipitation without extreme (according to standard definitions) rainfall.

Spatial and Temporal Scaling of Precipitation Extremes

Precipitation scaling in time and space is a problem that is closely related to the precipitation duration, although duration is only one aspect of scaling. For example, it is rarely the case that rain falls continuously for 3 complete days when data in a particular location indicate a 3-day wet period. More often, 3-day events consist of several relatively short rainy periods with extremely abundant precipitation that is occasionally observed for 1-2 hours or less. In this respect, precipitation statistics that are derived from daily and hourly or hourly and minute-by-minute precipitation data, including characteristics of core distributions, must be correlated. Figure 3 shows daily precipitation estimates derived from daily precipitation rain gauge data in the Krasnodar region, which is located near the Russian coast of the Black Sea, on 6 July 2012, during a disastrous short-term flash flood that resulted in 172 fatalities. The highest daily precipitation total was observed in Gelendgik (253 mm/day, which is equivalent to 0.18 mm/minute), exceeding the 50-year return value for this station (40 mm/day). However, the 5-minute-resolution precipitation data collected in Gelendgik using a pluviometer (Figure 3; Arkhipkin et al., 2013) demonstrated that more than 80 percent of this record-breaking daily total occurred during an 8-hour period. During this period, two episodes of extremely heavy rainfall were observed, with the precipitation intensity reaching 1.5 mm/minute. However, these extreme rainfall events lasted for only several tens of minutes each. Given the complicated orography of the area, this clustering of precipitation in time was critical for causing extreme water levels and the disastrous inundation of several towns and villages.

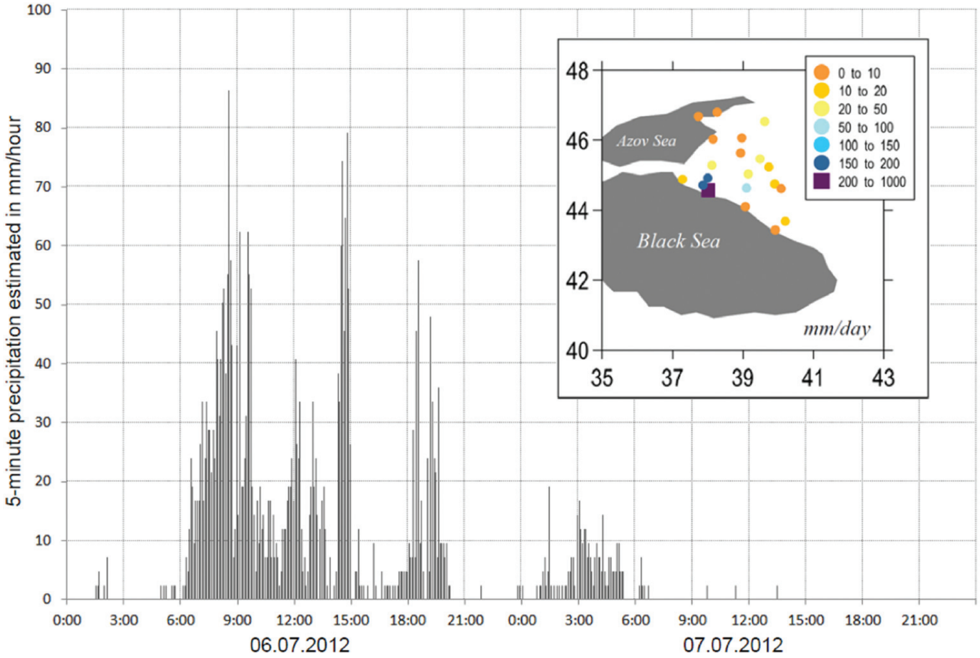

Figure 3. Precipitation record at 5-minute resolution collected in Gelendgik by the Pluviometer instrument from 6-7 July 2012 (Arkhipkin et al., 2013). Inlay map shows estimates of daily precipitation totals for 7 July 2012 for synoptic rain gauges in the region. Violet squared box in inlay map shows the location of Gelendgik station.

The scaling issue is also critically important for analyzing the spatial structure of precipitation extremes. Because it is closely related to the statistical downscaling of global and regional model results (e.g., Maraun et al., 2010), scaling is also important for the optimal setting and improvement of models. In many areas where the spatial coverage of observation gauges and pluviometers is sparse, only regional models can characterize high-resolution extreme precipitation patterns. However, validating the model results with observations is problematic. Models integrate precipitation that is computed by convective and stratiform precipitation schemes over entire grid cells, whereas stations track precipitation only at a specific site. Figure 4 shows that within a grid cell for which a model diagnoses extreme precipitation, stations may observe a variety of estimates that span from zero to very heavy precipitation amounts. The extent to which model-based precipitation estimates can be effectively compared to gridded estimates of station-based precipitation data is largely dependent on the density of the precipitation network. The spatial resolution of the state-of-the-art climate models is approaching 10 kilometers. Given that the spatial variability in precipitation in some mountainous areas may occur on scales from hundreds of meters to several kilometers, a reasonable spatial resolution requirement for precipitation networks is a few kilometers or less. This density of daily observation systems exists in only a few large regions of Europe; however, these observational records are not freely available from the national meteorological offices. Moreover, hourly or higher temporal resolution precipitation data are even more sparse, and their time coverage is generally limited to certain years. For appropriate model validation, in situ measurements are needed at timescales close to the temporal resolution of the model, which is on the order of minutes for high-resolution models.

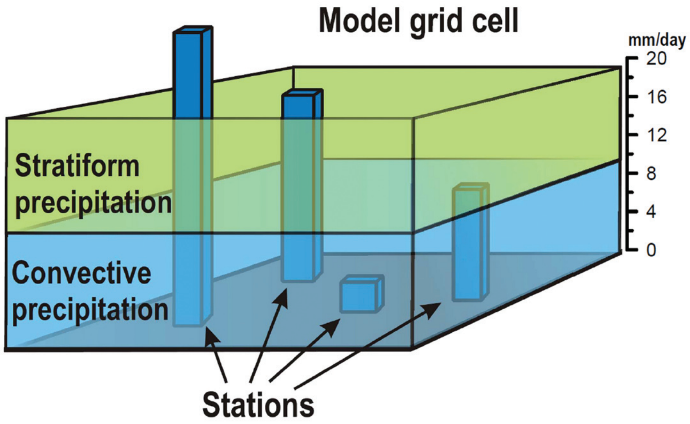

Figure 4. A hypothetical scheme demonstrating problems of attribution of the model precipitation estimate over the grid cell to a particular station. Transparent blue and green boxes correspond to the model estimates of stratiform and convective precipitation for the grid cell. Deep blue vertical bars show precipitation estimates from the stations within this grid cell. Scale is in mm/day.

Challenges and the Future

What are the most important challenges for studying extreme precipitation, understanding its mechanisms and improving its prediction within the GEWEX community? First, we must consolidate efforts to build an international multi-source observational database, which should consist of all available daily time series from the national datasets and all available high-resolution hourly and minute-by-minute precipitation records. These data must be supplied with extensive metadata information, including details for missing values, instrument types and exposure and changes in observational practices. Currently, a relatively small fraction of these data, and only at a daily resolution, is included in internationally recognized databases such as the European Climate Assessment (ECA) data set (Kwok and Klein Tank, 2009); most records remain stored at national meteorological offices and are not freely available. Special attention should be given to the development of an accurate methodology for detecting frozen precipitation in rain gauge and pluviometer data. The lack of a well-grounded methodology results in large uncertainties in estimating climate variability in winter precipitation events and impedes progress in understanding the mechanisms' underlying extreme snowfalls. Given that the density of rain gauge and pluviometer networks is highly inhomogeneous, the data from these networks should be supplemented with alternative data from extensive precipitation measurements, such as reports from moving cars (e.g., Rabiei et al., 2013) or retrievals from microwave links used in cellular communication networks (Overeem et al., 2013), even if these data are only obtained for limited areas and time periods.

When collected (ideally in a merged database), these multi-source and multi-resolution data will help identify regions and periods for which the extensive validation of satellite-based precipitation observations is most effective. The GEWEX Global Precipitation Climatology Project (GPCP) global daily time series is available beginning in the late 1990s. High-resolution Tropical Rainfall Measuring Mission (TRMM) data and other advanced products (e.g., CMORPH and PERSIAN) cover the period since the early 2000s; however, the spatial coverage of these products is limited in polar latitudes. These data will soon be enriched by measurements from the Global Precipitation Measurement (GPM) Mission. In addition to climatological analyses of precipitation, all of these data are frequently used in the diagnostics of individual extreme events; however, further efforts are needed to ensure their applicability for the analysis of climate variability in precipitation extremes. The recent pilot study by Lockhoff et al. (2014), comparing GPCP one-dimensional data and E-OBS data probability distributions, identified biases in estimates of extreme precipitation by satellites and station data in Europe. This comparison used the gridded E-OBS product (Haylock et al., 2008), which is based on a highly inhomogeneous station network and results in many poorly observed regions; therefore, these findings should be interpreted with caution.

Furthermore, for regions where multi-source data can resolve the spatial and temporal scales of extreme precipitation (i.e., mesogamma scales), considerable effort will be needed to validate modern-era reanalyses and model results. This validation should involve both regional and global climate models with different resolutions and dedicated model experiments using a single model run with different resolutions. This activity will help provide accurate estimates of spatiotemporal scaling parameters of precipitation and quantify the extent to which different models can replicate precipitation extremes and their climate variability. We will be unable to quantitatively describe the variability in hydroclimate extremes in the present climate and project changes in future extremes without such a paradigm. Although climate projections (SREX, Seneviratne et al., 2012; IPCC 2013) predict that hydroclimate extremes will intensify in the future, these assessments are built upon highly generalized estimates of the characteristics of extremes under present climate conditions and relatively coarse-resolution model experiments. Given the strongly localized nature of hydroclimate extremes, we can anticipate that accurately estimating the scaling parameters for precipitation in model results and in the observational data will allow for more accurate and region-specific projections of precipitation extremes, including predictions of absolute and relative extremeness.

Such improved modeling capabilities should further our understanding of the mechanisms underlying hydroclimate extremes and their accurate diagnosis in model experiments. Lenderink and van Meijgaard (2008) demonstrated that the scaling of the Clausius–Clapeyron relation may change across timescales; for example, hourly extremes may increase with rising temperatures much faster than implied by the Clausius–Clapeyron relation. The mechanisms underlying this phenomenon are likely related to local moisture advection in synoptic-scale and mesoscale systems (Trenberth et al., 2003). To incorporate moisture advection into investigations of the mechanisms' underlying extreme precipitation, scaling approaches must be applied to the well-established and large-scale computational techniques for advective terms (e.g., Trenberth et al., 2011; Trenberth and Fasullo, 2013). Such scaling approaches will help elucidate the link between precipitation extremes and atmospheric synoptic-scale and mesoscale dynamics and will aid in the development of more accurate and user-oriented projections of future extreme events.

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HiRes: A Proposal for a Coordinated GEWEX Initiative to Advance Projections of Hydrological Extremes

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Shifts in rainfall patterns associated with natural climate variability have led to serious consequences worldwide. Flooding now accounts for about 50 percent of the annual average of natural disaster losses in the United States and about 80 fatalities and $5.2 billion in damage annually. A series of winter storms with a combination of heavy rains, combined with strong winds and high waves ravaged southern England in 2013 and 2014, producing the wettest December and January ever recorded (Figure 1), which resulted in widespread flooding and severe coastal damage. Extreme rainfall associated with La Niña flooded almost the entire interior of Australia in 2010-2011. The water associated with this flooding was significant enough to produce a substantial drop in global sea level.

The corollary of extreme precipitation is drought, and the inadequacy of early warning systems has been brought into sharp focus with the persistent droughts in the Southwestern United States. The 12-month period of October 2010–September 2011 marked the worst 1-year drought in Texas since 1895, and March 2011 was the driest month in the history of Texas. Out of a total of 170 million acres, three million were lost to wild fires in the U.S., resulting in estimated losses of $10 billion in crops, livestock and timber. More recently, the Southwestern U.S. experienced a deep drought with California experiencing three consecutive years of below-normal rainfall, which resulted in major impacts on agriculture. Prediction of such changes in the distribution of rainfall and how these changes might be influenced by human activities represents one of the most profound challenges facing our society today. Addressing this issue is the underlying basis of the GEWEX Science Questions in the coming years.

Climate models are used to make projections about precipitation to quantify changes in extremes and to assess regional vulnerabilities to these changes. Future projections often use regional models to add details locally and process interactions. State-of-the-art global models have a resolution of 300-100 km; for regional models 30-10 km is quite typical. Downscaling global projections with regional models is inherently problematic and global climate models (GCMs) often do not agree on the sign of regional changes to future mean precipitation [Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports]. Furthermore, the reliability of the projections used, especially for extreme rainfall is unclear, because predicting changes in the distribution, frequency and intensity of rainfall remains a fundamental weakness in all climate models (Stephens et al., 2010). One hypothesis that is now widely accepted is that the main obstacle to more credible projections of extreme rainfall is insufficient model resolution. Therefore, critical features such as topography and processes such as convection within rain-bearing systems cannot be adequately resolved. One of the goals of the HiRes Project is to develop a systematic approach to test this hypothesis by bringing together models of varying resolutions and observations developed under GEWEX, and new observational resources to define performance metrics to quantify improvements.

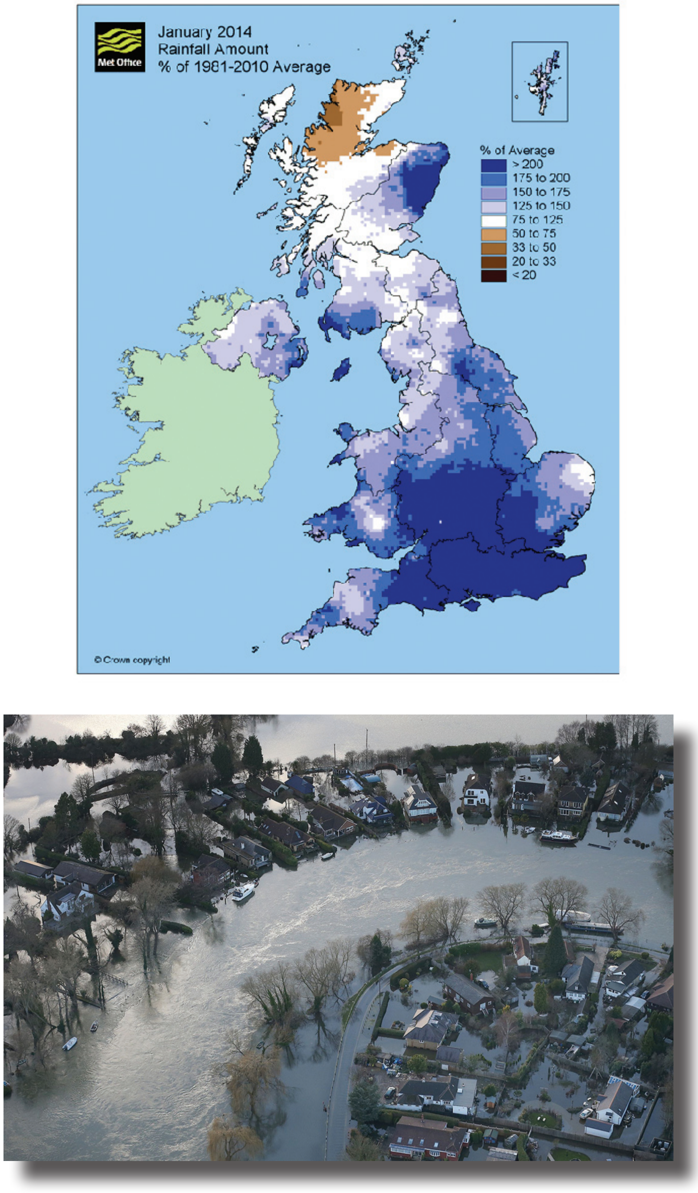

Figure 1. (Top) Anomalous January 2014 rainfall over the United Kingdom showing large regions of Southern England having received more than 200 percent of the average rainfall resulting in (Bottom) widespread flooding and major damage.

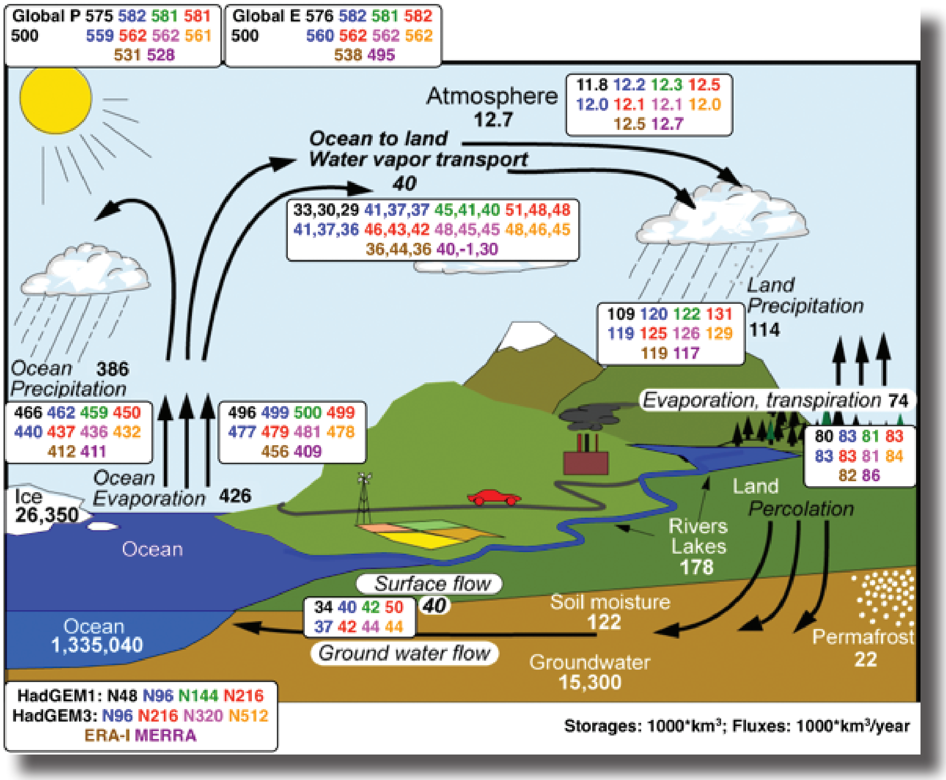

Figure 2. (Demory et al., 2013) The global hydrological cycle: water reservoirs (10^3 km^3) and flows (10^3 km^3/year). Background values are from Trenberth et al. (2011) for the period 2002-2008. In the boxes (legend on the lower left corner) are values from HadGEM1-A and HadGEM3-A models with various horizontal resolutions (N48: 270 km; N96: 135 km; N144: 90 km; N216: 60 km; N320: 40 km; N512: 25 km) (1979-2002 and 1986-2002 at N512), and ERA-I and MERRA reanalyses (2002-2008). Three values are given for the water vapor transport from ocean to land: (1) atmospheric moisture convergence; (2) E - P from the ocean; and (3) P - E from the land. Image adapted from Trenberth et al. (2011).

Two main factors in precipitation changes can then be investigated in a systematic and traceable way. The first is dynamical, large-scale changes (such as storm tracks) that are poorly constrained in current models but are potentially the cause of the 2013-2014 floods in the UK. The second factor is smaller-scale convective processes that may submit to improved representation at higher resolution but which are often embedded within larger-scale systems.

HiRes Objectives

The goal of the HiRes Project is to advance the capability to assess future risks of hydrological extremes by promoting the innovative development of high-resolution models of the ocean, atmosphere and land that use current and new observational resources to provide a systematic assessment of the impact of model resolution in representing the water cycle processes and extremes. The project will build upon and shepherd ongoing efforts that have already been initiated by individual modeling groups towards this goal. The initiative will be built around two related activities: HiRes Global and HiRes Regional.

HiRes-Global

HiRes-Global is one of several efforts worldwide to develop GCM simulations with weather-resolving horizontal resolutions of 10-30 km in the atmosphere. The UK Joint Weather and Climate Research Programme (a joint program between the Met Office and the Natural Environment Research Council) completed the Partnership for Advanced Computing in Europe (PRACE) UK on PRACE Weather-Resolving Simulations of Climate for Global Environmental risk (UPSCALE) campaign in 2012-2013 (Mizielinski et al., submitted). PRACE-UPSCALE is a five-member ensemble of 25-km Atmospheric Model Intercomparison Project (AMIP) type global simulations forced by Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) data and a three-member future scenario ensemble using OSTIA and Representative Concentration Pathway (RCP) 8.5 forcing data (27 years in duration). The results from these simulations show that increasing resolution improves a number of processes and also provides a strategy for studying the impact of improved representation of small-scale processes on the mean climate, its variability and extremes in a systematic way. The experiments have shown that the impact of model resolution on the simulation of the global-mean water cycle is significant (see Figure 2). The dynamical drivers of the hydrological cycle, such as the atmospheric moisture transport driven by eddy transport at mid-latitudes, notably increased by almost 60 percent as the resolution of the model was increased from 270 km to 60 km. These results converge at resolutions higher than 60 km, which underlines the ability of such a high-resolution GCM to simulate dynamical processes, such as eddy transport of moisture, that are under represented at lower resolution typical of IPCC-class GCMs (300-100 km). This eddy transport is an important source of water fuelling mid-latitude storms and is fundamental to properly representing hydrological extremes. Similar multi-model forced-atmosphere projects, such as Athena (Kinter et al, 2013) have shown how regional-scale projections of precipitation change can be quite different using models at high and low resolution; however, the lack of ensembles and large differences between models limited the comparability of results.

Although these changes to the global water cycle are substantial, we are yet to determine how dependent these sensitivities are to model formulation. HiRes-Global will aim to organize a systematic multi-model intercomparison of the water and energy cycles in an effort to delineate the resolution sensitivities of model physical parameterization (local unresolved processes) and model dynamics (large-scale resolved processes), which may help to depict the underlying causes of model disagreement. Such an intercomparison would, however, necessitate an effort in developing consistent simulations across formulations, which would be coordinated through HiRes-

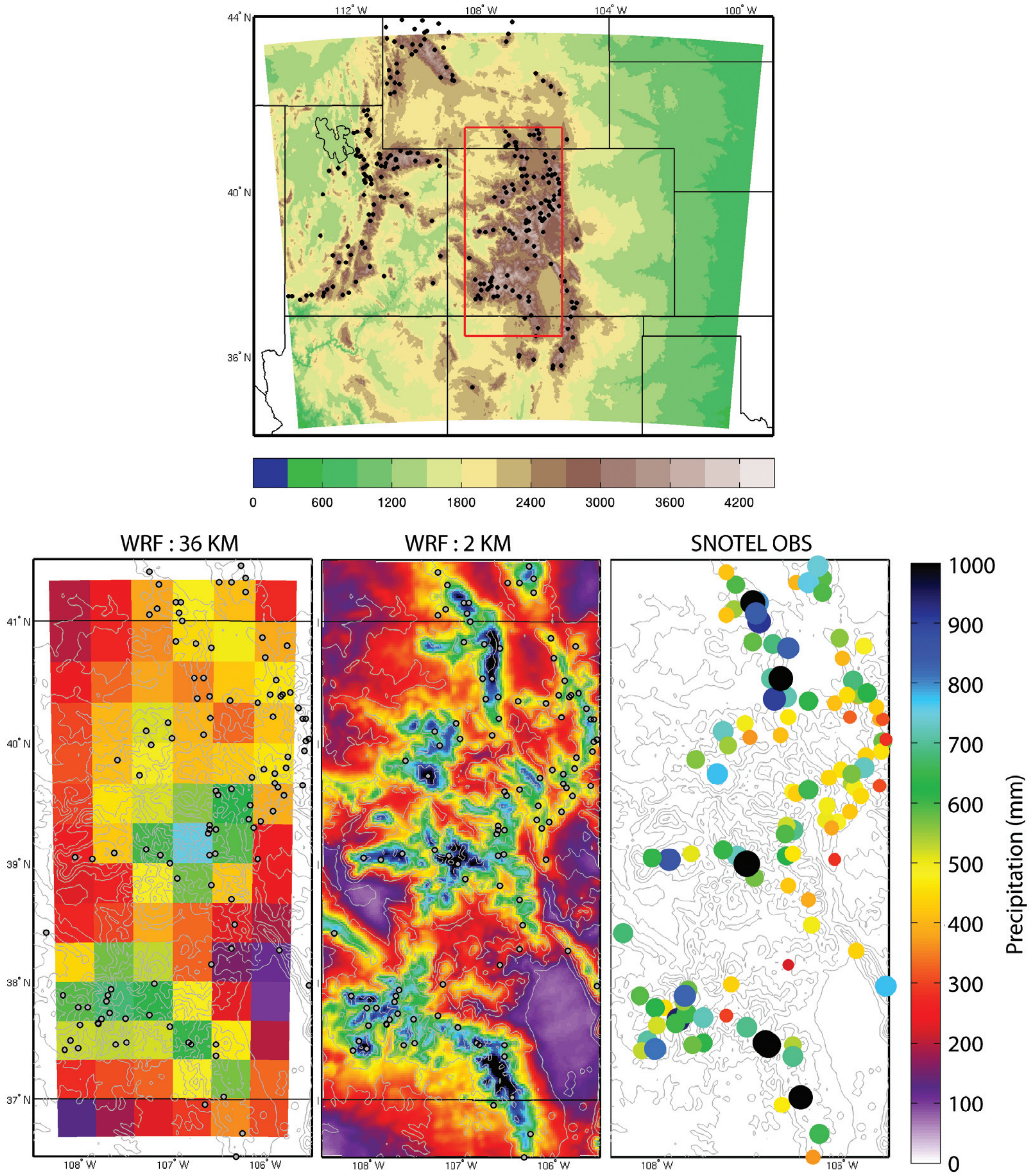

Figure 3. Example of a HiRes simulation of a 6-month winter season snow accumulation (in mm) of the Colorado Rocky headwaters (domain indicated by top panel). Simulations performed with the National Center for Atmospheric Research Weather Research and Forecasting (WRF) Model at two resolutions are shown, and compared to the SNOTEL observations (bottom panel). The 2-km resolution experiment with a more resolved topography produces much more realistic snowpack, and 18 percent more wintertime precipitation for the entire domain than the 36-km simulation (Rasmussen et al., 2011).

Global. HiRes will build on a new European Union initiative, the Process-based Climate Simulation: Advances in High Resolution Modeling and European Climate Risk Assessment (PRIMAVERA, proposed for 2015-2020), which aims to coordinate all European efforts in high-resolution global climate modeling and deliver a high-resolution protocol to the WCRP Coupled Model Intercomparison Project Phase 6 (CMIP6), as well as flagship coupled simulations, in two streams: (1) core simulation using an approximately 20-km atmosphere and one-quarter degree ocean; and (2) "Frontiers of Climate Modeling" simulation, with convective-resolving atmosphere and eddy-resolving ocean.

Together with these global modeling efforts, assessment using the latest global satellite observations can be used to understand large-scale movements of water around the planet and their relationship to global modes of climate variability.

HiRes-Regional

It has become clear that in order to simulate the processes within rain-bearing systems with any fidelity, regional models need to be run at much higher resolution (near 1 km) than is typical of current regional climate modeling (30-10 km; see Figure 3 on page 25). The regional part of the HiRes Project will examine the impact of processes resolved at convective scales (near 1 km) on the water cycle. Kendon et al. (2012) have shown how the representation of short period and high intensity convective rainfall extremes is greatly improved at such a resolution, even with a relatively small-domain model over the southern UK. Further work (Kendon et al., 2014) also suggests a quite different impact on summer rainfall under climate change at such resolutions. Simulations with state-of-the-art large domain (continental scale) regional models will produce outputs with detail comparable to the finest satellite observations of convective systems, which in turn open a door for many innovative uses of the most advanced measurements available. At this resolution, the rainfall and surface temperature and fluxes projected by a climate model are much more appropriate as inputs for regional water resource, agriculture and energy management models and earth process modeling. While the focus is expected to be nominally directed towards the study of precipitation extremes (and related droughts), the simulations represent a much broader resource for study of many other types of climate extremes, effects and processes.

Details of experimental design, the domains to study, the coupling of the regional models to global model simulations to force them and how the regional and global studies of HiRes-global might be jointly analyzed are currently being studied. While it is clear that the ambition is for convective scale modeling on continental domains and to carry this out in the climate change context (i.e., driven by high resolution global climate change simulations), the first stages are to understand the processes by modeling significant present day periods. The first candidate region is the continental U.S. domain, specifically enveloping the region of the Saskatchewan River Basin Regional Hydrology Project and the observational facilities in the U.S. Southern Great Plains. The Clouds Above the United States and Errors at the Surface (CAUSES) is a joint project of the GEWEX Atmospheric Systems Studies (GASS) Panel and U.S. Department of Energy Atmospheric System Research Program to evaluate and improve the representation of cloud and radiation processes in a number of models, by comparing simulations at a range of resolutions to the detailed observations collected in that area.

Connections to Other GEWEX Projects and Initiatives

The new HiRes Project will contribute to other ongoing GEWEX and World Climate Research Programme (WCRP) projects and initiatives. In particular, the investigation of the suitability of high-resolution simulations for precipitation extremes is of high relevance for the WCRP Grand Challenge on extremes. Furthermore, all GEWEX panels consider new developments related to the spatial or temporal resolution of simulations and/or measurements, and will thus benefit from and be able to contribute to HiRes. The Project will actively be discussed at the forthcoming 7th International Scientific Conference on the Global Water and Energy Cycle and the subsequent Pan-GEWEX Meeting this July in The Hague, where inputs to this proposal are welcome and encouraged.

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Cold/Shoulder
Season Precipitation Near 0°C
A Possible GEWEX/GHP Crosscut

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Many regions of the world are subjected to precipitation occurring near 0°C during the cold and shoulder (spring/autumn) seasons (hereafter, near-0°C precipitation). Major snowstorms obviously occur but a wide variety of precipitation types (including freezing rain, freezing drizzle, ice pellets and wet snow) do as well. Several types often occur simultaneously and rain occurring on top of snow is a critical, related phenomenon.

Small changes in atmospheric conditions lead to major changes in the types or amount of near-0°C precipitation. For example, if near-surface temperatures are slightly above (below) 0°C, rain or wet snow (snow) occurs; if a slightly above-freezing inversion occurs (or not) aloft, freezing rain (snow) can reach the surface. It also needs to be recognized that solid precipitation amounts near 0°C (such as wet snow) can be the highest in a winter storm. Such temperatures represent the maximum water vapor holding capacity (saturated water vapor pressure) of the atmosphere with its 0°C value being more than twice its -10°C value.

There are many impacts of near-0°C precipitation. Heavy snowfall generates hazards for infrastructure and transportation. Wet snow and freezing rain may create hazardous traffic conditions and icing on communication lines (Changnon, 2003), and they can have major effects on ecosystems and wildlife (Millward and Kraft, 2004; Zhou et al., 2011). Rainfall on mountainous terrain covered by melting snowpack (rain-on-snow events) may initiate intense snowmelt with flash flooding (Groisman et al., 2003; McCabe et al., 2007).

Even when the total amount of near-0°C precipitation is not considered unusual, it can represent a natural hazard. For example, 25 mm of rainfall usually goes unnoticed as a hazardous weather event but, if the same precipitation falls as freezing rain, as wet snow, or as rain on a mountain snowpack, it may become a hazard-generating event. Houston and Changnon (2007) showed that freezing rain in the U.S. has the potential for a more severe societal impact than snowfall or rainfall for the same mass of precipitation.

Near-0°C precipitation affects large regions of the world. Higher latitude areas such as Russia, Fennoscandia, Canada and United States are particularly prone, but on occasion, lower latitude regions are as well. For example, an ice storm in 1998 (Henson et al., 2007) remained the most costly natural disaster affecting Canada until rain on snow enhanced 2013 flooding in Alberta. Eastern portions of North America just suffered from such an event at Christmas 2013 with infrastructure losses in the billions of dollars, a number of fatalities, and inconvenience for millions of people. Shanghai suffered a devastating 2008 freezing rain event (Zhou et al., 2011). In Germany, Frick and Wernli (2012) pointed out the many consequences on infrastructure and transportation of a devastating 2005 wet snow event.

With global climate change in the extra-tropics, the 0°C isotherm will not disappear and associated precipitation events will continue to occur. Some studies have been conducted on recent trends in near-0°C precipitation and its parent storms in Europe (Førland and Hanssen-Bauer, 2000; Zolina et al., 2013) and North America (Mekis and Vincent, 2011; Hanesiak and Wang, 2005; Henson and Stewart, 2007; Zhang et al., 2010). Analyses of the frequency of winter extra-tropical cyclones over Eastern Europe (Partasenok et al., 2014) show that, while their number is decreasing, their intensity (atmospheric central pressure) is strengthening, which increases the possibility of more intense precipitation and stronger winds. Farther eastward over the Russian Federation (east of 40°E), higher amounts of maximum snow water equivalent in the snowpack (Bulygina et al., 2011) also suggest intensification of infrequent snowfalls.

Given overall warming, patterns of winter precipitation are expected to continue changing. Rain should fall farther upslope in mountainous regions, thereby increasing the risk of flooding. Alterations in temperatures, storm intensity and track will alter the likelihood and occurrence of near-0°C precipitation, including freezing rain (e.g., Lambert and Hansen, 2011). Weakening of the atmospheric circulation in the extra-tropical regions (e.g., Tilinina et al., 2013; Wang et al., 2012) may lead to more polar jet stream meandering (e.g., Francis and Vavrus, 2012) that can lead to more persistent near-0°C events. The overall warming, together with a larger influx of the water vapor in the winter atmosphere from the oceans (including ice-free portions of the Arctic Ocean) will allow more water vapor in the winter atmosphere that can increase the amount of near-0°C precipitation. And, near-0°C temperatures should generally move poleward and arrive at many locations earlier in spring or later in autumn. This could potentially affect the seasonal cycle of near-0°C precipitation. It may increase the duration of near-0°C conditions in the first half of the year

and what we term "transition from winter to spring" periods when this precipitation occurs, and it may also be associated with swifter shifts from autumn to winter which may potentially lead to a greater number of severe near-0°C precipitation events.

Despite significant progress in addressing near-0°C precipitation, it remains a challenging issue. Kunkel et al. (2013) indicated that freezing precipitation was associated with the lowest level of understanding for both detection and attribution amongst several types of hazardous weather conditions affecting the U.S. Some of this uncertainty stems from the difficulty of accurate measurement of key variables. It is difficult to measure some forms of cold season precipitation including their combinations. As well, we are not aware of any articles that have developed a global climatology of, say, freezing rain. There have been regional studies for North America (e.g., Cortinas et al., 2004) and Europe (e.g., Carriere et al., 2000) but this hasn't been brought together and combined with information over other regions. The general large-scale precursors for the occurrence of these hazardous conditions are somewhat known in that, for example, warm frontal circulations during the cold season may commonly lead to freezing rain, but there are still fundamental issues linked with detailed processes. This includes the precise manner through which hazardous precipitation arises, including the conditions leading to ice nucleation that is often critical as to whether freezing drizzle will occur or not. It is crucial to have a good sense of the physical processes before one can increase confidence in future projections.

Cold/shoulder season precipitation near 0°C is of interest to several components of GEWEX. It is certainly an important issue in some current and proposed GEWEX Hydroclimatology Panel (GHP) regional projects such as the Changing Cold Regions Network (CCRN) over western Canada, Baltic Earth and the Northern Eurasian Earth Science Partnership Initiative (NEESPI). Such precipitation is also important for the GEWEX Data and Applications Panel (GDAP) as it seeks to characterize precipitation globally, including its phase.

Cold/shoulder season precipitation issues have justifiably been recognized by GEWEX in its Science Questions. One of the activities identified in Science Question 4 (Extremes) is to examine "cold season extremes such as snowstorms, rain-on-snow episodes, freezing precipitation." Such an activity is undoubtedly of interest to the WCRP Climate and Cryosphere (CliC) Project and is within the scope of the WCRP Grand Challenge on extremes that is currently being developed.

Objective of Near 0°C

Given the importance of this issue and its contributions to GEWEX and WCRP, it is proposed that a GHP crosscut be developed to improve our understanding of future changes in hazardous cold/shoulder season precipitation, especially occurring near 0°C. This requires understanding past and present changes and as well as considering future conditions. Addressing these requires an examination of several issues including data requirements and availability, climatology of key variables and phenomena, simulation and understanding of key driving processes, and assessment of projections and their shortcomings. Assessing the current situation in these various categories will undoubtedly lead to the identification of specific gaps.

Summary and Next Steps

Events associated with near-0°C precipitation are not necessarily always "extreme" but they do represent natural hazards. Moreover, these events will not wane with global warming but some may became more intense and their temporal and spatial patterns are expected to shift. But, many uncertainties remain and further in-depth study is warranted.

The intention of this article is to garner as much interest as possible in this new GHP crosscut. An open organizational meeting will be held during the 7th International Scientific Conference on the Global Water and Energy Cycle on Monday afternoon,14 July 2014. The basic ideas expressed in this article will be discussed with a key focus being the identification of a 2-3 year do-able activity to be used as a basis for proposing a GHP crosscut.

If you wish to contact us before the meeting, or if you cannot attend, please send an e-mail to Pavel Groisman (*pasha.groisman@noaa.gov*) or Ronald Stewart (*ronald.stewart@umanitoba.ca*).

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GEWEX NEWS

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GEWEX/WCRP Calendar

For the complete Calendar, see the GEWEX website:
http://www.gewex.org/

30 June–4 July 2014—35th Session of the World Climate Research Programme Joint Scientific Committee—Heidelberg, Germany

30 June–2 July 2014—World Meteorological Organization Technical Conference on Climate Services—Heidelberg, Germany

2–3 July 2014—Takio Murakami Memorial Symposium on Tropical Meteorology and Monsoon—Honolulu, Hawaii

6–12 July 2014—GEWEX Summer Sessions for Early Career Scientists and Graduate Students—Delft University of Technology, The Netherlands

7–11 July 2014—14th AMS Conference on Atmospheric Radiation and 14th Conference on Cloud Physics—Boston, Massachusetts

10–14 July 2014—Satellite Soil Moisture Validation and Application Workshop—Amsterdam, The Netherlands

13–18 July 2014—IGARSS 2014—Quebec City, Canada

14–17 July 2014—7th International Scientific Conference on the Global Energy and Water Cycle The Hague, The Netherlands

17–18 July 2014—3rd Pan-GEWEX Meeting—The Hague, The Netherlands

17–18 July 2014—Pan-CLIVAR Meeting—The Hague, The Netherlands

21 July–1 August 2014—WCRP-ITCP Summer School on Attribution and Prediction of Extreme Events—Trieste, Italy

28 July–1 August 2014—Asia Oceania Geosciences Society 11th Annual Meeting—Sapporo, Japan

16–21 August 2014—First World Weather Open Science Conference-WWOSC-2014 - Weather: What's the Outlook?—Montreal, Canada

16–21 August 2014—WWRP Open Science Conference—Montréal, QC, Canada

28 August–3 September 2014—31st ICSU General Assembly—Auckland, New Zealand

9-–2 September 2014—Baseline Surface Radiation Network Meeting—Bologna, Italy

8-–10 September 2014—IPCC AR5: lessons learned for climate change research and WCRP—ISSI, Bern, Switzerland

21–26 September 2014—IWA World Water Congress—Lisbon, Portugal

24–26 September 2014—International Conference Deltas in Times of Climate Change II—Rotterdam, The Netherlands

6–10 October 2014—14th European Meteorological Society Meeting and 11th European Conference on Applied Climatology—Prague, Czech Republic

6–9 October 2014—Our Climate–Our future, Regional perspective on a global challenge—Berlin, Germany

8–10 October 2014—18th Session of the Working Group on Couple Modelling—Grainau Germany

13–17 October 2014—Climate Symposium 2014—Darmstadt, Germany

8–11 December 2014—GEWEX Hydroclimatology Panel Meeting—Caltech, Pasenda, California

7th International Scientific Conference on the Global Water and Energy Cycle

The World Forum, The Hague, The Netherlands

Preliminary Program

For details on poster sessions and program updates, see: http://gewex.org/2014conf/program.html

MONDAY, 14 JULY 2014

0700- Conference Registration

Opening and Welcome

0845-0850 – *Bert Holtslag* (Wageningen University)

0850-0900 – *Martin Kropff* (Vice-President, Rector Magnificus, Wageningen University)

0900-0905 – *Antonio J. Busalacchi* (Chair, Joint Scientific Committee, World Climate Research Programme)

0905-0915 *Expectations for the Conference and GEWEX Science Questions* – Kevin Trenberth (National Center for Atmospheric Research)

Session 1 – Trending Now: Water (*Chair: Bert Holtslag, Wageningen University)*

0915-0945 *Water and Society* – Howard Wheater (University of Saskatchewan)

0945-1005 *Water in The Netherlands* – Wim Kuijken (Commissioner of the Dutch Delta Programme)

1005-1025 *Future Prospects for Closing Water Budgets Over Land* – Eric Wood (Princeton University)

1025-1030 *Logistics for Panels, Posters, and Sessions* – Peter van Oevelen (International GEWEX Project Office)

Session 2 – Global Observations of Water and Energy Cycles (Chair: Toshio Koike, University of Tokyo)

1100-1130 *Energy Budgets* – Kevin Trenberth (National Center for Atmospheric Research)

1130-1150 *Closing Water Budgets Over the Ocean* – Carol Ann Clayson (Woods Hole Oceanographic Institute)

1150-1210 *A Synthesis of Water Budgets in Reanalyses and Observations* – Michael Bosilovich (National Aeronautics and Space Administration/Goddard Space Flight Center)

1210-1240 *Panel: GEWEX Data Analyzes and Assessments* – Chair: Toshio Koike (University of Tokyo); Christian Kummerow (Colorado State University); Norman Loeb (National Aeronautics and Space Administration)

1240-1400 Lunch and Poster Viewing

1400-1500 ***Session 3 – Posters (see conference website for schedule)***

1530-1730 ***Session 4 – Parallel Oral Presentations***

Topic:	*2. Advances in Analyses and Energy Cycles*	*9. Hydrology and Water Management*	*23. Land-Atmosphere Interface*
Co-Chairs:	*Jörg Schulz (EUMETSAT), Michael Bosilovich (NASA), and Mitch Moncrieff (UCAR)*	*March Bierkens (Utrecht University) and Jan Verkade (Deltares)*	*Bert Holtslag (Wageningen UR) and Paul Dirmeyer (GMU)*
1530-1543	William Rossow (CREST)	Stephan Thober (UFZ)	Erick Bazile (Meteo France)
1545-1558	Amadou Gaye (UCAD)	Shraddhanand Skukla (UCSB)	Benoit Guillod (ETH Zurich)
1600-1613	Obbe Tuinenburg (LMD)	Kara Smith (NC State Univ.)	Alexis Berg (IRI)
1615-1628	Matt McCabe (KAUST)	Misako Hatono (Univ. of Tokyo)	Mansi Bhowmick (U. of Leeds)
1630-1643	Sergey Gulev (IORAS)	Albrecht Weerts (Deltares/WUR)	Jordi Vila-Guerau de Arellano (Wageningen University)
1645-1658	Franklin Robertson (NASA)	Elodie Blanc (MIT)	Cathy Hohenegger (MPIM)
1700-1713	Stephanie Redl (U. of Cologne)	Chris Funk (USGS)	Volker Wulfmeyer (U. of Hohenheim
1715-1728	Paul Poli (ECMWF)	Sujan Koirala (MPIB)	Martin Best (Met Office)

1830 Welcome Reception

TUESDAY, 15 JULY 2014

***Session 5 – Extremes* (Co-Chairs: Ronald Stewart, Univ. of Manitoba and Gabi Hegerl, Univ. of Edinburgh)**

0830-0900 *Changes in Extremes* **–** Xuebin Zhang (Environment Canada)

0900-0920 *Observed Changes in Extremes* **–** Lisa Alexander (Climate Change Research Centre)

0920-0940 *Modeling and Prediction of Extremes* **–** Adam Scaife (Met Office, United Kingdom)

0940-1000 *Droughts* - Siegfried Schubert (National Aeronautics and Space Administration)

1000-1030 *Panel: Understanding, Attributing, and Coping with Extremes* **–**
Chair: Ronald Stewart (University of Manitoba); Sonia Seneviratne (Swiss Federal Institute of Technology, Zurich); Gabi Hegerl (University of Edinburgh)

1100-1230 ***Session 6 – Parallel Oral Presentations***

Topic:	*4. Observations and Climate Extremes*	*12 and 13. Anthropogenic Effects and High Resolution Hydrology in LSMs*	*22. Improving Atmospheric Models*
Co-Chairs:	*Ronald Stewart (Univ. of Manitoba) and Olga Zolina (LGGE/UJF)*	*Paul Bates (Univ. of Bistrol) and Justin Sheffield (Princeton Univ.)*	*Robert Pincus (Univ. of Colorado), Jon Petch (Met Office), and Steve Woolnough (Univ Reading)*
1100-1113	Woutert Dorigo (TU Wien)	Ruby Leung (PNNL)	Juan Pedro Mellado (MPIM)
1115-1128	Barrie Bonsai (Envir Canada)	Edwin Sutanudjaja (Utrecht U)	Chris Bretherton (U Washington)
1130-1143	Mimi Hughes (U Colorado)	Lan Wang (TU Delft)	Hugh Morrison (NCAR)
1145-1158	Geremy Panthou (INRS-ETE)	Xicai Pan (U Saskatchewan)	Jennifer Fletcher (Monash U)
1200-1213	Simon Brown (Met Office)	Dai Yamazaki (JAMSTEC)	Sylvie Malardel (ECMWF)
1215-1228	Seth Westra (U Adelaide)	Jean-P. Vergnes (Sorbonne U)	Catherine Rio (LMD)

1230-1400 Lunch and Poster Viewing

1400-1500 ***Session 7 – Posters (see conference website for schedule)***

1530-1730 ***Session 8 – Parallel Oral Presentations***

Topic:	*7. Water Cycle in Models*	*8. Global Precipitation*	*14 and 16. New Satellite Observations for Data Assimilation and Water Cycle Research*
Co-Chairs:	*Paul O'Gorman (MIT) and Yukari Takayabu (U of Tokyo)*	*George Huffman (NASA) and Robert Adler (UMD)*	*Rolf Reichle (NASA), Xin Li (CAS), and Dai Yamazaki (JAMSTEC)*
1530-1543	William Collins (LBL)	Soroosh Sorooshian (UCI)	Patricia de Rosnay (ECMWF)
1545-1558	Peter Bechtold (ECMWF)	Robert Adler (U Maryland)	Wade Crow (USDA ARS)
1600-1613	Simona Bordoni (Caltech)	Guojun Gu (ESSIC)	Matthias Drusch (ESA)
1615-1628	Kenneth Sperber (LLNL)	Haiyan Jiang (FIU)	Sujay Kumar (SAIC/NASA)
1630-1643	William Lau (NASA)	Cyril Palerme (CNRS, LGGE)	Richard Lawford (Morgan U)
1645-1658	Angeline Pendergrass (NCAR)	Ali Behrangi (JPL)	Parag Vaze (JPL)
1700-1713	Laura Wilcox (NCAS)	Robert Joyce (NOAA/NWS)	Shunlin Liang (UMD)
1715-1728	Harald Sodemann (ETH)	George Huffman (NASA)	Fabric Papa (IRD)

WEDNESDAY, 16 JULY 2014

***Session 9 – Plenary – Processes and Phenomena* (Chair: Bart van den Hurk, KNMI)**

0830-0900 *Clouds, Circulation, and Climate Sensitivity*–Bjorn Stevens (Max Planck Institute for Meteorology)

0900-0920 *Challenges and progress in improving the atmospheric water cycle in models!*–Christian Jakob
(ARC Centre of Excellence for Climate System Science, Monash University, Melbourne, Australia)

0920-0940 *Global Land Surface Modeling*–Eleanor Blyth (Centre for Ecology and Hydrology)

0940-1000 *Challenges and Prospects for Predicting Monsoons*– Harry Hendon (Centre for Australian Weather & Climate Research)

1000-1030 *Panel: What are the biggest weaknesses in model predictions of water?*
Chair: Christa Peters-Lidard (National Aeronautics and Space Administration); Graham Feingold (National Oceanic and Atmospheric Administration); Sandrine Bony (LMD/Centre National de la Recherche Scientifique)

7th International Scientific Conference on the Global Water and Energy Cycle
Preliminary Agenda

WEDNESDAY, 16 JULY 2014 *(Continued from page 31)*

1100-1230 ***Session 10 – Parallel Oral Presentations***

Topic:	*3. Modeling Climate Extremes*	*6. Predicting Monsoon Precipitation*	*10 and 11. The Role of Land*
Co-Chairs:	*Adam Scaife (Met Office) and Sonia Seneviratne (ETH)*	*Harry Hendon (CAWCR/BOM) and Jun Matsumoto (JAMSTEC)*	*Martin Best (Met Office) and Andrew Pitman (UNSW)*
1100-1113	Rein Haarsma (KNMI)	V. Kishnamurthi	Aaron Boone (Meteo-France)
1115-1128	Peter Greve (ETH Zurich)	Tomonori Sato (Hokkaido U)	Phil Harris (CEH)
1130-1143	Celine Bonfils (LLNL)	David Gochis (NCAR)	Patrick Broxton (U of Arizona)
1145-1158	Bart van den Hurk (KNMI)	D. Emmanuel Poan (Météo-France)	David Mocko (SAIC)
1200-1213	Bert Holtslag (Wageningen U)	Yongkang Xue (UCLA)	David Lawrence (NCAR)
1215-1228	Paul Dirmeyer (GMU)	Wilhelm May (DMI)	Manuela Grippa (GET)

1230-1400 Lunch and Poster Viewing
1400-1500 ***Session 11 – Poster Sessions (see conference website for schedule)***
1530-1730 ***Session 12 – Parallel Oral Presentations***

Topic:	*5. Energy and Water Budgets*	*18. High Elevation Hydrology*	*21.Coupling Clouds, Precipitation and Radiation to Circulation*
Co-Chairs:	*Taikan Oki (Univ. of Tokyo) and Pete Robertson (NASA/MSFC)*	*John Pomeroy (Univ. Saskatchewan), Richard Essery (Univ of Edinburgh), Yaoming Ma (CAS)*	*Chris Bretherton (Univ. of Washington) and Sandrine Bony (LMD/IPSL)*
1530-1543	Matt Rodell (NASA)	Yaoming Ma (CAS)	Mark Webb (Met Office)
1545-1558	Tristan L'Ecuyer (UW Madison)	Alain Pietroniro (Env. Canada)	Sandrine Bony (LMD/IPSL)
1600-1613	Filipe Aires (Estellus)	John Pomeroy (U of S)	Aiko Voigt (LDEO)
1615-1628	Albert van Dijk (ANU)	Roy Rasmussen (NCAR)	Chao-An Chen (RCEC)
1630-1643	Richard Allan (U of Reading)	Adam Winstral (USDA-ARS)	Hui Su (JPL)
1645-1658	Michael Mayer (U of Vienna)	Alvaro Ayala (ETH-Zurich)	Yen-Ting Hwang (SIO)
1700-1713	Norman Loeb (NASA)	Matthias Bernhardt (LMU)	Kevin Grise (LDEO)
1715-1728	Seiji Kato (NASA)	Ignacio López Moreno (CSIC)	Jennifer Kay (U of Colorado)

1900 Conference Banquet (Speaker: James Syvitski, International Geosphere-Biosphere Programme Chair)

THURSDAY, 17 JULY 2015

Session 13 – Water Resources (Chair: Soroosh Sorooshian, University of California, Irvine)

0830-0900 *Precipitation* – Christian Kummerow (Colorado State University)
0900-0920 *Changes in land and hydrology infrastructure impacting water availability and resources*–Taikan Oki (University of Tokyo)
0920-0940 *Climate change impact on water resources* – Richard Harding (Centre for Ecology and Hydrology)
0940-1000 *New Observations* – Jay Famiglietti (University of California, Irvine)
1000-1030 *Panel: Water Availability, Demand, and Use* –
Chair: Jan Polcher (Laboratoire de Météorologie Dynamique/Centre National de la Recherche Scientifique); Paul Houser (George Mason University); Jason Evans (Climate Change Research Centre, University of New South Wales)

Session 14 – WCRP Grand Challenge on Water (**Peter van Oevelen, International GEWEX Project Office)**

1100-1140 *Panel: WCRP Grand Challenge on Water*
Chair: Peter van Oevelen; Rene Garreaud (University of Chile); Lisa Goddard (International Research Institute for Climate and Society); Michael Ek (National Oceanic and Atmospheric Administration); Joseph Santanello (National Aeronautics and Space Administration)

1140-1220 *Future Plans for GEWEX*
– Hydrological Processes and Challenges–Graeme Stephens (Jet Propulsion Laboratory)
– Land-Atmosphere Interactions, Land Surface Exchanges and Climate Extremes–Sonia Seneviratne (ETH Zurich)

1230 Conference Adjourns