GEWEX QUARTERLY

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GEWEX is a Core Project of the World Climate Research Programme on Global Energy and Water Exchanges

A Proposed Regional Hydroclimate Project for the United States

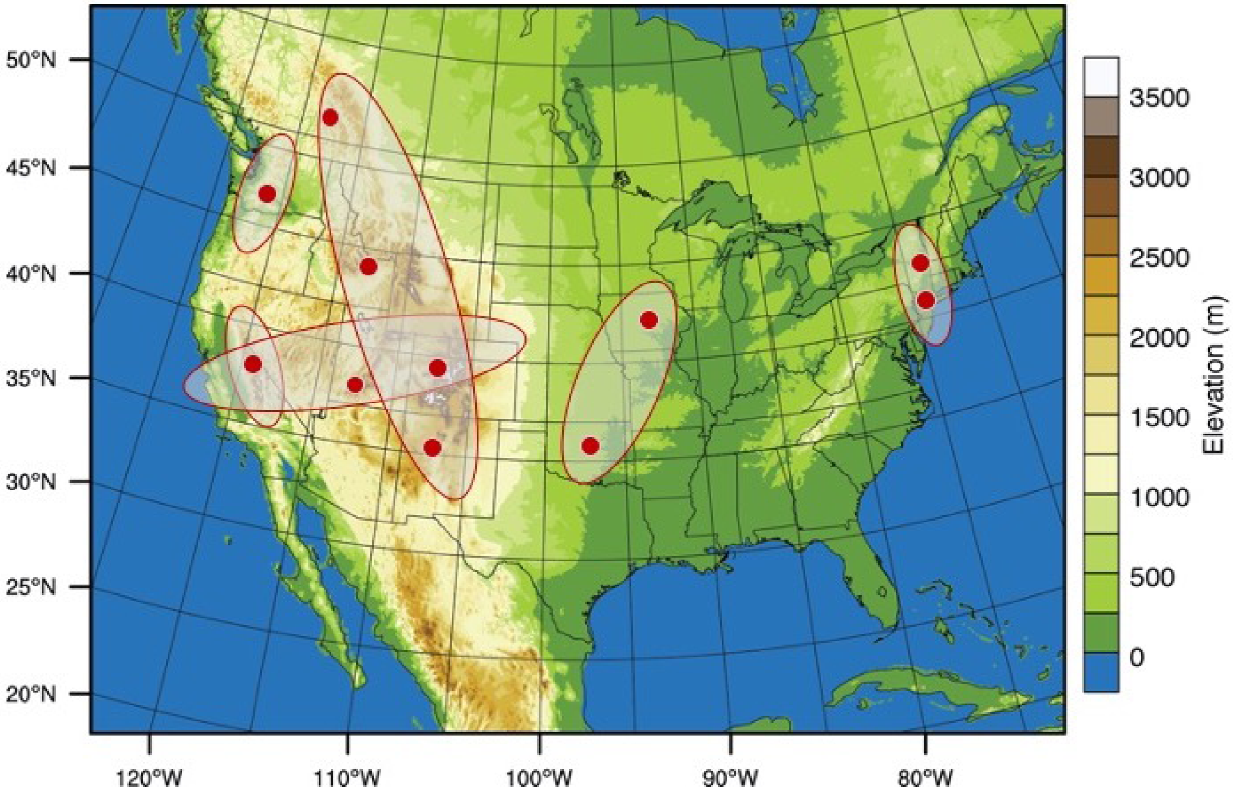

Figure 3: An illustration of the proposed modeling domain, with notional observational transects for the U.S. RHP. Red dots suggest existing or new observational sites (not intended to be literal or thorough in this figure) that can be integrated and coordinated to create the transects, as indicated by shaded ellipses.

Commentary: Land-Atmosphere Interactions at Different Time Scales–The Role of GEWEX

Xubin Zeng
Co-Chair, GEWEX Global Atmospheric System Studies (GASS) Panel

As the COVID-19 pandemic causes hundreds of thousands of fatalities worldwide, humanity has entered a dark moment. I wish all of you health and peace!

A time like this also gives us an opportunity to reinvent ourselves. Now many of us work from home, and I teach my class and interact with my students online. I remain hopeful:

- “While the wildfire rages, grasses will bloom again in the spring wind”[1]
- “O Wind, if winter comes, can spring be far behind?”[2]

Even in these verses GEWEX is relevant for its connection to wind, grasses, and wildfire. This leads me to contemplate the role of GEWEX in addressing some of the issues related to land-atmosphere interactions at different time scales.

The distinct diurnal cycle of 2m air temperature over land is primarily driven by solar radiation and well understood. When solar radiation is weak over the winter hemisphere high latitudes, however, the diurnal cycle is primarily driven by horizontal advection. As a result, the conventional use of daily maximum and minimum temperatures to compute monthly mean and diurnal temperature range would lead to misleading interpretations. The correct way would be to use hourly data to compute the monthly averaged diurnal cycle and then compute monthly mean and diurnal temperature range. Historical hourly observational temperature data are available over selected stations and observation-based value-added gridded hourly data are also available. However, it is unclear how monthly mean temperature and diurnal temperature range are computed in each global model and if their comparison against observations is “apple versus apple” or “apple versus orange” in numerous publications. GEWEX could take the lead to clarify this issue and provide best practices.

Furthermore, the diurnal cycle is closely coupled to the seasonal cycle. In particular, over regions with seasonal snow, snowpack acts as a switch, as seen in the article on page 4: from a solar radiation-driven regime of warm surface, unstable atmospheric boundary layer, and negative cloud radiative forcing when snow is absent, to a longwave radiation-driven regime of cold surface, stable boundary layer, and positive cloud radiative forcing when snowpack is present. GEWEX could take the lead in observing, understanding, and modeling this coupling.

At decadal and longer scales, land processes with the longest memories are most important for the Earth system. At the top of the list would be greenhouse gasses sequestered or released by land processes. As land-atmospheric interaction is poorly simulated in Earth system models, there are large biases in temperature and precipitation. If a dynamic vegetation model (that allows forest-grass-shrub competition) is included, such model biases could erroneously lead to large-scale forest die-off and/or spuriously thaw the permafrost, releasing large amounts of carbon dioxide and/or methane.

This challenge in Earth system component coupling in the presence of large model biases is similar to the one faced by the ocean-atmosphere interaction community 2–3 decades ago. That community’s initial remedy was to do flux corrections. Today, with better understanding and model improvement, most of the Earth system models no longer include flux corrections. GEWEX should make the reduction of land surface climatological biases in Earth system models one of its top priorities. This would involve the joint efforts of the four Panels of GEWEX on global observations, regional field experiments, land model improvement, and atmospheric model improvement (e.g., cloud microphysics, shallow and deep convection, the atmospheric boundary layer, aerosol-cloud interactions, dynamics-physics interactions).

GEWEX has been successful for three decades in the international coordination of scientific efforts. In the same spirit, beyond individual countries’ efforts, international cooperation will be crucial to successfully address the pandemic problem.

[1] In Chinese: 野火烧不尽, 春风吹又生; Chinese poet Bai Juyi, 772–846
[2] English poet Percy Bysshe Shelley, 1792–1822

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Commentary and News

General

Insights into the Direction of the YESS Community for 2020 and Beyond

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The Young Earth System Scientists (YESS) community is currently finishing up the development of a Strategic Action Plan for 2020–2023 and beyond. The plan outlines the vision and mission of our community and elaborates on the actions and activities to reach our identified goals for the coming years. YESS hopes to further strengthen our network globally, expand our network increasingly to early career researchers working in practice and operational entities (e.g., national weather services), and enhance our collaborations with national and international partners. Furthermore, YESS aims to continue to give early career researchers a collective voice in the international community and foster scientific excellence for the benefit of society. The first draft of the Strategic Action Plan has been developed in liaison with the members of the YESS Council, the YESS Executive Committee, and former YESS community members. The Strategic Action Plan is currently undergoing a consultation with partners and will be released before summer.

YESS also recently held its yearly elections and voted on the new Executive Committee and Regional Representatives. The new team of YESS executive committee members and the elected representatives can be found at *https://www.yess-community.org/2020/04/14/yess-elections-2020-results/*. The Executive Committee will guide the development of the network and its activities over the next year (2020–2021) and the Regional Representatives will address regional topics and aim to spread YESS further in their regions.

The YESS community also welcomes the new members of the four Working Groups: outreach, membership/website, online events, and science. If you are interested in getting involved, check for more information at *https://www.yess-community.org/aboutus/structure/workinggroups/*.

Finally, the YESS community is working to enhance interactions between early career researchers during the COVID-19 crisis. To support our members, we developed multiple online activities to make their science visible and to hear the challenges they faced during these difficult times. You can view all the activities at *https://www.yess-community.org/2020/04/09/yess-during-covid-19-crisis/*.

YESS is looking forward to the upcoming period to strengthen our network for early career researchers. Particularly in these challenging times, online networks form a useful outset to foster career developments and international exchange.

Cyberseminar Series from H3S and CUAHSI Provides Guidance to Early Career Scientists

Leila Saberi
AGU H3S Chair

The American Geophysical Union's (AGU) Hydrology Section Student Subcommittee (H3S), in collaboration with the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI), will be hosting a cyberseminar series the last Friday of every month at 12 pm ET. This series will provide career and personal guidance for students and early career scientists. Each event features a panel of experts from academia, government, and industry who will be discussing topics ranging from academic writing, navigating professional relationships, data management, and more! If you missed our previous cyberpanel on "Reviewing Manuscripts and Responding to Reviewers", you can watch it here: *https://www.youtube.com/watch?v=EZKtAKT_SZE*. Join us for our upcoming cyberseminars, such as "Discussing Data: Intersection of Data Privacy and Open Source Practices", which will review the ethics of data management and sharing, generating reproducible science, and online data storage platforms.

Another way that H3S promotes and highlights the success of early career hydrologists is through our Research Highlights section, which features cutting edge research conducted by early career hydrologists in a way that is accessible to the broader hydrological and Earth science community. This is done through 1) the Showcase Your Research feature and 2) Research Tidbits. Showcase Your Research provides early career hydrologists the opportunity to write a blog post about their own research, however they wish to communicate it, including pictures, diagrams, or even short videos. Research Tidbits are written monthly by H3S writers on a paper recently published by an early career hydrologist. Given that the hydrologic sciences are a diverse community–from snow hydrology on the highest mountains to groundwater discharge in the deepest oceans–these posts are written in a language that is easily digestible and understandable to the broader environmentally-interested community.

If you are interested in showcasing your research or have a recently published paper that your would like highlighted, please reach out at *H3S.agu@gmail.com* or *@AGU_H3S* on Twitter.

Land-Atmosphere-Cloud-Climate Coupling on the Canadian Prairies

Alan K. Betts[1] and Raymond L. Desjardins[2]

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Analysis of the remarkable hourly Canadian Prairie data for the past 60 years has transformed our quantitative understanding of land-snow-atmosphere-cloud coupling (Betts et al., 2013a,b; 2014a,b; 2015, 2017, 2018; Betts and Tawfik, 2016). The standard hourly measurements of pressure, temperature, relative humidity, and wind are calibrated back to standards and essentially complete. For key stations, such as Calgary, Regina, and Winnipeg (see Figure 1), more than 99.9% of the days have no missing hours in the first 40 years. Daily snow depth is measured. In addition, trained observers made hourly estimates in tenths of the opaque cloud fraction that obscures the sun, moon, or stars, following the same protocol for 60 years at all stations. These 24 daily estimates of opaque cloud data are of sufficient quality that they can be calibrated against Baseline Surface Radiation Network data to give the climatology of the daily short-wave, long-wave, and total cloud forcing (SWCF, LWCF, and CF).

Figure 1. Climate station locations, Canadian ecozones, regional zones, agricultural regions, and boreal forest.

We find that in the warm season, we can determine effective cloud albedo to ±0.08 from daytime opaque cloud, and net long-wave radiation to ±8 W/m^2 from daily mean opaque cloud and relative humidity. This key radiative forcing has generally been unavailable for surface climate datasets. As a result, we are able to separate the radiative and precipitation impacts on the diurnal cycle. On the seasonal timescale, net cloud radiative forcing reverses sign from negative in the warm season to positive in the cold season, when reflective snow reduces the negative SWCF below the positive LWCF. This in turn leads to a large climate discontinuity with snow cover giving a systematic cooling of 10°C. We found that snow cover acts as a climate switch.

This brief note will illustrate the seasonal and diurnal role of snow and cloud cover, and summarize other important results in the closing paragraphs. The top-left panel of Figure 2 is a 50-year composite of the six Saskatchewan stations (shown in Figure 1) of the fall in temperature with fresh snow falling on day 0 (mean date of November 15). Daily mean temperature falls across a snow event, from near 0°C a week before to -9.4 ± 0.7°C for days 2 to 8 afterwards. The albedo of the Prairies changes from about 0.2 with no snow cover to above 0.7 with snow cover. The large SW reflection, and other coupled changes in the surface energy balance, drive this nearly 10°C fall in temperature. The climate transition from fall to winter often comes abruptly with these snow events, as the snowpack may not melt till spring.

The top-right plot in Figure 2 shows the mean monthly temperature across the cold season (black line) and the simple partition into days with snow cover (blue) and days with no snow cover (red) for a single station (Lethbridge, Alberta) together with the mean snow depth. The difference between the blue and red curves (the magenta curve) shows the monthly climate cooling of snow cover, with a mean value of $\Delta T= -10.4 \pm 0.4$°C. The standard errors shown are small because of the large number of days in the 49-year record. Other stations have similar plots, indicating that the cold season climatologies with and without snow cover (red and blue curves) are quite distinct and non-overlapping. Conventionally, they have been merged to the black curve, but this is misleading. It is better to regard snow cover as a climate switch.

The lower curves show the diurnal cycle of temperature for all the station data for March and April, separated into days with and without snow cover, and partitioned by daily mean fraction of opaque cloud cover. The dataset is large with about 20,000 days per month, and lines are only shown if there are >200 days in a snow-cloud sub-class. The upper set of curves is the familiar rise of daytime temperature as cloud cover decreases that is characteristic of all days without snow. Essentially April without snow resembles May to October (Betts and Tawfik, 2016). The lower curves, where temperature falls with decreasing cloud cover, are characteristic of all cold season days: that is, March with snow resembles November to February with snow cover. As mentioned earlier, this fundamental difference comes from the reversal of the sign of the net cloud forcing with snow cover, which reduces the negative SWCF below the positive LWCF. Thus more cloud cover warms the surface in winter with snow cover, but cools the surface in summer.

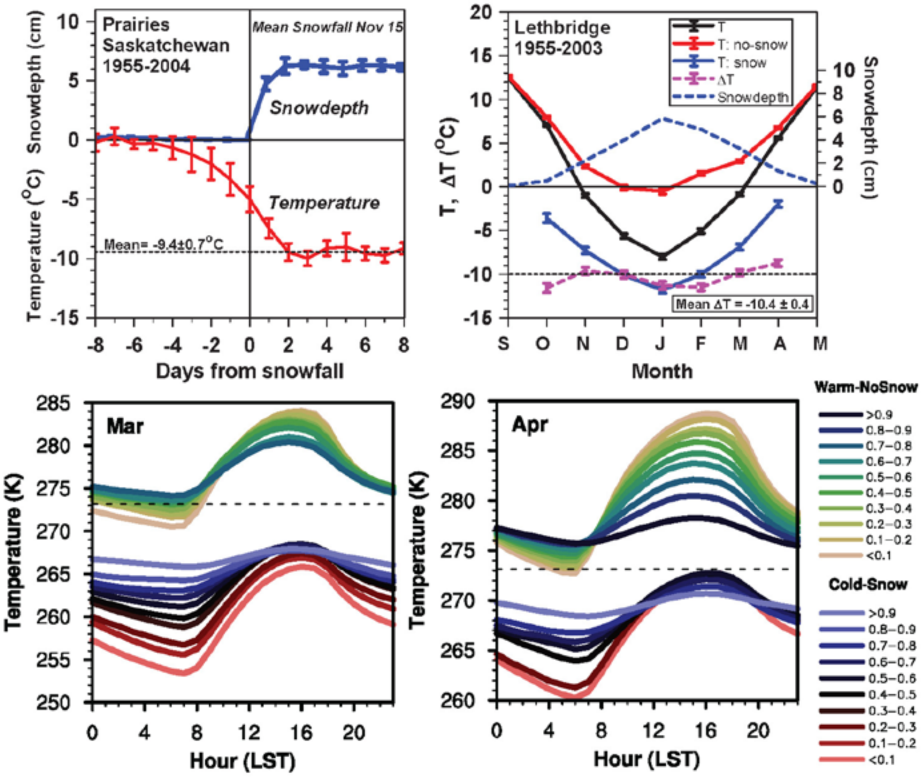

***Figure 2**. Top left: fall in temperature with fresh snow in Saskatchewan in November. Top right: cold season climatology partitioned into days with and without snow cover. Lower panels: diurnal cycle of temperature for March and April, with and without snow cover, partitioned by opaque cloud cover.*

Many other important results have come from these data. In the warm season with no snow cover, the diurnal ranges of temperature, relative humidity, equivalent potential temperature, and the pressure height of the lifting condensation level are all tightly coupled to opaque cloud cover, with almost a single curve from April to September (Betts and Tawfik, 2016). With 600 station-years of hourly data, we can also extract the coupling between cloud forcing and the warm season imbalance of the diurnal cycle, which changes monotonically from a warming and drying under clear skies, to a cooling and moistening under cloudy skies with precipitation. We explored the impact of surface wind speed on the diurnal cycle in the cold and warm seasons. In all months, the fall in minimum temperature is reduced with increasing wind speed, which reduces the diurnal temperature range. In July and August, there is an increase of afternoon maximum temperature and humidity at low wind speeds, and a corresponding rise in maximum equivalent potential temperature of 4.4K that appears coupled to increased precipitation.

Since we have the large daily cloud radiative forcing, our understanding of hydrometeorology becomes more quantitative (Betts et al., 2017). We show that the memory of water storage anomalies from precipitation and the snowpack goes back many months. The spring climatology shows the memory of snowfall back through the entire winter, and the memory in summer goes back to the months of snowmelt. Lagged precipitation anomalies modify the thermodynamic coupling of the diurnal cycle to the cloud forcing, and shift upward the diurnal cycle of mixing ratio, which has a double peak in the warm season. Using the gravity satellite data, Betts et al. (2014b) showed that the seasonal extraction of the surface total water storage is a large damping of the interannual variability of precipitation anomalies in the growing season. For questions and comments, please contact the authors at *akbetts@aol.com*.

Acknowledgement

This work has been supported by Agriculture and Agri-Food Canada, and partially funded by the Established Program to Stimulate Competitive Research (EPSCoR) National Science Foundation (NSF) grant OIA-1556770 to the University of Vermont. The hourly and daily mean data and their documentation are posted as a single zip file at *https://epscor.uvm.edu/owncloud/index.php/s/lWG2QuEobtsUsv5*.

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See *https://alanbetts.com*

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National Tibetan Plateau Data Center Established to Promote Third-Pole Earth System Sciences

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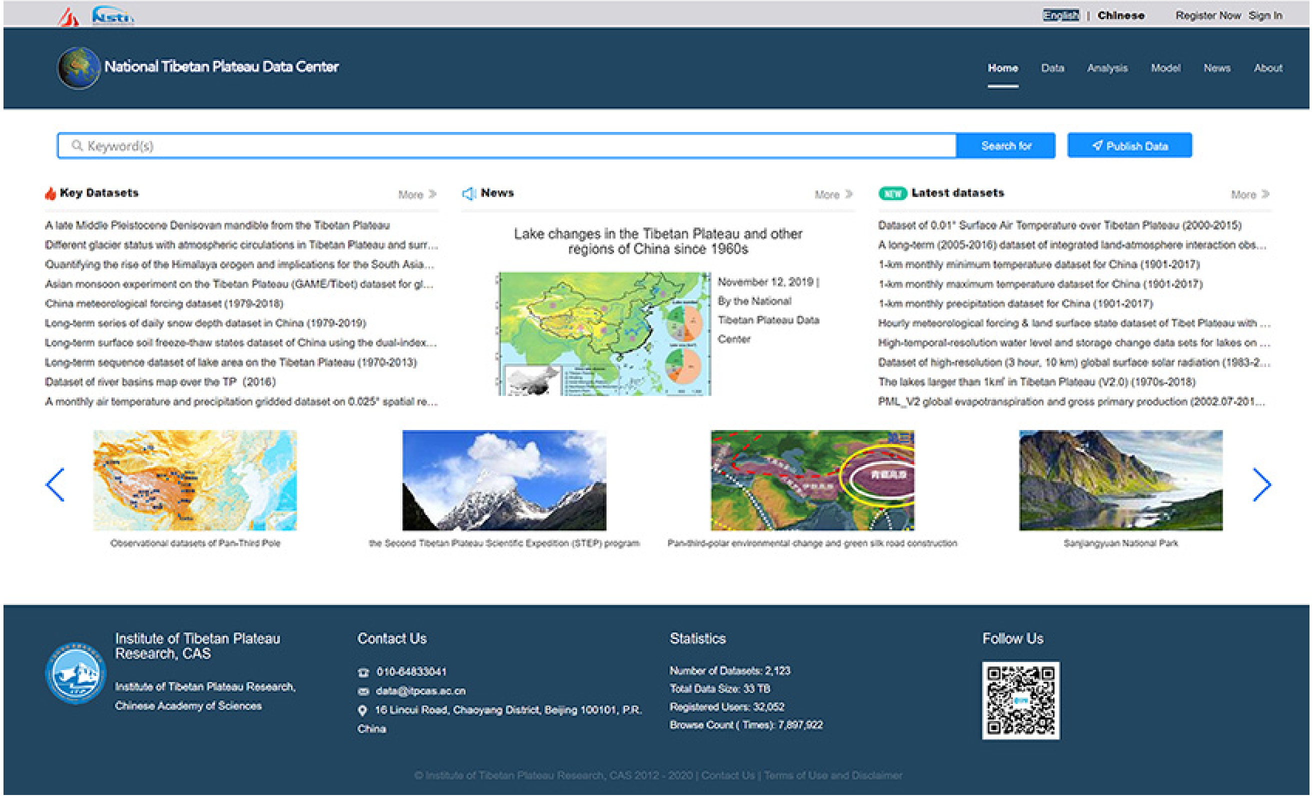
The National Tibetan Plateau Data Center (TPDC) is one of the first of 20 national data centers established in 2019 by the Ministry of Science and Technology of China. It is the only data center in China with the most complete scientific data for the Tibetan Plateau and surrounding regions. The mission of TPDC is to establish a big data center for Third Pole Earth system sciences to integrate Third Pole data resources, particularly those obtained through the implementation of the Second Tibetan Plateau Scientific Expedition and Research (STEP) program. These developments will facilitate the study of environmental changes in the Pan-Third Pole with improved accuracy and performance, as well as support decision-making for sustainable development of the Pan-Third Pole region.

Scientific data sharing is very important to promote Third-Pole Earth system sciences, where unique multi-sphere interactions make it particularly sensitive to global environmental change. The Third Pole is a high-elevation area in Asia with the largest volumes of ice outside of the polar regions, and it has experienced dramatic environmental changes (Yao, 2019; Yao et al., 2019) in recent decades. Datasets including in situ observations, remote sensing observations, reanalysis data, and other data sources are essential to comprehensively evaluate and analyze the characteristics of Third-Pole Earth system changes. However, these data resources have not been well collected, constructed, and published by an authoritative organization. TPDC was established to be such a platform, integrating and sharing data based on observational and research programs that will allow global scientists to explore the water resources, climate change adaptation, and disaster risk and resilience of the Third Pole. TPDC is also focused on acting as an important supporting platform for the ongoing STEP program, which was a national key program initiated in August 2017, led by the Chinese Academy of Sciences (CAS) (Yao, 2019). The STEP program covers an area of more than 5 million square kilometers and involves more than 50 disciplines, and will produce a series of massive cross-border, multi-scale, multi-disciplinary, and multi-type scientific data. TPDC is taking the lead on effective management and sharing of these data, which is an important basis for achieving the goal of this scientific expedition, as well as supporting the study of regional and global environmental change.

TPDC provides online sharing protocols for data users, supplemented by offline sharing protocols, with bilingual data sharing in Chinese and English (Figure 1, *https://data.tpdc.ac.cn/*). There are more than 1,900 datasets shared by TPDC, covering geography, atmospheric science, cryospheric science,



A late Middle Pleistocene Denisovan mandible from the Tibetan Plateau
Different glacier status with atmospheric circulations in Tibetan Plateau and surr...
Quantifying the rise of the Himalaya orogen and implications for the South Asia...
Asian monsoon experiment on the Tibetan Plateau (GAME/Tibet) dataset for gl...
China meteorological forcing dataset (1979-2018)
Long-term series of daily snow depth dataset in China (1979-2019)
Long-term surface soil freeze-thaw states dataset of China using the dual-index...
Long-term sequence dataset of lake area on the Tibetan Plateau (1970-2013)
Dataset of river basins map over the TP (2016)
A monthly air temperature and precipitation gridded dataset on 0.025° spatial re...

Lake changes in the Tibetan Plateau and other regions of China since 1960s

November 12, 2019 | By the National Tibetan Plateau Data Center

Dataset of 0.01° Surface Air Temperature over Tibetan Plateau (2000-2015)
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1-km monthly minimum temperature dataset for China (1901-2017)
1-km monthly maximum temperature dataset for China (1901-2017)
1-km monthly precipitation dataset for China (1901-2017)
Hourly meteorological forcing & land surface state dataset of Tibet Plateau with ...
High-temporal-resolution water level and storage change data sets for lakes on ...
Dataset of high-resolution (3 hour, 10 km) global surface solar radiation (1983-2...
The lakes larger than 1km² in Tibetan Plateau (V2.0) (1970s-2018)
PML_V2 global evapotranspiration and gross primary production (2002.07-201...

Observational datasets of Pan-Third Pole
the Second Tibetan Plateau Scientific Expedition (STEP) program
Pan-third-polar environmental change and green silk road construction
Sanjiangyuan National Park

Institute of Tibetan Plateau Research, Chinese Academy of Sciences

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Number of Datasets: 2,123
Total Data Size: 33 TB
Registered Users: 32,052
Browse Count (Times): 7,897,922

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Figure 1. *Data portal for National Tibetan Plateau Data Center* (https://data.tpdc.ac.cn/)

hydrology, ecology, geology, geophysics, natural resource science, social economy, and other fields. There are more than 31,600 registered users. TPDC complies with the "findable, accessible, interoperable, and reusable (FAIR)" data sharing principle, and takes a series of measures to protect the intellectual property rights of data and to give credit to data authors. Digital Object Identifiers (DOI) are used for scientific data access, tracking, and citation. The Creative Commons 4.0 protocol is used for data re-distribution and re-use. Data users are required to cite the dataset and provide necessary acknowledgement in order to give credit to data authors as journal papers. The data citation references are provided on the TPDC landing page of each dataset.

Moreover, TPDC has been strengthening cooperation with international programs and projects related to the Third Pole to improve collecting, integrating, and publishing data resources from these project outputs, while also providing the relevant data support for them.

The Third Pole Environment (TPE) is an international program for interdisciplinary study in the Third Pole region and beyond. It was initiated in 2009 by three world-renowned scientists, Professors Tandong Yao, Lonnie G. Thompson, and Volker Mosbrugger. The TPE International Program Office resides at the Institute of Tibetan Plateau Research of CAS, where TPDC is subordinate. TPDC is responsible for providing data and system support for TPE through developing data and information management mechanisms; storing, integrating, analyzing, excavating, and publishing scientific data; and developing online big data analysis for the Third Pole.

TPDC is strengthening cooperation with GEWEX. Some frequently-used GEWEX datasets have been published in TPDC, such as the "Asian Monsoon Experiment on the Tibetan Plateau (GAME/Tibet) dataset for global energy water cycle (1997–1998)" (Ma et al., 2008), and "China meteorological forcing dataset (1979–2018)" (He et al., 2020), which was developed using data from the China Meteorological Administration (CMA) and some of the GEWEX surface observations. At the same time, TPDC provides data and a platform to support GEWEX in enhancing access to water- and energy-related observations, data collection, and data sharing over broad high mountain regions. For example, at the 2018 GEWEX Hydroclimatology Panel (GHP) Meeting, TPE organized a joint action with GEWEX on water security in the Third Pole (Evans et al., 2018). In addition, the International Network for Alpine Research Catchment Hydrology (INARCH), a crosscutting project of GHP, has collected data in the Mountain Research Basins, which include the observation sites over the Third Pole: Nam Co Monitoring and Research Station for Multisphere Interactions, Qomolangma Atmospheric and Environmental Observation and Research Station, Southeast Tibet Observation and Research Station for the Alpine Environment, and Upper Heihe River Basin (Pomeroy et al., 2018). TPDC has organized all these in situ observations, which can contribute to these projects. TPDC not only provides various datasets for Third Pole research, but will also host the database that will store many model products for GEWEX projects [e.g., "Impact of initialized land temperature and snowpack on sub-seasonal to seasonal prediction" (LS4P) and "Third Pole Experiment Multi-Model Intercomparison" (TPEMIP) (Xue et al., 2019a; 2019b)].

In summary, TPDC was created in response to the urgent need for sharing scientific data concerning the Third Pole. It complies with the "FAIR" data sharing policy, and has effective intellectual property protection and sharing measures. Data citation ensures the proper credit of data authors. Furthermore, a cloud service platform will be constructed for the extensive integration of data, methods, models, and services and to promote the application of big data analysis in Third-Pole scientific research. In the future, TPDC will continue to enhance cooperation with international programs and projects to become a reliable data repository that both provides scientific data for Third Pole research and hosts the database that stores in situ observations and model outputs. If you would like to contact the TPDC team, please email the service team at *data@itpcas.ac.cn*.

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A Proposed Regional Hydroclimate Project for the United States: Water on the Edge in the Anthropocene

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Introduction

The global water and energy cycles encompass processes rising up from the bedrock through the depths and circulations of the atmosphere and oceans. But from a human perspective, it all gets real at the Earth's surface where the processes are highly scale-dependent and the impacts are localized. It can be helpful to return to the basics to remind ourselves of the simplified water budget equation for a watershed, which can be written as (after Healy et al., 2007):

$$P + Q_{\mathrm{in}} = ET + \Delta S + Q_{\mathrm{out}} \qquad (1)$$

where ET is evapotranspiration, P is precipitation, Q_{in} is water flow into the watershed, ΔS is change in water storage, and Q_{out} is water flow out of the watershed. Likewise, the simplified energy budget equation at the surface is:

$$R_n + G = H + \lambda{*}ET \qquad (2)$$

Here, R_n is net radiation at the surface (short-wave and long-wave components); G is the heat flux into the surface; H is sensible heat flux into the atmospheric boundary layer from the surface; and $\lambda{*}ET$ is latent heat flux from the surface [i.e., the product of latent heat of vaporization (λ) and evapotranspiration rate]. Note that the evapotranspiration appears in both equations, underscoring the direct connection between the water and energy budgets. Or to put it another way, one must understand and estimate both the water and energy cycles if one hopes to be able to predict them.

Figure 1 illustrates this point nicely. It shows the effects of groundwater feedback on the atmospheric temperature at 2 m above the surface over the central U.S. Using high-resolution (4 km grid spacing) Weather Research and Forecasting (WRF) model simulations, Barlage et al. (2020) were able to significantly reduce the warm bias in the WRF model during the summer months. An important finding of this study, one that is not self-evident in this brief description, is the high-spatial resolution required to realistically simulate the coupling of the subsurface water storage terms (ΔS) to the flux of latent heat ($\lambda{*}ET$) at the land-atmosphere interface.

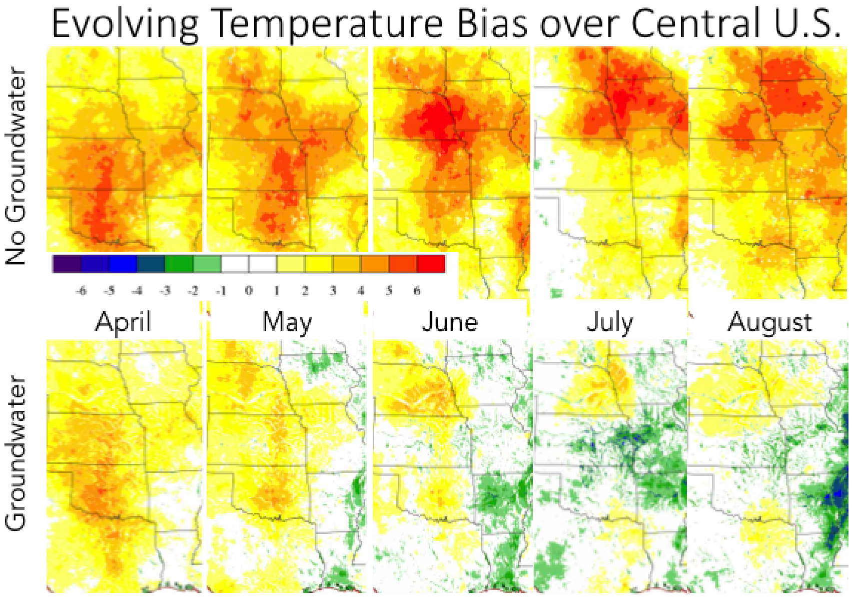

Figure 1*. Atmospheric temperature bias (2 m above ground) in WRF model simulations over the central United States (6 month simulation from April to September 2012) without (top) and with (bottom) ground-water coupling. Note that the warm biases seen in the top panel (oranges and reds) are greatly reduced when groundwater moisture sources are accounted for. From Barlage et al. (2020)*

The simplicity of these equations belies the complexity that is buried in each of the terms in them. It is the unpacking of the terms in these equations that has been the goal of GEWEX since its inception, a goal that is as relevant today as it was then. Understanding the intricacies of these coupled equations over the CONtiguous United States (CONUS) is the objective of a new, proposed GEWEX Regional Hydroclimate Project (RHP). Rising to this challenge will require broad engagement and interdisciplinary contributions across the scientific community, and the committed support of the relevant U.S. federal program offices.

Why Here, Why Now?

Why do we need an RHP in the CONUS, and why is now the time to do it? As humanity enters an epoch that many argue should be called the Anthropocene, the need to monitor and predict water quality, quantity, and use has never been greater. Like all nations, the United States faces increasing pressures from a changing climate, a growing population, changing demographics, and ageing infrastructure. Regarding the latter, the American Society of Civil Engineers periodically produces a report card for the nation's infrastructure. The most recent overall grade (2017) is a "D+", with dams, inland waterways, and drinking water each scoring a "D" (see: *https://www.infrastructurereportcard.org*). We need the best science, modeling, and observations that the nation and the international community can muster to understand, predict, and manage our ecosystems and our land, energy, and water resources.

Since the beginning of GEWEX 30 years ago, we have improved our understanding of key processes and implemented this knowledge in our models. Furthermore, steady advances in high-performance computing have en-

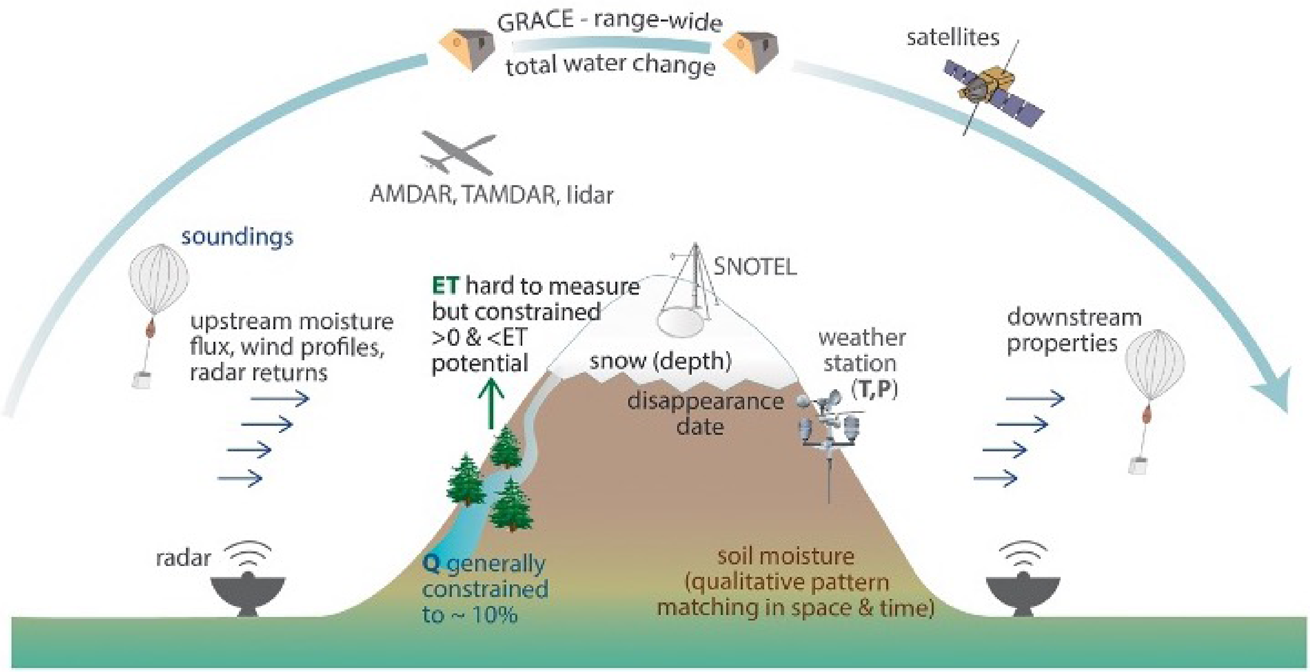

***Figure 2**. This figure is taken from Lundquist et al. (2019), which argues that our skill in modeling precipitation in mountainous regions has exceeded the skill of our ability to observe these processes.*

abled us to begin to model the Earth system at very high resolutions, effectively simulating climate at weather scales over large regions. In short, our ability to model energy and water cycle processes is beginning to outpace our observational capabilities to observe these processes with a sufficient data density to drive these models (e.g., through data assimilation) and to verify and validate the model's performance (Figure 2, Lundquist et al., 2019). In pushing to these finer resolutions, our models in some ways are also on the verge of outstripping themselves in that we are stressing the underlying assumptions of their parameterizations of physical processes. These are assumptions that should be tested, evaluated, and improved by observation and measurement.

For example, researchers are now conducting continental scale multi-decadal simulations at convection-permitting resolutions, i.e., with horizontal grid spacings of just several kilometers or less (e.g., Schär et al., 2020). Different approaches to tackle this kind of modeling are being employed. Top-down approaches like the Department of Energy's (DOE) study of the variability and extremes of large-scale precipitation employed the Model for Prediction Across Scales-Atmosphere (MPAS-A) with a variable-resolution unstructured grid to achieve high resolutions over a limited region (Hagos et al., 2018). The National Aeronautics and Space Administration (NASA)'s Goddard Earth Observing System (GEOS-5) global atmospheric model (Putman and Suarez, 2011), another top-down approach, is effectively a brute force method for global integrations at convection-permitting grid spacing. Bottom-up approaches include using regional weather models such as the Weather Research and Forecasting (WRF) model, forced by climate scenarios and boundary conditions (e.g., Liu et al., 2017). Meanwhile, the National Oceanic and Atmospheric Administration (NOAA), in partnership with the National Center for Atmospheric Research (NCAR), has implemented a high-resolution National Water Modeling system, which is based on the community WRF-Hydro hydrologic modeling system (*https://ral.ucar.edu/projects/wrf_hydro/overview*) and the Noah-Multiparameterization Land Surface Model (e.g., used in the WRF model). This model issues forecasts for 2.7 million stream reaches across the CONUS, as well as a variety of other terrestrial hydrologic variables (e.g., soil moisture, evapotranspiration, snowpack, and surface ponded water depths) with fine spatial and temporal resolution. A fundamental challenge in validating and improving this new system is the fact that at present there are only about 8,000 stream gauges, many of which do not sample water quality parameters. For other components of the water and energy balance, such as soil moisture, there are even fewer in situ measurements. Remotely-sensed observations can provide a useful complement to in situ measurements for some observations, such as precipitation, skin temperature, or snow cover, but not for others, such as deeper layers of soil moisture.

Looking at this from another angle, our representation or parameterization of the physical, biogeochemical, and human processes on these fine scales demands much greater fidelity. This was argued recently by Wulfmeyer et al. (2020) in their description of the GEWEX Land-Atmosphere Feedback Observatory (GLAFO). GLAFO aims to measure the energy and water flow below and at the surface and in the atmospheric boundary layer. This is an important conceptual step forward in monitoring these processes. With similar aims, the United States Geological Survey (USGS) is embarking on the implementation of the Next Generation Water Observing System (NGWOS, *https://www.usgs.gov/mission-areas/water-resources/science/usgs-next-generation-water-observing-system-ngwos*) to address the gap between hydrologic modeling and predictions, and our ability to monitor water quantity, quality, and use.

While this list of recent developments is far from complete, it helps to illustrate why the U.S. is uniquely positioned to perform such a large-scale endeavor at this time: the U.S. has extensive existing observational networks and the potential to grow and evolve them; a robust and diverse modeling community; high-quality and well-distributed educational and research institutions; and a unique collaborative potential with local, state, and federal stakeholders. Another key advantage in the U.S. is the existence of a comprehensive agency-supported research-to-operations (R2O) endeavor, which provides a strong foundation of existing institutional and stakeholder efforts to ensure maximized uptake of the project's generated knowledge and a swift translation to application and societal impact. In short, now is the time to rise to address these challenges by coordinating, leveraging, and complementing these existing infrastructural developments.

Over the next 5–10 years we will convene top scientists, nationally and internationally, to help develop and implement a bedrock-to-boundary layer observational network; to employ state-of-the-art, high-resolution coupled hydroclimate models; to develop high-fidelity reanalyses of the water and energy cycles; and to establish a scientific sandbox, in which we can test and challenge our understanding of, assumptions about, and hypotheses associated with these complex processes. Much has been learned from previous RHPs in the U.S.: the successful GEWEX Americas Prediction Project (GAPP) that ended in 2010, and the GEWEX Continental-scale International Project (GCIP), which ended in 2001. In the Western Hemisphere, this new RHP will fill a gap between Global Water Futures (GWF) in Canada and ANDEX in South America, which collectively fit into the global RHP puzzle picture as well. The U.S. RHP directly supports the World Climate Research Programme (WCRP) Grand Challenges on *Water for the Food Baskets of the World*; *Clouds, Circulation and Climate Sensitivity*; and *Weather and Climate Extremes*. Additionally, the RHP is aligned with all of the GEWEX Science Questions related to *Observations and Predictions of Precipitation*, *Global Water Resource Systems*, *Changes in Extremes*, and *Water and Energy Cycles and Processes*.

Science Drivers

At the most comprehensive level, this U.S. RHP is aimed at helping to close the coupled water and energy budgets over the CONUS with fidelity. This speaks to fundamental issues such as water use, availability, and quality; food production; energy production and use; healthy ecosystems; and others (e.g., AMS, 2017). Closing the coupled water and energy budgets drives towards questions that get to the heart of human interactions with the natural systems:

- How well can we characterize the variability and uncertainty of regional water and energy budgets?
- How well can we characterize climate change at regional and watershed scales? And, how well can we represent the land-atmosphere dynamics and the impacts of a changing climate at these scales?
- Can we distinguish and quantify the extent to which changes in the water cycle are driven by land cover/use change and irrigation practices versus climate change or low-frequency climate variability?
- How will headwater catchment supplies change in the future, especially in the Intermountain West (e.g., Galaudet and Petty, 2019)?
- Land-atmosphere feedbacks processes: how do land surface conditions (soil moisture, groundwater, land cover/land use) influence atmospheric thermodynamics and precipitation? And vice versa?
- What large-scale modes of hydroclimate variability favor the occurrence and severity of extreme events (drought and flood)? How are these linked to predictability? How will these modes change in the future, and will predictability be affected?
- What observations are needed to reduce water and energy budget and predictive uncertainties, and how can we optimally utilize existing observational capabilities?
- How do we build better coupled modeling systems to address these issues?
- How do we best incorporate human behaviors and responses into our predictive tools?

A High-Level Strategy

The U.S. RHP will work to address these questions through an integrated observational, modeling, and testbed research strategy, to rigorously understand and quantify the coupled water and energy budgets. It is a CONUS strategy in that we now have a demonstrated ability to model the CONUS at sufficient resolution. Within this modeling domain, carefully considered regional foci will be established, supported by comprehensive observational transects and case studies targeting regionally-specific drivers and issues. Figure 3 illustrates this concept with a proposed modeling domain (at 4 km or higher resolution in the atmosphere) and a highly-conceptualized illustration of an observational strategy.

Observational Approach

The observational strategy will establish an extensive and comprehensive "bedrock to boundary layer" observational network from existing (leveraged) and new observational sites, in such a way as to create transects (Figure 3). The transects will be designed to address key processes such as orographic precipitation and snowpack, or mesoscale convective systems. Obviously, the higher the observational density of the network and the longer the measurements are continuously conducted, the better. But equally important is the comprehensiveness (types and kinds) and quality of those measurements. In short, we need to be able to monitor and quantify all of the terms in equations 1 and 2. Fortunately there are forward-looking efforts spinning up, such as GLAFO and NGWOS as noted earlier, and long-standing resources such as NOAA's Hydrometeorology Testbed (HMT) sites, DOE Atmospheric Radiation Measurement (ARM) Observatories and Mobile Facilities, and NASA's extensive suite of satellite missions, to name only several. In addition to supporting modeling and scientific investigations, such a network enables improvements to observing system design and implementation, and planning future satellite missions.

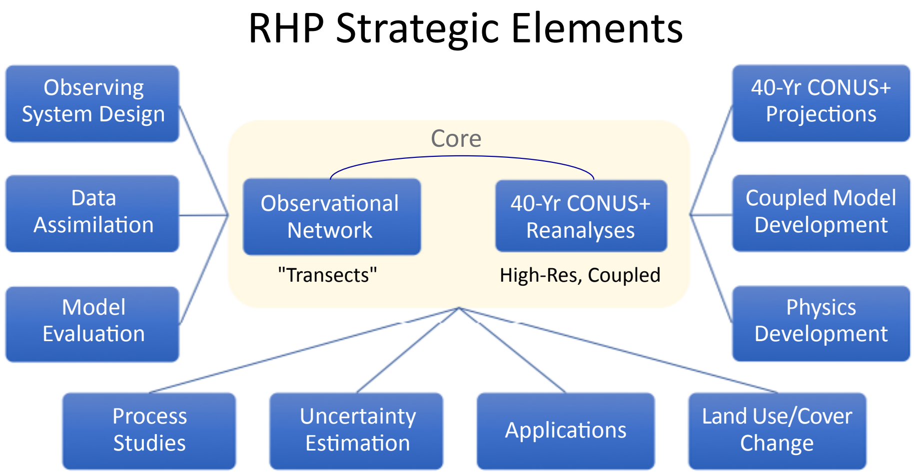

Figure 4*. The strategic elements envisioned for the RHP that come together in a testbed-like environment. A core observational network coupled with CONUS+ scale, high-resolution reanalyses forms the basis for a range of study and development activities.*

In short, the more observations we can bring to bear, in terms of the number of sites, the breadth of types of measurements, and the quality and longevity of those measurements, the more complete our understanding of the science will be, and the better we can evaluate and improve our predictive tools.

Modeling Strategy

The modeling strategy will build from multi-decade reanalyses (nominally 40 years) for a CONUS-plus domain (Figure 3, see cover). The reanalyses form the foundation of our modeling strategy because they establish an observationally-supported baseline, allowing us to characterize model skill and biases. Reanalyses also enable us to assess the relative contributions of various processes, such as disentangling the impacts of various human dimensions (for example, changes in land use/land cover) versus natural changes. Once this baseline is established, we can pursue multi-decadal climate projections and employ various model ensemble approaches, which are important to characterize uncertainty and natural variability. Another important consideration of this modeling approach is to consider coupled modeling strategies across the land-atmosphere interface, in coastal regions, and with human dimensions. In summary we propose:

- A new era of high-resolution (kilometer scale), fully coupled, CONUS-wide reanalyses of the past 40 years
- Multi-decade hydroclimate projections under various climate change scenarios
- Integrated, multi-scale, process-based models that can be both calibrated and validated for operational prediction
- Improved generation of actionable prediction and management products with high spatial and temporal fidelity
- An uncertainty framework approach via ensembles

A Testbed Approach

Finally, we envision a testbed approach that fosters collaboration and engagement with stakeholders. Such a framework enables analyses and studies building from the core observational and modeling capabilities, and permits the assessment of impacts for various applications. Key elements of this testbed include:

- Process studies and hypothesis testing
- Data assimilation techniques and application
- Model evaluation
- Process development (physical, biogeochemical)
- Land use/land cover change studies
- Coupled model development
- Applications (such as water resources management)

How these pieces fit together into a testbed-like capability are illustrated in Figure 4.

Timeline and Next Steps

A CONUS-focused RHP would have great societal impact and importance through its embodiment of the GEWEX Science Questions, and in that it directly addresses several of the WCRP Grand Challenges. These are also consistent with the U.S. GEWEX interests and goals. For the RHP to succeed, we need the best science and technology to be brought to bear, as well as strong and robust programmatic support. This concept will be further developed and coordinated with the group of program managers at the U.S. Global Climate Change Research Program (USGCRP), and with the community at large.

In the coming months we will be preparing a white paper to describe this RHP concept in greater detail, and to refine the scope, science drivers, and objectives. This draft white paper will be made available for the community to comment upon and contribute to. If you are interested in engaging in this RHP, this is a very good opportunity to start. We have also proposed sessions at the American Geophysical Union (AGU) Fall Meeting (December 2020) and the American Meterological Society (AMS) Annual Meeting (January 2021), so be on the lookout for those announcements, and please consider contributing your work to them. Given a solid white paper, we hope to formally submit a request to begin the initial phase of the RHP process by the fall of 2020.

Further questions or inquiries can be addressed to: *gewex@gewex.org*.

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GEWEX/WCRP Calendar

The COVID-19 pandemic has had an impact on the majority of scheduled meetings. Please see http://www.gewex.org/events/ for a list of events that have been cancelled, modified, or rescheduled. Some are now being held virtually. Please consult individual meeting websites for the most up-to-date information.

24–31 August 2020—6th International Baltic Earth Summer School on Climate of the Baltic Sea Region—Trosa, Sweden

30 August–4 September 2020—11th Annual Catchment Science Summer School—Virtual, via Zoom Conferencing

10–14 January 2021—101st American Meterological Society Annual Meeting—New Orleans, LA, USA

10–12 February 2021—2nd Evapotranspiration Workshop: Novel Insights through Models and Observations—Wageningen, The Netherlands

16–18 March 2021—GEWEX Integrated Product Workshop—Toledo, Spain

12 April 2021—The Gray Zone 2 Meeting—Toulouse, France

12–16 April 2021—Improvement and Calibration of Clouds in Models—Toulouse, France

12–14 October 2021—2nd Climate Observation Conference—Darmstadt, Germany

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