Statement of Research Interests and Vision

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Research Objectives

The goal of my research is to seek a better understanding of the fundamental hydrological and atmospheric processes and mechanisms, and their mutual interactions governing the water and energy cycle over a wide spectrum of spatial and temporal scales. Understanding of them is critical to the solution of critical environmental issues such as (1) the assessments of regional impacts on the sustainability of water resources due to climate change, increasing water demand, changes in water managing practices, etc; (2) the predictability of regional flood and drought as sources of significant natural hazards to human welfare; (3) the impact on regional hydroclimatology due to any land surface properties modification and climate change, and vice versa, the feedbacks of changing hydrological regimes on the regional climate.

Science Questions Asked

The main scientific questions asked in my research can be broadly classified into four related categories:

1. Global and Regional Water and Energy Budgets - What are the dynamic pathways, storages, and transfers of water and energy fluxes within the Earth system? How to better estimate and close water and energy budgets? Where are the current understanding, main challenges, and difficulties? How is the best conjunctive use of various in-situ, model-based, and remote-sensing data help in answering the above this questions?

2. Anomaly Propagation through the Hydrologic Cycle - How do the hydro-climatological anomalies propagate through the land and atmospheric branches of the hydrologic cycles? How do they link to the occurrence, magnitude and persistence of floods and droughts? What are the interactions, feedbacks, and relevant timescales behind the propagation?

3. Terrestrial Water Storage and Dependent Hydrologic Fluxes - How to best estimate the variations of terrestrial water storages and their individual components on various spatial and time scales? What are the functional relationships between the hydrologic states (TWS) and the dependent hydrologic fluxes (precipitation, evaporation, runoff, etc)? How the numerical land surface hydrologic models can be formulated and uniquely constraint to yield accurate simulations and meaningful projections?

4. Hydrological Response of Climate Change- How the above hydrologic mechanisms have changed and will change as atmospheric CO_2 and temperature continue to increase? What are the responses of atmospheric and terrestrial hydrologic states and fluxes to climate change in regional and global scale?

Research Strategy

The above objectives and science questions cover a wide spectrum of contemporary hydrologic issues, and hence they can only be achieved and answered by a multi-approach and multi-data research framework. My research strategy is to combine *in-situ* observations, atmospheric re-analysis data and remote sensing technologies in conjunctive with hydrological modeling approaches. Moreover, my methodologies often combine the strengths of both deterministic and stochastic (statistical) approach in accounting for complex land surface heterogeneities as well as the scale transition of the complex and highly nonlinear hydrological processes.

Main Research Directions

My current main research tasks can be broadly categorized into the following three directions:

1 Climate Change Impacts on Water Resources and Hydrology (Floods & Droughts)

According to the IPCC AR4 (Intergovernmental Panel on Climate Change Fourth Assessment Report), more flood occurrence could be anticipated in the 21st century as the Earth's temperature continues to rise on a global scale. For instance, the recent flood in Pakistan occurred in July 2010 had killed 1,700 people and affected more than 20 million people with overall economic loss estimated to be $9.5 billion.

A potential consequence of climate warming on water resources as well as flood and drought disasters has been increasingly investigated during last decades (*Barnett et al*., 2008; *Labat et al*., 2004; *Matthews*, 2006; *IPCC*, 2007). Numerous studies suggested that climate warming is likely leading to alter the hydrological cycle (*Huntington*, 2006; *Jung et al*., 2010; *Milly et al.*, 2005; *Oki and Kanae*, 2006; *Peterson et al.*, 2006). Under rising temperature, precipitation is more likely to arrive in the form of heavy rains under climate warming accompanied with an increase in flood risk (*Allen and Ingram*, 2002; *Goswami et al*., 2006; *Milly et al*., 2002; *Min et al*., 2011, *Nohara et al*. 2006; *Trenberth*, 1998; *Trenberth et al*., 2003). Decrease in the accumulation and melt of seasonal snow packs may cause a shift in the timing and amount of runoff and affect future water resources availability (*Barnett et al*., 2005, 2008). Furthermore, the upward trends of evaporation associated with the rising temperature can potentially result in larger decline in lake level (*Thomas*, 2000; *Walter et al*., 2004) and soil moisture (*Dai et al*., 2004), and even the depletion of groundwater aquifers (*Rosenberg et al*., 1999, *Rodell et al*., 2009, *Weider and Boutt*, 2010).

The long-term trends and dynamic properties of the hydrological cycle are governed by the interactions and feedbacks between atmospheric and land surface hydrological processes. Previous studies on global and continental river runoff have shown the linkage between the increasing runoff trends and the anthropogenic climate change associated with the concentration of greenhouse gases (*Betts et al*., 2007; *Gedney et al*., 2006; *Piao et al.*, 2007; *Labat et al.*, 2004). On the regional scale, the response of runoff to the change in climate variables, mainly precipitation and temperature, has also been examined in North America (*Barnett et al*., 2008; *Das et al*, 2009; *McBean and Motiee*, 2008), Europe (*Stahl et al*., 2010), Canada (*Burn*, 2008; *Whitfield*, 2001), and China (*Chen et al*., 2007). The observed large-scale change in river discharge in high-latitudes potentially disturbs ocean circulation and climate (*Curry* et al., 2003; *Peterson et al*., 2002, 2006).

2 Data Analysis and Remote Sensing Application in Hydrology

Recent launch of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002 by NASA has offered tremendous potential to begin monitoring total terrestrial water storage (i.e., surface water, snow and ice, soil water, groundwater, vegetation water) changes within large river basins at monthly or longer timescales. Recent research has demonstrated that GRACE can be used to estimate total water storage changes (TWSC) in large river basins, evaporation, continental discharges, and snow storage, depending on the size of the region (> 200,000 sq. km) and the magnitude of the variations themselves (at least a few mm). For regional- to global-scale water balance studies, GRACE will provide a direct measure of seasonal water storage, which is unprecedented in hydrologic analysis.

However, gravity measurement made by GRACE provides no information about the vertical distribution of mass. Thus, GRACE data can be used to constrain only the vertically integrated water storage variability, and cannot separate soil moisture from surface water or from water deeper underground. To make GRACE derived terrestrial water storage variations useful to hydrologists, two outstanding research issues need to be resolved. First, how to disaggregate vertically-integrated water storage information into its constituent components (i.e., surface water, soil water and aquifer stores), and second, how to merge it with large-scale hydrologic models to improve seasonal to inter-annual predictions of water availability. Solving the first problem will allow us to quantify monthly hydrologic fluxes across the boundaries of the different water stores (land surface, root zone, and aquifers), thereby providing better closure to the monthly water balance at the basin scale. The second issue is associated with the global water cycle and solving it will allow progress in understanding weather and climate linked processes leading to hydrologic extremes (droughts and floods). Moreover, GRACE has the potential to provide the first opportunity for monitoring shallow groundwater fluctuations from space (i.e., groundwater remote sensing).

Global hydrological models remain the only suitable tool to validate GRACE data before the extensive network (either from ground or from space) of monitoring terrestrial water storage is established. However, most continental hydrological models do not account for all water storage components such as groundwater and lakes. Since GRACE data can be another important constraint on the output of hydrological models as they represent the total vertically integrated effect of water mass changes, my recent research effort is directed towards the enhancement of parameterizations in global hydrological model; for example, the incorporation of water table dynamics into land surface models CLM (*Lo et al.,* 2008, 2010) and a Japanese model called MATSIRO (*Koirala et al.*, 2011a, b, submitted), as well as the development of robust spatial averaging algorithms to aggregate ground data into the scale that minimize the GRACE uncertainty.

3 Global Hydrologic Modeling with the Representation of Water Table Dynamics

Most of the current land surface models (LSMs) lack any representation of groundwater aquifers despite its importance in regional hydroclimatology has been well recognized for long. Such a simplification would result in significant errors in the predicted land surface states and fluxes at least for shallow water table areas in humid climate. My PhD dissertation (2003) addressed this deficiency by developing a lumped unconfined aquifer model, and interactively coupled to a NCAR land surface scheme. The sub-grid variability of water table depth and associated spatial variability in groundwater recharge and discharge have been accounted for by using a hybrid statistical-deterministic approach. The coupled model has been successfully tested in several geographical locations including Illinois. Since LSMs are aimed to be used in climate models, an efficient parameter estimation scheme feasible for computationally-demanding global simulation were developed. This scheme used observed stream flow in combination with base flow separation technique to calibrate groundwater model parameters and its applicability has been demonstrated (*Lo et al.*, 2008, 2010). The groundwater scheme has also been incorporated into NCAR CLM (Community Land Model) and Japanese LSM MATSIRO (the Minimal Advanced Treatments of Surface Interaction and Runoff) in order to investigate the importance of shallow groundwater dynamics in the continental- to global-scale hydrological simulations.

Another ongoing research is the development of the parameterizations of groundwater-related hydrological processes in the LSMs, including (a) the incorporation of lake-wetland module, (b) the groundwater-supported evapotransipiration for plant growth, (c) the anthropogenic influence on groundwater hydrology, i.e. groundwater pumping for agricultural irrigation use, and (d) the topographic and geomorphologic control on regional (lateral) groundwater flow. Despite of ample field evidence on their pervasive importance in land-surface hydrology, all of these groundwater-related processes have not yet well represented in most LSMs.

Under this broad topic ("global hydrologic modeling with the representation of water table dynamics"), there are at least three open science questions as follows which I have been rather enthusiastic in gaining understanding and provide contributions:

A. Role of Groundwater in the Climate System

The dynamic nature of groundwater storage has close linkage to land surface-vegetation-atmospheric processes, and hence weather and climate. However, the importance of groundwater as a hydrological and climatological variable has long been overlooked by the land modeling community. Based on the findings of my previous study on Illinois hydrometeorology (*Yeh et al.* 1998; *Eltahir and Yeh*, 1999; *Yeh and Famiglietti*, 2008), the role that shallow aquifers play in the Illinois regional hydroclimatology can be summarized as follows: (1) Groundwater storage is a major water balance component whose storage change is as important as that of soil moisture at monthly or longer time scale. (2) The regional water table depth is highly correlated with nearby streamflow in a strong nonlinear manner and explains 2/3 of the streamflow variance. (3) The unconfined aquifer amplifies drought anomalies and dissipates flood anomalies, which results in the observed asymmetric response of the aquifers to droughts and floods. (4) The unconfined aquifer supplies water to replenish root-zone soil moisture, which helps maintain the observed high rate of summer evapotranspiration.

B. Surface Water – Groundwater Interaction

One of my research goals strives for a better understanding of the transport of water and chemicals between SW and GW. The influences of this interaction on biological processes are essential to improve management of surface and groundwater resources and to protect the functionality of the associated ecosystems. Historically, SW and GW have been considered separately and essentially unconnected components of the hydrological processes water resources managers and scientific investigators. However, it has been recognized that hydrological exchange is critical for the sustainability of conjunctive use of groundwater and surface water, for the maintenance of water quality, and for the conservation of biodiversity and the ecological functions of the watersheds.

I am interested in the following scientific issues related to the interactions between SW-GW interaction: First, riparian zones are the most direct link between the atmosphere and groundwater, providing sites of enhanced direct recharge as well as discharge to the environment through baseflow and phreatophyte evaporation, and serving as an important source for aquifer salinization and mineralization. Thus the understanding of riparian-zone dynamics is important for the integrated river basin management. Second, the propagation of rainfall anomalies to shallow aquifers impacts basin-wide hydrology. The "teleconnections" between groundwater recharge through the mountain front and the riparian discharge near the valley floor has yet to be well understood. Third, native vegetation and introduced crops have water use requirements that have to be met through precipitation or irrigation (groundwater withdrawal). The type of plants is also associated with different rooting characteristics and responses to rainfall, affecting evapo-transpiration, soil moisture, recharge, carbon sequestration rates, and phyto-remediation capabilities. Last (and with the greatest implication to regional water balances), whether the SW-GW interaction exert a significant influence on the subsurface storage variations, and hence evapotranspiration, baseflow and surface runoff is still an open question. If they do, how can they be quantitatively estimated over areas as large as the Mississippi River basin?

C. Scale Issue: Sub-grid Variability and Aggregation

The unsolved problem regarding the process representation at disparate spatial scales in LSMs arises mainly because (1) the mathematical relationships describing relevant hydrologic processes are mostly scale-dependent (i.e., different dominate hydrologic processes may manifest at different scales), (2) most land surface hydrologic processes are nonlinear, and (3) most hydrologic model parameters cannot be fully calibrated against available data and hence cannot escape from equi-finality problems. In current atmospheric models, land surface hydrologic states and fluxes are estimated from parameterizations relating subgrid-scale hydrologic processes to the large-scale forcing variables resolved by atmosphere models. The most important is the soil moisture parameterizations, traditionally having the types that the flux is linearly related to soil moisture content. My current parameterization efforts are directed toward developing and incorporating more realistic nonlinear storage-flux relations and sub-grid variability of relevant variables or parameters, and testing their effects on the model-simulated hydrology. In improving upon the simplified parameterizations, the issue of spatial averaging becomes rather crucial on the typical grid scale of climate model. Formulations of suitable hydrologic theories at various scales and their subsequent verifications remain challenging.