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Impact of Climate Change on Physical and Biogeochemical Processes in the Hydrologic Cycle: Challenges and Perspectives

Wei Zhang^{1*}
Guest Editor

Ni-Bin Chang²,
Chief Editor

¹*Department of Plant, Soil and Microbial Sciences, & Environmental Science and Policy Program, Michigan State University, East Lansing, MI 48824. USA.*

²*Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, FL 32816. USA.*

Editorial

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ABSTRACT

This special issue “Impact of climate change on physical and biogeochemical processes in the hydrologic cycle” presents a collection of articles on interactions of climatic drivers and hydro-biogeochemical responses as well as the role of biogeochemical processes in controls and feedbacks with regard to climate change impact. While the in-depth disciplinary studies are critically needed as presented in this issue, we also strongly believe that systems approach transcending disciplinary boundaries is needed to address the climate change in integrated natural and human systems.

Keywords: Climate change; hydrology; water quantity; water quality; contaminants.

1. BACKGROUND

World population has reached 7 billion and is expected to be 9 billion by 2050 [1,2]. Facing tremendous challenges in a resources-limited environment to accommodate the 9-billion population [3,4], one can expect that these challenges will be further exacerbated in a changing climate. While average global temperature is projected to increase throughout the

*Corresponding author: Email: weizhang@msu.edu;

century, there will be more extreme events, i.e., some regions with more intense precipitations and other regions with more long-duration droughts [5-7]. Consequently, hydrologic processes will be profoundly altered, e.g., changing precipitation patterns, rising sea level, melting glacier and permafrost, depleting groundwater, etc. [5,6]. Urbanization and economic development would also be impacted, and societal changes would have to be made in response to the changes in availability, timing, and variability of fresh water resources [8,9]. In order to meet the growing food demand, there will be changes in agricultural geography, practices, and cropping systems [10-12]. In integrated human and natural systems, population growth and migration are strongly interconnected with physical changes of climate and other drivers [8]. In order to fully address the grand challenge of climate change impact on human society and ecosystems, an integrated systems approach will be needed, taking the interactions among climate change and variability, hydrologic processes, and societal adaptation into account [8]. This appears to be a daunting feat, and requires collective efforts across boundaries of scientific disciplines, nations, and political entities. This special issue focuses on investigating impacts of climate change on physical and biogeochemical processes within the hydrologic cycle, thus largely excluding human dimensions. In this editorial, we do not intend to be comprehensive and exhaustive, given enormous amount of work existent in the literature, but rather attempt to identify some knowledge gaps and research challenges.

2. IMPACTS OF CLIMATE CHANGE ON THE HYDROLOGIC CYCLE

Retrospectively speaking, the prior studies on corresponding response in the terrestrial hydrologic cycle have been going hand in hand with respect to various climate change scenarios. The quantity, quality, availability, and sustainability of fresh water resources are directly related to the very existence and survival of the mankind, and also determine health and function of natural ecosystems [13]. This special issue is concentrated on near-surface hydrologic components that can be conveniently used by local population for drinking and production of food and fiber [8,14], and can also be easily contaminated by human activities.

On the global scale, a continued increase of average global temperature will result in warmer lower atmosphere, and consequently increase evaporation and atmospheric water vapor concentrations, which increase global precipitation and frequency of extreme weather events such as intense storms and droughts [7,9,15-17]. Enhanced global hydrologic cycle is then manifested at regional and local scales as results of enhanced spatial heterogeneity and temporal variability in precipitation patterns and hydrologic flow regimes [13]. In wet regions, there could be more intense precipitations, thus increasing flooding risk and damage; whereas in dry regions, there could be elevated frequency and duration of droughts, thus worsening water scarcity [17]. Temporal variability is also shown differently in various areas of the world [17]. For example, in some parts of Northern Hemisphere, the spring is expected to arrive earlier and trigger snowmelt and river flows, often followed by long-duration droughts in the summer [7]. In fact, hydrological changes at regional and local scales are very important because it would directly impact local water use and economy, and subsequently determine the strategies of adaptation and mitigation.

The majority of previous studies have primarily examined the changes of water quantity in the hydrologic cycle, and less attention has been paid to potential impacts of climate change on water quality [18-20]. Understanding the impacts of climate change on contaminant hydrology is needed in order to develop better policies and management strategies for achieving water sustainability in a world of changing climate. Water quantity and variability, as influenced by climate change, would have huge impacts on agricultural practices such as

irrigation and drainage, use of agrochemicals, land use change, cropping patterns, and agricultural production areas [10-12,21]. Additionally, climate change would also profoundly alter loadings of agricultural contaminants (e.g., excess nutrients, pesticides, and microbial pathogens) and their fate and transport processes in agricultural watersheds [10,21,22]. However, this research area has not been extensively investigated. For example, Bloomfield et al. [10] observed that little quantitative study has been performed to specifically understand the impact of climate change on the fate and transport of pesticides. Similarly, the implications of climate change to nitrate transport to groundwater are currently not well understood [22]. The inherent complexity and heterogeneity in environmental systems and processes are responsible for our current deficiency in this area. There is a need to qualitatively highlight some foreseeable changes in hydrological pathways, biogeochemical processes, and ecosystem function and biodiversity.

Increased extreme hydrologic events under the impacts of climate change could lead to periods when fluxes of water and contaminants are drastically increased (i.e., "hot moments"), and locations that are vulnerable to export substantially large contaminant loadings (i.e., "hot spots") [23,24]. While the "hot moments" and "hot spots" could be present in natural environment even in the absence of climate change, one could expect that their numbers will be increased and their distributions will be altered under climate change scenarios. The two types of surface runoff, i.e., Hortonian overland flow and saturation excess overland flow, would be affected differently by climate change, because runoff generation mechanisms are fundamentally different. In regions with more intense rainstorms, Hortonian surface runoff may become more prevalent, because rainfall intensity could more often exceed soil infiltration capacity [25-27]. However, the change of saturation excess runoff is more difficult to assess, because soil water content and water table need to be tracked with relatively high spatial resolution. In the event of increased surface water flux, contaminant export would likely be increased. Additionally, increased surface runoff would increase soil erosion rates, and consequently the transport of contaminants strongly sorbed on soil particles [19]. In urban watersheds, frequent heavy rainfalls would cause more flash floods and sewage overflows, and subsequently export greater amount of contaminants (especially microbial pathogens) into receiving waters, which are of great concerns to public safety and health [18,28] as water-borne diseases are generally associated with heavy precipitation events. Also, flooding and inundation of contaminated area could result in re-suspension of sediments containing legacy contaminants [29]. Moreover, the changes in the hydrological cycle, contaminant fate and transport, and surface water quality are dependent on land use in urban regions and practices in agricultural fields, which would be affected in the context of climate change [19,29-31].

For subsurface flows in unsaturated vadose zone and saturated groundwater, the partition of water in surface and subsurface compartments would be altered by climate change [32-35]. Studies also demonstrated that in some regions total water distribution in surface and subsurface components is minimally changed, but the temporal patterns of hydrologic flows are greatly affected [36]. On regional scales, the assessment of changing water distribution in surface and subsurface components would also depend on the size of watersheds because groundwater and stream flow are often interconnected. Thus, hydrologic flows in individual components may be changed at smaller scale, but the overall change at a larger scale would be small because of the surface water-groundwater interactions [33,35]. Nonetheless, these changes would induce cascade effects on contaminant fluxes in the subsurface. For instance, Visser et al. [32] reported that the Cd and Zn concentrations in the surface water in a southern catchment of the Netherlands could be decreased due to decreased leaching to the surface water under future projected climate. Interestingly,

increased soil water content would result in higher soil hydraulic conductivity, thus higher flux of solutes and particles. While lower rainfall may potentially decrease the contaminant transport, drier soil condition could increase cracking of clayey soils, and thus increase macropore flows that are known to rapidly transport contaminants to shallow groundwater [10].

In integrated hydro-biogeochemical systems, kinetics of biogeochemical processes is influenced by temperature, which could affect cycling of carbon, nutrients, and trace elements, as well as biological degradation and biota uptake of contaminants in soil and aquatic environments [10,22,37]. Microbial community composition and function are influenced by soil temperature and moisture content [38-40]. Therefore, the biogeochemical processes could be changed because of climate change. In the similar line of thoughts, climate change could exacerbate nutrient loadings and resultant anoxia and hypoxia from eutrophication, which could severely threaten function and biodiversity of aquatic ecosystems [29]. Species under thermal stress may be more susceptible to other type of stressors [29]. Adaptability of biota to climate change (i.e., temperature rise) may also be influenced by their exposure to contaminants. So there are intertwined complexities to assess the impacts of climate change on ecosystem service and biodiversity.

In essence, the impact of climate change on the hydrological cycle require using systems approach that address physical, biological, and chemical processes, and should ideally include human dimensions. This complexity brings about new challenges in understanding fundamental processes, and transferring the scientific knowledge into adaptation and mitigation actions.

3. RESEARCH CHALLENGES

Given the complexity of the changing environmental systems, many challenges remain in regard to elucidating controls and feedbacks between hydrologic and climatic systems. Research directions that have been taken include reductionists' approaches to analyze the systems in detail and systems approaches to synthesize the system behaviors in a whole. Modeling work is confronted with uncertainty and scaling issues [26,41]. Down-scaling the global climate model output to local climate data suitable for hydrological modeling is obviously challenging. Also, the choice of scales may inherently influence the end results because these systems are highly non-linear. For example, world population living under severe water stress conditions was tripled when evaluating at a higher spatial resolution than at the country-level spatial scale [8]. Beyond a perspective of sole water quantity, research would become more complicated when coupling water quantity with water quality, due to additional physical, chemical, and biological processes, and associated controls and feedbacks. Philosophically speaking, more spatial and temporal heterogeneity would be revealed with increasing resolution. Impact of climate change interrelated with population growth and migration and local development, when combined, reveals a significant heterogeneity and uncertainty [8], which is important area of study. It is likely that these impacts will be highly exaggerated in developing regions that are confronted with very limited resources to adapt these changes.

The papers in this special issue have contributed to some of these challenges, but leave a wide open field for future research. In addressing the issue of water quantity in developing regions under climate change, Adhikari and Hong [42] investigated the potential changes in the hydrologic cycle at the Nzoia basin in Kenya, an agricultural region susceptible to climate change. It is projected that the Nzoia basin would experience a drier climate, which is

attributed increased evaporation and reduced runoff, despite of a greater precipitation. Yang et al. [43] compared the models to quantify surface-energy partition and thus predict evapotranspiration. Their results show that models need to include moisture availability in order to accurately predict evapotranspiration. On the aspect of biogeochemical processes, Kochsiek and Knops [44] investigated the effect of nitrogen addition to decomposition of soil organic carbon, which is related with carbon sequestration in soils. In another study, Liang et al. [45] studied surface functionality and cation exchange capacity of soil organic matter in the forms of black carbon or amorphous carbon (e.g., microbial biomass, humic substances), using advanced microscopic and spectroscopic techniques. Their results showed that surface oxidation of soil black carbon is responsible for its high cation exchange capacity. These two studies are relevant to potential climate mitigation strategies such as carbon sequestration using biochar land applications [46,47]. Finally, Lee et al. [48] presented convincing evidences that rising sea level and river base could increase groundwater residence time, and thus increase arsenic concentrations in groundwater due to the development of geochemical reducing conditions. Also, sea water intrusion from increased sea level could lead to arsenic desorption from iron hydroxides due to ionic competition and pH effects in coastal watersheds. In alluvial watersheds, contamination and bioaccumulation of mercury and other metals are also strongly influenced by climate-induced hydrologic changes such as salinity level, atmospheric deposition, and stream influx.

In summary, advancements in physical understanding of our hydro-climatic systems are needed in order to accumulate scientific knowledge base to mitigate negative impacts of climate change for informed policy decisions. One critical area that this special issue does not address is to implement a systems approach to bridge boundaries between multiple scientific disciplines. The papers herein are mainly from disciplinary perspectives, which are also critically needed, but we strongly believe that the researchers in all relevant fields should strive to communicate with each other and make their work understood and utilized by other researchers in a way transcending disciplinary boundaries.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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