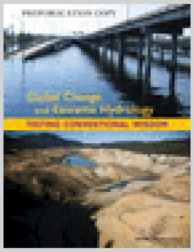

Global Change and Extreme Hydrology: Testing Conventional Wisdom

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Global Change and Extreme Hydrology: Testing Conventional Wisdom

Committee on Hydrologic Science

Water Science and Technology Board

Division on Earth and Life Studies

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Preface

The National Research Council (NRC) Committee on Hydrologic Science (COHS) held a workshop on January 5-6, 2010, that examined how climate warming translates into hydrologic extremes like floods and droughts. This issue represents a chief concern of scientists studying the societal implications of climate change. The event probed the "conventional wisdom" that climate change will "accelerate" the hydrologic cycle, fuel more evaporation, and generate more precipitation, based on an increased capacity of a warmer atmosphere to hold more water vapor. Associated with these theoretical expectations are increases in the frequency and severity of climate and weather extremes relative to present-day conditions, most notably severe floods and droughts.

The workshop, titled *Global Change and Extreme Hydrologic Events: Testing Conventional Wisdom*, brought together three groups of experts. The first two groups consisted of atmospheric scientists and hydrologists focused on the scientific underpinnings and empirical evidence linking climate variability to hydrologic extremes. The third group consisted of water managers and decision-makers charged with the design and operation of water systems that in the future must be made resilient in light of a changing climate and an environment of hydrologic extremes. Although the workshop attendees represented a diversity of perspectives from the scientific and engineering communities, including from researchers and decision-makers, not all perspectives related to this issue were represented. The workshop, focused on floods on day 1 and droughts on day 2, was organized by the climatological, hydrologic, and water management perspectives and featured presentations by invited experts (see Appendixes B-D for workshop agenda, speaker abstracts, and a summary of the presentations, respectively). Breakout sessions were convened each afternoon for focused discussion among participants, speakers, and committee members. We thank the following speakers for sharing their perspectives: Gerry Galloway, University of Maryland; Pavel Groisman, National Oceanic and Atmospheric Administration; Mike Hayes, University of Nebraska-Lincoln; Katie Hirschboeck, University of Arizona; Tom Huntington, U.S. Geological Survey; Harry Lins, U.S. Geological Survey; Mark Person, New Mexico Tech; Siegfried Schubert, NASA Goddard; Richard Seager, Columbia University; Kevin Trenberth, National Center for Atmospheric Research; and Richard Vogel, Tufts University. The abstracts from the workshop presentations (Appendix C) contain the opinions expressed by the speakers. Although the committee relied on these experts' opinions to identify and synthesize its findings, sole responsibility for the report findings rests with the committee.

The topic of global change and extreme hydrologic events is complex, involving a variety of dimensions and associated questions. This report does not attempt to "test" a hypothesis but instead presents an overview of the current state of the science in terms of climate change and extreme hydrologic events, drawing heavily from the workshop discussions. The report includes descriptions of the changes in frequency and severity of extremes, the ability (or inability) to model these changes, and the problem of communicating the best science to water resources practitioners in useful forums.

As noted later in this report, differing perspectives were evident across the three contributing groups (i.e., hydrology, atmospheric sciences, and water management). The COHS hopes that researchers will become aware of these differences and will be inspired to craft more coherent and unified linkages among climate-hydrology-water management issues. In this context, there is a special role for hydrologic sciences that will be articulated throughout the report.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with the procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible, and to ensure that the report meets NRC institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their review of this report: Gerald E. Galloway, Jr., University of Maryland, College Park; William Gutowski, Iowa State University; Mike Hayes, University of Nebraska-Lincoln; Tom Huntington, U.S. Geological Survey; Lee W. Larson, Hydrologist, retired, NOAA's Missouri Basin River Forecast Center; and Kevin Trenberth, National Center for Atmospheric Research. Although these reviewers provided many constructive comments and suggestions, they did not see the final draft of the report before its release. The review of this report was overseen by David T. Ford, David Ford Consulting Engineers, Inc. Appointed by the NRC Division on Earth and Life Studies, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authors and the institution.

Charles Vörösmarty, Chair
Planning Committee for the Workshop on
Extreme Hydrologic Events: Testing
Conventional Wisdom

Contents

APPENDIXES

Summary

The National Research Council (NRC) Committee on Hydrologic Sciences (COHS) convened a workshop, titled *Global Change and Extreme Hydrologic Events: Testing Conventional Wisdom*, to promote dialogue across the science and water resource management communities with respect to climate change and its links to extreme hydrologic events, specifically floods and droughts. The workshop's purpose was to probe the conventional wisdom that as the climate warms there will be an "acceleration" of the hydrologic cycle that will translate into potentially more frequent and severe floods and droughts. The issue is fundamental not only to the science of climate change but also to the capacity of the nation and, indeed, the world to adapt to changes in the Earth system in the 21st century. The workshop reviewed evidence supporting the conventional wisdom, assessed the degree to which the phenomenon—or at least its perception—is consistent across the atmospheric and hydrologic science realms, and assessed the effectiveness by which the scientific knowledge base is currently being translated into water policy and management. The workshop and deliberations of the host committee yielded several valuable findings as summarized here.

Climate theory dictates that core elements of the climate system, including precipitation, evapotranspiration, and reservoirs of atmospheric and soil moisture, should change as the climate warms, both in their means and extremes. The issue rests theoretically on the Clausius-Clapeyron relation, which describes how a warmer atmosphere can hold more water vapor, which in turn will support more vigorous precipitation and surface wetting, and more intense evaporation and evapotranspiration. Although the current generation of climate models effectively simulates this phenomenon's atmospheric components, there is mixed observational evidence on the hydrologic response to these postulated changes, namely, floods and droughts. This disconnect between climate model simulations and observational evidence is due in part to the pathways that these atmospheric changes take once they encounter the complexity of land-surface systems. Well-mixed and rapid atmospheric processes interact with heterogeneous substrates and storage and release processes that are regulated by vastly different time constants. In addition, traditional assumptions on the statistical distribution of hydrologic events used to analyze hydrologic extremes are predicated on stationarity, yet the recent record shows that this assumption is not accurate. Furthermore, the nature of hydrologic extremes is convolved with land cover change,

urbanization, and the operation of water management facilities such as dams, irrigation works, wells, and diversions. As a result, a coherent picture of the nature of likely future changes in hydrologic extremes has yet to evolve. A "grand challenge" thus faces the climate and hydrologic sciences communities—to understand the nature of ongoing changes in climate and hydrology and the apparent anomalies that exist in reconciling their extreme manifestations.

The climate science, water science, and engineering applications communities have yet to establish sufficient interaction to appreciate the value of information products generated by each community. For example, critical terms are used freely with different meanings and research agendas have not been unified even around the arguably well-defined question of climate extremes. From a hydrologic perspective this lack of interaction has not only limited fundamental research on climate extremes but also impeded the translation of new and potentially useful outputs from scientists into the planning and management realm. Risk to the nation's infrastructure from water-related extremes is a function of not only the climate-change-induced hydrologic hazards but also the exposure of assets (and their value) to these extremes, as humans continue to settle and build in hydrologically dangerous settings such as floodplains and river deltas. Without substantially greater interchange of research findings and ideas across these three communities as well as further understanding of the various dimensions of the risk, the design of effective climate change adaptation strategies will remain unrealized.

Hydrologists stand in a useful position between climate change scientists and practitioners to tackle research that expressly links the character of climate variability and change to essential hydrologic process studies and metrics over many scales. With hydrologic processes as the intermediary, hydrologists could lay the groundwork for a more effective translation of climate research findings into applications. Although a full understanding of the hydroclimatology is yet to be secured, practical designs to cope with the possibility of elevated climate and hydrologic extremes based on historical time series and ad hoc margins of error are available for use and these techniques do rely on sufficient observational data. Basic monitoring of key elements of the hydrologic cycle provides an irreplaceable information resource that is particularly critical in a non-stationary environment. Addressing basic questions about the hydrology of extremes requires long and unbroken time series. Although the United States has an enviable record of hydrologic measurement, its ability to maintain this effort is jeopardized by an increasingly fragmented network of water quantity and quality monitoring. Furthermore, reliance on observations-based, a posteriori analysis—although practical in the short-term—may obscure the inherent value of research aimed at causality and improved forecasting.

Introduction

Concerns have been raised in a number of venues about the implications of climate change with respect to hydrologic extremes, including floods and droughts (IPCC, 2007a,b; CCSP, 2008; Milly et al., 2008). The conventional wisdom is that greenhouse warming will result in an increased moisture load within the atmosphere, reflecting well-established physical principles embodied by the Clausius-Clapeyron relation (Box 1). Greater atmospheric moisture in turn supports "acceleration" of the hydrologic cycle, with postulated increases in the mean state and extremes of key hydrologic fluxes such as precipitation, evapotranspiration, tropospheric water vapor content, and runoff (Trenberth, 2011). These changes are often associated with a potential increase in the intensity, frequency, and/or duration of major storms (e.g., hurricanes) that result in a wide spectrum of adverse consequences, such as wind damage, erosion and sedimentation, landslides, and mudslides. These accelerations, however, do not interact uniformly with the general circulation of the atmosphere, topography, and proximity of land systems to the oceans. Thus, the allied postulation discussed here is that frequency and severity of floods and droughts will increase.

BOX 1
The Clausius-Clapeyron Relation

The Clausius-Clapeyron relation is a basic physical law that characterizes the transition between two given phases of matter, in this context the transition between water vapor and liquid water. It is a mathematical equation that, when applied, tells us that the water holding capacity of Earth's atmosphere increases by about 7 percent per degree Celsius increase in temperature (or 4 percent per degree Fahrenheit). In other words, air holds more water at higher temperatures. Thus as the planet warms, more moisture is available for storm events, for example.

The expected changes in precipitation inferred from theoretical knowledge are reasonably well simulated with global climate models (NRC, 2010b) and are confirmed by observations of more intense precipitation and more severe drought worldwide compared to the past 40 to 50 years (Trenberth, 1999; Groisman et al., 2005; Kharin et al., 2007; NRC, 2010) and by increases in precipitation levels in the United States over the 20th century (Groisman et al., 2004). Yet a clear picture of how precipitation translates into the hydrologic extremes is frustrated by observations and studies made by the U.S. hydrologic science community. Recent analyses of U.S. Geological Survey (USGS) long-term streamflow records show few statistically significant trends in floods from annual maximum streamflows as a result of intense precipitation within the United States (USGS, 2005). Evidence for changes in droughts in the United States, determined by the balance between precipitation and runoff, is mixed. Trends of increasing precipitation across much of the eastern and central United States appear to have reduced drought severity and length, while a general warming in parts of the West appears to have increased atmospheric evaporative demand more rapidly than precipitation, resulting in longer and more frequent and severe droughts (Groisman et al., 2004; Andreadis and Lettenmaier, 2006).

Floods and droughts are also complicated by the presence of other factors and are not simply climate-driven phenomena. Anthropogenic land-cover change such as deforestation and reforestation, urban expansion, and the pervasive impact of water engineering—impoundment, irrigation, and water diversions, as well as other social factors—confound these signals of change (Vörösmarty et al., 2005; Trenberth, 2011). Yet floods and droughts remain a primary concern for water managers. In the context of these factors, there is a pressing need for decision-makers to better understand the complexity of these interactions and to recognize the limits and opportunities of the current knowledge base upon which their decisions will rest. The implications for water management, agriculture, and other sectors of the U.S. economy, especially in light of widely publicized predictions of increased frequency and severity of hydrologic extremes as the climate warms, have yet to be fully articulated.

The workshop, *Global Change and Extreme Hydrologic Events: Testing Conventional Wisdom*, was convened by the NRC Committee on Hydrologic Science in January 2010 to probe the conventional wisdom surrounding the acceleration of the hydrologic cycle and its implications. The workshop, sponsored by the U.S. Nuclear Regulatory Commission, the National Aeronautics and Space Administration, and the National Oceanic and Atmospheric Administration, provided a forum for the science and engineering applications communities to identify differing perspectives and to seek common ground on the issue of climate-change-induced floods and droughts. In addition, the workshop provided an opportunity to recognize and potentially begin to transcend the array of contrasting definitions, scientific agendas, methodologies, and observations that separate the climate science, hydrologic, and engineering applications communities as they address the hydrologic extremes question. The statement of task, organized as a series of questions was as follows:

1. Is the global hydrologic cycle accelerating and what does this acceleration look like? Is precipitation becoming more intense? Is drought frequency and severity becoming more prominent?
2. Are hydrologic fluxes associated with floods and droughts changing at the regional scale?

3. Floods and droughts from a climatologic and hydrologic perspective—how do we reconcile the two?
4. How does the science compare to the public debate?

Climate scientists observing trends in atmospheric dynamics and operating global circulation models were invited to speak along with hydrologists who study the local- to regional-scale movements and distributions of water, focusing on surface and subsurface processes across the landmass (see Appendix D for a summary of the presentations). As a result, workshop participants were presented with global, national, and regional perspectives. U.S. water managers, who routinely seek to translate science into water management solutions, and representatives from several U.S. federal agencies also attended the workshop. Thus, this report strongly reflects a U.S. perspective; it should be recognized that the United States is unique in the overall increases in precipitation that have occurred and in the water infrastructure in place (IPCC, 2001 and others). Source material for this workshop report was drawn from both formal presentations and breakout sessions, which directly engaged speakers, committee members, and other workshop participants in discussion, as well as from the committee's deliberations.

This document is a synthesis of the workshop and the committee's findings pertaining to the statement of task. The first section, Characterizing the Conventional Wisdom, provides an overview of the state of the science and probes whether the evidence supports ongoing changes in the frequency and severity of various hydrologic extremes (Tasks 1 and 2). The section on Translating the Science of Hydrologic Extremes to the Policy and Management Sectors examines gaps between the science and management sectors. Both sections draw heavily upon information gathered and discussed at the workshop. Finally, in the third section, A Way Forward, the committee identifies possible steps forward using the knowledge and perspectives gained from the workshop, which includes a challenge for the hydrologic community to promote the translation of research findings into planning and applications. The second and third sections address Tasks 3 and 4.

Findings

The workshop presentations and discussions spanned an array of issues that coalesced around several major topics and research needs. These were identified primarily in the breakout sessions, based on discussions with speakers and workshop participants. In the committee's view, several key findings that address three major categories emerged from the workshop deliberations. The first category focuses on the current state-of-the-art in observation of atmospheric dynamics and the propagation of these dynamics into the land-based hydrologic realm. The second category assesses the status of translating the scientific knowledge base across the climate and hydrologic science communities. The third category identifies opportunities for progress to better unite the scientific perspectives and increase their usefulness in the water resource planning and management arenas.

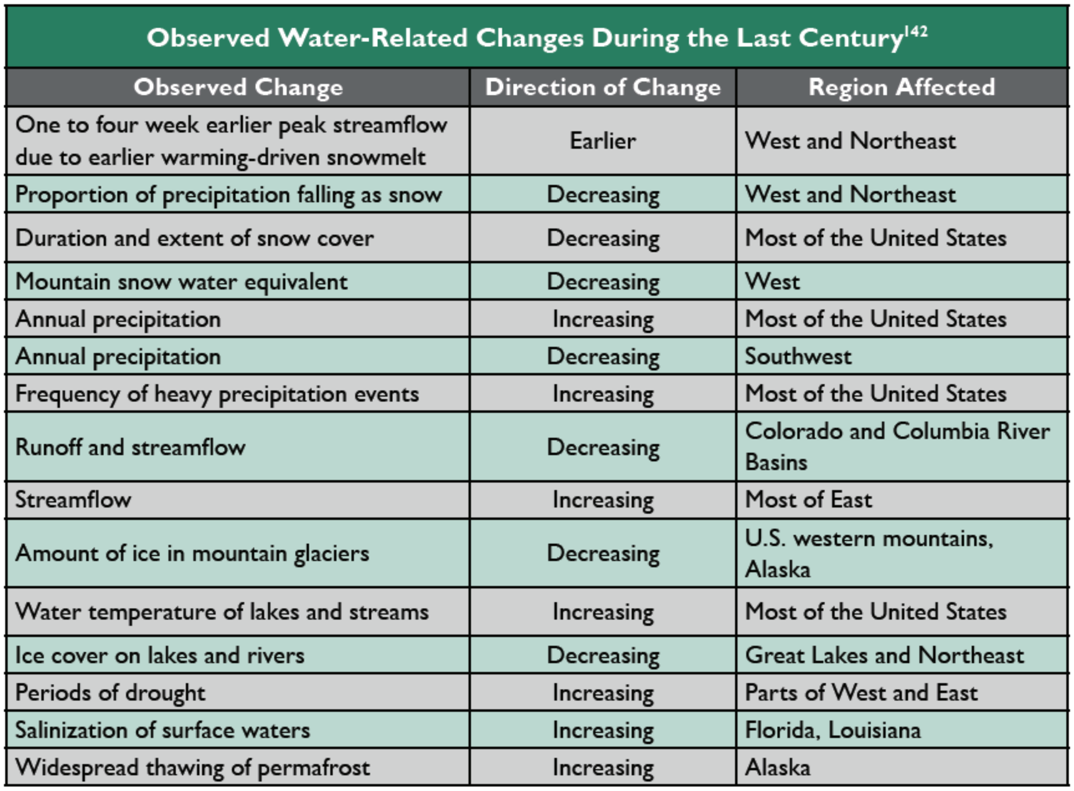
Although its focus is on the United States, this report necessarily considers a large body of research on the global climate and water system. Research at the global scale is relevant here in terms of its contributions to our general understanding of climate dynamics. But the global perspective also becomes relevant by providing a context for U.S. hydrologic extremes.

Characterizing the Conventional Wisdom

Observational evidence shows that the nation's hydrology is changing with respect to water cycle variables, yet uncertainties in the sources and characterization of this change persist.

One way by which scientists measure the presence of change in extreme hydrologic events is to represent the events through statistical distributions, from which they can assess changes in, for example, mean or median values and percentiles. Workshop participants noted that the weight of observational evidence shows an ongoing acceleration of the water cycle as the climate warms, with a broad spectrum of atmospheric and land surface variables associated with these changes (also see Huntington, 2006, 2010). Recent assessment of a broad array of water cycle variables for the United States corroborates this finding (Karl et al., 2009) (Figure1).

For the United States, changes in the upper percentiles of the precipitation distributions indicate that much of the nation has become generally wetter over the past century (IPCC, 2001 and others). These changes are manifested as increases in, for example, the number of days per year with precipitation exceeding fixed thresholds, such as ~50 mm per day (Karl and Knight,



Observed Water-Related Changes During the Last Century[142]

Observed Change	Direction of Change	Region Affected
One to four week earlier peak streamflow due to earlier warming-driven snowmelt	Earlier	West and Northeast
Proportion of precipitation falling as snow	Decreasing	West and Northeast
Duration and extent of snow cover	Decreasing	Most of the United States
Mountain snow water equivalent	Decreasing	West
Annual precipitation	Increasing	Most of the United States
Annual precipitation	Decreasing	Southwest
Frequency of heavy precipitation events	Increasing	Most of the United States
Runoff and streamflow	Decreasing	Colorado and Columbia River Basins
Streamflow	Increasing	Most of East
Amount of ice in mountain glaciers	Decreasing	U.S. western mountains, Alaska
Water temperature of lakes and streams	Increasing	Most of the United States
Ice cover on lakes and rivers	Decreasing	Great Lakes and Northeast
Periods of drought	Increasing	Parts of West and East
Salinization of surface waters	Increasing	Florida, Louisiana
Widespread thawing of permafrost	Increasing	Alaska

Figure 1 Century-scale changes in a broad array of water cycle variables contribute to the scientific evidence for a detectable greenhouse warming signal. Taken together, these variables indicate acceleration of the hydrologic cycle and the non-uniform spatial distribution of these changes. SOURCE: From the U.S. Global Change Research Program's national assessment of climate impacts. Reprinted, with the permission of Cambridge University Press, from Karl et al. (2009). © 2009 by University Corporation of Atmospheric Research.

1998). But for the associated hydrologic variables, results are mixed using standard hydrologic measures. Analysis of flood occurrence (i.e., the annual maxima series) shows essentially no trends at a set of U.S. Geological Survey (USGS) stream gages that were carefully selected to minimize any influences of water management (USGS, 2005). This phenomenon was also noted at a 2008 workshop hosted by the COHS, both by speakers citing the same USGS report as well as by participants citing other research (NRC, 2008). Yet, evidence of changes in U.S. drought characteristics is mixed. Across much of the eastern and central United States, trends in increasing precipitation appear to have resulted in reductions in drought severity and length. In contrast, in parts of the West a general warming appears to have increased evaporative demand more rapidly than precipitation, with the result that these areas tend toward more, longer, and more severe droughts (Groisman et al., 2004). These results point again to difficulties in interpreting climate- and weather-oriented extremes in a hydrologic context.

The breakout discussions noted that major uncertainties have presented themselves but have yet to be reconciled. Why have continental U.S. streamflow changes over the past 50-60 years been evidenced primarily in low flows and not in flood flows? Are there inconsistencies in observed precipitation extremes and streamflow extremes, and if so, why? What are the causes of pervasive increases in occurrence of low flows, for example, in the upper Midwest? To what extent is land cover, as contrasted with climate change, the cause of observed streamflow changes?

Assumptions on the occurrence of major hydrologic events to analyze extremes are based on the notion of stationarity, yet observational evidence increasingly shows that this assumption is untenable.

Stationarity represents the idea that hydrologic systems fluctuate in an unchanging envelope of variability (i.e., the mean and the degree of variability of hydrologic time series do not change over time). Water management systems have been traditionally designed based on this assumption. Therefore, it is critical to the protection of life and property to understand if and how these assumptions are being violated (Milly et al., 2008). From a scientific standpoint, fluctuations in stage heights and flood flows over the historical past constitute a natural experiment, with particular realizations that have in some cases been unexpected and changing over time. A good example is the American River in California, where over the past ~100 years the 5 largest three-day peak flood volumes all occurred in the second half of the record, as had 10 of the largest 13 (see also NRC, 1999). In other words, this hydrologic system no longer operates within its expected unchanging envelope of variability. The statistical distribution of flood volumes that represent this system has become non-stationary.

Bulletin 17B of the Interagency Advisory Committee on Water Data (IACWD, 1982), titled *Guidelines for Determining Flood Flow Frequency*, details a set of data-based methods that allows one to define flood potential. This document is the current standard in the United States, but it has not been updated since the early 1980s. The workshop participants broadly agreed that although Bulletin 17B was concerned about non-stationarity, a remedy is not well addressed in the document. Because the available evidence (at that time) indicated that major climate-induced changes occur on the scale of thousands of years, Bulletin 17B assumed that floods are unaffected by the shorter-term changes that have been documented in the context of anthropogenically induced climate change. Participants discussed the United States' unmet need for new flood-frequency guidelines that draw on advances in hydrologic and climate science over the past 25 years, an observation that is supported by presentations and agreement at a previous COHS workshop (NRC, 2008). Regular revision of the Bulletin 17B guidelines as modeling and understanding of relevant phenomena improves would also be valuable. Regardless, continuing to use the assumption of stationarity in designing water management systems is no longer practical or defensible.

How hydrologic extremes are intertwined with other anthropogenic effects is poorly understood.

The nature of climate-induced hydrologic extremes is currently confounded by other, engineering-based, anthropogenic effects. Interacting anthropogenic factors such as land cover change and the operation of water engineering facilities including dams, irrigation works, wells drawing on and drawing down aquifers, and interbasin transfers define the 21st century landscape and hydrologic dynamics of the continents. Additional confounding arises from the changing nature of climate variability, including the trajectories and patterns of storm tracks. Consequently, exploration of the climate extremes issue requires a better understanding of all of these factors and how they interact. Such an understanding would greatly benefit the applications community, which requires highly region-specific and, in many cases, site-specific information. This is precisely the scale at which the current state of the art in climate modeling is least robust and least certain—and would create opportunities to harmonize traditional hydrologic field research carried out on more local domains with next-generation, high-resolution atmospheric modeling.

Translating the Science of Hydrologic Extremes to the Policy and Management Sectors

Management and mission-oriented agencies with public-sector responsibilities have been provided with marginally useful scientific information about the likely manifestations of future climate change.

Future increases in flood extremes have often been inferred by climate modelers from extreme rainfall projections generalized in many cases within a global context. Yet, according to workshop participants, floods of interest to the user community occur locally in a magnitude and frequency context that is not the same as that implied by global models. It was noted during breakout sessions that the long time horizons, substantial uncertainty bounds, and relatively coarse-scale spatial resolutions (despite progress in downscaling) limit the usefulness of global climate model output for most hydrologic applications (e.g., water resources planning, floodplain management; see also, NRC, 2008). Although research from the climate modeling community enhances understanding of atmospheric dynamics, it generates outputs that are not directly comparable to hydrologic extremes and are even less applicable to operational needs (e.g., water regulation at dams, designing flood protection infrastructure) (NRC, 2007a).

Furthermore, smaller-scale regional climate models are not yet sophisticated enough to add significant value to this endeavor. Higher resolution regional climate models are now available that better resolve the effects of topography and may provide better estimates of precipitation extremes in areas where floods are mostly associated with large-scale storms (e.g., the western United States). However, the ability of these models to reproduce observed extremes remains to be demonstrated, and their resolution is insufficient to resolve the processes that control extreme precipitation in warm seasons, which dominate most of the United States outside of the West. In addition, distinguishing signal versus noise is a challenging issue in the prediction and assessment of hydrologic extremes. This challenge is exacerbated for regional climate models because variability from daily to interannual timescales is greater for small regions. Therefore, articulating regional results at a long enough timescale to tease out signal versus noise is difficult. Often this requires a time-frame that exceeds the infrastructure's useful life. Planning and operations for water management and design of new projects require high-quality information in a site-specific context that the current generation of climate models cannot yet deliver to respond to realities dictated by regulation, current public policy, and other factors.

There are insufficient interactions and knowledge exchange between climate scientists, water scientists, and engineers and practitioners to solve these challenges.

This contention is well illustrated by the use of terminology in the different communities involved with climatic and hydrologic extremes. For example, terms such as "extreme flood" and "change in extremes" are applied differently by climate modelers, agency hydrologists, and academic hydrologists. In a hydrologic context, "extremes" are usually connected with risk analysis, and at least indirectly to infrastructure design criteria. For instance, the "100-year floodplain" is widely used in land use planning, and the design discharge for culverts crossed by certain classes of roads is the "50-year event." Hydrologists usually consider events of this general magnitude "extreme." On the other hand, the climate literature often describes much more frequent events as "extreme." These varied metrics could lead to miscommunication regarding the degree and location of the exposure of the nation's infrastructure to flood risk (see also below).

If the scientific and practitioner communities can communicate and plan for extreme events now, then the results of their work will provide for improved preparation for events in the future. Close cooperation between these communities to better assist each other is critical. A common vocabulary or understanding of the meaning behind various types of "extreme events" would facilitate collaboration. In the absence of a common language, the different uses of important terms should be clearly defined and accepted, and each community should be more flexible and adaptable with respect to how the other uses the terms.

Risk to the nation's infrastructure from water-related extremes depends on not only the changing probabilities of climatic means or extremes but also the exposure of assets to these extremes and their value in economic terms.

Risk is generally defined as the probability of hazard occurrence multiplied by some measure of hazard consequence or capacity to be harmed given a particular level of hazard (i.e., the vulnerability) (NRC, 2010a). In the past, considerable emphasis was placed on the probability estimates for a particular hazardous process. This is illustrated by the traditional civil engineering approach that uses probabilistic entities (e.g., the "100-year" flood) as measures of the hazard. Flood and drought vulnerabilities are a consequence of human planning and actions. Humans have a propensity to settle in hydrologically dangerous settings, such as floodplains or drought-prone arid and semi-arid regions. Less emphasis has generally been placed on developing well-defined measures of vulnerability, which in this context is the varying level of susceptibility to and inability to cope with losses given exposure to extreme events of varying intensity and frequency (IPCC, 2007b). Vulnerability depends, in part, on social factors, and it continually changes in response to factors that differ from those measured in probabilistic analyses. Thus, the construction of dams and levees may decrease the probabilistic aspects of risk to "protected areas." Yet vulnerability may thereby be increased when an associated false sense of security results in the construction of more infrastructure in the at-risk zones.

Although one of the primary goals of research on extreme events such as floods and droughts is risk reduction, the current emphasis of global climate science using models and observations addresses the probabilistic hazard component of risk (NRC, 2010a). Efforts aimed more at the vulnerability component of risk (including placement of infrastructure) are much less well developed. Examples of agency interests include risk-based design, changes to the probable maximum flood or in the distributions employed in flood-frequency analysis, revisions of economic procedures for evaluating future projects, increasing of the skill for intermediate-term (6 to 60 days) projections, and the incorporation of more real-world data (not just model predictions). This latter issue specifically includes paleohydrological and paleoclimatological data to provide broad historical context for hydrologic variability.

A coherent set of research objectives has yet to be fully developed that simultaneously addresses the science needed to better understand the hydrologic events under climate change and their social dimensions and to provide policy that mitigates the consequences of these events. Until these definitive links are established, the public discourse will remain unclear.

A Way Forward

Hydrologists occupy a useful "nexus" between climate change scientists and practitioners, promoting the translation of critical research findings into better informed planning and applications.

Hydrology evolved in the service of water resource management with roots deep within civil engineering (NRC, 1991). Because emphasis has recently shifted toward addressing water-related scientific uncertainties rather than toward planning and management, strong linkages between the hydrologic sciences and the water management community are currently eroding (Loucks, 2007). Frustration abounds, as was observed during the workshop, when the climate science community provides research results that are not in a form that is easily translatable into management decisions (see also NRC, 2007a). Building better interactions between all relevant communities is necessary, and hydrologists serve a central and essential role in these interactions. Hydrologists can fill a critical niche at the interface between the climate science and engineering applications communities by translating research on climate extremes for the applications community.

One key issue to resolve is how the nature of extremes in the atmospheric phase of the hydrologic cycle translates into extreme hydrologic events. In the Southwest, where floods are generated by multiple mechanisms such as the El Niño-Southern Oscillation and snowmelt, understanding of the sources of floods has been advanced by analyses of the atmospheric conditions that accompanied observed hydrologic extremes (e.g., blocking, fronts, position of jet streams, sea surface temperature, storm tracks). Explicit analysis of the linkages between observed hydrologic data and atmospheric conditions and phenomena can help to develop a basis for flood risk estimation in a changing climate (NRC, 2007b) and to catalyze an interaction between the atmospheric and hydrologic science communities.

Another important topic addressed at the workshop was the translation of the science regarding hydrologic extremes into agency-relevant and policy-actionable knowledge. It was noted during a breakout session that the Harvard Water Program of the 1960s provided an important model for both cross-disciplinary and applications-oriented hydrology (Reuss, 2003; Lettenmaier, 2008; Milly et al., 2008). Thus, precedent exists for bridging the divide between hydrologic research and the operational community. To accommodate water planning and management in the context of an accelerating hydrologic cycle, workshop participants discussed a modern-era version of this program that would emphasize decision-based frameworks that incorporate risk and uncertainty from climate variability as well as other aspects of hydrologic change such as land management and hydraulic engineering impacts, including their associated uncertainties. Results from new environmental surveillance technologies that detect changes in extremes—for example, satellite remote sensing of groundwater fluctuations to micro-sensor arrays for soil moisture, data assimilation, econometric and coupled water resource system decision support tools—will arm policy-makers and managers with up-to-date monitoring capabilities and thus will better inform their decision-making processes. However, caution should be employed to select the more robust of these new technologies for operational needs.

Interim, practical approaches to cope with the possibility of elevated risks of climate and hydrologic extremes on infrastructure will remain essential as the scientific basis for improved methods to analyze the sources and consequences of such extremes continue to evolve.

Workshop participants articulated that irrespective of the status of all these factors—from research aimed at disentangling climate from land-based contributions to extreme events to a lack of robust statistical procedures to define risk—the nation will continue to make major investments in civil and private infrastructure. The design of water-related engineering facilities, such as dams and levees, and ecosystem restoration projects has obvious links to the climate extremes question. The specter of climate change is leading U.S. agencies to contemplate how they will deal with hydrologic extremes, with or without scientific certainty. But life, economic security, and property will all be placed at risk should there be more frequent and severe droughts and floods.

From a planning standpoint, increasingly uncertain flood or drought frequencies cause major problems with projects having long lifespans (e.g., sewers, levees, and dams). Infrastructure with design lifetimes on the order of 50 or more years operate on a timescale over which there is less certainty about various climate change scenarios, modeling results, and thus hydrologic stocks and fluxes. In such cases, measures of robustness of alternative future scenarios together with economic criteria are useful because design decisions, once implemented, are not easily changed over time (NRC, 2010a), which might necessitate larger safety margins. The City of New York has developed one of the most comprehensive approaches to climate change adaptation to date (NRC, 2010a). Workshop participants noted that infrastructure can be constructed in adaptable modular units, with shorter expected longevities (or design revisit times) on the order of 10-20 years, which in practical terms reflects the non-stationarity concept. In general, insights drawn from historical and paleohydrologic records, plus practical assumptions, can provide a basis for establishing margins-of-error on designing infrastructure or repositioning existing assets (e.g., to higher ground). Such strategies have been used to avoid future urban flood damage in the Mississippi River basin (Interagency Floodplain Management Review Committee, 1994; NRC, 2009b; USACE, 2011).

Basic monitoring of key elements of the hydrologic cycle is essential to support analysis of hydrologic extremes with any confidence.

Addressing basic questions on the hydrology of extremes will require continuing commitments to monitoring networks and routine observations, through climate, weather, and hydrologic monitoring networks and their integration (see also, NRC, 2010b). Although the United States has an enviable record of hydrologic measurement, its hydrologic networks have become increasingly fragmented (NRC, 2009a). Absent firm commitments to retain observational networks by federal, state, and municipal agencies, estimation of the risk of hydrologic extremes will be compromised, as will the ability to prepare, adapt, and mitigate the impacts of these extremes as climate conditions change. As one example, the USGS stream gaging network has monitored flow in the nation's rivers since 1889 (http://water.usgs.gov/nsip/history1.html), yet it and other USGS water monitoring programs are under continuing pressure to provide data with decreasing resources (NRC, 2009a).

Decisions about the design of hydrologic monitoring networks are increasingly confounded by hydrologic non-stationarity, not only because of a changing climate but also because of anthropogenic land cover change and water management effects. Procedures developed in the 1960s and 1970s to determine when stations can be discontinued are based on stationary statistical assumptions that are no longer defensible. These protocols therefore lead to management decisions regarding monitoring stations that are diametrically opposed to those that are applicable to a non-stationary world. The next generation of observational networks may include paleoclimatic and paleohydrologic data sets as well as newer technologies, such as precipitation radars, to augment basic data from stream gage networks.

Closing

The COHS-hosted workshop raised many questions and challenges in terms of characterizing hydrologic extremes, translating scientific knowledge to the policy and management communities, and identifying a productive future role for hydrologic sciences. Workshop participants confirmed the research findings that show that the water cycle is changing and indeed accelerating, but noted the many unknowns that remain with respect to the drivers of this change, the system response, and the implications for society. The issues discussed at the workshop are fundamental to the nation's environmental security as it embarks on a major climate adaptation strategy. The workshop was admittedly a modest step forward in uniting the perspectives of a broad research community in climate and hydrology as well as planners and engineers. Creating a more productive dialogue is essential in order to safely and efficiently deploy our 21st century strategic water investments.

References

Andreadis, K. M., and D. P. Lettenmaier. 2006. Trends in 20th century drought over the continental United States. Geophysical Research Letters 33:L10403.

CCSP (Climate Change Science Program). 2008. Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C. 164 pp.

Groisman, P. Ya., R. W. Knight, T. R. Karl, D. R.Easterling, B. Sun, and J. H. Lawrimore. 2004. Contemporary changes of the hydrologic cycle over the contiguous United States: Trends derived from in situ observations. Journal of Hydrometeorology 5: 64–85.

Groisman, P. Ya., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V.A.N. Razuvaev. 2005. Trends in intense precipitation in the climate record. Journal of Climate 18: 1326–1350.

Huntington, T. 2006. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology 319: 83–95.

Huntington, T. 2010. Climate warming-induced intensification of the hydrologic cycle: An assessment of the published record and potential impacts on agriculture. Advances in Agronomy 109: 1–53.

IACWD (Interagency Advisory Committee on Water Data). 1982. Bulletin 17B of the Interagency Advisory Committee on Water Data: Guidelines for Determining Flood Flow Frequency. U.S. Geological Survey, Reston, VA.

Interagency Floodplain Management Review Committee. 1994. Sharing the Challenge: Floodplain Management into the 21st Century. U.S. Government Printing Office, Washington, D.C.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the IPCC. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, (eds.). Cambridge University Press, Cambridge, UK, and New York. 881 pp.

IPCC. 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Millers, (eds. Cambridge University Press, Cambridge, UK. 996 pp.

IPCC. 2007b.Impacts, Adaptation, and Vulnerability Contribution of Working Group II to the Fourth Assessment Report of the IPCC. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, (eds.). Cambridge University Press, Cambridge, UK. 976 pp.

Karl, T. R., and R. W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bulletin of the American Meteorology Society 79: 231–241.

Karl, T. R., J. M. Melillo, and T. C. Peterson, (eds.). 2009. Global Climate Change Impacts in the United States. Cambridge University Press, Cambridge, UK.

Kharin, V. V., F. W. Zwiers, X. B Zhang, and G. C. Hegerl. 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. Journal of Climate 20:1419–1444.

Lettenmaier, D. P. 2008. Have we dropped the ball on water resources research? Journal of Water Resources Planning and Management 134:491–492.

Loucks, D. 2007. Water resources and environmental management: Issues, challenges, opportunities and options. Water Science and Technology: Water Supply 7(2):1–10.

Milly, P. C. D., et al. 2008. Stationarity is dead: Whither water management? Science 319:573–574.

NRC (National Research Council). 1991. Opportunities in the Hydrologic Sciences. National Academy Press, Washington, D.C.

NRC. 1999. Improving American Flood Frequency Analyses. National Academy Press, Washington, D.C.

NRC. 2007a. Analysis of Global Change Assessments: Lessons Learned. The National Academies Press, Washington, D.C.

NRC. 2007b. Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimactic Variability. The National Academies Press, Washington, D.C..

NRC. 2008. Research and Applications Needs in Flood Hydrology Science. The National Academies Press, Washington, D.C.

NRC. 2009a. The New Orleans Hurricane Protection System. The National Academies Press, Washington, D.C.

NRC. 2009b. Towards a Sustainable and Secure Water Future: A Leadership Role for the U.S. Geological Survey. The National Academies Press, Washington, D.C.

NRC. 2010a. Adapting to the Impacts of Climate Change. The National Academies Press, Washington, D.C.

NRC. 2010b. Advancing the Science of Climate Change. The National Academies Press, Washington, D.C.

Reuss, M. 2003. Is it time to resurrect the Harvard Water Program? Journal of Water Resources Planning and Management 129:357–360.

Trenberth, K. E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. Climatic Change 42:327–339.

Trenberth, K. E. 2011. Changes in precipitation with climate change. Climate Research 47:123–138.

U.S. Army Corps of Engineers. 2011. Fargo-Moorhead Metropolitan Area Flood Risk Management Supplemental Draft Feasibility Report and Environmental Impact Statement, April 2011.

USGS (U.S. Geological Survey). 2005. Streamflow Trends in the United States. USGS Fact Sheet 2005-3017. Reston, VA. http://pubs.usgs.gov/fs/2005/3017/ (March 2010).

Vörösmarty, C. J., C. Leveque, C. Revenga. 2005. Chapter 7: Fresh water. In: Millennium Ecosystem Assessment, Volume 1: Conditions and Trends Working Group Report (with R. Bos, C. Caudill, J. Chilton, E. M. Douglas, M. Meybeck, D. Prager, P. Balvanera, S. Barker, M. Maas, C. Nilsson, T. Oki, and C. A. Reidy). Island Press, Washington, D.C. 966 pp.

Appendixes

A

Statement of Task

A two-day workshop on *Global Change and Extreme Hydrology: Testing Conventional Wisdom* will be planned and conducted by a small ad hoc planning committee under the auspices of the standing Committee on Hydrologic Sciences (COHS). The workshop will foster discussions among the science and applications community about the hydrologic and climatologic perspective on extreme hydrologic events. The workshop will be held in Washington, D.C., and is expected to feature presentations by experts followed by open discussions on the following topics:

- Is the global hydrologic cycle accelerating and what does this acceleration look like? Is precipitation becoming more intense? Is drought frequency and severity becoming more prominent?
- Are hydrologic fluxes associated with floods and droughts changing at the regional scale?
- Floods and drought from a climatologic and hydrologic perspective—How do we reconcile the two?
- How does the science compare to the public debate?

The workshop planning committee will author a report based on the workshop.

B

Agenda

A Workshop on *Global Change and Extreme Hydrologic Events: Testing Conventional Wisdom*
Sponsored by the National Research Council Committee on Hydrologic Science (COHS)

January 5: Precipitation and floods

8:00 **Welcome and Introductions**
Charles Vörösmarty, Chair, COHS
Agenda Overview and Workshop Goals
Dennis Lettenmaier and Victor R. Baker, COHS

8:15 **Understanding Changes in Precipitation and Runoff with a Changing Climate**
Kevin E. Trenberth, National Center for Atmospheric Research

9:00 **Global to Regional Perspectives on Intensification of the Hydrologic Cycle: Implications for Extreme Events**
Tom Huntington, U.S. Geological Survey

9:45 **Is Precipitation Becoming More Intense?**
Pavel Groisman, National Oceanic and Atmospheric Administration

10:45 **A Process-Based "Bottom-Up" Approach for Addressing Changing Flood-Climate Relationships**
Katie Hirschboeck, University of Arizona

11:30 **The Ghosts of Flooding Past, Present, and Future**
Harry R. Lins, U.S. Geological Survey

1:00 **Planning for Non-Stationary Extreme Events: Statistical Approaches**
Richard M. Vogel, Tufts University

1:45 **Planning for Non-Stationarity and Floods: A Management Perspective**
Gerald E. Galloway, University of Maryland

2:45 **Breakout groups**
Rapporteurs: Victor R. Baker and Dennis Lettenmaier

4:00 **Rapporteurs report back and summary of research and operational needs**

January 6: Drought

8:30 **Welcome and Day 2 Agenda Overview**
Charles Vörösmarty, Chair, COHS

8:45 **Synthesis of Day 1**
Dennis Lettenmaier and Victor R. Baker, COHS

9:00 **Mechanisms for Global Warming Impacts on the Large-Scale Atmospheric Branch of the Hydrological Cycle**
Richard Seager, Columbia University

9:45 **Connecting Global-Scale Variability to Regional Drought: Mechanisms and Modeling Challenges**
Siegfried Schubert, NASA Goddard

10:45 **Do We Need to Put Aquifers into Atmospheric Simulation Models? Evidence for Large Water Table Fluctuations and Groundwater Supported ET under Conditions of Pleistocene and Holocene Climate Change**
Mark Person, New Mexico Tech

11:30 **Breaking the Hydro-Illogical Cycle: The Status of Drought Risk Management in the U.S.**
Mike Hayes, National Center for Drought Mitigation

1:00 **Breakout groups**
Rapporteurs: Victor R. Baker and Dennis Lettenmaier

3:00 **Rapporteurs report back and summary of research and operational needs**

4:00 **Adjourn**

C

Speaker Abstracts

Global to Regional Perspectives on Intensification of the Hydrologic Cycle: Implications for Extreme Events

T.G. Huntington, U.S. Geological Survey

Climate warming is expected to intensify or accelerate the global hydrologic cycle, resulting in increases in rates of evaporation, evapotranspiration (ET), and precipitation and an increase in the concentration of atmospheric water vapor. The strength of the hydrologic response, or sensitivity of the response for a given amount of warming, is a critical outstanding question in hydroclimatology. An assessment of the published record on observations of trends in various components of the hydrologic cycle and associated variables provides insight into this question. The weight of evidence from global and regional trends in evaporation, ET, and atmospheric water-vapor concentration supports an ongoing intensification of the hydrologic cycle. Global trends in precipitation, runoff, and soil moisture are more uncertain, in part because of high spatial and temporal variability and lack of consistent, high-quality, long-term records. Changes in regional ocean salinity indicate possible increasing evaporation at low latitudes and increasing freshwater inputs (precipitation, runoff, and melting ice) at high latitudes. Ongoing lengthening of the growing season may contribute to increasing ET rates. The evidence for an increase in the frequency, intensity, or duration of extreme weather events like hurricanes and floods is mixed; consequently, regional to global trends remain uncertain.

Understanding Changes in Precipitation and Runoff with a Changing Climate

Kevin E. Trenberth, National Center for Atmospheric Research

The global hydrological cycle and its changes over time are examined in light of observations and current understanding. A particular focus is on how precipitation changes as the climate changes and changes in extremes, including risk of flooding and drought. Net changes in surface evaporation are fairly modest, and a much larger percentage change occurs in the water-holding capacity as atmospheric temperatures increase (7% per C). In this talk we will examine the consequences of this, especially noting the differences over ocean, where water supply is unlimited, and over land. A description will also be given of the understanding of other large-scale changes in patterns and amount of precipitation, soil moisture, and drought. It is important to understand not only changes in mean precipitation, but also the intensity, frequency, duration, and type, and this also applies to the storms that bring precipitation. Understanding these profound consequences of climate change is especially important for water managers.

Is Precipitation Becoming More Intense?

Pavel Groisman, National Oceanic and Atmospheric Administration

An overview of 12-year-long National Climatic Data Center (NCDC) studies of changes of intense precipitation during the period of instrumental observations will be presented with a focus on North America. NCDC has created a database of daily and hourly time series of high scientific quality for use in assessment of changes in precipitation characteristics over the regions where we have sufficient amount of information to answer the question outlined in the talk's title.

Prior to 2005, NCDC constructed various time series of precipitation characteristics and analyzed their trends. Now (in addition to routine updates of these time series), we have

- analyzed the factors that control intense precipitation (e.g., CAPE and land-falling tropical cyclones trajectories),
- assessed the rainfall distribution characteristics (e.g., hourly rainfall rates), their changes, and their relationships with global and regional surface air temperatures, and
- investigated changes in "direct impact" characteristics of precipitation spectra such as prolonged no-rain periods, fire weather indices, and maximum rainfall intensity.

Our past and ongoing studies (as well as findings by other foreign researchers) embolden our opinion that in the past several decades over most of the extratropics precipitation became more intense. However, the changes in intense precipitation also occur with changes in several other precipitation characteristics and they too deserve our thorough attention.

A Process-Based "Bottom-Up" Approach for Addressing Changing Flood-Climate Relationships

Katie Hirschboeck, University of Arizona

In response to the unprecedented persistence of extreme drought conditions in the western United States, some western water managers have moved beyond conventional approaches to plan for future extreme low flow conditions in innovative ways involving paleo-records, scenarios, and climate projection modeling. In contrast, flood hazard managers are far more constrained in developing ways to incorporate climate change information operationally, in part because of existing flood policy, but also because of the short-term, localized, and weather-based nature of the flooding process itself. What is needed is information that is presented in an operationally useful format for flood managers and that describes how changes in the large-scale climatic drivers of hydrometeorological extremes will affect flooding variability in specific watersheds. This presentation outlines a framework for linking global climatic change to the gauged time series of peak flows in individual watersheds. Using a process-sensitive "bottom up" approach, each individual peak in a gauged record is associated with its flood-producing storm type and circulation pattern. This approach highlights the underlying physical reasons for flood variations in specific watersheds, defines how mixed flood distributions and outlier events may be linked to climate shifts, and challenges the underlying “iid” assumption that flood peaks are independently and identically distributed. Linking extreme flood events to meteorological causes driven by shifting circulation features can provide water managers with critical climate-based interpretive information for how flood probability distributions are likely to respond within individual watersheds under future climate change scenarios.

The Ghost of Flooding Past, Present, and Future

Harry F. Lins, U.S. Geological Survey

An element of human-enhanced greenhouse theory is that the hydrological cycle will accelerate. This has led to the hypothesis that extreme events, such as floods and droughts, will increase in frequency and/or severity. Published studies indicate that precipitation has increased over the past century, and this increase has been characterized as occurring in “extreme” and “intense” precipitation. However, empirical studies from North America and Europe find no evidence of an increase in flood frequency or magnitude during the 20th century, although increases in low to moderate streamflows have been widely reported. What, then, are the likely effects of an accelerated hydrological cycle on streamflow in general, and on floods in particular? This question is considered using data and the published literature with respect to two issues: What is known about the sensitivity of various return-period floods and annual precipitation? What is the likely impact of a given percentage change in precipitation on a flow quantile (e.g., Q_{100} versus Q_{mean})? Results indicate that the precipitation sensitivity of mean streamflow is much greater than that of peak streamflow, and that precipitation sensitivity decreases as flood return period increases. This suggests that human-induced greenhouse warming may be more likely to produce noticeable and significant changes in the mean state of hydrological regimes than in hydrological extremes.

Planning for Non-Stationary Extreme Events: Statistical Approaches

Richard M. Vogel, Tufts University

It is no longer possible to consider streamflow and other hydrologic processes as a stationary process. Nearly all of the methods developed for the planning, management, and operation of water resource systems assume stationarity of hydrologic processes. Non-stationarity can result from a myriad of human influences ranging from agricultural and urban land use modifications, to climate change and water infrastructure. Most previous work in trend detection associated with extreme events has focused on the influence of climate change, alone. This study takes a different approach by exploring flood and low flow trends in watersheds that are subject to a very broad range of anthropogenic influences. We define a decadal flood magnification factor as the ratio of the T-year flood in a decade to the T-year flood today. Using historical flood data across the entire United States we obtain typical flood magnification factors in excess of 2-5 for many U.S. regions, particularly those regions with higher population densities.

A simple statistical model is developed that can both mimic observed flood trends as well as the frequency of floods in a non-stationary world. This model is used to explore a range of flood planning issues in a non-stationary world. Importantly, non-stationarity in both extreme high and low flows is shown to result from a variety of processes including land use, climate, and water use, with likely interactions among those processes making it very difficult to attribute trends to a particular cause. Multivariate regression models are shown to provide a useful tool for developing the type of conditional forecasts of the moments of extreme events necessary for planning in a non-stationary world.

Planning in a non-stationary and uncertain world is not a new challenge for engineers, because the classic "capacity expansion problem" and other planning problems have always involved both non-stationarity and uncertainty. What is new is the increased variety of sources of uncertainty and non-stationarity that are now inherent in nearly all water resource planning problems, making it essential to incorporate non-stationary planning models of the type discussed here.

Planning for Non-Stationarity and Floods: A Management Perspective

Gerald E. Galloway, University of Maryland

Recent decades have seen a growing increase in flood damages across the nation. A resultant focus on reducing these flood damages has brought long-neglected attention to the systematic assessment and improvement of the quality of existing flood damage reduction structures and pleas for "protection" for areas not now ringed by levees, floodwalls, or other such structural measures. The specter of climate change has led many agencies, both in the United States and abroad, to closely examine how they would deal with more frequent and more severe floods and consider how they might adapt to these future conditions. Flood risk management has replaced flood damage reduction in the lexicon of federal engineers, and considerable effort is now focused on both how they might best manage flood risk and how they might communicate the level of future risk to the public. Given the uncertainties surrounding the calculation of recurrence intervals, how do managers and engineers decide how high their levees should be and how structural measures fit with non-structural actions such as zoning, floodproofing, evacuation, etc.? In 2008, a committee chartered by the Netherlands government recommended to the Parliament that standards for coastal and riverine defense (recurrence intervals) be raised by a factor of 10 to deal with the myriad flood and storm uncertainties faced by that nation. What guidance can be given today to U.S. planners to deal with an uncertain future? They must do something now, but what should this something be?

Mechanisms for Global Warming Impacts on the Large-Scale Atmospheric Branch of the Hydrological Cycle

Richard Seager, Columbia University

It is a robust prediction of state-of-the-art climate models that greenhouse gas-induced global warming will cause the wet regions of the planet (in the deep tropics and the mid to high latitudes) to get wetter while the subtropical dry zones get drier. It is also projected that the subtropical dry zones will expand poleward. Here we analyze the 13 models that made available all the required data to determine the mechanisms responsible for these changes in the hydrological cycle. The mechanisms are divided into first, thermodynamic ones that only rely on a change in specific humidity, second, dynamic ones that only rely on changes in the mean circulation and, third, changes in transient eddy moisture fluxes. Much of the basic pattern of change in precipitation—evaporation (P-E) is accounted for thermodynamically as humidity rises in a warmer atmosphere and intensifies existing patterns of moisture transport. However, changes in circulation are required to explain many changes of P-E in the tropics and, especially, to explain the poleward expansion of the subtropical dry zones. Increases in poleward transient eddy heat moisture fluxes also assist in drying the subtropics and moistening the higher latitudes. Causes of the increased transient eddy fluxes are shown to be complex.

Much of the thermodynamic-induced change in P-E can itself be accounted for simply by atmospheric warming under fixed relative humidity. The mechanisms for projected drying of southwestern North America will be analyzed. This region will dry no matter what, but it is also shown that the character of the tropical Pacific atmosphere-ocean response to increasing greenhouse gases will determine the relative magnitude of the drying. Recent climate change is reviewed for evidence of these changes already occurring, but it is concluded that recent trends have been dominated by large-amplitude natural decadal atmosphere-ocean variability. Near-term hydroclimate prediction therefore must account for both anthropogenic change and the evolution of natural modes of variability.

Connecting Global-Scale Variability to Regional Drought: Mechanisms and Modeling Challenges

Siegfried Schubert, NASA's Goddard Space Flight Center

Recent research has linked long-term drought (or more specifically extended periods of reduced precipitation) to a number of factors including slowly varying sea surface temperatures (SSTs), the influences of the land surface (e.g., atmosphere/soil moisture feedbacks, aerosols, and vegetation changes), as well as the chance occurrence of extended runs of dry years that can occur even in the absence of any year-to-year memory in the climate system. The possibility of predicting long-term drought rests largely on the strength of the SST linkages to the land component of the hydrological cycle, and of course on our ability to predict the relevant SST changes. The U.S. CLIVAR (Climate Variability and Predictability) working group on drought recently initiated a series of global climate model simulations forced with idealized SST anomaly patterns, designed to address a number of uncertainties regarding the impact of SST forcing and the role of land-atmosphere feedbacks on regional drought. This talk reviews some of those and related results, with a focus on the U.S. Great Plains, although the basic mechanisms appear to be relevant to drought in many other regions of the world. Issues to be addressed include the seasonality of the global SST response, the impact of soil moisture feedbacks, the potential predictability associated with SST changes, as well as model deficiencies currently limiting our ability to simulate and predict long-term drought.

Do We Need to Put Aquifers into Atmospheric Simulation Models? Evidence for Large Water Table Fluctuations and Groundwater Supported ET under Conditions of Pleistocene and Holocene Climate Change

Mark Person, New Mexico Tech

Aquifer-atmosphere interactions can be important in landscapes where the water table is shallow (<2m) and the watershed topography is gentle. Regional climate models that include aquifer hydrodynamics indicate that between 5 to 20% of evapotranspiration is drawn from the aquifer. The groundwater-supported fraction of evapotranspiration is higher under drought conditions, when evapotranspiration exceeds precipitation. The response time of an aquifer to drought conditions can be long—on the order of 200-500 years—indicating that feedbacks between these two water reservoirs act on disparate timescales. Analysis of Holocene and late Pleistocene paleowater table records suggests that water table fluctuations can be as great as 50 m during drought conditions. With recent advances in the computational power of massively parallel supercomputers, it may soon become possible to incorporate physically based representations of aquifer hydrodynamics into GCM land surface parameterization schemes. This may help to improve our predictions of the long-term consequences of droughts on water resources and climate dynamics.

Breaking the Hydro-Illogical Cycle: The Status of Drought Risk Management in the United States

Mike Hayes, University of Nebraska-Lincoln

This presentation will focus on drought risk management within the United States given the context of climate variability, climate change, and extremes. As the last presentation in the workshop, an attempt will be made to connect comments and issues addressed within previous presentations and breakout groups. A focus will be placed on drought monitoring, impact assessment, mitigation, and planning efforts taking place now across the country, and on suggesting where current efforts need more concentration. The National Integrated Drought Information System (NIDIS) will also be highlighted. Drought fits well into the enhanced efforts by the climate community to create and provide "services" and decision support tools. Each service and tool being designed for drought helps define the "big picture" of drought for policy-makers and others who need that scale of information. But they also work to localize drought, putting valuable information in the hands of agricultural producers and community, tribal, and other grassroots decision-makers—exactly what is needed to boost drought risk management through the rest of this century.

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Summary of Presentations

Kevin Trenberth from the National Center for Atmospheric Research began the workshop with a talk on how precipitation is expected to change in a warming climate and on the link between these changes and extreme hydrologic events. He discussed the physical basis for concurrent increases during extreme high precipitation and longer durations of dry periods, yet he noted that global and regional climate models are demonstrably poor at most aspects of forecasting the hydrological cycle. Pasha Groisman of the National Oceanic Atmospheric and Administration highlighted his past and ongoing observational studies (as well as findings by other foreign researchers) that strengthen the opinion that in the past several decades over most of the extratropics, or mid-latitude regions, precipitation has become more intense; however, he also acknowledged that the data presented could be analyzed in many ways. The presenters discussed the various approaches to categorizing the data and impacts that might have on the resulting conclusions. Richard Seager of Columbia University agreed with Groisman by articulating that it is a robust prediction of state-of-the-art climate models that greenhouse gas-induced global warming will cause the wet regions of the planet (in the deep tropics and the mid to high latitudes) to get wetter while the subtropical dry zones get drier. When recent climate observations are reviewed for evidence of these changes, trends are found to have been dominated by large-amplitude natural decadal atmosphere-ocean variability. He concluded that near-term hydroclimate prediction must account for both anthropogenic change and the evolution of natural modes of variability, but he noted that all models still have significant room for improvement. Seager presented an example of an ensemble analysis in which the underlying models were equally divided between wetter and drier results.

Aquifer-atmosphere interactions can be important in landscapes where the water table is shallow (<2m) and the watershed topography is gentle, stated Mark Person of New Mexico Tech. He found that it may soon become possible to incorporate physically based representations of aquifer hydrodynamics into Global Climate Models (GCMs) given recent advancements with supercomputers. This integration may help to improve predictions of the long-term consequences of droughts on water resources and climate dynamics. Siegfried Schubert of NASA's Goddard Space Flight Center offered thoughts on the nature of drought—he argued that the possibility of predicting long-term drought rests largely on the strength of sea-surface temperature linkages to the land component of the hydrological cycle, and on the ability to predict sea-surface temperature changes.

Tom Huntington from the U.S. Geological Survey assessed the published record of trend analysis in various components of the hydrologic cycle and associated variables. Huntington concluded that the evidence is mixed for an increase in the frequency, intensity, and duration of extreme weather events like hurricanes and floods. He noted that intensification of extreme weather events may be related to great recycling of water through the hydrologic cycle and may not be directly proportional to more extreme hydrologic events. Harry Lins of the U.S. Geological Survey posed the question of what the likely effects of an accelerated hydrological cycle might be on streamflow in general, and on floods in particular. Data and published literature indicate that the relative precipitation sensitivity (elasticity) of mean streamflow with respect to precipitation is much greater than that of peak streamflow, and that precipitation sensitivity decreases as flood return period increases. Hence, while flood peaks are quite likely to increase if precipitation increases, their fractional change relative to a given fractional change in the mean precipitation is less than the fractional increase in the mean flow.

Richard Vogel of Tufts University noted that multiple sources of uncertainty and non-stationarity are now inherent in nearly all water-resource planning problems, and it is important that the water resources engineering community shift away from the stationarity paradigm on which it has presumed for many decades. He described work that has analyzed several thousand flood peak records from across the United States. Although not yet definitive, his work suggests that, where non-stationarity is evident, it is more likely to be associated with changing land use (especially urbanization) than with climate change. Katie Hirschboeck of the University of Arizona argued for the necessity of moving beyond conventional methods for estimating the frequency of extreme hydrologic events. She described an approach based on parameterization of spatially and temporally varying hydroclimatic extremes (which she called synoptic hydroclimatology) as a starting place for making operationally useful decisions about the impacts of climate change on hydrologic extremes.

Gerald Galloway of the University of Maryland discussed the nature of guidance that can be given today to U.S. water management planners to deal with an uncertain hydrologic future. He acknowledged that floods are acts of nature, and flood consequences are a result of man, so while flood risk calculations are not precise, risk assessment provides insights and a basis for prioritization. U.S. water managers need to deal with present problems by using the Precautionary Principle in future planning with a newly developed national policy. Michael Hayes, of the University of Nebraska, Lincoln, spoke about the status of drought risk management in the United States. He highlighted several key issues that should be considered including the facts that drought is a local issue, monitoring is essential, mitigation and planning require innovative ideas, worse-case scenarios should be considered, and communication between scientists and the public is key.

Appendix E

Workshop Participants

Members of the Committee on Hydrologic Science

Charlie Vörösmarty, City University of New York
Dennis Lettenmaier, University of Washington
Victor R. Baker, University of Arizona
Daniel P. Loucks, Cornell University
George Smith, Riverside Technologies, Inc.
Chunmiao Zheng, University of Alabama

Members of the public and speakers present

Speakers
Gerry Galloway, University of Maryland, College Park
Pasha Groisman, National Oceanic and Atmospheric Administration
Michael Hayes, University of Nebraska, Lincoln
Katie Hirschboeck, University of Arizona, Tucson
Thomas Huntington, U.S. Geological Survey
Harry Lins, U.S. Geological Survey
Mark Person, New Mexico Tech
Siegfried Schubert, National Aeronautics and Space Administration
Richard Seager, Columbia University
Kevin Trenberth. University Corporation for Atmospheric Research
Richard Vogel, Tufts University

Participants
Dan Barnhurst, Nuclear Regulatory Commission
Ana Barros, Duke University
Doug Bellomo, Federal Emergency Management Agency
Geoff Bonnin, National Weather Service
Ralph Cady, Nuclear Regulatory Commission
Jill Caverly, Nuclear Regulatory Commission
Shyang-Chin (Samuel) Lin, National Aeronautics and Space Administration
Tim Cohn, U.S. Geological Survey

Ian Cozens, Nuclear Regulatory Commission
Ken Fearon, Federal Energy Regulatory Commission
Lisa Goddard, Columbia University
Russ Harmon, U.S. Army Corps of Engineers
Mohammad Haque, Nuclear Regulatory Commission
Robert Hirsch, U.S. Geological Survey
Jin Huang, National Oceanic and Atmospheric Administration
Joseph Kanney, Nuclear Regulatory CommissionJulie Kiang, U.S. Geological Survey
Joe Krolak, Nuclear Regulatory Commission
Daniel Mahoney, Federal Energy Regulatory Commission
Henry Manguerra, Michael Baker Corporation
Robert Mason, U.S. Geological Survey
Mark McBride, Nuclear Regulatory Commission
Karen Metchis, U.S. Environmental Protection Agency
Tom Nicholson, Nuclear Regulatory Commission
Rolf Olsen, U.S. Army Corps of Engineers
Sanja Percia, National Oceanic and Atmospheric Administration
David Raff, Bureau of Reclamation
Richard Raione, Nuclear Regulatory Commission
John Randall, Bureau of Reclamation
Karen Ryberg, U.S. Geological Survey
Ken See, Nuclear Regulatory Commission
Dave Shepp, U.S. Army Corps of Engineers
Eugene Stakhiv, U.S. Army Corps of Engineers
Nancy Steinberger, Federal Emergency Management Agency
Will Thomas, Michael Baker Corporation
Phil Turnispeed, U.S. Geological Survey
Jerry Webb, U.S. Army Corps of Engineers
Kathleen White, U.S. Army Corps of Engineers – Institute for Water Resources