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Summary

Water resources are important to Midwestern interests, including navigation on the Great Lakes and rivers, agriculture, hydropower, and recreation, and are likely to be subject to impacts from human-caused climate change. While the basic science of climate change is well established, many of the details of impacts on particular sectors at local to regional spatial scales are subject to greater uncertainty. Even though understanding is emerging, some more general patterns are emerging for water resources in the Midwestern US. In general, precipitation has been increasing and this trend is projected to continue. Precipitation increases are particularly pronounced when looking at the winter season and when looking at the few largest rain events of the year, and this is expected to continue. Methods of calculating evapotranspiration (ET) under changed climate are the subject of emerging research, showing that widely-used methods based on temperature as a proxy for potential ET exaggerate projected increases in ET, as demonstrated by severe imbalances in the surface energy budget. When incorporated into further simulations, this leads to excessive reductions in streamflow and lake levels. Simulations using a more energy-based approach to ET give more mixed results in terms of changes in streamflow and lake levels, and often show increases.

Introduction

The water resources of the Midwestern United States, and how they are managed under a future climate, have a significant collective impact on multiple economic sectors in the US, North America, and the world. The North American Laurentian Great Lakes, for example, hold nearly 20% of the earth's accessible surface fresh water supply and have a coastline, and a coastal population, on the same order of magnitude as frequently-studied ocean coasts around the world (Fuller et al. 1995). In light of growing demands for clean water, access to coastal resources, and an improved understanding of climate dynamics in the Midwest region, a significant amount of research has recently been focused on understanding climate impacts on the lakes (both large and small), rivers, and streams in this region.

Various interest groups and socio-economic sectors depend on different aspects of the water cycle, often on different time scales. Rain-fed agriculture does best if soil moisture is replenished at least every 15 days or so. Streamflow, important for flood control, hydropower, navigation, fish migration, and some other ecological factors, has its high extremes controlled by abundant precipitation and snowmelt on short timescales, but its low extremes are controlled primarily by baseflow, which is water that percolates through the soil into ground water, then gradually flows through the ground into streams, wetlands, and lakes. Levels of the Great Lakes are determined by net basin supply, which is the sum of inflow from the land portion of their drainage basin and the precipitation directly over the lake, minus the evaporation from the lake. Because of the large areal extent of the Great Lakes, the effect of short-term variability in net basin supply on lake level is attenuated. Other short-term effects on lake level include wind-driven surges and seiches (waves occurring on the scale of an entire lake).

While not a specific theme of this particular assessment, we find that this region also, through explicit and implicit partnerships with the Canadian government, represents an ideal test bed for establishing effective protocols for collaborative binational water resources and ecosystem services research (Gronewold and Fortin 2012). The value of the water resource management and climate change lessons to be learned from this region, however, depends on an explicit acknowledgement of those water budget components which are uncertain or unobservable (such as overlake evaporation and evapotranspiration), and how projections of regional climate dynamics are downscaled to a suitable local scale, translated into suitable water resource management metrics, and subsequently placed within an appropriate historical context.

Historic variability of hydroclimate

Seasonal to multi-year events

Pan and Pryor (2009) point out that the amount of water vapor in the atmosphere has been increasing at a greater rate in proportion to its historic values than the rate of precipitation. The total water vapor content of the atmosphere has increased in proportion to the Clausius-Clapeyron relation, i.e. it scales as an exponential function of temperature, with absolute humidity or water vapor mixing ratio increasing by about 7% per degree C. However, the mean rate of precipitation has increased by only about 2% per degree C, implying an increasing residence time of water vapor in the atmosphere. Additional theoretical consideration of this phenomenon can be found in Held and Soden (2006).

Pryor et al. (2009) have found statistically significant changes in total precipitation and number of rain days at many stations in the Midwest, mostly increases in both variables, but few stations have statistically significant change in precipitation intensity (precipitation per rain day). They also showed an increase in the amount of precipitation that came on the 10 days of the year with the greatest precipitation. However, this was not evaluated as a proportion of the total precipitation. They also found that there was generally a decrease in the mean number of consecutive days without precipitation.

Observed streamflow has shown an increasing trend since 1940 in the United States in general (Lettenmaier et al. 1994, Lins and Slack 1999, USGS 2005), and particularly in the Midwest region. More specifically, if you rank daily streamflows from least to greatest, the low to medium range values have increased in recent years, while the largest have not (Lins and Slack 1999). Similarly, Hodgkins et al. (2007) show increasing flow at most gauging stations within the Great Lakes basin, both for the period 1935-2004 and 1955-2004. Li et al. (2010) emphasize that outflow from a region of water in streams must be balanced by net inflow of water vapor in the atmosphere, meaning that atmospheric transport is crucial to terrestrial hydrology, including streamflow.

Net basin supply (NBS, which is tributary river inflow plus over-lake precipitation minus over-lake evaporation) is important for the Great Lakes because it sets the level to which the lake must rise or fall so that it is balanced by outflow. Lenters (2004) showed trends of reduced seasonal cycle in NBS and lake levels on Lake Superior. This change includes a reduction between 1948 and 1999 of the NBS during the spring, and an increase of NBS during the autumn. Each of these changes is primarily attributable to changes in runoff and over-lake precipitation, as given in the dataset of Croley and Hunter (1994). During the 1948-99 period, they did not note a strong overall trend in lake level.

A possible non-climatic cause of changes in the lake level regime of the Great Lakes was proposed by Baird and Associates (2005). They proposed that a deepening of the channel of the St. Clair River, which forms part of the connection between Lake Huron and Lake Erie, was responsible for a distinct reduction in the difference in level between these two lakes. With NBS remaining constant, a less impeded flow due to a deeper channel would require that the level of Lakes Huron and Michigan would need to be lower relative to the level of Lake Erie in order to maintain the same volume of flow out of Lake Huron. The International Joint Commission's International Upper Great Lakes Study (IUGLS, (2009) instead found that changes in climate during the period between about 1985 and 2005 was primarily responsible for this change in relative lake levels.

Trends in the entire range of hydrologic variables may depend on the range of dates that are considered in observational analysis. For example, a rapid drop in the level of Lakes Michigan and Huron occurred during the 1990s and 2000s (Baird and Associates, 2005; IUGLS 2009, 2012), so whether or not an analysis extends beyond that date could affect the magnitude of an apparent long-term trend.

Frequency of localized, short-term extremes

As stated above, Pryor et al. (2009) showed an increase in the amount of precipitation that came on the 10 days of the year with the greatest precipitation. That is, more precipitation came during very heavy downpours. However, this was not evaluated as a proportion of the total precipitation. They also found that there was generally a decrease in the mean number of consecutive days without precipitation. This is in basic agreement with the results of the seminal paper of Kunkel et al. (1999).

Changnon (2007) examined the frequency, intensity, and economic impact of severe winter storms in the US between 1949 and 2003. This generally showed an increase in intensity over time, and a decrease in frequency, with these effects most concentrated in the eastern US.

Non-climatic influences

One factor aside from climate that can affect the long-term water budget of the region, as well as the shorter-term temporal characteristics of response of runoff to precipitation events, is land use. Land use in the Midwest has evolved historically from natural forest and grassland to greater agricultural use and increasing urban and suburban development. Andresen et al. (2009) showed that urban landscapes lower percolation of water into soil and increase surface runoff. Grassland landscapes have the lowest evapotranspiration (ET), while forests have the greatest amount of soil percolation. Cultivated agricultural land has fairly high ET, but also quite high surface runoff. They did not extend their analysis to include how much land was transformed from one of these classes to another. Mishra et al. (2010a) also evaluated the effects of land use on hydrology, showing that conversion of forest to cropland can lead to decreased ET and increased runoff. These effects, when combined with climate change effects, can be additive or compensating. Direct comparison of the results of Andresen et al. (2009) and Mishra et al. (2010a) is difficult because of the differing sets of results that were reported by each and because of the more static land use approach of Andresen et al. (2009) in contrast to the emphasis on land use conversion in Mishra et al. (2010a).

Properties of agricultural landscapes can make them more vulnerable to climate variability and change (Knox 2001). Natural landscapes are better at buffering moisture, making it available to plants for longer periods of time and delaying the eventual runoff of water that does not undergo ET. Thus, even aside from the possibility that precipitation will fall in more concentrated events, cultivated environments, and especially those with tiling to deliver runoff more rapidly, will promote greater extremes in streamflow than forests, grasslands, and other natural land cover types. Similarly, Mao and Cherkauer (2009) used a hydrologic model to demonstrate that land use transformations from pre-settlement times to the present result in decreased ET and increased runoff throughout much of the states of Minnesota, Wisconsin, and Michigan, where the prevailing transformation was from forest to agriculture. Even conversion from evergreen to deciduous forest resulted in decreased ET and increased runoff. A specific difference from the general results of Knox (2001), though, was that conversion from grassland to agriculture, which occurred in much of the southern and western part of the domain, resulted in increased ET and decreased runoff.

Lake water temperature

Austin and Colman (2007) investigated surface temperatures of Lake Superior during the period 1979-2006, and found a positive trend in these temperatures. They found the rate of increase in annual maximum lake surface temperatures to be nearly twice as large as trends in summertime near-surface air temperature over the surrounding land. This was taken as indicating positive feedback mechanisms within the lake, including greater intake of solar radiation due to the reduced duration and extent of ice cover, and the shift in timing of spring overturning of the water column.

Dobiesz and Lester (2009) looked at surface temperatures throughout the Great Lakes, as well as throughout the water column at one station in western Lake Ontario. They also found a strong trend toward greater water clarity (as measured by Secchi depth) between 1968 and 2002, which is attributable to a combination of abatement of phosphorus loads into the Great Lakes and the invasion of non-native Dreissenid mussels (zebra mussels and quagga mussels). They found positive trends in water temperatures, both at the surface and at depth, and attributed this to a combination of changes in climate and changes in water clarity. Vanderploeg et al. (2012) reinforce this result regarding water clarity and extends this result to Lake Michigan for the difference between the 1994-2003 period (before expansion of quagga mussels to deep water) and 2007-08 (after expansion).

Some of the distinctions between the conclusions of Austin and Colman (2007) and Dobiesz and Lester (2009) illuminate a particular point. It has often been either explicitly or tacitly assumed that changes in temperature occur first in the atmosphere, and then propagate to changes in temperature of the surface (or other effects at the surface). Dobiesz and Lester (2009) hew close to this line of reasoning, implying that surface water temperatures are forced by surface air temperatures, with no notable effect in the opposite direction. Austin and Colman (2007), on the other hand, first present the difference in trends of water surface temperature and air temperature as being counterintuitive, but then offer mechanisms that occur within the water to explain this distinction. This means that the lake water is itself an active player in the climate system; we prefer to view climate and climate change as phenomena of the coupled atmosphere-surface system (including both land and water surfaces).

There was a long-standing gap in measurement of fluxes of water vapor, trace gases, and sensible heat flux from the Great Lakes., for purposes of analysis of moisture and energy budgets of the lakes, and for validation of models. New datastreams (starting in 2008) for in situ measurement of these variables are documented in Blanken et al. (2011) and Spence et al. (2011). These researchers have initiated these measurements at one station each in Lake Superior and Lake Huron.

Paleoclimatic studies

Booth et al. (2006) have characterized persistent anomalies in summer precipitation as being associated with anomalies in zonal surface winds. They show that July precipitation is negatively correlated with zonal wind index (mean sea level pressure gradient between 35º and 55º N across the western hemisphere), with a $p<0.05$ level of certainty for southern Minnesota, Iowa, and northern Missouri. Note that their zonal wind index quantifies pressure gradients over a range of latitudes farther south than those indicated by the more widely-used North Atlantic Oscillation and Arctic Oscillation (NAO/AO) indices. Their examination of the possibility of explaining an extended drought in this region between about 1200 and 1400 CE is inconclusive.

Croley and Lewis (2006) examined climatic conditions under which some of the Great Lakes might have been terminal lakes in the past (i.e. lakes with no outflow point because they lose sufficient water to evaporation to offset precipitation and runoff inputs). They arrive at figures of water level as a function of changes in air temperature and precipitation relative to late 20th century climate (their Figures 7 and 8). These figures show a range of climates yielding lake levels above the sill, meaning that there is continuous outflow from the lake. They also show a range with seasonally and interannually intermittent outflow, with the water level always very near to the sill level. Then there is a range with water below the sill level; within this range, the mechanism of balancing the water budget through changes in outflow is removed, and the water level becomes highly sensitive to climate because the water budget must be balanced by changing the evaporation from the lake surface via changing the lake area as a result of changing the lake level until a dynamic equilibrium is reached.

Future projections

Changes in the strength of the global hydrologic cycle provide a backdrop for the regional water budget. As in the historic record, general circulation model (GCM) projections of precipitation rate generally show an increase of about 2% per degree C, while the water vapor content of the atmosphere increases by about 7%, implying longer residence time of water vapor in the atmosphere (Held and Soden 2006, Pan and Pryor 2009). Note also that, in order to maintain an equilibrium value of atmospheric water vapor content, surface ET summed over the globe must equal precipitation summed over the globe. Therefore, when summed or averaged over the globe, the ET rate also increases by about 2% per degree C.

The magnitude of the most intense precipitation events has been projected to increase throughout the world due to increased greenhouse gases using both theoretical arguments (Trenberth et al. 2003) and analysis of output from global climate models (Sun et al. 2007). It is deemed likely that both floods and droughts will increase in frequency (Wetherald and Manabe 2002, Trenberth et al. 2003, Meehl et al. 2007). However, models remain a problematic tool for evaluating the magnitude and frequency of extremely heavy precipitation events, because in reality the spatial scale of the heaviest precipitation is smaller than the resolved scale of the model. This is true even for regional models with finer resolution than global models.

Trapp et al. (2007) evaluated the number of days that satisfy criteria for severe thunderstorm environmental conditions under historical greenhouse gas concentrations as compared to late 21st century concentrations. They found that there are more days with severe thunderstorm environment in the future over nearly all of the conterminous United States. Under one of the three GCMs that they showed, this tendency is most concentrated in the Midwest.

Some studies have projected a general increase in runoff for multiple drainage basins throughout the world (Wetherald and Manabe 2002, Manabe et al. 2004, Milly et al. 2005, Kundzewicz et al. 2007). Others have shown increases in the difference between precipitation and ET, which also imply increased outflow, and have extended these results to indicate increased soil moisture (Pan et al. 2004, Liang et al. 2006).

Cherkauer and Sinha (2010) used the Variable Infiltration Capacity (VIC) model to simulate changes in stream flow for six rivers, including four in the Upper Mississippi River basin. They found increased stream flow in these basins associated with warming by anthropogenic greenhouse gases. The anticipated influence of variability, particularly in precipitation, is to both decrease low flows and increase peak flows.

Increased winter precipitation is expected to lead to higher phosphorus loading in streams and draining into lakes (Jeppesen et al. 2009). This can lead to eutrophication, i.e. increased growth of algae and other aquatic plants, without much increase in life at higher levels of the food web. These effects are highly subject to multi-stressor effects, such as interaction with aquatic invasive species (Adrian et al. 2009).

Climate change is expected to warm the near-surface water of lakes more than water at greater depths. This will result in reduced vertical mixing of water, and in turn to reduced dissolved oxygen at depth (Fang et al. 2004). This is a threat to the habitat of fish and other species.

Upper Mississippi/Missouri/Hudson Bay watersheds

Using the Soil and Water Assessment Tool (SWAT), Lu et al. (2010) project that streamflow in the Upper Mississippi River basin will decrease when using climate data derived from GCM simulations in the 2046-65 period as compared to the 1961-2000 period. When averaging over the results using 10 different GCMs, these decreases occur during all seasons except winter. Wu et al. (2011) carried out similar projections for the Upper Mississippi River basin, and found increased water yield during the spring but large decreases in summer. The soil moisture likewise increases in spring and decreases in summer. Accordingly, there is increased risk of both flood and drought, depending on the season.

Ohio River watershed

Mishra et al. (2010b) used VIC driven by general circulation model output to investigate projected trends in drought in parts of Indiana and Illinois within the Ohio River watershed. They found that drought frequency increases during the middle part of the 21st century (2039-2068), while for later in the century, it increased only in the highest emission scenario for greenhouse gases.

Great Lakes watershed

Estimation of the impact of climate change on Great Lakes water budgets and levels began with Croley (1990). The same method has been used multiple times since then, but using results from different GCMs as input (e.g. Lofgren et al. 2002, Angel and Kunkel 2010, Hayhoe et al. 2010). A recent and very comprehensive example of this approach, Angel and Kunkel (2010) assembled results from over 500 GCM simulations from different modeling centers, using various greenhouse gas emission scenarios, and different ensemble members for each model configuration. They found spread among the results of the different model runs, but a general tendency for the lakes' net basin supply and water levels to be reduced, as was generally found in the preceding model studies using the same methods.

Lofgren et al. (2011), however, found fault with this long-used methodology, in particular its formulation of ET from land. This formulation relies excessively on using air temperature as a proxy for potential ET, and does not display fidelity to the surface energy budget of the GCMs that are used to drive the offline model of land hydrology. This is also in keeping with the findings of Milly and Dunne (2011). By substituting a simple scheme to drive the hydrologic model using changes in the GCMs' surface energy budget, rather than using the air temperature proxy as previously, Lofgren et al. (2011) projected water levels to drop by a lesser amount, or to actually rise in the future. The differential between water levels projected using the older method and the proposed new method differed by amounts on the order of one meter.

Lorenz et al. (2009) evaluated the water budget for Wisconsin under climate change scenarios based on 15 atmosphere-ocean general circulation models (AOGCMs). They found that there was greater agreement among the various AOGCMs regarding the sensitivity of air temperature to increased greenhouse gases than in the changes in precipitation. They found a negative correlation during July and August between changes in air temperature and ET throughout the central United States, with maximum magnitude over the lower Mississippi River. This was taken to indicate that evaporative cooling was occurring, making both the surface and the lower atmosphere cooler when abundant ET occurred, and cloud formation associated with higher ET may also enhance this effect. They also found that the amount of precipitation that occurred in the single wettest day of the year increased by an average of 33%, although individual models had increases between 5% and 66%. These results are similar to those of Sun et al. (2007), mentioned above.

Kutzbach et al. (2005) evaluated the Great Lakes basin's future water budget based on the convergence of atmospheric water vapor flux. That is, they inferred how much water is retained at the surface and becomes outflow based on how water was being transported in the atmosphere. Their analysis of AOGCM data indicated that enhanced greenhouse gas concentration will bring greater atmospheric moisture convergence to the Great Lakes basin, i.e. increased outflow, which also directly implies higher levels of the Great Lakes. This is in contrast to the results of Angel and Kunkel (2010) and its predecessor papers.

A newer wave of models will take a more direct approach at estimating hydrologic impacts of climate change in the Great Lakes basin. These involve development of regional climate models that are fully coupled to both the land surface and simplified formulations of the Great Lakes (Lofgren 2004, MacKay et al. 2009, Zhong et al. 2012, IUGLS 2012, M. Notaro and V. Bennington, personal communication). These Great Lakes-specific modeling efforts are complemented by downscaled climate models with a domain covering all of North America, created through the North American Regional Climate Change Assessment Program (NARCCAP, Mearns et al. 2009). Initial findings from these efforts (see, for example, Holman, et al. 2012) suggest that tools such as regional climate models can be used as an aid in estimating the spatial distribution of precipitation and other fields. In this light, there appears to be a need to revisit historical climate and hydrological data sets for the Great Lakes region which, to date, have served as a basis for water budget and water level planning decisions including those impacting hydropower, navigation, and shoreline recreation and infrastructure.

Commonality among many studies

Throughout most of the projections based on general circulation models of future climate noted above, for the Midwest, there is an increase in the annual mean precipitation. And in most of them, increased precipitation happens primarily during the cold season. On the other hand, summer has little projected change or a decrease in precipitation in most models.

Coupled atmospheric-hydrologic phenomenon--Warming hole

Pan et al. (2009) show observational evidence of a summer "warming hole," a region in the contiguous United States in which warming trends are reduced or even reversed for the summer season. Depending on which period is used for calculation of trends, the warming hole is located over the western portion of the Midwestern region and extending further west and south (1976-2000), or primarily to the south of the Midwestern region (1951-75). The proposed mechanism is increased influx of moist air due to the low level jet (LLJ), originating from the Gulf of Mexico. The increased moisture content of the LLJ is a straightforward result of warming of both the atmosphere and the surface, particularly the water surface of the Gulf of Mexico. The resultant increase in rainfall leads to increased evaporative cooling of the surface (the cooling effect is most pronounced for daily maximum temperatures during the summer). As noted, the location of the warming hole has shifted with time, and the mechanisms behind this shift are unclear.

Uncertainty and Probability

Acknowledging and quantifying uncertainty in historical climate data and climate projections, and clearly propagating that uncertainty into policy and management decisions, represent an ongoing challenge to the water resource and climate science community and the general public. Misconceptions about uncertainty, and the confusion associated with knowledge versus ignorance (Curry and Webster, 2011), have important implications for the water resource-climate science nexus, and (following Van de Sluijs, 2005) have led to the term "climate monster", a term intended to reflect that confusion, and represent a source of fear that drives reactions to a future we do not understand and cannot control (Curry and Webster, 2011). Confirming and validating models is, of course, one approach to building confidence in projections about future climate conditions, however there is no clear consensus within the water resources or the climate science community about a metric, or set of metrics, for which the skill of complex (and in some cases, probabilistic) models can be assessed (Guillemot, 2010).

Furthermore, agreement between a model and historical climatic data does not necessarily imply that projections of future climate states will be correct, or even physically reasonable, especially if the model is based more on empirical fitting rather than processes known from first principles. Curry and Webster (2011) say, "Continual ad hoc adjustment of the model (calibration) provides a means for the model to avoid being falsified." A particular example of the problem with empirically-based models being applied to unprecedented climate regimes is illuminated in Lofgren et al. (2011), in this case leading to demonstrably excessive sensitivity of ET to climate.

The uncertainty in the response of precipitation and ET to enhanced greenhouse gases is greater than the corresponding uncertainty of air temperature, as emphasized by Pan and Pryor (2009) and Lorenz et al. (2009). To compound this issue, the most important quantity in determining streamflow and lake levels is the difference between precipitation and ET. Thus it is the difference between two larger quantities, each having sizable uncertainty, and therefore the uncertainty proportional to this difference is even larger.

Additional insights into management of water resources in the face of uncertainty, as well as reviews of many of the findings mentioned in the current paper, can be found in Brekke et al. (2009).

Conclusions

In general, precipitation has been increasing and this trend is projected to continue. Precipitation increases are particularly pronounced when looking at the winter season and when looking at the few largest rain events of the year, and this is expected to continue. Methods of calculating evapotranspiration (ET) under changed climate are the subject of emerging research, showing that widely-used methods based on temperature as a proxy for potential ET exaggerate projected increases in ET, as demonstrated by severe imbalances in the surface energy budget. When incorporated into further simulations, this leads to excessive reductions in streamflow and lake levels. Simulations using a more energy-based approach to ET give more mixed results in terms of changes in streamflow and lake levels, and often show increases

Impacts on water resources at local to regional scales remain subject to greater uncertainty than projections of basic climate variables such as air temperature and precipitation, especially when these climatic variables are aggregated to the global scale. . Relevant policy responses may be to enhance resiliency in the case of occasional low levels on lakes and streams, as well as potentially larger flooding events.

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