Climate change and water resources in the Washington metropolitan area: research motivations and opportunities

Prepared by

Ani Kame'enui
Erik R. Hagen

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The Section for Cooperative Water Supply Operations on the Potomac

Interstate Commission on the Potomac River Basin
51 Monroe St., Suite PE-08
Rockville, Maryland 20850

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Interstate Commission on the Potomac River Basin (ICPRB)
Section for Cooperative Water Supply Operations on the Potomac (CO-OP)
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1 Introduction

As water resources managers, it is a privilege and obligation to investigate global and regional climate change research with regard to water resources. Water resources managers are responsible for maintaining a reliable system and must be prepared for uncertainty in regional water resources. It is important to consider evidence that the climate is changing and that global temperature and precipitation records reflect these changes. The debate over the legitimacy, cause, and direction of climate change and related research is heated, and no one can be certain of the future direction of climate change. However, there is a strong likelihood temperatures will continue to increase and precipitation patterns will change. Perhaps our greatest challenge is determining how much worse might climate change make the historical worst-case conditions? These facts and scenarios must be considered in long-term water supply planning and utility management.

This document, *Climate Change and water resources in the Washington metropolitan area: Research Motivations and Opportunities*, provides background on global and national climate change research and identifies a plan for investigating climate change impacts on water resources in the Potomac River Basin. **The main goal of the proposed research is to better understand how extreme event (drought) hydrology might be affected by climate change.** The following research steps are recommended in pursuing this goal:

1. Collaboration with regional climate change research groups
2. Extraction of General Circulation Models (GCM)/Historical Climatology Network (HCN) climate forecasts of temperature and precipitation;
3. Implementation of watershed runoff model;
4. Additional literature searches and communication with climate variability researchers to determine potential impacts of a possible long-term drought cycle (Atlantic Multidecadal Oscillation, AMO);
5. Consider societal impacts of climate change that might impact water demand, land use, or other natural resource variables.

The plan identified does not require additional funding by the WMA water suppliers. Rather, CO-OP plans to continue to develop the tools and expertise necessary to conduct the climate change research as an ongoing part of the CO-OP program. Should CO-OP require additional funding or collaboration with the research community to further the climate research, CO-OP will apply for outside grants to facilitate the research.

Many of the tools needed to develop the climate change research are being developed as ongoing activities in the regular work-plan for the CO-OP program. The impact of additional research on climate change should not detract from CO-OP activity and will serve to increase CO-OP expertise with regard to Potomac hydrology.

2 Introducing international and local climate change research

The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) responded to global concerns over and evidence of climate change and established the International Panel on Climate Change (IPCC) in 1988. A goal of the IPCC is to provide objective and consensus based science on climate change, representing the mainstream of current scientific thinking. Therefore, the IPCC has provided the framework for most contemporary conversations on climate change. With supporting members from scientific communities around the world, the goal of the IPCC is to "assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation" (IPCC website). Though the research does not take place within the IPCC, the panel acts as a governing body, providing assessments based on peer reviewed and published research by the greater scientific community involved in climate change research. Using working groups to assess different sectors of the climate change debate, the IPCC produces assessments, reports, and technical papers that attempt to bring international consensus to a controversial topic. The IPCC is currently working on the Fourth Assessment Report, to be released in 2007 (IPCC website). The Third Assessment was released in 2001 (IPCC, 2001a); the three primary working groups covered the scientific basis for climate change, research results related to impacts, adaptation, and vulnerability, and issues of mitigation.

Research conducted in the Mid-Atlantic is contributing to the growing global knowledge on climate change. The Mid-Atlantic Regional Assessment (MARA) has brought together research on the potential impacts of climate change on various resources throughout eight eastern states (NY, NJ, PA, DE, MD, WV, VA, and NC). MARA is sponsored by the U.S. Global Change Research Program (USGCRP) which is in turn funded by EPA. MARA published an overview of the climate research for the region called *The Potential Consequences of Climate Variability and Change* in March 2000. This overview provided context for the climate change scenario in the 2005 Demand Study.

With the foundation in climate change research laid by organizations such as the IPCC and the MARA group, it is possible to apply the research of others to the WMA in order to assess the vulnerability of the WMA to regional climate change. This document summarizes a growing body of international and regional research in climate change and its impacts on water resources. In addition, this report provides a detailed strategy to quantify the effects of potential changes to the WMA water supply from climate variability and/or change and its accompanying uncertainty, particularly considering conditions worse than those on record.

3 2005 Demand Study climate change assessment

The CO-OP 2005 Demand Study (Kame'enui et al., 2005) considered climate change as a factor affecting future water demand and supply for the WMA. This assessment demonstrates that even with a higher-than-expected growth scenario, the water supply system developed twenty-five years ago is adequate to meet 2025 demand under a repeat of the worst meteorological and stream flow conditions on record. Despite these optimistic results, a scenario which stressed the supply system was the 2025 climate change scenario. Although the system remained 100 percent reliable in simulations, the degree of uncertainty in the climate change scenario is high and the climate change scenario severely depletes reservoir reserves.

CO-OP estimated the effect of increasing temperature due to potential climate change on Washington metropolitan area water supply demands using tools developed for the 2005 demand study. The climate change scenario in the demand study included temperature records that were altered according to regional research for the Mid-Atlantic region. The projected change to temperature is based on two heavily cited and used GCM models for the Northeastern United States and the confidence level associated with these projected changes is considered "high" for temperature (Najjar et al., 2000; Neff et al., 2000). The higher temperatures due to climate change resulted in relatively modest changes in modeled demand. July, August, and September average demand in a drought year in 2025 is projected to be 687 MGD without climate change, and 698 MGD assuming higher temperatures due to climate change.

The reduction of streamflow by 10% in the climate scenario was an effective sensitivity analysis but entirely arbitrary, based only on an interest in testing the vulnerability of the system to a given threshold rather than on any specific scientific evidence. For more details on the technical assumptions for the climate change scenario, see section 4.13 of the 2005 Demand Study. Given the high degree of uncertainty associated with the streamflow reduction scenario discussed, there is ample room for improvement. Additional research can investigate how climate change might affect the resource (streamflow) itself rather than demand alone.

4 Climate change and variability in the Mid-Atlantic

4.1 Identifying climate change

The IPCC refers to climate change as a change in climate over an extended time period, regardless of whether this is a result of natural variability or human activity. Other references to "climate change" often suggest a change in climate over time that is a result of human activity altering the state of the atmosphere, in addition to natural climate variability (IPCC, 2001b). Climate variability, on the other hand, refers to naturally occurring fluctuations in weather patterns. This is represented in trends such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), or the Atlantic Multidecadal Oscillation (AMO). Such trends take place over shorter time periods and though their impacts may be worsened by human activity, they are not the direct result of human activity. Research on the impacts of climate change and climate variability is valuable to our assessment of how water resources may be affected in the future.

While the IPCC provides a framework for global research, the MARA provides more specific regional information. Climate variability has played a prominent role in the long-term climate record in the Mid-Atlantic. Most of the historic exceedingly warm or cool time periods have been attributed to natural climate variability and global weather circulation patterns (Fisher, 2000). The impacts of anthropogenic changes on climate are even less certain, but as evidenced by global research, not unlikely.

Long-term temperature records were examined in the broader WMA for the months of June, July, and August by ICPRB (Kame'enui et al., 2005). The data show a clear warming trend for July and August. While these positive trends may be entirely related to the heat island effect of increasing urbanization or other climate variability factors in the WMA, they are clear indications that the climate in the WMA has in fact changed during the last century.

Further investigation of environmental indicators of regional climate change included an assessment of long-term streamflow records. More specifically, the USGS evaluated whether droughts have increased in recent decades in response to climatic conditions (Lins, 2005). USGS reports that stream flow has been increasing in the United States since 1940, with the Mid Atlantic among those regions experiencing the most increase. Increases were most prevalent in low to moderate stream flows (seen at 40 percent of the stream flow gaging stations), with relatively few decreases (seen at 8 percent of stations). The pattern of trends is dominated by increases in the months of September through December. This pattern is consistent with observed increases in streamflow at the low to moderate percentiles, which generally occur during the late summer and autumn period. This result also is consistent with increases in reported precipitation in the United States, which have been greatest during the autumn season. The USGS reports that stream flow increases occurred as a sudden rather than gradual change around 1970, suggesting the climate shifted to a new regime. According to the USGS, a regime shift from one set of conditions to another suggests that the new conditions are likely to persist until the next sudden shift occurs. The rapidity of the shift suggests the changes are due to variability in climate whereas a slow, gradual trend implies a pattern that is likely to continue into the future. The USGS concludes that what this may mean for future variations and changes in U.S. stream flow will only be revealed with time but that we should expect our rivers and streams to continue to be characterized by both short- and long-term variations.

Potential increases in both temperature and precipitation may alter streamflow, groundwater, and water-quality given the strong links between climate variables and streamflow (Najjar et al., 2000; Neff et al., 2000). Expected regional changes can be summarized in Table 1 below.

Table 1: Climate change impacts for average climate conditions in the MAR

Parameter	2030		2095		Reliability of prediction according to author
	Mean	Range	Mean	Range	
Temperature (ºC)[1]	+1.3	+1.0 to +1.5	+4.0	+2.7 to +5.3	High
Precipitation (%)[1]	+4	-1 to +8	+15	+6 to +24	Medium
Streamflow (%)[2]	+2	-2 to +6	+11	-4 to +27	Low

Notes: Table partially duplicated from Najjar et al. (2000). [1]Taken from Polsky et al. (2000); change is based on 1983-1994 baseline conditions. [2]Taken from Neff et al. (2000); change is based on 1985-1994 base period, using temperature and precipitation conditions of 1900-1987.

These changes are based on the multi-state region of the Mid-Atlantic and average conditions. How these variables might be altered within the Potomac and Patuxent river basins where the resources are located and under extreme climate is more uncertain, but the regional research provides at least an approximation of the magnitude of potential changes. Additional uncertainty is introduced by urban heat island effects.

4.2 Local need for climate research

The results of the 2005 Demand Study suggest that despite the high reliability of the system, the WMA water supply is vulnerable to changes in resource availability. A focused study on this vulnerability would answer questions about long-term water supply and potential climate change impacts.

The output from GCMs used to explore climate change represents changes in *average* conditions. Precisely what is needed in the WMA is an examination of changes in *extreme* drought year events. For example, the changes forecast in Table 1 reflect changes to average conditions. Of more significant concern to managers is the impact climate change might have on extreme conditions such as the drought of record. How much worse might climate change make the historical worst-case conditions? The WMA's susceptibility to a worsening of the drought of record is unknown, though it has been considered in previous study by ICPRB. ICPRB Report No. 94-3 (Steiner, et al., 1997) identified the need for improved climate change impact research on a temporally and spatially disaggregated basis, and also identified the need to explore climate change impacts during extreme events (droughts). While the sensitivity analysis explored in decreasing streamflow in the 2005 Demand Study is a recent attempt to address this issue, a more thorough analysis can be completed to draw more reliable conclusions.

Our knowledge of regional research and potential climate change impacts is growing. In keeping with the noted research plan, additional investigation of the work completed by the MARA and others, as well as continued research on regional temperature and precipitation trends, and diligent reviews of national and international progress in climate change research only serves to enhance our knowledge and accomplishes three of the recommended research steps:

- Collaboration with regional climate change research groups
- Additional literature searches and communication with climate variability researchers to determine potential impacts of a possible long-term drought cycle (Atlantic Multidecadal Oscillation, AMO);
- Consider societal impacts of climate change that might impact water demand, land use, or other natural resource variables.

5 Results, methods, and limitations of global climate change research

Evidence provided by IPCC summarizes some of the most dramatic results of recent research in climate change. Some of this evidence includes the following: Since the late 1950s surface temperatures as well as temperatures in the lowest 8 kilometers of the atmosphere have risen by 0.1ºC per decade. Snow cover appears to have decreased by 10% since the 1960s and similarly, sea-ice has decreased by 10-15% since the 1950s in the Northern Hemisphere. Sea level is also on the rise as is precipitation over most mid- and high latitudes of the Northern Hemisphere (IPCC, 2001b). Improved climate models, indicate that while some of these changes may be natural, *most* of the warming can be attributed to human activity. Regardless of its origins, we can be sure that the climate is changing.

Specifically relevant to our interests are studies on climate change impacts on water resources. Water resources' impacts studies have been performed in the Willamette Valley (Portland and Tualitan), Colorado, Columbia, Sacramento-San Joaquin River Systems, and Cedar Tolt River systems (Seattle, WA) (Wiley, 2004). Though there may be additional motivation in the western U.S. to investigate climate change impacts considering the potentially devastating impacts to snowpack, climate change research in the eastern U.S. has not been neglected. The Massachusetts Water Resource Authority and the New York City Water Supply have both conducted studies. Both studies' results varied considerably, revealing climate signals that projected both increases and decreases in temperature and precipitation. Massachusetts' results were not conclusive given conflicting results between GCM models. Unfortunately, the study only confirmed the high degree of uncertainty associated with climate change impact studies. Unlike the Massachusetts study, the New York study used three GCM models to downscale climate signals; these were then used in comparison to historic floods and droughts. This helped identify possible changes in flood and drought frequency, as predicted by the GCMs, and did indicate that an increase can be expected in both flood and drought frequencies.

5.1 Methods of Research—Global modeling

As the primary tool in climate change research today, General Circulation Models (GCMs) are a global means to the reconstruction and prediction of long-term climate. GCMs represent multiple dimensions of the earth's environment, representing land, air, and oceanic processes and interactions. Though there are dozens of GCMs, the IPCC reviews and endorses far fewer. The IPCC states that “Climate models are applied, as a research tool, to study and simulate the climate, but also for operational purposes, including monthly, seasonal and interannual climate predictions” (IPCC, 2001b). The earth is divided into cells in these models. The size of these cells can vary based on the model speed and details, and represent area and depth. Exchanges between cells, or fluxes, of heat, air, and water can occur and are critical to representing the dynamics of a complex environment. GCMs are often made up of multiple models, each one representing a different climate piece. These “linked models” are known as coupled models and include the following components: atmosphere, ocean, sea ice, and land surface (Wiley, 2004).

The computation power needed to run a GCM is significant; models can take days to run. Models are often managed by research institutes and are accessible to the larger scientific community. The IPCC has made this possible by working with these institutes and providing GCM results online. Outputs can be in terms of multiple climate components, such as precipitation, temperature, air pressure, and so on.

Given the scale of GCMs and their limited inputs, considering the complexity of the natural environment, there is considerable uncertainty associated with these models. Most climate research utilizes the output of several GCMs, thus providing a range of climate change impacts. A range allows researchers and regional resource managers to plan for various conditions. An example of this range for several GCMs prediction of changes in future temperature is shown in Figure 1 (Wiley, 2004).

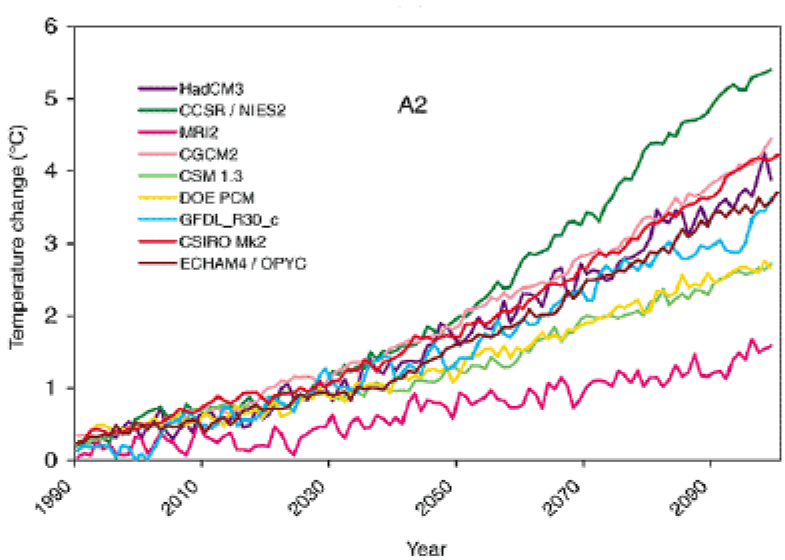

Figure 1: Example. Predicted temperature change (degrees C) from 1990 to 2100 for a suite of GCMs.

Despite the uncertainty associated with GCMs, these models are the best means to reconstructing and projecting climate change based on average conditions. With the foundation of a research guide like the IPCC, these models are evolving and improving at a steady pace.

5.1.1 Downscaling of GCMs

Output of GCMs is typically on a monthly timestep and represents large spatial scales. Large spatial scales are necessary because of limitations in computer power. In order to identify the results of a GCM on a local or regional scale, the model results require a process called "downscaling" in order to produce data that can be used at the watershed level, such as the Potomac. Both temporal and spatial results must be downscaled, as typical inputs to regional watershed models require at least daily time steps and are spatially heterogeneous. Like the models themselves, downscaling is a complicated process that has several methods.

Local climate change is influenced greatly by local topography, which is not well represented in global models because of their coarse resolution. Two approaches can be used to address this problem. The two main classes of downscaling are statistical downscaling and Regional Climate Models (RCM). A method commonly used in the assessment of climate change impacts on water resources is a statistical approach. This method depends heavily on the historical record to reproduce frequency and variability in climate variables, duplicating the spatial variability of historical records as represented by statistical properties. Regional Climate Models are more time consuming and expensive to implement. RCMs, with a higher resolution (typically 50 km), are built for smaller areas and run for shorter periods. RCMs take their input at their boundaries and for sea-surface conditions from the global GCMs. Unfortunately, RCMs are not currently a dependable source of information for regional climate change research.

Downscaling GCM data is one of the more time-consuming and expensive tasks to complete, so if this has been done by others then the cost and effort involved in addressing the potential effects of climate change on WMA resources will be significantly less than anticipated and remove a major obstacle to conducting solid research. It is hoped that ongoing research by professionals related to the MARA will significantly reduce the effort required for this process for the Washington metropolitan area as they will provide already downscaled climate data (through statistical means) for several climate stations within the Potomac River basin.

5.2 GCM modeling limitations

5.2.1 Extreme conditions

The ability to predict changes in the frequency or intensity of extreme weather events using global and regional models has been limited by their lack of small-scale spatial and temporal resolution and uncertainties about representation of some processes (IPCC, 1998). Climate records of extreme events are also limited due to the infrequency of the events themselves (Polsky et al., 2000). Current GCM output indicates how climate change might occur given average weather conditions. The inability of GCMs to mimic extreme events and better capture interannual variability is of concern to the entire research community. A priority on the agenda of the IPCC's Fourth Asssessment, consideration of extreme conditions is critical (IPCC, 2002; Polsky et al., 2000).

Broadly scaled GCMs are unable to capture short, periodic climatic episodes such as droughts. It seems statistically feasible, however, to develop relationships between the shifts in mean climate variables due to climate change and the tails of the distributions, representing extreme conditions. That is, hopefully the frequencies represented by the mean should be able to provide some information about the frequency of extreme events (IPCC, 2002). The IPCC's Workshop on Changes in Extreme Weather and Climate Events in 2002 drew attention to this issue and provided helpful solutions and recommendations.

5.2.2 Climate variability

Natural climate variability cycles such as ENSO, PDO, and AMO which represent long-term changes in sea surface temperature (SST) and atmospheric pressure (SO of ENSO) can have a powerful affect on weather patterns. These cycles are not entirely understood features of our climate. Given the limited understanding of these cycles incorporating such natural climate variability into GCMs has been less than successful (Wiley, 2004).

Given this brief introduction to GCMs, it is clear that the body of research associated with these models is complex and constantly evolving. In order to adequately address climate change impacts in the WMA we must focus our efforts on our second research goal (2. Extraction of General Circulation Models (GCM)/Historical Climatology Network (HCN) climate forecasts of temperature and precipitation), discussed in further detail in the following section.

6 Future climate change research in the WMA

6.1 Methodology

Many methods are feasible for assessing effects of potential climate change in the WMA. The outline provided below was developed by Frederick and Gleick (1999) for the Pew Center on Global Climate Change in reference to climate change studies in the context of water resources, these guidelines/steps provide a framework for the pursuit of climate change research within the WMA. These steps are described below and serve to accomplish all of the aforementioned CO-OP research goals:

1. Using GCMs to simulate future climate conditions on a global scale,
2. The re-scaling of global climate data down to a river basin scale,
3. Hydrologic modeling of downscaled GCM data to simulate stream flows under altered climate conditions,
4. The use of a systems simulation model to assess the effects of altered stream flows on water resource systems, and
5. Assessment of impacts on the users of water resource systems, including potential changes in demand and demographics under climate change scenarios.

6.2 Regional collaboration

Many of the contributors to the MARA research are also part of an EPA sponsored group called the Consortium for Atlantic Regional Assessment (CARA). CARA is a collaborative group that includes four universities (Penn State, Carnegie Mellon, University of Rhode Island, and the Virginia Institute of Marine Science), the input of the EPA, as well as many public and private stakeholders (CARA, 2005). The purpose of CARA is to "provide resources that decision makers can use for understanding current and future vulnerability to changes in land use and climate and for developing and evaluating adaptation changes" (CARA, 2005). CARA's work goals can be characterized by three primary features (CARA, 2005):

- Providing data and research tools via the CARA website (www.cara.psu.edu) on land use, socio-economic and demographic information, historical climate data, projections of future climate data, decision making strategies for using scientific information in problem solving and stakeholder discussion.
- Support for decision makers and stakeholders in their exploration of potential climate change impacts. This can include an assessment of current and future vulnerability and opportunities to adapt.
- Offering resources and tools for data integration. For example, CARA data can be combined to provide an analysis of socio-economics, land use, and climate projections for a particular region or community. This may help decision makers recognize relationships between sectors of their community in the face of climate change.

In considering a climate change impacts study in the Potomac River Basin, communication with members and organizers of CARA has helped guide understanding of what kind of research is underway in the region. As a result of this communication ICPRB's CO-OP Section was invited to join the CARA Advisory Committee. The benefits to both CARA and CO-OP of this collaboration are numerous. Though CARA is still in the process of developing datasets and research tools to be used in the aforementioned three work goals, participating with CARA provides CO-OP the opportunity to access various data and research tools related to climate change in the Mid-Atlantic. In addition, the Advisory Committee also provides a venue for developing relationships with a diverse group of resources mangers, educators, and climate researchers within and beyond the Potomac Basin. These meetings provide decision maker and stakeholder input to a complicated task of preparing our regions for potential climate change impacts.

6.3 Regional application of GCMs and downscaling techniques

The first two steps in the Frederick and Gleick (1999) method require the acquisition and downscaling of GCM models. As discussed above, free regional climate data will be available through the CARA website. CARA is planning to use seven IPCC-approved GCMs as listed below, as is the model developed by each institution.

- Max Planck Institute für Meteorologie (MPIfM): ECHAM4/OPYC3

- Hadley Centre for Climate Prediction and Research (HCCPR): HADCM3
- Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO): CSIRO-Mk2
- National Centre for Atmospheric Research (NCAR): NCAR-PCM
- Geophysical Fluid Dynamics Laboratory (GDFL): R30
- Canadian Center for Climate Modeling and Analysis (CCCma): CGCM2
- Center for Climate System Research (CCSR) National Institute for Environmental Studies (NIES) (CCSR/NIES): CCSR/NIES AGCM + CCSR OGCM

List gathered from IPCC data center website: http://cera-www.dkrz.de/IPCC_DDC/SRES/index.html

Given the range of variability we might expect from these GCM results, it is helpful to have a number of GCM models, as demonstrated in Figure 2, to provide a range of possible results. The use of multiple GCM results supports planning for a number of climate change impact scenarios.

GCM climate projections will be downscaled by CARA using a smoothing and interpolation method to bring them to smaller scale estimates. The downscaled climate data will then be made available at Historical Climatology Network (HCN) sites. According to CARA, HCN sites were selected as downscaling locations because HCN data have been subject to “standardizing procedures to ensure the climate data are comparable across stations” (CARA, personal communication, 2005). In addition, HCN has a number of sites across the Mid-Atlantic region, including several within the Potomac River Basin. Records for temperature and precipitation from HCN sites have been collected since 1900. A map of the region and HCN sites is shown in Figure 2.

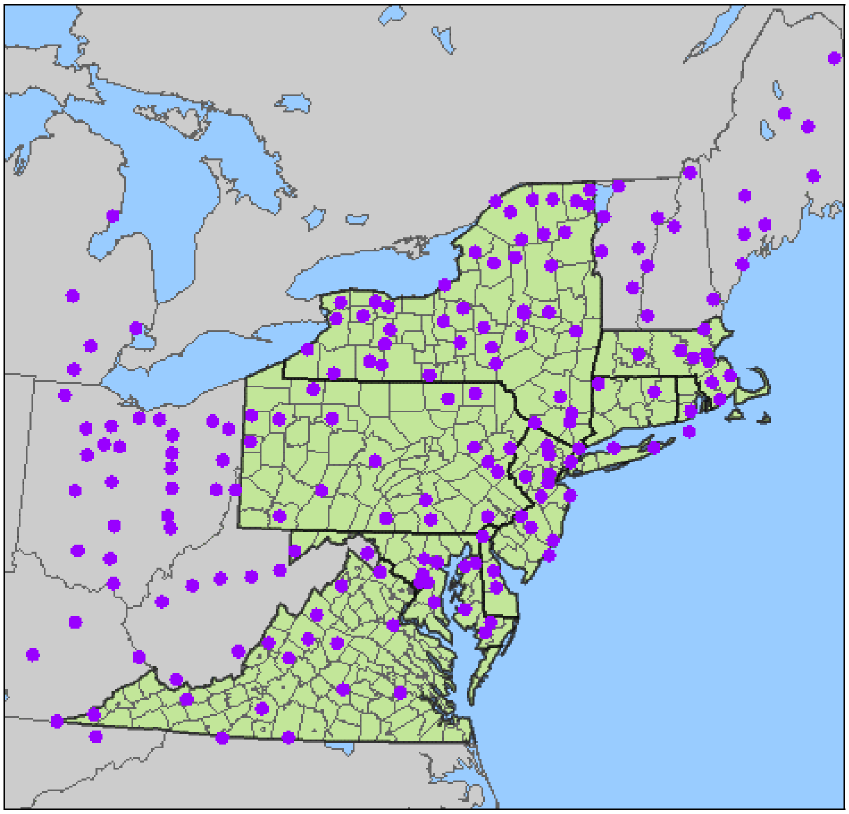

Figure 2: Mid-Atlantic region with HCN climate station locations noted as solid dots.

The downscaled temperature and precipitation forecasts, acquired through CARA and the HCN sites, can be used in Frederick and Gleick (1999), step 3, hydrologic modeling (Section 4.4). As we are most interested in how climate change might alter the most extreme conditions, the projected changes in temperature and precipitation would be applied to the worst drought on record (1930s). Until international climate research has a more thorough grasp on modeling actual climate change impacts to extreme events, such as droughts or floods, altering the existing record by the anticipated changes from average conditions (as produced by the suite of GCM models) must suffice.

6.4 Watershed hydrology model

A choice of watershed runoff models is available to CO-OP. The Hydrologic Simulations Program Fortran (HSPF) was developed by the EPA for watershed hydrology and quality modeling. A model was built and calibrated using HSPF for the the Chesapeake Bay watershed on behalf of the Chesapeake Bay Program, but the Fortran-based user interface is difficult to master and weakly supported. Another option available through USGS is supported and based on a modular system called the Modular Modeling System (MMS). MMS was developed for multidisciplinary research by the National Research Program's (NRP) Precipitation-Runoff Modeling Project (PRMS). Though not a model itself, MMS provides a framework for model coupling in order for the user to create an optimal model using algorithms appropriate for their purposes. Numerous other watershed runoff models exist but have not been evaluated by ICPRB at this time.

A new watershed runoff modeling tool would transform predicted temperature and precipitation data from GCMs into new streamflow forecasts for the Potomac River. Translating monthly precipitation values into daily streamflow values is a very complex task. While statistical methods can be used to connect runoff with streamflow, it is the recommendation of CO-OP staff that a calibrated physically-based watershed runoff model be used to translate precipitation into streamflow. Rather than depend on our arbitrary 10% decrease in Potomac streamflow, as was conducted in the 2005 Demand Study, the HSPF model or USGS MMS can utilize changes in temperature and precipitation to alter streamflow under climate changed conditions. A suite of temperature and precipitation changes, produced from a number of GCM results, can provide a range of climate change impacts.

Ideally, the watershed hydrology modeling tool will be developed for general CO-OP purposes but as a side-benefit it can be used to explore the vulnerability of the system due to climate change/variability. A new watershed hydrology model will be useful for a number of applications, including answering the question of how land use changes since the drought of record (1930) might affect low flows if a similar drought were to occur today. The tool may also be useful for drought operations and for improvements in system efficiency. Though a helpful tool, it should be noted that development of this model is complex and time-consuming, and may require several years to develop.

6.5 Systems simulation model

The Potomac Reservoir and River Simulation Model (PRRISM) is often used by CO-OP to simulate a diverse menu of system operations on the Potomac River. A variety of results can be generated to illustrate the reliability of the system, reservoir capacity, type and quantity of water use restrictions and so on under specific demand, climate, and streamflow conditions. This output is illustrated in Chapter 7 of the 2005 Demand Study and details the results of numerous growth and climate scenarios. In conducting a new study to incorporate a more thorough approach to climate change impacts in the WMA, the PRRISM model can be used to complete steps 4 and 5 of the aforementioned Frederick and Gleick (1999) method.

Similar to the application of PRRISM in the 2005 Demand Study, a revised climate change study could make use of altered streamflow input from watershed runoff models to produce results based on 2025 demands and beyond. Presented with a range of GCM and watershed model results, the PRRISM scenarios could evaluate both extreme and average conditions.

How consumer behavior might be affected in the climate changed conditions is somewhat uncertain. However, altered temperature and precipitation records will also shift CO-OP demands. Because the recently-developed demand forecast model is driven by climate variables, CO-OP can model demand changes due to variable weather conditions. Additional changes in consumer behavior or demographics may have significant effects on water demands in the climate change assessment in the Potomac Basin.

The combination of the research discussed in sections 6.1 through 6.5 can be summarized in the figure below.

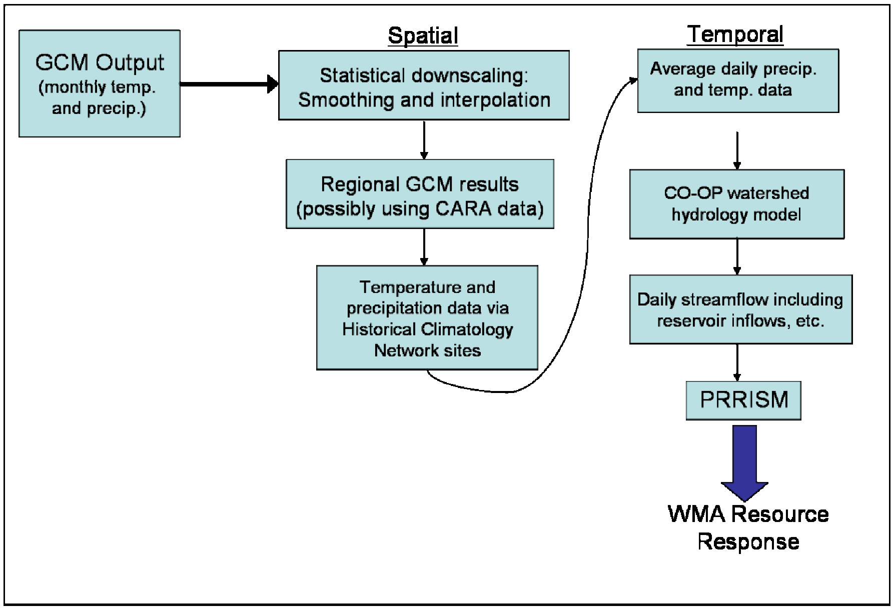

Figure 3: Schematic of proposed ICPRB research plan.

6.6 Climate Variability

Before addressing the potential social or economic changes due to climate change, climate variability ought to be considered. Though GCMs are not capable of truly representing climate variability, there exists a strong contingency of research dedicated to determining the influence of cycles like PDO and AMO on weather extremes such as drought. A growing number of studies suggest that the long-term predictability of drought frequency could be attributed to cycles of the North Atlantic Ocean (McCabe et al., 2004). McCabe et al. (2004) also suggest 52% of the variance in multidecadal droughts is due to the influences of either the PDO or the AMO and that the current positive signal in the AMO is cause for some concern regarding a potential drought in the coming decade.

While limited historical records reduce the certainty of conclusions that might be made about the natural climate cycles, researchers use available patterns of drought to relate these dry spells to any PDO or AMO signals. AMO signals, in particular, are of interest given their direct relationship to SST anomalies. For example, positive AMO conditions have coincided with periods of extreme drought in the last century (e.g., 1930-1960) (McCabe et al., 2004). Whether developing drought frequency indices (McCabe et al., 2004) or developing proxy records to more fully examine AMO behavior in the last 300 years (Gray et al., 2004), research on the possible influence of climate variability on current drought prospects is evolving and can be considered in a regional climate change study.

7 Conclusions/recommendations

The opportunity to refine understanding of potential impacts of climate change on water supply in the WMA is great. Though the results of the climate change scenario in the 2005 Demand Study indicate a highly reliable system, it is in the best interest of resource managers and their communities to address and prepare, as necessary, for the potential conditions of climate change. Though its impacts may not be effective for years to come, the opportunity to take a progressive approach to climate change research is prudent.

Provided the five critical steps to climate change research of Frederick and Gleick (1999) and the opportunity to collaborate with regional climate change researchers, the road map to an effective climate change study has been presented. Because the method incorporates outputs from a variety of GCM models, the results will include a range of possible outcomes, illuminating potential impacts to resource availability in the WMA under various climate conditions or extremes. These results can provide a refined understanding of the water supply system's long-term sustainability and possible need for additional supply.

The main goal of the proposed research is to better understand how extreme event (drought) hydrology might be affected by climate change. The following research steps are recommended in pursuing this goal:

- Continued collaboration with CARA Advisory Committee
- Extraction of GCM/HCN (Historical Climatology Network) climate forecasts of temperature and precipitation (depending on CARA research timeframe, USGS data availability);
- Implementation of watershed runoff model;
- Additional literature searches and communication with climate variability researchers to determine potential impacts of positive AMO cycle;
- Consider societal impacts of climate change that might impact water demand, land use, or other natural resource variables.

As our interest and pursuit of climate change research evolves, these steps will support an updated and well-educated climate change knowledge base, build relationships with regional research groups, improve the modeling skills of CO-OP staff, and prepare the WMA area and CO-OP suppliers for both long and short-term climate change impacts.

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