University of Maryland
Sustainable Development and Conservation Biology
CONS 670 Conservation Biology
Fall, 2014

The Frederick City Watershed: Forecasting Climate Change Impacts

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Executive Summary

This report serves to assist The City of Frederick in making future planning decisions about the Frederick City Watershed, a 7,000 acre, forested property just west of the city. Specifically, this report will address the question of how the Frederick City Watershed will be impacted by anticipated shifts in precipitation and extreme weather events due to climate change.

To assess the potential impacts that climate change may have on the Frederick City Watershed, climate models were applied to the watershed area and a forecast of several climate variables such as temperature, precipitation, snowfall, runoff, evapotranspiration and wind speed were evaluated. The data used for forecasting climate change impacts was taken from the *Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections* website (Maurer et al, 2007; Reclamation, 2014). The datasets aim to provide a set of high resolution, bias-corrected climate change projections. These can be used to evaluate climate change impacts on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions. Two scenarios were projected: the RCP 4.5 business-as-usual trajectory, and RCP 8.5 worst case emissions scenario. In addition to the climate modeling, an extensive literature review of potential climate factors on ecosystem services was conducted.

Under both modeling scenarios, temperatures are predicted to increase significantly across seasons and over the course of the century. Precipitation will remain fairly constant, but the greatest increase will occur in winter and spring; more of the precipitation will fall as rain rather than as snow. Runoff and soil moisture is expected to increase slightly during the winter and spring for both emissions scenarios, while evapotranspiration is expected to see significant increases in the spring, summer and fall. The models project no change in wind speed.

Overall, the results demonstrate a significant increase in temperature, which would seasonally affect the duration and type of precipitation, evapotranspiration, soil moisture and runoff. Changes in these variables translate to specific implications for the Frederick City Watershed ecosystem, including decreased water quality due to increased storm water runoff, an increased spread of invasive plant species, and a rise in plant diseases.

In order to effectively manage The City of Frederick's drinking water supply, the city should prepare for anticipated changes in climatic variables. Given the model projections, The City of Frederick should consider the following management techniques for the City of Frederick Watershed: commit to creating a Frederick City Watershed water balance model; incorporate regional water management and storage strategies; implement storm water management techniques; monitor water quality; and prepare for increased pest outbreaks. These suggested management measures will strengthen the city's resilience and ensure that The City of Frederick will be able to continually provide adequate supplies under both current and potential future climate change conditions.

Forecasting Climate Change Impacts on the Frederick City Watershed

As global climate change spurs rising temperatures around the globe, experts predict a surge in the frequency and intensity of localized, “extreme” weather events. Faced with a future of erratic weather patterns, governing bodies are being forced to address serious issues surrounding water management. This report serves to assist The City of Frederick in making future planning decisions. Specifically, it will address the question of how the Frederick City Watershed will be impacted by anticipated shifts in a number of climatic variables and extreme weather events due to climate change. Using downscaled climate modeling projections and an extensive literature review, the forecasted effects of future climate change on the Frederick City Watershed are presented and their impacts analyzed in order to offer management recommendations.

This project inherently fits into the larger conservation challenge of understanding how the effects of climate change are influencing management techniques, as communities around the globe adapt to new environmental conditions. Because the City of Frederick uses the Watershed for recreation and as a source of drinking water for the City, it is imperative that management officials know what to expect under projected climate change scenarios. Warmer temperatures and intense sporadic rainfall—exacerbated by increased demand for resources, for example—may require specialized water management techniques. The goal of this report is to project these changes as specifically as possible, in order to meet future demands and encourage the best management practices of the Frederick City Watershed.

Background

The Frederick Municipal Forest Watershed, located upstream of the City of Frederick, is approximately 7,000 acres of hilly, forested area rising sharply above the surrounding Piedmont plain. This forested area, which will be referred to as the Frederick City Watershed, is an important contributor to the City’s drinking water supply and is therefore vital to the well-being of the City’s resident population. Currently, The City of Frederick’s source water supplies come from three main surface sources; the Upper Monocacy River, Linganore Creek and Fishing Creek Reservoir.

The Monocacy is the largest Maryland tributary to the Potomac. The drainage area above the City’s intake on the Monocacy River includes approximately 448,000 acres (700 square miles) of mixed land use, of which approximately 45 percent is agricultural, 41 percent forest and 14 percent urban use (Upper Monocacy River Watershed Report 2012). The City of Frederick only owns a small portion of land surrounding the intake structure and water treatment plant. In addition to the densely populated urban center, the major transportation corridors of U.S. Highway 15 and state Highways 194, 26 and 140 are also located within the watershed (SWA Frederick). The mixed use of land upstream of the City’s intake—both agricultural and dense urban areas—leaves this tributary particularly vulnerable to runoff from concentrated impermeable surfaces and could cause water quality concerns.

Linganore Creek, a tributary of the Monocacy, is the second source of the city's surface water supply, with Lake Linganore acting as the largest impoundment in the county. It has the capacity to store over 800 million gallons of water (SWA Linganore 2004). The source water protection area for Lake Linganore encompasses 52,000 acres (85 square miles) of mixed land use, predominantly cropland and forested land (SWA Frederick). Based on 2000 land use data, 11.2 percent of the watershed is characterized as low-density residential, 48.6 percent as cropland and 27.6 percent as forest (SWA Linganore 2004). A comparison between 1990 and 2000 land use data showed significant changes as increases in residential land use reduced the acreage of cropland in the watershed (SWA Linganore 2004).

Lastly, the third largest surface water source is Fishing Creek Reservoir, which lies mostly within the Frederick City Watershed and has a current capacity of 50 million gallons. The source water protection area for the Fishing Creek Reservoir watershed encompasses 4,775 acres (7.4 square miles) above the reservoir and two streams, Fishing Creek and Little Fishing Creek, drain into the reservoir (SWA Frederick). Land use within the watershed is almost entirely forested; based on 1997 land use data for the reservoirs, 0.8 percent is residential, less than 1 percent is cropland, 98.8 percent is forest and 0.3 percent is open water (SWA Frederick). Specifically, The City of Frederick owns 3,065 acres of land in the watershed of Fishing Creek Reservoir and the land is part of the Frederick Municipal Forest (SWA Frederick). There are no residences adjacent to the reservoir; the few residences in the area are sparsely distributed along Little Fishing Creek Road and Gambrill Park Road, within the source water protection area. Due to the forested protection of this watershed, the Fishing Creek Reservoir is the least likely of the three water sources to be impacted by potential contaminants.

The City of Frederick, like the rest of Frederick County, has a humid and temperate climate with an average temperature of 50 ^{o}F and an average precipitation range between 44 and 46 inches (SWA Linganore 2004). The three main surface water sources discussed above depend on this reliable climate in order to maintain the ecology, soils and geology of the watershed, which are necessary for supplying high quality water to the city. For example, as described above, both the Linganore and Monocacy watersheds are surrounded by large amounts of agriculture and concentrated urban areas; any increases in infrequent and high rainfall events would significantly increase erosion and pollution for these watersheds (Versar, Inc., 2013). Therefore, the maintenance of the city's water supply is reliant on the ecosystem services of the surrounding area. Knowing this historical baseline information enables managers to plan for any shifts that may occur in temperature or average precipitation and what effects those shifts might have on the city's drinking water supply.

Projecting climatic conditions and determining what natural processes may affect a region's environment in the future is an incredibly difficult task. Using climate models that take into account a wide range of variable inputs, scientists are able to determine future scenarios with some level of certainty. To assess the potential impacts that climate change may have on the Frederick City Watershed, existing climate models were applied to the watershed area and a forecast of several climate variables such as temperature, precipitation, snowfall, runoff, evapotranspiration and wind speed were evaluated. In addition to the climate modeling, an extensive literature review of potential climate factors on ecosystem services was conducted.

Methods

Climate Modeling

For the purposes of the Frederick City Watershed project, it was important that the climate model be free, widely used, reliable and at a high enough resolution that the results accurately reflect The City of Frederick's potential future scenarios. The data used for forecasting climate change impacts was taken from the *Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections* website (Maurer et al, 2007; Reclamation, 2014). These are based on high resolution translations of climate projections that use statistical downscaling (Reclamation, 2014). The dataset is comprised of downscaled climate scenarios for the United States that are derived from global climate projections from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 5 (Taylor et al. 2012).[1] The projections were generated using a set of global climate models[2] that collectively reflect the advancements in climate science and integrated assessment modeling, in order to characterize future developments in global greenhouse gas (GHG) emissions. These are conducted across the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs) (Meinshausen, et al., 2011)), developed for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.[3]

Data was selected from the *Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections Project* datasets for the smallest area that contains the entire Frederick City Watershed, to include the Fishing Creek, Linganore Creek and the Monocacy River. The selected tributary area contains 12 cells of 1/8 degree latitude-longitude (~12Km by 12km) and an approximated area of 689 mi^2(1,785 km^2)[See Figure 1].

Specifically, the data for the following variables, which, through literature reviews, are believed to have the most significant implications for how the Frederick City Watershed may be most efficiently managed under climate change, were analyzed:

- Surface air temperature, monthly mean and minimum and maximum(°C)
- Precipitation, mean daily rate during each month (mm/day)
- Snow water equivalent in snow pack, state of 1st day of month (mm)
- Total runoff depth, sum of surface runoff and base flow (mm)
- Soil moisture content, state 1st day of month (mm)
- Evapotranspiration (mm)
- Mean wind speed (m/s)

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[1] For WCRP information, see http://www.wcrp-climate.org/. For CMIP5 information, see http://cmip-pcmdi.llnl.gov/cmip5/.

[2] Knutti R., and J. Sedláček, 2012. "Robustness and Uncertainties in the New CMIP5 Climate Model Projections," Nature Climate Change, doi: 10.1038/nclimate1716.

[3] van Vuuren, D.P., et. al, 2011. "The Representative Concentration Pathways: An Overview," Climatic Change, 109:5-31.

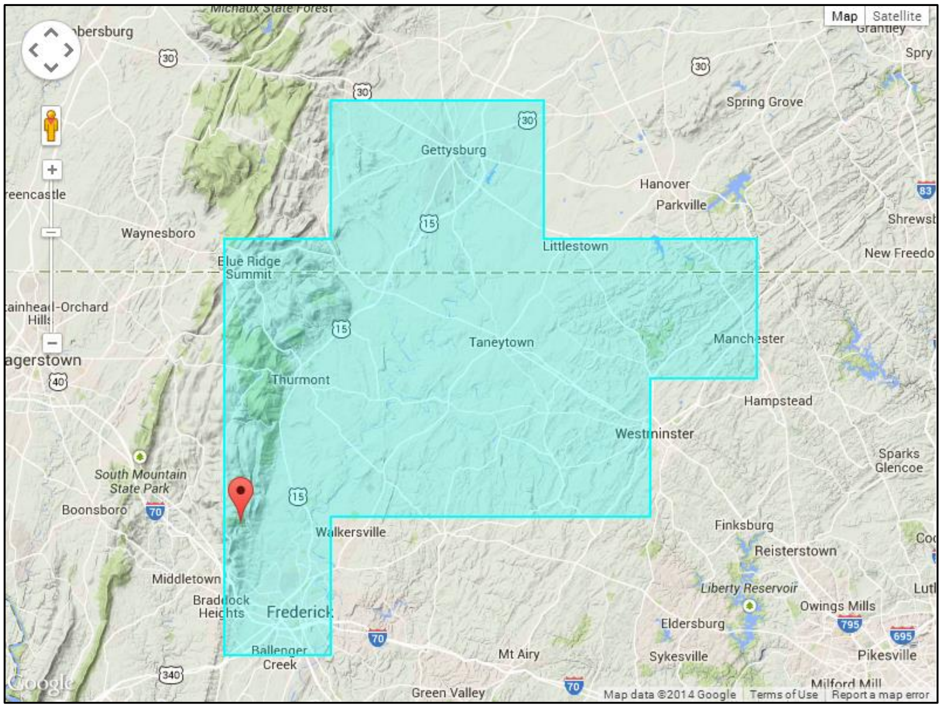

Figure 1: Tributary area. Area of study selected – contains 12 grid cells of 1/8 degree lat-long and approx. 689 mi2.

The forecasts look at only two of the four scenarios, RCP 4.5 and RCP 8.5. The RCP 4.5 emissions scenario is a conservative/business-as-usual trajectory, while RCP 8.5 is a worst case emissions scenario. The dataset includes downscaled projections from 70 models, as well as a suite of statistics calculated for each RCP from all model runs available, which were averaged for the purposes of the forecast projections. While every effort was taken to limit uncertainty to as small a degree as possible, the nature of climate predictions are inherently uncertain. The information ultimately provided here is based on the best work and the best models available at the time, to address this question: How will the Frederick City Watershed be impacted by shifts in precipitation and other extreme weather events due to climate change?

Literature Review

Several reports were used to understand the effects of future climate change on plant species and water resources, including: the *Water Resources Element* (The Frederick County Division of Planning, 2010); the *Frederick County Stream Survey 2008-2011 Four-year Report* (Versar, Inc., 2013); the *Source Water Assessments for City of Frederick* (Water Supply Program Water Management Administration); and annual water quality reports. The literature review was primarily used to understand the likely role various climate variables may have on the watershed water quality.

In addition, the literature review helped assess the projected effects climate change may have on the forest community structure within the watershed, including the incidence of invasive species, pests and disease.

Results

Temperature[4]

Generally in Maryland, temperature is predicted to increase by about 3.6 degrees Fahrenheit (°F) by 2050 and by as much as 9°F in summer by 2100 (Boesch 2008). Regardless of emissions scenario, models project an additional 2°F of warming by 2025. Yet by 2050, a difference begins to emerge in winter versus summer temperatures, depending on the emissions path (Boesch 2008). Under RCP 8.5, temperatures are projected to increase sharply after mid-century, compared to RCP 4.5. By 2100, the difference between the two scenarios is striking. Even more, summertime warming is projected to be greater in Western Maryland because the area will not receive the moderating influence of the ocean (Boesch 2008).

While the likelihood of warming is high, the exact magnitude of the amount of increases is less so. Yet, none of the models on which the "Comprehensive Assessment of Climate Change Impacts in Maryland" was based projected less than 4°F of warming in the summer by 2100 (Boesch 2008). It is unlikely that as years progress, each year will be warmer than the preceding one. Instead, it is more likely there will be months and even years that will be cooler on average than current seasonal norms. However, focusing on average temperatures over long periods, as this report and model do, illustrates that temperatures continue to warm in all emission scenarios.

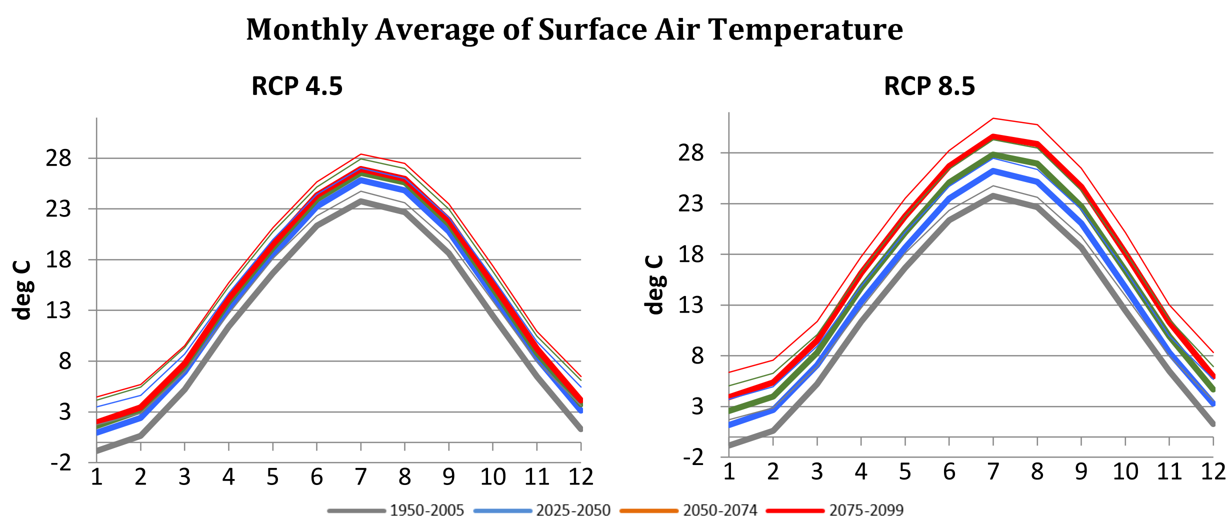

Figure 2: Monthly average of surface air temperature for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

As of 2014, the CMIP5 models suggest that the average surface air temperatures for the winter months of December, January and February under both emissions scenarios is approximately 35.6 °F (2 C). In

[4]The average surface air temperatures presented in our analysis are absolute and presented in degrees Celsius. The format in the body of the paper will be ° F followed by its equivalent in Celsius in parentheses. Our model is broken down into the four seasonal groupings.

2025, average temperature could increase slightly to 37.4°F (3 C). By 2100 there is a projected increase to 41°F (5 C) under RCP 8.5. While there is little change between 2025 and 2050 under both scenarios, there is potential for a 3.6°F increase between 2050 and 2100 in a high emissions situation.

For the spring months of March, April and May, temperature was approximately 51.8°F (11 C) under both emissions scenarios in 2014. By 2025, there is potential for temperatures to increase to 53.6 °F (12 C) under both scenarios. Under RCP 8.5, temperatures may be approximately 57.2 °F (14 C) in 2050 and may rise to 60.8 °F (16 C) by 2100. There is potential for a 1.8 °F increase between 2025 and 2050 under RCP 4.5. Under higher emissions, there is potential for a 3.6 °F increase between 2025 and 2050 as well as between 2050 and 2100.

For the summer months of June, July and August, the model suggests that the temperature in 2014 was 73.4 °F (23 C) under both emissions scenarios. By 2025, temperatures are projected to rise to 75.2 °F (24 C). Under RCP 8.5, temperatures may sharply rise to 82.4 °F (28 C) by 2100. There is the potential for a 1.8 °F increase between 2025 and 2050 under both emissions scenarios and a much larger increase of 5.4 °F between 2050 and 2100 under higher emissions.

Seasonal Average of Surface Air Temperature

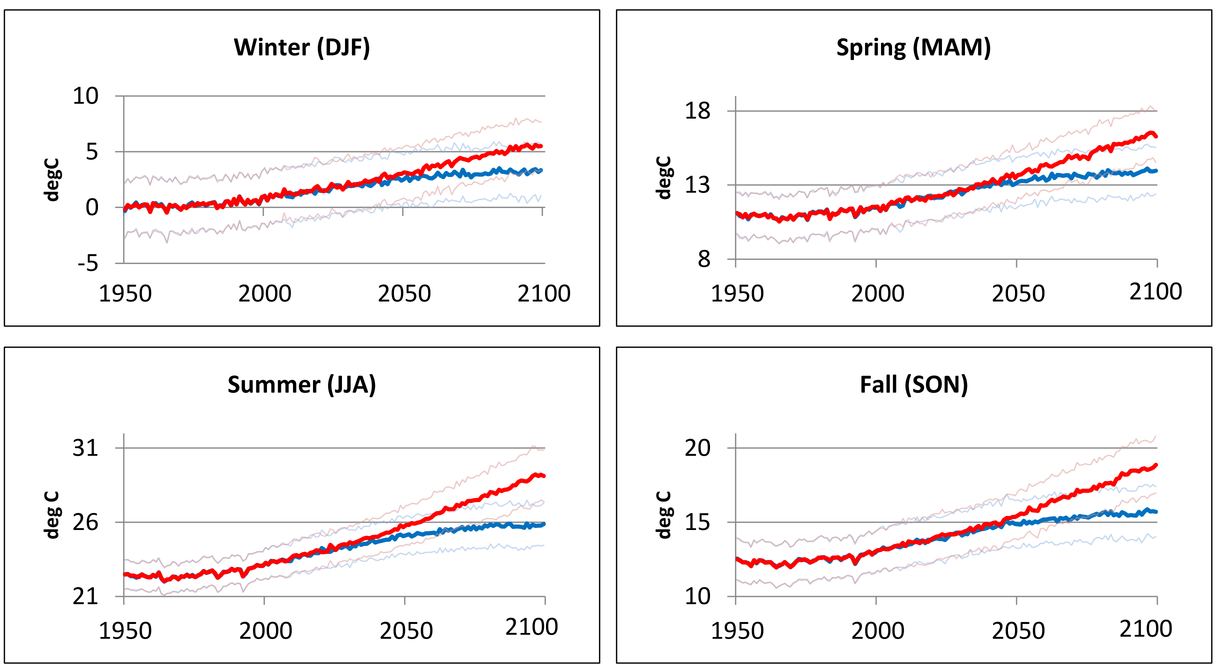

Figure 2.2: Seasonal average time series of surface air temperature for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

For the fall months of September, October and November, the temperature was approximately 55.4 °F (13 C) under both scenarios in 2014. In 2025, the temperature under both is projected to be 57.2 °F (14 C). Under RCP 8.5 in 2050, temperature is projected to reach 60.8 °F (16 C) and steadily increase to approximately 66.2 °F (19 C) by 2100. There is the potential for a 1.8 °F increase between 2025 and 2050 under RCP 4.5, a 3.6 °F increase between 2025 and 2050 and a 5.4 °F increase from 2050 to 2100 under a higher emissions scenario.

For all four seasons, under both emissions scenarios, the maximum and minimum surface air temperature closely parallel each other until 2050. Up until this divergence point, maximum and minimum temperatures slowly but steadily increase to temperatures in 2050 that are, on average, 3.6 °F more than maximum and minimum temperatures currently in 2014.[5] After 2050, maximum and minimum temperatures under RCP 4.5 continue to slightly increase but generally level off, whereas maximum and minimum temperatures under the RCP 8.5 higher emissions scenario increase much more steeply and rapidly.

Precipitation

The Frederick City Watershed and other watersheds of Frederick County provide an abundant water supply to The City of Frederick. However, this abundance can fluctuate as seasonal precipitation historically varies throughout the course of a year (Frederick County Planning Commission 2010). In the past decade, Maryland has experienced both its wettest and driest years on record (Boesch 2008). It is predicted that in a dry year in the Blue Ridge foothills, where the Fishing Creek Reservoir of The Frederick City Watershed lies, the total water availability would be reduced to half of that of an average year (Frederick County Planning Commission 2010). As climate change continues, it is possible record precipitation and drought events could occur more frequently. One report suggests Maryland will likely experience overall increased precipitation throughout the year, but with greater seasonal variability (Boesch 2008). For example, over the course of the next century the historically driest months of the year are expected to remain dry while more rainfall, as well as more rain per rain event, is expected in the wettest months, specifically during the winter (Boesch 2008). Current emission scenarios for Maryland suggest a 3-10 percent increase in storm events with over five inches of rain by 2100 (Boesch 2008).

The models show little variation in precipitation between the two emission scenarios during the fall. Summer precipitation, which does not vary between emissions scenarios, increases by 0.19mm/day (compared to the baseline) in the earlier part of the century (2025 to 2050) and by 0.30mm/day by the end of the century (2075-2099). This suggests the difference in the amount of emissions in the two scenarios has little effect on the amount of precipitation. Both scenarios show the greatest—yet still small—change in rainfall over the course of a century in winter and spring, with an increase of approximately 0.26mm/day from 2025 to 2050 (compared to the baseline) and an increase of 0.39mm/day by the end of the century (between 2075 and 2099) in the RCP 4.5 emissions scenario. The models predict the highest increases in rainfall during the winter, but the highest levels of rainfall (in mm/day) in spring by the end of the century. Given that climate change predictions for Maryland suggest more sporadic, intense rain events, it is likely that the increases in mm/day expressed by these

[5] This 3.6 degree F difference holds true in all instances

Monthly Average of Precipitation

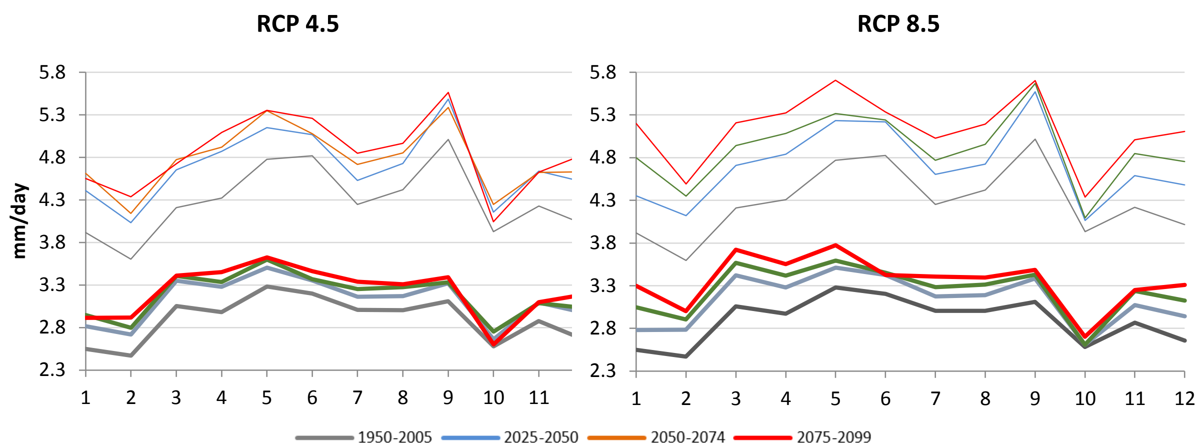

Figure 3: Monthly average of precipitation for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

models will not be distributed evenly across months or seasons and will likely result in stronger and more frequent rain events, rather than consistent precipitation over time.

Snow Water Equivalence

Predictions made by the Maryland Commission on Climate Change reveal a reduction as great as 50 percent in snow by the year 2100 (Boesch 2008). Therefore, it stands to reason that there will be less snow to feed the rivers as it melts into the spring (Boesch 2008). Because precipitation is expected to increase in winter, the decrease in snow volume reflects a shift from snow to rainfall, most likely due to warmer temperatures. The CMIP5 models show a significant drop in snow water equivalent during winter months from the latter part of the 20th century to the end of the 21st century for both emission scenarios. Under the RCP 4.5 scenario, snow water equivalent decreases by 1.66mm in the first half of the century (2025 to 2050) and decreases by 2.44mm by the end of the century. In the case of RCP 8.5, snow water equivalent decreases by 1.71mm from 2025 to 2050 (compared to the baseline) and decreases by 2.62mm between 2075 and 2099. Decreases in spring snow water equivalent are much smaller, fluctuating between 0.18mm and 0.36mm over the course of the century, for both emission scenarios.

The models also show great variation between years. While the overall trend for snow water equivalent is decreasing, the models showed a few years in the latter part of the century where snow water equivalent for the RCP4.5 scenario equals that of the latter part of the 20th century. Both scenarios, however, level out to a consistent 0-1mm of snow water equivalent a year as they approach 2100. Spring snow water equivalent levels were historically low, fluctuating between 0 and 1mm from 1950 to 2000. The RCP4.5 shows a continuation of this fluctuation until about 2060, where it then levels out to

0mm each year. The RCP 8.5 emissions scenario levels out near 0mm of snow water equivalent per year after 2000.

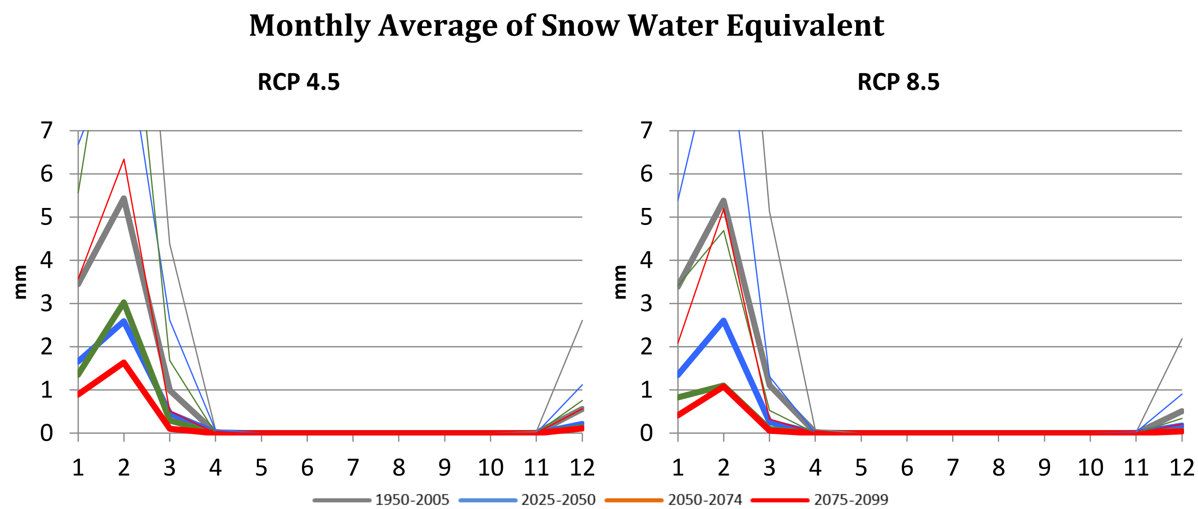

Figure 4: Monthly average of snow water equivalent (*) for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

Runoff and Soil Moisture

Surface runoff occurs when precipitation does not completely permeate into the ground and excess water runs across the surface. Meteorological factors affecting runoff include the type of precipitation, the intensity, and the amount and duration of the event. Some of the main physical characteristics that affect runoff when considering the future effects of climate change are land use, vegetation, soil type, drainage area and drainage network patterns (USGS, 2014). Land use change can be particularly problematic as urbanization increases. Impervious surfaces such as roads, trails, buildings and parking lots prevent water from being absorbed into soil, allow large amounts to enter streams rapidly and deposit sediment, nutrients and other pollutants into waterways. Further urbanization in the Frederick City Watershed, along with increased use of forest trails, will increase runoff and contribute to the degradation in the quality of the city’s water source.

In analysis of the CMIP5 climate change models and those of the literature review, precipitation is expected to change—and more specifically increase—during the winter season (Boesch, 2008). This increase in precipitation has implications for the amount of runoff from The City of Frederick, particularly in the likely event that the numbers of impervious surfaces in the area were to increase. Additional runoff in the winter and spring months is likely to result in more frequent flash flooding, degradation in water quality and increased nutrient deposition. The RCP4.5 scenario of runoff in the CMIP5 models of the winter season, which has a baseline of 47.93 mm, show an increase of 10.37 mm in fifty years and 13.50 mm in seventy-five years. Alternatively, the RCP8.5 scenario predictions range from 13.61 mm to 20.15 mm in fifty and seventy-five years, respectively.

Another variable connected to runoff is soil moisture. Yet, soil moisture, like many other variables, will be difficult to predict due to the complexity of multiple intersecting factors, such as temperature, water, or carbon dioxide concentrations (Boesch, 2008). The CMIP5 climate models shows little change in soil moisture as a result of climate change effects. A small increase in soil moisture content is expected during the winter season due to increases in precipitation. Specifically, the CMIP5 climate models show an increase in soil moisture, with a RCP8.5 scenario prediction of 5.80 mm in fifty years and 8.97 mm in seventy-five years during the winter months.

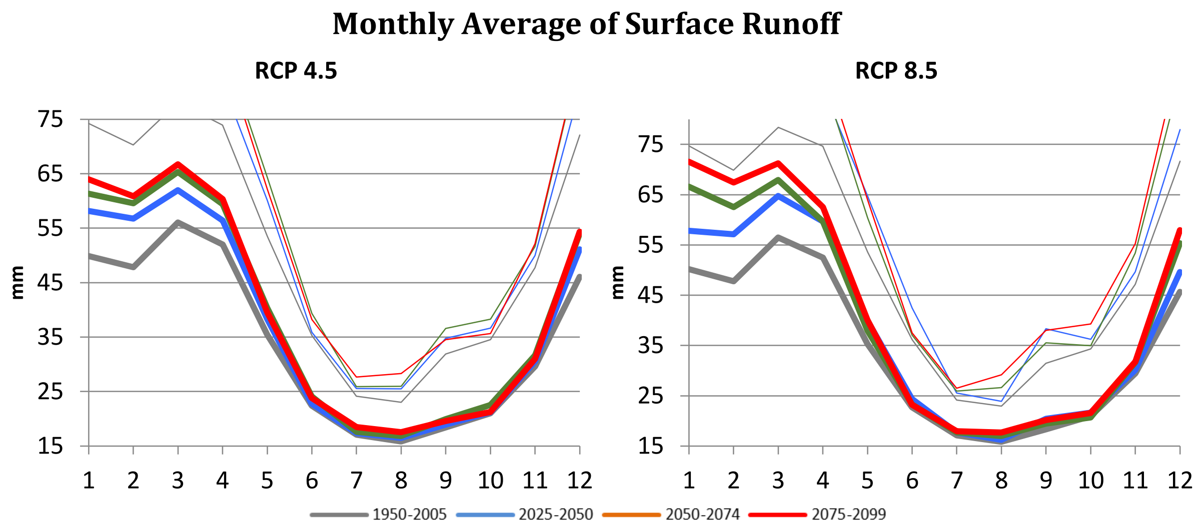

Figure 5: Monthly average of surface runoff and baseflow for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines

According to the literature, both severely reduced soil moisture and highly saturated soils can produce negative effects, particularly when considering runoff (Bot & Benites, 2004). Based on the CMIP5 climate change models, Frederick will not experience either end of these extremes. The Frederick City Watershed is expected to see minimal effects of soil moisture at its highest increase, which is during the winter months; under the RCP8.5 scenario, the Watershed would see a 5.80-8.97 mm increase. This trend differs during the summer months, in which the CMIP5 models predict a decrease of 4.26 mm and 4.51 mm in fifty and seventy-five years, respectively. This is likely connected, in part, to increases in the evapotranspiration of natural vegetation that the CMIP5 predicts. However, soil moisture is affected by multiple factors, so it is likely that other variables affect these data as well.

Evapotranspiration, Vegetation Potential and Wind

The Maryland Commission on Climate Change expects modest increases in precipitation during winter and spring, but throughout the year rain is expected to fall in fewer events of a more extreme nature, particularly during summer. Apart from precipitation, the most significant component of the hydrologic budget is evapotranspiration, evaporative losses from surfaces and plants. Evapotranspiration varies

regionally and seasonally; during a drought it varies according to weather and wind conditions (Hanson, 1991).
Although rainfall in summer is expected to increase slightly, simultaneous increases in summer temperatures will result in greater evaporative losses, rendering the overall net change of water available (to plants) during summer close to zero. However, droughts lasting for several weeks during summer are likely to be more common (Boesch, 2008). The CMIP5 climate models predict increases in evapotranspiration from plants during summer periods, tapering to slight decreases during winter. Both the RCP4.5 and the RCP 8.5 scenarios increase average evapotranspiration at least 7 percent in the spring, 4 percent in the summer and 7 percent in the fall during 2025-2049. Between the years 2075-2099, evapotranspiration is expected to increase by 11-19 percent in the spring, 7-8 percent in the summer and 13-17 percent in the fall. The forecasts of potential natural vegetation evapotranspiration, as well as the potential open water surface evapotranspiration, fall in line with the same trends of an increased monthly average actual evapotranspiration.

Under the CMIP5 climate models, monthly average wind speed does not vary with any significance.

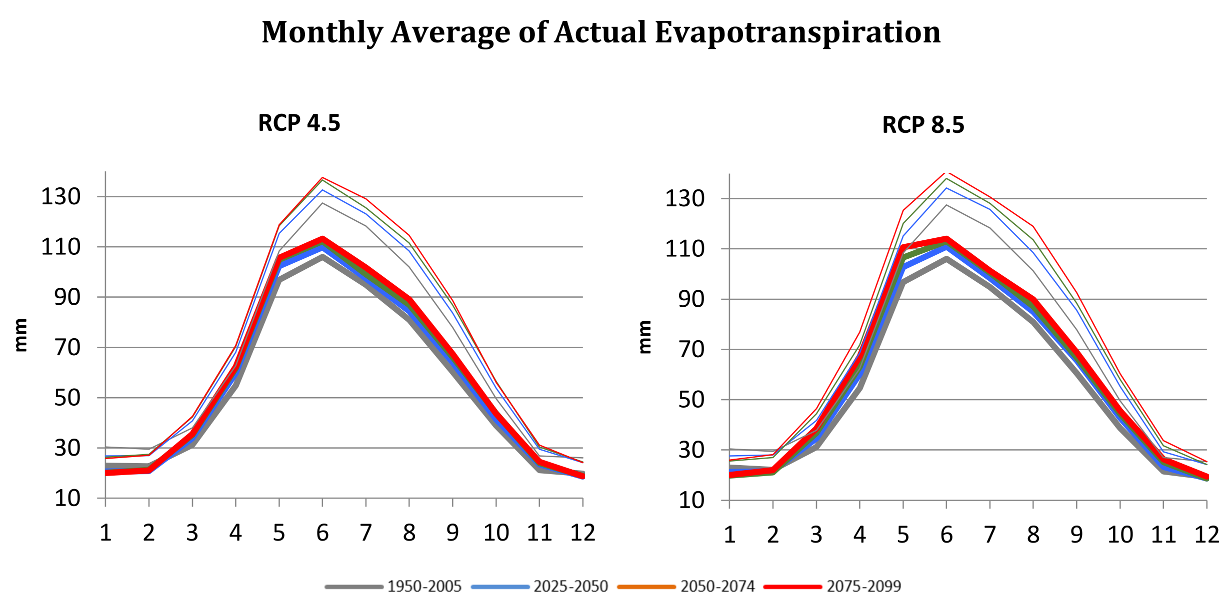

Figure 6: Monthly average of actual evapotranspiration for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin line

However, the forecast and projection tables have been included in Appendix A for reference purposes.

Discussion

Climate change is dynamic, with realized outcomes dependent upon the relationship between all the different variables previously described in this report. Overall, the results showed a significant increase in temperature which would drive seasonal changes in the duration and quantity of precipitation, evapotranspiration, soil moisture and runoff. Changes in these variables translate to specific implications for the Frederick City Watershed ecosystem:

Variable:	Temperature	Precipitation	Snow Water Equivalent	Runoff	Soil Moisture	Evapotranspiration
Model Results:	- Significant increase across seasons over time -Scenarios differ in latter half of the century	- Overall increase -Greatest increases in winter and spring	- Significant decrease over time -Annual variation	-Increase in winter and spring	-Small increases during winter	-Significant increases in fall, spring and summer -Greatest increases in fall and spring

Table 1 Summary of results based on the RCP 4.5 and RCP 8.5 modelling scenarios

Temperature

Projected increases in temperature have possible consequences for The City of Frederick's drinking water supply. In winter months, increased surface air temperatures will cause a shift in precipitation from snow events to rain events. Average surface air temperatures will most strongly manifest themselves, however, in summer months through more intense heat, humidity and the presence of more frequent heat waves. The number of days with temperatures above 90°F is anticipated to double by 2100 under the business-as-usual emissions scenario and triple under the high emissions scenario, where nearly all summer days would exceed 90°F in an average summer (Boesch 2008). Currently, heat waves tend to be of limited duration, however, longer lasting heat waves are likely under high emissions scenarios (Boesch 2008).[6]

Changes in average surface air temperatures as a result of climate change have the potential to affect The City of Frederick's drinking water supply by 1) increasing evaporation rates leading to less water availability, 2) increased algal blooms from toxins and disinfection byproducts, 3) increased raw and finished water temperatures that would involve treatment changes and 4) increased water demand for irrigation (Maryland Department of the Environment, 2012).

Precipitation and Snow Water Equivalence

While increases in precipitation alone may not seem large based on the CMIP5 models, these changes must be combined with other factors, such as increased water demands as well as changes in temperature, soil moisture and runoff. Similarly, it is important to note that the average daily increases in precipitation expressed by the models do not show the distribution or timing in rain events. Based on the CMIP5 models for snow water equivalence, there will likely be a significant drop in snow water equivalent during winter months from the latter part of the 20th century to the end of the 21st century for both emission scenarios, implying that there will be an increase in winter rainfall events. In the likely case of more intense sporadic, increased rainfall events that are predicted for the state of Maryland

[6] From Boesch 2008: "The predictions for increasing heat waves and temperature extremes are likely, with moderate confidence.

(Boesch, 2008), consequences may include increased runoff volume, erosion, changes in peak flows, flooding, less water storage due to sedimentation, or changes in the Fishing Creek Reservoir habitat (Furniss et al. 2010). Dry periods in between those rain events would affect groundwater recharge and reservoir water supply, especially during high demand summer season (Boersch 2008, Furniss et al. 2010).

Despite the fact that 70 percent of the Fishing Creek Watershed is protected by at least 60 meters of riparian buffer, 90 percent of the watershed's banks show mild erosion and 20 percent of the watershed area is considered poorly protected from storm water events (Versar, Inc. 2013). The volume and rate of intense rain events could erode the banks of Fishing Creek and deposit sediment into the stream and reservoir, reducing the water quality (Versar, Inc. 2013). This is a threat to fish, whose gills can become clogged from the influx of sediment (Versar, Inc. 2013). The possible effects of changes in the timing and volume of flows and turbidity on infrastructure such as the Fishing Creek Dam and Lester Dingle WTP should also be considered. The Lester Dingle wastewater treatment plant, for example, can process 1.7 million gallons of water per day (Boesch 2008). If, however, turbidity levels reach 2.0 NTU or if flows are too low, the water cannot be used or processed by the water treatment plant (Water Supply Program Water Management Administration). These limitations must be taken into account with the predicted changes in hydrology to determine their implications for the Fishing Creek Watershed specifically, and the Frederick City Watershed more generally.

Runoff and Soil Moisture

It is imperative that increased runoff be taken into consideration in order to protect the water quality of the Frederick City Watershed, especially during the winter and spring months where the CMIP5 models have predicted significant increases. Maintaining the forest's health will also be important if the area surrounding the Frederick City Watershed continues to be developed, as this will increase the number of impervious surfaces, further exacerbating the issues of storm water runoff. Taking action to protect the forest area from habitat loss due to increased road expansion, trails, and housing development will improve forest health and contribute to the absorption of runoff, mitigating the negative impacts of impervious surfaces.

Another variable connected to runoff is soil moisture. Plant production potential, rainfall runoff volume, soil conservation and watershed management are just a few of the relevant factors affected by the availability of soil moisture (USGS, 2013). Plant species are directly affected by the soil's ability to absorb and store water; the less it absorbs, the higher amount of runoff will be produced. As discussed previously, forest health and the reduction of surface runoff are important factors to be considered in the management of the Frederick City Watershed, both of which are linked to soil moisture.

Evapotranspiration, Vegetation Potential and Wind

As climate change progresses in the region in the coming decades, the area's ecosystems are likely to experience a change in species composition while undergoing increased drought stress and pest outbreaks. These changes could reduce the water quality provided by the watershed (Pannill & Eriksson,

2005) (Boesch, 2008). The CMIP5 climate models predict increases in evapotranspiration from plants during the spring, summer and fall seasons, resulting in increased drought stress on canopy tree species during summer. The increased rainfall during the winter will offer little benefit to vegetation due to winter dormancy. With the forest under cyclical periods of drought stress during the summer, the trees will be more susceptible to outbreaks of pests and disease (Boesch, 2008).

Historically, the city's forest ecosystem has suffered catastrophic losses of canopy species due to gypsy moth infestation (*Lymantria dispar*), an exotic invasive species (Pannill & Eriksson, 2005). The changing climate is expected to increase the frequency and severity of gypsy moth outbreaks (Simberloff, 2000). Eastern hemlocks in the watershed may also be under increased pressure from Hemlock woolly adelgid (*Adelges tsugae*), a pest that is currently limited in the region by cold winter temperatures (Boesch, 2008). A smaller number of frost days could support the infiltration of other forest pest species as well (Boesch, 2008). The creation of open, sunny areas within the watershed through tree death and logging is cited as the primary mechanism for the spread of invasive plant species in the forest (Miller, 2014).

Wildfires too have been a historic cause of widespread stand mortality within the watershed (Pannill & Eriksson, 2005). The Maryland Commission on Climate Change predicts that these too will increase with climate change (Boesch, 2008). Although the model suggests that average monthly wind speed will remain constant, this is contradicted by the Maryland Commission report, which posits an increase in the number of severe wind storms, ice storms, as well as heavy precipitation events (Boesch, 2008).

Stress from heat waves, seasonal drought, wind storms, ice storms and wildfires will weaken the ability of trees to fight diseases and pests, and will likely cause mortality within the forest, creating gaps of open sunny areas (Boesch 2008). In the short term, following stand mortality under a climate with more heavy precipitation events, water quality within the watershed would decline. Less water would be infiltrated and filtered by the soil through living root systems, resulting in more water running off with greater turbidity due to erosion. There would also be greater pulses of water during flood events, rather than evenly spread out over a season. Longer periods of dry streams would result in a decline in numbers of brown trout, brook trout and other fish (Boesch, 2008). In all, the forest's ability to regulate the water cycle would be hampered (Boesch, 2008).

The occurrence of wildfire and gypsy moth outbreaks in the past have resulted in the current stand composition of the watershed, one dominated in many areas by red maple, black gum and black birch (Pannill & Eriksson, 2005). According to the Maryland Commission, the maple-beech-birch forests of western Maryland are likely to be replaced by oak-hickory type forests with a more dominant pine component, currently typical of areas in eastern Virginia and North Carolina (Boesch, 2008). Other species ranges might shift northwards (or merely upwards in elevation within the watershed) to be replaced by more southerly species (Boesch, 2008). Species with limited dispersal ability and highly specific habitat requirements (such as rare wetland plant species found within the watershed) are likely to go locally extinct (Boesch, 2008). Rare orchid species found within the watershed have already experienced precipitous declines in numbers (Knapp & Wiegand, 2014) and therefore may be unable to mount an effective response to climate change. Given the fragmented nature of natural ecosystems within the region due to urban, suburban and agricultural development, the possible movement of species in response to climate change will likely be hampered (Boesch, 2008). This makes the watershed all the more important as a refuge for intact ecosystems with topographical variability and physical continuity to other preserved areas in the region. The effects of climate change on the dynamics and interactions within and among complex ecosystems are uncertain and difficult to quantify, but is likely to reduce overall biodiversity on a human timescale (Thomas et al, 2004).

Management Recommendations

The following management suggestions are important to address the issues described in this report:

1. Create a Frederick Municipal Forest Water Balance Model

   A water balancing model could capture the total impact of changing water availability and changing future demand. This tool could better predict whether Fishing Creek Reservoir has the capacity to meet future population water demands while also maintaining its ecosystem functions (Yin & Yang, 2011).

2. Incorporate regional water management and storage strategies

   With the likelihood of increased heavy, infrequent rain events over the course of the century, as well as reduced water availability from higher demand, it is important to determine whether current reservoirs have the capacity to store added precipitation. This is especially important for dry summer months when demand is high. Using a water balance model from management suggestion 1 could, for example, determine if Fishing Creek Reservoir has the capacity to hold water from heavy rain events over to periods of dry spells. If Fishing Creek or other watersheds in Frederick County do not have this capability, it would be of interest to invest in water storage infrastructure or technologies.

3. Storm Water Management

   Given the expected increase in heavy rain events, runoff and the watershed's vulnerability to erosion, management techniques to reduce erosion and turbidity should be implemented. Strategies to address flows and their impacts on the Lester Dingle Water Treatment Plant should require attention as well.

4. Monitoring of water quality

   Because of likely increases in runoff in the form of sediment and nutrient loads combined with increased temperatures, water should be monitored to anticipate water quality issues and mitigate these issues early on. Improved and continuous monitoring of all reservoirs that create Frederick's drinking water supply will be necessary to detect any impairments to source water quality, inform operational decisions and plan for any modifications to system facilities. Lastly, because temperature changes may lead to *changes in the treatment processes necessary to supply adequate drinking water, Frederick should be ready to increase and improve treatment capability if necessary.*

5. Prepare and monitor for increased pest outbreaks

   The changing climate of the Frederick Municipal Watershed forest is expected to increase the incidence of drought and heat stress, pest outbreaks and wildfires, which could result in the infiltration of invasive plant species as well as the eventual naturalization of native plant species whose ranges are currently further south (Pannill & Eriksson, 2005) (Boesch, 2008). It is therefore important that managers anticipate these changes, adapt strategies to deal with them and hopefully maintain the range of services that this ecosystem provides to both humans and wildlife. It would also be important for water managers who are responsible for planning and adjudicating the distribution of water resources to have a thorough understanding of the evapotranspiration process and knowledge about the spatial and temporal rates of evapotranspiration.

The drinking water supply system of The City of Frederick will be better prepared for the anticipated changes in surface air temperature, soil moisture, runoff, precipitation, snow-water equivalent and evapotranspiration if the City commits to an ongoing process of assessing its vulnerabilities and developing and implementing appropriate measures to lessen expected impacts. The suggested management measures are those that will strengthen the system's resilience and ensure that Frederick will be continually able to provide adequate supplies under both current and potential future climate change conditions.

Bibliography

Boesch, D. F. (2008). *Global Warming and the Free State: Comprehensive Assessment of Climate Change Impacts in Maryland. .* Cambridge, Maryland: Report of the Scientific and Technical Working Group of the Maryland Commisssion on Climate Change. Univresity of Maryland Center for Environmental Science.

Bot, A., & Benites, J. (2004). Drought-resistant soils: Optimization of soil moisture for sustainable plant production. Rome: Food And Agriculture Organization of the United Nations.

Downscaled CMIP3 and CMIP5 Climate and Hyrdology Projections. (2014, July 25). Retrieved from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

Hanson, R. (1991). Evapotranspiration and Droughts. *U.S. Geological Survey Water-Supply*, 99-104. Retrieved from http://geochange.er.usgs.gov/sw/changes/natural/et/)

Knapp, W. M., & Wiegand, R. (2014). Orchid (Orchidaceae) decline in the Catoctin Mountains, Frederick County, Maryland as documented by a long-term dataset. *Biodiversity and Conservation, 23*(8), 1965-1976.

Maryland Department of the Environment. (2012). *Climate Chage Adaptation for Maryland Water Utilities.* Retrieved from http://www.mde.state.md.us/programs/Water/Water_Supply/Documents/120516_CCbrochure_Web.pdf.

Meinshausen, M., Smith, S., Calvin, K., Daniel, J., Kainuma, M., & et al. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*(109), 213-241.

Miller, A. (2014, September 19). Maryland Department of Natural Resources. (K. Farge, Interviewer)

Pannill, P., & Eriksson, P. (2005). *Forest Stewardship Plan for Frederick City Watershed.* City of Frederick.

Simberloff, D. (2000). Global climate change and introduced species in United States forests. *The Science of the Total Environment*(262), 253-261.

The Frederick County Division of Planning. (2010). *Water Resources Element, Frederick County, Maryland. A Functional Element of the 2010 County Comprehensive Plan.*

Thomas, C., Cameron, A., Green, R., Bakkenes, M., Beaumont, L., & Collingham, Y. (2004, October 13). Extinction Risk form Climate Change. *Nature*(427), 145-148.

USGS. (2013, January 10). *A Method of Determining Soil Water Content from Remotely Sensed Data*. Retrieved from USGS Center of Excellence for Geospatial Information Science (CEGIS): http://cegis.usgs.gov/soil_moisture/

USGS. (2014, March 17). *Why Is This House Wearing Stilts?* . Retrieved from Impervious Surfaces and Urban Flooding: USGS Water-Science School: http://water.usgs.gov/edu/impervious.html

Versar, Inc. (2013). *Frederick County Stream Survey 2008-2011 Four-year Report.* Community Development Division.

Water Supply Program Water Management Administration . (n.d.). *Source Water Assessments for City of Frederick.* Frederick: Maryland Department of the Environment.

Yin, & Yang. (2011). Development of a coupled reservoir operation and water diversion model: Balancing human and environmental requirements. *Ecological Modeling, 222(2)*, 223-231.

Appendix A: Additional Climate Variable Graphs

Maximum Surface Air Temperature

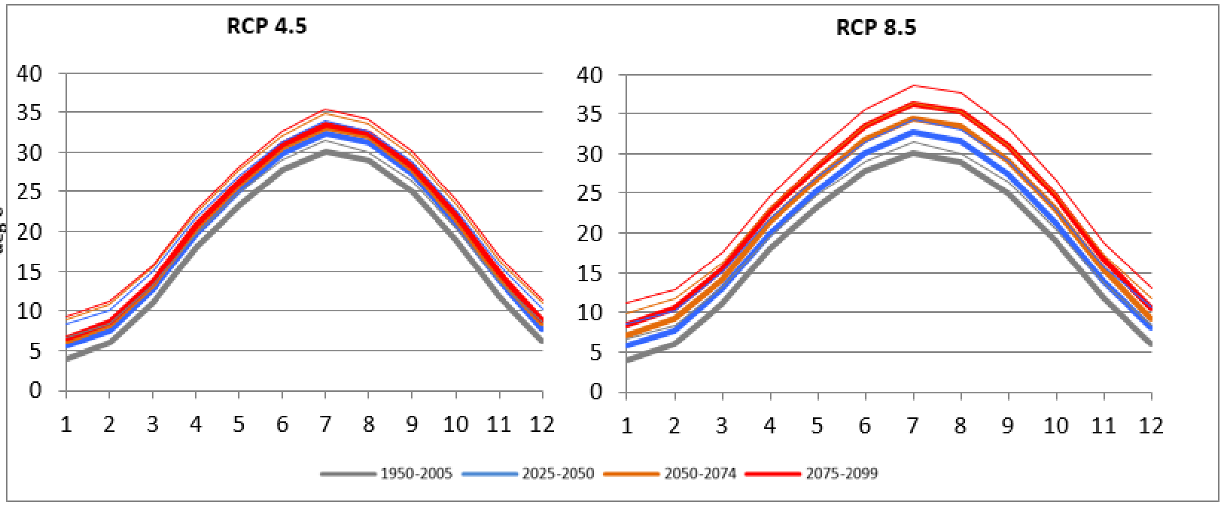

Figure 7: Monthly average of maximum surface temperature for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

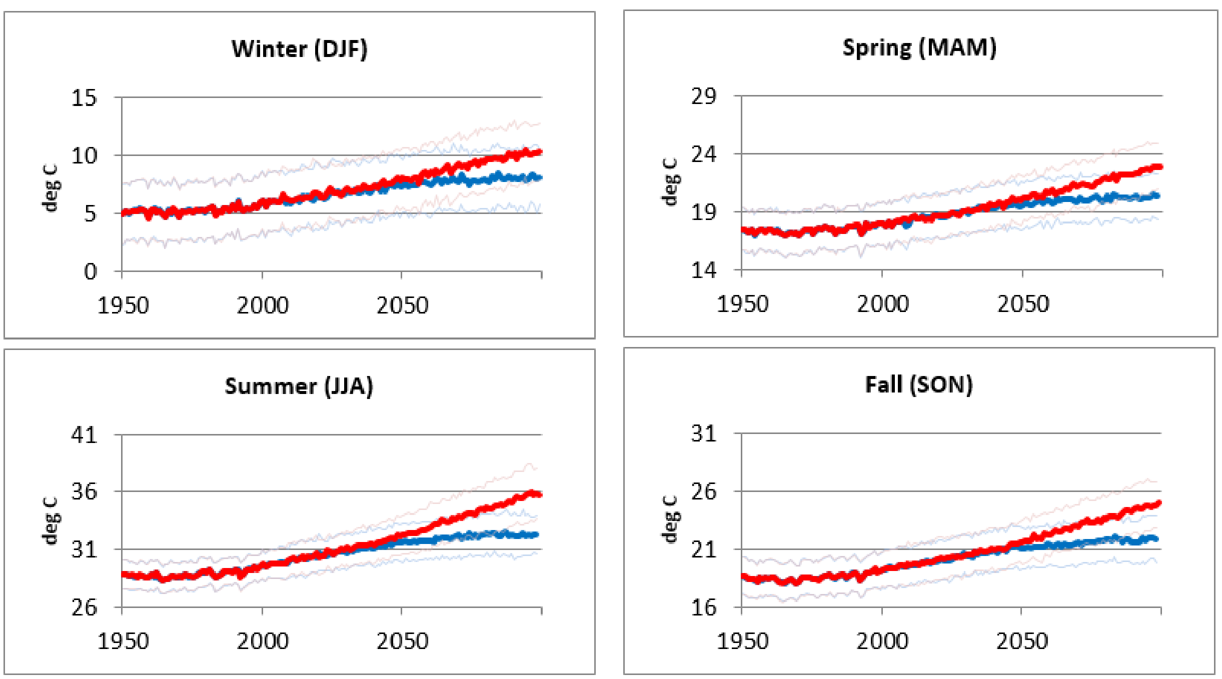

Figure 7.2: Seasonal average time series of maximum surface temperature for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

Minimum Surface Air Temperature

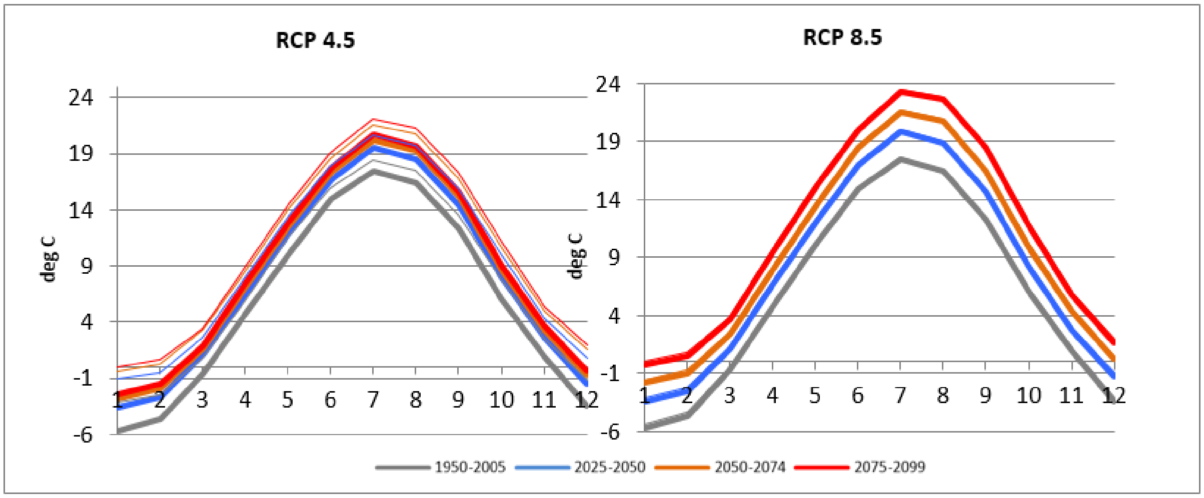

Figure 8: Monthly average of minimum surface temperature for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

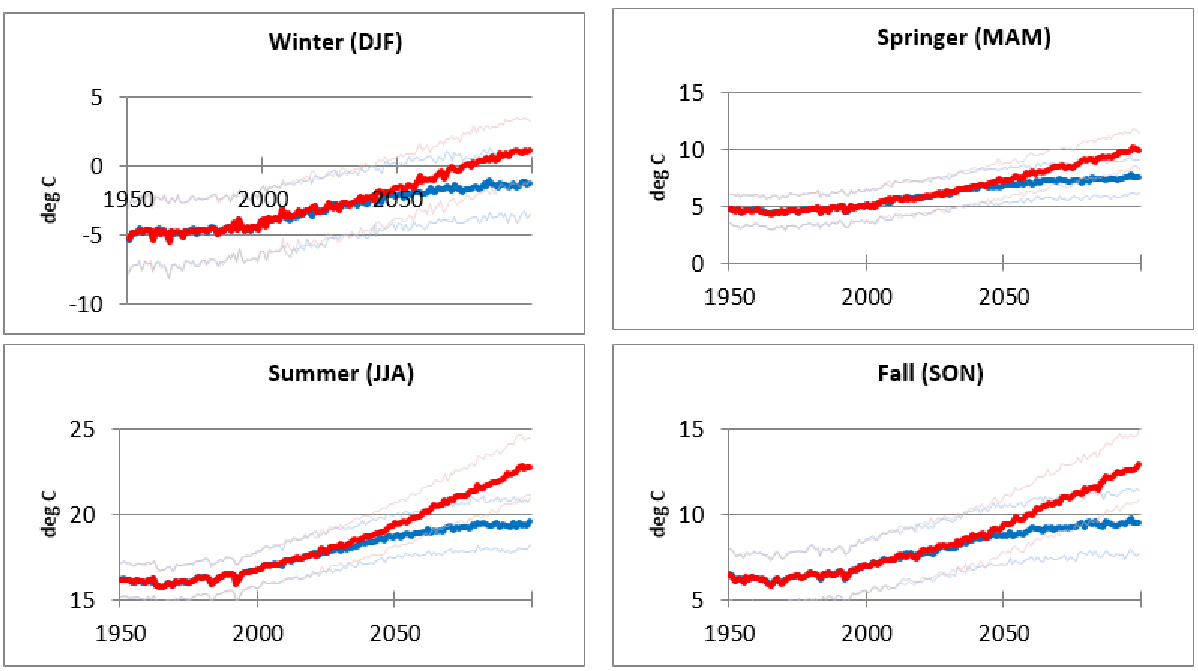

Figure 8.2: Seasonal average time series of minimum surface temperature for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

Seasonal Average Precipitation & Snow Water Equivalence

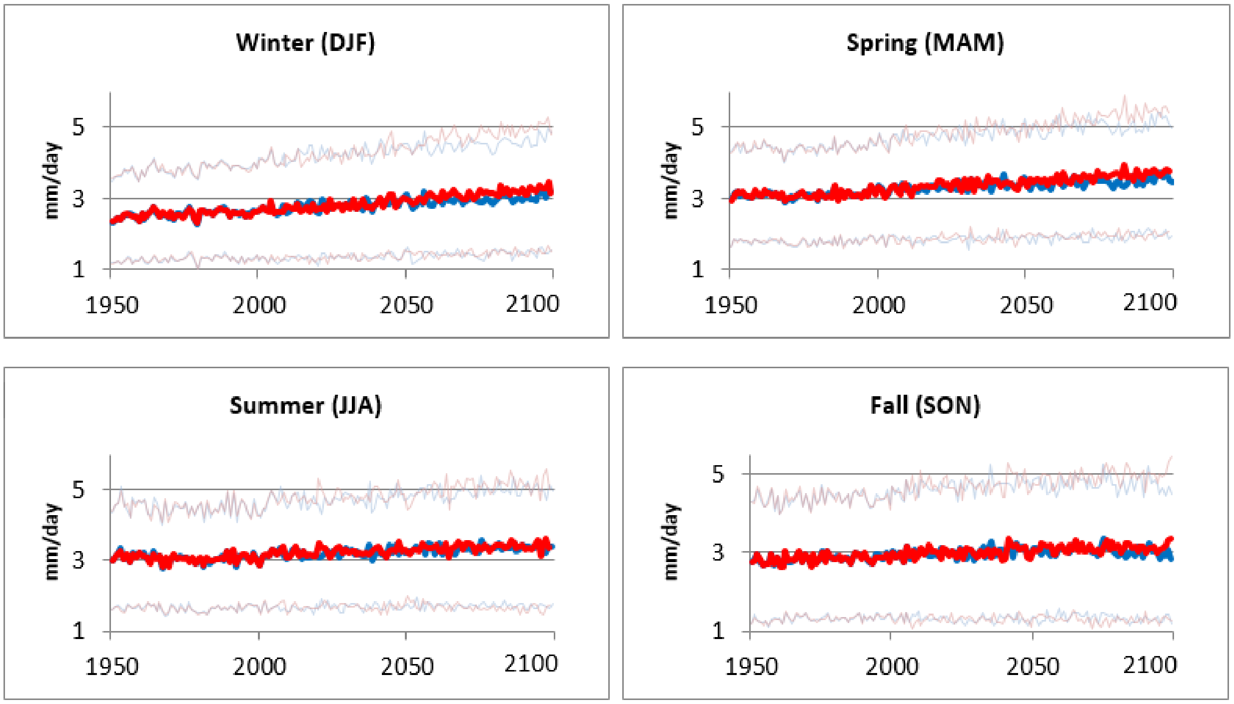

Figure 9: Seasonal average time series of precipitation for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 70 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

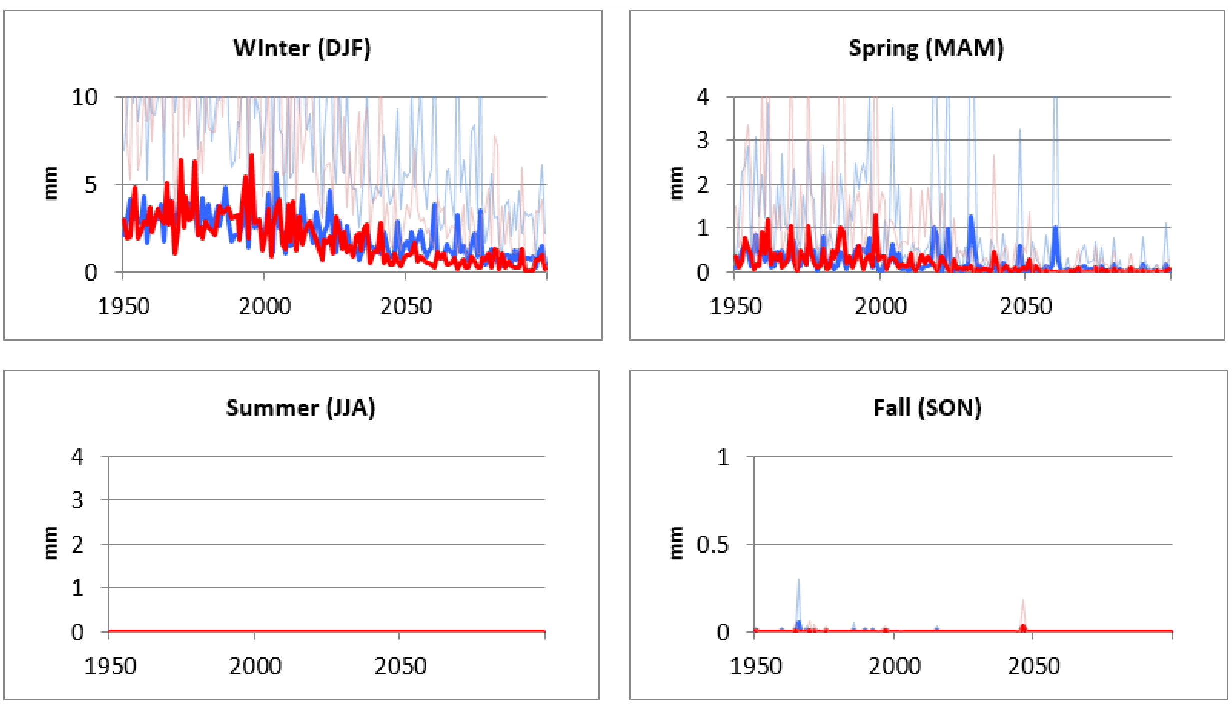

Figure 10: Seasonal average time series of snow water equivalent* for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines. *Snow water equivalent in snow pack, state 1st day of month (mm).

Seasonal Average Surface Runoff

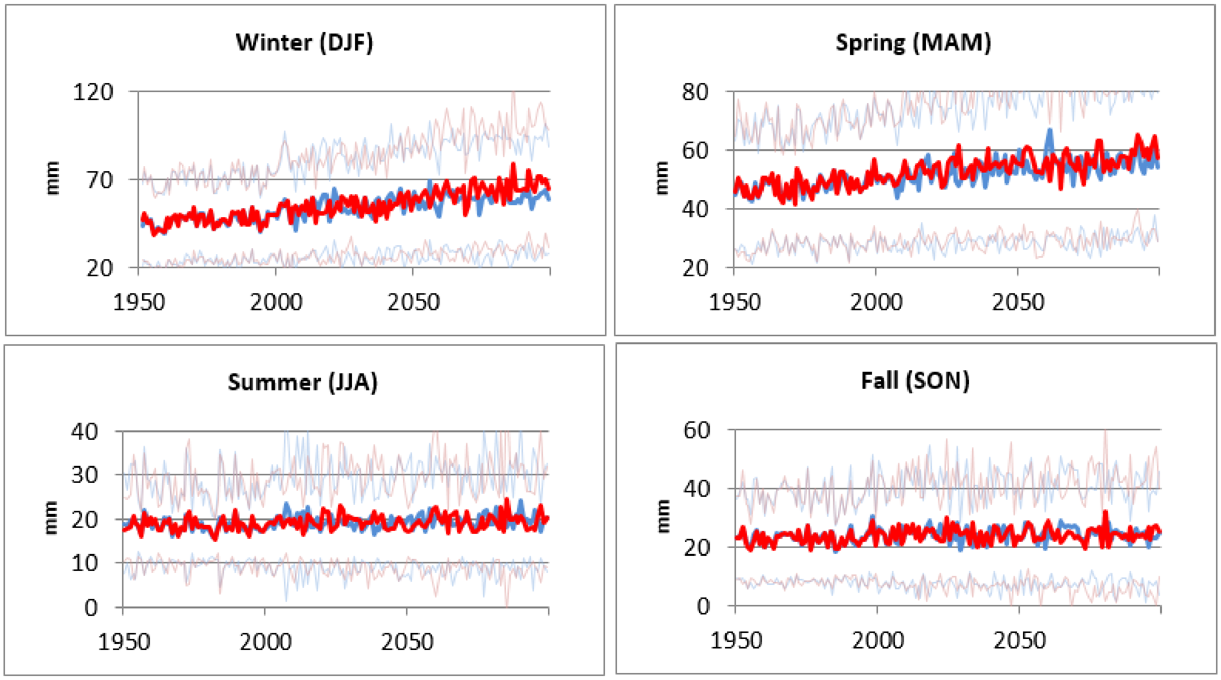

Figure 11: Seasonal average time series of surface runoff and baseflow for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

Soil Moisture Content

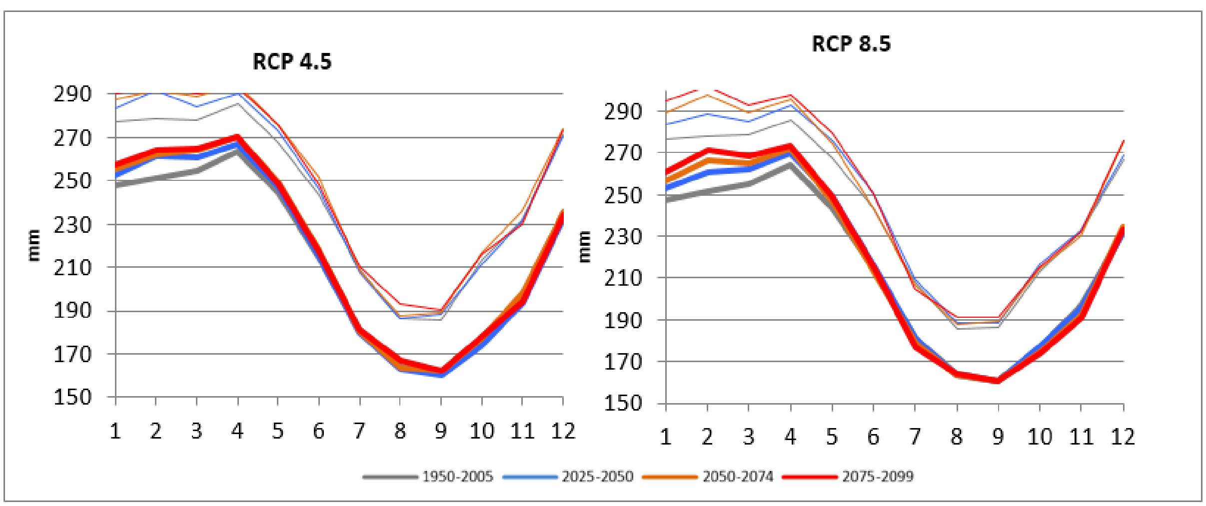

Figure 12: Monthly average of soil moisture content (*) for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines. (*) Soil moisture content, state 1st day of month (mm).

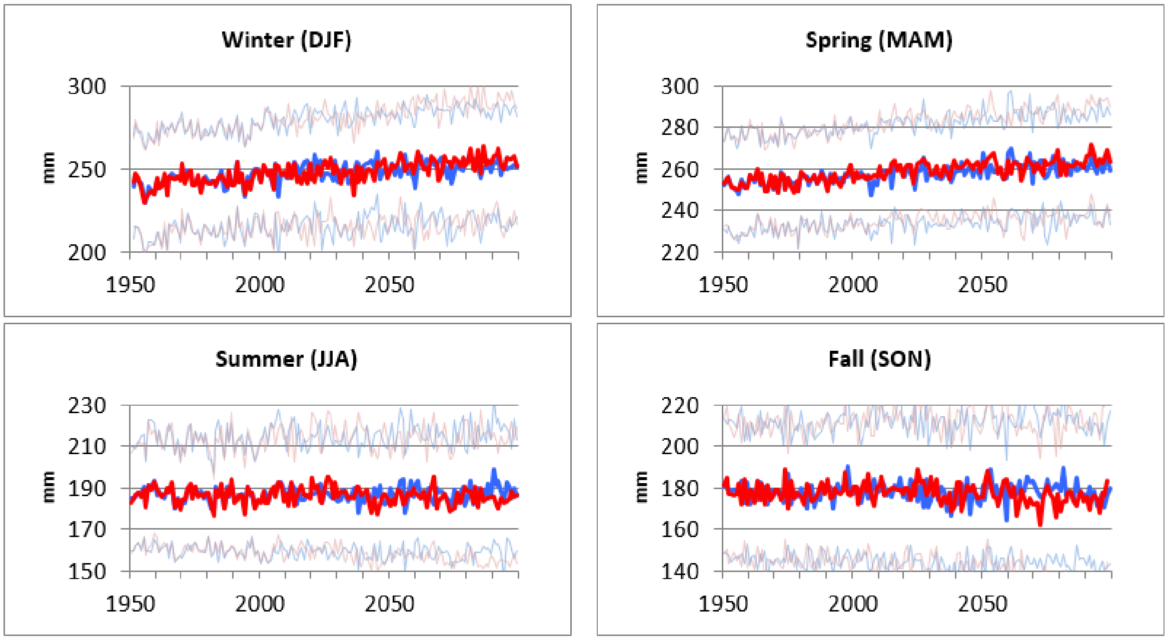

Figure 12.2: Seasonal average time series of soil moisture content (*) for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines. (*) Soil moisture content, state 1st day of month (mm).

Evapotranspiration

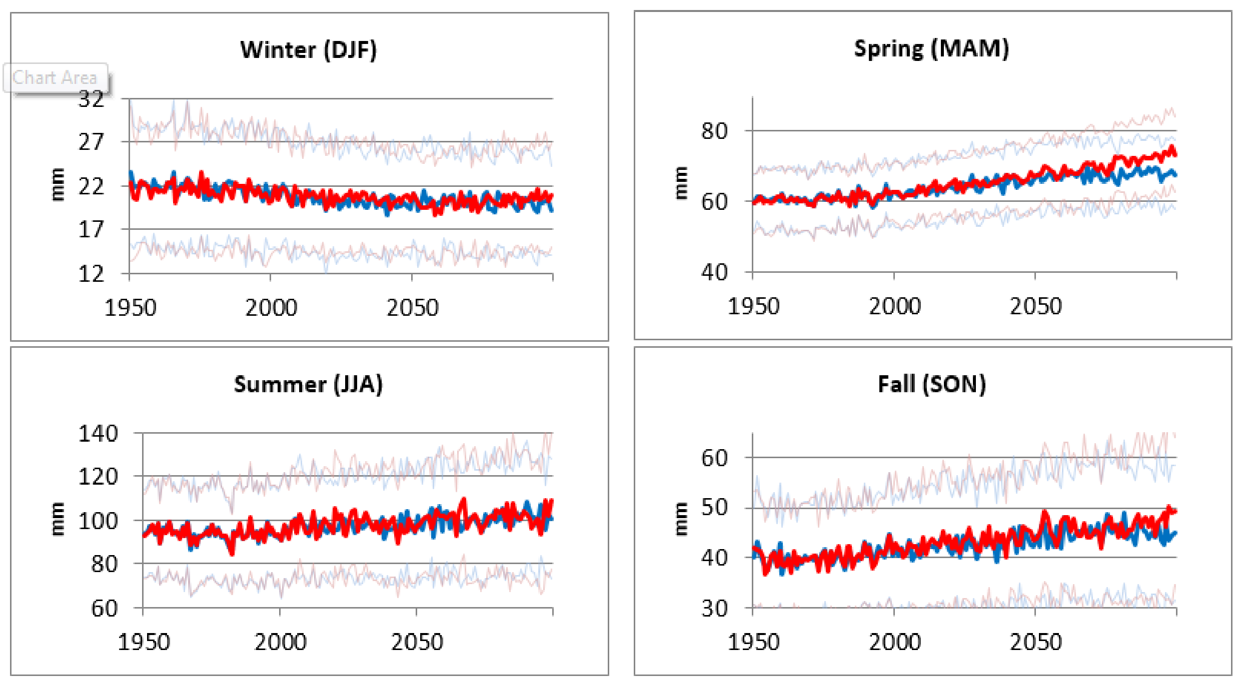

Figure 13: Seasonal average time series of actual evapotranspiration for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

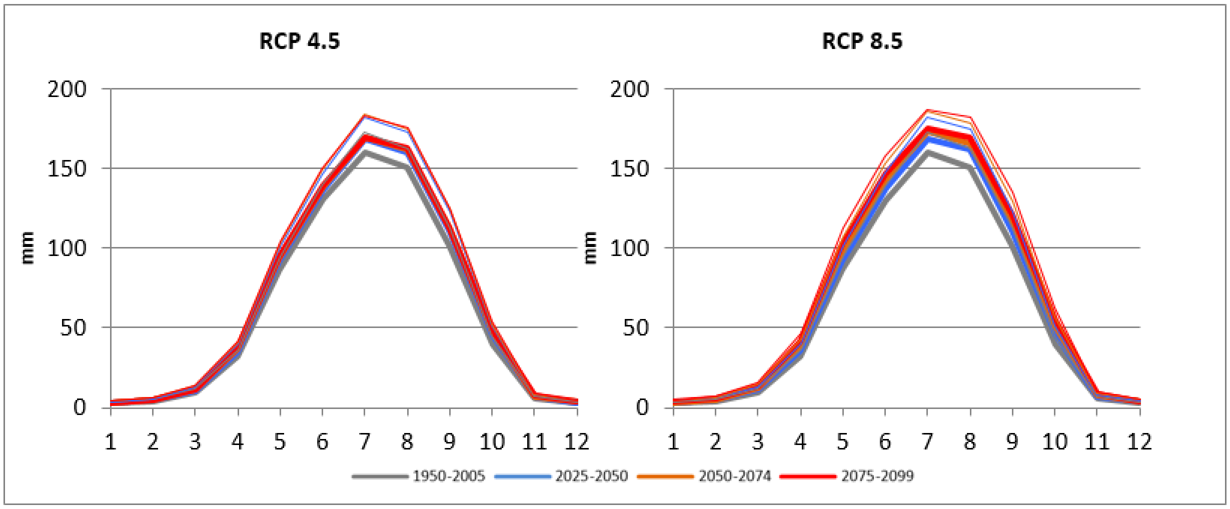

Figure 14: Monthly average of natural vegetation potential evapotranspiration for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

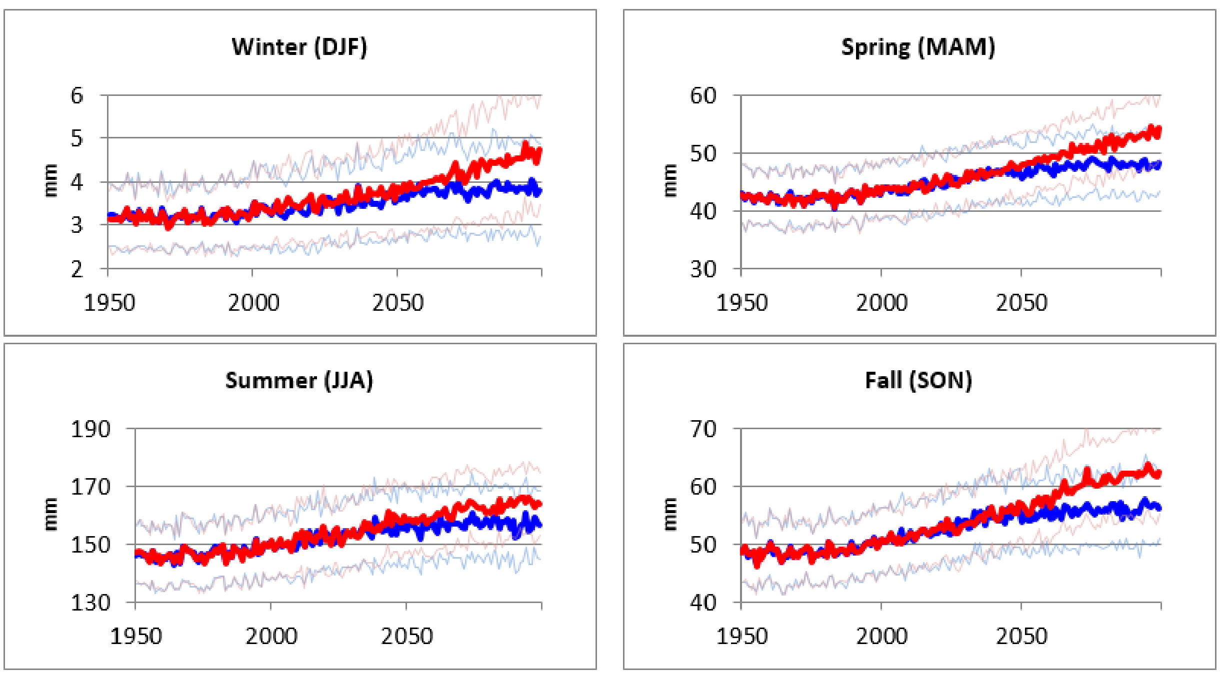

Figure 14.2: Seasonal average time series of natural vegetation potential evapotranspiration for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

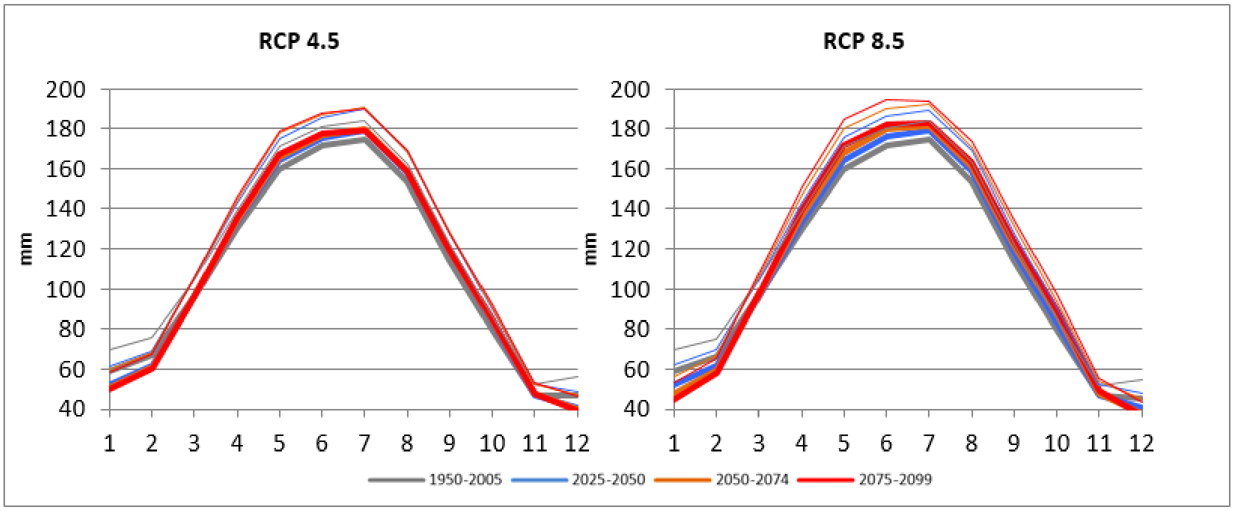

Figure 15: Monthly average of open water surface potential evapotranspiration for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines.

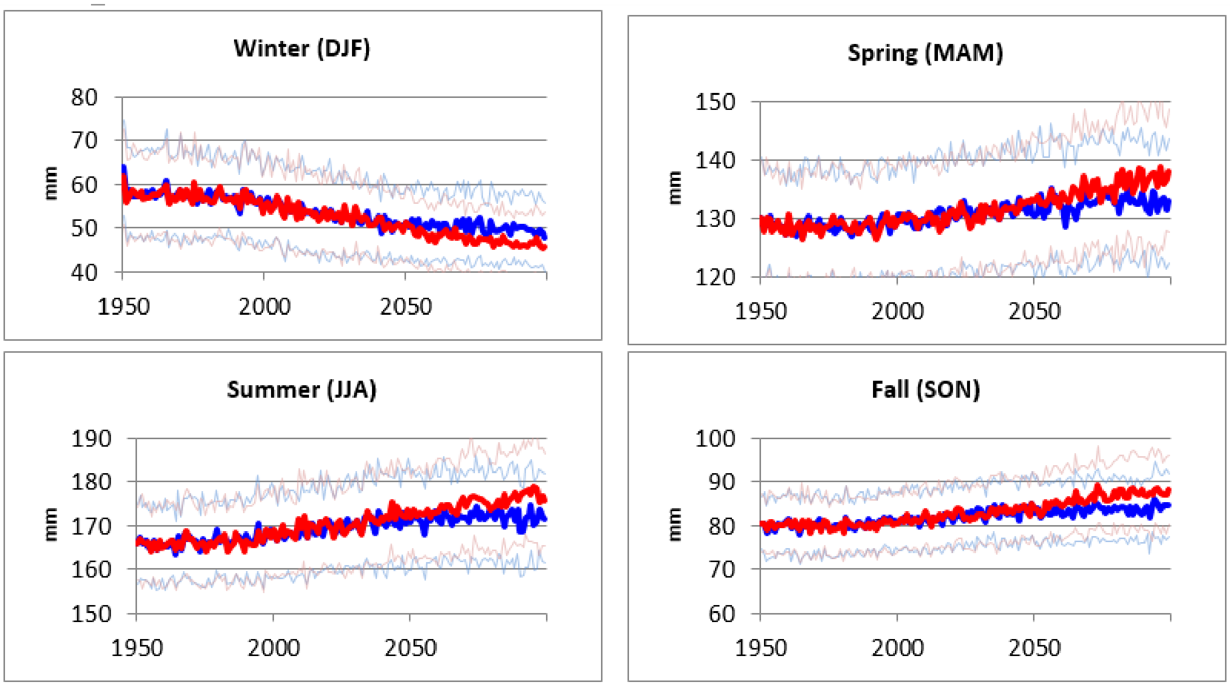

Figure 15.2: Seasonal average time series of open water surface potential evapotranspiration for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines.

Wind Speed

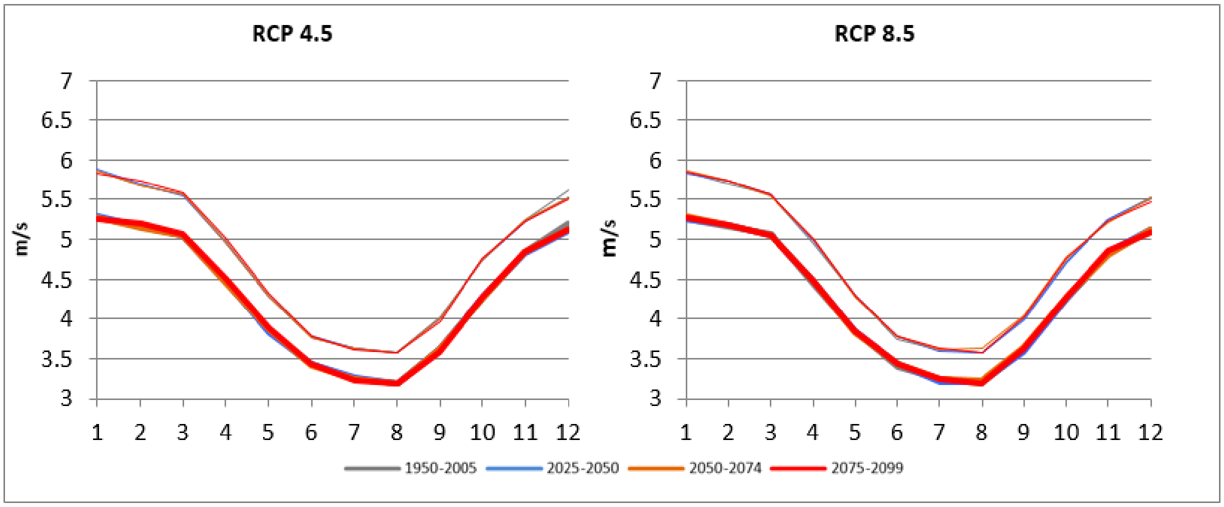

Figure 16: Monthly average of wind speed (*) for four periods for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the bold lines and the upper boundaries of the standard deviations are indicated by the thin lines. (*) Mean monthly wind speed (m/s).

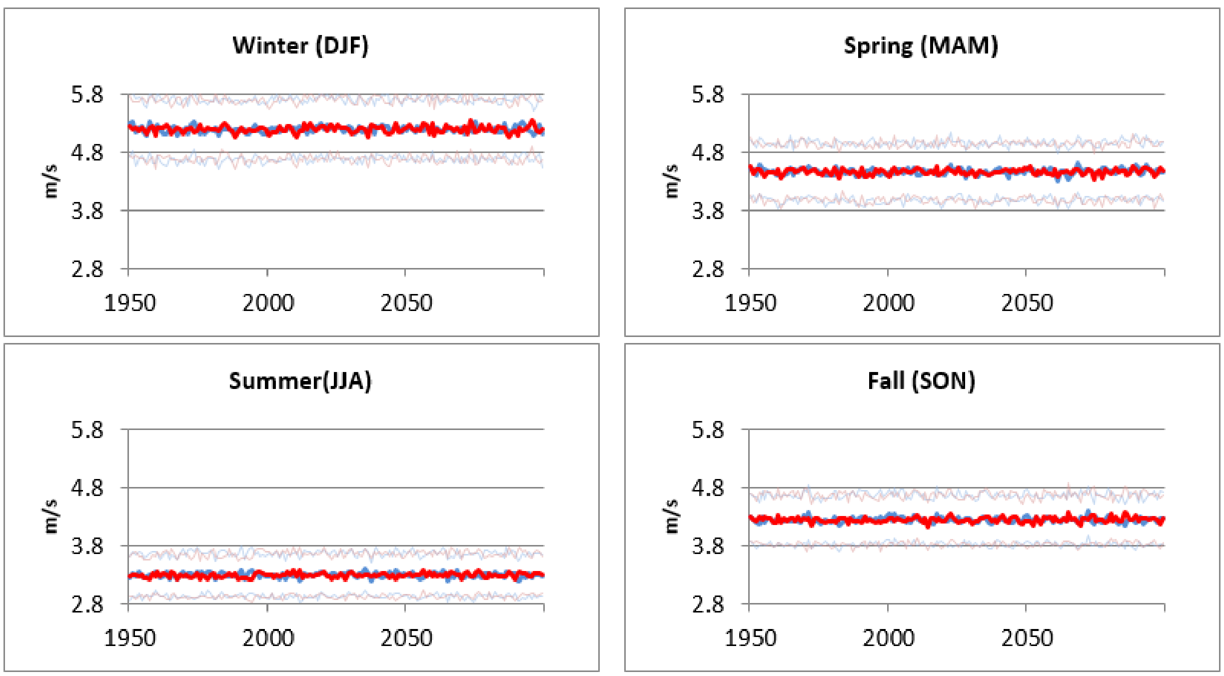

Figure 16.2: Seasonal average time series of wind speed (*) for RCP 4.5 (blue) and RCP8.5 (red) scenarios. The average of 31 CMIP5 models is indicated by the main lines and their standard deviations are indicated by the thinner upper and lower lines. (*) Mean monthly wind speed (m/s).

Appendix B: Detailed Summary of Climate Change Modeling Results

[a] TAS - Average surface air temperature (degree Celsius).

[b] TASMIN - Minimum surface air temperature (degree Celsius).

[c] TASMAX - Maximum surface air temperature (degree Celsius).

[d] SWE - Snow water equivalent in snow pack, state first day of month (mm).

[e] SMC - Soil moisture content, state first day of month (mm).

[f] RUNOFF - Stream flow, surface runoff and base flow (mm).

[g] PRCP – Average precipitation rate (mm/day).

[h] PETWATER - Open water surface potential evapotranspiration (mm).

[I] PETNATVEG – Natural vegetation potential evapotranspiration (mm).

[j] ET – Actual evapotranspiration (mm).

[k] WIND – Mean monthly wind speed (m/s).

[l] Baseline – 1950/2005 mean value.

[m] Period: 2025-2049 mean values. Variation from the baseline (Δ).

[n] Period: 2050-2074 mean values. Variation from the baseline (Δ).

[o] Period: 2075-2099 mean values. Variation from the baseline (Δ).

[p] All numbers in parenthesis represent the standard deviation.

		Winter				Spring				Summer				Fall			
		Baseline[l]	25-49(Δ)[m]	50-74(Δ)[n]	75-99(Δ)[o]	Baseline[l]	25-49(Δ)[m]	50-74(Δ)[n]	75-99(Δ)[o]	Baseline[l]	25-49(Δ)[m]	50-74(Δ)[n]	75-99(Δ)[o]	Baseline[l]	25-49(Δ)[m]	50-74(Δ)[n]	75-99(Δ)[o]
TAS[a] deg C	**RCP4.5**	0.36 (2.38)[p]	1.81 (2.35)	2.48 (2.40)	2.34 (2.36)	11.09 (1.49)	1.77 (1.60)	2.41 (1.64)	2.72 (1.65)	22.60 (0.97)	2.04 (1.19)	2.77 (1.32)	3.15 (1.43)	12.53 (1.37)	3.79 (1.55)	4.44 (1.61)	4.86 (1.69)
	RCP8.5	0.36 (2.36)	2.03 (2.39)	3.40 (2.34)	4.28 (2.32)	11.09 (1.49)	1.93 (1.65)	3.29 (1.67)	4.71 (1.75)	22.60 (0.97)	2.37 (1.21)	4.02 (1.43)	5.80 (1.74)	12.53 (1.37)	4.01 (1.56)	5.66 (1.68)	7.43 (1.85)
TASMIN[b] deg C	**RCP4.5**	-4.63 (2.35)	2.04 (2.29)	2.77 (2.34)	2.78 (2.30)	4.71 (1.34)	1.73 (1.47)	2.36 (1.52)	2.68 (1.53)	16.26 (0.99)	1.97 (1.19)	2.71 (1.30)	3.10 (1.45)	6.44 (1.45)	3.55 (1.65)	4.25 (1.72)	4.64 (1.80)
	RCP8.5	-4.61 (2.34)	2.22 (2.33)	3.72 (2.29)	4.87 (2.33)	4.71 (1.34)	1.89 (1.50)	3.21 (1.57)	4.63 (1.63)	16.26 (0.99)	2.30 (1.20)	3.96 (1.39)	5.71 (1.69)	6.44 (1.45)	3.78 (1.63)	5.43 (1.79)	7.29 (1.97)
TASMAX[c] deg C	**RCP4.5**	5.35 (2.50)	1.64 (2.53)	2.31 (2.60)	2.08 (2.58)	17.47 (1.81)	1.77 (1.92)	2.43 (1.97)	2.74 (1.94)	28.94 (1.20)	2.19 (1.50)	2.94 (1.66)	3.34 (1.77)	18.61 (1.55)	4.04 (1.74)	4.65 (1.77)	5.10 (1.86)
	RCP8.5	5.32 (2.49)	1.89 (2.54)	3.19 (2.59)	3.95 (2.56)	17.48 (1.81)	1.93 (1.95)	3.29 (1.97)	4.71 (2.11)	28.94 (1.21)	2.48 (1.55)	4.22 (1.85)	6.12 (2.26)	18.61 (1.55)	4.23 (1.74)	5.86 (1.86)	7.56 (2.06)
SWE[d] mm	**RCP4.5**	3.15 (10.38)	-1.66 (5.75)	-1.64 (6.17)	-2.44 (3.50)	0.34 (1.49)	-0.18 (0.89)	-0.24 (0.56)	-0.30 (0.17)	0	0	0	0	0.00 (0.01)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
	RCP85	3.10 (7.11)	-1.71 (4.01)	-2.43 (2.15)	-2.62 (1.99)	0.37 (1.36)	-0.29 (0.35)	-0.34 (0.14)	-0.36 (0.09)	0	0	0	0	0.00 (0.00)	0.00 (0.01)	0.00 (0.00)	0.00 (0.00)
SMC[e] mm	**RCP4.5**	244.91 (30.76)	3.84 (33.28)	5.80 (33.66)	8.97 (33.99)	254.27 (23.01)	3.85 (24.43)	6.84 (25.09)	6.78 (25.32)	186.28 (26.38)	-0.60 (27.51)	0.81 (28.53)	1.76 (29.22)	177.97 (32.31)	-7.18 (34.42)	-4.26 (34.86)	-4.51 (34.17)
	RCP8.5	243.54 (30.35)	4.71 (32.28)	8.82 (35.15)	13.52 (35.87)	254.27 (22.96)	6.27 (24.01)	7.01 (25.11)	9.28 (26.47)	186.18 (25.90)	0.53 (29.39)	-1.03 (27.60)	-0.99 (30.31)	178.15 (32.34)	-5.36 (34.88)	-6.86 (35.28)	-7.69 (37.89)
RUNOFF[f] mm	**RCP4.5**	47.93 (24.26)	7.42 (29.16)	10.37 (31.09)	13.50 (32.30)	47.84 (20.68)	4.40 (23.84)	7.22 (26.71)	7.70 (25.68)	18.45 (9.02)	0.41 (10.12)	1.07 (10.88)	1.48 (11.48)	23.01 (15.06)	-1.43 (16.89)	-0.29 (17.45)	-1.07 (16.81)
	RCP8.5	47.87 (24.20)	6.97 (28.88)	13.61 (33.54)	20.15 (34.52)	48.08 (20.79)	6.72 (25.41)	7.11 (26.30)	9.85 (27.22)	18.55 (9.21)	0.88 (11.21)	0.76 (10.55)	1.06 (11.45)	22.89 (14.76)	-0.56 (17.34)	-1.16 (17.37)	-0.46 (19.65)
PRCP[g] mm/day	**RCP4.5**	2.58 (1.30)	0.26 (1.48)	0.35 (1.54)	0.39 (1.57)	3.11 (1.33)	0.28 (1.52)	0.34 (1.57)	0.39 (1.56)	3.07 (1.42)	0.19 (1.55)	0.23 (1.58)	0.30 (1.65)	2.86 (1.53)	0.15 (1.73)	0.19 (1.69)	0.15 (1.71)
	RCP8.5	2.56 (1.29)	0.28 (1.48)	0.47 (1.61)	0.69 (1.73)	3.10 (1.33)	0.30 (1.53)	0.42 (1.59)	0.58 (1.73)	3.07 (1.43)	0.19 (1.59)	0.28 (1.64)	0.33 (1.78)	2.85 (1.54)	0.15 (1.72)	0.20 (1.78)	0.26 (1.87)
PETWATER[h] mm	**RCP4.5**	57.36 (9.81)	-5.77 (8.30)	-6.88 (8.16)	-7.77 (7.78)	128.76 (9.45)	2.45 (9.78)	3.29 (10.46)	4.27 (10.23)	166.55 (9.14)	4.20 (10.35)	5.24 (10.24)	5.33 (10.41)	80.24 (6.62)	13.20 (6.95)	13.46 (7.13)	13.91 (7.11)
	RCP8.5	56.84 (9.63)	-5.32 (8.47)	-8.46 (7.53)	-10.94 (7.41)	128.76 (9.37)	2.46 (10.10)	5.09 (10.48)	7.57 (11.40)	166.41 (9.15)	4.78 (10.13)	7.45 (10.57)	9.70 (11.13)	80.20 (6.54)	13.09 (7.19)	15.92 (7.65)	17.95 (8.27)
PETNATVEG[i] mm	**RCP4.5**	3.24 (0.77)	0.29 (0.92)	0.52 (1.00)	0.31 (1.05)	42.43 (4.77)	3.64 (5.14)	4.83 (5.37)	5.53 (5.27)	147.00 (10.71)	7.57 (12.25)	9.51 (12.31)	9.87 (12.25)	48.92 (5.41)	19.19 (6.26)	20.23 (6.28)	21.03 (6.28)
	RCP8.5	3.20 (0.75)	0.44 (0.95)	0.82 (1.13)	0.90 (1.29)	42.44 (4.73)	3.80 (5.15)	6.95 (5.31)	9.81 (5.81)	146.93 (10.78)	8.55 (11.98)	13.18 (12.07)	16.44 (11.75)	48.96 (5.43)	19.23 (6.16)	23.97 (6.60)	27.85 (7.36)
ET[j] mm	**RCP4.5**	21.80 (6.83)	-1.81 (5.99)	-1.67 (5.95)	-1.84 (5.75)	60.98 (8.70)	4.36 (9.38)	6.29 (9.77)	6.87 (9.52)	93.95 (21.95)	3.28 (24.16)	5.51 (25.09)	7.40 (25.76)	40.15 (11.26)	8.32 (12.75)	10.37 (13.27)	10.94 (13.41)
	RCP8.5	21.44 (6.94)	-0.92 (6.12)	-1.61 (5.74)	-1.11 (6.03)	60.88 (8.64)	5.00 (9.28)	7.94 (9.95)	11.28 (10.73)	93.90 (21.80)	4.19 (24.71)	6.36 (26.32)	7.89 (28.36)	40.20 (11.28)	9.54 (12.87)	11.05 (13.97)	12.61 (15.32)
WIND[k] m/s	**RCP4.5**	5.21 (0.52)	-0.01 (0.51)	-0.02 (0.51)	0.01 (0.50)	4.45 (0.50)	0.00 (0.48)	0.00 (0.48)	0.03 (0.49)	3.29 (0.36)	0.01 (0.36)	-0.01 (0.37)	0.00 (0.37)	4.24 (0.43)	-0.17 (0.42)	-0.17 (0.42)	-0.18 (0.42)
	RCP8.5	5.18 (0.50)	0.01 (0.51)	0.02 (0.51)	0.04 (0.50)	4.45 (0.48)	0.00 (0.49)	0.00 (0.49)	0.01 (0.49)	3.28 (0.36)	0.00 (0.37)	0.02 (0.37)	0.02 (0.36)	4.23 (0.42)	-0.18 (0.42)	-0.15 (0.43)	-0.15 (0.41)

Appendix C: Modeling Acknowledgements

"We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the following climate modeling groups for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals."

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2 CanCM4 CanAM4
University of Miami - RSMAS	RSMAS	CCSM4(RSMAS)*
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5) CESM1(CAM5.1,FV2) CESM1(FASTCHEM) CESM1(WACCM)
Center for Ocean-Land-Atmosphere Studies and National Centers for Environmental Prediction	COLA and NCEP	CFSv2-2011
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CESM CMCC-CM CMCC-CMS
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5 CNRM-CM5-2
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
EC-EARTH consortium	EC-EARTH	EC-EARTH
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University	LASG-CESS	FGOALS-g2
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP	FGOALS-gl FGOALS-s2
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM

NASA Global Modeling and Assimilation Office	NASA GMAO	GEOS-5
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM2.1 GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GFDL-HIRAM-C180 GFDL-HIRAM-C360
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadCM3 HadGEM2-CC HadGEM2-ES HadGEM2-A
Institute for Numerical Mathematics	INM	INM-CM4
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC4h MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR MPI-ESM-LR MPI-ESM-P
Meteorological Research Institute	MRI	MRI-AGCM3.2H MRI-AGCM3.2S MRI-CGCM3 MRI-ESM1
Nonhydrostatic Icosahedral Atmospheric Model Group	NICAM	NICAM.09
Norwegian Climate Centre	NCC	NorESM1-M NorESM1-ME