Project Number WR10R001

DEVELOPMENT OF A USER-FRIENDLY INTERFACE FOR PREDICTING CLIMATE CHANGE INDUCED CHANGES IN EVAPOTRANSPIRATION

S. P Loheide II
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

D. R. Joachim
Department of Civil and Environmental Engineering
University of Wisconsin-Madison

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Development of a User-Friendly Interface for Predicting Climate Change Induced Changes in Evapotranspiration

A final report prepared for the University of Wisconsin Water Resources Institute

S. P Loheide II
Department of Civil and Environmental Engineering
University of Wisconsin – Madison

D. R. Joachim
Department of Civil and Environmental Engineering
University of Wisconsin - Madison

Project WR10R001

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TABLE OF CONTENTS

LIST OF FIGURES

PROJECT SUMMARY

Title: Development of a User-Friendly Interface for Predicting Climate Change Induced Changes in Evapotranspiration

Project I.D.: WR10R001

Investigators:
Principal Investigator: Steve Loheide, Assistant Professor
Research Assistant: Doug Joachim, M.S.
University of Wisconsin-Madison, Dept. of Civil and Environmental Engineering

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Background/Need:

Evapotranspiration (ET) is the second largest component of Wisconsin's (WI) hydrologic budget after precipitation, yet the expected changes to this process due to climate change are not well understood. Changes to ET will impact agriculture, tourism, recreation, and ecosystems.

Objectives:

The objectives of this study were: (1) to develop and calibrate a Penman-Monteith model of ET that predicts daily ET in nine WI regions and for five broad vegetation communities for a range of soil types using downscaled global climate model (GCM) data through 2100, and (2) to package the model into a publically-accessible graphical user interface (GUI) to allow interested parties to evaluate the likely changes to ET in their specific location.

Methods:

Our modeling approach uses the dual crop coefficient approach to solving the Penman-Monteith ET equation recommended by the Food and Agriculture Organization (Allen et al. 1998; Penman 1948; Monteith 1965) combined with the Jarvis-Stewart model of stomatal conductance (Jarvis 1976; Stewart 1988) to model vegetation-specific ET on a daily timestep. The model was calibrated using eddy flux covariance data from five Ameriflux sites in WI, Minnesota, and Illinois that provide half-hour measurements of climate parameters and actual ET. Surface conductance and growing season parameters were optimized for each of five vegetation types using a Markov Chain Monte Carlo technique (Zobitz et al. *in review*) to best match modeled ET with observed ET at each location. Three GCMs that have been downscaled by the Wisconsin Initiative on Climate Change Impacts provide daily climate data to drive the model during three climate periods: 1981-2000, 2046-2065, and 2081-2100. Nine broad regions coinciding with the National Climate Data Center's climate divisions for the state WI were selected to provide spatial coverage across the state.

The final calibrated model was packaged in a Matlab-based GUI that is freely available to interested users online (http://hydroecology.cee.wisc.edu/research/WisconsinET/index.htm; Joachim & Loheide 2011). Results can be used to better understand the likely changes to future ET in specific regions. Daily ET output can also be used as ET forcing in hydrologic modeling efforts. Default parameters are the values obtained during calibration, but advanced options allow users with additional knowledge of plant phenology to adjust parameters as desired.

Results and Discussion:

Model results differ by GCM, with two relatively wet models predicting an increase in ET between 8-10% by 2100, while a dry model produces a net decrease in ET of 2-5% in southwest WI and a small increase in ET of 1-5% in northeast WI by the end of the century as conditions become increasingly water-limited. Annual ET is expected to be about 100 mm higher in southern WI than northern WI at the end of the century, with annual ET in northern WI in 2100 reaching southern ET levels seen prior to 2000, effectively shifting today's annual ET regime northward.

The impacts of changing ET are important from a water balance perspective. As ET increases, the annual depth of water available after ET is subtracted from precipitation (P – ET) is likely to decrease, unless precipitation increases more quickly that ET. In two of the three GCMs we analyzed, one with marginal precipitation changes and one with large decreases in annual precipitation, P – ET decreased substantially by 2100. Under the wettest GCM, however, P – ET actually increased by the end of the century signifying wetter conditions overall.

Conclusions/Implications/Recommendations:

The implications of this study depend strongly on which GCM most accurately predicts future conditions in WI. While potential ET is expected to increase in every region and for every vegetation type by 2100, regardless of GCM selected, the true impacts of changing actual ET depend largely on how precipitation changes over the same period. Under the wettest GCM we considered, the annual depth of water available for overland flow and groundwater recharge (P – ET) is expected to increase by over 50 mm by 2100. This suggests WI will become wetter, with a decreased need for irrigation, but a higher potential for flood conditions. In contrast, the driest GCM we used leads to a decrease in P – ET of nearly 150 mm. In this scenario, WI will be much drier than in the past, with lower lake levels, increased irrigation demands, and decreased recreational opportunities as possible implications.

To decrease the level of uncertainty in how water availability is likely to change in WI, refined GCM projections of future precipitation would be needed. All models agree that temperatures will increase, with broad agreement on the magnitude of change. Precipitation changes, on the other hand, are less clear with some models predicting more precipitation by 2100 and others predicting substantially less. Until the rainfall changes through 2100 are better understood, considerable uncertainty remains in how WI hydrology will change in the future.

Related Publications:

Joachim, D; Loheide, SP; Desai, AR. Simulated Implications of Future Climate Change on Groundwater Recharge, *in preparation*

Joachim, D (2011). Modeling the Impacts of Future Climate Change on Groundwater Recharge and Evapotranspiration and Wisconsin. *Master's thesis, UW-Madison*

Joachim, D; Loheide, SP (2011). Evaluating the changes to Wisconsin Evapotranspiration under a Future Climate. *AWRA – WI Section*, Annual Meeting.

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INTRODUCTION

ET is the second largest component of WI's water budget after precipitation, yet the impacts of climate change on this important process are poorly understood. A suite of models of increasing atmospheric carbon-dioxide concentrations under the A1B scenario proposed by the Intergovernmental Panel on Climate Change by 2100 have predicted an increase in average temperature in Wisconsin of ~4°C (IPCC, 2007), which will increase the energy available for ET while increasing growing season lengths across the state. Conversely, changing precipitation and cloud patterns combined with the changing stomatal response of vegetation to environmental factors could serve to counteract these expected increases. A better understanding of how climate change will affect ET across WI will improve the ability of water resources managers and land-use planners to make informed decisions.

The fundamental physics of evapotranspiration as affected by radiation, temperature, wind speed, and relative humidity are well described using a Penman-Monteith approach (Penman 1948, Allen et al, 1998), but vegetation also exerts a strong control on ET, particularly under water-limited conditions. These effects can be quantified by developing relationships between environmental factors and stomatal response (e.g. stomatal conductance). Many studies have shown that increasing atmospheric CO_2 concentrations are likely to increase plant water use efficiency and reduce stomatal conductance in the future (Ainsworth and Rodgers 2007; Field et al. 1995; Karnosky 2003; Medlyn et al. 2001; Saxe et al. 1998; Bunce 2004; Curtis and Wang 1998). Although an increase in atmospheric vapor pressure deficit acts to increase potential ET, it also tends to decrease stomatal conductance which can offset any increases in actual ET (Johnson and Ferrell 1983; Turner et al. 1984; Monteith 1995). It has also been shown that stomatal conductance decreases above or below an optimal air temperature at which conductance is maximized (Stewart 1988), thus increasing temperature could either increase or decrease stomatal conductance. Finally, stomatal conductance tends to increase as solar radiation increases leading to higher stomatal resistance to transpiration on cloudy days (Stewart 1988).

The Ameriflux network of eddy flux covariance towers was established in 1996 to provide continuous observations of CO_2, water, energy and momentum fluxes (Baldocchi et al. 1988; Goulden et al. 1996; Grelle and Lindroth 1996) across North and South America. While the network is largely used to measure CO_2 exchange in ecosystems, the observations also include long term records of vertical water vapor flux (actual ET), radiation, temperature, humidity, wind speed, and precipitation over the same period which make them ideal for comparing observed actual ET and modeled actual ET using climate parameters measured at the same location.

The Wisconsin Initiative on Climate Change Impacts (WICCI) Climate Working Group has statistically downscaled a suite of general circulation models (GCMs) that predict future daily temperature and precipitation with a 0.1° by 0.1° latitude and longitude resolution across WI. The models show an average increase of annual precipitation by 2100, although the differences among models can be large. Changes to temperature, on the other hand, are relatively consistent among models, with a projected increase of ~3.9 °C in average maximum summer temperature by 2100. While the possible changes to precipitation and temperature have been examined in detail, their effects on the partitioning of precipitation into runoff, recharge, and ET remain unclear.

optimum. This process continues until a specified number of iterations are complete and the global optimum, or best possible parameter set has been obtained (Zobitz et al.*in review*).

Three GCMs were chosen for inclusion in the model, one wet (CCCMA), one dry (MIROC) and one intermediate precipitation model (CNRM). The resolution of these three GCMs is the same over the continental United States, which is very coarse at the scale of the state of WI with just six model cells covering the entire state. However, because the National Climate Data Center has designated nine climate divisions in WI which are defined as "areas of the state that have relatively uniform climate characteristics" we adopted these nine regions for predicting future ET. We used WICCI-downscaled maximum and minimum temperature and precipitation at the center of each of the nine climate regions, but we used non-downscaled data for all other climate parameters.

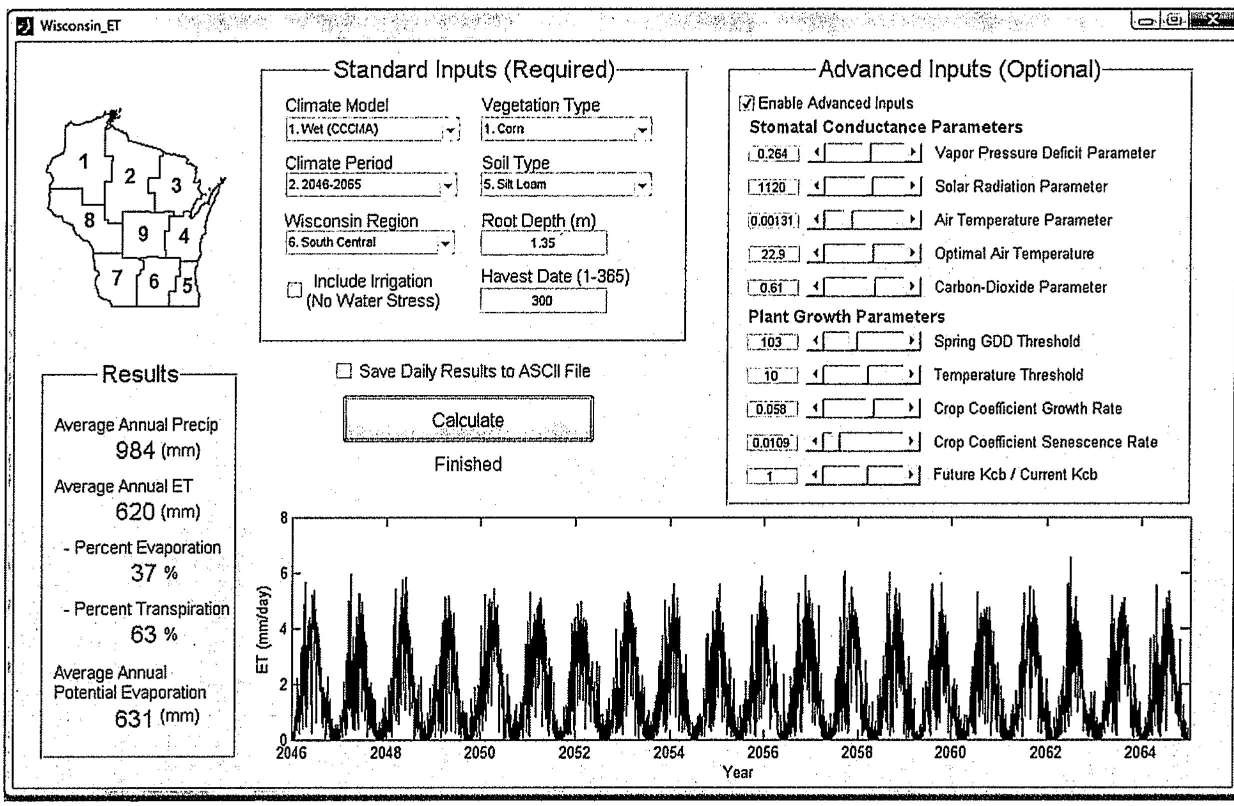

Figure 1. A screen-shot of the graphical user interface developed to allow users to predict future changes to ET. The model is available at http://hydroecology.cee.wisc.edu/research/WisconsinET/index.htm

All three models indicate that average daily temperature will be increasing substantially by 2100. The magnitude of this temperature rise, however, is unclear. MIROC tends to be the warmest of the three and indicates an increase of up to 7 °C can be expected in WI. In contrast, CCCMA and CNRM predict a roughly 4 °C increase on average, more in line with the average of all models submitted to the IPCC.The inter-model variability with regard to precipitation is much larger than that of temperature. In general, CCCMA is the wettest of the models we examined; it predicts an increase in average annual precipitation of over 100 mm by 2100. CNRM predicts an increase of nearly 75 mm by 2046-2065, but a slight decline from 1981-2100 by the end of the century. The MIROC model is the driest of the three and predicts a decrease of about 75 mm in average annual precipitation by 2100. By the end of the 21st century, the inter-model spread in annual precipitation exceeds 150 mm.

After completing the model calibration and parameterization and obtaining future climate predictions for each of the nine WI climate divisions, we created a user-friendly GUI using Matlab (MathWorks, 2011) to allow interested users to predict how ET will change in the future. The GUI, shown in figure 1, allows users to select from three climate models and periods, nine WI regions nine soil types, and five vegetation types to obtain future ET estimates specific to a given location. For users with knowledge of plant phenology and stomatal response, advanced options are available that are used to adjust how plants respond to environmental factors with regard to stomatal conductance and the onset and rate of growth in the spring. The GUI is freely available online (http://hydroecology.cee.wisc.edu/research/WisconsinET/index.htm) and does not require Matlab software to operate (Joachim & Loheide, 2011).

RESULTS AND DISCUSSION

Model results for predicted future ET across the state of WI under the CNRM GCM are plotted in figure 2. The average change in annual ET from 1981-2000 to 2081-2100 is obtained in each region by assuming 20% land cover of each vegetation type is also included in the figure. Similar plots for CCCMA and MIROC are not included here, but the results using these models are described below and are available in Joachim (2011).

Based on model results, ET is likely to increase in the future for all Wisconsin regions and vegetation types by an average of between 8 and 10% under the wet and intermediate models (CCCMA and CNRM) with a maximum relative increase of 13% seen in one region each for both models. Conversely, annual ET is expected to decrease by 2-5% in southwest WI and increase a more moderate 1-5% in northeast WI by the year 2100 under the driest model (MIROC) as water availability decreases and root water uptake becomes more severely limited more often. All models predict an increase in ET for each region and vegetation type through 2065, but these increases are offset by decreases in the later period for CNRM and MIROC, while CCCMA produces another slight increase in ET in the late century.

The model results suggest that differences in ET among vegetation types are important. In CCCMA, for instance, corn is the only vegetation type to see a consistent drop in ET from mid- to late-century, due to the canopy resistance of corn being more affected by increasing atmospheric CO_2 and cloudy conditions than other species. Overall, ET is largest in hardwood forests and shrubs, a result that is consistent under each GCM, time period, climate region, and soil type. The absolute difference in expected annual ET by 2100 between forests and prairies is generally less than 100 mm, or a difference of about 15-18%, which is of similar magnitude to the differences between annual ET in northern and southern WI under a static vegetation community.

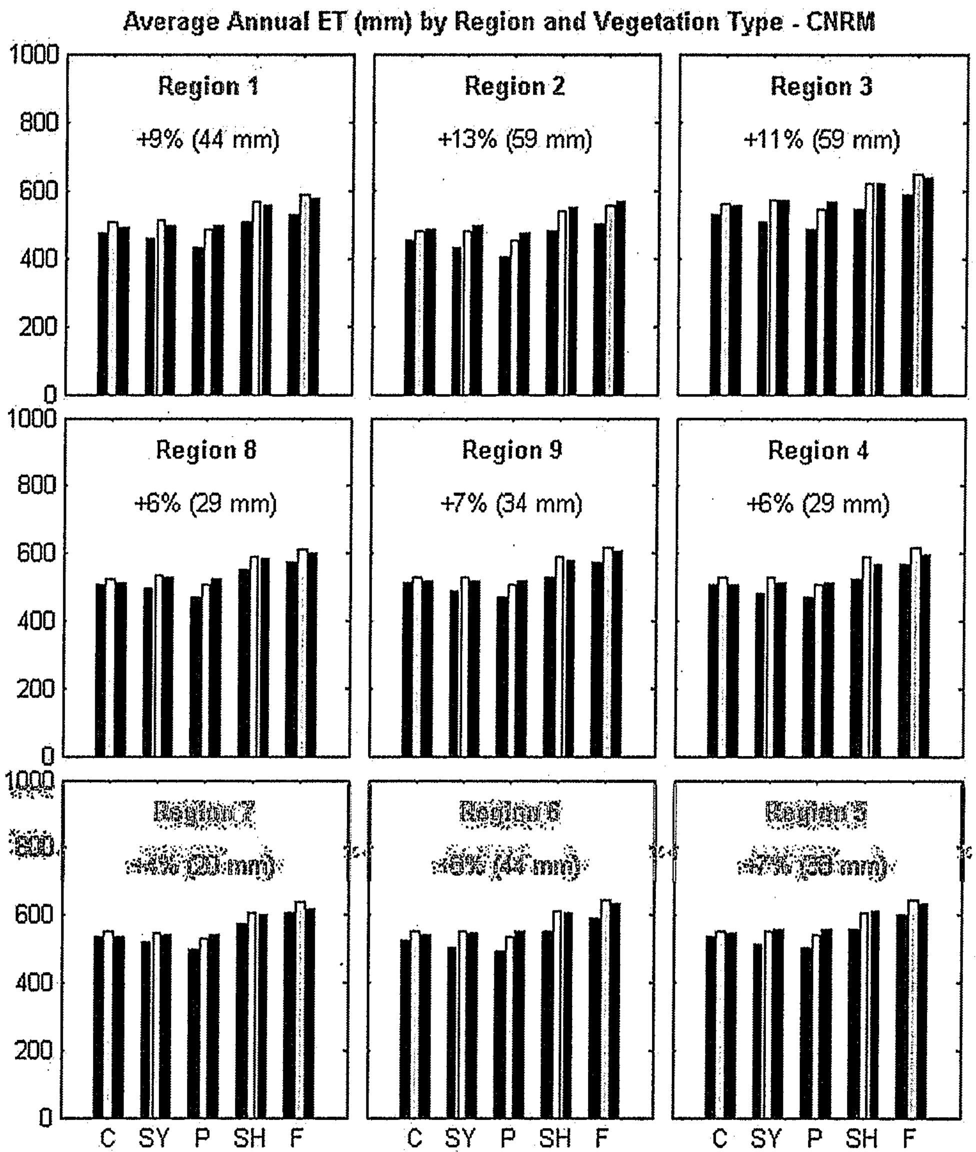

Figure 2. Average annual ET (mm) from a silt loam soil using CNRM. C = Corn, SY = Soybeans, P = Prairie, SH = Shrubs, F = Forest. Blue = 1981-2000, Green = 2046-2065, Red = 2081-2100. Percent change and absolute change from 1981-2000 to 2081-2100 averaged across all species are printed in each panel.

Importance of Soil Texture

The effect of soil texture on future ET is also noteworthy; annual ET is maximum for a silt loam and decreases under both increasing soil coarseness (sand, loamy sand) and decreasing soil coarseness (clay, silt clay) as shown in Fig 3. The differences can be large, particularly in very coarse sandy soils where annual ET can be up to 33% less than seen in silt loam soils. Under these conditions, deep drainage increases and water is more easily able to escape the root zone. Fine grained clay and silt clay soils also see a decrease in annual ET of up to 17% relative to silt loam soils because there is more overland flow.

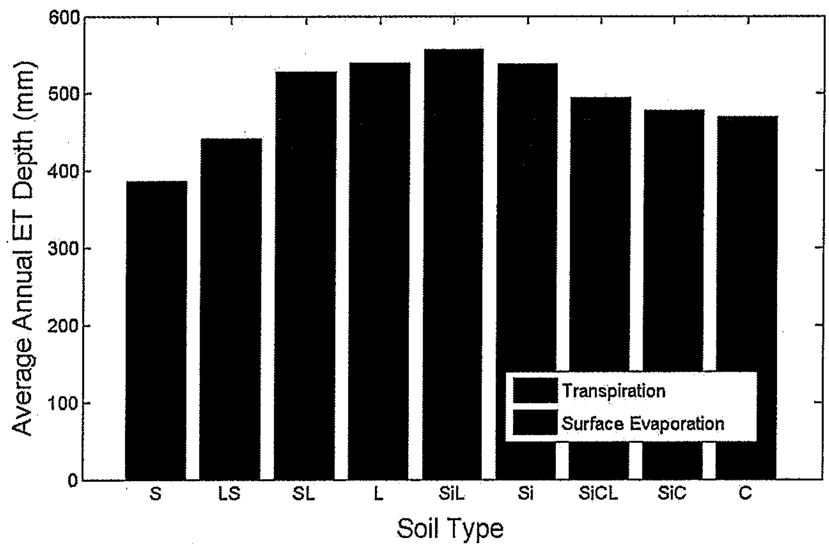

Figure 3. Average annual depths of ET, E and T by soil type under MIROC for WI region 6 and corn. Soils from left to right are sand, loamy sand, sandy loam, loam, silt loam, silt, silt clay loam, silty clay, and clay.

Predicted Changes to the Difference Between Precipitation and ET

The changes to the difference between annual precipitation and ET (P – ET) over time vary greatly among GCMs. Figure 4 shows P – ET changes under CNRM, with changes under other GCMs described below. Under the wettest GCM (CCCMA), P – ET increases substantially by 2046-2065 before decreasing slightly by 2081-2100 resulting in a net increase in annual P – ET of 34% (67 mm) compared to the base case of 1981-2000. In contrast, under the CNRM scenario, P – ET increases slightly by 2046-2065 before dropping to less than that seen in the base case by 2081-2100 with an average decrease of 15% (41 mm) across the state. The driest GCM (MIROC) produces the most pronounced shift in P – ET by 2081-2100, declining an average of 36% (74 mm) which indicates much drier conditions overall.

Spatially, the change in P – ET over time also varies. Under CCCMA, the eastern and central regions of WI see a small increase or decrease in P – ET relative to the large increases in the rest of the state. Northwest WI in particular experiences a very large (> 50%) increase in P – ET. Under the CNRM scenario, P – ET decreases most in the north and southwest (> 15%), with relatively smaller decreases in the rest of the state (< 10%). Under the driest scenario (MIROC) P – ET decreases by about 40% across much of the state, with a somewhat smaller decrease seen in the northeast corner (< 30%).

While the changes to the absolute magnitude of ET expected by 2100 are important, it is the changes in P – ET that will likely have the most direct impact on tourism, agriculture and water resources planning in Wisconsin. P – ET represents the amount of water available for streams, ecosystems, recreation, and many other important functions. An increase in P – ET as seen in CCCMA suggests generally wetter conditions in the future, with an increase in the amount of water supplied to streams by overland flow and baseflow. Depending on the timing and intensity of precipitation, it could also indicate a higher likelihood of flooding events and high lake and groundwater levels. In contrast, a decrease in P-ET as seen in CNRM and MIROC indicates less water is available to be partitioned to streamflow for ecosystem functions and recreation.

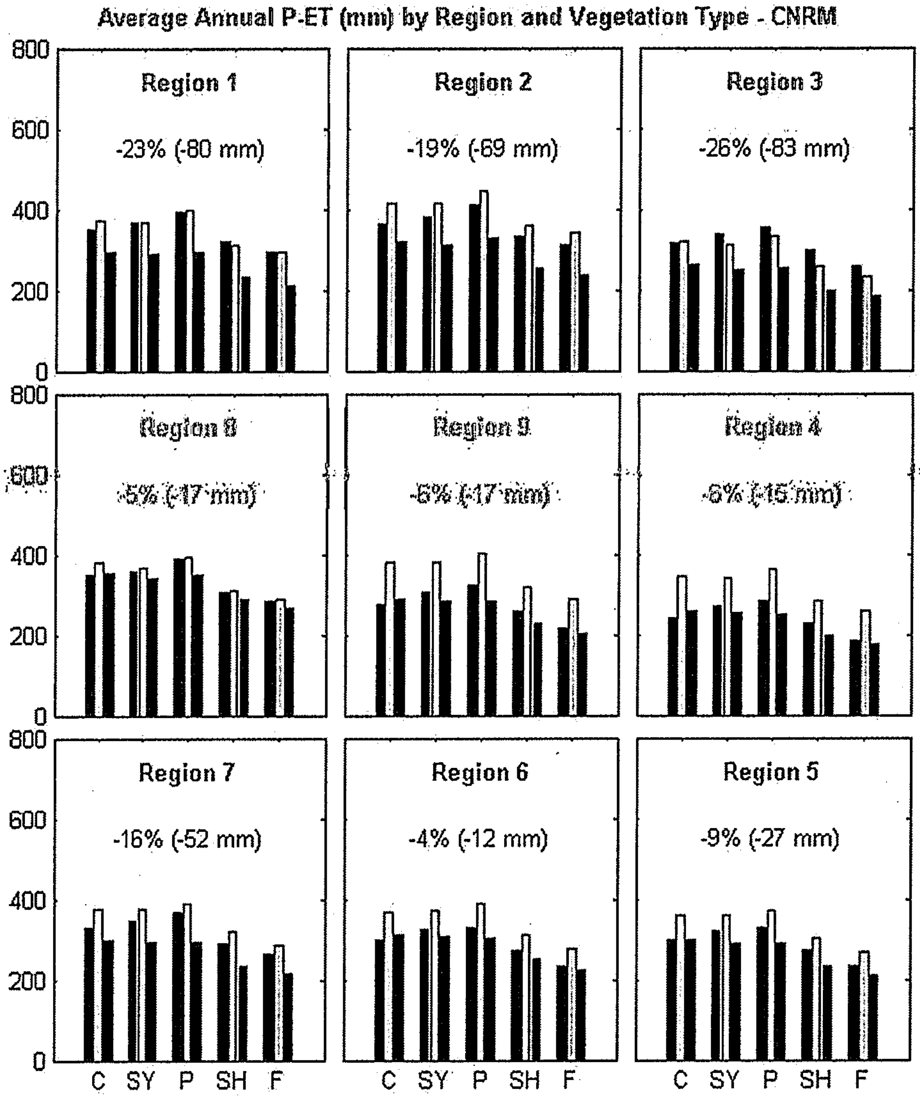

Figure 4.Average annual difference between precipitation and ET (mm) from a silt loam soil using CNRM. C = Corn, SY = Soybeans, P = Prairie, SH = Shrubs, F = Forest. Regional change is the difference between the average ET from all vegetation types in 2081-2100 and average ET under the base case. Blue = 1981-2000, Green = 2046-2065, Red = 2081-2100. Percent change and absolute change from 1981-2000 to 2081-2100 averaged across all species is printed in each panel.

The wide differences among GCMs with regard to future P – ET changes are driven largely by a disagreement in future predicted precipitation patterns. The wettest model (CCCMA) suggests WI will become a wetter state as a result of climate change and that precipitation will increase faster than ET through 2100. Under this scenario, P – ET increases through time. Conversely, the driest model (MIROC) predicts WI will become substantially drier by 2100, with increases in ET combined with decreases in annual precipitation. These results highlight the importance of improving our understanding of future precipitation changes and in using a variety of GCMs when evaluating water resources changes in the future.

CONCLUSIONS AND RECOMMENDATIONS

The methods, program, and GUI developed in this project can be applied to help predict how ET will change in the future. They provide a simple way for users interested in ET to better understand how climate change will impact them. The model provides three different sets of future climate data which allows for a range of possible changes to ET so that the user can assess the implication of uncertainty inherent in the GCMs themselves. The inclusion of three climate periods from 1981-2000, 2046-2065, and 2081-2100 allows for a better understanding of how ET is expected to change through time. The model also divides WI into nine different climate regions, which provides a spatial representation of ET change. The five broad vegetation categories in the model allow users to investigate the importance of land cover in determining any ET changes. Finally, the inclusion of nine separate soil types helps explain the impact of soil characteristics on the hydrologic budget in a future climate.

The results of this study indicate that substantial ET increases will occur across the state as long as precipitation does not decrease substantially over the same period. After applying each GCM to our ET model, we noted 8-10% increases in annual ET from baseline levels under two GCMs, one wet and one intermediate, with some regional increases totaling 15% or more. Under the driest GCM, ET increased by 2046-2065, but decreasing precipitation led to a higher likelihood of water-limited conditions in 2100 and ET decreased slightly in southwest WI (by 2-5%) and increased slightly in northwest WI (by 1-5%) for each vegetation type relative to the base case.

The expected changes to P – ET are less clear, with strong disagreement among GCM scenarios driven by the different precipitation patterns predicted from each model. Under the wettest GCM studied (CCCMA), P – ET increases by the mid-21st century before declining slightly during the latter half of the century, leading to a net gain of 67 mm of P – ET relative to the base case. This may indicate there will be less need to irrigate lawns and crops and could produce greater streamflow on average. This could also lead to a higher likelihood of flood conditions and higher lake levels in the state. In contrast, the GCM with the lowest future precipitation (MIROC) experiences a decrease in P – ET of 150 mm, a decrease of about 35% relative to the P – ET seen in the base case. This change would suggest a large decrease in the amount of precipitation partitioned into streams and lakes, causing stresses to aquatic ecosystems and human recreation that relies on adequate water levels. These results indicate that the impacts of rising ET on WI hydrology depend largely on how precipitation ultimately changes in the coming century.

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