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1. INTRODUCTION

The question of the net effect of global warming, and of other changes in climate on water resources can often be more complex than is indicated by individual simple measures.* The dimensions of total precipitation, evapotranspiration, soil moisture, runoff, and net basin supply can interact in ways that are not related at a simple intuitive level. Different methodologies of modeling these variables can yield different results. But some simple conservation laws can help in creating a qualitative sense of how the water cycle of continents and oceans are constrained, how this is likely to change with increased greenhouse gas concentrations, and how this might play out in the case of the water supply of the Laurentian Great Lakes.

Some simple conservation laws will be presented in qualitative form in section 2. Section 3 will summarize some contrasting results derived from different methods for determining the effect of global warming on Great Lakes net basin supply and water levels. Relations will be drawn using the simple conservation laws to help explain the different results that come of using different methodologies.

2. INTEGRAL CONSTRAINTS ON WATER BUDGET

A simple law that acts on all land surfaces is that, without a net underground source of water, evapotranspiration cannot exceed precipitation. Also, over the long term, net basin supply or streamflow from a drainage basin (for the drainage basin of a lake, net basin supply is defined as the runoff from the land portion of the basin, plus the precipitation directly over the lake, minus the evaporation from the lake) must be equal to precipitation minus evapotranspiration, which in turn must be equal to the convergence of atmospheric water vapor flux over the region. Thus, the atmospheric flux of water vapor must be

convergent over the continents and, by continuity, divergent over the oceans.

The amount of this divergence of water over the oceans is proportional to the net amount of energy they have available to go into the latent heat of evaporation. Although much of this heat will be re-released through precipitation over the oceans, some of it will result in water vapor being carried onto the continents. This will result in runoff.

With greenhouse warming, the amount of energy available for evaporation from the oceans will be increased (in general, they will retain more longwave radiative flux and will be exposed to warmer overlying air). So, unless all of this surplus energy goes into precipitation directly over the oceans, there will be greater divergence of water vapor from the oceans, and thus greater runoff over the continents.

This places a constraint on the continents that, even though they have additional energy available, which could perhaps be used for evapotranspiration, their increase in precipitation much exceed their increase in evapotranspiration. This would indicate that evapotranspiration more frequently enters a moisture-limited state, giving rise to more sensible heat flux from the land surface. One solution that satisfies this constraint is if land-based precipitation were to occur less frequently but more intensively, thus producing additional runoff but creating long periods between precipitation events in which a moisture-limited evapotranspiration state can develop.

Because of the large thermal capacity of the oceans, the situation in which more energy is available for evaporation of ocean surface water may take considerable time to fully develop. So the arguments above are likely to be closer to the truth at least several decades, and perhaps centuries, into the future. Nevertheless, this is an argument worth considering.

Now, let us consider the Laurentian Great Lakes basin. The drainage basin of the Great Lakes is 33% covered by water, and thus shares some of the characteristics of land and oceans as described above. Therefore, it is an open question whether the response in this region will be more representative of a land or ocean type. Additionally, the characteristics of the Great Lakes diverge from those of the oceans in that they have

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a faster thermal response than the oceans. This is due in part to the lakes being shallower than the oceans, and also to their having an annual unstratified period, meaning that the entire lake water volume comes in thermal contact with the surface at least once a year.

3. SAMPLE RESULTS

As summarized in Croley (2003), a series of studies of the effects of greenhouse warming on Great Lakes water supplies and levels has generally shown a decrease in net basin supplies and water levels. These studies have generally used a methodology in which general circulation model (GCM) results are transferred to an off-line hydrologic model suite by using the differences and ratios between variables as modeled for future time periods in comparison to past time periods. Exceptions to this have occurred, however, as in Lofgren et al. (2002) for the Hadley Centre Coupled Model version 2 (HadCM2, Johns et al. 1997), and using a different general methodology (regional climate model) in Lofgren (2003). Criticism has been leveled at the HadCM2 model for its overly active parameterization of the direct effect of sulfate aerosols and consequent small increase in temperature into the future. However, this model does include a rudimentary representation of the water of the Laurentian Great Lakes, in contrast to most other models, which assume land in this region.

By using the results of GCMs that were not directly coupled to the Great Lakes and coupling them to hydrologic models to calculate runoff from the land and evaporation from the lake surfaces, the constraint that area-integrated runoff be equal to precipitation minus evapotranspiration is not satisfied. Within the GCM framework, this constraint is maintained, but the off-line hydrologic model independently calculates evapotranspiration from land and water surfaces, using different assumptions about the surface characteristics (specifically, whether the surface is land or water and what water surface temperature might be expected). Under the regional climate modeling methodology, the equality of atmospheric moisture flux convergence to net basin supply is satisfied within the regional climate model framework, but because the lateral boundary conditions are nudged and not strictly held equal to the driving GCM, the amount of moisture transferred into and out of the regional climate model domain may not agree with the GCM.

In any case, a comparison of results in terms of net basin supply for the Lake Superior drainage

basin is shown in Table 1. Lofgren (2003) used a regional climate model known as the Coupled Hydrosphere-Atmosphere Research Model (CHARM) with two-way interaction between the surface (both land and water). The results show a mixture of increases and decreases in annual mean net basin supply. But those of Croley (2003), which use newer GCM model versions and greenhouse gas emission scenarios of newer design than those used in Lofgren et al. (2002) designed to “bracket” the overall results of a variety of GCM models and scenarios in terms of changes in precipitation and temperature, show only decreases in net basin supply.

Table 1. Results of climate change hydrologic simulations of the Lake Superior drainage basin.

Croley (2003), off-line hydrologic simulation	Annual mean net basin supply, m ³ /s	Percent change
Base case	2189	
Change in hot-dry case	-469	-21
Change in warm-dry case	-141	-6
Change in hot-wet case	-419	-19
Change in warm-wet case	-208	-10
Lofgren (2003), regional climate model		
1989 case	2430	
Change to 2030 case	-260	-11
Change to 2090 case	+360	+15

Figure 1 shows that the annual cycle of net basin supply simulated by CHARM has an increase in net basin supply in the future manifest primarily during the spring season. In the 2030 case relative to the 1989 case, this spring increase is not large enough to result in an annual mean increase. While there are some known problems with CHARM, including excessive stratus cloud cover and a wintertime warm bias (Lofgren 2003), the arguments given here related to its satisfaction of integral relationships help to lend it credibility relative to the results of the off-line hydrologic models.

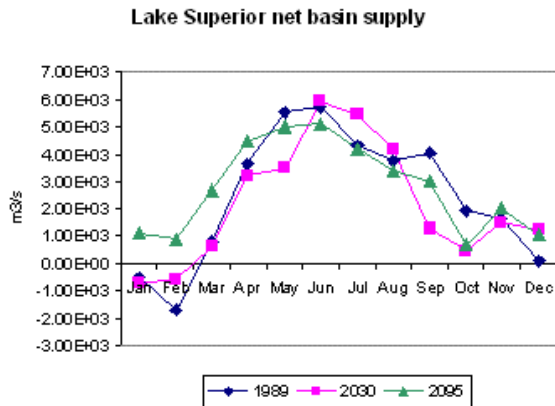


Figure 1. Net basin supplies for the Lake Superior basin derived from the regional climate model CHARM (Lofgren 2003).

4. ACKNOWLEDGMENTS

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