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Energy budget considerations for hydro-climatic impact assessment in Great Lakes watersheds

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ABSTRACT

Given the large share of the water budget contributed by evapotranspiration (ET), accurately estimating ET is critical for hydro-climate change studies. Routinely, hydrologic models use temperature proxy relationships to estimate potential evapotranspiration (PET) when forced using GCM/RCM projections of precipitation and temperature. A limitation of this approach is that the temperature proxy relationships do not account for the conservation of energy needed to estimate ET consistently in climate change scenarios. In particular, PET methods using temperature as a proxy fail to account for the negative feedback of ET on surface temperature. Using several GCM projections and a hydrologic model developed for the Great Lakes basin watersheds, the NOAA Large Basin Runoff Model (LBRM), the importance of maintaining a consistent energy budget in hydrologic and climate models is demonstrated by comparing runoff projections from temperature proxy and energy conservation methods. Differences in hydrologic responses are related to watershed characteristics, hydrologic model parameters and climate variables. It is shown that the temperature proxy approach consistently leads to prediction of relatively large and potentially unrealistic reductions in runoff. Therefore, hydrologic projections adhering to energy conservation principles are recommended for use in climate change impact studies.

Introduction

In the upper midwestern United States, annual evapotranspiration (ET) is approximately 30–50% of annual rainfall (Sanford and Selnick, 2013). Given this large proportion of the water budget, accurately estimating ET is critical for hydro-climate change studies. As direct measurements of ET (e.g. using pans, eddy covariance flux towers, and weighing lysimeters) are expensive and not frequently available, ET is commonly estimated as a function of moisture storages and potential evapotranspiration (PET), i.e., the evaporative potential given unlimited moisture availability. PET, in turn, is often estimated only as a function of daylight hours (season) and temperature (Hamon, 1963), and sometimes as a function of humidity, wind speed, and surface radiative fluxes as well (Penman, 1948; Priestley and Taylor, 1972). Full energy budget approximations are seldom used due to intensive data requirements.

Contrary to the expectation that increased air temperature would lead to increased evaporation, pan evaporation measurements around the world show a steady decrease over the last 50 years (Peterson et al., 1995; Golubev, 2001). An explanation of this 'pan evaporation paradox' is that increased land surface evaporation alters the humidity regime, causing air over the pan to be more saturated (Brutsaert and Parlange, 1998). Another explanation is that increased cloudiness and decreased solar irradiance due to aerosol deposition have in fact resulted in reduced land surface evaporation, as reflected in pan evaporation records (Stanhill and Cohen, 2001; Ramanathan et al., 2001). Further, it is claimed that large-scale groundwater depletion has accelerated significantly since the mid-twentieth century, affecting the terrestrial evaporative budget, as well as increasing runoff that contributes to sea level rise (Aeschbach-Hertig and Gleeson, 2012; Konikow, 2013; Pokhrel et al., 2012; Wada et al., 2010). This limited understanding and agreement in historical evaporation trends have complicated accurate actual ET quantification (Barnett et al., 2005), and it has been suggested that the components of the hydrological cycle be considered together to interpret inter-relationships of pan, potential, and actual evapotranspiration when estimating the net evaporative budget (Sumner and Jacobs, 2005).

A general method to estimate ET uses a water balance equation given by $\Delta S = P - Q - ET$, where ΔS is the change in water storage over the basin and P, Q and ET are precipitation, runoff and evapotranspiration, respectively. For water budget analyses on annual or longer time scales, the net change in annual storage may be assumed zero. In order to estimate runoff at finer timescales, using precipitation and temperature as inputs to hydrologic models, ET is typically estimated as a function of PET. PET may be an exogenous input to hydrologic models,

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as in HEC-HMS (USACE, 2010), or it may be computed internally, as in LBRM (Croley, 2002) which uses a temperature proxy method conceptually similar to Thornthwaite (1948).

As climate model outputs other than precipitation and temperature have received relatively little attention among hydrologists, hydrologic projections have continued to use empirical temperature proxy relationships to estimate PET (e.g. Croley, 2002; Hartmann, 1990; Chao, 1999; Lofgren et al., 2013; Angel and Kunkel, 2010). Recent findings have shown that the temperature proxy methods fail to account for the surface radiation balance within the GCMs (Lofgren et al., 2011; Milly and Dunne, 2011; Shaw and Riha, 2011), including the negative feedback of increased ET on surface temperature (Lofgren et al., 2013). A potential artifact of the temperature proxy approach is that reduced runoff is projected into the future as a result of an inconsistent energy budget between climate and hydrologic models. Among other studies describing limitations of temperature-based PET estimation, Shaw and Riha (2011) argue that temperature-based equations will shift with climate change and likely exaggerate PET in a warmer climate. Wild and Liepert (2010) illustrate that the improved knowledge of surface radiation balance is the key to better understanding variations in the hydrologic cycle, and shortcomings in the simulation of the surface radiation balance in climate models may contribute to the poor simulation of decadal variations in precipitation during the 20th century. Haddeland et al. (2012) demonstrate that radiation, humidity and wind speed estimates have potentially large effects on simulated water fluxes, and that using these values directly from climate models can result in very different evapotranspiration and runoff estimates than when using values based on reanalysis and observational data.

Lofgren et al. (2011) show how ET responses in the Great Lakes region can be exaggerated when the watershed models are forced only by air temperature and precipitation from GCMs, as opposed to when ET is directly simulated from the same GCMs with integrated land surface–atmosphere models. In a similar experiment conducted by Milly and Dunne (2011), it was shown that the air temperature-based modified Jensen–Haise formula, used in the hydrologic model Precipitation Runoff Modeling System (Leavesley et al., 1983), estimates a change in PET that is typically three times the change implied by the climate models with surface energy budget considerations. These findings warrant caution when projecting changes in PET using hydrologic models to evaluate climate change impacts on water resources.

This study compares hydrologic projections from temperature proxy and energy conservation methods in the Great Lakes basin at a watershed scale. The flow responses across the Great Lakes watersheds are further evaluated in relation to climate projections, hydrologic model parameters and watershed characteristics. The following “Methods” section describes the overall radiative energy budget, including latent and sensible heat fluxes, used to estimate PET from respective GCMs for input to LBRM; the selection of representative future climate scenarios; and the LBRM simulations using either the temperature proxy method or the energy conservation approach. The “Results” section discusses the ET and PET projections; streamflow projections and relationship to watershed characteristics; and identified streamflow regimes and snow water equivalent (SWE) projections from LBRM simulations across the Great Lakes watersheds. Finally, the “Conclusion” section includes a discussion of seasonal and regional variability of flow regimes, along with future directions of research to look more closely at the sensitivity of evaporative responses using additional climate model outputs and PET estimation methods in the Great Lakes basin.

Methods

This section focuses on the energy conservation PET formulation and inputs to the LBRM. The temperature-proxy PET formulation (which does not consider energy conservation) and the model structure of LBRM are described in greater detail in Lofgren et al. (2011). The ET estimation method herein is also similar to Lofgren et al. (2011), but a larger array of GCM projections is included to inform a multi-model ensemble approach to climate change impact assessment. Furthermore, unlike the aggregated lake level responses evaluated by Lofgren et al. (2011), watershed-specific responses are evaluated by comparing PET, runoff, and snow water equivalent (SWE) projections from the temperature proxy and energy conservation approaches for 14 Great Lakes watersheds (Fig. 1), selected based on their nutrient ' (LaBeau, 2012).

Radiative energy budget

In order to maintain a balance between incoming and outgoing energy at the surface, the following equation must be satisfied:

$$SW – LW – SH – LH – G – SM = 0 \qquad (1)$$

where SW is net shortwave radiation; LW is net long-wave radiation; SH is sensible heat flux; LH is latent heat flux of evapotranspiration and sublimation; G is heat flux into the ground; and SM is latent heat of snowmelt. As discussed in Lofgren et al. (2011) and Milly and Dunne (2011), PET is explicitly dependent on the quantity ($SW - LW - G - SM$). For estimation of PET as input to LBRM using the energy conservation approach, this quantity is equated to the sum of latent and sensible heat fluxes ($LH + SH$) as derived from the respective GCMs. Latent heat flux is the energy required for the separation of attractive intermolecular forces to vaporize water to a gaseous phase. Sensible heat flux is the portion of radiant energy intercepted at the Earth's surface not used for evaporation, but used in warming the air in contact with the ground. The direction of sensible heat energy is upward from the ground during the day and downward at night (Maidment, 1993). The net radiative heat fluxes at the surface area are major drivers of PET.

Climate scenario selection

Climate scenarios are selected from an ensemble of 53 projections archived in World Climate Research Program's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3) database (Meehl et al., 2007). These 53 projections come from 16 GCMs combined with four emissions scenarios (a1, a2, a1b, and b1) and different initial conditions. Daily GCM outputs (precipitation and temperature) are downscaled using the bias-corrected construction analogue (BCCA) method, which uses a quantile mapping bias correction on large scale data prior to using a constructed analogues (CA) approach at finer scales. The CA method is based on the premise that an analogue for a given coarse-scale daily weather pattern for a given GCM simulation can be constructed by combining the weather patterns from a library of historic patterns (Hidalgo et al., 2008). The BCCA CMIP3 projections include maximum air temperature, minimum air temperature and precipitation downscaled at 1/8th of a degree (~12 km resolution) at a daily time step. Although the downscaled data are already bias-corrected, residual precipitation biases were found to exist in the U.S. Great Lakes region (Gyawali, 2013). These biases were corrected using the change factor method (e.g. Rasmussen et al., 2012) prior to input to LBRM.

The selection of a representative set of climate scenarios is based on percent changes in precipitation and absolute changes in air temperature between the historical baseline period (1980–1999) and a future period (2046–2065), as shown in Fig. 2. The quadrants are divided according to median changes in precipitation and temperature. A total of nine scenarios were selected to be representative of the entire ensemble. A few scenarios which reported outlier future radiative fluxes were not included in the analysis. A similar scenario selection approach based on precipitation and air temperature changes is employed in Brekke et al. (2009). Table 1 summarizes the selected scenarios, including the GCM runs, corresponding grid sizes and representative future climates.

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