



Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology

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ABSTRACT

Hydrologic impacts of climate change are regularly assessed with hydrologic models that use air temperature as a proxy to compute potential evapotranspiration (PET). This approach is taken in the Large Basin Runoff Model (LBRM), which has been used several times for calculation of the runoff from the terrestrial part of the Great Lakes basin under climate change scenarios, with the results widely cited. However, a balance between incoming and outgoing energy, including the latent heat of evaporation, is a fundamental requirement for a land surface, and is not enforced under this approach. For calculating PET and evapotranspiration (ET) in climate change scenarios, we use an energy budget-based approach to adjusting the PET as an alternative that better satisfies conservation of energy. Using this new method, the increase in ET under enhanced greenhouse gas concentrations has reduced magnitude compared to that projected using the air temperature proxy. This results in either a smaller decrease in net basin supply and smaller drop in lake levels than using the temperature proxy, or a reversal to increased net basin supply and higher lake levels. An additional reason not to rely on a temperature proxy relation is that observational evidence demonstrates that the correlation between air temperature and ET (or PET) is restricted to the mean annual cycle of these variables. This brings into question the validity of air temperature as a proxy for PET when considering non-annual variability and secular changes in the climate regime.

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Introduction

Evapotranspiration (ET) is one of the terms in the water budget of the Great Lakes. Along with over-land precipitation, it determines the amount of tributary river flow into the Lakes, which, along with over-lake precipitation and evaporation, determine trends in lake levels and outflow through the connecting channels (the St. Marys, St. Clair, Detroit, and Niagara Rivers, as well as the final outflow of the Great Lakes, the St. Lawrence River). In several studies projecting the effects of climate change on the Great Lakes water budget (e.g. Lofgren et al., 2002), tributary river flow is projected to decrease despite increased precipitation, indicating a sharp rise in ET. This is a large contributor to drops in lake levels. Similarly, in Croley (2003), reduced river outflow is the main contributor to projected reduced net basin supply, and potentially to lowered lake levels, because of a near balance between increased precipitation and evaporation over the lakes.

ET has been estimated for watersheds in various ways. In the class of methods known as surface vegetation-atmosphere transfer schemes (SVATS), e.g. SiB2 (Sellers et al., 1996), ET is based on the estimated local vertical gradient of water vapor pressure along with estimates of eddy diffusivity within the boundary layer. These are functions of the state variables air temperature, humidity, wind, surface temperature, and soil moisture, along with land cover parameters such as surface albedo, surface roughness, leaf area index, soil texture, and stomatal resistance, depending on the exact formulation. ET is calculated along with other components of the local surface heat budget and used to prognostically determine surface temperature. To maintain a balance between incoming and outgoing energy at the surface (energy conservation), the following constraint must be fulfilled:

$$SW-LW-SH-LH-G-SM = 0. \quad (1)$$

Here the terms are, respectively, net shortwave radiation (positive value indicates energy being added to the surface), net longwave radiation, sensible heat flux, latent heat flux of evapotranspiration and sublimation, heat flux into the ground, and latent heat of snowmelt. In versions of the Priestley–Taylor formulation (Priestley and Taylor, 1972), used for ET from a land surface without moisture stress, the equation for ET is explicitly dependent on the quantity $SW-LW-G-SM$, and the maximum amount of ET that can occur under conditions of no water stress (i.e. potential ET), is closely related to this quantity. (See

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discussion in Milly and Dunne, 2011.) Under more general conditions (water-stressed or not), this quantity is the sum of latent heat flux and sensible heat flux, and the partitioning between these two forms depends on moisture availability as well as temperature.

SVATS-type surface hydrologic components are used by nearly all, if not all, general circulation models (GCMs) and regional climate models (RCMs). They include formulations to calculate each of the terms of Eq. (1). Any imbalance among these terms results in a change in temperature of surface features, such as leaves and soil, altering the values of the other fluxes. This leads to a negative feedback that limits the magnitude of change in any of the fluxes. For example, if a sudden gust of dry air comes along, it will increase the amount of energy lost to latent heat flux. This would cool the surface and, in turn, that cooling would reduce the water vapor mixing ratio at the surface of the leaves or soil, thus reducing the amount of ET.

In practice, observed values of the radiative energy terms, ground heat flux, and latent heat of snowmelt are generally unavailable. Therefore, methods have been developed to use air temperature as a proxy for potential evapotranspiration (PET, see Xu and Singh, 2001), but these methods usually do not explicitly enforce energy conservation Eq. (1). This paper examines the consequences of using air temperature as a proxy for PET in the commonly applied surface hydrologic model, known as the Large Basin Runoff Model (LBRM), developed by Croley (1983) and further described in Croley and Hartmann (1984). LBRM was designed specifically for use in the land portion of the basins of the Great Lakes.

The LBRM has been used to project impacts of warming caused by greenhouse gasses on Great Lakes basin watersheds in a number of primary research articles (Croley, 1990, 2003; Hartmann, 1990a; Chao, 1999; Lofgren et al., 2002; Angel and Kunkel, 2010). These results have been extensively cited and used in impact studies (e.g. Hartmann, 1990b; Millerd, 1996, 2005; de Loe et al., 2001; Croley and Luukkonen, 2003; Buttle et al., 2004; Schwartz et al., 2004; Rahel and Olden, 2008) and in assessments and other secondary literature (e.g. Mortsch et al., 2000; Easterling and Karl, 2001; Beeton, 2002; International Lake Ontario-St. Lawrence River Study Board, 2006; Field et al., 2007; McBean and Motiee, 2008; Hall and Stuntz, 2008; Karl et al., 2009; Moy et al., 2010; Hayhoe et al., 2010). While there is some appearance of these various studies being independent projections of lake level changes, given that several different GCM runs were used as input in various studies (Angel and Kunkel, 2010, used 565 model runs from 23 different GCMs), all of the sources cited above refer back to a single hydrologic model of the land, the LBRM. The reasonableness of its sensitivity to climate change has not been scrutinized.

Lofgren (2004), Manabe et al. (2004), Kutzbach et al. (2005), and Milly et al. (2005) have used methods more directly dependent on SVATS formulations, not involving LBRM or a temperature proxy for PET. This resulted in different results from those using LBRM, but has attracted less attention in secondary literature. This is likely due to their projecting increases in net basin supply or lake outflow rather than lake water level, even though these necessarily imply elevated lake levels.

In this paper, we examine the validity and internal consistency of the LBRM by comparing the predictions of changes in ET under climate change scenarios given by LBRM driven by a GCM to those given by the GCM itself. This is conceptually similar to the comparison done by Milly and Dunne (2011), in which GCM-calculated ET is compared to ET estimated by feeding GCM output into an air temperature proxy-based formula. However, the geographic focus and the specific proxy formulation are different. Then eddy flux covariance data is used to examine the validity of a key assumption within the LBRM, that a single formula of air temperature as a proxy for PET works across all time scales and climate regimes. Then we apply an alternative method of adjusting the LBRM for greenhouse gas-induced climate change, in which GCM land surface energy budget results are used instead of temperature proxies.

Formulation and calibration of LBRM

Key features of the formulation of the LBRM model for purposes of this study include the determination of “energy available for evapotranspiration” (for convenience referred to here as PET; see further discussion below) and the proportion of PET that is manifested as ET. As stated in Croley (1983), due to considerations of data availability, an *a priori* constraint in developing LBRM was that only daily air temperatures and precipitation be used as input data. Explicit justification was not given for the principle of using air temperature as a proxy for PET, but one well-known literature source for this usage is Thornthwaite (1948). This source investigated a number of possible predictors of PET and found that air temperature is the best single predictor. However, it used strictly monthly mean data, so that the main differentiation among data points was based on location and time of year, and thus was highly intertwined with the radiative energy budget. Forcing by changes in the atmospheric concentration of human-emitted greenhouse gasses was not a well-known consideration at that time.

PET is assumed to take the form Ae^{T/T_b} , where T_b is a parameter with units of temperature fitted through calibration. During the calibration process, the annual total of PET is taken to be such that its latent heat equivalent is equal to the annual incoming solar radiative energy:

$$LA \sum^{\text{year}} e^{T/T_b} = \sum^{\text{year}} SR, \quad (2)$$

where L is the latent heat of evaporation per unit mass, A is a parameter with units of cm/day or other units of evapotranspiration, T is daily mean air temperature, and SR is the incident solar radiation. The summation in Eq. (2) uses a daily timestep for the snow-free portion of the year. In the calibration process, for each test value of T_b , the value of A is uniquely determined using Eq. (2). It should be noted, however, that outside of the calibration process, including in future projections using adjustments to the temperature based on GCM results, the constraint of Eq. (2) is not enforced. That is, the PET increases by a factor of $e^{\Delta T/T_b}$ corresponding to the change in temperature between current and future conditions, as if the solar radiation was also increasing by the same factor. The consequent very large changes in PET are discussed later in this paper.

In LBRM, ET draws water from two soil layers, the upper soil zone and the lower soil zone. For each soil layer, the amount of water stored in that layer is multiplied by a calibrated parameter, B . The resulting total ET from both soil zones is calculated as:

$$ET = PET \times (B_{usz} \times M_{usz} + B_{lsz} \times M_{lsz}) / (1 + B_{usz} \times M_{usz} + B_{lsz} \times M_{lsz}), \quad (3)$$

where M indicates the soil moisture. This formula ensures that the total ET from both soil layers never exceeds PET and generally is considerably less.

To clarify the difference in nomenclature between this paper and Croley (1983), we here use the term potential evapotranspiration to refer to the quantity Ae^{T/T_b} , because it is the variable in LBRM that best corresponds to the intuitive and widely-used definition of PET as the amount of ET that would occur in the absence of moisture stress. Within the formulation of LBRM, this amount of ET can be approached, but is only reached when soil moisture is infinite. When multiplied by L , this quantity is referred to in Croley (1983) as “energy available for evapotranspiration.” Croley uses the term PET to refer to the water equivalent of the portion of the energy available for ET that does *not* actually result in ET—i.e. PET (by the definition used in this paper) divided by the denominator of Eq. (3).

In addition to T_b and the parameters B_{usz} and B_{lsz} from Eq. (3), there are six parameters that govern the rate of flow of water among the four water reservoirs for each sub-basin in LBRM, as well as the rate of snowmelt as a function of air temperature. These were

all calibrated in Croley (1983) by running the model using temperature and precipitation data as inputs and river outflow measurements as calibration data. A successive approximation method was used, varying each parameter in turn to get lower values of root mean squared difference between the simulated and observed river outflow. Since there is interaction among the parameters in determining the simulated outflow, the process must be repeated until all parameters have converged simultaneously. The period of calibration stated in Croley (1983) is 1957–1972, and this calibration remains in use.

Croley and Hartmann (1984) made some attempt at physically interpreting and justifying the relative values among the various sub-basins of some of these calibrated parameters. However, a comprehensive interpretation of the physical meaning of the parameters is elusive, especially given the very wide range of values of each parameter among the sub-basins. LBRM must ultimately be regarded as a black box, and its parameters justified mainly by saying that they are the values that give the optimal fit to observed river flow. This is in contrast to SVATS models, in which, even though the spatial distribution is aggregated to areas of about 40,000 km² in a GCM, each of the parameters represents a real physical characteristic (e.g. albedo or leaf area index), and affects the coupled energy and water budgets accordingly.

GCM-LBRM latent heat flux comparison

The experiments reported here compare the predictions of ET by the LBRM driven by a GCM using a method consistent with previous work (Croley, 1990, 2003; Hartmann, 1990a; Chao, 1999; Lofgren et al., 2002), to the ET simulated directly by the same GCM. The results shown here used the Coupled General Circulation Model Version 3 (CGCM3) of the Canadian Centre for Climate Modelling and Analysis (Flato, 2005). This model run used the Intergovernmental Panel on Climate Change's (IPCC) A2 scenario for greenhouse gas emissions and concentrations (Intergovernmental Panel on Climate Change, 2000). This is the "business as usual" scenario, the highest level of emissions among the set of scenarios officially approved by the IPCC in 2000.

The delta method

In the LBRM simulation, we ran a base case that used observed meteorological data as the driver for the years 1950–2005. Next, screen-level air temperatures from CGCM3 averaged for each month of the year during the base period 1981–2000 were subtracted from the same variable during the projected period 2081–2100 interpolated to the centers of 1 km grid squares, and then areally averaged to get values for drainage sub-basins. (The LBRM is defined on the sub-basins that correspond to the drainage areas of one or more tributary rivers of the Great Lakes, and all calibrated parameters and input and output variables represent areally lumped values over the sub-basin.) We also calculated monthly precipitation values from CGCM3, and the ratio of the future values to the near past values was determined and spatially interpolated to the sub-basins. The LBRM was then re-run, using the same observed inputs from 1950 to 2005, but with the air temperatures adjusted by the difference in temperature given by the CGCM3 for each month, and the precipitation adjusted by the ratio of precipitation given by the CGCM3 for each month. This procedure is known as the delta method.

Results

The results using the delta method are compared to averaged ET values given directly by CGCM3 on a monthly basis and interpolated to the same sub-basins. In order to highlight the implications to the energy budget of differences in simulated ET, results are shown in terms of latent heat flux. In months when the mean temperature was above 0 °C, this conversion was made using 1 mm day⁻¹ of evaporation equivalent to

29.07 W m⁻² of latent heat flux. When the monthly mean temperature is below 0 °C, the process is regarded as sublimation, requiring a higher amount of latent heat, so 1 mm day⁻¹ is equivalent to 32.95 W m⁻².

As an example, in the drainage basin of Lake Michigan, the increase in rate of latent heat flux between the 1981–2000 period and the 2081–2100 period is greater when simulated by LBRM than simulated by CGCM3 directly, except during the month of December (Fig. 1). Some of the greatest discrepancies occur during the spring, when soil moisture is generally plentiful, although there are also large discrepancies during the summer and fall. The annual mean difference is about 15 W m⁻², equivalent to about 0.5 mm day⁻¹ or nearly 200 mm/year. Another run of a GCM (the Geophysical Fluid Dynamics Laboratory CM2.0) and a corresponding run of LBRM are not shown here, but yielded similar results. Other Great Lakes drainage basins (not shown) also have similar results, demonstrating consistency in the excess of latent heat flux derived from LBRM over that directly computed by GCMs.

The changes in surface net radiation calculated by CGCM3 (downward solar + downward longwave – reflected solar – upward longwave) are also shown for reference. The annual mean increases in net radiative flux are even smaller than the increases in latent heat flux in CGCM3. If we ignore the ground heat flux and snowmelt terms in Eq. (1), this indicates a reduction in the Bowen ratio (sensible heat flux divided by latent heat flux). To the extent that it was evaporated, the increase in precipitation in the future by an annual mean of 0.26 mm day⁻¹, equivalent to 7.5 W m⁻² of latent heat flux, can be taken to largely account for the excess of change in ET over change in net radiation in CGCM3.

Additionally, some of the discrepancy between CGCM3-calculated latent heat flux changes and net radiation can be accounted for by ground heat flux and snowmelt, which are not directly quantified in CGCM3 output. Typical monthly mean values of the sum of these two fluxes deduced from GCM energy budgets are in the range of ± 10 W m⁻². Mean values of ground heat flux over several years will approach zero, so the annual mean is accounted for by the latent heat of snowmelt, with typical values of around 3 W m⁻².

When the delta method is applied to LBRM, the GCM's air temperature is strongly influenced by its calculated ET. But when executing the LBRM, the GCM's air temperature is regarded as correct and fixed, while the LBRM's projected ET can be very different from that in the GCM.

Observed relationship between air temperature and ET

Observed data on air temperature, latent heat flux, and sensible heat flux can be used to examine the range of validity of the proxy relationship between air temperature and PET used under the LBRM. Observed values of latent heat flux, sensible heat flux, and air temperature were acquired from the flux tower located in Park Falls, Wisconsin, USA, a part of the AmeriFlux network, a subset of the global FLUXNET network

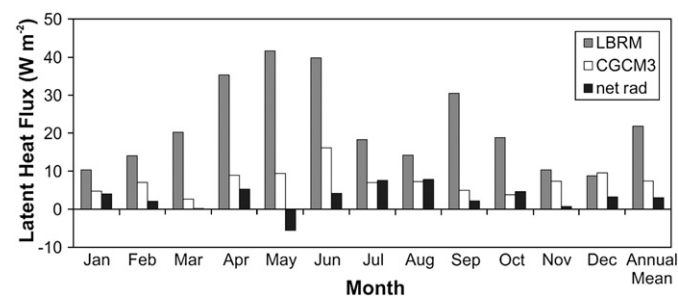


Fig. 1. Changes in latent heat flux from the Lake Michigan drainage basin for the 2081–2100 period minus the 1981–2000 period as simulated by the Large Basin Runoff Model driven by CGCM3, compared to that predicted directly by CGCM3, as well as the change in net radiation at the surface in the CGCM3.

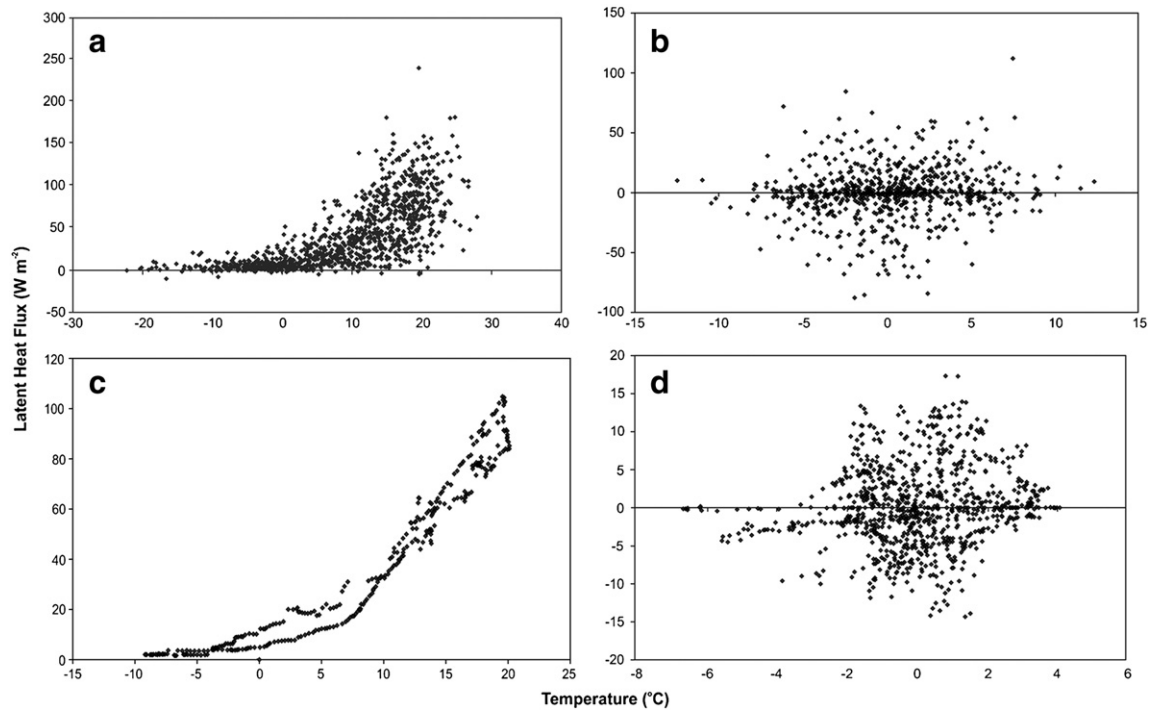


Fig. 2. Scatterplots of latent heat flux vs. air temperature at the Park Falls, Wisconsin Ameriflux site, for (a) all daily averaged data, (b) filtered for short-term variability (less than one month), (c) the mean annual cycle, and (d) filtered for long-term variability (greater than a month, but not associated with the mean annual cycle).

(Baldocchi et al., 2001). These data were acquired on an hourly basis, and were first averaged over individual days. Fig. 2a shows a scatterplot of these data for all available dates (1997–2001). Then we filtered the data into three modes of variability: the annual cycle, long-term variability (roughly longer than a month), and short-term variability. Starting with the daily mean values, 29-day running means were calculated. The difference between the daily mean data and the corresponding 29-day running mean data is considered the short-term variability and is shown in Fig. 2b. Next, for each day of the year, the 29-day running

mean values centered on that day within each year were averaged. These values, representing the mean annual cycle, are plotted in Fig. 2c. The difference between the 29-day running mean values for each individual year from the mean annual cycle value is considered the long-term variability, and is plotted in Fig. 2d.

The raw daily mean data in Fig. 2a show a distinct relationship between latent heat flux and air temperature, with additional variability superimposed on it. There is a tighter correspondence between the two when only considering the mean annual cycle of each of these

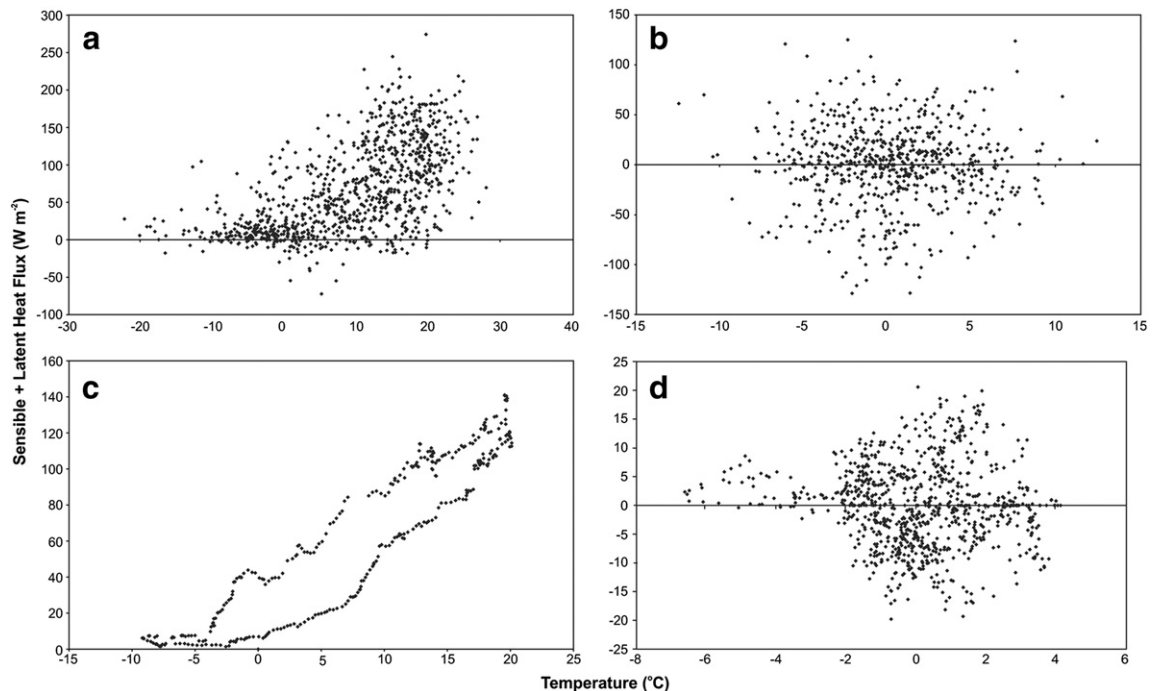


Fig. 3. As in Fig. 2, but for latent heat flux plus sensible heat flux (proportional to an approximation of potential ET) vs. air temperature.

variables (Fig. 2c). However, when considering other modes of variability of air temperature and latent heat flux, whether short-term (Fig. 2b) or long-term (Fig. 2d), there is at best a much weaker relationship between the two or perhaps no correspondence at all.

The same analysis was carried out (Fig. 3) using latent heat flux plus sensible heat flux (LH plus SH divided by L approximates PET). There is a greater amount of sensible heat flux during the spring than during the fall, so the spring and fall branches of the mean annual cycle are separated more (Fig. 3c) than when analyzing the latent heat flux alone (Fig. 2c). But similar to the latent heat flux alone, the short-term and long-term variability show no systematic relationship between PET and air temperature (compare Figs. 2b, d, 3b, and d).

These results demonstrate that the proxy relationship between air temperature and PET is best applied when the mean annual cycle of temperature is a dominant mode of variability. The best causal explanation of the proxy relationship seems to be that the increased solar radiation input and consequent increased net radiation during the summer promote both higher air temperature and greater PET. On the other hand, departures from the mean annual cycle of air temperature are poorly correlated with ET or PET, so the proxy relationship breaks down when forcing by solar radiative heating is not a primary driver of the temperature variations. Cyclic variability in temperature can lead to canceling errors in PET when averaged over longer terms, but secular changes in temperature can lead to systematic biases in PET when the proxy relation is taken to apply to them.

Alternative energy adjustment formulation of LBRM

As an attempt to better apply the LBRM to climate change questions, we have developed a variant of the delta method that is more consistent with the energy budget projected by GCMs, and more in keeping with the concepts of energy-conserving ET formulations like Priestley and Taylor (1972). Instead of using the full Priestley–Taylor formulation, we use the fact that PET is approximately proportional to net radiation minus ground heat flux, which is equivalent to

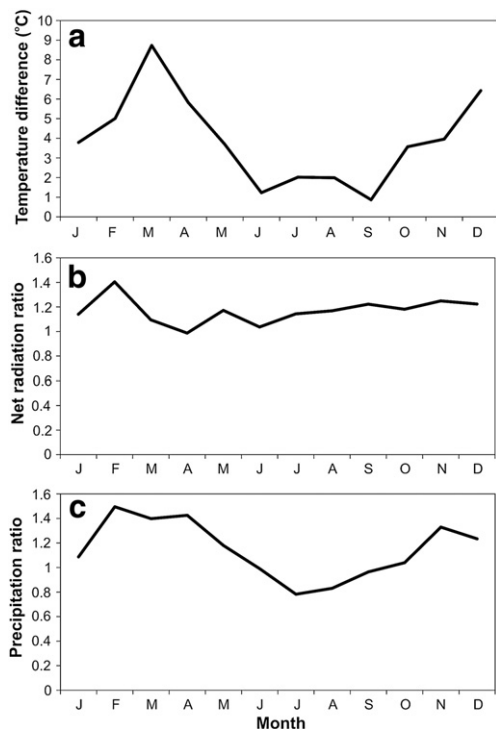


Fig. 4. Climatological changes for the Lake Superior basin, using CGCM3, in (a) surface air temperature, expressed as a difference in degrees Celsius, 2081–2100 period minus 1981–2000; (b) ratio of surface net radiation, 2081–2100 divided by 1981–2000, and (c) ratio of precipitation.

latent heat flux plus sensible heat flux Eq. (1). This assumes that changes in temperature are not large, so that the slope of the saturation vapor pressure curve with respect to temperature (a term in the Priestley–Taylor equation) is not changed by a large amount.

Therefore, instead of adjusting the air temperature using the change given by the GCMs and then calculating the PET using Eq. (2), the PET was directly adjusted by the ratio of future values of latent plus sensible heat flux to those of historical periods as represented by the GCM. This leads to a smaller adjustment in PET, in keeping with the energy available within the GCM. The LBRM was again driven by the CGCM3. Both the revised method (indicated as “energy adjustment” or “EA”) and the older air temperature adjustment method (“TA”) were run.

To simulate evaporation from the lake in order to derive the full lake basin water budget as in Croley (1990), the Large Lake Thermodynamics Model (LLTM, Croley 1989) was also run, driven by each of these GCMs’ outputs of air temperature, humidity, wind speed, and cloud cover. The formulation of LLTM includes adjustments to the atmospheric variables observed over land to make them more consistent with over-lake conditions. Our use of LLTM is consistent with Croley (1990) and other applications.

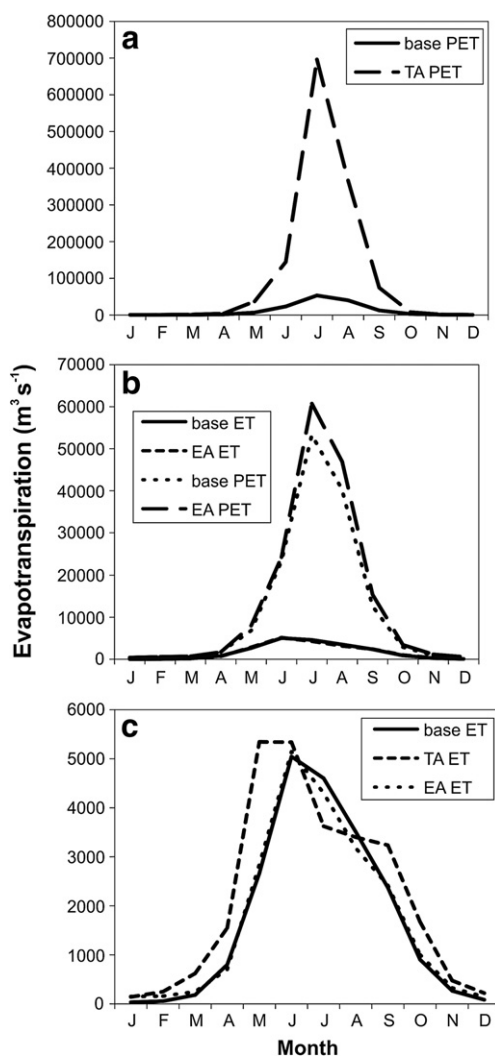


Fig. 5. (a) Potential ET (cubic meters per second) over the land portion of the Lake Superior drainage basin in the base case and for future projections using the temperature adjustment method driven by the CGCM3 model. Actual ET is not shown here because on the scale of this chart, it is virtually indistinguishable from zero. (b) Potential and actual ET for the base case and the future using CGCM3 results under the energy adjustment method. (c) Actual ET under the base case and future projections using CGCM3 results and both the temperature adjustment and energy adjustment methods.

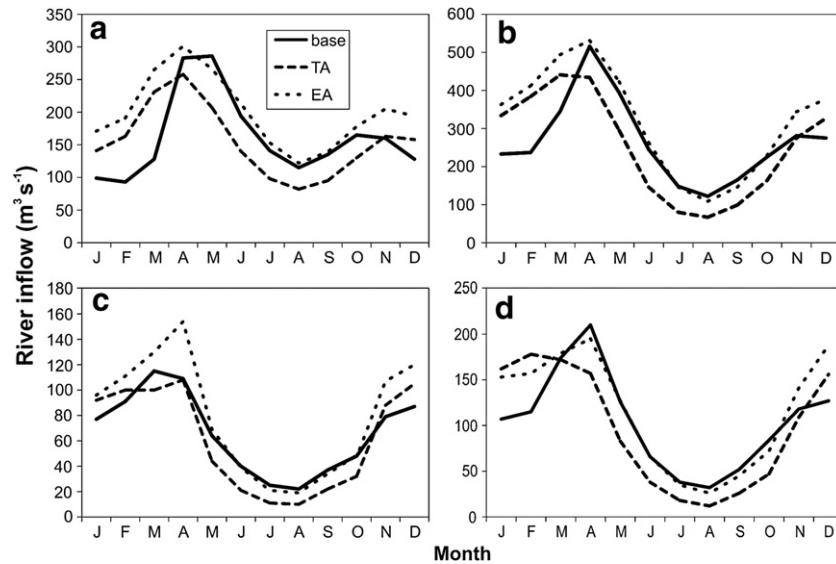


Fig. 6. Climatological simulated river outflow integrated across each drainage basin (cubic meters per second) in the base case as well as using the temperature adjustment and energy adjustment methods for projections to 2081–2100 based on the output from the CGCM3 model. (a) Lake Superior (b) Lake Michigan-Huron, (c) Lake Erie, (d) Lake Ontario.

Fig. 4 shows the outputs from CGCM3 that are used to drive LBRM. The temperature differences (Fig. 4a) range from greater than 8° in March to less than 1° in September. The ratio in net radiation (Fig. 4b) mostly ranges between about 1 and 1.2, except in February, when it rises to 1.4. The precipitation ratio (Fig. 4c) shows increased precipitation during most of the year, but a decrease of about 20% during July and August.

Using the TA method driven by CGCM3, there is a very large increase in projected PET relative to the base case (Fig. 5a shows the areal average over the terrestrial portion of the Lake Superior basin as an example). At the peak during July, PET increases by a factor of 10. Among the most significant sub-basins yielding this result is Lake Superior sub-basin 13, which is located by the eastern end of Lake Superior and includes the drainage of the Montreal River. In this sub-basin, the calibrated value of T_b is 1.1°C and the air

temperature is increased by 4.51°C . So $e^{\Delta T/T_b}$ is 60.34, and PET increases by this factor for this sub-basin. Also notable is the sub-basin with the largest area, Lake Superior sub-basin 19, corresponding to the Nipigon River, next to the north-central part of the lake. In this sub-basin, T_b is 2.0°C and the air temperature is increased by 4.75°C , yielding an increase in PET by a factor of 10.75. The extreme responses of PET in a few sub-basins help to skew the area-weighted arithmetic mean values shown in Fig. 5a, but indicate the potential for drastic changes in PET when using LBRM.

Using the EA formulation, projected PET increases by a smaller amount relative to the base case (Fig. 5b), corresponding to the net radiation ratio shown in Fig. 4b. On the scale used in Fig. 5b, ET under the base case and the EA case are barely distinguishable. Fig. 5c shows the contrast between the ET driven by the TA and EA methods. While the TA method shows large increases in ET except during the summer, the EA method

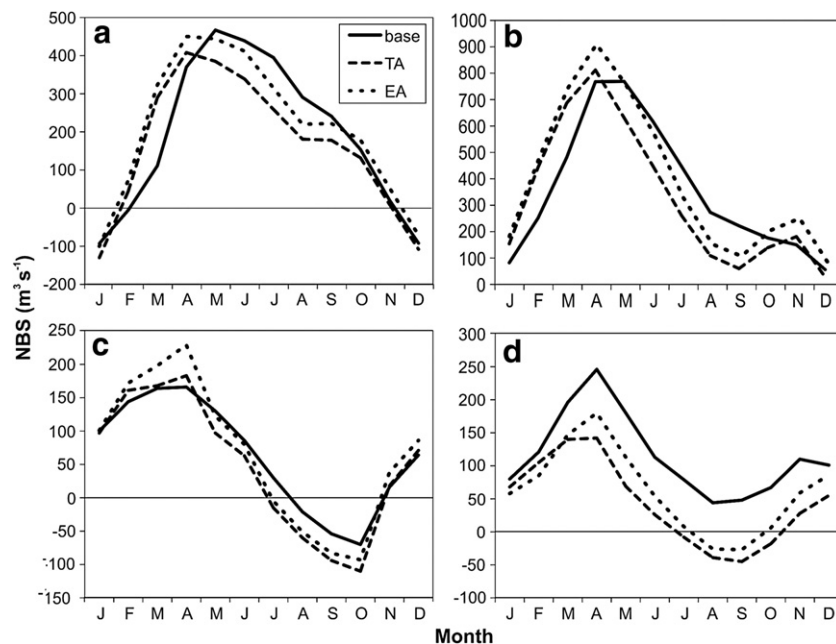


Fig. 7. Climatological simulated net basin supply for each drainage basin (cubic meters per second) in the base case as well as using the temperature adjustment and energy adjustment methods for projections to 2081–2100 based on the output from the CGCM3 model. (a) Lake Superior (b) Lake Michigan-Huron, (c) Lake Erie, (d) Lake Ontario.

has much more limited increases. During July and August, the reduced precipitation in the future time period of CGCM3 (Fig. 4c) results in reduced ET under both the TA and EA method. In particular, the TA method becomes very moisture deficient, so that in contrast to the large increase in June ET relative to May in the base case and EA case, ET in the TA case levels out in June. This is followed by a large reduction of ET in July in the TA case, in contrast to a lesser drop in the base and EA cases.

River outflow, when using the CGCM3 as a driver (Fig. 6), is projected to increase during the winter months due to increased snowmelt and liquid precipitation during the winter. During the warm season, the TA case projects sizable reductions in outflow. The river outflow from the EA case, however, tracks quite closely with the base case. In the Lake Superior basin, the annual mean river outflow is reduced by 3% in the TA case, while in the EA case, it is increased by 25%.

Net basin supply (NBS) is defined as the river flow from the drainage basin into the lake, plus the precipitation over the lake, minus the evaporation over the lake. It does not include inflow from other Great Lakes upstream, but when combined with such inflow, it results in a combination of outflow from the lake and change in lake level with time. The NBS (Fig. 7) is generally lower in future projections than in the base case during the warm season, but higher during the winter. The exception is the Lake Ontario basin, where NBS is lower throughout the year. In all basins and throughout the year, the TA case shows a lower NBS than the EA case. In the Lake Superior basin, the annual mean NBS is reduced by 13% in the TA case, while in the EA case, it is increased by 10%.

NBS on a monthly basis was input to the Coordinated Great Lakes Regulation and Routing Model (CGLRRM), which calculates lake levels and outflow on a daily basis. This model is not fully functional for Lake Ontario, so only results for the mean annual cycle of lake levels for Lakes Superior, Michigan-Huron, and Erie are shown in Fig. 8. All future projections show a shift toward earlier winter minima and summer maxima in lake levels, due to enhanced winter snowmelt and liquid precipitation. For example, while the base case has its maximum water levels for Lakes Michigan-Huron in August, both the TA and EA cases have theirs in July. The TA method shows drops in lake levels, while the EA method moderates the increase in ET enough that the net effect is a rise in lake levels, as much as 41 cm in Lake Michigan-Huron.

The same model runs were performed using another GCM, the GFDL CM2.0 (Delworth et al., 2006), with an A1B emission scenario (somewhat lower greenhouse gas concentrations than A2). The results of these runs are shown in the Supplementary Figures. The GFDL CM2.0 shows larger decreases in summer precipitation than CGCM3, resulting in larger projected decreases in runoff, NBS, and lake levels in both the TA and EA cases. In contrast to CGCM3, NBS and lake levels decrease in the EA case, although less than in the TA case. Summaries of the annual mean trends using both the CGCM3 and GFDL CM2.0 models are shown in Table 1.

These results demonstrate that a modified formulation of a land hydrologic model that keeps it more consistent with the energy budget simulated by a GCM can affect the magnitude, and sometimes the sign, of the sensitivity to climate change of the amount of ET, river discharge, net basin supply, and lake level simulated by the model.

Discussion

In understanding the implications of the overall discrepancy between the ET predicted by GCMs and that predicted by a hydrologic model driven by the same GCM, the following are relevant points:

1. One may well ask whether the two results being different means that one is necessarily correct. It does not directly imply this, but does show that the system of the LBRM driven by GCM output lacks self-consistency. Within the GCM, the air temperature is strongly influenced by the assumption that the ET predicted by

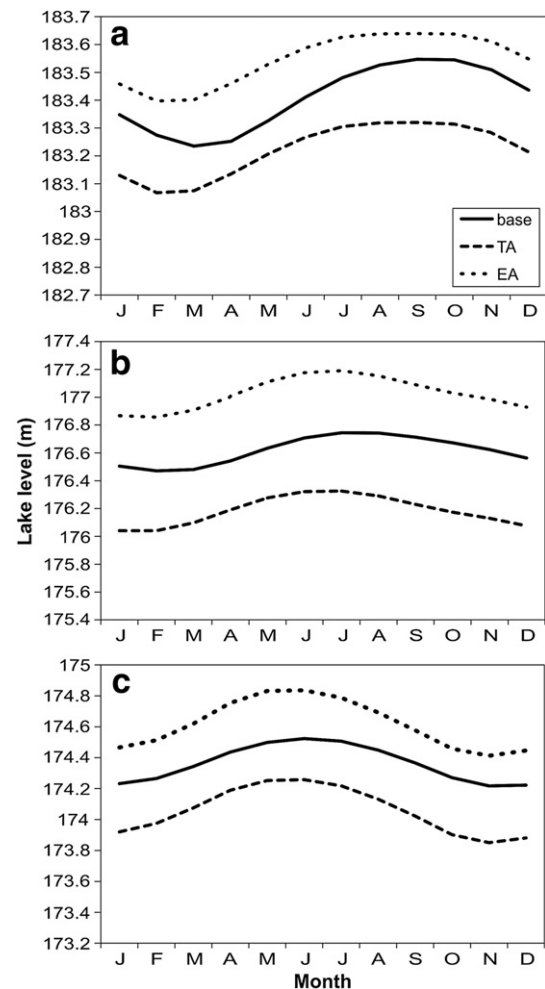


Fig. 8. Climatological lake levels (meters above mean sea level) in the base case compared to the temperature adjustment and energy adjustment cases using CGCM3 for (a) Lake Superior (b) Lake Michigan-Huron, and (c) Lake Erie.

the GCM is correct. But when using the delta method, the GCM's air temperature and precipitation are regarded as correct, while the LBRM can calculate a drastically different ET from that in the GCM, as shown in Fig. 1.

2. A fundamental assumption underlying the formulation of LBRM is that a single proxy relation between air temperature and PET is valid for all timescales and climate regimes. However, the causal relationship seems to be that temperature and ET are positively correlated because both are dependent on an influx of energy from radiation, mainly solar radiation.

The relationship between air temperature, PET, and ET is different between the annual cycle and other modes of variability (Figs. 2 and 3). It cannot be presumed that climate change caused by greenhouse gases will behave similarly to the annual cycle rather than other modes of variability. The usual caution regarding values of variables lying outside of the range over which an empirical relationship is determined, and the caveat that correlation is not the same as causation, are both amplified by the additional complication of different mechanisms for warming caused by season vs. warming caused by greenhouse gases.

The assumption of validity of the same temperature proxy in different climate regimes is functionally equivalent to assuming that air temperature actually causes PET, and confusion can arise on this point. The literature generally stops just short of actually stating this, such as in section 3.2 of the IPCC 4th Assessment Report Working Group II (Kundzewicz et al., 2007), which starts with, "With higher temperatures, the water-

Table 1

Summary of annual mean results from the LBRM and LLTM for each lake's basin. Quantities in parentheses indicate the change from the base case, expressed in percent except for the lake level.

	Evapotranspiration (cubic meters per second)	River discharge (cubic meters per second)	Net basin supply (cubic meters per second)	Lake level (meters)
<i>Lake Superior</i>				
Base	1710	1607	1916	183.41
GFDL TA	1968 (+15%)	1351 (−16%)	1074 (−44%)	182.70 (−0.71)
GFDL EA	1517 (−11%)	1801 (+12%)	1548 (−19%)	183.08 (−0.33)
CGCM3 TA	2156 (+26%)	1564 (−3%)	1658 (−13%)	183.22 (−0.19)
CGCM3 EA	1717 (<+1%)	2004 (+25%)	2100 (+10%)	183.54 (+0.13)
<i>Lake Michigan-Huron</i>				
Base	3922	2637	3578	176.62
GFDL TA	4372 (+11%)	2064 (−22%)	1914 (−47%)	174.51 (−2.11)
GFDL EA	3540 (−10%)	2839 (+8%)	2700 (−25%)	175.63 (−0.99)
CGCM3 TA	4806 (+23%)	2525 (−4%)	3300 (−8%)	176.18 (−0.44)
CGCM3 EA	4112 (+5%)	3179 (+21%)	3960 (+11%)	177.03 (+0.41)
<i>Lake Erie</i>				
Base	1108	673	629	174.36
GFDL TA	1207 (+9%)	518 (−23%)	222 (−65%)	172.99 (−1.37)
GFDL EA	1013 (−9%)	712 (+6%)	413 (−34%)	173.72 (−0.64)
CGCM3 TA	1369 (+24%)	620 (−8%)	483 (−23%)	174.06 (−0.30)
CGCM3 EA	1186 (+7%)	803 (+19%)	662 (+5%)	174.62 (+0.26)
<i>Lake Ontario</i>				
Base	1062	1047	1154	–
GFDL TA	1266 (+19%)	846 (−19%)	272 (−76%)	–
GFDL EA	973 (−8%)	1138 (+9%)	562 (−51%)	–
CGCM3 TA	1356 (+28%)	970 (−7%)	436 (−62%)	–
CGCM3 EA	1167 (+10%)	1156 (+10%)	619 (−46%)	–

holding capacity of the atmosphere and evaporation into the atmosphere increase...”, and other examples are numerous.

- As shown in Fig. 5, GCM-projected increases in temperature can cause the LBRM to project increases in PET by very large factors. This is in part due to the removal, in future scenarios, of the integral constraint on energy available for ET Eq. (2).

Another red flag is raised by the fact that the calibrated formulas for PET in LBRM in most sub-basins are considerably more sensitive to air temperature than is the saturation humidity. One can derive an approximate exponential form of water vapor pressure by assuming that it takes the form $e^* = Ae^{T/T_b}$, just as in Eq. (2), then solving for T_b using $de^*/dT = e^*/T_b$. Values of e^* can be acquired from tables or from equations that give close approximations, but all agree that for a reference temperature of 0 °C, the best fit for T_b is 13.8 °C, while at 30 °C, T_b is 17.5 °C. Compare this to most calibrated values less than 5 °C in LBRM, and some less than 2 °C.

- Some other hydrologic models are used that depend on air temperature as a proxy for ET, and caution is warranted about their use in climate change scenarios. This includes studies that use the methods of Thornthwaite (1948) and the Jensen-Haise scheme investigated by Milly and Dunne (2011). Hobbins et al. (2008) have shown that potential evapotranspiration, as indicated by pan evaporation, can frequently decrease even in the context of increasing air temperature, in contrast to any temperature proxy method.

In a broader sense, analysts of the impacts of greenhouse gas-induced climate change need to exercise caution and ask this question: Is the correlation between air temperature and the impacted system of interest really caused by air temperature, or might it rather be due to some other aspect of the seasonal cycle, such as the amount of sunlight?

Conclusions

An undesirable situation occurs when GCMs are used to drive an off-line hydrologic model that uses air temperature as a proxy for potential evapotranspiration, in comparing recent history to a future with

enhanced greenhouse gas concentration. The off-line hydrologic model examined here projects a considerably larger increase in evapotranspiration than do the GCMs themselves. Thus we find the paradoxical state that in using the GCM results as input to the hydrologic model, one is taking the GCM temperatures at face value, while predicting a drastic alteration to the GCMs' surface energy budget (namely, latent heat flux), that strongly influences those temperatures.

It was further found that correlation between ET or PET and air temperature is mainly due to the very strong relationship when considering only the mean annual cycle. Departures from the mean annual cycle of air temperature and ET or PET are poorly correlated with one another. This implies that solar energy input is the strongest driver of PET, and air temperature also responds to it. This calls into question the validity of the proxy relation for application to variability other than the annual cycle, including greenhouse gas-induced climate change scenarios.

When using a modified version of LBRM in which adjustments to PET are based on changes in the net radiative energy projected by GCMs, rather than assuming the calibrated proxy relationship, the previously projected (Croley, 1990, 2003; Hartmann, 1990a; Chao, 1999; Lofgren et al., 2002; Angel and Kunkel, 2010) reductions in net basin supply and drops in lake levels are moderated or reversed. The case using the GFDL CM2.0 as input had a very large reduction in summertime precipitation. This led the new “energy adjustment” method to project a reduction in net basin supply and a drop in lake levels, although of lesser magnitude than the extreme changes using the older “temperature adjustment” method. Using the CCCma CGCM3 as input, the EA method projected increased net basin supply and rising lake levels, opposite in sign to the trends projected using the TA method.

The EA method is not intended to be the final answer to changes in the water budget and lake levels associated with climate change. It is rather intended to prompt a revisitation of the nearly exclusive use of the TA method in association with LBRM as the method of projecting climate change impacts on the water budget of the Great Lakes basin. Indeed, in impact and assessment contexts, it often seems as if it is not recognized that net basin supply and lake level projections do not come directly from GCMs themselves, but that an intermediate step is necessary, whose form can affect the outcome. Even though Manabe et

al. (2004), Milly et al. (2005), and Kutzbach et al. (2005) have used GCMs to project increased net basin supply in the future, which necessarily implies rising lake levels, their studies have lacked the specific focus on lake levels and that extra step of analysis that have attracted the attention of those who do impact and assessment studies. A potential future study would be to do similar analyses to these, using more current GCMs, and extend the results so that they yield lake level projections.

While this study specifically examines one off-line hydrologic model, it likely applies also to other similar models, and should serve as a caution to their users. In a broader sense, when looking at the impacts of temperature increases due to enhanced greenhouse gasses on various natural and human systems, the investigator needs to be sure that air temperature is a proper proxy for the forcing of the system of interest before using it as such.

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