Methodological Approaches to Projecting the Hydrologic Impacts of Climate Change*

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ABSTRACT: Climate change due to anthropogenic greenhouse gases (GHG) is expected to have important impacts on water resources, with a variety of societal impacts. Recent research has shown that applying different methodologies to assess hydrologic impacts can lead to widely diverging projections of water resources. The authors classify methods of projecting hydrologic impacts of climate change into those that estimate potential evapotranspiration (PET) based on air temperature and those that estimate PET based on components of the surface energy budget. In general, air temperature–based methods more frequently show reductions in measures of water resources (e.g., water yield or soil moisture) and greater sensitivity than those using energy budget–based methods. There are significant trade-offs between these two methods in terms of ease of use, input data required, applicability to specific locales, and adherence to fundamental physical constraints: namely, conservation of energy at the surface. Issues of uncertainty in climate projections, stemming from imperfectly known future atmospheric GHG concentrations and disagreement in projections of the resultant climate, are compounded by questions of methodology and input data availability for models that connect climate change to accompanying changes in hydrology. In the joint atmospheric–hydrologic research community investigating climate change, methods need to be developed in which the energy and moisture budgets remain consistent when considering their interaction with both the atmosphere and water resources. This approach should yield better results for both atmospheric and hydrologic processes.

KEYWORDS: Climate change; Surface processes; Water resources; Evapotranspiration

1. Introduction

Greenhouse gas (GHG)–driven anthropogenic climate change (ACC) has led to warmer temperatures at the surface and throughout the troposphere, as supported historically by a combination of modeling studies and global observations. Current climate models and earth system models, which are developed from fundamental theory, project this warming to continue into the future (Alley et al. 2007; Meehl et al. 2007). The trends in GHG concentration and climate can influence many aspects of the earth's physical, ecological, and human systems. Many of these key impacts are manifested in the hydrologic cycle (Kundzewicz et al. 2007). The wide-ranging potential effects of ACC on hydrology have been addressed in prior studies with varying methodology (e.g., Wood et al. 1999; Held and Soden 2006; Angel and Kunkel 2010; Milly and Dunne 2011). These studies have highlighted the possibility of the role of climate change on altered streamflow and inland water body levels, causing concerns for hydrologic planners and water resource managers (Brekke et al. 2009).

The complexity of the interactions between surface hydrology and the atmosphere is increasingly a topic of climate change studies. Mahmood et al. (Mahmood et al. 2010) assert the importance of an assessment of climate and climate change that goes beyond the traditionally well-observed variables of air temperature and precipitation. Furthermore, they find that the index of radiative forcing function, which has been defined to describe increases in GHGs, is not adequate to characterize the complete set of potential forcings of climate change. They propose an expansion of climate change metrics to include the redistribution and magnitude of latent and sensible heat fluxes from the land surface, precipitation, and atmospheric moisture convergence and changes in local and regional-scale gradients of radiative fluxes. These all play roles in the interaction between the budgets of surface energy and water. As Overgaard et al. (Overgaard et al. 2006) assert, ''Located at the borderline between atmosphere and hydrology, the land-surface provides the link between several scientific disciplines.''

Prior reviews have surveyed the *results* of studies projecting hydrologic impacts of climate change at the global scale (Kundzewicz et al. 2007; Seneveratne et al. 2010) or at the national or continental scale (e.g., Lettenmaier et al. 2008). Here, we survey the *methods* for projecting the influences of climate change on hydrology with the goal of understanding their methodological strengths and weaknesses. Specifically, we focus on the methods that calculate evapotranspiration (ET) and potential evapotranspiration (PET) in future climate projections. The reason for this focus is that ET and PET have been projected using a wide variety of methods that may be influenced by changing climate; therefore, biases in the methods may lead to divergent projections of hydrology in a changing world. We also make some recommendations for cooperation between the atmospheric and hydrologic communities, with a goal of creating consistency in modeling results in terms of energy and water budgets at the surface–atmosphere interface.

In section 2, we will cover some of the broad concepts that underlie surface processes that are relevant to both hydrology and atmosphere, particularly the intersection between surface energy and water budgets. In section 3, we discuss how surface processes are of interest in both the realms of atmospheric and hydrologic science but, because of different variables of interest, different methods have often been developed, with conflicting results. Section 4 gives a definition of PET and presents various alternative methods that have been used to calculate it. Section 5 presents the results of several studies that used temperature proxy–based methods to calculate PET under climate change scenarios. Section 6 similarly looks at studies using energy budget–based methods for PET and also studies that compare the results using temperature proxy–based and energy budget–based methods. In section 7, we illuminate a few examples of special considerations based on particular regions. Section 8 briefly discusses issues of the uncertainty of joint climatic–hydrologic projections and whether these projections can yield practical value in terms of impacts and adaptation related to water resources. In section 9, we give an overall discussion and outline a vision for producing climatic projections in which the methodologies for surface processes are shared among hydrologic and atmospheric scientists and serve the union of their needs. Finally, section 10 presents conclusions.

2. Broad concepts

In this review, we consider climate in terms of the atmosphere and land surfaces and time scales of at least a few decades: that is, relevant to climate change driven by anthropogenic GHGs. The initial conditions of the physical climate that require long time scales to come into equilibrium (e.g., the ocean and cryosphere) can drive climate on decadal and multidecadal time scales (Pielke 1998; Giorgi 2005; Meehl et al. 2009). Because we will concentrate on

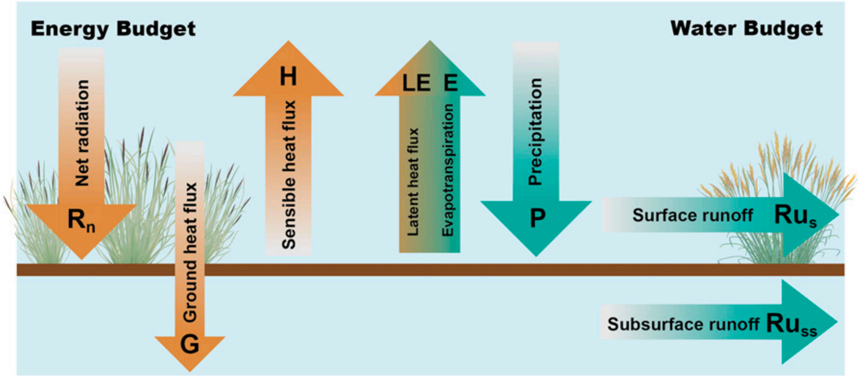

Figure 1. A schematic illustration of the energy budget and water budget of a land surface and their point of intersection. The latent heat of evaporation per unit mass *L* is only very weakly dependent on temperature, so ET and latent heat flux are proportional to one another. Therefore, ET has an equivalent influence on both the heat and water budgets and impacts the other terms of both budgets.

interactions between the atmosphere and terrestrial surfaces, GHG concentrations as well as ocean and cryosphere conditions can be considered forcings that are extrinsic to the system at hand, and we therefore regard climate as a boundary value problem.

The basic components of surface energy and water budgets and their intersection are illustrated in Figure 1 (concepts from, e.g., Budyko 1974). The components of the surface energy budget are net radiation R_n (the net amount of energy exchanged from the surface with the sun, atmosphere, and outer space via shortwave and longwave radiation); latent heat flux (LE) carried by water evaporating from the surface or transpiring from plants; sensible heat flux (SH) that directly transfers heat between the surface and immediately overlying atmosphere; and ground heat flux G that diffuses between the surface and subsurface. These components must be in balance with one another. The components of the surface water budget are precipitation P as a source and sinks that include evapotranspiration E either directly from the ground surface or transpired through plants, surface runoff R_s, and subsurface runoff R_{ss}. A limited amount of water can be stored in the soil within the rooting zone of local vegetation, but in the long term the water flux terms must be in balance. Because the latent heat of evaporation per unit of water L is a weak function of temperature, the E term in the water budget and the LE term in the energy budget are nearly proportional, constituting a direct linkage between these two budgets and the conservation laws that govern them. This creates an indirect linkage among all of the terms in these two budgets. It further implies that, since ET is an exchange of water vapor that is influenced by the conditions of both the surface and the atmosphere and affects both, conceptualizing the surface as being forced by the atmosphere or vice versa creates an incomplete picture. The more complete picture includes the surface and atmosphere's influence on each other.

Another conservation law that is important to hydrology under altered global climate is the conservation of water within the atmosphere. Water vapor enters the atmosphere via evapotranspiration from land and water surfaces; it can be transported through the atmosphere; and it is removed by precipitation processes and, to a lesser extent, surface condensation (dew). Globally, the source (ET) and sink (precipitation) terms of atmospheric water vapor must be equal. Changes in these processes with climate can affect the spatial distribution of precipitation and ET (e.g., Held and Soden 2006; Trenberth et al. 2007), but global conservation of atmospheric water vapor must be satisfied. Although the global atmospheric water budget will not be discussed in detail in this paper, there is a danger that local impact studies may use formulations of ET that are inconsistent with the GCMs that are driving them. If similar inconsistent assumptions are made over all land areas, their sum over a global domain can lead to imbalances in the atmospheric water vapor budget, possibly severe. The approximate increase in actual ET with temperature in ACC scenarios is around $2\%–3.5\%\,^{\circ}\mathrm{C}^{-1}$ (Allen and Ingram 2002; Held and Soden 2006; Lorenz et al. 2010), so projections of local changes in ET that depart strongly from this number and are not coupled to a global atmospheric water vapor budget should be viewed with caution.

3. Meteorological and hydrological motivations for understanding surface processes

Atmospheric and hydrologic research and modeling have differing goals with overlapping methods and processes. From a hydrologic perspective, ET is crucial for calculation of several variables, including soil moisture, surface runoff, soil water percolation, and water yield of a drainage basin (Shaw et al. 2010). From a meteorological perspective, ET is a source of water vapor to the atmosphere and represents a loss of latent heat from the surface, therefore modulating other terms in the surface energy budget (Budyko 1974; Houghton 2002). For example, for a constant net input of solar radiation and downward longwave radiation, an increase in ET must be offset by a decrease in upward longwave radiation, sensible heat flux, and downward heat flux into the ground. This implies a decrease in the surface temperature and reduced heat input to the atmosphere, which forces atmospheric dynamics. The importance of surface hydrologic processes for atmospheric modeling, especially at time scales longer than a small number of days, was recognized quite early in the process of developing global general circulation models (GCMs). This led to the incorporation of simple formulations of soil moisture and evapotranspiration in climate models (Manabe and Holloway 1975).

The difference in desired outputs between the atmospheric and hydrologic communities has led to the adoption of different methodologies for calculating ET. Hydrologic studies strive to accurately predict streamflow and regularly use relationships calibrated using the most readily available atmospheric variables (air temperature and precipitation). On the other hand, atmospheric models frequently use parameterizations of the surface–atmosphere fluxes of moisture and energy to predict temperature and humidity in the atmospheric boundary layer, and these conditions can ultimately affect conditions throughout the atmosphere.

4. Potential evapotranspiration

4.1. Definition

PET is a maximum value of ET, with ET approaching PET under wet conditions (Milly and Dunne 2011). In the dichotomy between energy-limited and moisture-limited ET, PET represents the amount of ET under energy-limited conditions. We group methods of calculating PET into two classes: temperature proxy based, in which air temperature is used to infer an amount of energy available for ET, and energy budget based, in which terms of the surface energy budget are available and directly drive PET.

4.2. Temperature proxy–based potential evapotranspiration

The origin of using air temperature as a proxy for PET is unclear, as it is applied in many older literature sources. In developing a scheme for categorizing geographic regimes of climate, Thornthwaite (Thornthwaite 1948) lists climatic variables that have been widely observed with good accuracy but notes that ET is conspicuously missing. He states that the relative magnitude of precipitation and ET defines a climatic zone as wet or dry, and thus a reliable parallel is sought between PET and a more directly and routinely observed environmental variable. Thornthwaite (Thornthwaite 1948) found that near-surface air temperature is a more reliable predictor of PET than other candidate predictor variables that he investigated, including net solar radiation, despite acknowledging that solar radiation as ‘‘the basic factor.’’ Other investigators who have also classified climatic regimes on a similar conceptual basis include Köppen (Köppen 1900) and Holdridge (Holdridge 1947). The PET algorithm of Thornthwaite (Thornthwaite 1948) was also used as a basis for the Palmer drought severity index (PDSI; Palmer 1968), which is still widely used to characterize drought on an operational basis. Other air temperature proxy–based formulations of PET include Blaney and Criddle (Blaney and Criddle 1950) and Croley (Croley 1983); in some cases, solar radiation is used in conjunction with air temperature to determine PET (e.g., Jensen and Haise 1963).

4.3. Energy budget–based PET

As a means to represent the energy limitations of PET, the Priestley–Taylor method calculates PET as a function of incoming solar radiation R_n and the heat flux density G to the ground, as modified by the air temperature and pressure. Since its inception, other energy budget–based methods have been developed, and these methods generally outperform temperature-only methods such as those described in section 4.2 (Amatya et al. 1995; Vorosmarty et al. 1998; Lu et al. 2005). Further energy-driven approaches include a combined approach known as the Penman–Monteith method (Monteith 1973), which requires inputs of net radiation R_n, air temperature, wind speed, and relative humidity. While this method requires a large suite of observed values, it is considered a reference benchmark for other methods and is used in many newer applications of Soil and Water Assessment Tool (SWAT) models. In global climate models, a land surface energy balance (e.g., balance among R_n, soil heat flux, latent heat flux, and sensible heat flux) determines the partitioning of available surface energy to ET and is limited by either the incoming energy or soil moisture (Seneveratne et al. 2010). The bucket model of Manabe and Holloway (Manabe and Holloway 1975) is an early example, with a major advance being made with the advent of schemes that included more detailed vegetation processes (Dickinson et al. 1986; Sellers et al.1986). Because climate models typically include both surface energy budget and soil moisture, a coupled energy balance method is a scheme that fits well into these models.

With respect to the surface energy balance approach, many studies have used atmospheric reanalysis products to investigate global and regional PET. For example, Trenberth et al. (Trenberth et al. 2007) uses several atmospheric reanalysis datasets to investigate the precipitation minus ET ($P - E$) balance and notes that $P - E$ tends to be too small over land and overestimates land–atmosphere moisture recycling. A revised study over North America shows that newer reanalysis products are improved compared to older generation datasets (Trenberth and Fasullo 2013). Generally, these studies show that the $P - E$ term is largest in winter and smallest in the summer, mostly due to changes in the ET component. Overall, many studies show that using the atmospheric moisture budget to derive $P - E$ can provide better results as compared to ground-based observations and could help to constrain the water budget (Trenberth et al. 2007; Trenberth and Fasullo 2013). This is because of the errors and uncertainties associated with measuring and estimating both the P and ET components at the surface.

5. Studies applying temperature proxy–based PET

5.1. Projections

An example of applying a temperature proxy–based method of calculating PET within the context of climate change scenarios is Evans and Schreider (Evans and Schreider 2002). They used a version of the IHACRES rainfall–runoff model (Evans and Jakeman 1998) for a small river catchment in western Australia and showed that increased GHG concentrations resulted in decreased mean river flow but also increases in flood events, due to increased incidence of extremely high precipitation events.

A series of studies have been done regarding the water budget of the Laurentian Great Lakes and their drainage basin under ACC scenarios, culminating in projections of lake levels. These have largely used the land surface model of Croley (Croley 1983), known as the Large Basin Runoff Model (LBRM), to calculate runoff and water yield from land. This is paired with spatially interpolated precipitation along with evaporation from the lake calculated using the model of Croley (Croley 1989) to calculate a net basin supply of water for each lake. Climate change scenarios were created by altering the meteorological inputs (primarily precipitation and air temperature) according to changes projected by GCMs. Using this methodology, Angel and Kunkel (Angel and Kunkel 2010) ran a set of 565 GCM realizations as input, through a combination of different GCMs, GHG emission scenarios, time horizons, and different plausible initial conditions. They showed that drops in lake levels are generally expected during the twenty-first century, with considerable spread among the GCMs.

Air temperature is often used within indices that classify climatic regimes according to their level of aridity. Rubel and Kottek (Rubel and Kottek 2010) determined Köppen classifications at different time periods using climatic variables simulated under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (SRES) A1FI scenario. They show that, in comparing the 2075–2100 time period to 1975–2000, a net of 9.6% of the area originally classified under C (warm temperate) are reclassified as B (arid). Maps shown in Rubel and Kottek (Rubel and Kottek 2010), which instead compare 2075–2100 with 1901–25, show a few particular locations of this transformation—the Iberian and Anatolian Peninsulas, the eastern margin of the U.S. Great Plains, and encroachment of arid classes into some coastal regions of northern and southern Africa and Australia. They also show 3.9% of the area of class D (characterized by seasonal snow) shifting to class B, mainly in the northern part of the U.S. Great Plains as well as central Asia to the north of the Caspian and Aral Seas.

In the Arctic, results have been derived from approaches using downscaled temperature and precipitation projections in conjunction with PET calculated using Priestley and Taylor (Priestley and Taylor 1972) or Hamon (Hamon 1961) for projections of the future water balance (O'Brien and Loya 2008). However, this work has come under criticism for the arbitrariness of coefficients used in the Priestley–Taylor scheme and is likely to have overestimated the drying effect on Alaska (McAfee 2013).

5.2. Caveats to temperature proxy–based potential evapotranspiration

Several studies in recent years have struck strong notes of caution to employing a temperature proxy–based framework to parameterize changes in PET in the context of climate change scenarios. Hobbins et al. (Hobbins et al.2008) have shown that pan evaporation (generally accepted as a good indicator of PET) can actually decrease at the same time as air temperature increases. Milly and Dunne (Milly and Dunne 2011) have compared the sensitivity of PET to climate change as simulated internally by climate models with those projected using a Jensen and Haise (Jensen and Haise 1963) formulation. The projections using the air temperature–based Jensen–Haise scheme had increases in PET about 3 times as large as simulated by the GCMs. Lofgren et al. (Lofgren et al. 2011) noted that climate change-driven ET rates and the implied surface energy budgets diverged widely between the Large Basin Runoff Model (LBRM; Croley 1983) and the GCMs used to drive it. In one scenario, LBRM's PET increased by a factor of about 10 during the twenty-first century for the Lake Superior basin. Shaw and Riha (Shaw and Riha 2011) showed much higher sensitivity of PET as projected by a hydrologic model than a GCM. Sheffield et al. (Sheffield et al. 2012) use versions of the PDSI (Palmer 1968) with different formulations of PET to evaluate historical time periods, with diverging results (see section 6.1).

Within the temperature proxy–based class of models, intercomparison among different specific formulations can lead to different outcomes. Gyawali and Watkins (Gyawali and Watkins 2013) compared river outflow changes resulting from simulations by the method of Croley (Croley 1983) and the Hydrologic Engineering

Center Hydrologic Modeling System (HEC-HMS; U.S. Army Corps of Engineers 2000). They showed that the change in river flow is highly sensitive to which of these models is chosen as the means of translating climate into river flow. Joetzjer et al. (Joetzjer et al. 2012) also compared projections of drought frequency using drought indices that included Thornthwaite (Thornthwaite 1948) PET with those using Hargreaves and Samani (Hargreaves and Samani 1985) PET: the latter of which more explicitly separates the effects of incoming solar radiation from air temperature. The indices that incorporated Thornthwaite PET showed larger trends toward drought than those using Hargreaves and Samani PET, which showed greater similarity to indices based only on precipitation changes. The divergence was greater at longer time horizons of projection.

It is likely that different sensitivities can be explained by the extent to which solar radiative factors are explicitly used within a model to explain differences in PET on the basis of latitude and season, complementing the terms that explicitly attribute PET to air temperature. For example, HEC-HMS includes options for using PET estimated using the method of Jensen and Haise (Jensen and Haise 1963), which uses solar radiative input as a variable in the algorithm, or the methods of Hamon (Hamon 1961) and Thornthwaite (Thornthwaite 1948), which include day length as an input. However, the method of Croley (Croley 1983) is strictly temperature based and thus lumps the effects of season and latitude together with any effects that might be more reasonably attributed to air temperature.

5.3. Possibly spurious positive feedback mechanism

The potential confusion between a proxy relationship between air temperature and PET and an actual causal relationship can result in an apparent positive feedback mechanism. As proposed by Romm (Romm 2011), high values of PET (as projected using air temperature) relative to precipitation result in depletion of soil moisture. This results in limited ET, causing more heat to be dissipated from the surface as sensible heat flux, raising the air temperature and implying even higher PET, closing a positive feedback loop.

More cautious analysis (e.g., Scheff and Frierson 2013, manuscript submitted to *J. Climate*) uses a Penman–Monteith formulation. While their results indicate that increasing air and surface temperatures can lead to net radiation at a hypothetically moist surface being partitioned with a greater fraction as latent heat flux rather than sensible heat flux, energy budget constraints make the linkage to feedback mechanisms more complicated than a simple temperature proxy relation. This brings the positive feedback mechanism proposed by Romm (Romm 2011) into doubt. Although we are not aware of other sources in the literature that have explicitly proposed this positive feedback mechanism, it is implicitly contained in simulations that directly use projected air temperatures to calculate PET. Such calculations do not distinguish between the case in which higher air temperatures are caused by greater input of solar radiation on the one hand, which would have a strong positive influence on net radiation and PET, and a dry surface on the other hand, which would lead to increased outgoing longwave radiation and decreased net surface radiation. Thus, rather than having a positive feedback mechanism, we

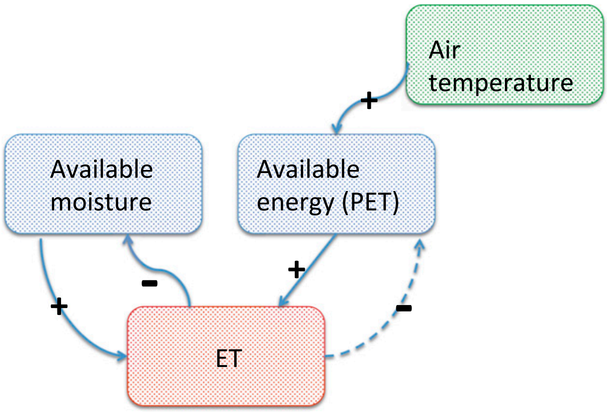

Figure 2. Causal loop diagram of surface energy and moisture budget components. An increase in a variable causing an increase in another is indicated by a plus sign, and an increase in a variable causing a decrease in another is indicated by a minus sign. Temperature proxy–based PET methods neglect the negative (balancing) feedback that ET has on available energy, which is shown as a dashed line.

propose that temperature proxy–based PET methods primarily lack an important negative (balancing) feedback mechanism, whereby ET (latent heat flux) reduces air temperature and the energy available at the surface. Figure 2 shows this missing energy feedback as a dashed line, along with the balancing feedback between ET and moisture availability.

6. Studies applying energy budget–based PET

6.1. Projections

SWAT (Arnold et al. 1998) is frequently used to estimate hydrologic impacts of climate change. SWAT offers three methods for calculation of PET: 1) Penman–Monteith (Monteith 1973); 2) Priestley–Taylor (Priestley and Taylor 1972); and 3) Hargreaves–Samani (Hargreaves and Samani 1985). The Penman–Monteith and Priestley–Taylor options require net surface radiation as an input (among other variables), while Hargreaves–Samani requires surface air temperature plus maximum possible solar radiation at the surface.

Wu et al. (Wu et al. 2012) applied SWAT to the Upper Mississippi River basin and used the Penman–Monteith formulation of PET. Using four GCMs as input, they found a mixture of changes in water yield and soil moisture. There was a trend toward increased water yield (precipitation minus evapotranspiration) during winter and spring but a decreasing trend in summer and fall. Soil moisture increased in winter, decreased through much of the summer, and was mixed among the GCMs in spring and fall. Actual ET generally increased, except in the late summer, presumably due to earlier onset of moisture-limited conditions.

Also using SWAT, Gosling et al. (Gosling et al. 2011) compared the response of a global hydrologic model to climate change scenarios applied to several river catchments with the response of hydrologic models developed specifically for each of those catchments. In some catchments, the response in terms of water yield was similar, but for others, it was quite different. Each of these models was calibrated and validated elsewhere in the literature, and found to agree well with observations. However, the disagreement noted among models shows that agreement with observations is not a sufficient condition for getting consistent and accurate projections of the sensitivity of the hydrologic system to climate change scenarios.

6.2. Comparisons between temperature proxy and energy budget–based methods

Dai (Dai 2011) examined values and trends in the PDSI (Palmer 1968) during the period 1900–2008. Recognizing some of the issues with using air temperature as the primary driver of PET, Dai (Dai 2011) compared a version of PDSI with the Thornthwaite (Thornthwaite 1948) method for calculating PET to another version using the Penman–Monteith method. He illustrated notable differences in the trend (1985–2004 minus 1950–69) of PET between the Thornthwaite method and the Penman–Monteith method. However, the trends in actual ET were similar under the two methods.

For those regions where the trends in ET did differ between the two methods, the discrepancy seemed to be driven by PET: that is, there was a lesser increase in PET and ET when using Penman–Monteith than when using Thornthwaite or even a decrease. Notable examples are north-central North America, Amazonia, equatorial Africa, and Indonesia, which can be generalized as regions dominated by energy-limited ET. Further analysis led to the conclusion that for the remaining bulk of land areas, trends in ET were largely attributable to changes in precipitation, even if the region had moisture-limited ET only seasonally. Dai (Dai 2011) did not evaluate runoff, water yield, or river flow.

Sheffield et al. (Sheffield et al. 2012) used versions of the PDSI with different formulations of PET to evaluate historical time periods. They found that global mean trends in PDSI between about 1990 and the present differ significantly between the version using the temperature-based Thornthwaite PET and the energy budget–based Penman–Monteith formulation (Figure 3). The Thornthwaite version yielded greater decreases in PDSI (a trend toward more drought) than Penman–Monteith during that time. This has wider implications, since PET and actual ET drive other variables, including soil moisture, water table, runoff, streamflow, and the water level of wetlands and lakes. Similarly, Donohue et al. (Donohue et al. 2010) have compared estimates of PET in Australia using Penman–Monteith (Monteith 1973), Priestley–Taylor (Priestley and Taylor 1972), Morton (Morton 1983), and Thornthwaite (Thornthwaite 1948) formulations of PET. Because their area of interest had largely moisture-limited ET, they found little change in actual ET among these formulations, but they found a high degree of divergence in the results in terms of PET, soil moisture, and runoff.

Therefore, the methods of calculating PET may not have a large influence on the actual ET, especially where it is moisture limited. However, they can have a large proportional influence on measures related to the balance between ET and precipitation. These include soil moisture; several indices of aridity; and the residual

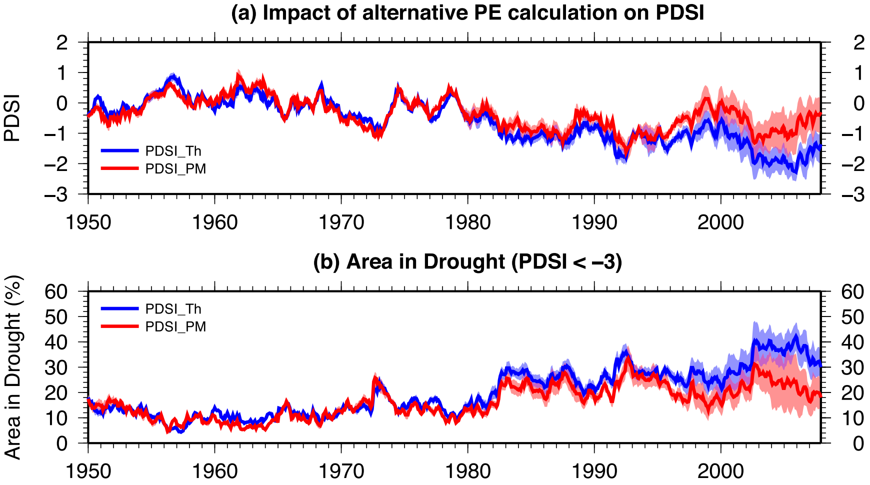

Figure 3. Global average time series of the PDSI and area in drought. (a) PDSI using the Thornthwaite method to estimate PET (PDSI_Th) is shown in blue, and PDSI using the Penman–Monteith method (PDSI_PM) is shown in red. (b) Area in drought (PDSI < -3.0) for the PDSI_Th (blue curve) and PDSI_PM (red curve). The shading represents the range derived from uncertainties in precipitation (PDSI_Th and PDSI_PM) and net radiation (PDSI_PM only). This figure is from Sheffield et al. (Sheffield et al. 2012; see their text for further details).

quantity of precipitation minus evapotranspiration, which drives streamflow and levels of inland water bodies.

6.3. Caveats regarding energy budget–based PET

The additional complexity of the equations involved in energy budget–based PET formulations is easily overcome by modern computing power, so the primary disadvantage is data availability, and this situation is improving. In addition to near-surface air temperature and precipitation as in the temperature proxy–based approaches, the required atmospheric variables are near-surface humidity, wind speed, and net surface radiation. In some variants, cloud cover may be used to estimate surface radiation, although using this alone can miss the direct influence of greenhouse gases. For historical time periods, reanalysis data can be useful in providing the required input, especially if it is at fine spatial resolution.

Direct usage of hydrologic variables simulated by coupled atmosphere–surface climate models with either global or regional domains (Fowler et al. 2007) has the advantage of explicitly enforcing conservation of energy at the surface. However, such an approach can have problems with acquisition of the required land-cover data at appropriate spatial scales for potential domains of interest (Evans and Jakeman 1998), as well as the computational expense of running at the fine spatial resolutions that will yield the most useful information.

7. Special considerations by region

The Arctic has a number of features that make future hydrologic projections particularly uncertain. These include complex topography, glaciers, features associated with permafrost and frozen ground, coastal areas, and areas that are paradoxically both arid and lake dominated because of underlying permafrost, such as Alaska's North Slope. Even solid precipitation, which dominates the Arctic for 6–9 months a year, is extremely difficult to measure and is poorly represented in climate models (Cherry et al. 2007).

The Laurentian Great Lakes basin has been investigated with a focus on potential long-term changes in lake levels (e.g., Angel and Kunkel 2010; Lofgren et al. 2011). The driver of lake levels is the net total supply, which is defined as the tributary flow from land in the drainage basin, plus precipitation over the lakes minus evaporation from the lakes (collectively known as net basin supply) plus the channel inflow from other major lakes. A number of factors come into play in determining net basin and net total supply, including the interaction among snowpack formation and ablation, net radiation, and other meteorological variables in determining ET from the land, as well as the interaction among lake energy budgets, ice cover dynamics, and lake circulation in determining evaporation from the lake surface. Newer perspectives on Great Lakes water levels in response to climate also emphasize historical ranges of variability and coastal risk, with comparison to risk of sea level rise (Gronewold et al. 2013).

Held and Soden (Held and Soden 2006) have concentrated on tropical regions in taking an approach that combines moisture and energy budgets with atmospheric circulation in the Hadley cell. They assert that large-scale patterns of atmospheric water vapor transport and hence of precipitation minus ET are likely to be magnified under climate change. They also show that, although water vapor mixing ratio in the atmosphere can be expected to increase with air temperature roughly according to the Clausius–Clapeyron relationship, the overall rate of evapotranspiration and compensating precipitation will increase in a smaller proportion, implying a longer residence time of water vapor in the atmosphere with increasing temperature.

8. Sufficiency and uncertainty of climate models in hydrologic applications

Kundzewicz and Stakhiv (Kundzewicz and Stakhiv 2010) call into question the appropriateness of using the results of climate change projections from models as a basis for evaluating hydrologic impacts, as well as water management and adaptation strategies. They are correct to point out that GCMs' projections of change in precipitation are in poor agreement with one another, indicating large uncertainty. Furthermore, uncertainty increases when focusing on regions or specific locales, rather than continental to global scales, and the smaller scales are the most important in the hydrologic realm. Bennett et al. (Bennett et al. 2012) tried to separate the uncertainty associated with the hydrologic parameterizations (average of 31%), the GCMs in a multimodel experiment (average of 84%), and the emissions scenarios (average of 58%). However, they consider a specific region, which enhances the uncertainty of climate change and disagreement among GCMs (e.g., Tebaldi et al. 2005).

The problems illuminated by Kundzewicz and Stakhiv (Kundzewicz and Stakhiv 2010) are compounded by the issues discussed in the present paper. Their arguments rest against a tacit assumption that air temperature and precipitation are the decisive variables for mapping from climate to hydrologic impacts and that we know the correct way to do this mapping. Other model-predicted variables of high relevance to hydrologic impacts include surface energy budget components and atmospheric water vapor flux convergence, although they unfortunately have a poor observational basis for validation.

The overall implications for uncertainty of hydrologic impacts of climate change are formidable. In addition to the large uncertainties quantified by Bennett et al. (Bennett et al. 2012), which included uncertainties surrounding the values of parameters within a hydrologic model, there is also the question of what formulation and forcing variables are correct for bridging from climate projections to hydrologic impact projections. We do not yet have a quantitative estimate of the uncertainty associated with this question.

9. Discussion: A synergy between approaches

Increased collaboration between atmospheric and hydrologic modelers is needed to improve projections of the hydrologic impacts of climate change, as well as provide mutually consistent answers to both communities. Historically, each community has tried to distill the portion of surface processes essential to their own goals, but the two communities and their submodels have often failed to fully respect the context set jointly by the surface and atmosphere and their exchange of energy and moisture. By exploiting the common ground of energy and moisture exchange, surface hydrology can take its proper place as an aspect of climate and climate change and not merely a result of it. Meanwhile, the utility of coupled atmosphere–surface climate models can be enhanced by incorporating a greater range of hydrologic processes (e.g., groundwater recharge, flow, and discharge; vegetation phenology; and ephemeral wetlands) and data (e.g., small-scale topography and heterogeneity of soil and vegetation). Such cooperative model development and research is a component of full earth system simulation, which has been put forward as a means to enhance the vitality of all disciplines involved (Rosenfeld 2010; Shapiro et al. 2010). As a step in this direction, there are some examples of energy budget–based models being used both within coupled climate models and within stand-alone surface models, such as the incorporation of the Community Land Model (CLM) into the Process-Based Adaptive Watershed Simulator (PAWS) (Thornton and Zimmermann 2007; Shen et al. 2013).

The major challenge remains striking a proper balance. On the one hand, most process-based surface hydrologic algorithms suffer from a lack of full spatial coverage of land-cover data; the range of meteorological data needed as input; and the most direct type of validation data for model intermediate results, such as direct measurement of evapotranspiration and soil moisture. Therefore, validation and calibration or tuning of these models at the process level is problematic. However, like conceptual models, process-based models can be validated in terms of outputs such as river flow that generally reflect the interaction of multiple processes. Their strength that helps to ensure reliable sensitivity to changed climatic conditions is their reliance on the fundamental law of conservation of energy, which applies across climate regimes.

On the other hand, conceptual models that are often driven by air temperature as a proxy for PET are calibrated in a historical time period, so their accuracy during those and nearby time periods may be excellent, but their validity in altered climate regimes cannot be ensured. They can also fail at fulfilling the fundamental physical constraint of conservation of energy at the surface (Lofgren et al. 2011).

10. Conclusions

Wagener et al. (Wagener et al. 2010) call for a greater emphasis on a holistic approach to hydrology, encompassing its full range of interactions with all components of the physical, biological, and human environment. In the context of climate change, this means regarding hydrologic processes not as a result of climate change, but as an interactive component of the complete climate system.

We have the following key conclusions regarding existing methods for evaluating hydrologic impacts of climate change:

1) Surface budgets of water and energy are intimately tied together through ET and the associated latent heat flux (Figure 1). Methods that project hydrologic impacts across climate regimes without maintaining fidelity to this concept (viz., temperature proxy–based methods) are prone to error. This is due to a lack of mutual consistency between the surface energy budget in the driving atmospheric model and in the hydrologic model. Model results can differ substantially among different formulations of temperature proxy–based PET.
2) Methods that do account for latent heat flux and full energy budget show less sensitivity of the hydrologic system to climate change than those that do not. The fundamental advantage of the energy budget type of method is its basis on the law of conservation of energy, which is universally applicable across time and climate regimes. Because climate models incorporate both the atmosphere and surface and enforce conservation of energy at the surface, doing so in an offline hydrologic model helps to maintain consistency between these components.
3) The conservation of water vapor in the atmosphere is a fundamental law that impacts hydrology. On a global basis, all ET must be offset by precipitation, and global increases in ET with time must also be balanced by increased precipitation (see Trenberth et al. 2007; Held and Soden 2006). Again, use of energy budget–based ET helps to maintain mutual consistency between atmospheric models and offline hydrologic models in terms of ET, atmospheric concentration, and transport of water vapor.
4) Uncertainty is a major concern in projections of hydrologic impacts of climate change. This uncertainty can stem from uncertainty in GHG emissions and concentrations and uncertainty in climate change projections. However, as this paper points out, uncertainty and potential bias in the methods for deriving hydrologic impacts from climatic projections also need to be considered.
5) There are special considerations depending on the region. For instance, ice and snow processes are a special challenge at high and middle latitudes for varying portions of the year. Regions with a high amount of inland water or with ocean coasts have special interactions between land and water surfaces, mediated by the atmosphere. Again, energy budget–based methods

of ET maintain consistency between the surface and atmosphere by making the interaction mutual.

6) Greater cooperation between the atmospheric and hydrologic communities should help to provide more accurate projections of future hydrologic and climatic conditions. It will also help to harmonize the results arrived at by both communities. Research is ongoing at many different institutions and with many geographic thrusts to further this goal.

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