Ecological Modelling 297 (2015) 86–97

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Estimation of potential evapotranspiration from extraterrestrial radiation, air temperature and humidity to assess future climate change effects on the vegetation of the Northern Great Plains, USA

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ARTICLE INFO

Article history:
Received 18 April 2014
Received in revised form 20 October 2014
Accepted 27 October 2014
Available online 19 November 2014

Keywords:
Climate change
MC1
Great Plains USA
Potential evapotranspiration
Vegetation dynamics

ABSTRACT

The potential evapotranspiration (PET) that would occur with unlimited plant access to water is a central driver of simulated plant growth in many ecological models. PET is influenced by solar and longwave radiation, temperature, wind speed, and humidity, but it is often modeled as a function of temperature alone. This approach can cause biases in projections of future climate impacts in part because it confounds the effects of warming due to increased greenhouse gases with that which would be caused by increased radiation from the sun. We developed an algorithm for linking PET to extraterrestrial solar radiation (incoming top-of atmosphere solar radiation), as well as temperature and atmospheric water vapor pressure, and incorporated this algorithm into the dynamic global vegetation model MC1. We tested the new algorithm for the Northern Great Plains, USA, whose remaining grasslands are threatened by continuing woody encroachment. Both the new and the standard temperature-dependent MC1 algorithm adequately simulated current PET, as compared to the more rigorous PenPan model of Rotstayn et al. (2006). However, compared to the standard algorithm, the new algorithm projected a much more gradual increase in PET over the 21st century for three contrasting future climates. This difference led to lower simulated drought effects and hence greater woody encroachment with the new algorithm, illustrating the importance of more rigorous calculations of PET in ecological models dealing with climate change.

1. Introduction

Climate change may affect watershed hydrology and plant water availability by altering patterns of precipitation and evapotranspiration (ET), thereby influencing the growth and survival of plants. These water-dependent effects are often related to potential evapotranspiration (PET), commonly defined as the ET of a uniform, densely vegetated area with abundant soil water in the rooting zone (Rao et al., 2011). PET has been used to calculate a variety of aridity, drought and soil moisture indices, including the ratio of precipitation to PET, precipitation–PET, PET–ET, or ET/PET. The widely used Palmer Drought Severity Index is also linked to potential evapotranspiration (Guttman, 1998 Sheffield et al., 2012). Such PET-based indices are used (along with other climate variables) to model plant productivity (Churkina et al., 1999), drought-induced tree mortality (Gustafson and Sturtevant, 2013), the extent and frequency of wildfire (Littell et al., 2010) and the geographic ranges of plant species (Gray and Hamann, 2013).

Evaporation, and therefore PET, is influenced by incoming solar radiation, which provides the energy required to evaporate water, and aerodynamic effects dependent on wind, humidity, and temperature. These two aspects of evaporation are incorporated in the Penman formula applied to open water by Penman (1948). The approach was adapted to vegetation by Monteith (1965) in the Penman–Monteith equation, which includes the additional resistance to water vapor transfer imposed by plant stomata. These methods can provide accurate estimates of water use by irrigated crops (Howell and Evett, 2006), but have substantial data requirements, including net radiation (or a parameterization to

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http://dx.doi.org/10.1016/j.ecolmodel.2014.10.037

calculate it from shortwave radiation), near-surface air temperature, vapor pressure or dewpoint temperature, and wind speed (Jensen et al., 1990). Other than temperature and vapor pressure, direct measures or station-based interpolations of these variables are not available over most of the earth, though coarse-scale estimates derived from reanalyses of station data have recently become available (Mitchell et al., 2004). Thus, more empirical methods, often reliant solely on temperature, have remained in use for estimating PET (e.g., Thornthwaite, 1948). In such methods, temperature is assumed to act as a proxy for both net radiation and vapor pressure deficit.

However, empirical approaches may differ substantially from each other in their PET predictions (Lu et al., 2005) and give rise to varying biases across geographic regions (Hobbins et al., 2008; Fisher et al., 2011). In many regions, pan evaporation, which is closely related to PET, has decreased over the 30–50 year period preceding ~2000, even though temperature has generally increased over this period. Thus, temperature-based methods may yield increases in PET that are at variance with observed trends (Roderick et al., 2009).

Temperature-based methods may be particularly prone to error when extrapolated into the future to assess the effects of greenhouse-gas driven warming on PET (Milly and Dunne, 2011). Such biases are derived from the fact that increasing temperature by increasing solar radiation would likely cause a greater increase in PET than would increasing temperature by increasing greenhouse gases, because radiation provides the energy driving evapotranspiration (Scheff and Frierson, 2014). Thus, projections of future drought severity and its effects on vegetation may be overestimated by the use of temperature-based estimates of PET derived from historical climate data. One such example of this potential for bias involves the future rate of woody encroachment of grasslands, which we consider here.

One could prevent such biases by making use of radiation outputs from the general circulation models (GCMs) used to project future climates (IPCC, 2007; Taylor et al., 2012), but the GCM outputs are at coarse scales (>100 km resolution) and must be spatially downscaled for use at the increasingly fine scales of ecological models, commonly at resolutions of 1–10 km. Methods for statistically downscaling temperature, precipitation, and water vapor pressure are readily available, based on the fine-scale spatial pattern of historical means for these variables (Fowler et al., 2007). These historical means can be derived from gridded values of historical data, such as that available from the PRISM group (Daly et al., 2008). Fine-scale gridded data for net radiation is not yet available, and this variable is seldom used in ecological assessment models. However, ground level radiation has been linked to the incoming solar radiation at the top of the atmosphere (extraterrestrial radiation), which is a function of site latitude and time of year (Thornton and Running, 1999), thereby providing an alternative method for estimating PET.

Unbiased estimates of future PET are especially important for assessing how climate change may affect semiarid ecosystems, where water substantially limits plant productivity. One such region is the Northern Great Plains, USA, which harbors exceptional and distinctive biodiversity (Olson and Dinerstein, 2002). Although more than 70% of the region's mixed-grass prairie has been converted to row-crop agriculture or otherwise developed, the region still contains more than 15 million ha of native grassland (Samson et al., 1998). Trees and shrubs have increasingly invaded the remaining Great Plains grasslands over the past century, reducing habitat for grassland specialist birds and mammals and forage production for domestic livestock (Eggemeyer et al., 2006; Spencer et al., 2009; Barger et al., 2011). Climate change may accelerate or decelerate this process, depending on the direction and degree of change in temperature, precipitation, and humidity; direct effects of increased CO_2 on productivity and water use efficiency; and fire and grazing regimes.

To assess the threat of woody encroachment in the Northern Great Plains, USA (NGP), we have used the dynamic vegetation model MC1 (Bachelet et al., 2001), which calculates monthly water balance and plant growth as limited by water and other factors. In the standard version of MC1, these calculations are based on PET determined with Linacre's (1977) algorithm, which is derived from the Penman equation, but uses semi-empirical temperature relations to estimate net radiation. This approach makes future PET estimates susceptible to bias. We therefore derived a method that reduces the potential bias in estimating net radiation from temperature alone by linking it to extraterrestrial radiation, as calculated from site latitude and time of year. We calibrated the new PET algorithm with radiation data from the NGP to assess the likelihood of woody encroachment of NGP grasslands as influenced by future climate and land management practices.

Here we compare our new PET values with gridded estimates of monthly pan evaporation synthesized by the PenPan model of Rotstayn et al. (2006) using a comprehensive set of climate and radiation inputs derived from the North American Land Data Assimilation System. Pan evaporation is a widely reported measure of evaporative demand, which can be used to approximate PET when multiplied by a factor of 0.7 (Eagleman, 1967). Next, we compare PET calculated with the new algorithm to that of the original algorithm of MC1 for three contrasting future climates, chosen for use in our assessment of woody encroachment of the NGP. We then project future woody encroachment by MC1 with the new vs. original PET algorithm for the three future climates with three fire-management scenarios. For this purpose we used the MC1 version of King et al. (2013a,b); King et al. (2013a,b) that was calibrated for the ponderosa pine (*Pinus ponderosa*)–grassland ecotone at Wind Cave National Park in the southern Black Hills of South Dakota, which lie within the larger NGP region. For the current projections we further calibrated MC1 for *Juniperus virginiana* (eastern redcedar), a native tree that has been particularly invasive of grasslands of the SE portion of the NGP and with future warming may threaten much of the NGP, and for *Juniperus scopulorum* (Rocky Mountain juniper), which is encroaching into grasslands in the western portion of the NGP.

2. Materials and methods

Our approach takes the following steps:

1. Determine an empirical relation for atmospheric transmittance of solar radiation as a function of monthly maximum and minimum temperatures (T_{max},T_{min}), where transmittance = monthly shortwave insolation on a horizontal surface/monthly extraterrestrial insolation.
2. Use Linacre's (1968) approach to estimate net radiation from mean monthly temperature and solar irradiation (i.e., transmittance × extraterrestrial insolation).
3. Use net radiation (Q_n) and Linacre's (1977) approximations of the relevant properties of air and water vapor in the Penman equation to derive an algorithm relating PET to mean monthly values of Q_n, temperature and dewpoint temperature.
4. Compare our estimates of historical monthly PET for the NGP with those of the standard MC1 PET algorithm and the synthetic pan evaporation estimates of Hobbins et al. (2012), which were multiplied by 0.7 to approximate PET. Hobbins and co-workers' estimates involve additional inputs and processes, such as wind speed, not included in our algorithm.
5. Compare our estimates of PET for the NGP with those of the standard PET algorithm of MC1 using future climate variables