Journal of Hydrology 521 (2015) 389–394

Contents lists available at ScienceDirect

Journal of Hydrology

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

Technical Note

Inter-annual and spatial variability of Hamon potential evapotranspiration model coefficients

Gregory J. McCabe [a,*], Lauren E. Hay [a], Andy Bock [a], Steven L. Markstrom [a], R. Dwight Atkinson [b]

[a] U.S. Geological Survey, Denver, CO, USA
[b] U.S. Environmental Protection Agency, Washington, D.C., USA

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 4 December 2014
Accepted 6 December 2014
Available online 15 December 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Potential evapotranspiration
Hamon
Water balance
Surface water hydrology

SUMMARY

Monthly calibrated values of the Hamon PET coefficient (*C*) are determined for 109,951 hydrologic response units (HRUs) across the conterminous United States (U.S.). The calibrated coefficient values are determined by matching calculated mean monthly Hamon PET to mean monthly free-water surface evaporation. For most locations and months the calibrated coefficients are larger than the standard value reported by Hamon. The largest changes in the coefficients were for the late winter/early spring and fall months, whereas the smallest changes were for the summer months. Comparisons of PET computed using the standard value of *C* and computed using calibrated values of *C* indicate that for most of the conterminous U.S. PET is underestimated using the standard Hamon PET coefficient, except for the southeastern U.S.

1. Introduction

Potential evapotranspiration (PET) provides an estimate of the climatic demand for water. PET is energy limited since the definition of PET assumes an unending supply of water (Wilm and Thornthwaite, 1944). PET is an integral part of water balance computations and of climatic indices such as aridity indices (Budyko, 1948; Thornthwaite, 1948; Willmott and Feddema, 1992; Arora, 2002; Weiskel et al., 2014). Temperature based PET models have been used for over 50 years and have been applied in a wide range of climatic and physiographic regions. These models have been applied widely because they only require mean monthly temperature as input and these data are readily available for long time periods and for many locations across the globe. Although temperature-based PET models are empirical and do not include representation of many physical processes, they have been found to provide reliable estimates of monthly and annual PET for many locations (Lu et al., 2005; Federer et al., 1996; Vörösmarty et al., 1998; Hay et al., 2011).

Thornthwaite (1948) provided one of the best known and widely used methods to compute PET. Thornthwaite's method required monthly temperature and mean monthly daylength as inputs to the equations. Hamon (1961) presented a PET model that was developed based on measurements of PET published by Lowry and Johnson (1942) and Thornthwaite (1948). The Hamon PET model was developed as an improvement of the well-known Thornthwaite PET model and included the effects of saturation vapor density on PET. In 1963 Hamon provided a slightly updated version of his model (Hamon, 1963).

The Hamon PET equation is simple and does not explicitly include the effects of humidity, wind speed, and land cover on PET. However, because the Hamon equation only requires inputs of monthly temperature it can be widely applied in both time and space. Additionally, although conceptually simple, the Hamon PET equation has been evaluated and compared with a number of other models and is considered to provide reliable monthly PET estimates (Lu et al., 2005; Federer et al., 1996; Vörösmarty et al., 1998). In a study of five PET models for use with global water balance models, Federer et al. (1996) found that estimates of PET from the Hamon model agreed with estimates from other models across a wide range of climates. In addition, Vörösmarty et al. (1998) compared 11 different PET models for a wide range of climatic conditions across the conterminous U.S. and found that the Hamon model was comparable to more input-detailed models.

The Hamon model includes an empirically determined model coefficient that remains constant for all applications. Some studies have shown that improved PET estimates are obtained using the Hamon model if a correction factor is applied (Sun et al., 2008).

* Corresponding author at: U.S. Geological Survey, Denver Federal Center, MS 412, Denver, CO 80225, USA. Tel.: +1 303 236 7278.
E-mail address: gmccabe@usgs.gov (G.J. McCabe).

http://dx.doi.org/10.1016/j.jhydrol.2014.12.006
0022-1694/Published by Elsevier B.V.

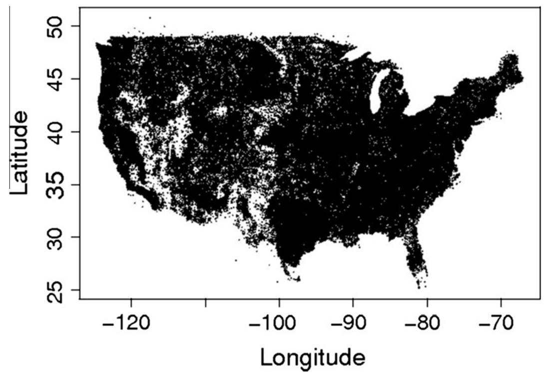

Fig. 1. Map of the centers of hydrologic response units.

Instead of applying a correction factor, a better approach may be to use Hamon PET coefficients that vary by month and by location. The objectives of this study are to (1) determine useful Hamon PET coefficients for each month and for locations across the conterminous U.S., and (2) examine the effects of varying monthly coefficients on PET estimates.

2. Data and methods

The original Hamon (1961) monthly PET model is,

$$\mathrm{PET} = CD^2P_t/100 \tag{1}$$

where PET is in inches day, C is an empirical dimensionless coefficient equal to 0.55, D is the possible hours of daylight in units of 12 h, and P_t is the saturated water vapor density at the daily mean temperature in grams per cubic meter (Hamon, 1961). By multiplying by 25.4 and the number of days in a month provides Hamon PET estimates in millimeters per month.

Hamon (1963) provided a slightly modified version of his PET model. The updated model is,

$$\mathrm{PET} = CDP_t \tag{2}$$

where in the 1963 version of the model, $C = 0.0065$. The difference in C is due to additional testing by Hamon (1963) and because the values are not divided by 100 as in Eq. (1).

Both models have the same form, use the same variables, and provide similar PET estimates. We used both the Hamon (1961, 1963) versions of the model, but because the results were so similar we only present the results using the 1963 model in this paper. The calibrated Hamon coefficients for the 1961 and 1963 models can be downloaded from ftp://brrftp.cr.usgs.gov/pub/mows/data/hamonCoef/.

Mean monthly measured free-water surface (FWS) evaporation for 1956 through 1970 from Farnsworth et al. (1982) were used for calibration of the Hamon PET model. The FWS data are considered representative of mean monthly measured PET (Farnsworth et al., 1982). These data were digitized and interpolated to a 5-km (km) by 5-km grid by the National Weather Service.

PET was computed using monthly temperature data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data set (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu). The PRISM data set provides monthly temperature and precipitation data for the conterminous U.S. on a 4-km by 4-km grid for the period 1895 to present. The

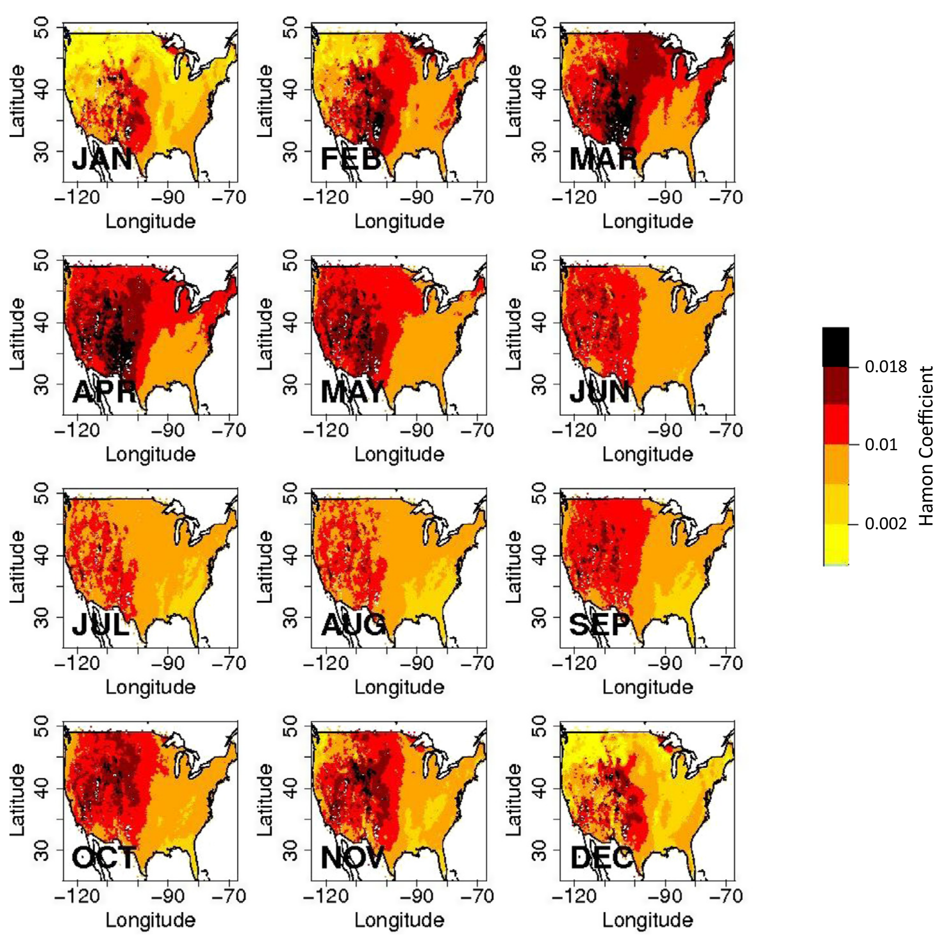

Fig. 2. Monthly Hamon potential evapotranspiration model coefficients determined through calibration.

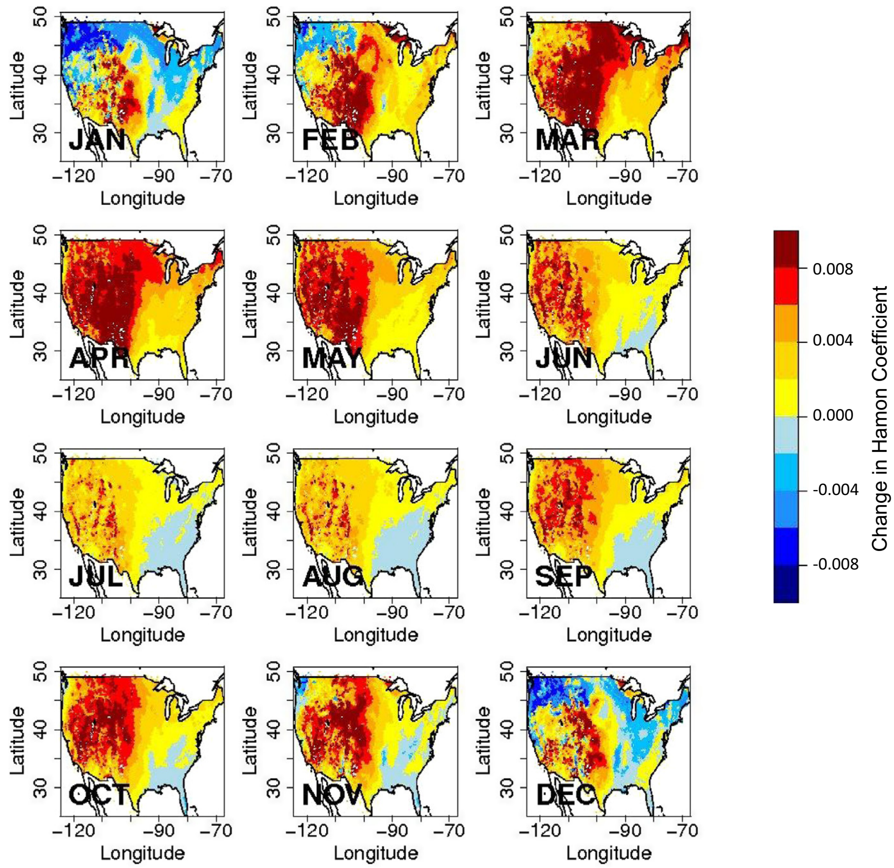

Fig. 3. Changes in monthly Hamon potential evapotranspiration (PET) model coefficients from the standard coefficient of 0.0065 after calibration.

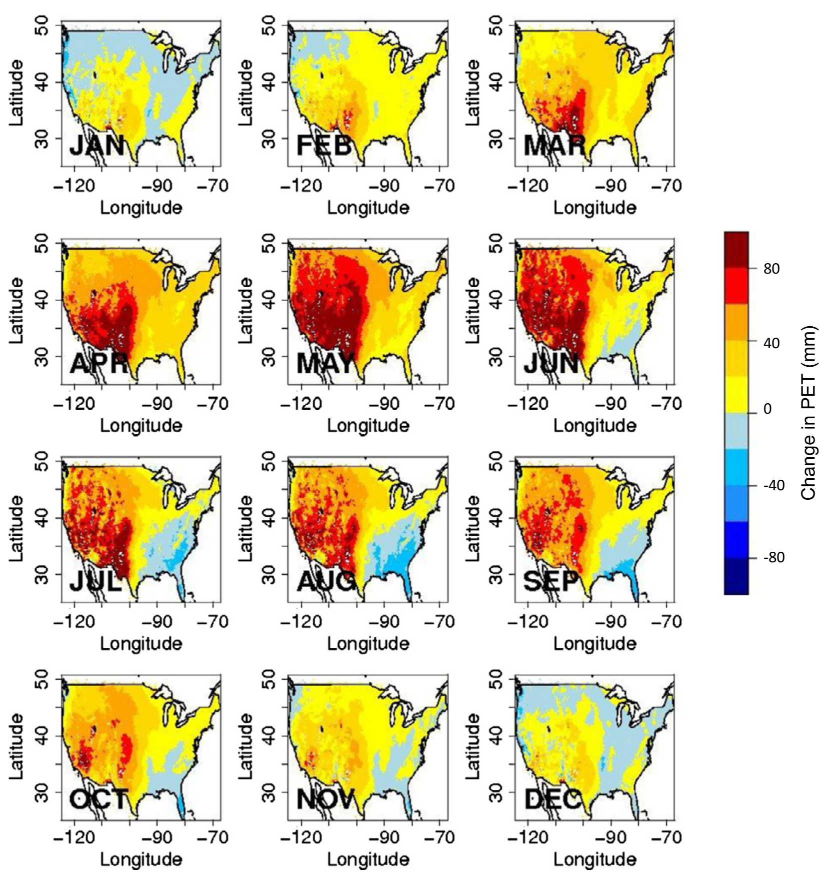

Fig. 4. Changes in mean monthly Hamon potential evapotranspiration (PET) computed using calibrated monthly coefficients.

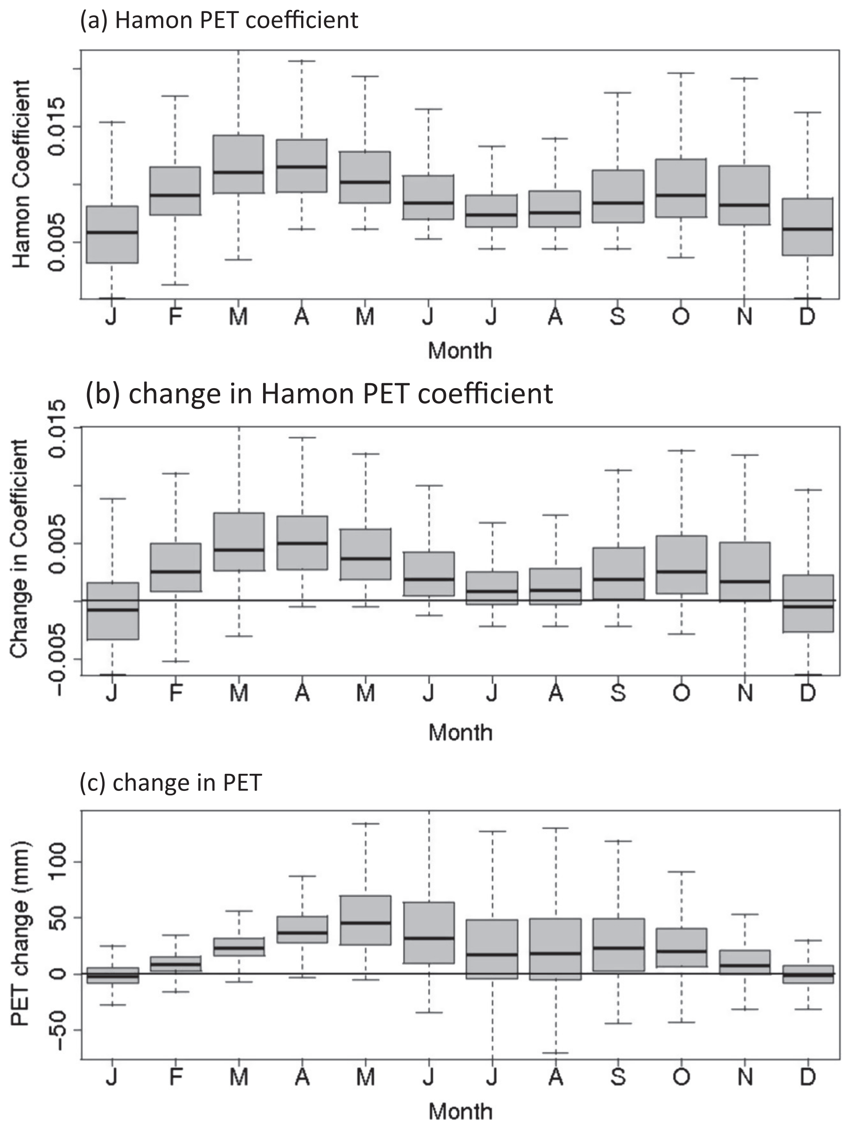

Fig. 5. Boxplots of (a) calibrated monthly Hamon coefficients, (b) changes in the monthly Hamon coefficient from the standard value of 0.0065, and (c) changes in mean monthly PET (in millimeters (mm)) resulting from the changes in the Hamon coefficient.

gridded monthly PRISM temperature data were used to compute area-weighted averages of temperature for 109,951 hydrologic response units (HRUs) (Fig. 1). The HRUs are part of the Geospatial Fabric developed by Viger and Bock (2014) for hydrological modeling across the United States. The sizes of the HRUs used in this analysis range from less than 1 km^2 up to 67,991 km^2, with an average size of 74 km^2.

The HRU-averaged temperature values subsequently were used to compute monthly PET for each HRU. Monthly PET was computed for 1956 through 1970 to match the period of FWS data. The time series of monthly PET for 1956–1970 were subsequently used to compute long-term mean monthly PET for each HRU for this period. The mean monthly FWS data also were averaged for each HRU for comparison with the HRU PET estimates.

PET was computed in two ways; (1) using the Hamon (1963) equation with the standard coefficient (i.e. $C = 0.0065$), and (2) calculating (i.e. calibrating) C so that mean monthly Hamon PET was equivalent to mean monthly FWS evaporation (Farnsworth et al., 1982). The changes in mean monthly PET computed using $C = 0.0065$ and calibrated C were subsequently evaluated.

For each HRU and month, calibrated Hamon model PET coefficients were determined using mean monthly temperature and mean monthly FWS evaporation (as a surrogate for PET) and solving for the Hamon coefficient (C) in the following manner,

$$C = \frac{FWS}{DP_t} \tag{3}$$

3. Results and discussion

By solving for C, the calibration procedure produced mean monthly PET from the Hamon model that was equivalent to mean monthly PET represented by the Farnsworth FWS evaporation data. Fig. 2 illustrates maps of the resulting monthly Hamon PET coefficients. Generally, the highest coefficients occur during the spring and fall months, whereas the range in coefficients is largest for cool season months and lowest for warm months (Figs. 2 and 5a). The highest coefficients occur for the southwestern U.S., the Rocky Mountain region, and the northern central plains. The lowest coefficient values occur in the northwestern U.S., and parts of the central and northeastern U.S.

Fig. 3 illustrates the magnitude and direction of the changes in calibrated Hamon PET coefficients (i.e. calibrated coefficients minus 0.0065). Large changes in the coefficients for much of the western U.S. are evident. In contrast, the calibrated coefficients are only slightly different than 0.0065 for much of the eastern U.S. This is especially true for the southeastern U.S., where (Hamon, 1961) originally developed the method.

The effects of calibrated coefficients on PET are illustrated by differences in mean monthly PET computed using the 0.0065 coefficient and the calibrated coefficients (Figs. 4 and 5c). The differences indicate relatively large increases in PET computed using the calibrated coefficients compared with using the 0.0065 coefficient for the western U.S., particularly during the months of March through October. These results indicate that PET is underestimated for much of the western U.S. during these months when the standard coefficient is used. This is an interesting result given that several previous studies have argued that temperature-based PET models such as the Hamon model over-estimate PET (Milly and Dunne, 2011; Sheffield et al., 2012).

To examine the climatic and geographic factors affecting the spatial distribution of changes in the PET coefficients, the changes in the PET coefficients were correlated with spatial distributions of mean monthly temperature, mean monthly precipitation, and the latitude, longitude, and elevation of the center of each HRU (Fig. 6). Correlations between the changes in the coefficients and temperature are slightly positive for the months of December through March, and negative for the months of April through November (Fig. 6a). The most negative correlations with temperature are for the months of June through September (Fig. 6a). The negative correlations for these months are a result of the negative changes for locations in the warm southeastern U.S. and positive changes in the cool northern U.S. and the cool regions of the mountainous western U.S. The monthly correlations between the change in the Hamon coefficients and latitude is generally opposite of those for temperatures (Fig. 6c). This is because temperature is inversely correlated with latitude.

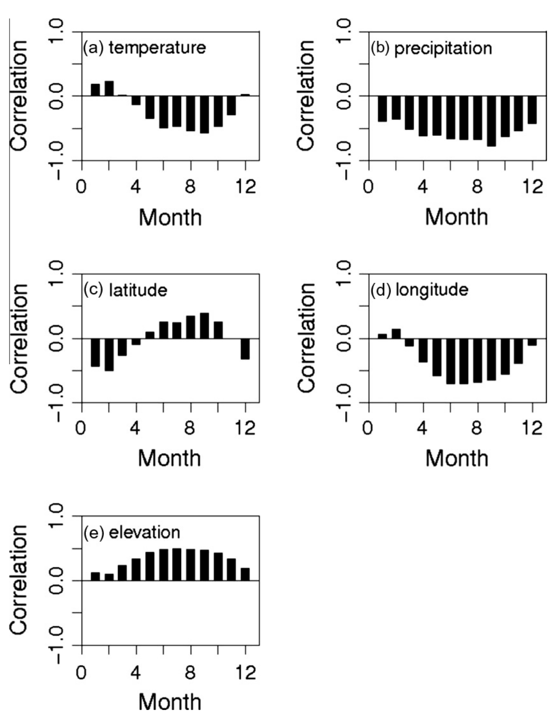

Fig. 6. Correlations between the change in the Hamon coefficient (from the standard value of 0.0065) and (a) mean monthly temperature, (b) mean monthly precipitation, (c) latitude of each hydrologic response unit (HRU), (d) longitude of each HRU, and (e) mean elevation of each HRU. (Because of the large number of HRUs (i.e. 109,951) all of the correlation coefficients are statistically significant at a 95 percent confidence level.)

Correlations of mean monthly precipitation with the changes in the Hamon coefficients are negative for all months (Fig. 6b). These correlations indicate that for locations with relatively high precipitation the calibrated Hamon coefficient was less than the standard coefficient, which indicates that for wet areas PET is over-estimated when the standard coefficient is used.

The correlations between the longitude of an HRU and changes in the Hamon coefficient are negative for almost all months (except January and February) (Fig. 6d). The negative correlations with longitude reflect the general pattern of positive changes in the Hamon coefficients for most months for sites in the western U.S. and negative changes in coefficients for the eastern U.S. (Figs. 3 and 6d).

Correlations between the elevation of the HRUs and changes in the Hamon coefficient are positive for all months (Fig. 6e). These correlations indicate that through calibration the Hamon coefficients increased for locations with high elevations compared with those with low elevations. These results suggest that at high elevation sites, particularly in the western U.S., the standard Hamon coefficient of 0.0065 results in an under-estimation of PET.

The results of this analysis provide temporally and spatially varying coefficients for use with the Hamon PET model in the conterminous U.S. The method employed in this study may be useful to modify model coefficients used by other empirical PET models (Droogers and Allen, 2002).

Useful future research includes exploring ways to develop modified Hamon PET model coefficients for other parts of the globe. There may be reliable relations between the spatial variability of Hamon PET coefficients and the spatial variability of physical characteristics of locations (e.g. climate, topography, etc.) that can be used to derive modified Hamon model PET coefficients for locations where FWS data are unavailable for coefficient calibration. For example, regressing the changes in monthly PET coefficients computed in this study for each HRU against the respective mean monthly temperature, mean monthly precipitation, latitude, longitude, and elevation for each HRU resulted in explained variances in the spatial variability of model coefficients that ranged from 32 percent for December and January to 71 percent for September and October.

4. Conclusions

Monthly varying coefficients were determined for the Hamon PET model so that mean monthly PET would be equivalent to measured mean monthly FWS evaporation. The monthly varying coefficients in space and by month can provide improved monthly estimates of PET. Additionally, in contrast to previous studies that reported that temperature-based PET models over-estimate PET, PET computed using the standard Hamon coefficient is under-estimated for a large part of the country, especially the western U.S.

Acknowledgements

This research was partially financially supported by the U.S. Department of Interior South Central Climate Science Center and the U.S. Environmental Protection Agency Office of Water.

References

Arora, V.K., 2002. The use of the aridity index to assess climate change effect on annual runoff. J. Hydrol. 265, 164–177.
Budyko, M.I., 1948. Evaporation Under Natural Conditions. Gidrometeorizdat, Leningrad, English translation by IPST, Jerusalem.
Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under inaccurate conditions. Irrig. Drain. 16, 33–45.
Farnsworth, R.K., Thompson, E.S., Peck, E.L., 1982. Evaporation Atlas for the Contiguous 48 United States, NOAA Technical Report NWS 33, National Oceanic and Atmospheric Administration, Washington, DC, 27p.

Federer, C.A., Vorosmarty, C., Fekete, B., 1996. Intercomparison of methods for calculating potential evaporation in regional and global water balance models. Water Resour. Res. 32, 2315–2321.

Hay, L.E., Markstrom, S.L., Ward-Garrison, C., 2011. Watershed-scale response to climate change through the twenty-first century for selected basins across the United States. Earth Interact. 15. http://dx.doi.org/10.1175/2010EI370.1.

Hamon, W.R., 1961. Estimating potential evapotranspiration. J. Hydraul. Div. Proc. Am. Soc. Civ. Eng. 87, 107–120.

Hamon, W.R., 1963. Computation of direct runoff amounts from storm rainfall. Intl. Assoc. Scientific Hydrol. Publ. 63, 52–62.

Lowry, R.L., Johnson, A.F., 1942. Consumptive use of water in agriculture. Trans. Am. Soc. Civ. Eng. 107.

Lu, J., Sun, G., McNulty, S.G., Amataya, D.M., 2005. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. J. Am. Water Resour. Assoc. 3, 621–633.

Milly, P.C.D., Dunne, K.A., 2011. On the hydrologic adjustment of climate-model projections: the potential pitfall of potential evapotranspiration. Earth Interact. 15, 1–14.

Sheffield, J., Wood, E.F., Roderick, M.L., 2012. Little change in global drought over the past 60 years. Nature 491, 435–440. http://dx.doi.org/10.1038/nature11575.

Sun, G., Zuo, C., Liu, S., Liu, M., McNulty, S.G., Vose, J.M., 2008. Watershed evapotranspiration increased due to changes in vegetation composition and structure under a subtropical climate. J. Am. Water Resour. Assoc. 44, 1164–1175.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.

Viger, R.J., Bock, A., 2014. GIS Features of the Geospatial Fabric for National Hydrologic Modeling, US Geological Survey, doi: http://dx.doi.org/10.5066/F7542KMD.

Vörösmarty, C.J., Federer, C.A., Schloss, A.L., 1998. Potential evaporation functions compared on US watersheds: possible implications for global-scale water balance and terrestrial ecosystem modeling. J. Hydrol. 207, 147–169.

Weiskel, P.K., Wolock, D.M., Zarriello, P.J., Vogel, R.M., Levin, S.B., Lent, R.M., 2014. Hydroclimatic regimes: a distributed water-balance framework for hydrologic assessment and classification. Hydrol. Earth Syst. Sci. Discuss. 11, 2933–2965. http://dx.doi.org/10.5194/hessd-11-2933-2014, <www.hydrol-earth-syst-sci-discuss.net/11/2933/2014/>.

Willmott, C.J., Feddema, J.J., 1992. A more rational climatic moisture index. Prof. Geogr. 44, 84–88.

Wilm, H.G., Thornthwaite, C.W., 1944. Report of the committee on evaporation and transpiration, 1943–1944. Trans. Am. Geophys. Union 25, 686–693.