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RESEARCH ARTICLE

Complementary-relationship-based evapotranspiration mapping (cremap) technique for Hungary

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Abstract

Monthly areal evapotranspiration (ET) rates for 2000–2008 are mapped for Hungary at a spatial scale of about 1-km with the help of MODIS daytime land surface temperature as well as sunshine duration, air temperature and humidity data. Mapping is achieved by a linear transformation of the MODIS daytime land surface temperature values employing the complementary relationship of evaporation. Validation of the ET rates has been performed with the help of eddy-covariance measurements. The calibration-free CREMAP method is very simple, easy to implement, requires minimal data and works accurately when conditions for the complementary relationship are met. The resulting maps testify that the spatial structure of ET is much more intricate than what has been captured in previous generalized ET maps.

Keywords

evaporation · evapotranspiration · complementary relationship · MODIS data

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1 Introduction

The Complementary Relationship (CR) states that under constant available energy at the surface (Q_n) the regionally representative (ET) and potential (E_p) evapotranspiration rates are complementary:

$$ET = 2E_w - E_p \tag{1}$$

where the Priestley-Taylor equation (Priestley and Taylor [8]) describes the wet environment evaporation as

$$E_w = 1.26\frac{\Delta}{\Delta+\gamma}Q_n \tag{2}$$

with Δ being the slope of the saturation vapor pressure curve at the temperature of the air, and γ ($\approx 0.67\,\mathrm{hPa\,K^{-1}}$) the psychrometric constant. Penman [6] defined E_p as

$$E_p = \frac{\Delta}{\Delta+\gamma}Q_n + \frac{\gamma}{\Delta+\gamma}f(u)(e* - e) \tag{3}$$

where e and $e*$ are the actual and saturation vapor pressure at the temperature of the air, respectively, and $f(u)$ is the wind function.

Morton et al. [4] in their WREVAP model specify E_p and E_w somewhat differently, but in a way that (1) is still valid [9]). They suggest (1) to be employed for time-periods equal or longer than about a week for improved accuracy. This is so because the CR is based on an assumed equilibrium state of the atmosphere and the underlying land, the latter influencing the humidity of the air through ET regulated by various feedbacks across the land-atmosphere interface. To attain such an equilibrium takes some time following each weather fronts passing through the area. Since in their approach the calculation of E_p via an iterative method does not require knowledge of the mean wind speed, WREVAP is employed here for obtaining the regionally representative areal evapotranspiration rate.

2 Model description

Spatial disaggregation of the regionally representative ET rates is based on a linear transformation [10] of the 8 day composited MODIS daytime surface temperature (T_s) values into actual ET rates. The transformation requires specifying two anchor points in the T_s–ET plane. The first anchor point is defined by the spatially averaged daytime surface temperature, $< T_s >$, and the (1)-obtained ET values. The second anchor point results from a spatial averaging of the coldest pixel values, $< T_{sw} >$, within the region and E_w of (2) out of consideration that the coldest pixels are the wettest, evaporating at the wet environment evapotranspiration rate, E_w. The two points define the linear transformation of the T_s pixel values into ET rates for each month by employing monthly means. This transformation is justified as long as Q_n (and thus surface albedo) and the aerodynamic resistance (r_a) are about constant among the pixels. The 1 km MODIS pixel-size in this sense is ideal, since the pixel is large enough for albedo and r_a changes to remain negligible between the cells, but small enough to provide for a good spatial resolution of ET at the watershed scale.

3 Model application

For calculating the anchor points of the transformation the following meteorological data were used: 0.1° (~7.6 km west-east and ~11 km north-south) gridded mean monthly air temperature, specific humidity (provided by OMSZ) and sunshine duration for the 2000–2008 period (provided by VITUKI). The gridded values were derived by OMSZ from measurements. 8-day composited MODIS daytime surface temperature data for the same period were averaged for each month to obtain one surface temperature per pixel per month. Such an averaging further reduces any possible cloud contamination effect that may remain in the 8 day composited images. With these data, the linear transformation of the monthly T_s values into monthly ET rates can be performed on a pixel-by-pixel basis. Note that co-location of the two grids is of secondary importance (i. e., how the representative cell value is chosen when one MODIS cell covers several cells of a given meteorological variable), since on a pixel-by-pixel basis only T_s is needed for obtaining pixel ET.

Due to the not negligible relief differences (the lowest point of the country is 78 m, and the highest is 1015 m), Hungary was divided into three elevation zones to account for changes in T_s by elevation: below 200 m, between 200 and 500 m, and above 500 m (Fig. 1). Since the country's area is quite small, such division was not necessary horizontally (i.e., within each elevation zone one spatially representative value of the anchor points was calculated for each month).

E_w in (2) was calculated with the help of the 30–50 coldest T_s points each month in all three zones (30 in the highest region). In the middle elevation zone the wettest points were taken from the 300–400 m strip and in the highest zone from the 550–650 m one. No such restrictions were applied for the lowest zone due to the small change in elevation there. The Q_n value for E_w was calculated by WREVAP from the zonal means of the 0.1-degree gridded sunshine duration values. The other anchor point of the linear transformation was obtained by averaging the MODIS T_s values for each zone and calculating the corresponding E of (1) by WREVAP from the spatial mean of air temperature, specific humidity and sunshine duration values within the zone.

To avoid sharp jumps in the evaporation values at the zone boundaries, the transformation equation was allowed to change linearly with pixel-elevation (z) between the limiting equations of the lower (l) and upper (u) zones. Mathematically,

$$ET(z) = \frac{(z_u - z)[a_l T_s(z) + b_l] + (z - z_l)[a_u T_s(z) + b_u]}{z_u - z_l} \tag{4}$$

where a and b are the parameters of the linear transformations by zone, obtained with the help of the anchor points. Here the reference elevations (z_u or z_l) are taken at 100, 350, and 600 meters.

Fig. 2 displays the linear transformations by months for the lowest elevation zone. The line sections in the figure are bounded by the anchor points. During the calculations they are allowed to extend downward to accommodate for pixels warmer than the zonal-mean. The lines, however, remain bounded from above, i.e., when the pixel temperature is lower than $<T_{sw}>$, the corresponding ET value assigned is still E_w. The transformations were not performed for the winter months (December, January, and February) because then the ground may have patchy snow cover (or the mountainous areas have snow but the lower grounds do not), which violates the constant Q_n assumption since the albedo of snow is markedly different from that of the land.

Lake evaporation (for the ten largest lakes in Hungary) again is calculated by the WREVAP program (and thus the transformation ET values overwritten), because water albedo is much smaller than that of the land (i.e., ~5% vs ~15%). WREVAP gave accurate estimates of lake evaporation in earlier studies [3].

4 Results

Fig. 3 displays the monthly mean evaporation rates in Hungary. In March the ET is comparatively low and uniform. From April till June the air temperature gradually increases and its saturation deficit becomes greater which enhances the extent and spatial differences of evaporation. Although July and August are the warmest months in Hungary, the areal evaporation culminates in June due to favorable soil moisture conditions (resulting from a within-year peak in precipitation) in early summer.

The spatial variance of ET is quite substantial and results from a combination of rain, land cover and access to groundwater: high rates in (a) the forested mountainous regions of northern Hungary with annual precipitation of 700–800 mm (the average for Hungary is about 600 mm), and; (b) the south-western region of the country where precipitation is in excess of 800 mm. Where there is a constant shallow groundwater-supply, typically in the floodplains along the Danube and Tisza Rivers, ET is similarly high, especially in the gallery forests, the largest of which is Gemenc in south-central Hungary. The driest region with the lowest overall evaporation (as well as precipitation) rates in the country is found in the Hungarian Lowland, where grass cover and croplands dominate. This is especially valid for the sandy inter-fluvial plateau between the Danube and the Tisza River where the groundwater table has steadily declined over the past several decades. Other low evaporation areas can be found e.g., within the karst-plateau of the Balaton Highland and the large urban conglomerate of Budapest (Fig. 4 and 5). The maps naturally show the highest evaporation rates (about 900 mm annually) for the lakes throughout the year.

Validation of the results was performed with the help of three eddy-covariance sites. While continuous data from the two CarboEurope sites, Bugac and Mátra [5], [7]), were available for almost each month of our study period, from the third site, Hegyhátsál [1], continuous measurements were available only for a somewhat more limited number of months displayed in Fig. 6 which, together with Table **??**, summarize the results of the validation.

The CREMAP ET values yield an unbiased estimate of the observed ET rates overall. The originally uncorrected Hegyhátsál (lat 46.95 N, long 16.65 E, surface elevation 248 m) measurements (with a 44% systematic underestimation) had to be multiplied by 1.78 to satisfy the energy balance. The accuracy of the local measurements (from Z. Barcza) for the latter was separately validated by the WREVAP-model estimates using sunshine duration measurements. Accounting for the large footprint (measurement height is 82 m above ground) at Hegyhátsál, the CREMAP ET values were averaged over 8 x 8 = 64 MODIS pixels around the tower, and yielded a perfect 1:1 relationship (R^2 = 0.95) with measurements (Fig. 6).

Evaporation measurements at the Bugac site (46.69 N, 19.6 E) began in 2002, and in 2004 at Mátra (47.85 N, 19.73 E). The CREMAP estimates yield R^2= 0.79 and R^2= 0.80, respectively, with measurements which is again remarkable considering that at these locations the footprints are only a fraction (about 10 and 16%) of the corresponding MODIS cell area. At an annual level CREMAP yields an error of only -6 mm (absolute relative error of 1.4%) at Bugac, and 13 mm (3.3%) at the Mátra site. The CREMAP ET estimates for the 2000–2006 period could be validated over the whole country (i.e., the period when independent water balance estimates were available for Hungary). The overall ratio of ET and precipitation is 89.2% by CREMAP versus the water-balanced derived value of 89.6%, a remarkable match.

5 Summary and conclusions

The present ET estimation model (CREMAP) is a modified and updated version of the ET estimation technique of Szilágyi and Józsa [11] and utilizes 1 km 8 day composited MODIS daytime surface temperature, T_s, and basic atmospheric data (air temperature, humidity and sunshine duration) to estimate the latent heat flux (i.e., evaporation rate) at the same spatial and temporal scale. Here a monthly time-step was chosen, as typical for regional hydrologic modeling. The approach is based on a linear transformation of the monthly MODIS T_s pixel values into ET rates (Fig. 2). The resulting linear equation, valid always only for the given computation interval (i.e., month), is then applied for each pixel after an elevation correction. The model was validated with monthly eddy covariance measurements.

The resulting 1 km spatial resolution monthly and annual ET maps are novel in Hungary (as well as in the world for such a long period) and provide a richness in spatial detail that contrasts starkly with previously available greatly generalized ET maps [8].

The model is simple, requires only a minimum amount of typically easily accessible data, and calibration free. From the first author's personal website, documentation of the WREVAP program with its FORTRAN source code is also available (snr.unl.edu/szilagyi/szilagyi.htm).

Generally, the model is expected to work accurately in regions where the complementary relationship is valid [10]. In its present form, it is not recommended to be applied in steep mountainous areas of rugged terrain or in areas with large surface-albedo changes at a scale larger than the 1 km resolution of the MODIS data. Furthermore, due to its inherent assumptions (mainly a spatially constant Q_n), it is not advised to be applied at a spatial resolution finer than about 1 km.

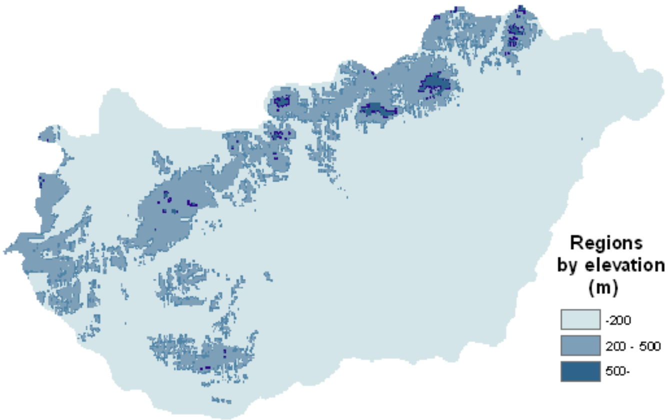

Fig. 1. The extent of the three elevation zones employed in the model.

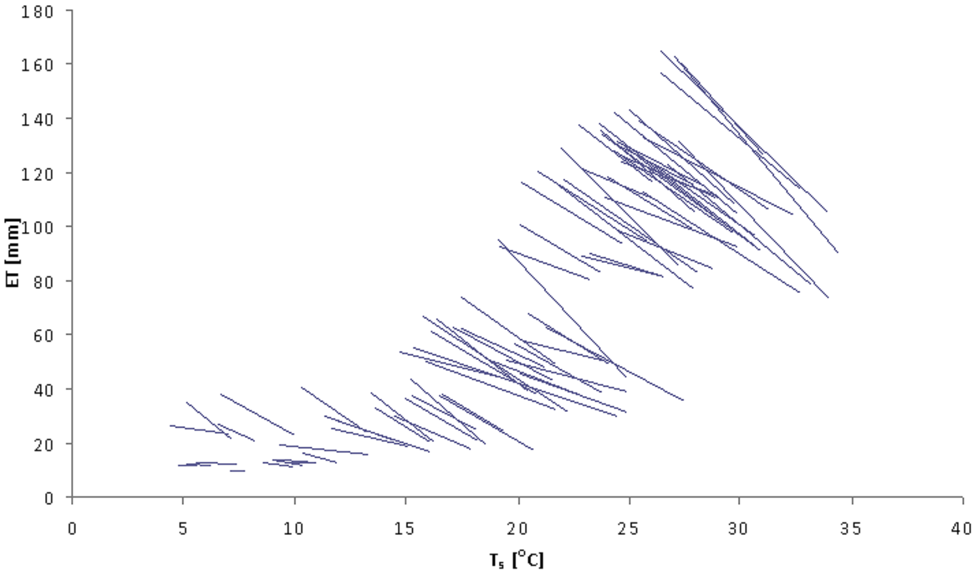

Fig. 2. Linear transformations for the lowest elevation zone, displayed by month for 2000 – 2008. Each line ends in the anchor points ($T_s - ET$ and $T_{sw} - E_w$).

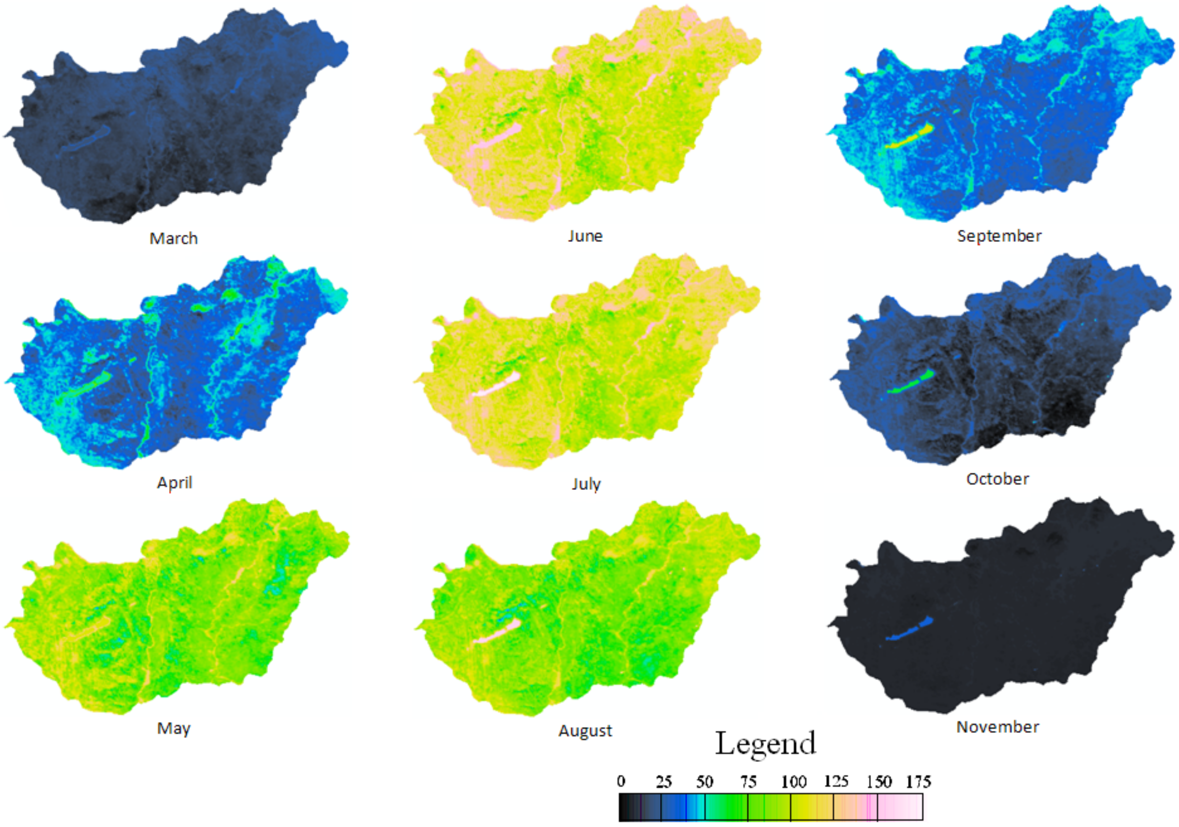

Fig. 3. 9-year averaged (2000-2008) mean monthly ET rates (mm).

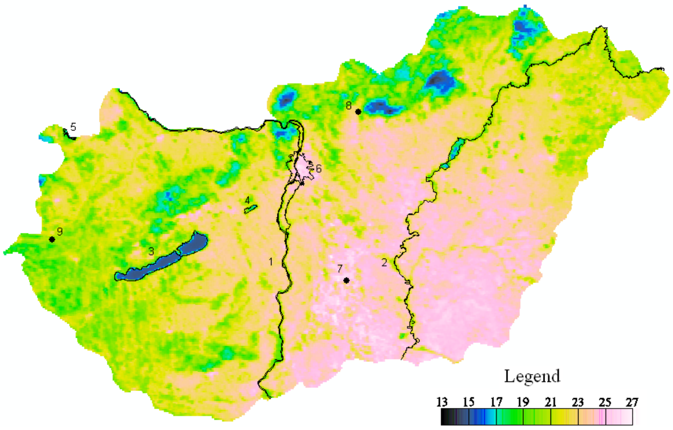

Fig. 4. 9-year averaged (2000-2008) spatial distribution of the MODIS T_s values (°C). 1: Danube; 2: Tisza; 3: Balaton; 4: Lake Velencei; 5: Lake Fertő; 6: Budapest, 7: Bugac, 8: Mátra, 9: Hegyhátsál.

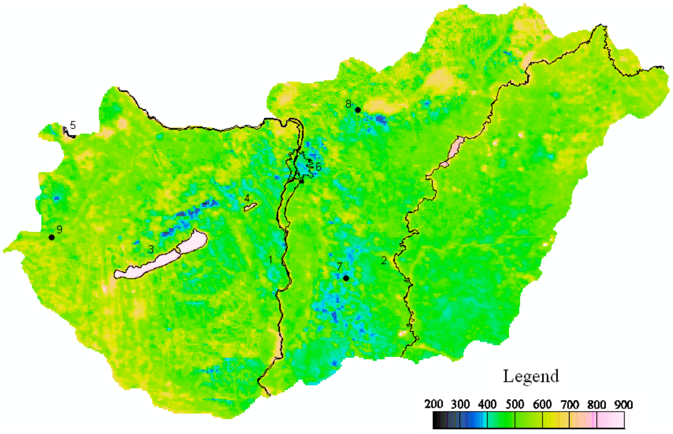

Fig. 5. 9-year averaged (2000 -2008) mean annual ET rates (mm).

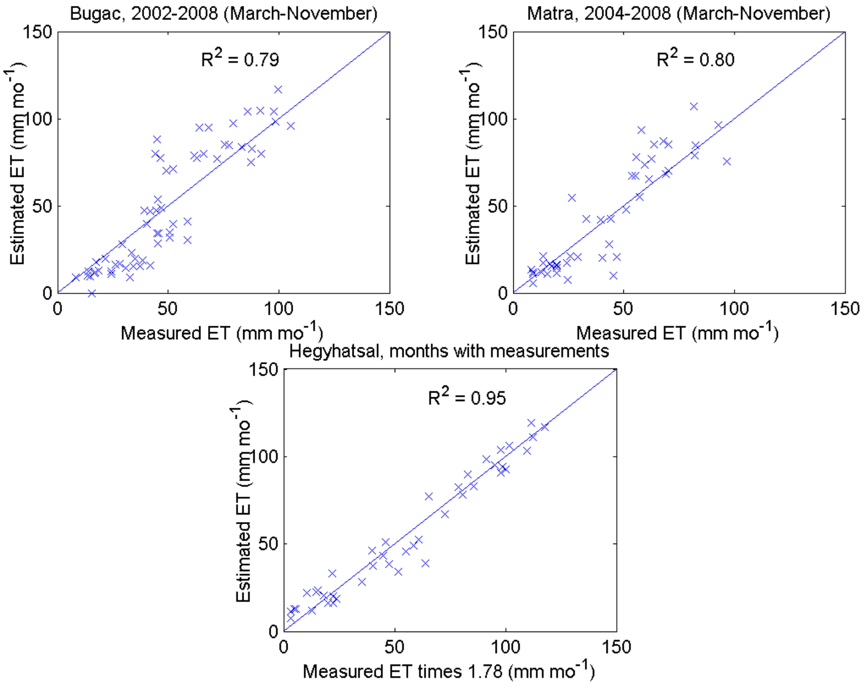

Fig. 6. Validation of the CREMAP ET estimates with eddy-covariance (Bugac, Mátra and Hegyhátsál) data.

Tab. 1. Validation of the ET estimation method with eddy-covariance measurements on a monthly basis. mv: measurement mean; me: error mean; de: standard deviation of error; n: number of months.

Month	Bugac				Mátra				Hegyhátsál			
	n	Monthly (mm mo^{-1})			n	Monthly (mm mo^{-1})			n	Monthly (mm mo^{-1})		
		mv	me	de		mv	me	de		mv	me	de
MAR	6	24	-10	15.5	5	19	-2	8.0	5	19	0	10.0
APR	6	49	-18	14.7	5	43	-19	28.2	6	49	-9	22.1
MAY	7	75	4	22.6	5	71	-4	19.3	4	89	0	9.7
JUN	7	82	13	39.7	5	77	13	24.5	3	108	-3	3.0
JUL	7	64	21	28.4	5	60	21	24.5	4	105	5	5.1
AUG	7	59	9	27.5	5	53	13	4.0	4	78	2	13.9
SEP	7	44	-11	22.2	5	34	-4	4.9	4	52	-3	11.5
OCT	7	32	-15	17.4	5	19	-6	17.6	3	16	10	2.6
NOV	7	15	-4	5.8	5	10	1	6.6	3	4	7	2.6

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