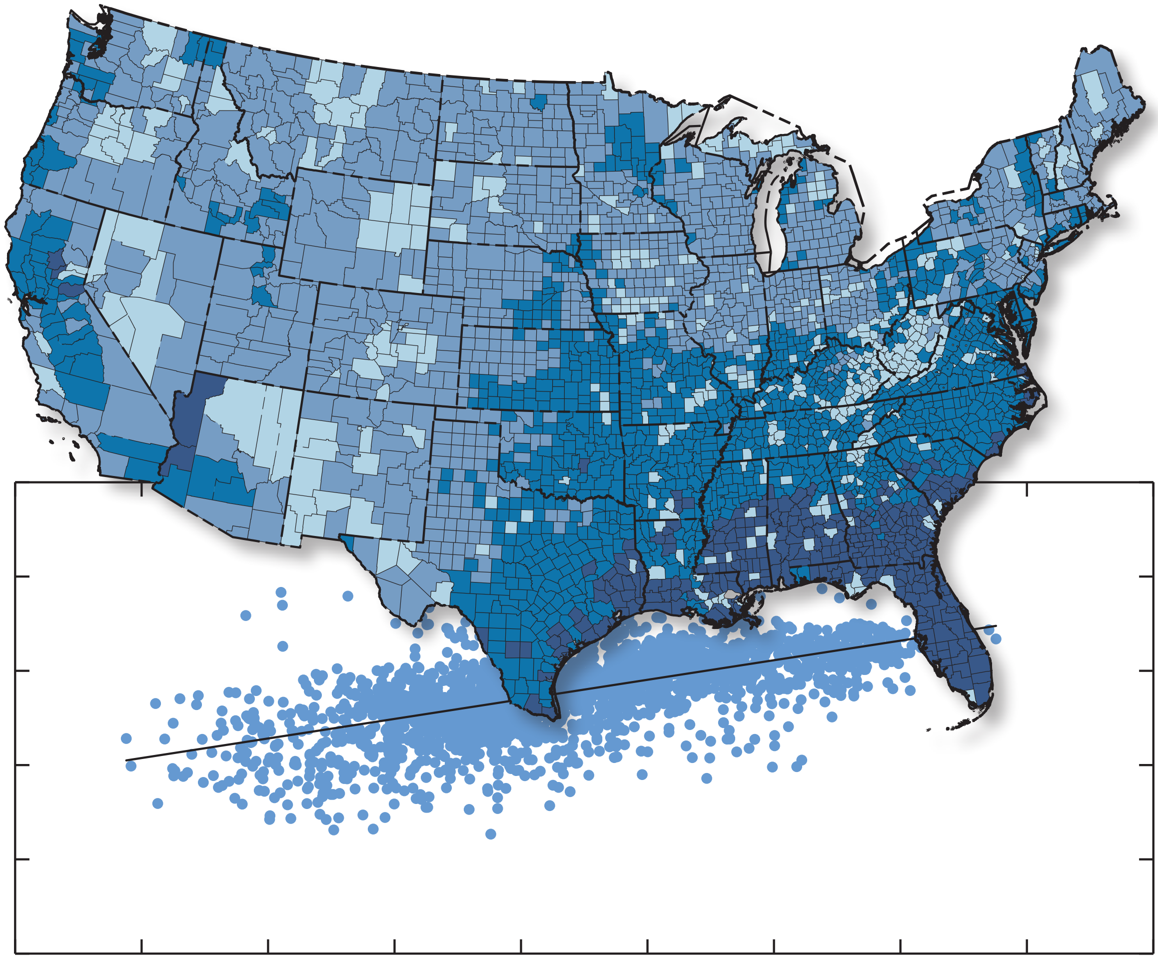
Groundwater Resources Program

Actual Evapotranspiration Modeling Using the Operational Simplified Surface Energy Balance (SSEBop) Approach



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Contents

Figures

Conversion Factors and Abbreviations and Acronyms

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	.6214	mile (mi)
millimeter (mm)	.0394	inch (in.)

Abbreviations and Acronyms

CONUS	conterminous United States
CU	consumptive use
EROS	USGS Earth Resources Observation Systems
ET	evapotranspiration
ETa	actual evapotranspiration
ETf	evapotranspiration fractions
ETo	reference evapotranspiration
ETp	potential evapotranspiration
LST	land surface temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NWUIP	National Water Use Information Program
PRISM	Parameter-elevation Regressions on Independent Slopes Model
SSEB	Simplified Surface Energy Balance
USGS	U.S. Geological Survey

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Abstract

Remote-sensing technology and surface-energy-balance methods can provide accurate and repeatable estimates of actual evapotranspiration (*ETa*) when used in combination with local weather datasets over irrigated lands. Estimates of *ETa* may be used to provide a consistent, accurate, and efficient approach for estimating regional water withdrawals for irrigation and associated consumptive use (CU), especially in arid cropland areas that require supplemental water due to insufficient natural supplies from rainfall, soil moisture, or groundwater. *ETa* in these areas is considered equivalent to CU, and represents the part of applied irrigation water that is evaporated and/or transpired, and is not available for immediate reuse. A recent U.S. Geological Survey study demonstrated the application of the remote-sensing-based Simplified Surface Energy Balance (SSEB) model to estimate 10-year average *ETa* at 1-kilometer resolution on national and regional scales, and compared those *ETa* values to the U.S. Geological Survey's National Water-Use Information Program's 1995 county estimates of CU. The operational version of the operational SSEB (SSEBop) method is now used to construct monthly, county-level *ETa* maps of the conterminous United States for the years 2000, 2005, and 2010. The performance of the SSEBop was evaluated using eddy covariance flux tower datasets compiled from 2005 datasets, and the results showed a strong linear relationship in different land cover types across diverse ecosystems in the conterminous United States (correlation coefficient [r] ranging from 0.75 to 0.95). For example, r for

- woody savannas (0.75),
- grassland (0.81),
- forest (0.82),
- cropland (0.84),
- shrub land (0.89), and
- urban (0.95).

A comparison of the remote-sensing SSEBop method for estimating *ETa* and the Hamon temperature method for estimating potential ET (*ETp*) also was conducted, using regressions of all available county averages of *ETa* for 2005 and 2010, and yielded correlations of r = 0.60 and r = 0.71, respectively. Correlations generally are stronger in the Southeast where *ETa* is close to *ETp*. SSEBop *ETa* provides more spatial detail and accuracy in the Southwest where irrigation is practiced in a smaller proportion of the region.

Introduction

Advances in remote-sensing technology and energy-balance methods allow for increasingly accurate and repeatable estimates of actual evapotranspiration (*ETa;* the amount of water that evaporates from the surface and is transpired by plants if the total amount of water is limited) when used in combination with local weather datasets for irrigated lands. The evaporation of water takes place when water changes from liquid to gas, and requires a substantial amount of latent heat energy. Because of this latent heat energy, a fully transpiring vegetated area will appear up to 20°C cooler than bare areas with little evaporation. This temperature differential is the basis for remote-sensing technology and energy-balance method estimates of ET. Estimates of *ETa* may be used to provide a consistent, accurate, and efficient approach for estimating regional water withdrawals for irrigation and associated consumptive use (water removed from available supplies without return to a water resources system), especially in arid cropland areas that require supplemental water because of insufficient natural supplies from rainfall, soil moisture, or groundwater. *ETa* in these areas is considered equivalent to consumptive use (CU), and represents the part of applied irrigation water that is evaporated and/or transpired, and is not available for immediate reuse. Irrigation includes the irrigation of cropland by various methods to enhance agricultural productivity. Water for irrigation is supplied through groundwater pumping or by surface-water diversion. Typically, the amount of water used for irrigation has been reported by farmers using flow meters or estimates from hours and pump rates, approximated from groundwater and surface-water irrigation permits, or calculated using crop irrigation requirements and ancillary data, such as soil conditions, irrigation system conveyance losses, and weather parameters.

There are at least six methods to compute ET. They are:

1. Water budget method (Guitjens, 1982)
2. Mass transfer method (Harbeck, 1962)
3. Combination method (Penman, 1948)
4. Radiation method (Priestley and Taylor, 1972)
5. Temperature method (Thornthwaite, 1948; Hamon, 1961)
6. Method of estimating actual ET from satellite data using an energy-balance method (Senay and others, 2013)

A recent U.S. Geological Survey (USGS) study (Maupin and others, 2012) demonstrated the application of the remote-sensing-based Simplified Surface Energy Balance (SSEB) model to estimate 10-year average *ETa* at 1-km resolution on national and regional scales, and compared those *ETa* values to the USGS National Water-Use Information Program's (NWUIP) 1995 county estimates of CU. As described in Maupin and others (2012), the energy-balance-based approach gives a "total" *ETa* value that is a summation of ET from all water sources, including rainfall, soil moisture or groundwater in the vadose zone, and irrigation. Although this is useful for estimating total water use by crops, it does not differentiate the various source contributions. This is not a major problem in regions of the west and southwest that are largely dependent on irrigation to grow crops, and rainfall and groundwater resources are minimal compared to the crop needs met by irrigation. However, in humid regions of the east and southeast, irrigation still may be necessary on a smaller scale. In these eastern and southeastern areas, it is difficult to determine whether the exact source of the water that is evaporated or transpired is from irrigation or a natural source such as rainfall or groundwater.

The operational version of the SSEB method (SSEBop) is now used to construct monthly, county-level *ETa* maps of the conterminous United States (CONUS) for 2000, 2005, and 2010. Prior to this study, Senay and others (2013) evaluated the performance of the SSEBop using eddy covariance flux tower datasets using 2005 datasets and the results showed strong linear relationships in different land cover types across diverse ecosystems in the CONUS (correlation coefficient [r] ranging from 0.75 to 0.95). For example, r for

- woody savannas (0.75),
- grassland (0.81),
- forest (0.82),
- cropland (0.84),
- shrub land (0.89), and
- urban (0.95).

This report documents the use of the operational version of the SSEB method (SSEBop) to construct monthly, county-level *ETa* maps of the CONUS for 2000, 2005, and 2010. A comparison of the remote-sensing SSEBop method for estimating actual ET (*ETa*) and the Hamon temperature method (Hamon, 1961) for estimating potential ET (*ETp*) for the CONUS also was conducted for 2005 and 2010.

Methods

The main concept of the SSEB approach in Senay and others (2007, 2011a, 2011b) is the joint use of potential ET (*ETp;* the amount of water that would evaporate from the surface and be transpired by plants where the supply of water is unlimited) and Land Surface Temperature data. The surface energy-balance is first solved for each 1-km pixel (the smallest addressable element in the raster image) for a reference crop condition (assuming full vegetation cover and unlimited water supply) using the standardized Penman-Monteith Equation (Allen and others, 1998). USGS Earth Resources Observation Systems (EROS) (Senay and others, 2008) produce daily reference ET (*ETo;* the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec/m, and an albedo of 0.23) for the globe at 100-km resolution from weather data generated every 6 hours by the National Oceanic and Atmospheric Administration's (NOAA) Global Data Assimilation System. A statistically disaggregated version at 10-km pixels was used for this study. Although the approximate upper limit is determined by the *ETo*, the reduction from the potential and, thus, the spatial variability of *ETa* is estimated from the Land Surface Temperature (LST) through an ET fraction approach. ET fractions (*ETf*) account for spatial variability of water availability and vegetation health in the landscape. Spatially explicit *ETf* are used to adjust the *ETo* magnitudes based on the LST of the pixel (eq. 1). In this case, LST data were derived from 8-day average MODIS (MOD11A) datasets with a 1-km spatial resolution. MODIS data are available on daily and 8-day average format. For this study, we chose the 8-day average because the 8-day average is created from non-cloudy periods. Although the 8-day average data reduces the likelihood of cloud cover, there are periods where persistent clouds prohibit the calculation of ET in a given 8-day period. In this case, the previous or next 8-day period *ETf* is used to estimate the missing ET period (Senay and others, 2013).

In this study, we used the operational SSEB (SSEBop) formulation (Senay and others, 2013) where *ETf* are calculated from the LST datasets based on the assumption that "hot" pixels experience little or no ET (Bastiaanssen and others, 1998; Allen and others, 2007), "cold" pixels represent "maximum" ET, and that ET can be scaled between these values in proportion to the LST.

Instantaneous LST at satellite overpass time can be used to identify "hot" and "cold" pixels that can be used to calculate fractions of ET on a per-pixel basis. This approach works well in a region with uniform hydro-climatic conditions such as arid, irrigated basins. However, in order to eliminate the manual selection of "hot" and "cold" reference pixels, which also introduces subjective errors, SSEBop pre-defines the "hot" and "cold" limits, specific to a given location and period, using a combination of air temperature and clear-sky energy-balance calculations (Senay and others, 2013). The *ETf* is calculated for each MODIS pixel "x" by applying equation 1 to each of the 8-day LST grids.

$$ETf = \frac{Th - Ts}{Th - Tc} \quad (1)$$

where

Ts is the satellite-observed LST of pixel "x," the *ETf* of which is being evaluated on a given time-period (8-day average for MODIS);

Th is the LST at the idealized reference "hot" condition of the image for the same time period

Tc, the cold reference value, is the LST at the idealized reference "cold" condition of the image at the same time period, and is estimated from the monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) maximum air temperature for the given 8-day period as described in Senay and others (2013).

PRISM monthly values were used because they were the only readily available gridded data for the CONUS available at the time of this study. The difference between *Th* and *Tc* is simply the difference temperature, *dT.*

With this simplification, *ETa* is estimated using equation 2 as a fraction of the *ETo*.

$$ETa = ETf \times ETo \quad (2)$$

where

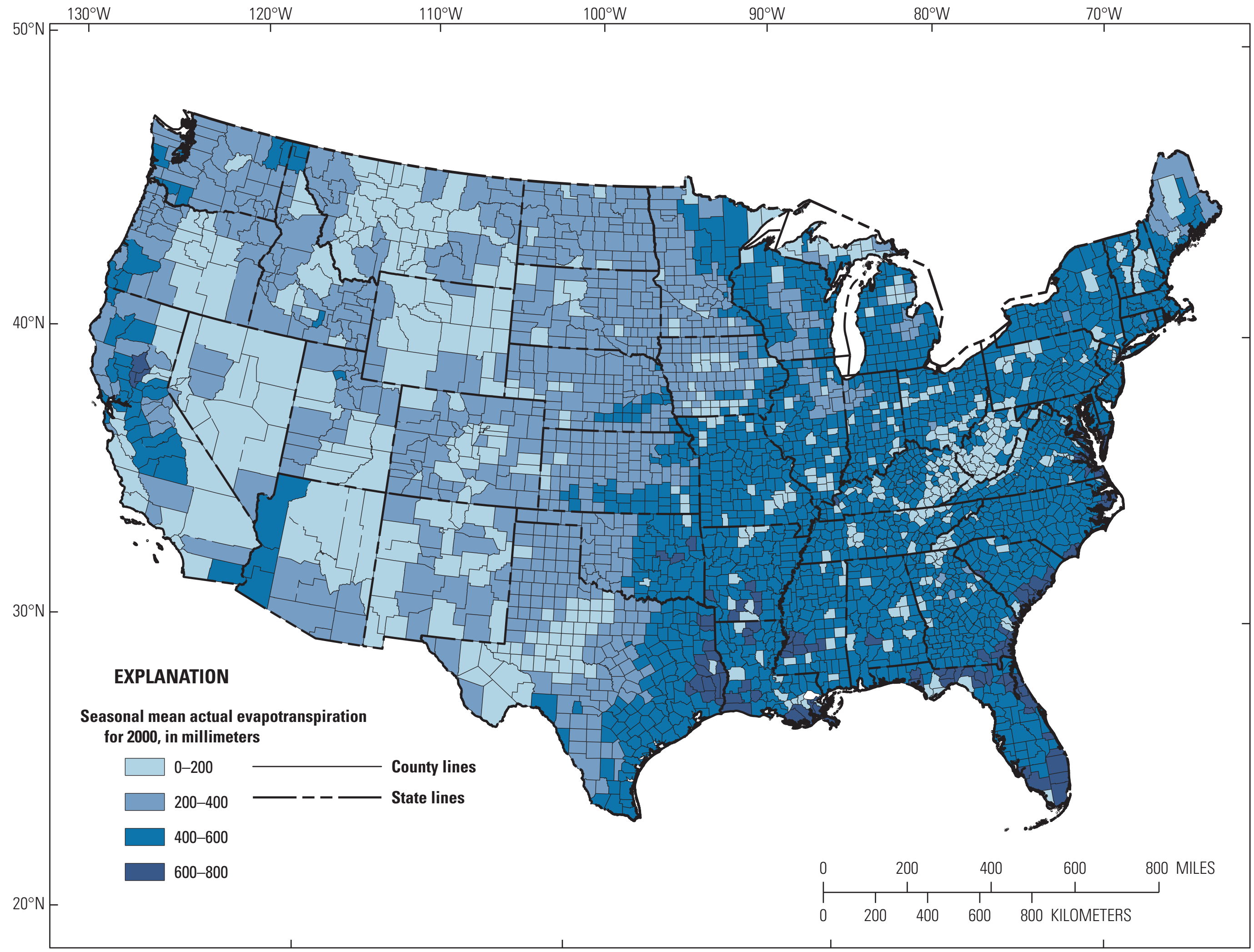
ETo is the cumulative reference ET amount for the 8-day period.

Once *ETa* grids were calculated at 8-day time steps, monthly and seasonal (May–September) *ETa* summaries were produced for each modeling pixel in the CONUS at 1-km spatial resolution for 2000, 2005, and 2010 that coincide with the NWUIP's reporting years. To compute monthly and seasonal ET for only those areas with cropland irrigation, an irrigation mask was obtained from EROS (Pervez and Brown, 2010), and seasonal county-average ET depths (in millimeters) were calculated using only the masked irrigated areas. SSEBop *ETa* was first calculated for all pixels in the CONUS. The irrigation mask was then used to remove non-irrigated pixels, and the remaining irrigated pixels were averaged to represent the average irrigated area *ETa* for the county. The method used (Pervez and Brown, 2010) to delineate areas with cropland irrigation were reasonably accurate in California and semiarid Great Plains States with overall accuracies of 92 and 75 percent and kappa statistics of 0.75 and 0.51, respectively. A quantitative accuracy assessment of the Moderate Resolution Imaging Spectroradiometer (MODIS) Irrigated Agriculture Dataset for the eastern region has not yet been conducted, and qualitative assessment shows that model improvements are needed for the humid eastern regions where the distinction in annual peak Normalized Difference Vegetation Index between irrigated and non-irrigated crops is minimal and county sizes are relatively small. The NWUIP has produced national datasets for 2000 and 2005 with county totals for irrigated acres, irrigation groundwater withdrawals, and irrigation surface-water withdrawals. Irrigation CU values exist for few States in 2000 and 2005, but the last complete national compilation of CU county values was 1995. Estimates of irrigated acreage in 2010 were not yet available for each county at the time of this study. Therefore, the 2010 irrigated acreage was assumed to be equal to that for 2005. County-level *ETa*-depth maps were produced using images from May to September in each of the three years. These depths may underestimate the annual total *ETa* in parts of the country where irrigation is practiced outside of the May–September peak season. However, the results will still depict the relative *ETa* differences between counties despite a potential bias in magnitude because of incomplete information on the seasonal aggregation.

The remote-sensing SSEBop method (Senay and others, 2013) for estimating ETa, and the Hamon temperature method (Hamon, 1961) for estimating ETp, were compared using data for 2005 and 2010. Hamon (1961) developed a simple method for estimating average daily potential evapotranspiration as proportional to the product of daytime hours squared and the saturated water vapor concentration (absolute humidity) at the mean temperature. The daytime factor was determined from a consideration of the disparity between net radiation and temperature, lattitudinally, and the fact that transpiration is restricted during darkness. Values of ETp were computed from the Hamon equation (Hamon, 1961) using temperature data from PRISM (Oregon State University, 2007) for 2005 and 2010, and were compared with ETa derived from satellite data (Senay and others, 2013). This assumes that the cropland is fully irrigated, and therefore SSEBop is nearly equal to the ETp computed using the Hamon method.

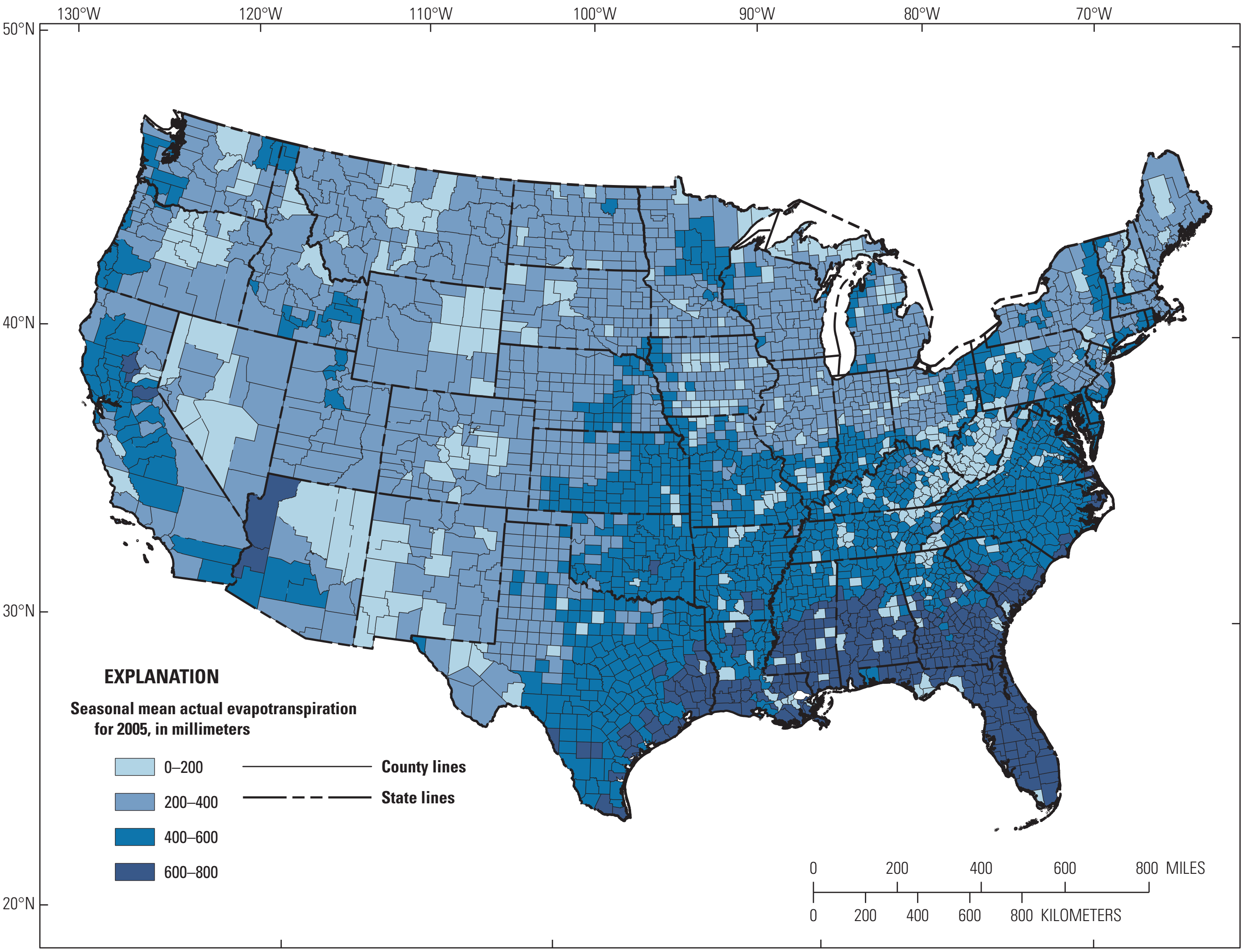
Results

Pixel-based monthly and seasonal ET depths were converted into county-based ET depths using an irrigation-area mask derived from remotely sensed images, and county-based seasonal-mean *ETa* depth maps were produced for 2000 (fig. 1*A*), 2005 (fig. 1*B*), and 2010 (fig. 1*C*). Grids for 1-km monthly *ETa* depths and associated metadata are available from the USGS upon request.



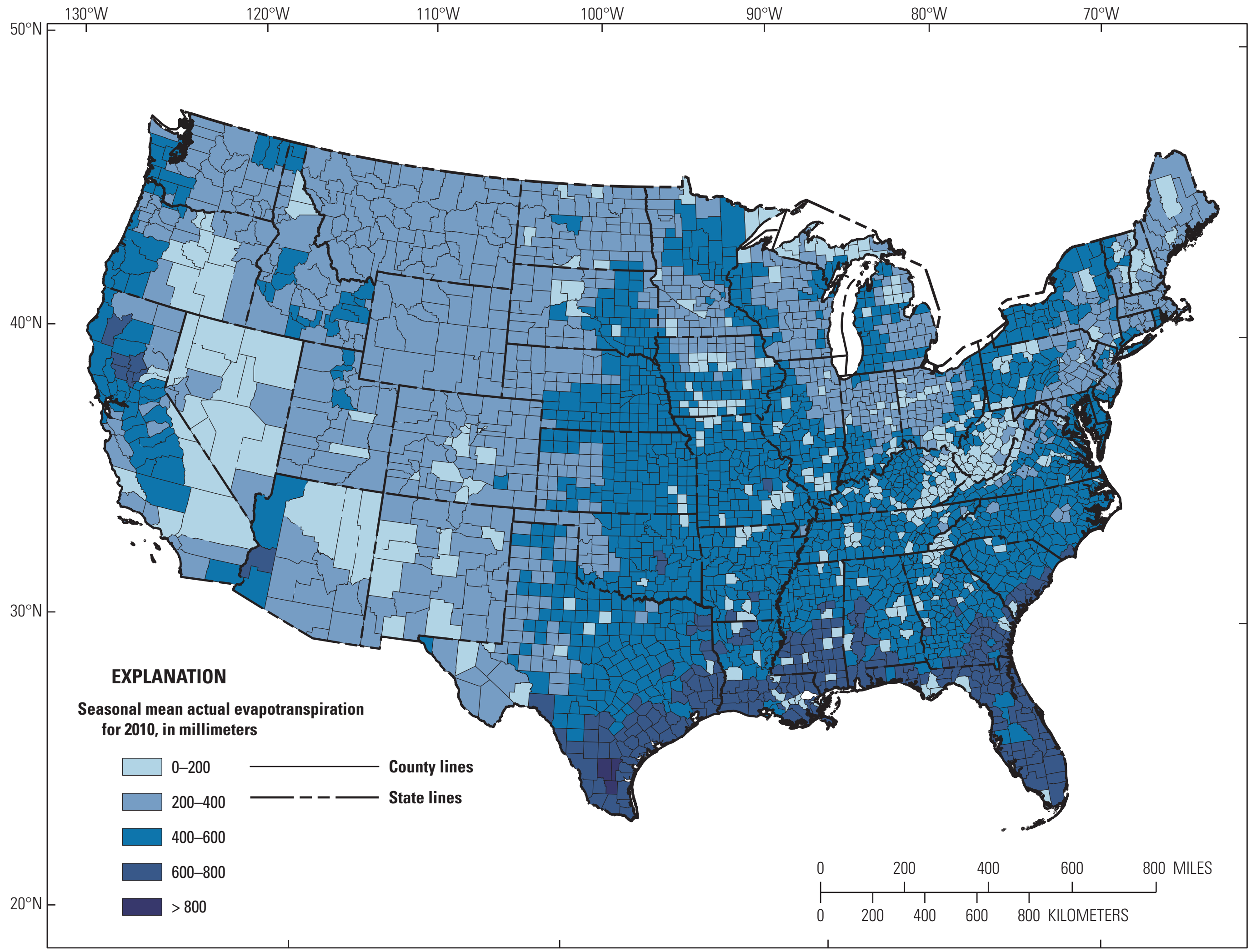
A. 2000

Figure 1. County-based seasonal mean actual evapotranspiration (*ETa*) depth, 2000, 2005, and 2010.



B. 2005

Figure 1.—Continued



C. 2010

Figure 1.—Continued

A comparison of the remote-sensing-SSEBop method for estimating county-wide *ETa* and the Hamon temperature method (Hamon, 1961) for estimating *ETp* in the CONUS was conducted for 2005 and 2010. The Hamon method is recommended for regional applications for determining *ETp*, especially the Southeastern United States (Lu and others, 2005). If the cropland is fully irrigated, the *ETa* will be approximately equal to the *ETp*.

Spatially-averaged *ETa* during the growing season (May–September) for the SSEBop method was generated using this energy-balance method to represent counties in the CONUS where irrigation is practiced. A nationwide irrigated area mask was generated independently by Pervez and Brown (2010). Regressions of all available county averages of *ETa* and *ETp* for 2005 and 2010 yield a correlation of r = 0.60 and r = 0.71, respectively (fig. 2*A*, r^2=0.36; fig. 2*B*, r^2=0.51). Some states showed higher correlations (Alabama and Arizona, figs. 3*A* and 3*B*), while others showed very low correlation (Texas, fig. 3*C*). Correlations generally are stronger where values of *ETa* are close to values of *ETp* in the southeast.

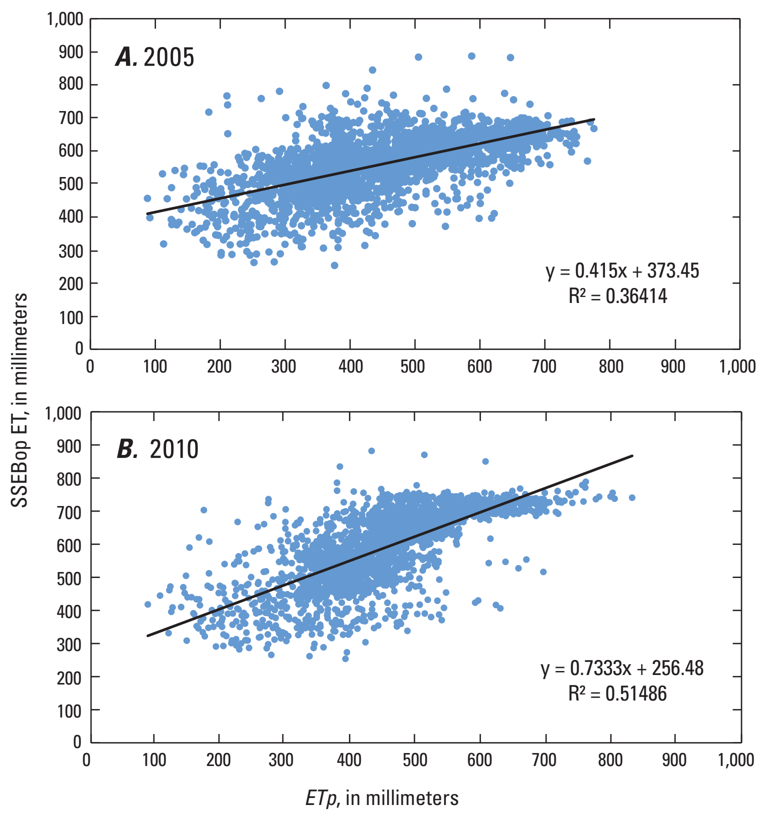


Figure 2. Relation between county-based seasonal mean potential evapotranspiration (*ETp*) and Simplified Surface Energy Balance Method evapotranspiration (SSEBop ET) depths, 2005 and 2010.

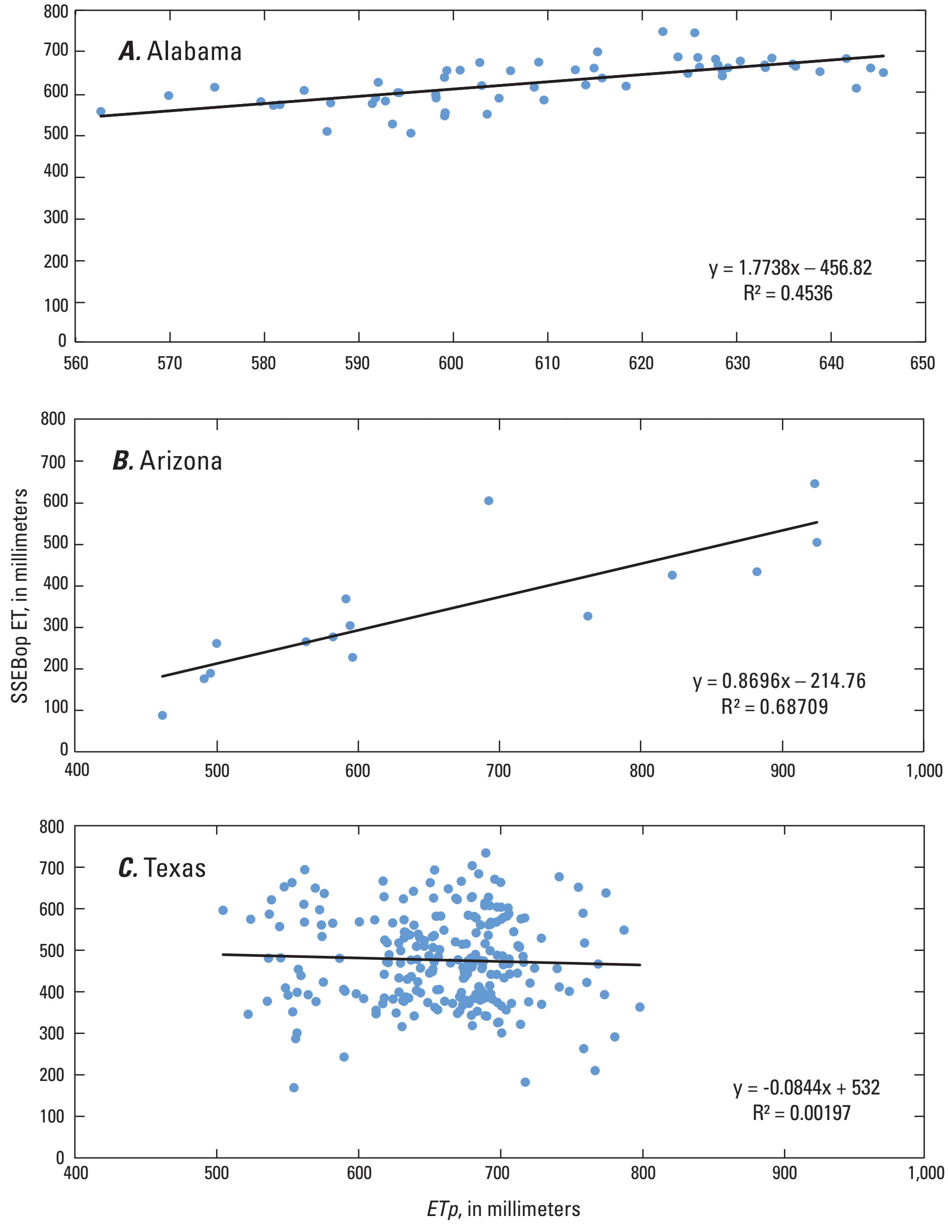


Figure 3. Relation between county-based seasonal mean potential evapotranspiration (*ETp*) and Simplified Surface Energy Balance Method evapotranspiration (SSEBop ET) depths for Alabama, Arizona, and Texas, 2005.

County-wide *ETa* estimates follow a pattern similar to that of *ETp*. For 2005, *ETa* values (fig. 4) generally matched values of *ETp* (fig. 5). There is an approximate 100-mm bias between the SSEBop estimates and the Hamon estimates of evapotranspiration (see scale for range of ET on maps). For 2010, the patterns between *ETa* (fig. 6) and *ETp* (fig. 7) also show similarities. Black areas on figures 4 and 6 are counties where *ETa* was not estimated because there were no irrigated areas within the irrigation mask for those counties.

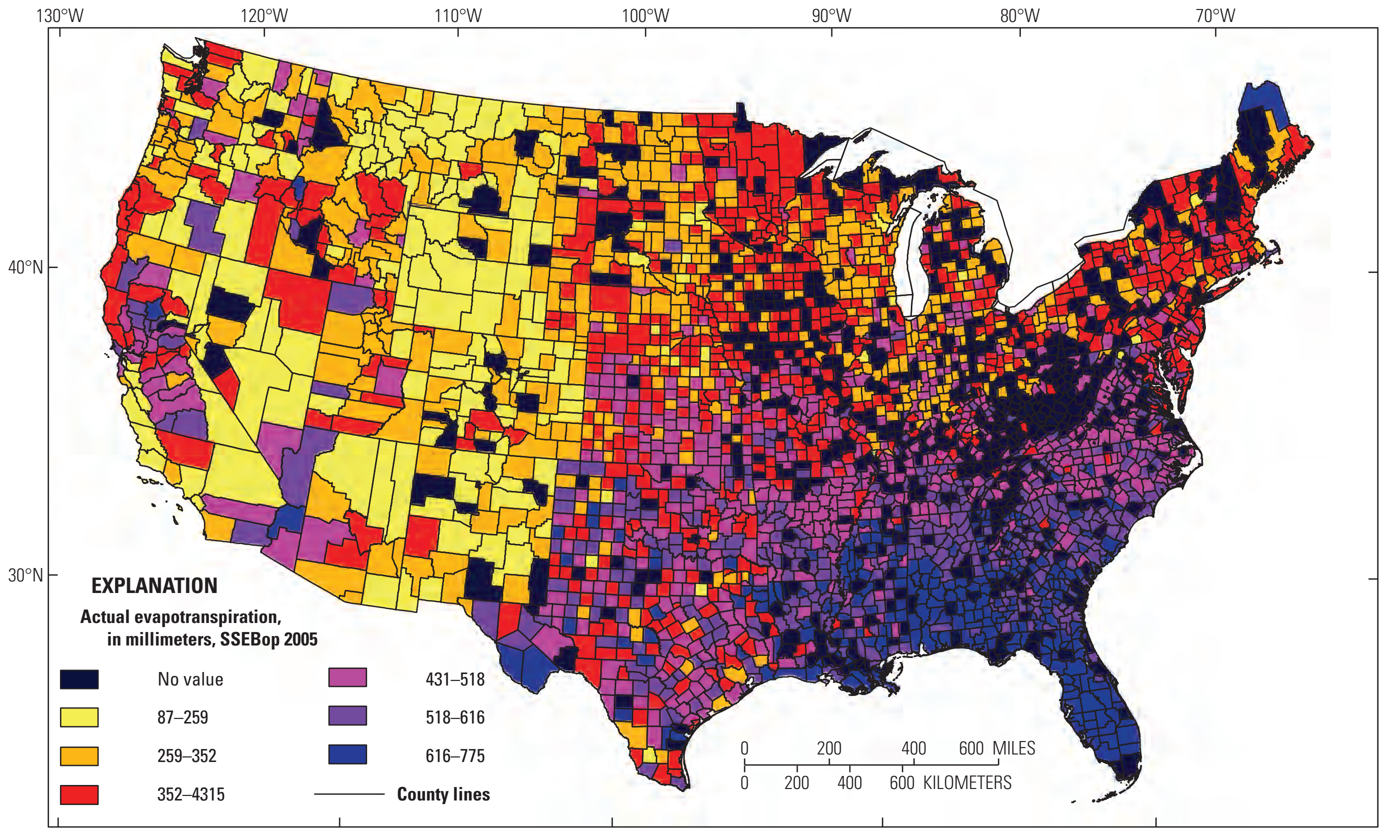


Figure 4. County-based seasonal mean Simplified Surface Energy Balance Method evapotranspiration (SSEBop ET) depth, 2005.

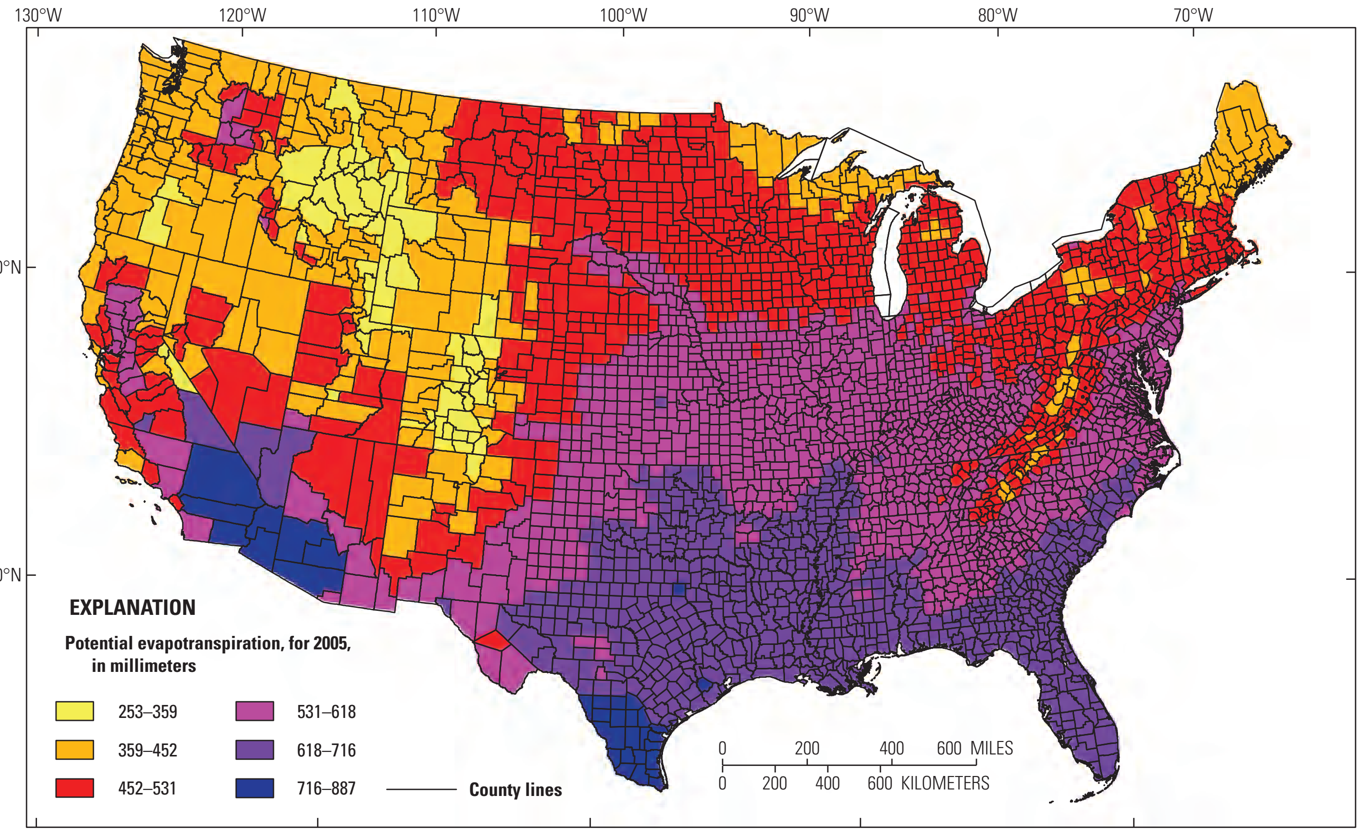


Figure 5. County-based seasonal mean potential evapotranspiration (*ETp*) depth, 2005.

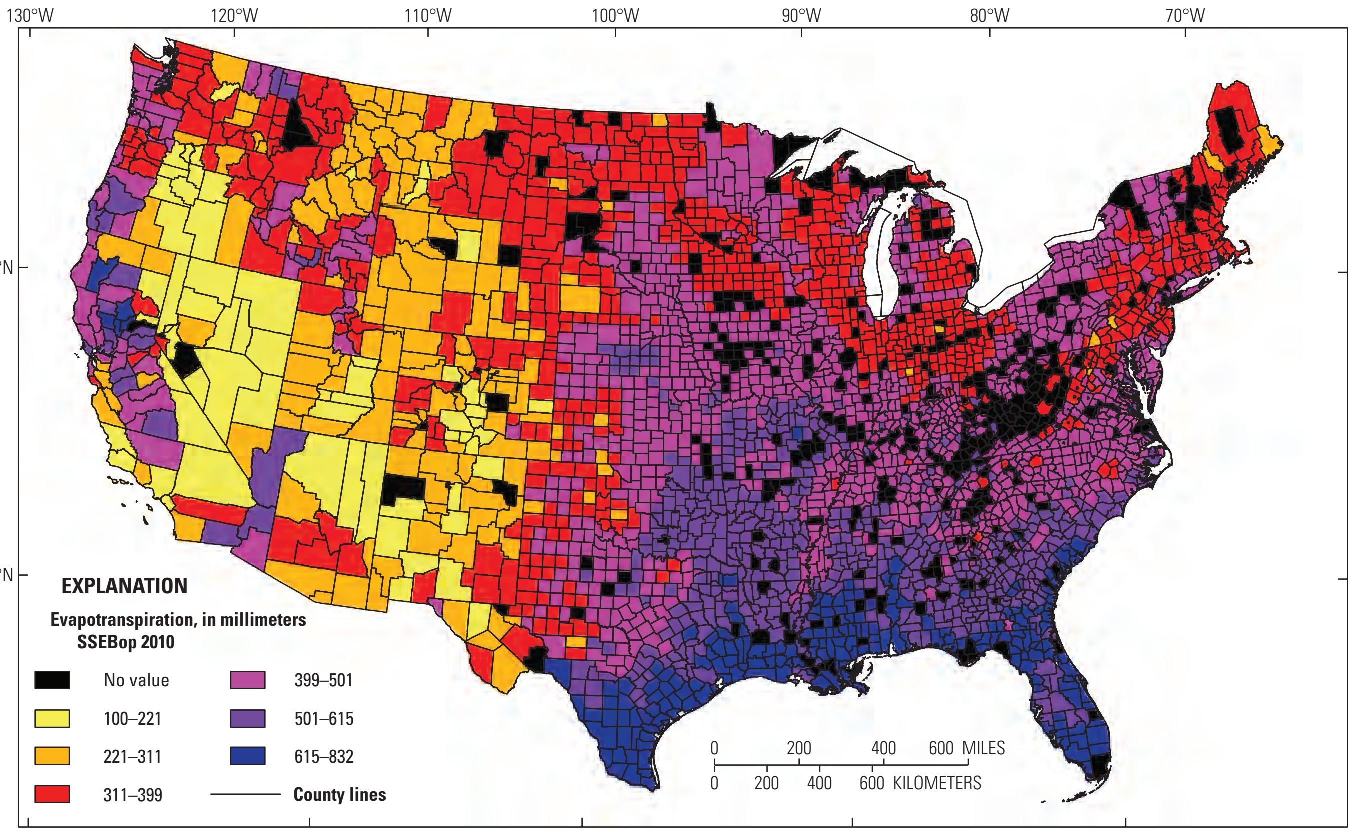


Figure 6. County-based seasonal mean Simplified Surface Energy Balance Method evapotranspiration (SSEBop ET) depth, 2010.

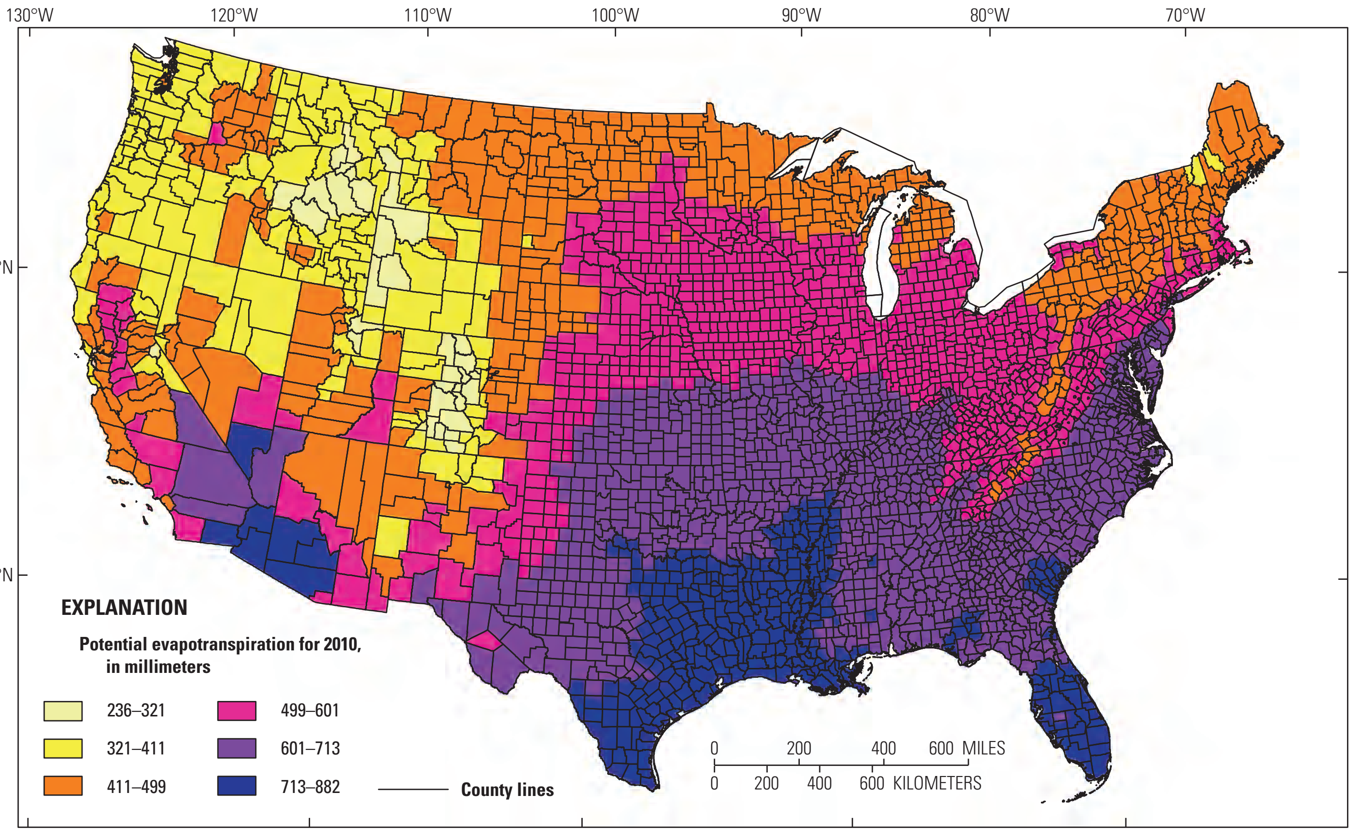


Figure 7. County-based seasonal mean potential evapotranspiration (*ETp*) depth, 2010.

A map of *ETp* estimates, minus a water-balance estimate (McCabe and Wolock, 2011) of *ETa* (fig. 8), was developed from county values for 2005. This map shows areas that are deficient in water for 2005, where irrigation might enhance productivity. The SSEBop *ETa* values could be generally evaluated as being comparable to the Hamon temperature method of computing *ETp*, but SSEBop *ETa* provides higher spatial resolution and accuracy in the Southwest where only irrigation can meet the atomospheric demand and is practiced in a smaller propotion of the region. Other methods (1 through 4) were not evaluated in this analysis.

Results from the SSEBop method (for 2000) also were compared to a method developed by Sanford and Selnick (2012) for estimating mean county-wide annual *ETa* (for 1971–2000) in the CONUS that combines a water-balance approach with a regression equation based on climate and land-cover factors. A comparison of *ETa* values for these two methods indicates a similar pattern in the CONUS of higher *ETa* primarily in the Southeast and along the Gulf Coast, and lower *ETa* values primarily in the High Plains and the desert Southwest.

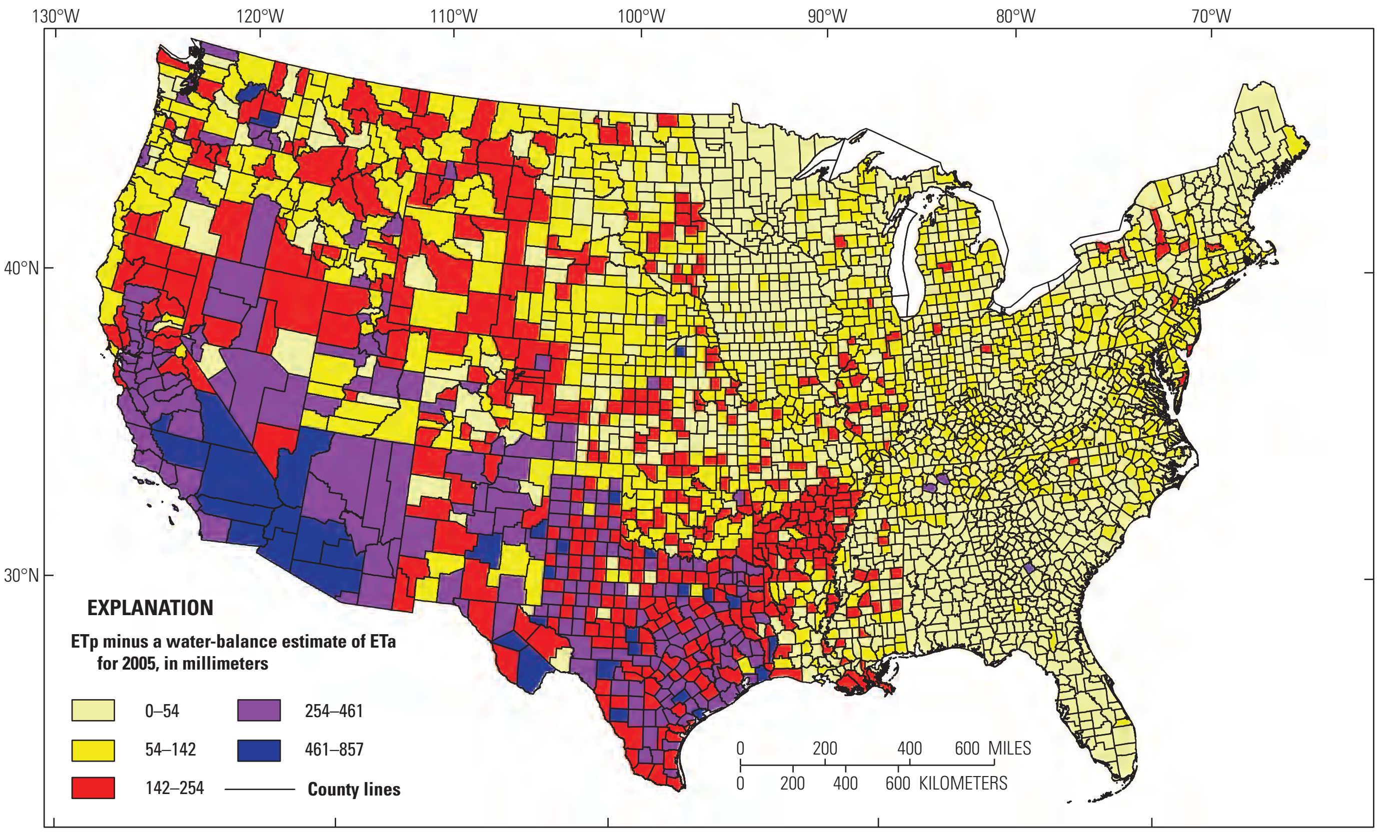


Figure 8. County-based seasonal mean potential evapotranspiration (*ETp*) depth minus a water-balance estimate of actual evapotranspiration (*ETa*), 2005.

Summary

Remote-sensing technology and surface energy-balance methods can provide accurate and repeatable estimates of actual evapotranspiration (*ETa*) when used in combination with local weather datasets for irrigated lands. Estimates of *ETa* may be used to provide a consistent, accurate, and efficient approach for estimating regional water withdrawals for irrigation and associated consumptive use (CU), especially in arid cropland areas that require supplemental water due to insufficient natural supplies from rainfall, soil moisture, or groundwater. *ETa* in these areas is considered equivalent to CU, and represents the part of applied irrigation water that is evaporated and/or transpired, and is not available for immediate reuse. A recent U.S. Geological Survey study demonstrated the application of the remote-sensing-based Simplified Surface Energy Balance (SSEB) model to estimate 10-year average *ETa* at 1 kilometer resolution on national and regional scales, and compared those *ETa* values to U.S. Geological Survey National Water-Use Information Program 1995 county estimates of consumptive use CU.

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A comparison of the remote-sensing SSEBop method for estimating *ETa* and the Hamon temperature method for estimating potential ET (*ETp*) also was conducted using regression analyses of all available county averages of ET for 2005 and 2010. The comparisons yielded correlations of r=0.60 and r=0.71, respectively. Correlations generally are stronger where *ETa* is close to potential ET in the Southeast. SSEBop ET provides more spatial detail and accuracy in the Southwest where irrigation is practiced in a smaller propotion of the region.

The energy-balance based approach gives a pixel average of “total” ET that is a summation of ET from all water sources, including rainfall, soil moisture, and groundwater in the vadose zone, and irrigation. Although this is useful in estimating total water use by crops, it does not differentiate the various source contributions. This is not a major problem in regions of the West and Southwest that are largely dependent on irrigation to grow crops, and rainfall and groundwater resources are minimal compared to the crop needs met by irrigation. However, in humid regions of the East and Southeast, irrigation still may be necessary on a smaller scale; it is difficult to determine whether the exact source of the water that is evaporated or transpired is from irrigation or a natural source, such as rainfall or groundwater. Future research will include an effort to separate the contribution of rainfall towards meeting the seasonal ET.

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