MAPPING STATEWIDE PRECIPITATION AND EVAPOTRANSPIRATION IN NEW MEXICO: YEAR ONE

By

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ABSTRACT

The objective of this study is to evaluate the accuracy of eight existing nationwide operational data bases for precipitation and evapotranspiration volumes over New Mexico. Five precipitation products have been evaluated: the AHPS Precipitation (National Weather Service Advanced Hydrologic Prediction Service) product, the CHIRPS Climate Hazards Group InfraRed Precipitation with Stations) , the PERSIANN-CCS (Precipitation Estimation from Remote Sensed Information using Artificial Neural Network – Cloud Classification System) model , the PRISM (Parameter-elevation Relationships on Independent Slopes) model and the TRMM / GPM model (Tropical Rainfall Measuring Mission / Global Precipitation Measurement). Three evapotranspiration products have been evaluated: the ALEXI (Atmosphere-Land Exchange Inverse) model that will become the operational ET product of NOAA , the MOD 16 (MODIS Global Evapotranspiration Product) model of NASA , and the SSEB (Simplified Surface Energy Balance) model used by the USGS. The operational precipitation product PRISM provides reliable daily precipitation data at a spatial resolution of 800 m over the entire state of New Mexico and has been selected as the operational precipitation product for the statewide water assessment. The operational evapotranspiration products ALEXI and SSEB provide adequate monthly evapotranspiration products for analysis of actual evapotranspiration in different eco-hydrological regions of the state as well as between different water years. However, the current accuracy of these products is not adequate for a reliable statewide assessment of groundwater recharge in the mountainous regions. It is proposed for Year II to (1) focus on the improvement of ALEXI and SSEB for evapotranspiration mapping in the flat areas of the state by the NMSU research team and (2) implement an existing proven soil water balance model for evapotranspiration mapping in the mountains using optical/thermal satellite images by the NMT research team.

Key words: precipitation, evapotranspiration, New Mexico

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LIST OF ABBREVIATIONS AND ACRONYMS

ALEXI	Atmosphere-Land Exchange Inverse model
AHPS	National Weather Service Advanced Hydrologic Prediction Service
CHIRPS	Climate Hazards Group InfraRed Precipitation with Stations
PERSIANN-CCS	Precipitation Estimation from Remote Sensed Information using Artificial Neural Network – Cloud Classification System
PRISM	Parameter-elevation Relationships on Independent Slopes and the
EC	Eddy Covariancy system to measure sensible and latent heat fluxes
EF	Evaporative Fraction
ET	Evapotranspiration
ETr	Reference Evapotranspiration for Tall Crop
ETrF	Reference ET Fraction
GPM	Global Precipitation Measurement
GPS-WAAS	Global Positioning System Wide Area Augmentation System
IRGA	Infrared Gas Analyzer
LAS	Large Aperture Scintillometer
LIS	Land Information System
METRIC	Mapping ET at high spatial Resolution with Internalized Calibration model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOD16	MODIS global evapotranspiration product
NDVI	Normalized Difference Vegetation Index
NLDAS	North American Land Data Assimilation Systems
NMWRRI	New Mexico Water Resources Research Institute
PRISM	Parameter-elevation Relationships on Independent Slopes and the
SAVI	Soil Adjusted Vegetation Index
SEBAL	Surface Energy Balance Algorithms for Land
TRMM	Tropical Rainfall Measuring Mission
USGS	U.S. Geological Survey
USDA	U.S. Department of Agriculture

1. INTRODUCTION

The economic vitality of New Mexico depends on its water availability. However, nobody knows exactly where, when and how much water is available in the state. The proposed statewide integrated water assessment that will consist of the water budgets for all major river basins and aquifer systems in the state, addresses this critical information gap for the management of New Mexico's water resources.

Precipitation and evapotranspiration are the biggest components of the water balance in New Mexico so it is crucial to acquire these data in a cost-effective manner as input into the statewide water assessment. Since existing meteorological stations in New Mexico don't cover the entire state and leave many areas without accurate information, the objective of this study is to evaluate the accuracy of existing nationwide operational data bases for precipitation and evapotranspiration over New Mexico. Our effort is complimentary to that of other members of the Statewide Water Assessment Steering Committee who focus on other components of the water balance such as stream flow, groundwater recharge, and changes in aquifer water storage.

Due to the hydrological conditions in New Mexico inaccurate precipitation and evapotranspiration data are not acceptable for statewide assessment of water availability. Because precipitation and evapotranspiration are much larger components of the statewide water budget than stream flow and groundwater recharge combined, a small error in precipitation and/or evapotranspiration will lead to large errors in these two smaller components and the final estimation of water availability [*Gee and Hillel*, 1988; *Hendrickx and Walker*, 1997].

2. OPERATIONAL PRECIPITATION AND EVAPOTRANSPIRATION PRODUCTS

Efficient statewide water assessment can only be accomplished by using operational products that are reasonably accurate and easy to use with nearly real-time availability to support water resources decisions during ongoing flood or drought events. Based on our team's experience and consultations with colleagues we identified five precipitation and three evapotranspiration products that are currently operational over New Mexico.

The five precipitation products listed in alphabetical order are: the AHPS Precipitation (National Weather Service Advanced Hydrologic Prediction Service) product[1], the CHIRPS Climate Hazards Group InfraRed Precipitation with Stations) [*Funk et al.*, 2014], the PERSIANN-CCS (Precipitation Estimation from Remote Sensed Information using Artificial Neural Network – Cloud Classification System) model [*Hong et al.*, 2007], the PRISM (Parameter-elevation Relationships on Independent Slopes) model [*Daly et al.*, 2008] and the TRMM / GPM model (Tropical Rainfall Measuring Mission [*Braun et al.*, 2011] / Global Precipitation Measurement [*Hou et al.*, 2013]). The three evapotranspiration products are: the ALEXI (Atmosphere-Land Exchange Inverse) model that will become the operational ET product of NOAA [*Anderson et al.*, 1997; *Anderson et al.*, 2004; *Norman et al.*, 2003], the MOD 16 (MODIS Global Evapotranspiration Product) model of NASA [*Mu et al.*, 2011; *Mu et al.*, 2007], and the SSEB (Simplified Surface Energy Balance) model [*Senay et al.*, 2007; *Senay et al.*, 2011; *Senay et al.*, 2013] used by the USGS.

An initial comparison of the eight products consisted of a simple plot of the annual precipitation and evapotranspiration volumes during the period 1990–2013 (Figure 1). Considering that (1) this study found the PRISM precipitation product to have reasonably accurate precipitation values over New Mexico (see Section 3.1) and (2) precipitation and evapotranspiration volumes are nearly equal over most of our arid state, the performances of PERSIANN and MOD16 are disappointing. PERSIANN consistently predicts more than double the amount of annual precipitation as compared to PRISM while MOD16 consistently predicts an evapotranspiration volume much less than the precipitation volume. This pattern is confirmed by the histograms of the wet year 2004 (Figure 2) and the dry year 2012 (Figure 3) although PERSIANN performs better during the wet year than the dry one.

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[1] http://water.weather.gov/precip/about.php
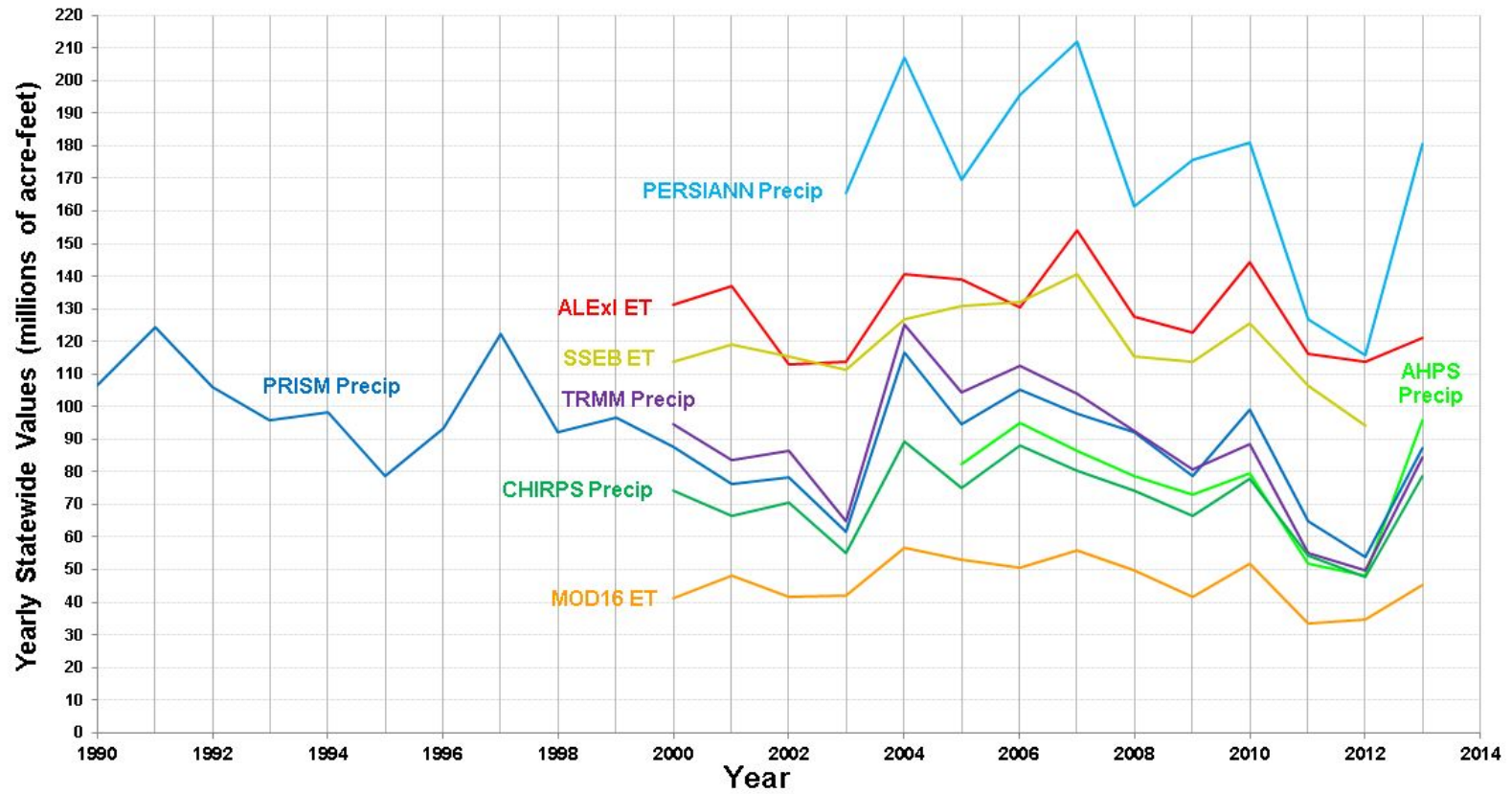
Figure 1. Annual Precipitation and Evapotranspiration volumes (acre-feet $\times 10^6$) during the period 1990 – 2013 as predicted by the PERSIANN, TRMM, PRISM, AHPS, and CHIRPS precipitation products and the ALEXI, SSEB and MOD16 evapotranspiration products.
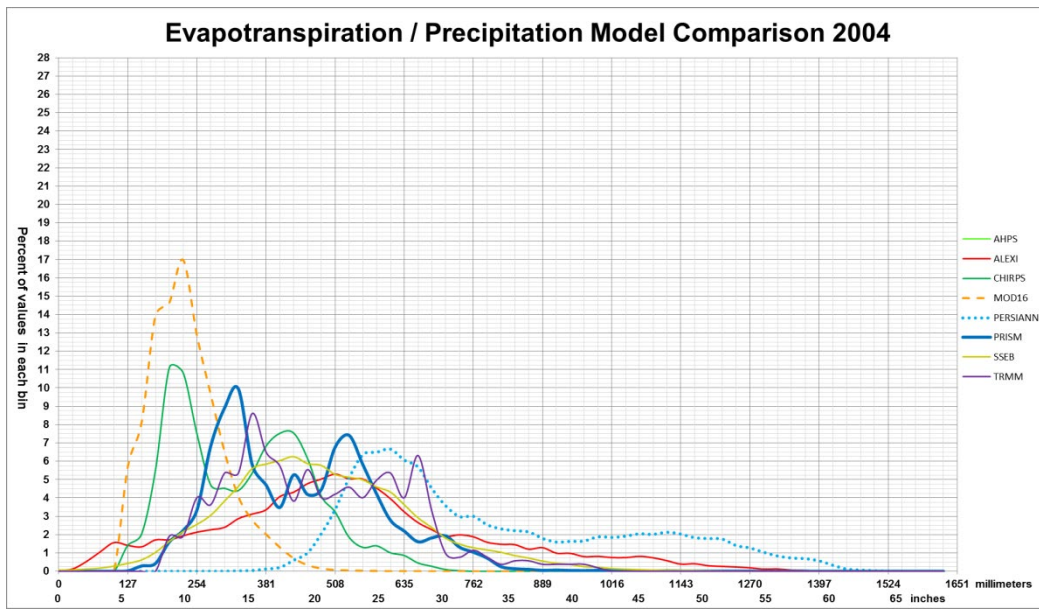
Figure 2. The histograms of the PERSIANN, TRMM, PRISM, AHPS, and CHIRPS precipitation products and the ALEXI, SSEB and MOD16 evapotranspiration products during wet year 2004. As compared to PRISM, PERSIANN over-predicts precipitation and MOD16 under-predicts evapotranspiration.
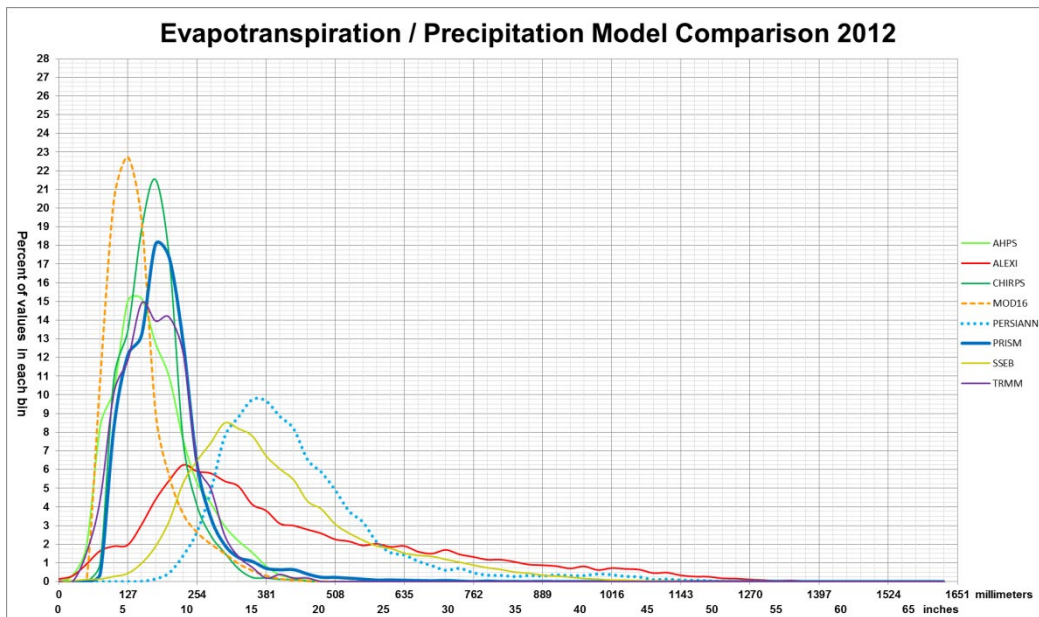
Figure 3. The histograms of the PERSIANN, TRMM, PRISM, AHPS, and CHIRPS precipitation products and the ALEXI, SSEB and MOD16 evapotranspiration products during dry year 2012. As compared to PRISM, PERSIANN over-predicts precipitation and MOD16 under-predicts evapotranspiration.

PERSIANN has been developed for the global prediction of high intensity precipitation events that can cause flooding. While its absolute error margin might be quite acceptable in regions with large annual precipitation volumes, its application in New Mexico cannot be justified. MOD16 has been developed for the global prediction of actual evapotranspiration on clear and overcast days using only meteorological and atmospheric data bases. Specifically, it doesn't need any information on soil moisture conditions which may hamper its reliability in arid regions with vast areas of irrigated lands and riparian corridors. Its application in New Mexico cannot be justified.

The differences between the AHPS, PRISM, and TRMM precipitation products are much less pronounced in Figs. 1–3 but CHIRPS has consistent lower precipitation volumes than PRISM. AHPS and TRMM are not available as raster files and require additional processing before their use. In addition, AHPS, CHIRPS and TRMM have a coarser spatial resolution than the PRISM product and are not available for as long a time period. In the end the daily PRISM precipitation product with its spatial resolution of 800 m and its period of record from 1895 to present, was selected as the precipitation product that will best serve the state of New Mexico.

The two evapotranspiration products ALEXI and SSEB are predicting an annual evapotranspiration volume that considerable exceeds the annual precipitation volume in all years except for the wet year 2004 (Figs. 1–3) when the over-predictions of SSEB and ALEXI exceed the PRISM precipitation volume by not more than about 10 and 20%, respectively. For lack of a better operational product ALEXI and SSEB have been examined more thoroughly on their current and future potential for ET prediction in New Mexico.

3. VALIDATION OF PRISM, ALEXI AND SSEB IN NEW MEXICO

In this section the precipitation predictions by PRISM and the evapotranspiration predictions by ALEXI and SSEB are compared with ground measurements at selected locations in New Mexico. A direct comparison between the precipitation or evapotranspiration measured on the ground at a specific site with the one predicted by PRISM, ALEXI or SSEB over a large pixel is not straightforward but inspection of the correlation between time series of measurements and predictions will serve as a useful reality check.

3.1 Validation of PRISM precipitation product

PRISM (Parameter-elevation Relationships on Independent Slopes) uses an interpolation method between nearly 13,000 rain gauges for the prediction of daily precipitation patterns with a spatial resolution of 30-arcsec (~800 m) in the United States. The algorithm calculates a climate-elevation regression for each digital elevation model (DEM) pixel where rain gauges are assigned regression weights based on the physiographic similarity of the gauge location to the pixel. Factors taken into account are location, elevation, coastal proximity, topographic facet orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain [*Daly et al.*, 2008]. PRISM is used by thousands of agencies, universities and companies; it is the official spatial climate data set of the US Department of Agriculture [*Daly and Bryant*, 2013]. Figure 4 presents the PRISM annual precipitation amounts during the wet year 2004 and the dry year 2012.

The comparison of all the precipitation models (PRISM, CHIRPS, AHPS, TRMM and PERSIANN) with 34 rain gauges at the Jornada Experimental Range has been completed and the agreement is very good for PRISM and satisfactory for the others with the exception of PERSIANN which substantially overestimated the precipitation. The analysis of yearly totals for the 5 models for the years 2000 - 2013 have been compared with the yearly totals for the rain gauges at the Jornada. The PRISM model gave the best agreement for the average over the entire range. Figure 5 presents the comparison of the yearly totals for the PRISM and TRMM rain estimates compared with the 34 gauge average.
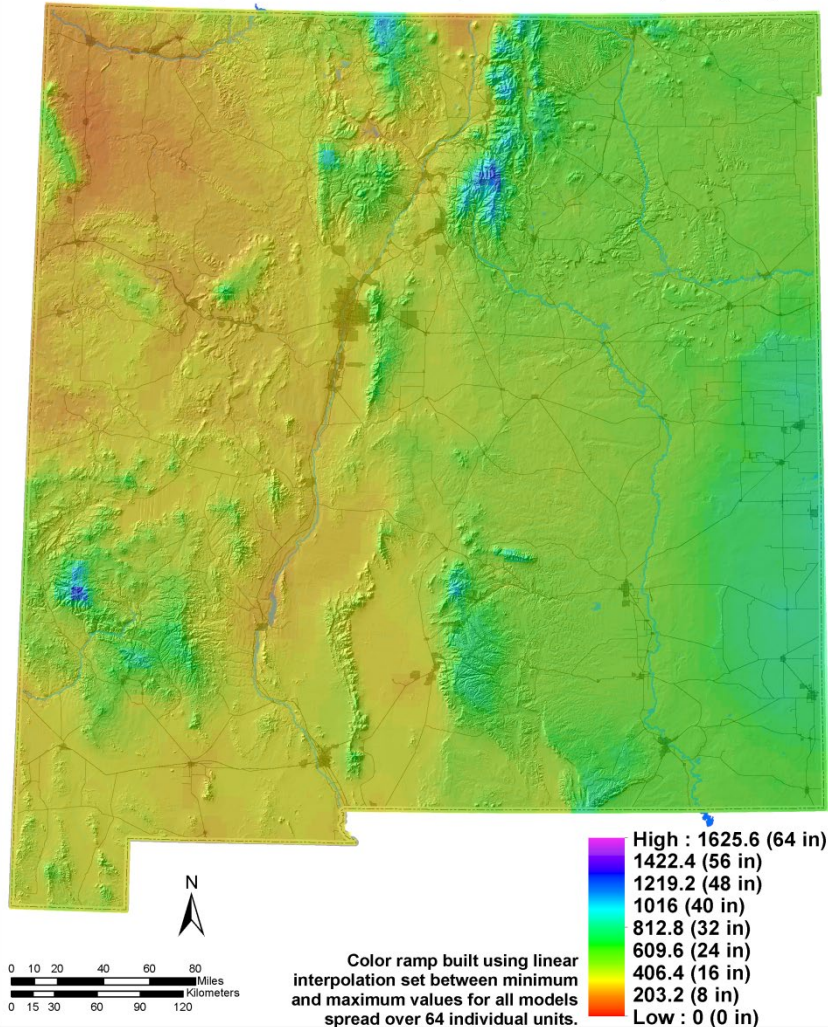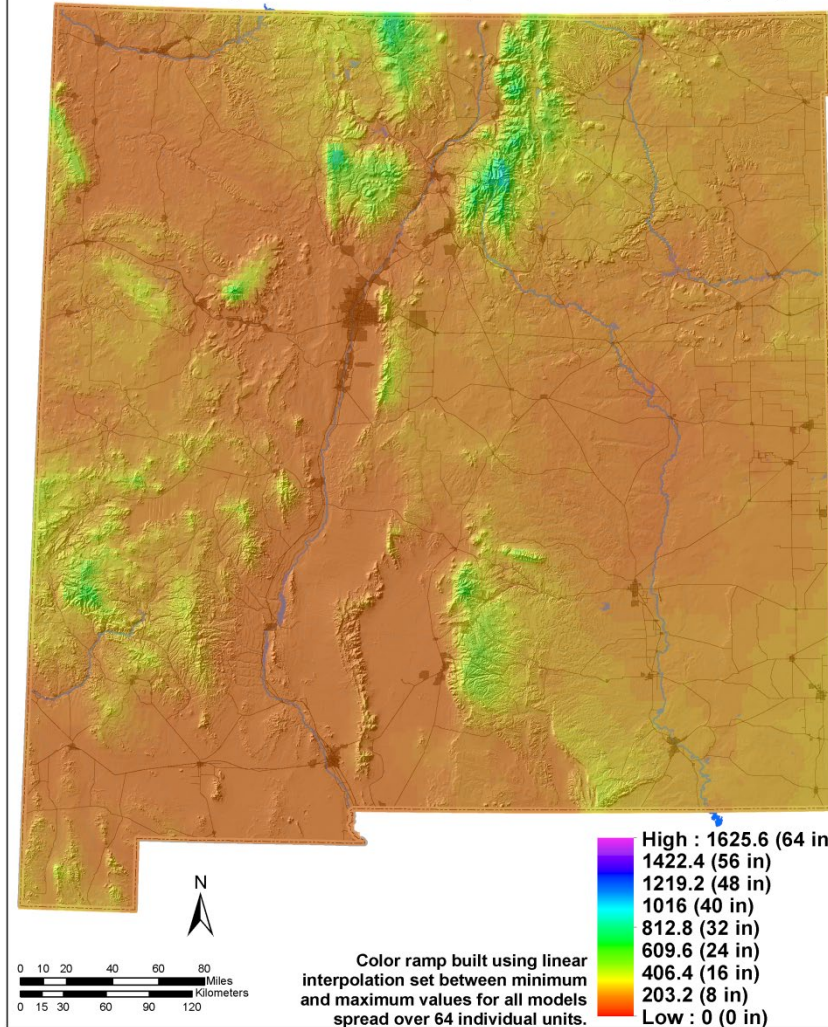
Figure 4. PRISM annual precipitation over New Mexico during the wet year 2004 and the dry year 2012.

Figure 5. Yearly totals of rainfall at the Jornada Experimental Range.
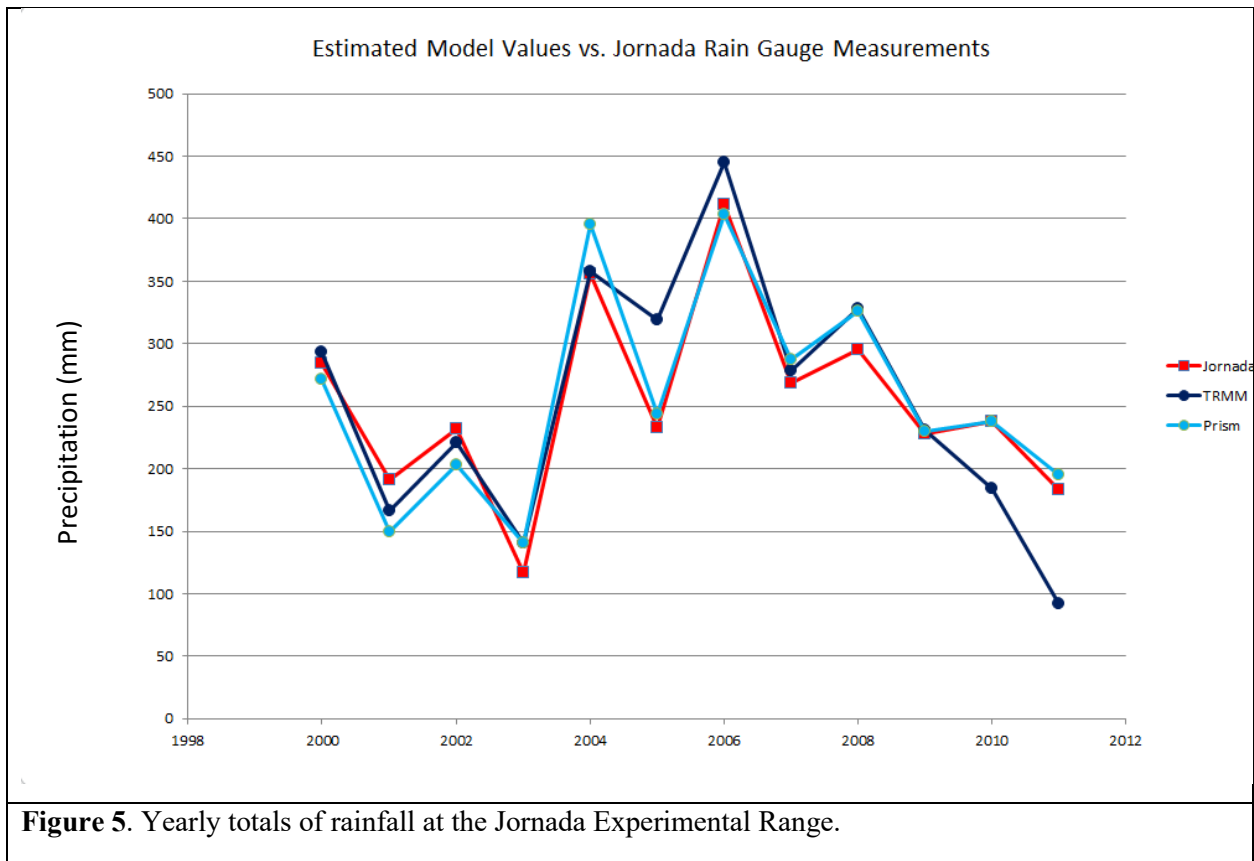
However when compared with yearly totals for the individual gauges, it was clear that PRISM and the other models do not account for the small scale variations of rain fall observed by the gauges as seen in Figure 6. The flat top and bottom of the scatterplot indicate that the PRISM estimates do not capture the small scale spatial variation seen in the gauge data. For example at the low end, PRISM has a variation of 120 to 140 mm/year while the gauges vary between 60 and 210 mm/year for these dry years.
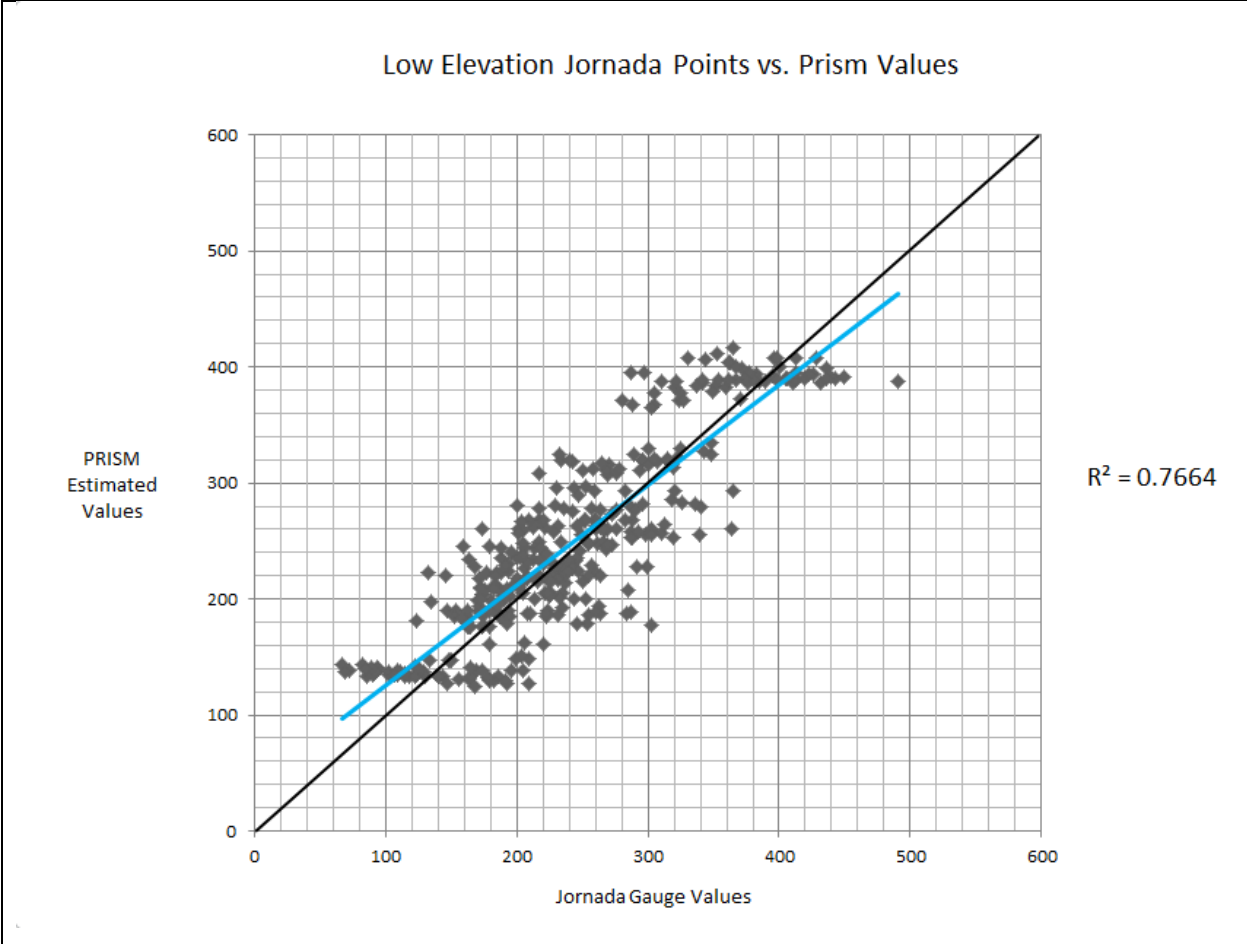
Figure 6. Scatterplot of PRISM estimates and gauge observations.

3.2 Description of ALEXI and SSEB evapotranspiration products

Knowing where, when, and how much water evaporates from the land surface is critical for management of water resources at the field, local and regional scale. Proven remote sensing evapotranspiration (*ET*) models (e.g. SEBAL by *Bastiaanssen et al.* [1998]; S-SEBI by *Roerink et al.* [2000]; SEBS by *Su* [2002]; Two-Source by *Kustas and Norman* [2000]; METRIC by [*Allen et al.*, 2007]; and ALEXI by *Anderson et al.* [1997]) are based on the physics of the full energy balance and start with the calculation of net radiation R_n (W/m2), soil heat flux G (W/m2), and sensible heat flux H (W/m2). Then, the instantaneous latent heat flux LE (W/m^2) is computed as the residual of the surface energy balance

$$LE = R_n - G - H \qquad\qquad [1]$$

Advantages of the full energy balance approach are (1) the inclusion of the effects of wind speed, surface roughness and atmospheric stability on the sensible heat flux; (2) inspection of the R_n, G and H values makes it easier to flag anomalous LE values. Disadvantages are (1) a background in micrometeorology is required to use these algorithms with confidence; (2) automation is coming along slowly [*Morton et al.*, 2013]; (3) routine operational applications covering entire states or large river basins are not yet available but the Earth Engine Evapotranspiration Flux (EEFlux) that is patterned after METRIC may before too long make *ET* information available through Google's Earth Engine within seconds [*Kilic et al.*, 2014].

For this study operational evapotranspiration maps for New Mexico have been acquired through direct collaboration with Dr. Anderson at USDA and Dr. Senay at USGS whose teams developed, respectively, ALEXI (Atmosphere-Land Exchange Inverse) [*Anderson et al.*, 1997; *Anderson et al.*, 2004; *Norman et al.*, 2003] and SSEB (Simplified Surface Energy Balance) model [*Senay et al.*, 2007; *Senay et al.*, 2011; *Senay et al.*, 2013; *Singh et al.*, 2014]. ALEXI is based on calculation of the full energy balance (Eq. [1]) while SSEB derives the *ET* in a heuristic manner (see the interactive discussion on the paper by *Senay et al.* [2014]) from a normalized difference surface temperature index using statistical regression techniques.

SSEB starts with the calculation of a normalized difference surface temperature index that is called the evapotranspiration fraction ET_f

$$ET_f = \frac{T_h - T_s}{T_h - T_c} \qquad [2]$$

where T_s is the radiometric surface temperature observed by Landsat or MODIS at the time of satellite overpass in late morning, T_h is the estimated land surface temperature at the idealized reference "hot" condition in the pixel for the same time period, and T_c is the estimated land surface temperature at the idealized reference "cold" temperature of the pixel for the same time period.

Then –without calculation of net radiation R_n, soil heat flux G or sensible heat flux H– the actual evapotranspiration ET_a (mm/day) is calculated as

$$ET_a = ET_f \, k \, ET_o \qquad [3]$$

where ET_o is the reference evapotranspiration for a short crop and k is a coefficient that scales the grass reference ET_o "into the level of a maximum ET experienced by an aerodynamically rougher crop" [*Senay et al.*, 2013] such as alfalfa. A recommended value is 1.2 [*Senay et al.*, 2013] but *Singh et al.* [2014] used k=1 while *Senay et al.* [2014] used k=1.25. The need for adjustment of parameters is common for statistical methods because parameter values are only valid for the environmental conditions under which they were derived. The direct calculation of ET_a without taking into account the effects of wind speed, surface roughness and atmospheric stability on evapotranspiration makes SEBB quick and easy to understand. However, not knowing the other components of the energy balance (R_n, G and H) disallows flagging anomalous ET_a values.

Figures 7 and 8 present the annual evapotranspiration over New Mexico during the wet year 2007 and the dry year 2012 estimated by ALEXI and SEBB, respectively. Both models predict less evapotranspiration in the dry year but ALEXI predicts in both the wet and dry year higher annual evapotranspiration volumes than SEBB.
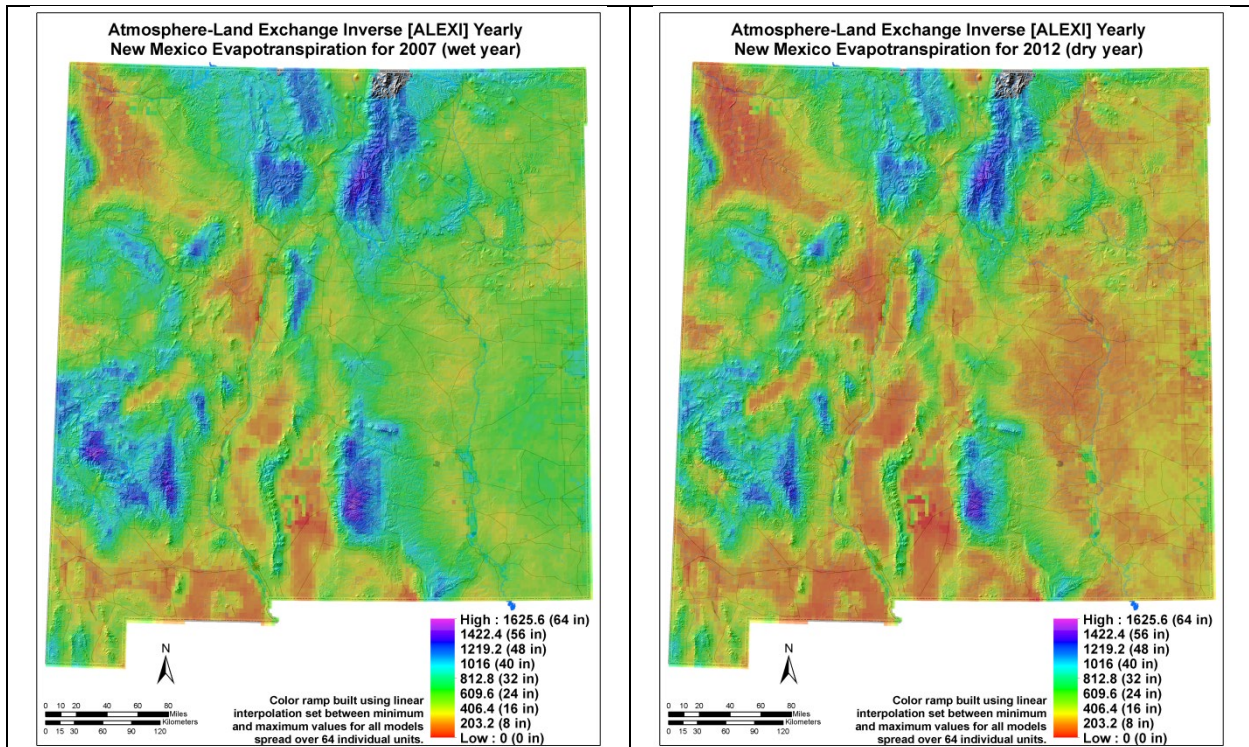
Figure 7. ALEXI annual evapotranspiration over New Mexico during the wet year 2007 and the dry year 2012.
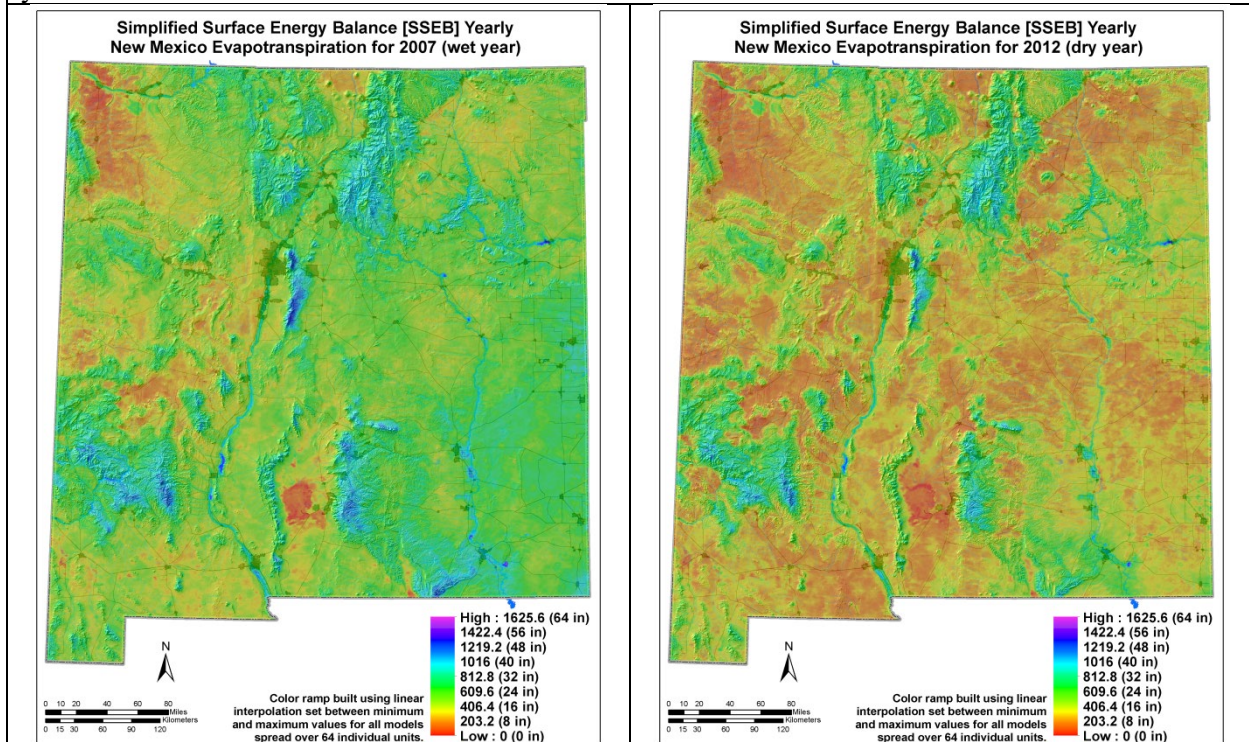
Figure 8. SEBB annual evapotranspiration over New Mexico during the wet year 2007 and the dry year 2012.

3.3 Validation of ALEXI and SSEB evapotranspiration products

The validation of evapotranspiration products based on remote sensing is often done by comparing the ET pixel values with ground measurements conducted with the eddy-covariance method. This comparison is not straightforward because the footprint of the ET flux sensors is quite variable. These sensors include a fast water vapor concentration analyzer next to a fast three dimensional sonic anemometer (Figure 9). Both sensors take 20 measurements per second of the water vapor concentration and the wind speed in the horizontal x and y direction as well as in the vertical z direction. In addition, the anemometer measurements also yield 20 estimates per second of the air temperature. The ET flux footprint is the area "seen" by the ET flux sensors installed on a tower (Figure 10). On clear days when remote sensing images are available a typical ET flux footprint of a riparian or irrigated area covers about 5,000 to 10,000 m^2 which is about 100 or 10,000 times smaller than, respectively, a SSEB pixel of 1000×1000 m^2 or an ALEXI pixel of 10,000×10,000 m^2. Making the assumption that the measured ET flux is a good measure for the ET provided by an ET product with large pixels is not correct for moist areas (irrigated lands, riparian corridors and mountains) in New Mexico due to a spatial variability scale of a few hundred meters. For example, Figure 11 presents the sub-pixel variability of the sensible heat flux within 1000×1000 m^2 pixels in the Middle Rio Grande Valley. Because a small sensible heat flux represents a large latent heat flux, i.e. ET, and vice versa this figure also gives an indication of the sub-pixel variability of the ET. Except for the desert areas in the upper half of the map, the

Figure 9. CSAT3 sonic anemometer and LI7500 open-path water vapor concentration analyzer (hpwren.ucsd.edu/news/20080516/). No accurate measurements are possible when wind comes from the right where the tower poses an obstruction; the eddy covariance system has a dead angle.
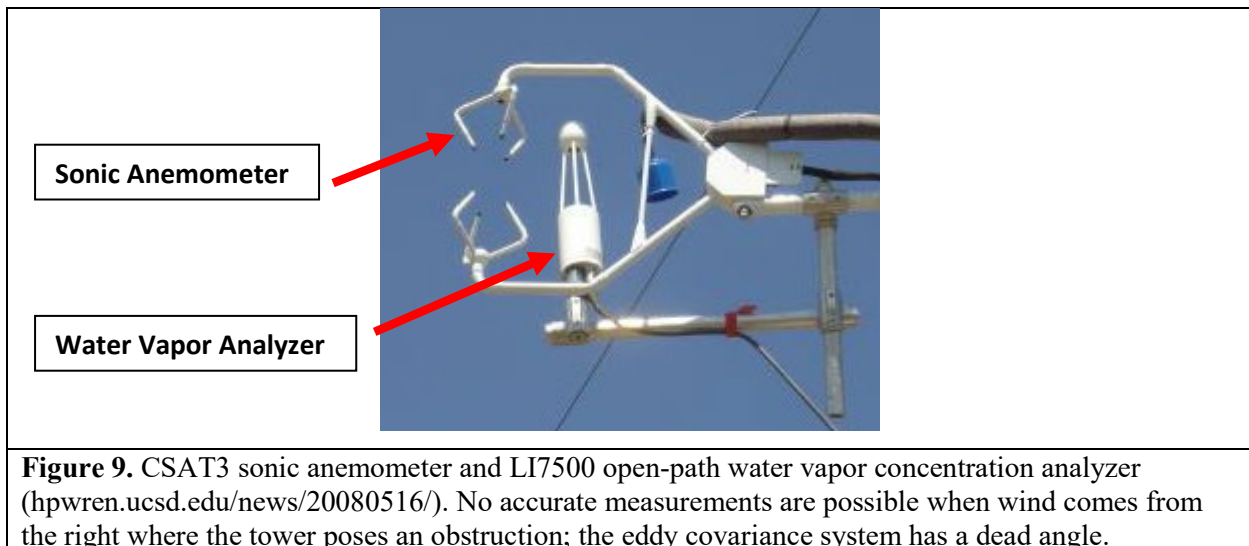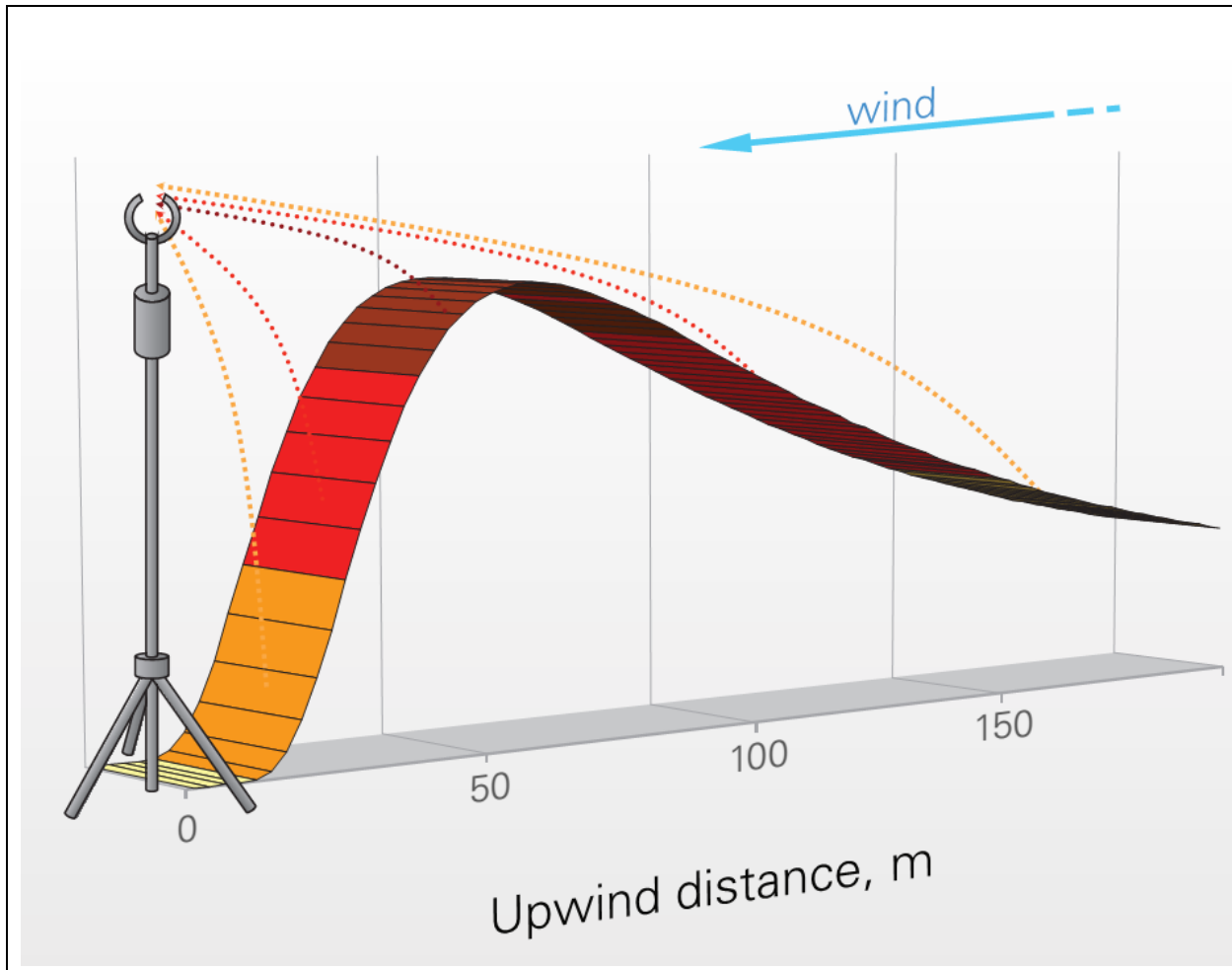
Figure 10. Visualization of the ET flux footprint: the darker the red color, the larger the ET flux contribution that is coming from the area under consideration [*Burba*, 2013]. No or very small contribution to the ET flux is coming from underneath the tower or from many hundreds of meters away. On clear days in New Mexico most of the contribution comes from the area between 30 to 150 m upwind from the tower [*Hong*, 2008]. Comparison of the remotely sensed ET product with the ET measured from the eddy-covariance footprint is not straightforward. If *the pixels of the remote sensing ET product are small*, for example Landsat 30×30 m, the ET value of the tower pixel can be different from the footprint weighted ET derived from about five pixels upwind of the tower pixel. The difference depends on the homogeneity of the area around the tower as well as the wind direction during satellite overpass.[*Hong*, 2008]. A larger error can result if *the pixels of the remote sensing ET product are large* such as the 1×1 km SSEB [*Senay et al.*, 2013] or 10×10 km ALEXI [*Anderson et al.*, 2007] pixels. In this case the measured ET flux over a footprint of about 5,000 to 10,000 m^2 is assumed to be a good estimate for a SSEB or ALEXI pixel that is, respectively, 100 or 10,000 times larger. This assumption is not justified in New Mexico's moist areas (irrigated lands, riparian, mountains) with pronounced spatial variability at a scale of a few hundred meters or less.
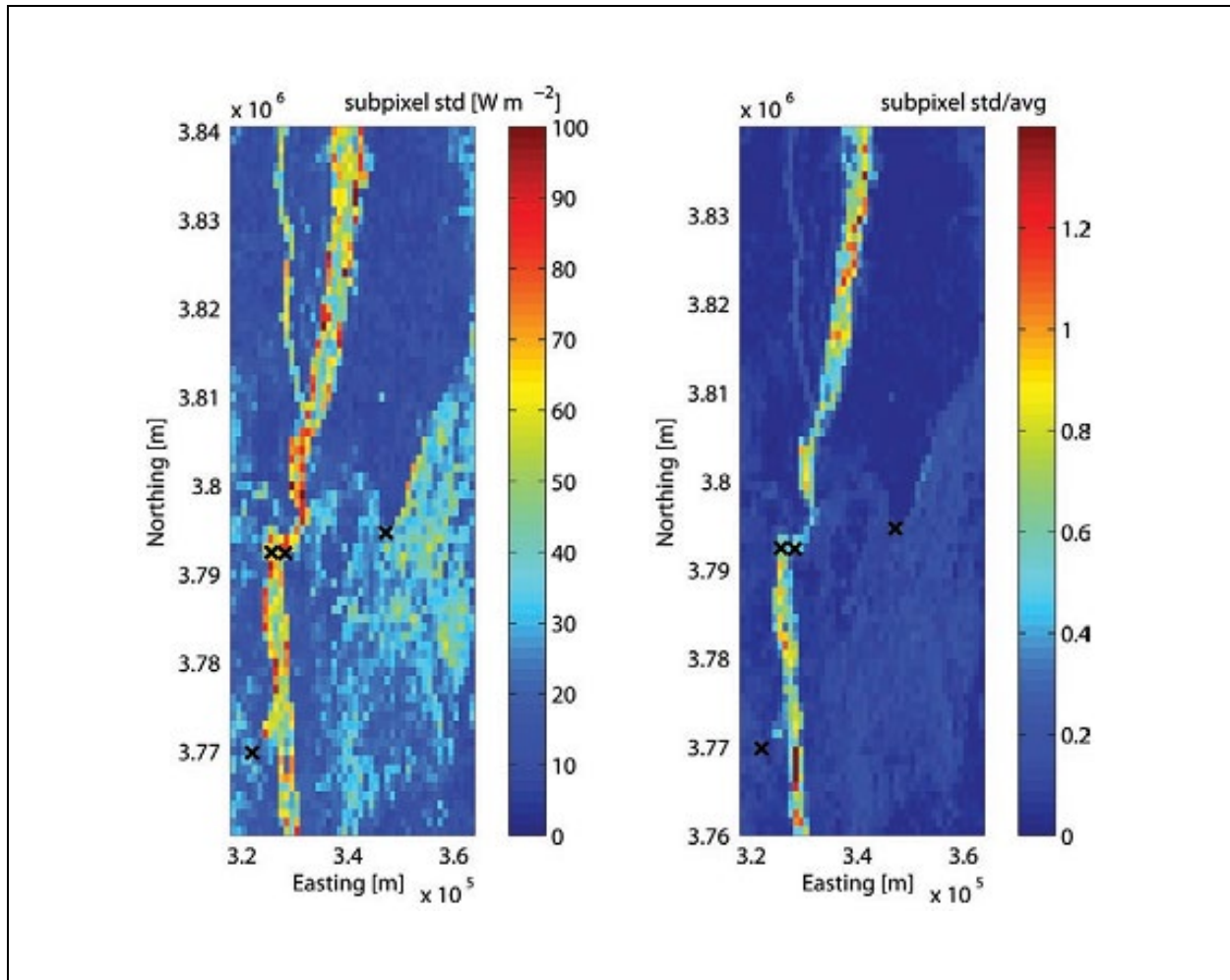
Figure 11. One-kilometer subpixel-scale variability in the sensible heat flux H based on METRIC analysis of a 30-m-resolution Landsat image on 16 Jun 2002 in the Middle Rio Grande Valley. (left) Standard deviation of ~1,111 30-m pixels within a 1 km^2 area. (right) Coefficient of variation (standard deviation/mean) within the 1 km^2 pixel [*Kleissl et al.*, 2009].

sub-pixel variability is so large that the probability of agreement between the measured ET over a small footprint and the predicted ET over a much larger pixel is rather low.

Before the *ET* fluxes measured with eddy covariance systems can be used for validation of remotely sensed evapotranspiration products, it should be verified that energy balance closure is satisfied. For example, *Hong* [2008] rejected 21 out of 48 days of eddy covariance measurements in riparian areas of New Mexico, Arizona and California because of a closure error lower than 65%. The closure error is typical for eddy covariance measurements [*Masseroni et al.*, 2014; *Twine et al.*, 2000] and the energy balance deficits at FLUXNET sites has been reported to average about 20 [*Wilson et al.*, 2002] to 26% with a range from 6 to 51% [*Franssen*

et al., 2010]. The eddy covariance ET flux measurements used for validation of the SSEB and ALEXI evapotranspiration products consisted of the actual measurements without closure of the energy balance.

Figure 12 shows the network of eddy-covariance stations in New Mexico. They cover a wide range of environmental conditions with monthly evapotranspiration rates varying from 240 mm (9.45 inch) per month in a salt cedar stand at the Bosque del Apache in July 2005 to zero mm (inches) in desert shrubland at the Jornada in July of 2010 (Figure 13). Considering the studies by *Franssen et al.* [2010] and *Wilson et al.* [2002] we expect –somewhat subjectively– that the monthly evapotranspiration values in the latter figure are under-estimations by about 15 to 30 percent. Nevertheless the eddy covariance measurements capture quite well the regional differences in evapotranspiration that occur over the entire state: from a high evapotranspiration of 240 mm/month in salt cedar in July to less than 10 mm/month during November through February in the desert to intermediate values around 100 mm/month in July in the Valles Calderas.

Figures 14 and 15 show the graphs of the monthly ET values of the eddy covariance stations against those predicted by the remote sensing algorithms ALEXI and SSEB, respectively. In all cases the R^2 is above 60% which means that the remote sensing algorithm capture 60% or more of the variability in the measured ET values. The one exception is found in the Jornada where ALEXI predicts the ET quite well with a R^2 of 54% but SSEB fails with a R^2 of 4%.

Based on the strong correlations between the operational remote sensing monthly ET products and the eddy covariance measured monthly ET rates, we conclude that the operational ET products have sufficient quality to inform policy makers, water resource managers and the general public about the spatial and temporal ET differences in the state. For example, inspection of Figures 4, 7 and 8 shows higher precipitation rates in the mountains than in the deserts and as a consequence higher ET rates in the mountains than in the deserts. These figures also show large differences between dry and wet years. Even although the absolute ET values can have relative errors of 10 to 50%, knowing the locations and years of high and low ET values in New Mexico will assist with the development of water resources policies that are fair for all stakeholders. The remotely sensed operational ET products are expected to improve in the near future because improved ET predictions have a high research priority in USDA, NASA, NOAH

Figure 12. Network of eddy covariance systems in New Mexico.

and USGS. However, improvement in the mountains is less likely because their more frequent cloud cover prevents the regular acquisition of the optical/thermal images needed by ALEXI and SEBB.
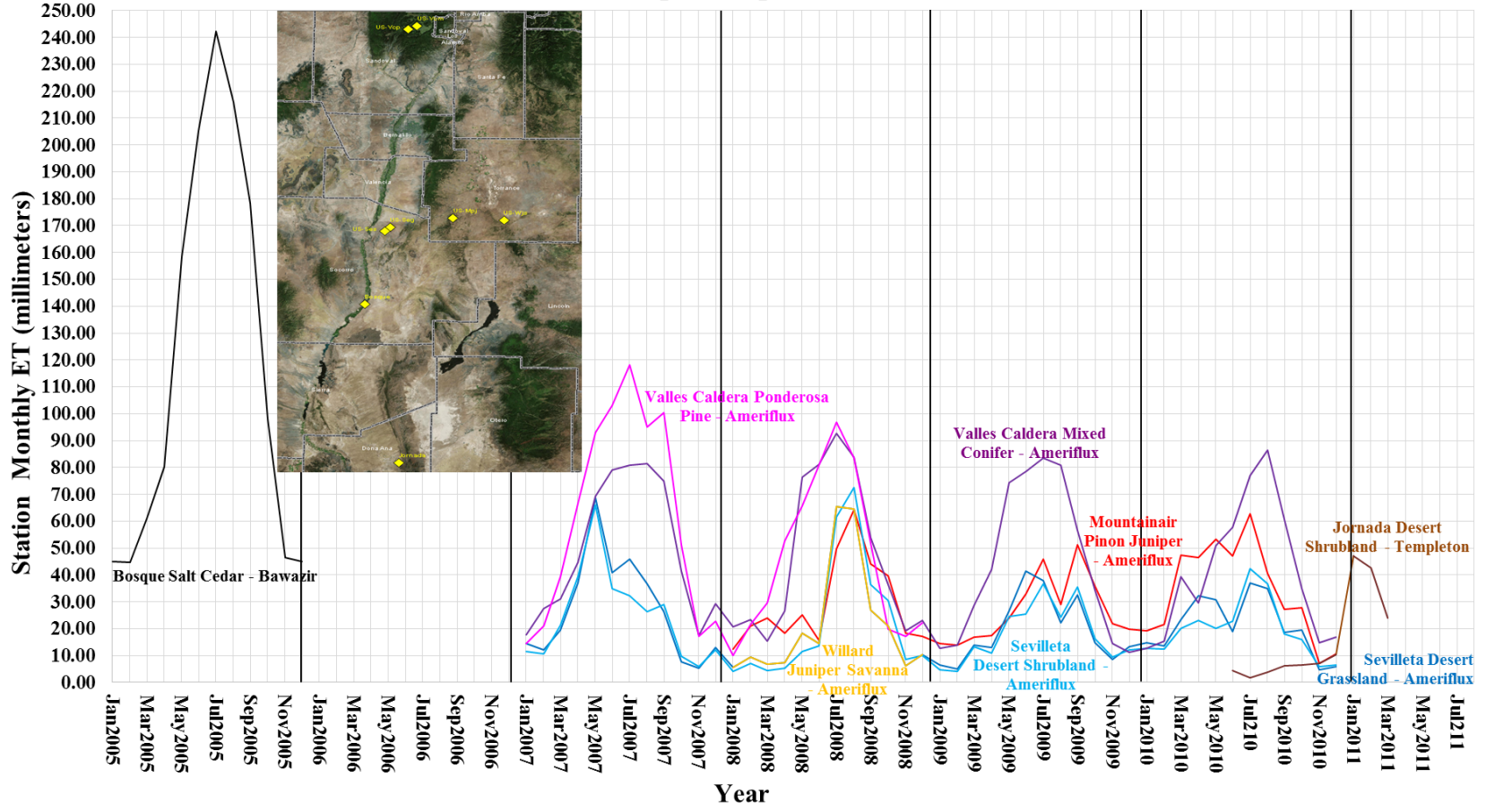
Figure 13. Monthly evapotranspiration rates measured by the eddy covariance systems in New Mexico.
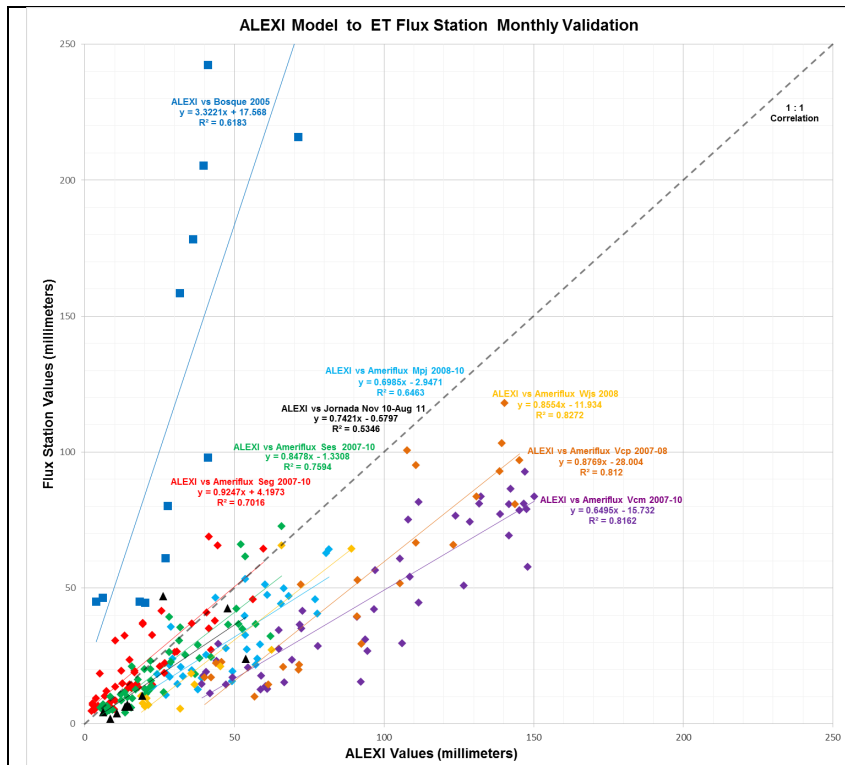
Figure 14. Comparison of eddy covariance flux station measurements of monthly ET versus ALEXI remotely sensed ET.
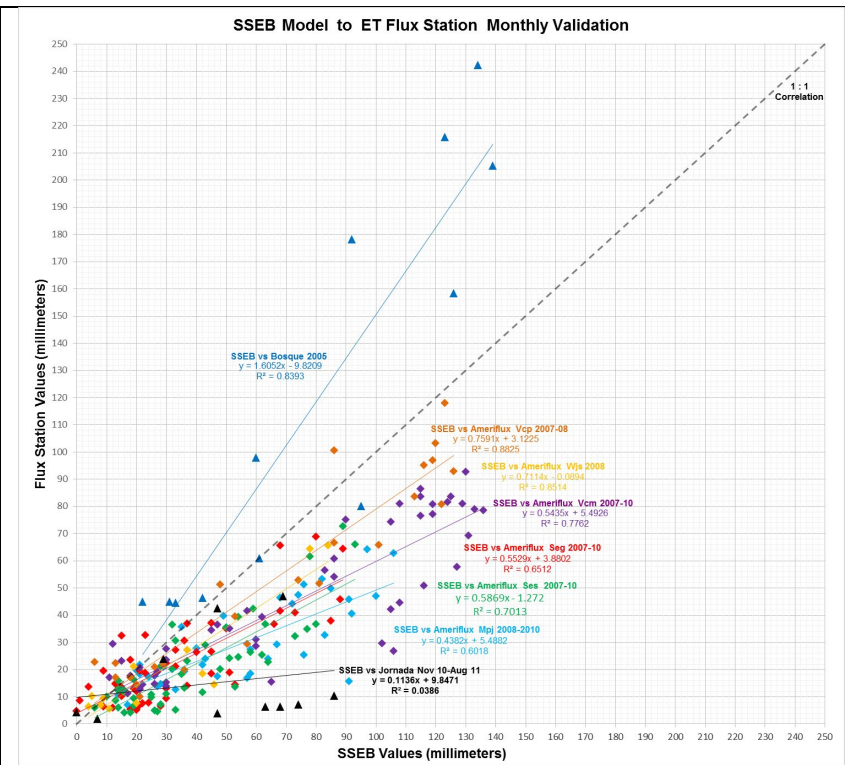

Figure 15. Comparison of eddy covariance flux station measurements of monthly ET versus SSEB remotely sensed ET.

4. EVAPOTRANSPIRATION AND GROUNDWATER RECHARGE

While the operational remote sensing ET products ALEXI and SSEB yield acceptable data for assessment of statewide water availability in a semi-quantitative manner in flat areas, they fall short for the prediction of groundwater recharge volumes because a small error in precipitation and/or evapotranspiration volumes will lead to a large error in recharge volume. For example, in 2012 the PRISM annual precipitation volume at higher locations in the Sangre de Cristo Mountains can reach 1,016 mm (40 inches) (Fig. 4) while the annual evapotranspiration volume predicted by ALEXI is about the same (Fig. 7) and by SSEB is about 914 mm (36 inches) (Fig. 8). Assuming no runoff, the recharge predicted using ALEXI is negligible while SSEB yields about 100 mm (4 inches) of recharge. Because even a recharge difference of as little as 6 mm (0.25 inch) is important in semi-arid regions [*Hendrickx et al.*, 2016], ALEXI and SSEB cannot be used for groundwater recharge evaluation in the mountainous areas of New Mexico.

One proven method for the evaluation of ET from semi-arid partially vegetated lands is the soil water balance method [*Allen et al.*, 1998; *Ritchie*, 1972] because it respects the water balance by constraining ET to values equal to or less than the available water supply, i.e. precipitation, irrigation, runon, runoff and/or capillary rise. An added benefit of this model is that it also provides estimates of groundwater recharge [*Daniel B. Stephens & Associates*, 2010; *Sandia National Laboratory*, 2007; *U.S. Geological Survey*, 2008]. Because recharge quantification in semi-arid regions requires a daily time step [*Gee and Hillel*, 1988; *Hendrickx and Walker*, 1997] our approach will use daily PRISM precipitation data for each 800×800 m cell and calculate the daily tall crop reference evapotranspiration, ET_r, for each 250×250 m cell [*ASCE*, 2005]. Because the groundwater recharge areas of New Mexico are located at higher elevation in mountain ranges with a distinct topography the reference ET will take into account differences in available energy caused by slope, aspect and shading of each pixel following *Aguilar et al.* [2010].

The principal equation for calculation of the actual evapotranspiration ($ET_{c\ act,i}$) (mm/day) on day i is [*Jensen and Allen*, 2015]

$$ET_{c\ act,i} = K_{c\ act,i}ET_{r,i} = (K_{s,i}K_{cbr,i} + K_{er,i})ET_{r,i} \qquad [5]$$

where on day i $K_{c\ act,i}$ is the "actual" crop coefficient that includes the effect of environmental stresses; $ET_{r,i}$ is the reference ET for a tall crop (mm/day); $K_{s,i}$ is a dimensionless transpiration reduction coefficient [0.0 - 1.0] that reduces $K_{cbr,i}$ when the average soil water content in the root zone is not conducive to sustain full plant transpiration; $K_{cbr,i}$ is the basal crop coefficient that represents the ratio of ET_c/ET_r under conditions when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration; $K_{er,i}$ is the soil evaporation coefficient that represents the majority of evaporation from soil following wetting by precipitation or irrigation.

$ET_{r,i}$ is obtained from the tall crop reference ET while $K_{cbr,i}$ is estimated as

$$K_{cbr,i} \approx 1.25 NDVI_i \qquad\qquad [6]$$

where $NDVI_i$ is the Normalized Difference Vegetation Index obtained from the MODIS imagery at a spatial resolution of 250×250 m. The MOD13Q1 product consists of the NDVI observed by MODIS for each 16 day period of the year with spatial resolution of 250 m. We obtain the daily $NDVI_i$ by linear interpolation between the center days of two consecutive 16 day periods. Eq. [2] produces good results in agricultural areas [*Allen et al.*, 2011] but will be evaluated for native vegetation and adapted –if needed– in our project. The use of a vegetation coefficient for determination of a crop coefficient is a common procedure for evaluation of ET on a regional scale [*Nagler et al.*, 2005].

The stress coefficient $K_{s,i}$ is determined as

$$K_{s,i} = \frac{TAW - D_{r,i-1}}{TAW - RAW} = \frac{TAW - D_{r,i-1}}{(1-p)TAW} \qquad for\ D_{r,i-1} > RAW \qquad\qquad [7]$$

where TAW is the total available water (mm) in the root zone of the vegetation, RAW is readily available water in the root zone (mm), $D_{r,i}$ is the depletion of the root zone (mm), and p is the fraction of TAW that can be depleted before water stress and ET reduction occur. Parameter p varies from 0.3 for shallow rooted plants at high rates of $ET_{c\ act}$ (>8.0 mm/day) to 0.7 for deep rooted plants at low rates of $ET_{c\ act}$ (<3.0 mm/day). When $D_{r,i} \leq RAW$ then $K_s=1.0$. The total available water (TAW) that can be stored in the root zone is

$$TAW = (WCFC - WCWP)Z_r \qquad\qquad [8]$$

where *WCFC* is the soil water content at field capacity (m^3/m^3), *WCWP* is the soil water content at wilting point (m^3/m^3), and Z_r is the effective rooting depth (mm) that contains the effective depth of the evaporation layer Z_e (mm). Values for WCFC and WCWP are derived from the soil data base using pedotransfer functions while Z_r is estimated from the USGS 2010 land cover map.

$K_{c\ max\ r}$ is the maximum value of $K_{c\ act}$ following rain or irrigation and represents an upper limit on evaporation and transpiration from the vegetated surface. It is a measure of the natural constrains on available energy. For the tall reference ET_r

$$K_{c\ max\ r} = \max[1.0, (K_{cbr} + 0.05)] \qquad\qquad [9]$$

A general model for the soil evaporation coefficient K_{er} for estimating the evaporation from the surface layer of soil after rain or irrigation for use with the basal crop coefficient K_{cbr} is

$$K_{er,i} = K_{r,i}\left(K_{c\max r,i} - K_{s,i}K_{cbr,i}\right) \qquad such\ that\ K_{er,i} \le K_{c\max r,i} \qquad [10]$$

where $K_{r,i}$ is a dimensionless evaporation reduction coefficient. In Eq. [10] transpiration is given priority access to the available energy over evaporation because $K_{s,i}K_{cbr,i}$ is subtracted from $K_{c\max r,i}$ before calculation of $K_{er,i}$. For a completely bare soil $K_{s,i}K_{cbr,i}$ is set equal to zero.

A common model for soil evaporation considers two stages of evaporation: the energy limiting stage 1, and the falling stage 2. When the soil is wet (in stage 1) the evaporation reduction factor $K_{r,i}$ is assumed to be 1.0. When the water content in the effective evaporation layer begins to limit evaporation (in stage 2), $K_{r,i}$ decreases below 1.0. The value for $K_{r,I}$ is set to zero when the total amount of water in the effective evaporation layer is depleted during the drying cycle. The depth of the evaporation layer tends to be between 0.1 and 0.15 m. Assuming that the soil in the evaporation layer is at field capacity (WCFC) shortly after rainfall or irrigation and that it can dry to halfway between 0 and the wiltingpoint (WCWP), the total amount of water

that can be depleted by evaporation (TEW) from the effective evaporation layer during one drying cycle is estimated as:

$$TEW = (WCFC - 0.5\,WCWP)Z_e \qquad [11]$$

Where *TEW* is the total evaporable water (mm) and Z_e is the effective depth of the evaporation layer (mm). The cumulative depth of evaporation or depletion D_e at the end of stage 1 is the readily evaporable water (*REW*) that normally ranges from 5 to 12 mm depending on soil texture. The value of $K_{r,i}$ is calculated using TEW and the fraction of the time step (day) that resides in stage 1 evaporation [*Jensen and Allen*, 2015].

During Year Two the soil water balance model will be implemented for mountainous watersheds in New Mexico for the calculation of actual evapotranspiration and groundwater recharge.

5. CONCLUSIONS AND RECOMMENDATIONS

Year One of the project revealed the strengths and limitations of operational precipitation and evapotranspiration products for New Mexico. We conclude:

1. The operational precipitation product PRISM provides reliable daily precipitation data at a spatial resolution of 800 m over the entire state of New Mexico.

2. The operational evapotranspiration products ALEXI and SSEB provide adequate monthly evapotranspiration products for analysis of differences in actual evapotranspiration between different ecohydrological regions of the state as well as between different water years. However, the current accuracy of these products is not adequate for a reliable assessment of groundwater recharge in the mountainous regions.

3. The most promising option for assessment of evapotranspiration in the mountains is the implementation of a soil water balance model that respects water balance closure and constrains evapotranspiration by deriving it from soil moisture conditions in the root zone of the vegetation.

For Year Two we recommend to proceed with:

1. Continuation of the validation and improvement of ALEXI and SSEB for statewide mapping of evapotranspiration.

2. Implementation of a soil water balance model for mapping of evapotranspiration in the mountainous regions of New Mexico.

3. Merging the soil water balance model for evapotranspiration with the groundwater recharge model under development by the groundwater recharge team.

4. Dividing the evapotranspiration assessment effort in two parallel pathways: A. Statewide evapotranspiration mapping using ALEXI and SSEB by Dr. Schmugge and his colleagues at NMSU; B. Evapotranspiration mapping in mountainous regions in support of groundwater assessment by Dr. Hendrickx and his student.

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