

Evaluation of Water Use Monitoring by Remote Sensing ET Estimation Methods

Final Report

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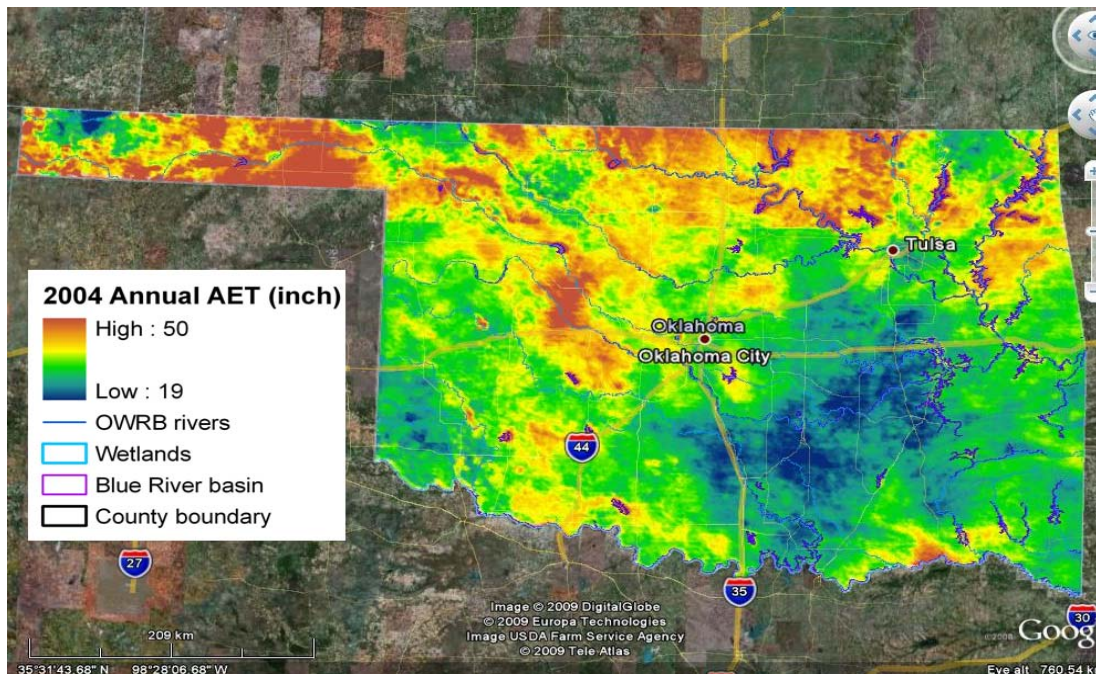
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SYNOPSIS

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Principal Investigators: Yang Hong, Associate Professor, University of Oklahoma

Problem Statement:

Irrigation consumes the highest share of fresh water around the world as well as US, according to the World Bank estimates 70% of fresh water use is for agriculture. The U.S. irrigates over 50 million acres of agricultural land and 32 million acres of recreational landscapes. In Oklahoma, irrigation accounts the largest water use. The hydrologic conditions in irrigated areas of Oklahoma, viz. Tillman and Texas Counties, dictate that irrigation pumped from aquifers and to a limited degree, streamflow, must supplement or entirely satisfy the crop water requirements of corn, wheat, soybeans, and other high value crops. Due to scarcity of water resources in Tillman County, the allocation by OWRB is limited to 1 ac-ft rather than 2 ac-ft that are allocated in Texas County. As the Olagalla aquifer and other sources of water supply continues to decline through exploitation, resource conflicts will arise that exacerbate the difficult allocation of insufficient water resources.

As demand for water increases, water managers need to know how much water is actually consumed in agriculture, urban, and natural environments. Increased demand for scarce water supplies has shifted water management strategy from increasing water supply to innovatively managing water use at sustainable levels. However, in order to more effectively allocate limited water, water resources managers must understand water consumption patterns over large geographical areas. There is a particular need to understand and measure the EvapoTranspiration (ET) flux where irrigated agriculture is the primary consumptive use in Oklahoma. At broader scale, measurement of ET flux would be useful in all watersheds where streamflow must satisfy demand by current and future permitted users and the ecological functions that minimum baseflow must satisfy.

The ability to monitor ET and the hydrologic water balance through the proposed approach will improve our ability to manage scarce water resources. For vegetated and agricultural land, the conversion of water into water vapor by the dual process of evaporation from the soil and the transpiration from plants' stomata, is synonymous with water consumption. Additionally, ET plays a critical role in controlling soil moisture and affecting both surface runoff and ground water flow to river channel, lakes and reservoirs.

The current Oklahoma ET model operated by the Oklahoma Climate Survey (Mesonet, 2007) estimates daily reference ET of uniform length grasses at each individual Mesonet site. Weakness of the ET Model is that it estimates the hypothetical reference ET not actual ET, and that the estimates are sparsely located across the State. First, the hypothetical uniform crop coefficient of 1.0 is not representative of the diversity of plant types in an irrigated area or watershed, thus unable to obtain actual ET to account for spatial variability of water deficit/surplus. Second, both crop coefficients and actual *ET*

are inherently variable because of crop variety, irrigation methods, weather, soil types, salinity and fertility, and/or field management that can be very different from the field used to derive the reference values. Thus, the inevitable spatial variability of actual ET in large irrigation schemes makes reference ET practice almost impossible to accurately monitor water use over large regions.

Project Objectives:

The overall objective of this project was to assess the ability and usefulness of the remote sensing ET estimation techniques/methods for monitoring regional ET and water use in Oklahoma that does not require placement of in-situ monitoring/metering devices in every field. The test beds chosen for this investigation are located in Texas and Tillman County. Towards this goal, study activities are scheduled into three phases:

- 1) We first reviewed and evaluated current remote sensing ET estimation methods used in Idaho, New Mexico, and California.
- 2) Then we calibrated and improved existing remote sensing ET estimation algorithm, with focus on surface irrigation water usage, specifically for applications in Oklahoma agricultural counties (e.g. Texas and Tillman) given its unique climate, soil, and land surface types. As a result, an improved remote sensing ET algorithm will be developed to provide actual ET that can be utilized for monitoring water use in Oklahoma.
- 3) As a natural extension, we also attempted to combine the actual ET estimation with a water balance model *Vflo*TM and evaluate the consistency between estimates of actual

ET produced from basin-scale water balance modeling with those derived from remotely sensed estimates.

The specific objectives are:

1. Estimate the actual **ET** by integrating the **MODIS** (Moderate Resolution Imaging Spectroradiometer) daily products and Oklahoma environmental observational network with 5-minute data acquisition through a **Modified Surface Energy Balance** approach in Oklahoma (thereinafter **M/M-ET**);
2. Evaluate the robustness of the M/M-ET approach using site-based flux tower observations and basin-scale water balance modeling results; and
3. Assess the feasibility of implementing the M/M-ET for an operational actual ET estimation algorithm appropriate for regional scales (e.g., the scale of irrigation projects, rather than individual fields) in real-time.

Methodology:

The M/M-ET algorithm mainly solve the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass and extrapolate instantaneous LE to daily ET values. The central scientific basis of SEB methods is to compute the *LE* as the residual of the energy balance equation:

$$LE = R_n - H - G \quad (1)$$

Whereas the available net radiant energy R_n (Wm^{-2}) is shared between the soil heat flux G and the atmospheric convective fluxes (sensible heat flux H and latent heat flux LE ,

which is readily converted to ET). The R_n and other components (H and G) of SEB can be derived through remote sensing information and surface properties such as albedo, leaf area index, vegetation cover, and surface temperature (T_s) etc. The following components of energy balance were solved and are explained here

Net Radiation (R_n)

R_n is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes and includes solar and thermal radiation

$$R_n = RS\downarrow - \alpha RS\downarrow + RL\downarrow - RL\uparrow - (1 - \epsilon_o)RL\downarrow \quad (2)$$

Where $RS\downarrow$ =incoming short-wave radiation (Wm^{-2}); α =surface albedo (dimensionless);

$RL\downarrow$ =incoming long-wave radiation (Wm^2); $RL\uparrow$ =outgoing long-wave radiation (Wm^2);

and ϵ_o =broad-band surface thermal emissivity (dimensionless). The $(1-\epsilon_o) RL\downarrow$ term represents the fraction of incoming long-wave radiation reflected from the surface.

Soil Heat Flux (G)

Soil Heat Flux (G) is the rate of heat storage in the soil and vegetation due to conduction.

General applications compute G as a ratio G/R_n using an empirical equation by Bastiaanssen (2000) representing values near midday

$$G = (T_s - 273.16) (0.0038 + 0.0074\alpha) (1 - 0.98NDVI^4) R_n \quad (3)$$

Where T_s is surface temperature (K), and α =surface albedo. The Normalized Difference Vegetation Index (NDVI) is used to predict surface roughness and emissivity.

Sensible Heat Flux (H)

Sensible Heat Flux (H) is defined by the bulk aerodynamic resistance equation, which uses aerodynamic temperature (T_{aero}) and aerodynamic resistance to heat transfer (r_{ah}):

$$H = \rho_{air} C_{pa} (T_{aero} - T_a) / r_{ah} \quad (4)$$

where: ρ_{air} is air density (kg m^{-3}), C_{pa} is specific heat of dry air ($1004 \text{ J kg}^{-1} \text{ K}^{-1}$), T_a is average air temperature, (K), T_{aero} is average aerodynamic temperature (K), which is defined for a uniform surface as the temperature at the height of the zero plane displacement (d , m) plus the roughness length (Z_{oh} , m) for sensible heat transfer, and r_{ah} is aerodynamic resistance (s m^{-1}) to heat transfer from Z_{oh} to Z_m [height of wind speed measurement (m)].

From instantaneous ET_i to daily accumulated ET

At the instant of the satellite image, Latent Heat (LE) is calculated for each pixel from Equation (1-4) and is converted to instantaneous ET (ET_{inst}) in mm h^{-1} by dividing LE by latent heat of vaporization:

$$ET_{inst} = (3600 \times LE) / (\lambda \rho_w) \quad (5)$$

Where ρ_w =density of water ($\sim 1000 \text{ kg m}^{-3}$); 3,600 converts from seconds to hours; and latent heat of vaporation (J kg^{-1}) representing the heat absorbed when a kilogram of water evaporates and is computed as

$$\lambda = [2.501 - 0.00236 \times (T_s - 273.15)] \times 10^6 \quad (6)$$

Reference ET fraction (ET_{rF}) is the ratio of ET_{inst} to the reference ET_r that is defined by the American Society of Civil Engineers and can also be computed using the standard Penman-Monteith alfalfa reference method (ASCE-EWRI, 2005) at overpass time (hourly average). Finally, the computation of daily or 24-h ET (ET_d), for each pixel, is performed as:

$$ET_d = ET_{rF} \times ET_r \times 24 \quad (7)$$

Accuracy of the estimated ET, runoff, and soil moisture results were evaluated at both field and catchment scales using available Mesonet weather station and other in-situ observations. Given future funding availability, this project will further assimilate the seamless satellite-based actual ET estimates into a distributed high-resolution water balance model. Compared with traditional applications of water balance models (i.e. without the satellite-based actual ET assimilation), the combined procedure can provide significant improvements in understanding the latent heat fluxes (i.e. ET) with application to estimation of water usage by irrigated crops. Therefore, applications in watershed studies, water resource allocation, and operational flood forecasting are follow-on contributions expected from the proposed research.

Publications:

Referred Journal Papers:

Khan, S. (student), Y. Hong, B. Vieux, and W. Liu (student), Development and Evaluation of an Actual Evapotranspiration Estimation Algorithm Using Satellite Remote Sensing and Meteorological Observational Network in Oklahoma, International Journal of Remote Sensing Special Issue (submitted)

Liu, W (student), Y. Hong, S. Khan (student), P. Adhikari (student), and M. Huang, Evaluation of Global Daily Reference ET's Hydrological Utility using Oklahoma's Environmental Monitoring Network-MESONET, Water Resources Research, (submitted)

Referred Conference Paper:

Yang Hong, S. Khan, and B. Vieux (2008), Integrating Remotely Sensed and Hydrological Modeled ET for Better Water Resources Management in Oklahoma, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract H32B-08, SF, CA, 2008

Conference Abstract and Presentation:

Sadiq Khan, Yang Hong, and Baxter Vieux, Integrating Remotely Sensed and Hydrological Modeled ET for Water Use Management in Oklahoma, Governor Conference on Water, Oct. 2008, Oklahoma City, OK

Abstracts of Journal Papers generated from this project

Khan, S. (student), Y. Hong, B. Vieux, W. Liu (student),

Development and Evaluation of an Actual Evapotranspiration Estimation Algorithm
Using Satellite Remote Sensing and Meteorological Observational Network in Oklahoma,
International Journal of Remote Sensing Special Issue (submitted)

Abstract

In the past few years satellite remote sensing applications in actual Evapotranspiration (ET) estimation have opened frontiers in water management at local and regional scales. However previous applications have been retrospective in nature, in part because of the lack of timely availability of polar-orbiting satellite sensor in relatively high spatiotemporal resolution. Furthermore, many ground networks do not provide data in near real-time, so that the ET estimates, though useful in retrospective studies, cannot be used in operational water management decision making. **The main objective of this paper is to develop and evaluate a real-time ET estimation algorithm by integrating satellite remote sensing and environmental monitoring network in Oklahoma, USA for operational daily water management purpose.**

First, a surface-energy-balance ET estimation algorithm, MODIS/METRIC (M/M-ET), is implemented for the estimation of actual ET by integrating ET by integrating the MODIS twice daily products and Oklahoma environmental observational network with 5-minute data acquisition through a simplified Surface Energy Balance approach METRIC in

Oklahoma (i.e. MOD/METRIC and thereafter M/M-ET). Second, accuracy of the estimated ET is evaluated at the site scale using AmeriFlux tower's latent heat flux and Mesonet site crop ET on daily, 8-day and seasonal basis. The results show that M/M-ET estimation agrees with these ground observations, with daily ET bias less than **15%** and seasonal bias less than **8%**. Additionally, modeled actual ET from a water balance budget analysis in a heavily instrumented basin is compared favorably (bias <**3%**) with the M/M-ET at catchment scales on the order of several hundreds of square kilometers.

This study demonstrates that (1) the M/M-ET estimation is acceptable for daily and seasonal actual ET estimation and (2) it is feasible to implement the proposed M/M-ET algorithm at real-time rather than retrospective manner for irrigational water resources management at the scale of irrigation projects in Oklahoma.

Keyword: Evapotranspiration; MODIS; Oklahoma; Remote Sensing

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**Evaluation of Global Daily Reference ET's Hydrological Utility using Oklahoma's
Environmental Monitoring Network-MESONET, *Water Resources Research*,**
(submitted)

Abstract

The central objective of this study is to evaluate the potential hydrological utility of the National Oceanic and Atmospheric Administration's Global Data Assimilation System (GDAS) 1-degree daily reference Evapotranspiration (ET₀) products by using Oklahoma world-class environmental monitoring network (MESONET) daily ET₀ over two year period (2005-2006). It showed a close match between the two independent ET₀ products, with bias within a range of 10% for most of the sites and the overall bias of -2.80%. The temporal patterns between GDAS ET₀ and MESONET ET₀ are strongly correlated, with correlation coefficient above 0.9 for all groups. This study further proposed a MODIS Land Surface Temperature (LST)-guided downscaling scheme that utilizes the MODIS 1-km LST products to disaggregate the 1-degree GDAS ET₀ to 1-km spatial resolution. Compared to a linear downscaling method as a benchmark, the MODIS LST-guided scheme not only improved the temporal correlations but also reduced the bias, absolute bias and root mean square error by 18.6%, 22.5% and 17.9%, respectively. In summary, we conclude that (1) the consistent low bias shows the original 1-degree GDAS ET₀ products have high potentials to be used in climate modeling particularly for macro-scale land surface and regional climate modeling; (2) the high temporal correlations demonstrate the capability of GDAS ET₀ to represent the major atmospheric processes

that controls the daily variation of surface hydrology; (3) with a proper downscaling method, a global daily high-spatial resolution (e.g. 1 km) of ET₀ can be derived from the GDAS ET₀ dataset and can be potentially used for a number of hydrologic applications and water resources management practices at a much improved spatial scales. The prospect of availability of global daily 1-km ET₀ has an enormous potential in hydrologic and water resources modeling because for practical purpose various techniques estimate actual ET as a fraction of ET₀ based on the soil-water content and vegetation conditions. However, additional evaluation and downscaling of GDAS ET₀ in different hydro-climatic zones should be emphasized before its hydrological utility can be fully realized.

Keywords: Evapotranspiration (ET) · Reference ET · GDAS · Oklahoma · MODIS.

Principal Findings

Mapping actual ET with satellite remote sensing eliminates a lot of expensive equipments and other time intensive tasks. Applications of the accurate and high-resolution remote sensing ET in watershed studies, water resource allocation, and operational flood forecasting are follow-on contributions expected from the proposed research.

This project demonstrated that 1) Satellite remote sensing-based ET estimation methods can be used to monitor water use in Oklahoma; 2) it is feasible for us to develop and implement a real-time remote sensing-based actual ET estimation system for water managers to monitor actual water use and thus better regulate water rights in Oklahoma.

Significance:

ET is among the most important processes in the hydrologic cycle and considered as a critical component in diverse disciplines such as those involved in water resource management, agriculture, ecology, and climate science. ET is a good measurement of irrigation effectiveness and the most important component of total water consumption in agriculture. Moreover, it is projected that climate change will influence the global water cycle and intensify ET globally. Water regulators have long wanted an efficient and inexpensive procedure to accurately map ET (irrigation consumption) over large regions and thus to improve water use regulation given limited water supply.

Results of this study show substantial promise to implement a high-resolution satellite remote sensing ET estimation system as an efficient, accurate, and inexpensive approach

to estimate the actual ET over irrigated lands in Oklahoma. Prospects of the project are very attractive for water users and managers as they cover large areas and can provide estimates at a very high resolution (30m and daily). Intensive field monitoring is also not required, although some ground-truth measurements can be critical in interpreting the satellite images. In summary, remote sensing ET estimation method complements or even replaces conventional procedures used by state and other management ministries that solely rely on land surface point-based ET estimation approaches.

Success of this project guarantees data assimilation of the seamless actual ET products into distributed high-resolution water balance models to improve predictions of hydrologic cycle. Further applications in watershed studies, water resource allocation, and operational flood forecasting are follow-on added-value contributions expected from this research.

Students supported by this program

Student Status	Number	Disciplines
Undergraduate	1 (partial support)	Environmental Science
M.S.	0	
Ph.D.	2 (partial support for the second one)	Geography; Agriculture and Forestry Science
Post Doc	0	
Total	3	

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1. Introduction

1.1 Overview

Evapotranspiration (ET) is among the most important processes in the hydrologic cycle and considered as a critical component in diverse disciplines such as those involved in water resource management, agriculture, ecology, and climate science. Estimation of spatially distributed ET from agricultural areas is important as irrigation consumes the largest share in water use (Glenn et al. 2007, Shiklomanov 1998). Particularly in arid and semi arid biomes, around 90% or more of the annual precipitation can be evapotranspired, and thus ET determines the freshwater recharge and discharge from aquifers in these environments (Huxman et al. 2004). Moreover, it is projected that climate change will influence the global water cycle and intensify ET globally (Meehl et al. 2007; Huntington et al. 2006), consequently this will impact the scarce water resources.

Today, ET estimation from satellites remote sensing data in Idaho and California shows substantial promise as an efficient, accurate, and inexpensive approach to estimate the actual ET from irrigated lands throughout a growing season. Particularly, *the Idaho state-university partnership providing near-real time actual ET that helps manage irrigation water demand is among the 2007 Top 50 Government Innovations named by the Ash Institute for Democratic Governance and Innovation at Harvard University's John F. Kennedy School of Government today.* Similar water resources scarcity and need for improved estimation of available water for management of permitted water use exists in the South Central Plains, especially in Oklahoma.

1.2 Scope of the study

Remote sensing methods can provide ET maps over large areas at very high resolutions (30m and daily) although some ground-truth measurements can be critical in interpreting the satellite images. However, transforming remotely sensed images into quantitative water use information at scales relevant to water management agencies is a primary goal that has not been fully realized. Main objective of this project is to evaluate and improve the ability and usefulness of the remote sensing ET estimation algorithms in Oklahoma that does not require placement of in-situ monitoring/metering devices.

This project combined the seamless satellite observations and our existing knowledge for water balance modeling by assimilating the remote sensing ET estimates into a distributed water balance model. Compared with traditional applications of water balance models (i.e. without the satellite-based actual ET assimilation), the combined procedure can provide significant improvements in understanding the latent heat fluxes (i.e. ET) with application to estimation of water usage by irrigated crops. Application in watershed studies, water resource allocation, and operational flood forecasting are follow-on contributions expected from the proposed research.

1.3 Proposed Studies

We will first review and evaluate the remote sensing ET algorithms that have only been applied to western U.S. Then we calibrated and improved remote sensing algorithms, with focus on surface irrigation water usage, specifically for applications in Oklahoma agricultural counties (e.g. Texas and Tillman) given its unique climate, soil,

and land surface types. As a natural extension, we also proposed to combine a water balance model *Vflo* with remote sensing estimates of ET to provide more accurate prediction of runoff, soil moisture etc for better water use management. Accuracy of the estimated ET, runoff, and soil moisture results will be evaluated at both field and catchment scales using available Mesonet weather station and other in-situ observations.

Deliverables:

1) Evaluation of current satellite remote sensing-based ET estimation algorithms to monitor water use in Oklahoma; 2) Calibration of an improved algorithm to estimate seamless high-resolution actual ET for irrigation land in OK; 3) Assessment of the feasibility of implementing a real-time remote sensing-based ET estimation system for water managers to better monitor actual ET and thus regulate water use in Oklahoma.

1.4 Justification of the Study

Recent developments in ET monitoring by remote sensing methods has been applicable in the western U.S. and such technology especially benefits management of water demand in agricultural areas that depend on irrigation. However, transforming remotely sensed images into quantitative water use information at scales relevant to water management agencies is a primary goal that has not been fully realized in Oklahoma. With the advent of new satellite technology and comprehensive water balance and runoff models, opportunities exist to develop algorithms and apply remote sensing information for the benefit of water resources management. Some of the potential sensors that are used and can be utilized in Oklahoma for water resource management are listed in table 1.

Table 1: Satellite sensor used for rainfall, ET and soil moisture estimation.

Satellite	Repeat cycle	Spatial resolution	Parameters
TMI/PR/GOES	3-hour	4-km	Rainfall, soil moisture, vegetation index and fraction, Thermal Infrared, Surface Skin Temperature, air temperature, infrared/clouds, incident solar and atmospheric radiations, albedo, leaf area index, land cover and land use, sensible heat and latent heat fluxes.
AMSR-E	Daily	25km	
MODIS	0.5 day	250m	
AVHRR	0.5 day	1100m	
GOES	15 minutes	4000m	
LANDSAT 5	16 days	30m	
LANDSAT 7	16 days	30m	
ASTER	16 days	15m or 60m	

2. Study Area and Data

2.1 Study Area

Oklahoma provides a unique setting to implement and evaluate remote sensing ET estimation methods. The region has an extensive and well distributed meteorological observation network, known as Mesonet stations (Figure 1). In addition to Mesonet towers, there are a fair number of surface flux observation stations (AmeriFlux towers) in the Southern Great Plain (SGP), the first field measurement site is established by USA

DOE's Atmospheric Radiation Measurement (ARM) Program. AmeriFlux, part of the global Fluxnet network that was established in 1996 provide continuous observations of ecosystem level exchange of CO₂, water, energy and other climatological variables (<http://www.daac.ornl.gov/FLUXNET/fluxnet.html>). Moreover, Oklahoma has several heavily instrumented watersheds, which enable us to compare the remote sensing actual ET estimates with water balance modeled results at the catchment scale. The Blue River basin is located in south central Oklahoma, covering an approximate area of 1,200 km². The upper part of the basin overlies the Arbuckle-Simpson aquifer, which provides water to streams and rivers as baseflow, constituting the principal water source of many towns in the Chickasaw National Recreation area, including Ada and Sulphur, where the water is used for public water supply, irrigation, recreation, agriculture, industrial use and mining. Map of the study area, AmeriFlux towers, Mesonet sites, and the Blue River basin characteristics are shown in (Figure 5). The study area extends over the states of Oklahoma with longitude from 94.4° W to 103.0° W and latitude from 33.6° N to 37.0° N.

2.2 Data sets

2.2.1 Oklahoma Meteorological Observations: Mesonet

The Oklahoma Mesonet is a world-class network of environmental monitoring stations jointly managed by the University of Oklahoma (OU) and Oklahoma State University (OSU). Established as a multipurpose network, it operates more than 120 automated surface observing stations covering the state of the Oklahoma and measures comprehensive meteorological, hydrological, and agricultural variables since the early

1990's. These monitoring sites have collected Over 3,758,558,640 observations since January 1st, 1994. (<http://www.mesonet.org>; McPherson et al. 2007). At each site, the environment is measured by a set of instruments located on or near a 10-meter-tall tower. The measurements are packaged into "observations" every 5 minutes; then the observations are transmitted to a central facility every 5 minutes, 24 hours per day year-round. The Oklahoma Climatological Survey (OCS) at OU receives the observations, verifies the quality of the data and provides the data to Mesonet customers. It only takes 5 to 10 minutes from the time the measurements are acquired until they become available to the public.

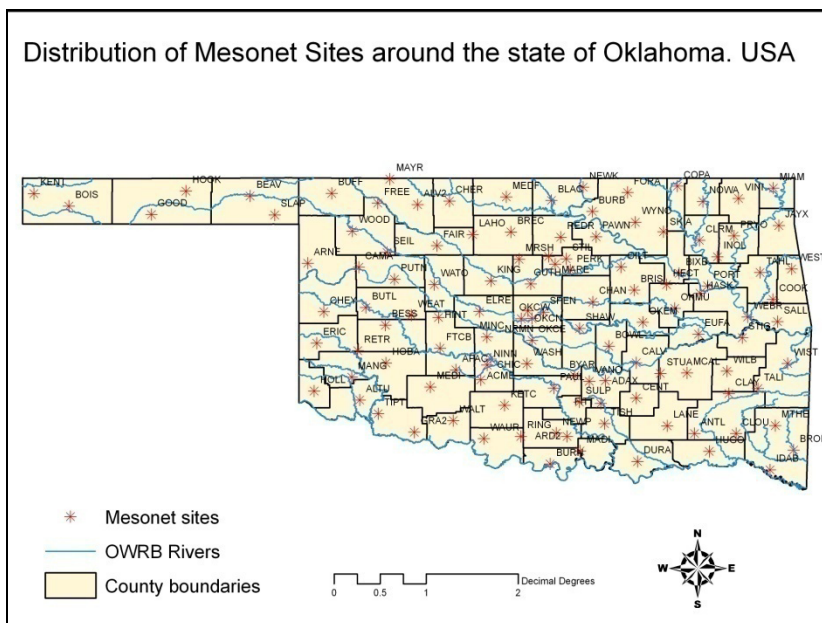


Figure 1: Oklahoma's World-Class Network of Environmental Monitoring Stations (red asterisks) with station ID's. At the right is the 10-meter tall monitoring tower and instrumentations.

2.2.2 Satellite Remote Sensing Data

The MODIS (Moderate Resolution Imaging Spectroradiometer) sensors, with 36 spectral bands (20 reflective solar and 16 thermal emissive bands), provide unprecedented information regarding vegetation and surface energy (Justice et al. 2002), which can be used to develop a remotely sensed ET model (Mu et al. 2007). ET-relevant MODIS data used in this study are listed in (Table 2). Wan and Li (1997) described the retrieval of MOD11 land surface temperature (LST) and emissivity from MODIS data. Detailed information about MOD09 surface reflectance products is provided in Vermote et al. (1997) and Xiong et al. (2007). The algorithm for retrieving the Vegetation Index (MOD13) is presented by Huete et al. (2002). The computation of broadband Albedo (MOD43B3) by integrating bi-hemispherical reflectance data modeled over MODIS channels 1-7 (0.3-5.0 μm) is explained in Schaaf et al. (2002). All NASA MODIS land products include so called Quality Assessment Science Data Sets (QA-SDS), which considers the atmospheric conditions in term of cloud cover and aerosol content, algorithm choices, processing failure, and error estimates (Colditz et al. 2006). These data products were extracted and processed from the Land Processes Distributed Active Archive Center (LP DAAC) at the USGS EROS Data Center), with the standard Hierarchical Data Format (<http://LPDAAC.usgs.gov>). For more information on MODIS, please refer to <http://modis.gsfc.nasa.gov>.

Table 2: ET-Relevant NASA MODIS data products

Product ID	Layer	Spatiotemporal resolution	MODIS QA-SDS ^a Analysis (Quality flags passed)
MOD11A2	Land Surface Temperature (LST)	1-km ^b , overpass	General quality: good
	Emissivity	1-km, overpass	
	View Angle	1-km, overpass	
	Recording time	1-km, overpass	
MOD13Q1	Vegetation index	1-km, 16-day	quality: good ~ perfect
	NDVI		mixed clouds: no
MOD43B3	Albedo	1km, 16-day	Quality: good and acceptable Snow: no
MOD09Q1	Red reflectance	250m, 8-day	Quality: good
	NIR reflectance		Clouds: clear Band quality: highest
MOD15A2	Leaf Area Index (LAI)	1km, 8-day	Quality: good Cloud: clear or assumed clear
MOD12Q1	Land Cover Type	250m, annual	Quality: good

^aQuality Assessment Science Data Sets

^bThe swath products were gridded using the MODIS reprojection tool (MRT)

^cThe view angles were analyzed to remove effects from scan geometry caused by increasing IFOV towards the edges of the scan lines

2.2.3 AmeriFlux Data

The location and general site characteristics are summarized in (Figure 5) and (Table 3). Table 2 lists the two Atmospheric Radiation Measurements (ARM) SGP eddy covariance tower sites, located at the ARM SGP extended facilities in Lamont and El Reno, Oklahoma, respectively. The two Mesonet sites at El Reno and Medford with Crop ET data are also selected for comparison.

ARM SGP Burn (OK, USA) and ARM SGP Control (OK, USA)

Both of these sites are inactive at the moment but we used the available data sets from previous years. The ARM SGP Burn and control sites are located in Canadian county and are very close to each other. The coordinated are latitude 35.54 and longitude 98.04. The elevation of the both areas is 421 meters (Table 3). IGBP classifies the vegetation in the both area as grassland.



Figure 2: ARM SGP Burn Site

ARM SGP Main (OK, USA)

The IGBP classifies the vegetation type as croplands, and AmeriFlux website classifies the vegetation type as agricultural and dominant vegetation types are wheat, corn, and soybean that have periodic rotation. The elevation of the area is 315 meters (Table 3). The canopy height of the area is ranging from 0 to 0.5m. The soil type of the area is silty clay loam, fine mixed thermic Underitic Paleustolls. Climate of the area is classified as temperate continental. Total precipitation is not very high; in 2003-2004 the range of annual sums were 552-901. Seasonal temperatures vary greatly such as



Figure 3: ARM SGP Main Site

the maximum air temperature in 2003-2004 was 43.6 °C and the minimum air temperature is -17.5 °C.

Table 3: Validation locations of ARM SGP AmeriFlux towers and Mesonet sites

ARM SGP Site	Elevation (m)	County	Vegetation
El Reno	421	Canadian	Pasture (ungrazed)
Lamont	315	Grant	Pasture and wheat
Mesonet Site	Elevation (m)	County	Ecosystem
Medford	332	Grant	Wheat and Pastures
El Reno	419	Canadian	Pasture

3. Evaluation of Surface Energy Balance methods for Oklahoma.

3.1 Net Radiation R_n Calculation

As modification of Equation 1 in previous section, in practice net radiation R_n is computed from the land surface radiation balance as:

$$R_n = (1 - \alpha) R_s + (\varepsilon L_{in} - L_{out}) \quad (8)$$

Where α is surface albedo, R_s is solar radiation (Wm^{-2}), ε is land surface emissivity and L_{in} and L_{out} are incoming and outgoing longwave radiation (Wm^{-2}). The α is determined by integrating spectral reflectance in the six shortwave bands of the Landsat images, and L_{in} and L_{out} are computed as functions of surface temperature derived from the satellite images. The ε is computed from vegetation indices derived from two of the shortwave bands. First, it requires radiometric and atmospheric calibration of satellite images for estimating spatial ET using METRIC. For this purpose, the digital numbers (DN) stored in the satellite image are first converted into radiance (L_b), for each band as $L_b = (\text{gain} \times \text{DN}) + \text{bias}$, then at 'sensor' or 'Top-of-the-Atmosphere' (TOA; exoatmospheric) reflectance values for the shortwave bands are estimated. Reflectance values are calculated by dividing the detected radiance at the satellite (for each band) by the incoming energy (radiance) in the same shortwave band. The incoming radiance is a function of mean solar exoatmospheric irradiance, solar incidence angle, and the inverse

square of the relative earth-to-sun distance. In case of the thermal band, the spectral radiance values are converted into effective at-satellite temperatures of the viewed earth-atmosphere system under an assumption of unity for surface emissivity and using pre-launch calibration constants by means of an inverted logarithmic formula. Subsequently, surface reflectance values are computed after applying atmospheric interference corrections, on the TOA reflectance image, for shortwave absorption and scattering using narrowband transmittance values for each band. Radiative transfer models will be used in the parameter calibration.

3.2 Soil Heat Flux (G)

For several applications of Equation 3 in western U.S., approximate values of $G=0.5R_n$ has been generally assigned for water and snow. Snow is distinguished according to T_s 277 K, NDVI=0 and high surface albedo, and water is distinguished as NDVI=0 and low albedo. However, the $G =0.5R_n$ for water should be refined according to the depth and turbidity of water bodies and time of season (Allen and Tasumi 2005). For example, G/R_n will be less than 0.5 for turbid or shallow water bodies due to the absorption of short-wave radiation near the water surface for turbid water and the reflection of solar radiation from and warming by the bottom for shallow systems. For 24 h periods, G/R_n will be less than the instantaneous value for water. The G/R_n ratio for snow for 24 h periods is assumed to be nearly zero or slightly positive during snowmelt. Alternative methods to derive G will be calibrated by USDA-ARS for irrigated crops at Texas and Tillman Counties:

$$G = R_n (0.05 + 0.18e^{-0.521 \text{ LAI}}) \text{ (LAI} \geq 0.5) \quad (9a)$$

$$G = (1.80 (T_s - 273.15) + 0.084 R_n \text{ (LAI}<0.5)) \quad (9b)$$

Eq. 9a indicates that G/R_n decreases with increasing leaf area, for the same reason, and Eq. 9b indicates that for bare soil G increases in proportion to surface temperature. Eq. 9 has been used with applications in Idaho, California, and New Mexico (all desert or semi-arid soils). When applying METRIC to semi-arid soils where near-surface thermal conductivities are most likely smaller than tilled soils due to cracks, delaminated crust, lack of structure, or very low soil water content, the G/R_n from Eq. 9b is limited and even reduced for T_s of the dry hot pixel. Thus, modifications and re-calibration are necessary when the surface is covered by vegetation that functions as an insulator on the surface.

3.3 Sensible Heat (H)

Remote sensing algorithms obtain ET as the residual of the SEB after measuring and/or modeling net radiation R_n , ground heat flux G , and sensible heat flux H . Among these fluxes, H is the most complex to estimate and its value is associated with greater uncertainty. In practice, METRIC estimates H from wind speed and surface temperature using a unique “internal calibration” of the near surface to air temperature difference (dT) as modified from Equation 4 (Bastiaanssen et al. 2005):

$$H = \rho_{\text{air}} C_{p\text{a}} (a + bT_s) / r_{\text{ah}} = (\rho_{\text{air}} c_p dT) / r_{\text{ah}} \quad (10)$$

Where a and b are empirical coefficients. dT (K) is a parameter that represents the near surface temperature difference between surface and near surface at height about 2m, and that the indexing of dT to T_s does not rely on absolute values of T_s , which allegedly reduces the error in calculating H substantially. While apply the equation to agricultural

lands in OK, coefficient a and b are required to be calibrated for different land surface types from the remote sensing images. The determination of a and b involves locating a hot (dry) pixel in an agricultural field with higher T_s and a cold (wet) pixel with a lower T_s (typically one in an irrigated agricultural setting) in the remote sensing image. Once these pixels have been identified, the energy balance of Equation (1) can be solved as:

$$H_{cold} = (R - G)_{cold} - LE_{cold} \quad (11)$$

$$H_{hot} = (R - G)_{hot} - LE_{hot} \quad (12)$$

Where H_{hot} and H_{cold} are the sensible heat fluxes for the hot and cold pixel, respectively. A hot, dry pixel (typically a dry, bare soil surface) is selected as the “hot pixel”, and latent heat flux LE_{hot} from the pixel is assumed zero, which means that all available energy is partitioned to the sensible heat H . And the H , from the cold pixel is assumed zero ($LE=R_n-G$). With the calculation of H_{hot} and H_{cold} , the coefficients a and b can be calibrated for other pixels within the same remote sensing image using a linear interpolation based on T_s between these two extreme pixels where H and dT are known. However, LE_{hot} can be non-zero and can be calculated according to a soil water budget if rainfall has occurred shortly before the image acquisition date. Therefore, we propose to use Antecedent Precipitation Index (API) from radar and satellite rainfall to adjust the LE_{hot} . As an extension of this project, we plan to incorporate the ET estimates into a distributed water balance model *Vflo* in order to validate the components of water balance budget (see Section 4.4 for detail).

3.4 Integrating MODIS data for higher temporal resolution

In Equation 6-7, the instantaneous ET_{inst} or ET_{iF} values at the satellite image time are assumed to be equal to values representing the ET for the 24 h period. The ASTER and Landsat satellites are polar orbiters and revisit the same path every 16 days. The frequency is also decreased by cloudy condition. Thus, monthly and seasonally ET are estimated by linearly interpolating the ET_{rF} values for periods in between two consecutive images. However, this linear interpolation does not account for the daily wetting and drying events of individual fields that are not captured by Landsat images. Therefore, the interpolation generates uncertainty in the ET estimates, especially for short time periods. We will use MODIS surface skin temperature data with 1-2 day revisit period to increase the temporal resolution of ET estimates from LANDSAT and ASTER.

3.5 Weather Station Measurement and Ground Verification

We will use measurements of Lysimeters and Scintillometers from the Oklahoma Mesonet network, a system of 115 automated measurement stations across Oklahoma. These measurements will verify the remote sensing estimates of boundary layer fluxes of sensible, latent, and ground heat, as well as the radiation balance. Particularly, the weather stations used in this project are listed in Table 3. We will use spatially distributed meteorological weather stations (one of the advantages of OK state) to measure energy balance components (R, G, and H) and determine in particular how the H is related to temperature lapse rate, wind speed, water vapor deficit, and vegetation heights. First, the weather station measurements H will be used to validate estimates derived from the remote sensing ET estimation (METRIC) algorithm applied on data from synchronous ASTER and MODIS satellite overpasses. Second, parameters in the METRIC algorithm

for Texas county high terrain lapse rates, wind speeds, and surface roughness will be critically calibrated and improved by considering meteorological measurements and archived numerical weather model data. Through this work we will make a lasting contribution to ET estimation from METRIC and other SEB-based remote sensing algorithms for current and future satellite mission.

4. M/M-ET: (Actual ET Estimation from MODIS through a Modified SEB-METRIC Approach)

4.1 Estimation of instantaneous actual ET using SEB approach

In this paper we utilized a simplified version of the Surface Energy Balance (SEB) approach to estimate actual ET while maintaining and extending the major assumptions in the SEBAL and METRIC method. The central scientific basis of SEB is to compute the ET as the residual of the energy balance equation:

$$LE = \lambda ET = R_n - G - H \quad (13)$$

ET is calculated as a “residual” of the energy balance

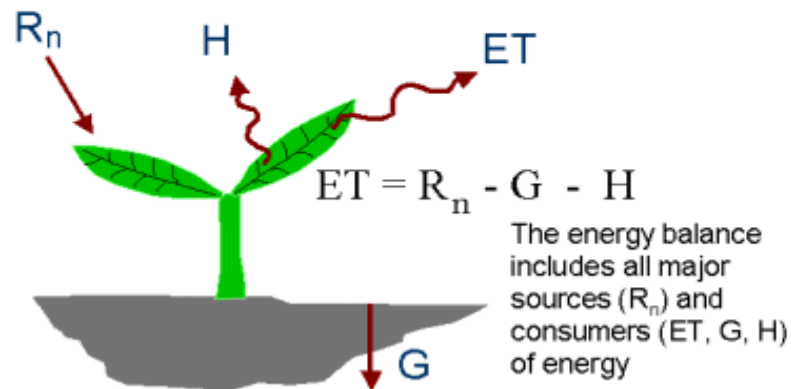


Figure 4: The ET is computed as a residual of the surface energy balance budget.

where λ is the latent heat of water evaporation constant; R_n is net radiation flux; G is soil heat flux; and H is sensible heat flux to the atmosphere (units are Wm^{-2}). Thus, ET is calculated as the residual amount of energy remaining from the surface energy balance budget, where the available R_n is shared between the G and the atmospheric convective fluxes (sensible heat H and latent heat LE). The R_n and other components (i.e. G) of SEB can be derived through remote sensing information and surface properties such as albedo, leaf area index, vegetation cover, surface temperature, and meteorological observations within the study area (Su et al. 2002; Bastiaanssen et al. 2005; and Allen et al. 2007). The equation to calculate the net radiation flux is given by

$$R_n = (1 - \alpha) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_s^4 \quad (14)$$

Where α is surface Albedo; R_{swd} and R_{lwd} are incoming shortwave and longwave radiation respectively; ε is surface emissivity; σ is the Stefan-Boltzmann constant, and T_s is the land surface temperature. Soil heat flux (G) was modeled as a function of R_n , vegetation index, surface temperature, and surface albedo (Bastiaanssen, 2000):

$$G = R_n \cdot [(T_s - 275.15) \cdot (0.0038 + 0.0074\alpha) \cdot (1 - 0.98NDVI^4)] \quad (15)$$

where, NDVI is the Normalized Difference Vegetation Index $[(R-NIR)/(R+NIR)]$. R is reflectance in the red band and NIR is reflectance in the near infrared band.

Sensible heat flux (H) is defined by the bulk aerodynamic resistance equation, which uses aerodynamic temperature (T_{aero}) and aerodynamic resistance to heat transfer (r_{ah}):

$$H = \rho_a \cdot Cp_a (T_{aero} - T_a) / r_{ah} \quad (16)$$

where: ρ_a is air density (kg m^{-3}), Cp_a is specific heat of dry air ($1004 \text{ J kg}^{-1} \text{ K}^{-1}$), T_a is average air temperature (K), T_{aero} is average aerodynamic temperature (K), and r_{ah} is aerodynamic resistance (s m^{-1}) to heat transport. In SEBAL and METRIC (Allen et al. 2005; Tasumi et al. 2005), H usually results from dividing the gradient of vertical temperatures (dT) by the aerodynamic resistance of heat transport (r_{ah}), without needing to know T_a or T_{aero} .

$$H = \rho_a \cdot Cp_a \left(\frac{dT}{r_{ah}} \right) \quad (17)$$

Allen et al. (2007a) explained that dT (K) is a parameter that represents the near surface temperature difference between two different elevation z_1 and z_2 , and that the indexing of dT to T_s does not rely on absolute values of T_s , which allegedly reduces the error in calculating H substantially. One key assumption of SEBAL and METRIC is the linear relationship between dT and T_s land surface temperature (Bastiaanssen et al. 1998; Allen et al. 2005), characterized in Equation (18).

$$dT = a + b \cdot T_s \quad (18)$$

where a and b are empirically determined constants.

The determination of a and b in Equation (18) involves locating dry or wet limiting cases, a dry-limit pixel with high T_s and a wet-limit pixel with low T_s . Thus, the linear equation can be computed using the two anchor points. Typically a dry bare soil surface is selected as the “hot pixel”, and latent heat flux LE_{dry} from the pixel is assumed zero, which means that all available energy is partitioned to the sensible heat H_{dry} . Therefore, at the dry limit,

the latent heat (or the evaporation) becomes zero due to the limitation of soil moisture, and the sensible heat flux is at its maximum value. Once these pixels have been identified, the energy balance of Equation (13) can be solved for

$$LE_{dry} = (R_n - G)_{dry} - H_{dry} \equiv 0 \text{ or } H_{dry} = (R_n - G)_{dry} \quad (19)$$

And for the wet-limit, the H_{wet} is assumed zero and LE_{wet} is assumed to have an LE value equal to 1.05 times that expected for a tall reference crop (i.e., alfalfa; Allen et al., 2007a). Therefore, the energy balance of Equation (13) for the wet-limit can be solved as:

$$LE_{wet} = (R_n - G)_{wet} - H_{wet} = (R_n - G)_{wet} = 1.05 \cdot ET_{reference} \quad (20)$$

With the determination of H_{dry} and H_{wet} , proportional coefficients of other pixels can be calibrated within the same remote sensing image using a linear interpolation based on LST between these two extreme pixels. For more detail, please refer to Bastiaanssen et al. (1998) and Allen et al. (2005). Here we adopted the METRIC approach to identify hot and cold pixels. The landscape is simplified as a mixture of vegetation and bare soil. Fractional canopy coverage f_c , whose value is between 0 and 1, is related to MODIS Normalized Difference Vegetation Index (NDVI):

$$f_c = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (21)$$

The surface energy balance computation is then based on the determination of the relative instantaneous ET fraction (ET_f) given by:

$$ET_f = \frac{\lambda E}{H + \lambda E} = \frac{\frac{H_{dry} - H}{H_{dry} - H_{wet}} \cdot \lambda E_{wet}}{R_n - G} \quad (22)$$

Eqs. (13) – (22) above constitute the basic formulation of SEB. The actual sensible heat flux H is obtained by solving a set of non-linear equations and is constrained in the range set by the sensible heat flux at the wet-limit H_{wet} and the dry-limit H_{dry} . An alternative to compute the ET_f is to assume, according to Senay et al. 2008 that dry-hot pixels experience very little ET and wet-cold pixels represent maximum ET throughout the study area, and the temperature of hot and cold pixels can be used to calculate proportional fractions of ET on a per pixel basis. Thus, the ET_f can also be calculated for each pixel by applying the following equation (Equation 23) to each of the MODIS land surface temperature grids:

$$ET_f = \frac{T_{hot} - T_{i,j}}{T_{hot} - T_{cold}} \quad (23)$$

Where T_{hot} is the average of the *hot* pixels selected for a given scene; T_{cold} is the average of the *cold* pixels selected for that scene; and $T_{i,j}$ is the MODIS land surface temperature value for any pixel in the composite scene.

In practice, the ET_f is used in conjunction with reference ET (ET_r) described in the following 3.2 section to calculate the per pixel instantaneous actual ET (ET_a) values in a given scene according to METRIC in Allen et al. 2005:

$$ET_a = ET_f \cdot ET_r \quad (24)$$

A key assumption of the method is that the ET_f is nearly constant, which is often observed to be the case according to [Shuttleworth *et al.* 1989; Sugita and Brutsaert, 1991; Brutsaert and Sugita, 1992; Crago, 1996]. This allows instantaneous estimates of the ET_f at MODIS overpass times to be extrapolated to estimate daily average ET. The daily ET can thus be determined as:

$$ET_{daily} = \sum_{i=1}^{day} (ET_f \times ET_r^i) \quad (25)$$

Where ET_{daily} is the actual ET on a daily basis (mm d^{-1}), i is temporal resolution of computed reference ET (e.g. hourly or 5-minute), the λ is the latent heat of vaporization (JK g^{-1}), ρ_w is the density of water (Kgm^{-3}) and $\overline{R_n}$ is the daily net radiation flux.

4.2 Oklahoma Mesonet Reference ET Model

The Oklahoma reference ET calculations are based on the standardized Penman-Monteith reference ET equation recommended by the American Society of Civil Engineers (ASCE) and the computational procedures found in [Allen et al.](#) (1994a, 1994b) based on the experimental work in Kimberly, Idaho ([Wright](#), 1996):

$$\text{Reference ET} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(C_d u_2)} \quad (26)$$

Where:

Reference ET = Standardized reference evapotranspiration (mm d^{-1} for daily or mm h^{-1} for hourly time steps),

R_n = Calculated net radiation at the crop surface ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly time steps),

G = Soil heat flux density at the soil surface ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily time steps or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly time steps),

T = Mean daily or hourly air temperature at 1.5 to 2.5-m height ($^{\circ}\text{C}$),

u_2 = Mean daily or hourly wind speed at 2-m height (m s^{-1}),

e_s = Saturation vapor pressure at 1.5 to 2.5-m height (kPa), for daily computation, the value is the average of e_s at maximum and minimum air temperature,

e_a = Mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

Δ = Delta, the slope of the saturation vapor pressure-temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$),

γ = Psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$),

C_n = Numerator constant that changes with reference type and calculation time step, and

C_d = Denominator constant that changes with reference type and calculation time step.

5. Results and Evaluation

We implemented the above mentioned M/M-ET estimation algorithm for three years (2004-2006) based on MODIS remote sensing data listed in (Table 2) and Oklahoma Mesonet observational network shown in (Figure 1). For more details of the 5-minute Mesonet weather variables, please refer to (<http://mesonet.org>). In this study M/M-ET estimates are evaluated on daily, 8-day and seasonal basis at both field and catchment levels.

5.1 Evaluation Indices

For the evaluation, we employed commonly used performance indicators: bias, absolute bias, root mean square error and correlation coefficient for each of the two years and two years combined.

5.1.1 Relative bias (Bias):

It is a measure of total volume difference between two time series. The bias between observations (A) and estimates (B) were then calculated as:

$$\text{Bias (\%)} = \frac{\sum_{i=1}^N A_i - \sum_{i=1}^N B_i}{\sum_{i=1}^N B_i} \times 100 \quad (27)$$

5.1.2 Absolute bias (Abs. bias):

It is a measure of timing difference between the two time series besides the volume difference. For example, if the percent bias measure between two time series is small and at the same time, the absolute percent bias measure is large, then one can say the two time series have close total volume but their timing are not as close. A good agreement between the two requires both percent bias and absolute percent bias are small. The absolute percent bias is always greater than or equal to percent bias.

$$\text{Abs. bias (\%)} = \frac{\sum_{i=1}^N |A_i - B_i|^2}{\sum_{i=1}^N B_i} \times 100 \quad (28)$$

5.1.3 Root Mean Square Error (RMSE):

RMSE measures the average error of magnitude between the two datasets. The comparison between the observation and estimates were evaluated as:

$$\text{RMSE (\%)} = \frac{\sqrt{\frac{\sum_{i=1}^N (A_i - B_i)^2}{N}}}{\frac{N}{B}} \times 100 \quad (29)$$

5.1.4 Correlation coefficient (CC):

The correlation coefficient (CC) is used to assess the relation between observations and estimation values.

$$CC = \frac{\sum_{i=1}^N (A_i - \bar{A}) \cdot \sum_{i=1}^N (B_i - \bar{B})}{\sqrt{\sum_{i=1}^N (A_i - \bar{A})^2 \cdot \sum_{i=1}^N (B_i - \bar{B})^2}} \quad (30)$$

5.2 Validation at AmeriFlux sites

Two different field sources described below are used to compare the estimated results: one with AmeriFlux towers for latent heat flux observation and the other with Mesonet sites for crop ET.

The ARM instruments and measurement applications (<http://www.arm.gov>) are well established and have been used for validating estimates of net primary productivity, evaporation, and energy absorption that are being generated by sensors on the NASA TERRA satellite (<http://public.ornl.gov/ameriflux/>) in many studies (Heilman & Brittin, 1989, Halldin & Lindroth, 1992; Lewis, 1995; Shuttleworth, 1991 Venturini et al. 2008). The ARM stations are widely distributed over the whole study domain but only two provides the latent flux data for the study time period. Thus, ET estimates were compared with the flux tower observations at Lamont and El-Reno as shown in (Figure 6) and (Figure 7), respectively.

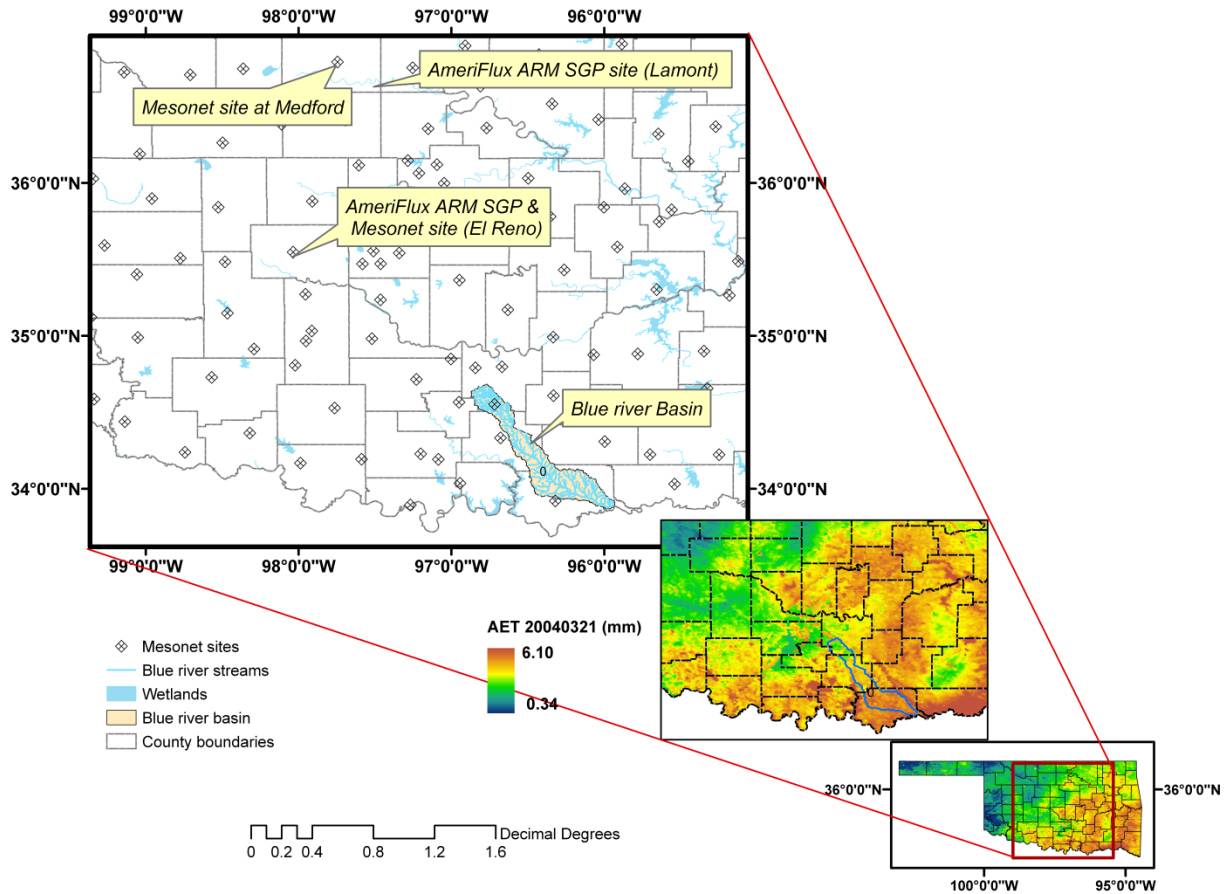


Figure 5: Study Area with AmeriFlux towers, Mesonet sites and Blue River Basin.

Table 4: Comparisons of daily and 8-day mean actual ET estimates with AmeriFlux observations at ARM SGP Lamont site for year 2004

Lamont site	AmeriFlux mean (mm)	M/M mean (mm)	Bias (mm)	Bias ratio	CC
Daily	1.63	1.87	0.28	14.72	0.64
8-day	1.46	1.70	0.24	13.44	0.77
Summer	2.46	2.62	0.16	6.45	-
Fall	1.70	1.83	0.13	7.97	-

Table 4 provides statistical variability for observed and estimated actual ET for the defined temporal scales. In Table 4, the bias ratio, and correlation coefficients are presented for each day, every 8 day and for summer and fall seasons. In general, bias ratios are less than 15% of the mean values for daily and 8-day with a correlation of 0.64 and 0.77, respectively. These values indicate the ET estimates correlate relatively well with the measurements. It should be noted that daily and 8 day results are impacted by the image quality in terms of cloud cover. Therefore, the daily and 8-day bias and RMSE for those days tend to be larger than the seasonal values. The bias ratios are less than 8% at Lamont site for both summer and fall season.

Table 5: Comparisons of daily actual ET estimates with AmeriFlux observations at ARM SGP, El-Reno site for year 2005

El Reno site DOY	AmeriFlux mean (mm)	M/M mean (mm)	Bias (mm)	Bias ratio	CC	% RMSE
20050424 - 20050527	2.49	2.68	0.19	7.626	0.86	27.50
20060424 - 20060605	3.04	3.22	0.17	5.90	0.75	28.15

Table 5 lists the comparison results for another AmeriFlux tower site at El-Reno for growing seasons in 2005 and 2006. Both seasons show relative small bias ratio (7.6% and 5.9%), high correlation (0.86 and 0.75), and low RMSE (27% and 28%).

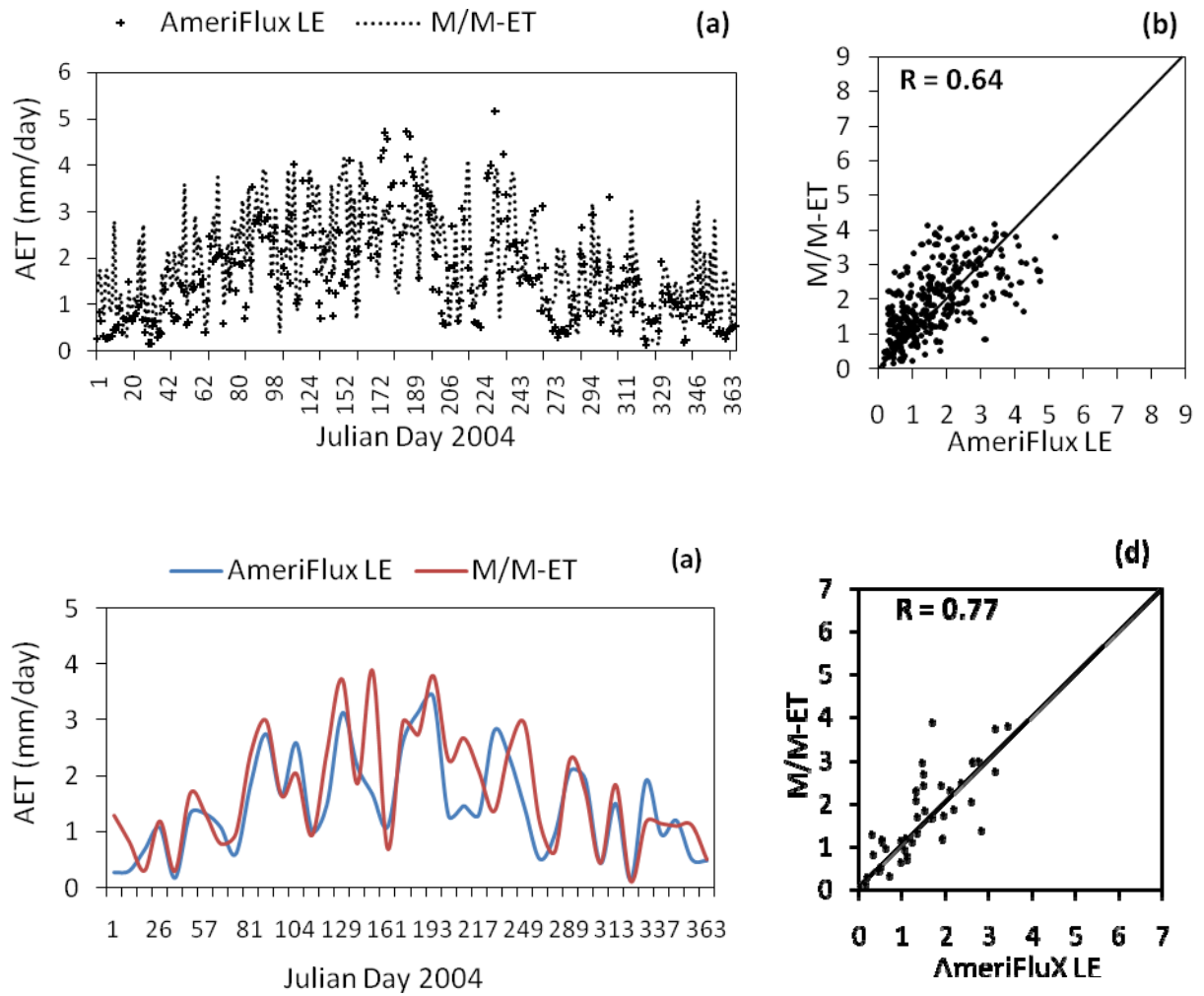


Figure 6: 2004 comparisons of daily and 8-day mean actual ET from AmeriFlux tower observations and the M/M-ET estimates through the Simplified Surface Energy Balance (SSEB) approach at ARM SGP Lamont site (when available). Panels (a) and (b) shows the daily time series and scatter plot comparison; (c) and (d) are for every 8-day.

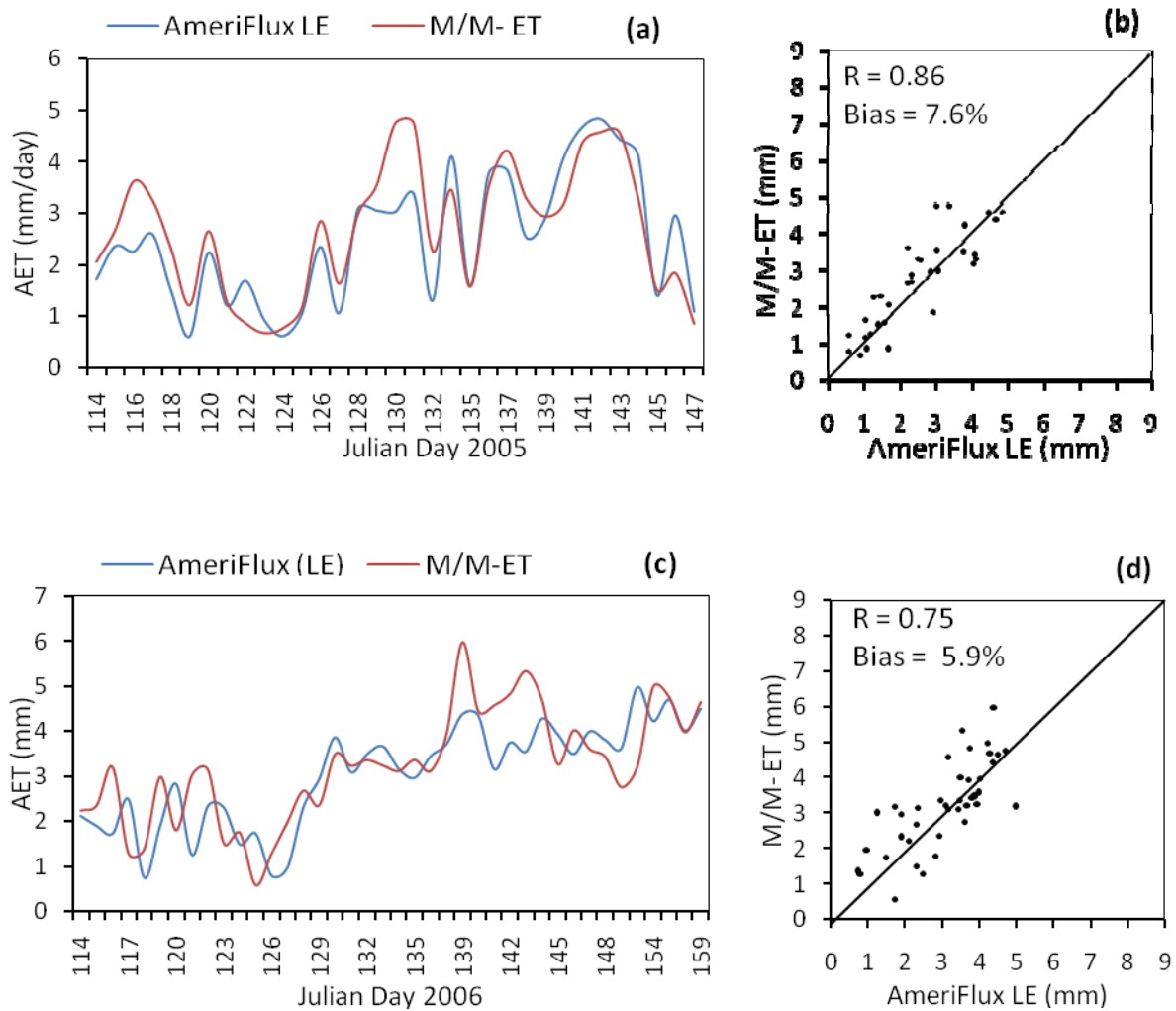


Figure 7: Comparisons of actual ET from AmeriFlux tower observations and SSEB-based M/M-ET estimates at ARM SGP El-Reno site. Panels (a) and (b) shows the daily time series and scatter plot comparison for 2005; (c) and (d) are for 2006.

5.3 Validation with Crop ET at Mesonet sites

The ET estimates are also evaluated with the crop ET at Grant (Medford site) and Canadian (El-Reno site) Counties (Figure 1 and Table 3) during wheat growing season in 2004-2006.

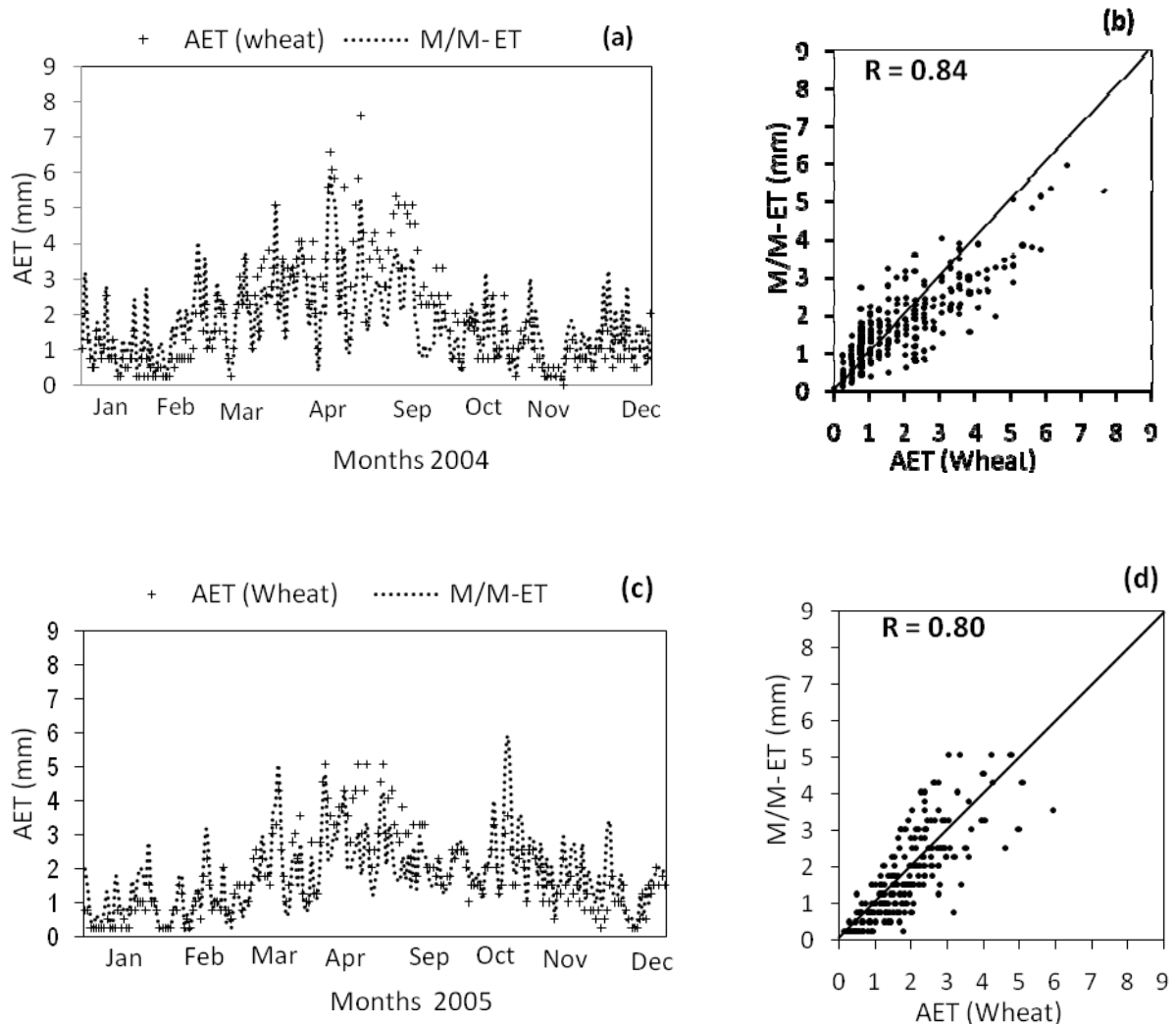


Figure 8: Comparisons of crop ET (wheat) and SSEB-based M/M-ET estimates at ARM SGP Medford site. Panels (a) and (b) shows the 2004 time series and scatter plot; (c) and (d) are for 2005.

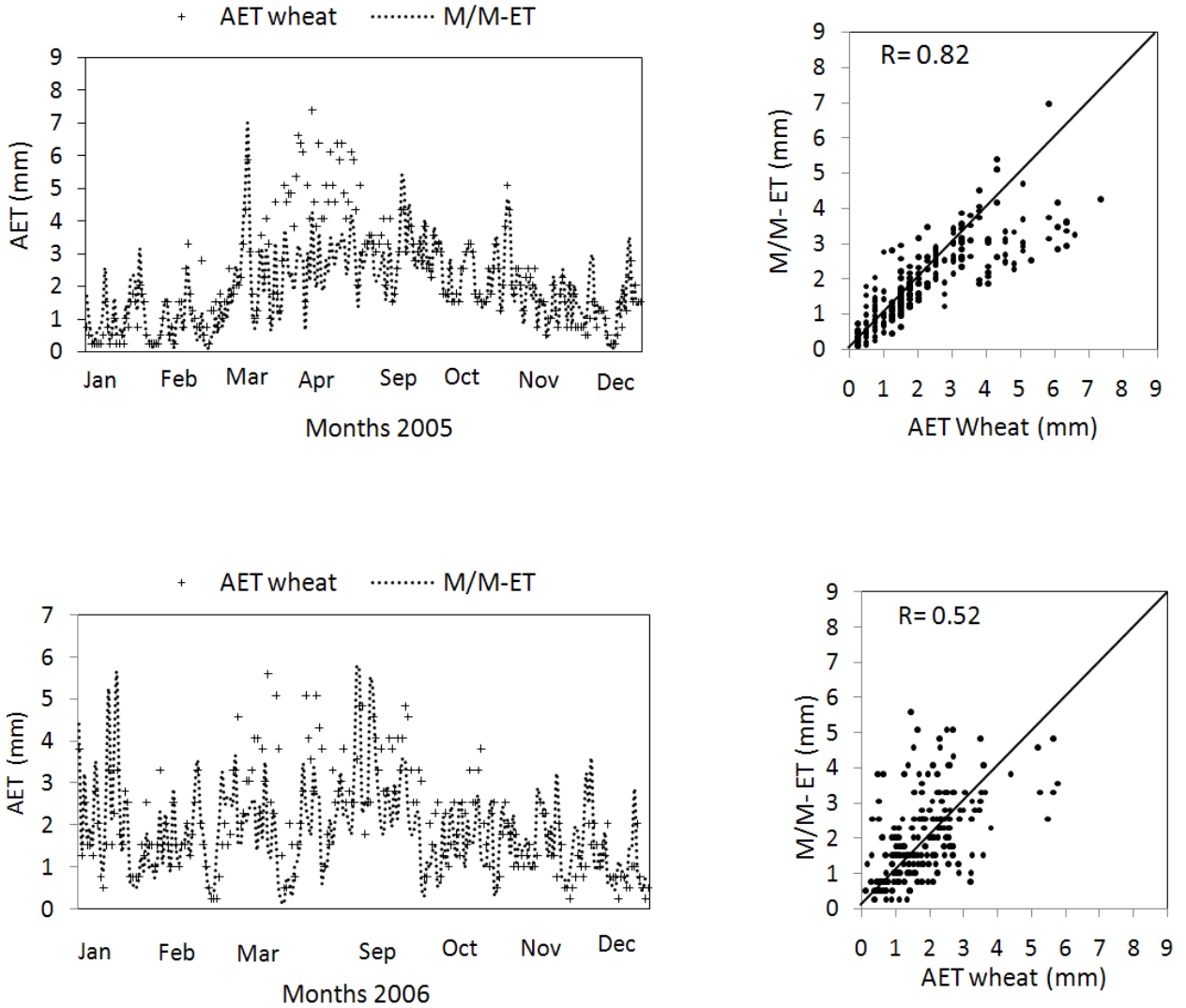


Figure 9: Comparisons of crop ET (wheat) and SSEB-based M/M-ET estimates at ARM SGP EL-Reno site. Panels (a) and (b) shows the 2005 time series and scatter plot; (c) and (d) are for 2006

Figure 8 and Figure 9 shows the daily time series and scatter plots for the sites, respectively. There is a good agreement as the scatter graphs correspond well with the in-situ crop ET observations from the Agweather site

(<http://agweather.mesonet.org/index.php/data/section/crop>).

Table 6: Comparisons of actual ET estimates with crop ET at Medford site and El Reno site for wheat growing seasons.

1) Medford site	ET Wheat crop mean (mm)	M/M mean (mm)	Bias	Bias ratio	CC	% RMSE
2004 wheat crop season	1.91	1.77	-0.14	-7.46	0.84	42.65
2005 wheat crop season	1.77	1.83	0.06	3.55	0.80	41.58
2) El-Reno site						
2005 wheat growing season	2.28	1.97	-0.31	-13.73	0.82	42.50
2006 wheat growing season	2.06	1.87	-0.19	-9.46	0.51	54.56

Table 6 summarizes the comparisons at both Medford and El-Reno site. The bias ratios are around -7% and 3% at Medford site for 2004 and 2005 respectively. Similarly, the correlation coefficients indicate the ET estimates correlate strongly with values of 0.84 and 0.80 for 2004 and 2005 observations at Medford site. M/M-ET estimates at El-Reno show slightly higher biases but in general agreement with the measurements. The correlation coefficient also indicate the ET estimates correlate relatively well with values of 0.82 and 0.51 for 2005 and 2006 measurements at El-Reno site.

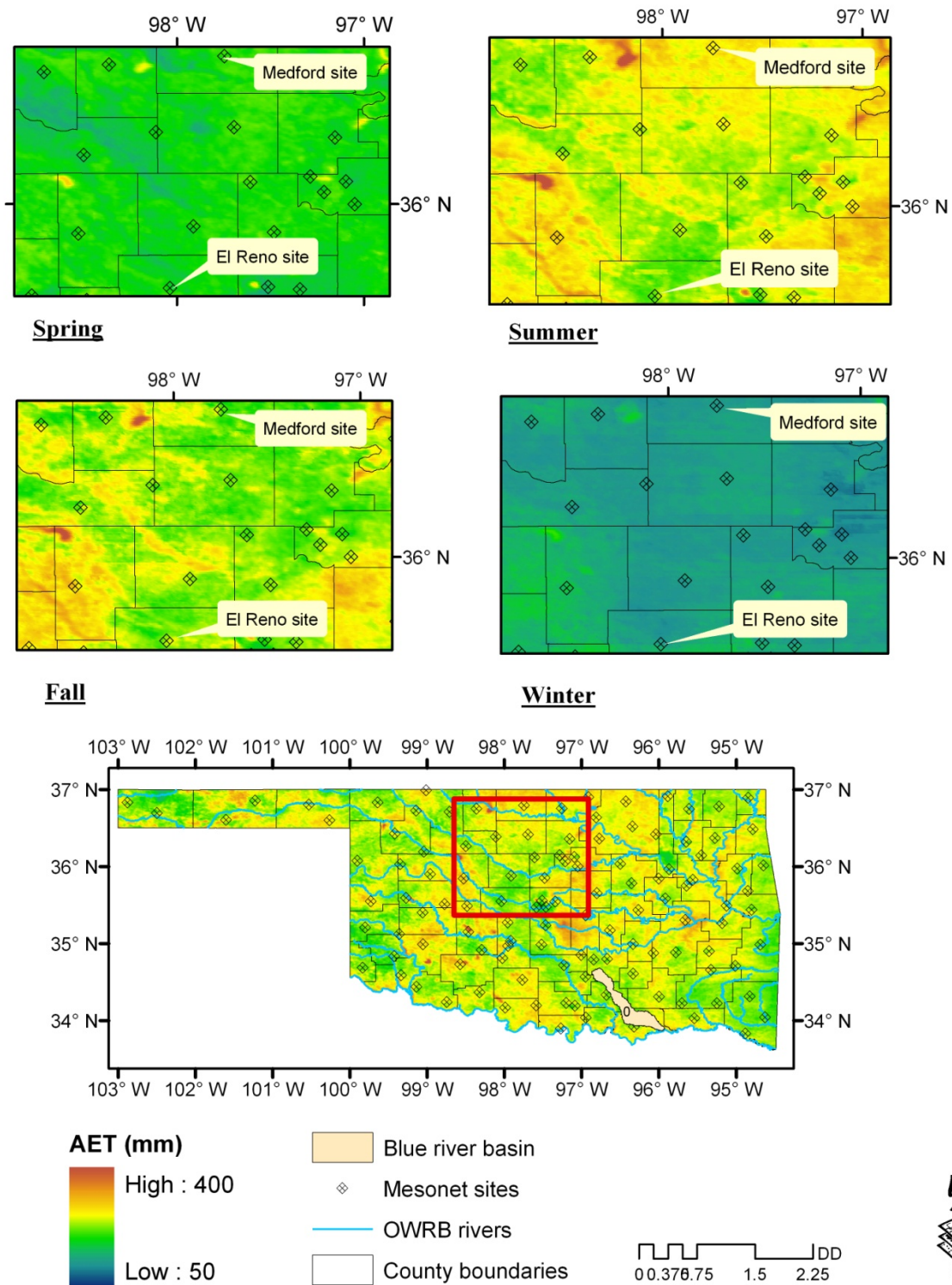


Figure 10: 2004 Seasonal Actual ET based on M/M with mesonet sites locations at Grant and Canadian Counties. The bottom panel shows the statewide summer ET.

5.4 Validation at Blue River Basin

In this study the water balance budgeted ET from a parallel study in the Blue River basin was used to compare the M/M-ET. Shown in Table 7, several hydro-meteorological records for the period 2004-2006 are collected to conduct water budget analysis for the basin. One fundamental assumption of the water balance analysis is that over a period of multiple years when the change in storage becomes relatively insignificant the ET can be assumed equal to the difference of the precipitation and runoff (Morton 1983). Pan evaporation observations were also incorporated to calculate the ET. Shown in Figure 12, monthly comparison between M/M-ET and water balance budget ET shows favorable agreement, with bias ratio less than 3% at the catchment scale.

Table 7: Data for Blue River Basin used for the Water Balance.

COMPONENT	DATA	Blue River near Connerville	
Precipitation (P)	Rainfall from radar, local bias corrected	Station (s)	Radar KTLX and the following Mesonet stations: Centrahoma, Tishomingo, Sulphur, Ada, Ardmore, Lane, Madill, Newport, and Pauls Valley
		Period	Jan 2004 – Dec 2006
Baseflow (Gw)	Derived from streamflow using the <i>PART</i> program	Station (s)	USGS 07332390
		Period	Jan 2004 – Dec 2006
Direct Runoff (R)	Streamflow daily time series, baseflow removed	Station (s)	USGS 07332390
		Period	Jan 2004 – Dec 2006
Potential Evapotranspiration (pET)	Monthly Pan Evaporation	Station (s)	Mesonet station
		Period	Jan 2004 – Dec 2006

We compared the spatially varied parameters used in the determination of actual ET such as NDVI and spatially averaged actual ET over Blue river basin for three years. As shown in Figure 13, it reconfirms a strong correlation of ET with vegetation indices in this mixed natural ecosystems and agricultural areas as previous studies (Seevers and Ottomann, 1994; Szilagyi, 2000, 2002; Nagler et al. 2005; Choudhury et al. 1994; Bausch, 1995; Hunsaker et al. 2003, 2005; Houborg and Soegaard, 2004; Senay et al. 2007). The existence of a clear spatial and temporal pattern in the NDVI-ET relationship may help define biophysical conditions prerequisite for the successful application of vegetation indices in basin-based water-balance modeling (Szilagyi, 2002).

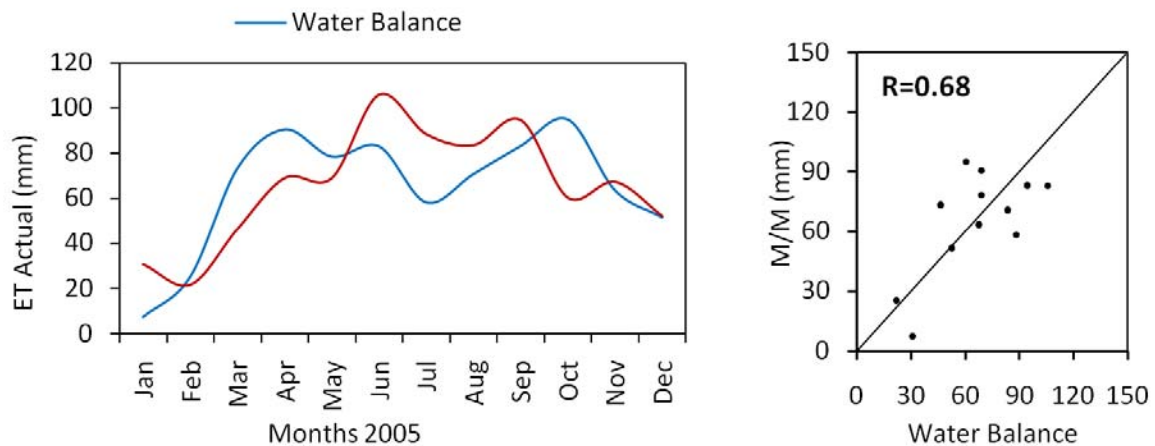


Figure 11: Comparison of the ET estimates from SSEB-based M/M –ET approach and Water-balance budget Analysis for 2005 monthly average at Blue River Basin (Bias ratio = 2.1%).

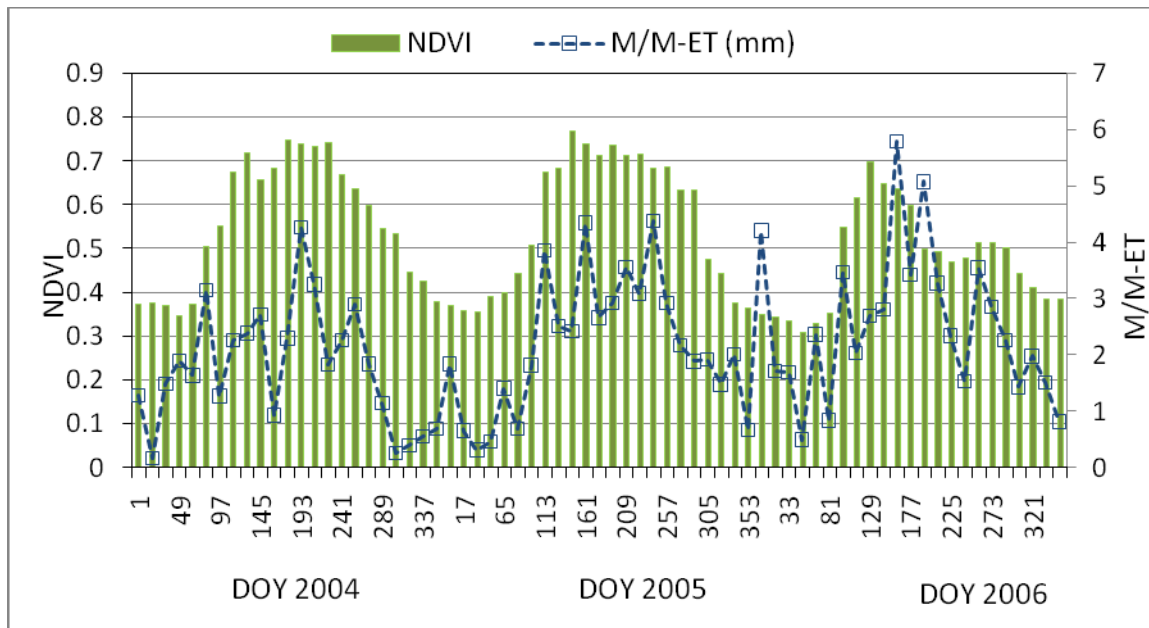


Figure 12: Temporal comparison of spatially averaged crop/vegetation index NDVI and actual ET estimates from SSEB approach over Blue river basin during 2004, 2005 and 2006 (Growing season typical has high NDVI and high actual ET; also noticeable dry year 2006 has less crop/vegetation but slightly higher actual ET due to sufficient supply from ground water).

6. Actual ET for two counties in Oklahoma:

Several ET estimation algorithms, including METRIC, have only been applied in the western U.S. (Idaho, California, and New Mexico) and have not been evaluated for the advective conditions of the great plain. Both the test beds (Texas and Tillman counties) (Table 8) have distinct characteristics of climate, soils, vegetation, geomorphology, and drainage types in contrast to the western US, thus, our M/M-ET algorithm has been calibrated by local surface observations in the Great Plain. During the calibration processes, several key surface energy balance components and processes were evaluated and improved by considering meteorological measurements and archived numerical weather model data.

Through this work we developed an improved ET estimation algorithm (i.e. M/M-ET) for applications in the Southern Great Plains and demonstrated in two counties in Oklahoma. Site details for these locations are listed in Table 8. The seasonal dynamics of Actual ET accumulated from daily at these two counties are show in the Figures 13 and 14.

Table 8: Oklahoma Mesonet Stations located in Texas and Tillman County

County	Location	Site #	Lat.	Long.	Elev.
Texas	Hooker	48	36° 51' 18" N	101° 13' 31" W	912m
Texas	Goodwell	41	36° 36' 6" N	101° 36' 4" W	997m
Tillman	Grandfield	117	34° 14' 21" N	98° 44' 39" W	341m
Tillman	Tipton	94	34° 26' 22" N	99° 8' 15" W	387m

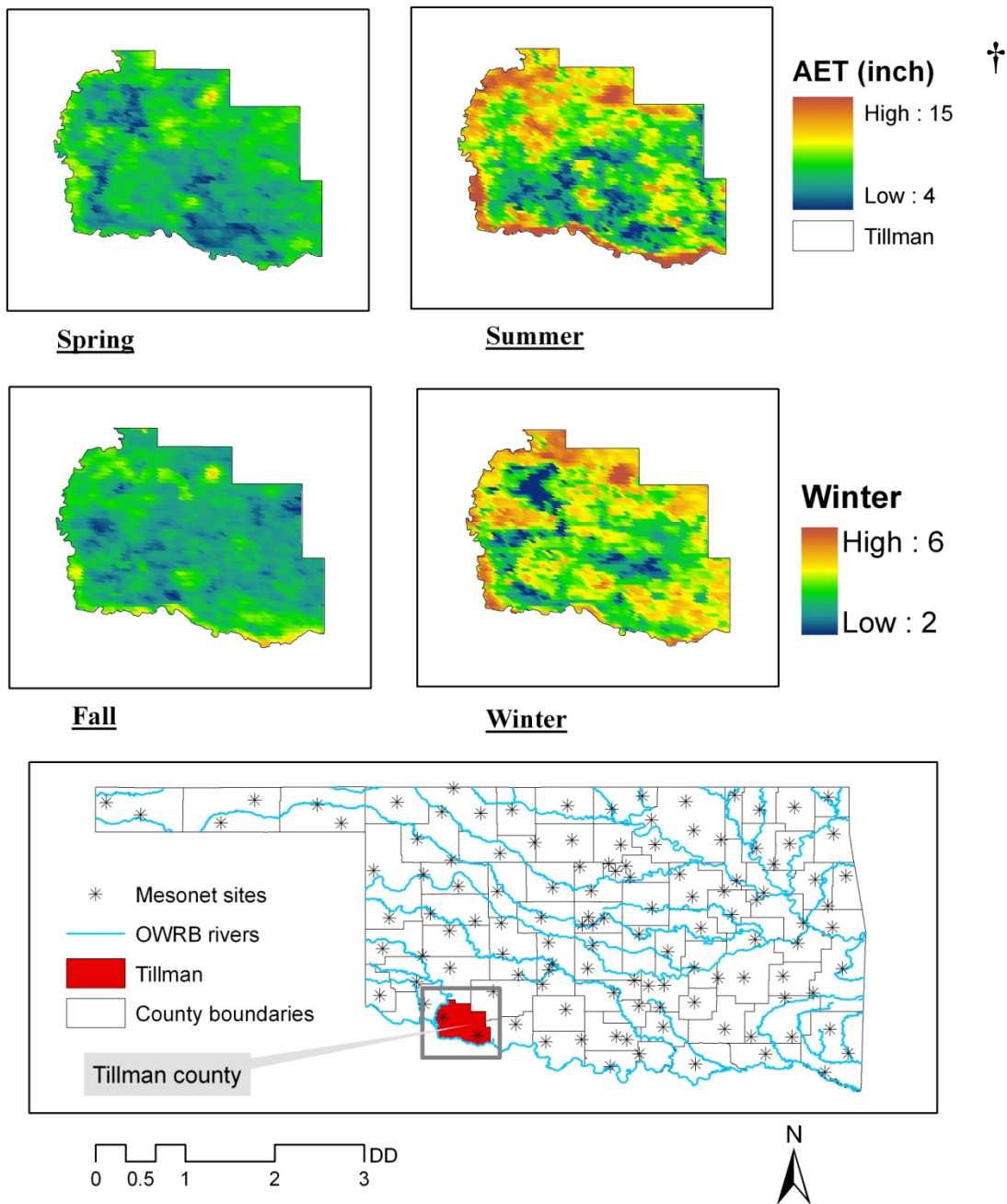


Figure 13: 2005 Seasonal Actual ET (inch) for Tillman County.

†. The 1st color scheme is for spring summer and fall and the 2nd one is for winter season.

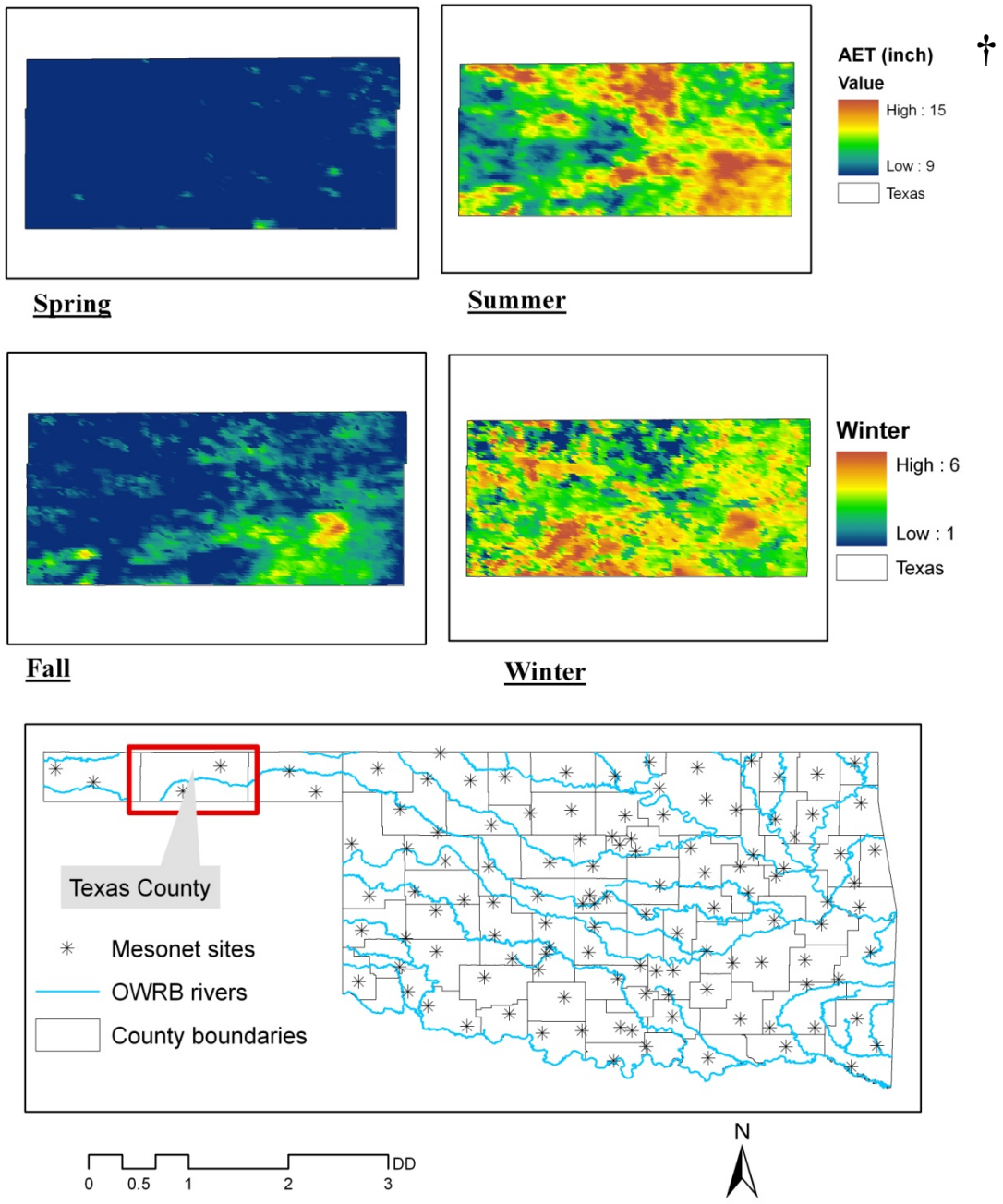


Figure 14: 2005 Seasonal Actual ET (inch) for Texas County

†. The 1st color scheme is for spring summer and fall and the 2nd one is for winter season.

7. Summary

In the past few years satellite remote sensing applications in actual ET estimation have opened frontiers in water management at local and regional scales. However previous applications have been retrospective in nature, in part because of the lack of timely availability of satellite images in relatively high spatiotemporal resolution. Furthermore, many ground observational networks do not provide data in real-time, so that the ET estimates, though useful in retrospective studies, cannot be used in real-time water management decision making (Tang et al., 2009). With the availability of the world-class environmental monitoring network from Mesonet (<http://mesonet.org>) at every 5-minute acquisition frequency, Oklahoma provides a unique setting to develop and apply a real-time ET estimation algorithm for timely water use and irrigation management. Therefore, the central objective of this study is to answer the question: is it possible to implement a real-time actual ET estimation algorithm in Oklahoma for daily operational water use management purpose?

In doing so, we first developed a surface-energy-balance ET estimation algorithm, M/M-ET, by integrating the daily open-access MODIS products and the Oklahoma's well-distributed quality-controlled Mesonet data (every 5-minute acquisition frequency) through a Modified METRIC method. A comprehensive evaluation of the M/M-ET estimates has been conducted on daily, 8-daily, and seasonal basis for multiple years (2004-2006) using AmeriFlux tower's latent flux observations, Mesonet in-situ crop ET database, and water-balance-model-derived catchment-scale ET. The results show that

M/M-ET estimation agrees with these ground observations, with daily ET bias less than **15%** and seasonal bias less than **8%**. Additionally, hydrological modeled actual ET in Blue River basin is also compared favorably with the M/M-ET at catchment and monthly scale (bias ratio < **3%**).

Results from this study demonstrate that (1) the calculated daily ET through the simplified surface-energy-balance approach (i.e. M/M-ET) is acceptable for actual ET estimation given its accuracy within the range (15%) reported by several studies around the world and (2) it is feasible to implement the proposed M/M-ET estimation algorithm at real-time rather than retrospective manner for operational irrigational water resources management in Oklahoma. This operational ET estimation system will be useful at the scale of irrigation projects, rather than individual fields. At the time of writing of this paper, the M/M-ET estimation algorithm is being implemented for entire Oklahoma State with a focus on growing season.

8. Future Work

Integration of the proposed ET scheme with a water balance model will enhance the estimation and validation of ET estimates derived from satellite. Coupling of the two approaches will afford the comparison of the estimated actual ET with computed soil moisture availability. The water balance and soil moisture module of Vflo will be coupled and operated independently of runoff generation for the test beds. As described in Vieux et al. (2006a, b), this model has been setup and evaluated for a range of climatic conditions and used to verify runoff, and indirectly, ET and soil moisture including locations across Oklahoma.

The theoretical basis for tracking soil moisture in *Vflo* is the Green and Ampt infiltration equation and a single-layer soil depth that relies on soil properties estimated from county-level soil survey maps. Infiltration rate and saturation excess runoff is computed in each grid cell as a function of soil properties and antecedent conditions. Once the soil moisture storage capacity is filled, then saturation excess runoff is computed. When the soil moisture is modeled over time, the infiltration rate is adjusted to account for a range of soil moisture. Impervious area and initial abstraction may be set to account for urbanization effects and ponding on the land surface. The rate of soil moisture depletion is limited by the climatologically ET rate and available soil moisture. A limitation of this approach is the knowledge of field-specific or even regional ET fluxes during a specific season, especially where irrigation water is applied to supplement soil moisture deficits.

Assimilation of actual ET into the model can be accomplished by updating time series input to *Vflo*. The computation will track the depletion of soil moisture through ET and replenishment by distributed radar rainfall input affects runoff volume and deep percolation/recharge for the testbed. Climatic controls, soil properties, and vegetative characteristics exert an effect on soil moisture and runoff that becomes apparent during simulations. Model tracking of the soil moisture state is performed efficiently by modifying potential or climatological ET (Vieux, 2004). The model can produce more reliable and site-specific results if ET estimated over each grid is available. The land surface characteristics affecting soil moisture are soil properties including depth, vegetative cover, and atmospheric forcing of ET. While potential ET is used by the model to estimate actual ET constrained by available soil moisture rainfall, a more direct approach can be planned for this proposed approach of using satellite-based ET estimates.

Future studies can utilize the available distributed rainfall derived from radar maps generated at hourly time steps in support of simulations during the year with focus on the growing season when irrigation is prevalent in the test bed areas.

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