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DEVELOPING A REFERENCE CROP EVAPOTRANSPIRATION CLIMATOLOGY FOR THE SOUTHEASTERN UNITED STATES USING THE FAO PENMAN-MONTEITH ESTIMATION TECHNIQUE

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1. INTRODUCTION

Evapotranspiration (ET) is a combination of evaporation and plant transpiration processes into a total moisture flux from the ground to the atmosphere. As a result, ET plays an integral role in environmental processes at global, regional, and local scales (Naoum et al. 2003). It is an important part of the water and energy balance on earth's surface.

Atmospheric factors influencing ET include not only availability of water and energy but also the gradient of vapor concentration and turbulence of the atmosphere (Oke 1987). Allen et al. 1998 describes three other factors that can affect ET, which are environmental conditions, crop factors, and management practices. Environmental conditions such as ground cover, density of plants, and soil water content play a role in the rate of ET. Crop factors such as crop type, variety, and stage of development can impact the rate of ET, especially for large, well-managed fields. Management practices such as type of cultivation and irrigation system can also influence this process.

ET affects many industries across the southeastern United States, such as agriculture and irrigation practices. In North Carolina, agriculture contributes an annual $71 billion to the economy, encompasses 19% of the state income, and employs over 16% of the work force (NCDA&CS 2008). In a 2002 study by NOAA, agriculture ranked to be the largest consumer of water in the United States. Across the southeastern US, the drought of 2007 was one of the worst on record (Brooks 2009). In recent years, water supply issues have become major economic and social concerns across the southeastern United States.

While ET is one approach to quantify water loss, observations are only available for a limited number of locations across the southeastern United States. Empirical models are usually used to estimate ET at local and regional scales. No estimation technique is universal, but a standard method is the Penman-Monteith equation as specified by the UN Food and Agriculture Organization (FAO) in 1998. Other simpler, temperature-based methods, such as Hargreaves 1985, require local calibration.

Internationally recognized as a standard, the FAO56 Penman-Monteith method estimates ET rates for a well-watered, actively growing reference surface based on physical atmospheric observations of solar radiation, temperature, wind speed, and relative humidity at a height of 2m. This estimate is commonly referred to as reference crop ET. The reference surface is a theoretical grass reference crop with a height of 0.12m, an albedo of 0.23, and a constant surface resistance of 70 s/m. While dependent on time of year and location, the equation is developed for the hypothetical grass reference crop and is thus independent of specific crop characteristics and soil factors. Only climatic variables influence the Penman-Monteith ET estimate. Crop coefficients can be applied to adjust the estimate for a particular crop (Allen et al. 1998).

By developing climatology of ET across the Southeast, this study explores spatial and temporal variability of average monthly total ET. Across the southeastern US, this research examines the sensitivity of ET to input parameters of the equation.

2. DATA AND METHODOLOGY

Quality-controlled hourly meteorological observations provided by the State Climate Office of North Carolina were used to model daily ET using FAO Penman-Monteith (equation 1). Estimation of ET requires input of daily average solar radiation, daily minimum and maximum temperature, daily average wind speed, daily minimum and maximum relative humidity, Julian day, latitude and longitude, and elevation for each monitoring location. All weather observations should be reported at the standard agrometeorology height of 2m (Allen et al. 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

The FAO-56 method utilizes mean temperature to compute the slope of saturation vapor pressure curve, Δ. The daily average solar radiation input is used to determine net radiation, R_n. On daily time scales, the soil heat flux, G, can be neglected (Allen et al. 1998). The psychrometric constant, γ, is computed from elevation. Mean daily air temperature, T, and daily average wind speed, u_2, are input parameters as shown in equation 1. Saturation vapor pressure, e_s, is a function of minimum and maximum temperature while actual vapor pressure, e_a, is computed from minimum and maximum temperature as well as minimum and maximum relative humidity. The saturation vapor pressure deficit is represented by the difference between saturation vapor pressure and actual vapor pressure, e_s - e_a.

A short-term climatology of reference crop ET for the southeastern United States is developed at daily and monthly time steps for 2002-2008. Across six states (Alabama, Florida, Georgia, North Carolina, South Carolina, Virginia) and five station networks (ASOS, AWOS, NC ECONET, RAWS, USCRN), spatial and temporal variability in ET are analyzed for all seasons. With 402 stations as the upper limit (Figure 1), the number of stations for which ET is calculated depends on internal quality control procedures, such as a minimum data requirement of five years for the daily and monthly climatology. It is important to note that since ASOS and AWOS stations do not measure incoming solar radiation, an estimate based on Hargreaves 1985 is used (equation 2). An empirical coefficient, k_{RS}, is utilized in this equation to adjust for proximity to water, with a value of 0.16 representing interior locations and a value of 0.19 signifying coastal locations (Allen et al. 1998). The Hargreaves 1985 estimate requires Julian day and latitude to compute extraterrestrial radiation, R_a. Diurnal temperature range, TD, is represented by the difference between maximum and minimum temperature, as shown in equation 2.

$$R_s = (k_{RS})(R_a)(TD)^{0.5} \quad (2)$$

To reduce noise in the short-term daily climatology, a 7-day moving average is used. Average monthly totals are computed across the region to develop the monthly climatology.

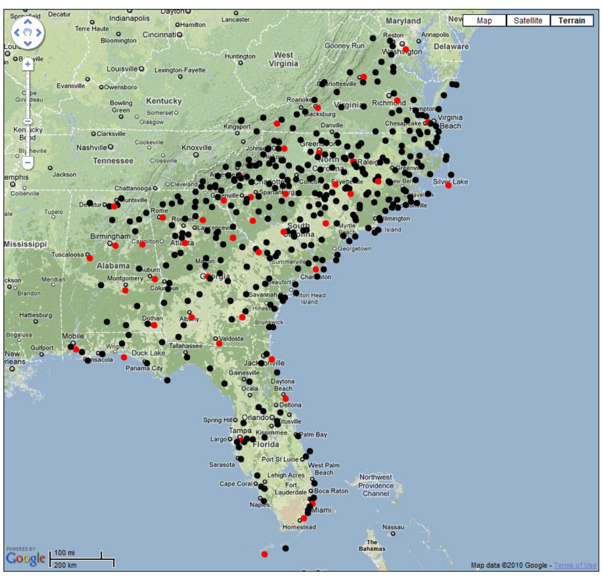

Figure 1. Five station networks across the Southeast, with stations of sensitivity study in red (one per climate division)

For one station in each climate division (Figure 1), a sensitivity study is performed on input parameters of the ET equation. Since all station types are ASOS or AWOS except one RAWS station type, in most cases an estimate of incoming solar radiation is used for the sensitivity study. This paper presents a case study for the month of July across all stations and all input parameters. Although the relationships are inherent to the ET equation, it is nonetheless important to determine this relationship. For each station and input parameter, all other inputs are constant while that parameter is varied. The sensitivity study explores how ET responds to a given parameter independent of all other variables in the equation. For parameters that are not varying, the 2002-2008 monthly averages serve as the constants.

3. RESULTS

Typical patterns of monthly average total ET during the winter and summer seasons are explored. Values in January are between about 30 to 90mm with highest values along the coast and in lower latitudes, such as Florida (Figure 2). During the winter season, defined bands appear across the region while the summer season shows no distinct pattern, as shown in Figure 3. Values during July are higher in magnitude, mainly ranging from about 110 mm to over 170 mm. In mountainous regions, average ET for July does not exceed 170mm. The lowest average ET for July across the southeastern US is 83.5mm, which corresponds with the highest elevation site of 5469 feet above sea level at Wayah Bald Mountain (WINE) in Franklin, NC.

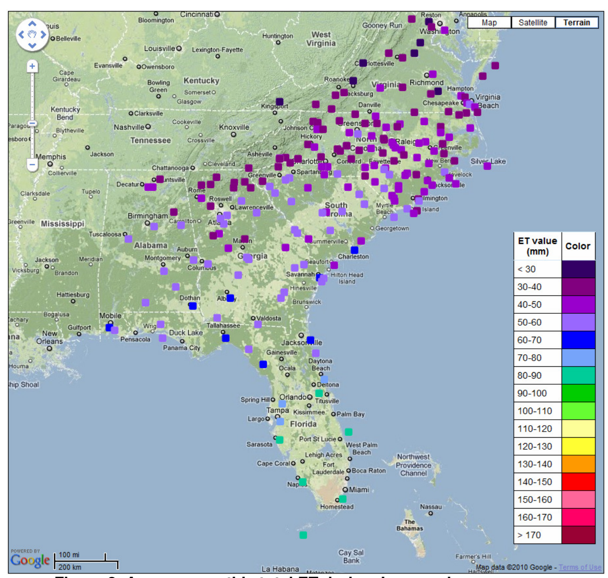

Figure 2. Average monthly total ET during January, in mm

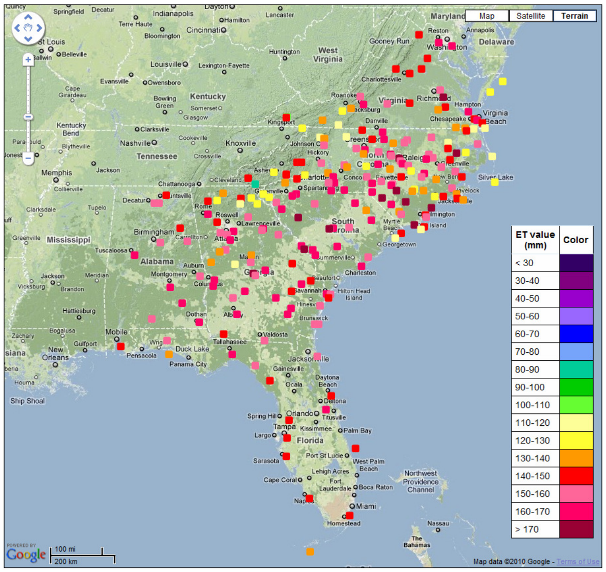

Figure 3. Average monthly total ET during July, in mm

Monthly mean values of average monthly total ET across all stations in the southeastern US are computed, as shown by the red line in Figure 4a. For a given month, the number of stations ranges from 148 to 255. Minimum monthly mean estimates occur during the winter season, with values between 50mm and 100mm. Monthly mean values peak during July at 149mm.

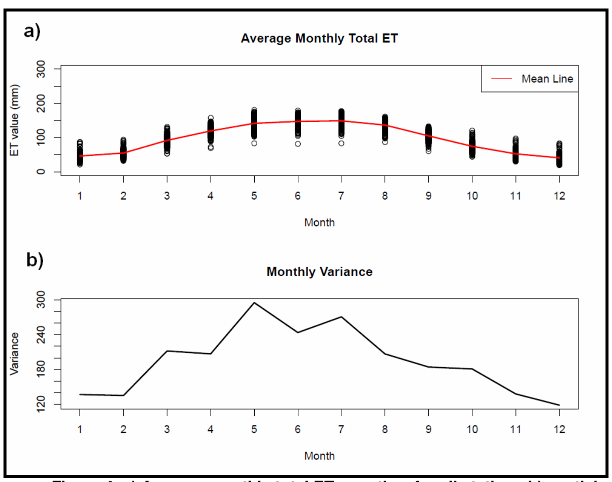

Figure 4. a) Average monthly total ET over time for all stations b) spatial variance of average monthly total ET over time (bottom)

The monthly variance of ET reaches a maximum value of 311mm during May, as shown in Figure 4b. Contrary to the hypothesis, winter months exhibit less variance in ET. The summer season is most likely more variable because localized convection is typical while during winter, mainly large scale synoptic systems affect the entire region.

Daily ET values, such as that of a typical summer day on August 12, 2009, signify conditions for one given day instead of average conditions (Figure 5). This particular date exemplifies the high variability during summer since a region of lower values in the western part of the Carolinas lies close to an area of higher values in southeastern Georgia. Lower values of ET indicate a cloudy region while higher values represent clear sky conditions.

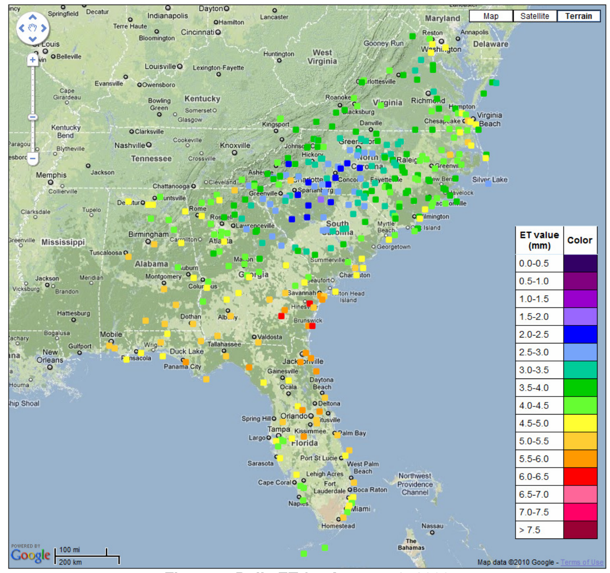

Figure 5. Daily ET for August 12, 2009

To study the sensitivity of ET to each input variable, monthly averages of these parameters are generated. Although this study only presents the results for July, other months demonstrate similar relationships yet have different magnitudes of ET. All stations are displayed in order to establish regional trends, as shown in Figure 6. A relationship is established between the response of ET to each varying input parameter, with all other input variables are held constant.

Across all stations, ET increases with higher values of maximum temperature. Similarly, a direct relationship exists between minimum temperature and ET yet with a more subtle upward trend. Higher temperature indicates more available energy for the process of ET. Minimum and maximum temperatures are varied between -15°C and 40°C in order to determine how ET responds to extreme values of temperature.

Higher values of average solar radiation yield higher ET rates. Assuming other variables are constant, a linear relationship exists among these two variables. Similar to temperature, solar radiation provides an energy source for the ET process.

An exponential and direct relationship exists between ET and average wind speed, with ET rates increasing as values of average wind speed rise. Wind speed advects any moist air away from the source region allowing for drier air to replace it. Drier air has a higher moisture deficit which increases likelihood of the ET process. Wind can also advect more heat energy to the region which enhances ET.

For all stations, the opposite trend occurs between maximum relative humidity and ET. With higher values of relative humidity, ET rates decrease due to a higher gradient of vapor concentration which results in a lower potential for ET. A similar indirect relationship occurs between minimum relative humidity and ET.

Based on the magnitude of the slope of each input parameter, critical inputs appear to be solar radiation and wind speed, as shown in Figure 6.

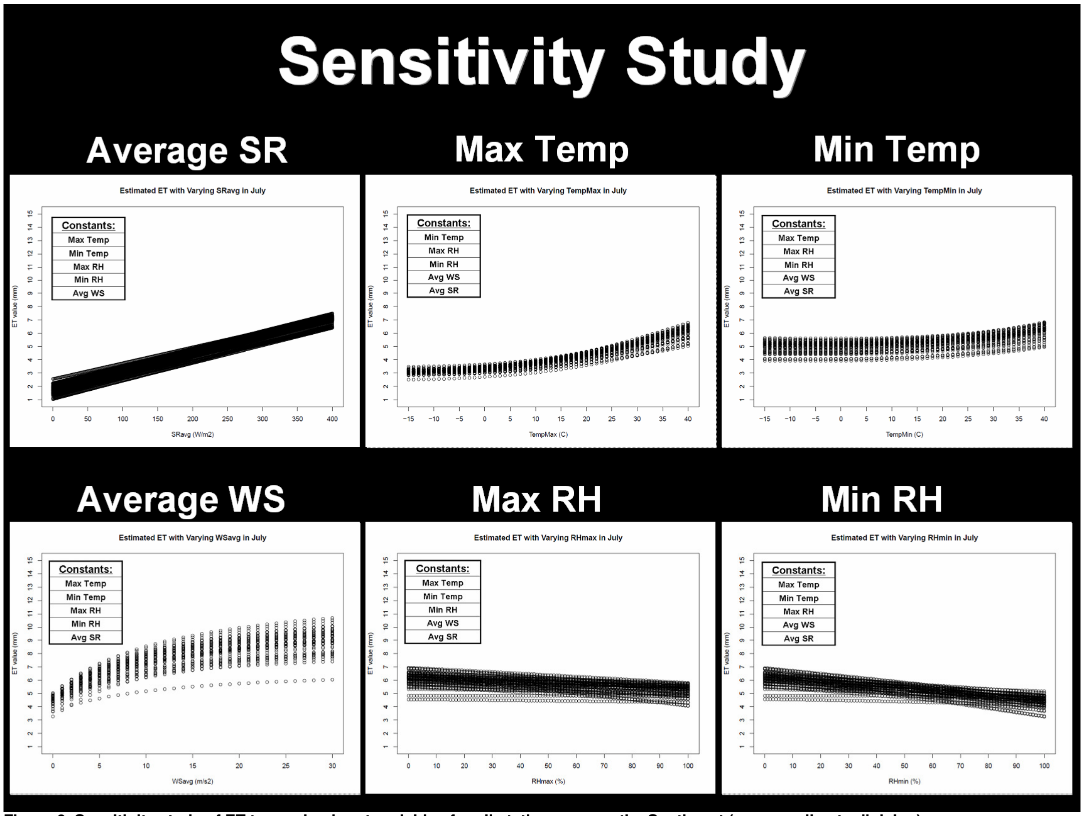

Figure 6. Sensitivity study of ET to varying input variables for all stations across the Southeast (one per climate division)

4. APPLICATION

One application of this research is a decision support tool which is mainly for purposes of crop management and irrigation planning. Using Google technology, map and chart displays are developed for public use.

Two products use Google Maps to display reference crop ET values estimated using the FAO56 Penman-Monteith method. One product is a daily ET estimate, which allows the user to select a date from January 1, 2002 to yesterday. The other product is a historical climate tool, which displays average monthly total and daily average ET values, both calculated over the 7-year period from 2002-2008. Users can choose to display an annual time series for a particular station.

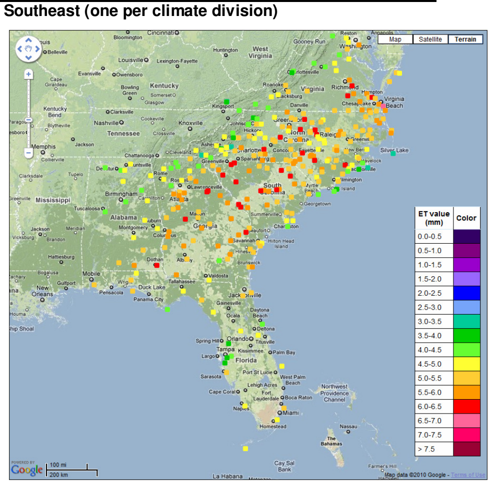

Figure 7. Penman-Monteith estimated total ET for August 5, 2009

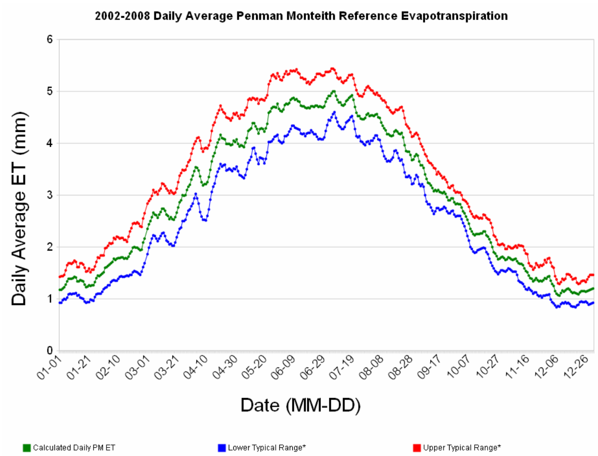

Figure 8. Annual time series of daily average ET at Pamlico Aquaculture Field Lab (AURO) in Aurora, NC using the Penman-Monteith method

For more information or to view this product, please visit http://www.nc-climate.ncsu.edu/et.

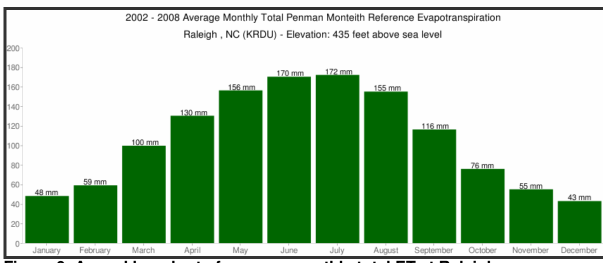

Figure 9. Annual bar chart of average monthly total ET at Raleigh-Durham Airport (KRDU) using the Penman-Monteith method

5. SUMMARY

Analysis of spatial and temporal ET patterns across the southeastern US from 2002-2008 reveal the highest variability during the summer season. This is most likely due to localized convection during summer while the winter season precipitation is mainly synoptic scale and affects the entire region.

Spatial and temporal trends led to an investigation of the driving mechanisms behind this equation. According to the sensitivity study on input parameters, solar radiation and wind speed are crucial variables in the Penman-Monteith ET equation.

6. ACKNOWLEDGEMENTS

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