

Remote Sensing of Evaporative Fraction in Big Cypress National Preserve: A Comparison of Methods

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Introduction

Evapotranspiration is an important component of the hydrologic cycle. The amount of water evaporated and transpired over the US land surface accounts for approximately 2/3 of the rainfall (Spellman, 2009). The variation of evapotranspiration (ET) can vary rather abruptly in space due to changes in surface wetness and land cover. It is infeasible to construct a surface based monitoring network that could resolve these variations. Therefore, even though remotely sensed solutions to mapping ET might not be as accurate, they have the advantage of being capable of describing patterns of ET in the landscape. A combination approach can be useful. Although the atmospheric boundary layer is too thin to be remotely sensed, surface flux measurements are able to incorporate boundary layer information into the land surface information acquired with remote sensing (Laymon and Quattrochi, 2004). Most approaches use an energy balance approach which incorporate surface temperature, SW and LW radiation and NDVI. Two very popular methods are the “residual method” such as SEBAL (Bastiaansena, et al., 1998) and the “triangle method” (Owen et al., 1998; Carlson, 2007). The basic principle is that the colder areas will have more ET due to evaporative cooling (given that the available energy is fairly constant across a scene). Typically the problem is broken up into determining the available energy (A) in the form of net radiation minus losses into the surface and the evaporative fraction (EF) of that energy allocated to ET. This is done because satellite measures a snapshot from which the EF can be measured. It is then typically assumed that snapshot EF equals daily EF during clear sky conditions (Llhome, 1999), and multiplied by the daily available energy to find daily ET.

This paper intends to compare 3 methods of varying complexity for creating EF maps. Using LANDSAT imagery and eddy flux weather stations two sites in Florida will be analyzed. The objective of this study is to determine the differences in these methods. If differences are not discovered for some methods it will be assumed that the simpler method will suffice. Where differences are found future work will need to determine whether uncertainties introduced by the complex model might outweigh the shortcomings of the simpler model. This will require validation which can be difficult due to the scarcity of tower flux data along with the need to calibrate the ET retrievals using tower flux data.

Methods

Method 1 (Triangle Method)

The implementation of the Triangle method as described in (Jiang et al., 2009) is used. In this method $EF = EF_{cold} (T_{hot} - T_s) / (T_{hot} - T_{cold})$. T_{hot} and T_{cold} are found by plotting NDVI vs. T and finding the hot and cold limits of T. First the warm edge is found which follows the warm side of a given NDVI. The cold and hot limits are found where this warm edge intersects NDVI = 1 and

0. EF_{cold} is approximated by setting it equal to $\phi_{max} \Delta / \Delta + \gamma$ where $\phi_{max} = 1.26$, $\Delta(T)$ is the slope of saturation vapor pressure w.r.t. temperature and γ is the psychometric constant.

Method 2 (EF Calibration Method)

This is similar to method 1 except that the method 2 uses surface weather station flux data in order to find EF_{cold} . T_{cold} is found by averaging T from satellite image over a 1 km footprint surrounding the tower. EF is assumed to be zero at some other hot dry pixel in the image. NDVI and NDWI can be used to confirm the pixel is not green and not wet. $EF = a + b T$ is assumed and a straight line is fit using ordinary least squares regression. In order to find EF for the tower the relationship, $EF = E / (E + H)$ is used where E is latent heat flux, H is sensible heat flux. The advantage that this method has over triangle method is that it is calibrated using surface flux data hence the name.

Method 3 (H Calibration Method)

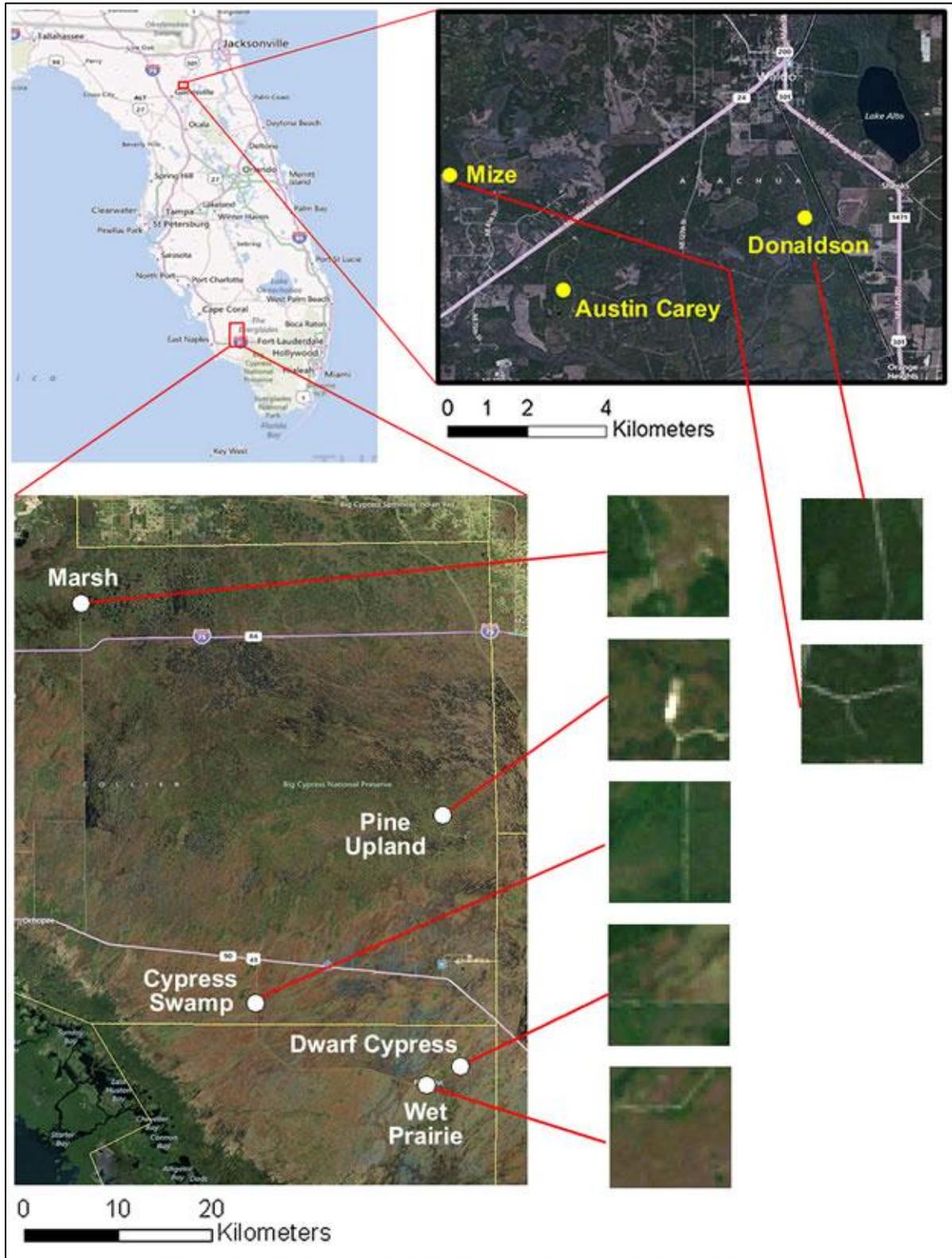
This method is basically the residual method assuming surface roughness is constant. The residual method uses $E = A - H$ or $EF = 1 - H/A$ where $H = g_A (T - T_A)$. g_A is the atmospheric conductance which depends on wind speed u_A at top of the surface boundary layer, the stability of the atmosphere, the depth of the surface boundary layer, and the roughness of the surface. T_A is the temperature at the top of surface boundary layer. The top of surface boundary layer varies but is on the order of 100 m in the middle of the day. It is assumed that the atmosphere at this height varies much more gradually in space compared to the surface so that u_A and T_A can be assumed to be constant over reasonable spatial extents (Foken, 2008a). In reality surface roughness varies in space, but for simplicity it will be assumed constant in the proposed method so that $H = a + b T$. H measured from the tower is not used because it can be notoriously inaccurate. The best working solution at the time is to assume $EF = E/(E+H)$ is more reliable (Foken, 2008b). In addition it is desirable to calculate $H = (1 - EF_{tower}) * A_{satellite}$ because systematic errors in $A_{satellite}$ will tend to cancel. Also $H = A_{satellite}$ for the hot spots so it would not be good to combine satellite sources and surface sources of energy when fitting relationship. $A_{satellite}$ is estimated using SEBAL method as outlined in (Kosa, 2011). $R_{net} = (1 - \alpha) R_{solar} + R_{LW down} - R_{LW up}$ and $A_{satellite} = R_{net} - G$ where G is the ground flux calculated using $G/R_{net} = (T - 273) (0.0038 + 0.0074 \alpha) (1 - 0.98NDVI^4)$ (Bastiaanssen, 2000). The advantage method 3 has over the others is that it accounts for variability of available energy but the disadvantage is the uncertainty in calculating available energy.

Study Areas and Data

There are 2 study areas analyzed in this paper as shown in Figure 1. The first area is a 12 km x 10 km area in the vicinity of Waldo, FL in northern Florida near Gainesville while the second is 60 km x 80 km area located in the Big Cypress National Preserve in southern Florida. The Waldo, FL area consists of pine plantations while Big Cypress National Preserve consists of wetter environments such as marsh, wet prairie, and cypress swamps.

Data for this study comes from eddy flux towers and LANDSAT satellite imagery. For the Waldo area, 30 minute average sensible and latent heat flux data was provided via the AmeriFlux network. AmeriFlux is a network of flux data freely available to the public for download at

Figure 1: Study Areas in Big Cypress, FL and Waldo, FL



Source: Author

<http://ameriflux.ornl.gov/>. Only data from the Mize and Donaldson stations were used because Austin Carey did not provide reliable data for our time period. In Big Cypress, the USGS recorded sensible and latent heat fluxes from 10/10/2007 to 10/11/2010 for 5 locations as shown in Figure 1 (1 km square foot prints surrounding the 5 towers are also shown in Figure 1). Although it would be desirable to have 30 minute averages of the sensible and latent heat flux, only daily averages are released from the USGS at this time. AmeriFlux data for Mize, FL station showed daily averages of evaporative fraction (EF) to be +/- 0.1 during 4/18/2008 to 4/23/2008 during clear sky days.

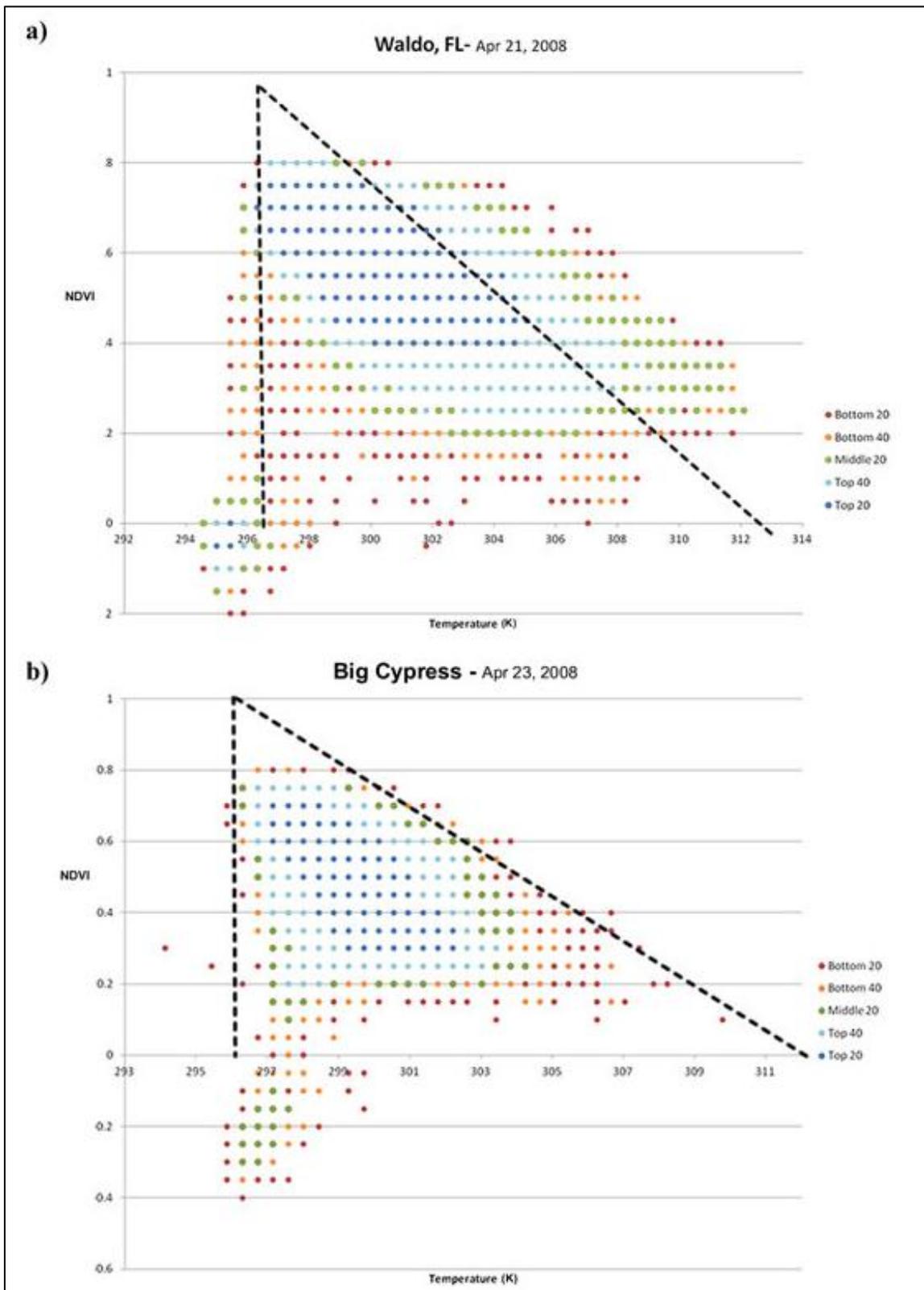
LANDSAT TM 5 imagery was used in this study. It consists of 7 bands: blue, green, red, Near IR, SW IR, Thermal IR and Middle IR 2. The thermal band (which provides temperature) has 120 m spatial resolution while the other 6 have 30 m resolution. For Waldo, FL, one Cloud free LANDSAT image on 4/21/2008 at 3:50 PM for WRS path 17 and row 39 was obtained. For Big Cypress five cloud free LANDSAT images were acquired for 4/23/2008, 10/3/2009, 10/19/2009 and 2/8/2010 at 3:40 PM for WRS path 15 and row 42.

Results and Discussion

Using the triangle method to build a relationship between EF and T left a lot to interpretation. Determining the “warm edge” was done “by eye” while taking into account where the majority of the pixels were represented. The color of each point on Figure 2 represents which percentile the number of pixels with that NDVI / Temperature pair belongs to. Big Cypress on 4/23/2008 followed a triangle pattern more so than Waldo on 4/21/2008 which looked more like a trapezoid. The trapezoid pattern demonstrates the existence of water-stressed vegetation since it has high NDVI but is warmer than wetter vegetation (Moran et al., 1994). There are very noticeable differences the EF to T relationship for method 1 vs. the method 2 in Figure 3. Method 1 overestimates the cold EF as to be expected since it was chosen to simply be the maximum Priestly Taylor EF. For the Big Cypress scenes this approximation is closer than for Waldo because Big Cypress is a wetter environment. Another noticeable difference is that Waldo is warmer than Big Cypress for the same EF using method 1, but it is colder using the method 2. All of this results in method 1 consistently overestimating EF when mapped.

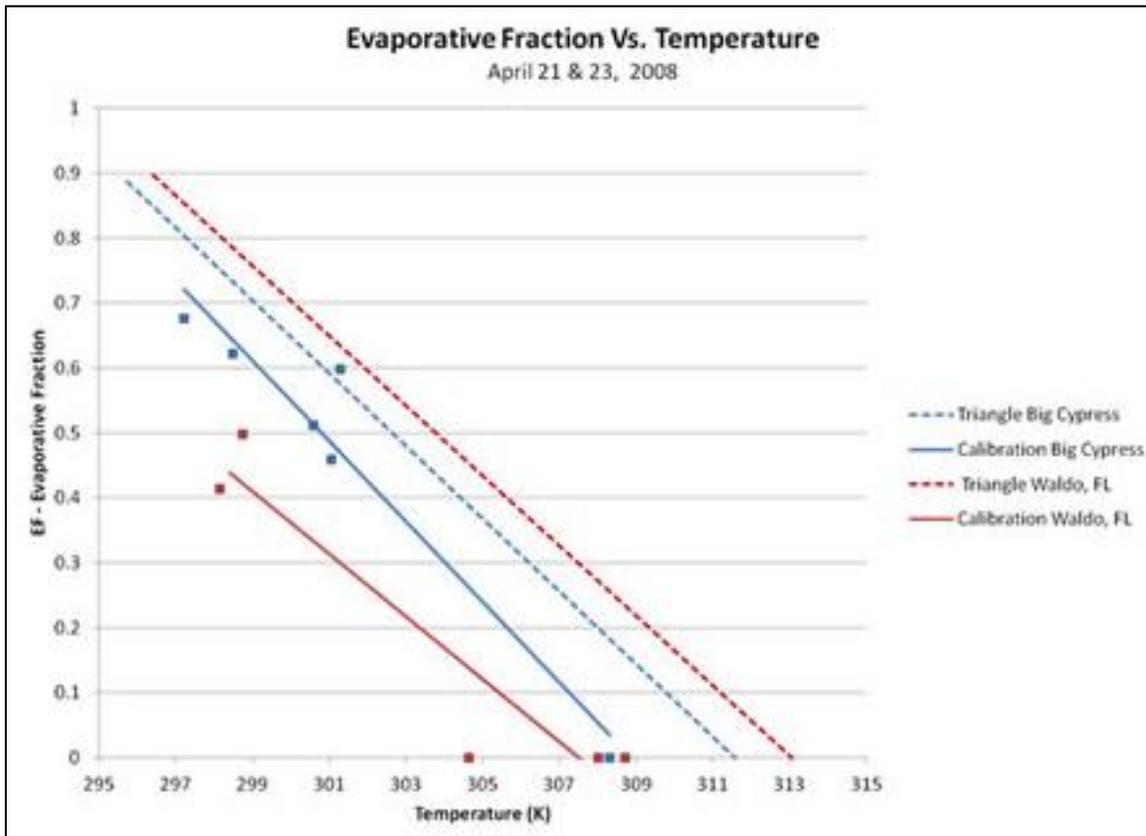
Looking at Figure 4a and 4b offers insight into methods 2 and 3. The Big Cypress sites make a good linear fit in Figure 4a except for the wet prairie site. The deviance of the wet prairie site could possibly be explained by looking at the 1 km footprint in Figure 1. It is noticeable that the northern part of footprint is greener than southern part. The eddy flux tower measures what is happening upwind of the tower, therefore if the wind was from the north, the EF would be higher than would be expected because the 1 km footprint average temperature included brown dry areas to the south. The marsh could be experiencing the opposite effect since the EF is drier than expected and has some dry areas to the north. For Waldo, Mize had a higher EF than Donaldson but similar footprint temperatures. The footprint effect can't explain this since both appear to be homogenous slash pine stands. For Waldo 3 hot spots were used in order to demonstrate one of the drawbacks of method 2. Looking at NDWI confirmed that the hot spots were dry and EF was close to zero, but there is a large variation in T for EF=0. This is due to variation in the albedo with higher albedo surfaces being cooler. Figure 4b reveals method 3 greatly reducing the scatter of the hot spots since it accounts for the variation of albedo. The Big Cypress towers became more scattered possibly due to uncertainties added when calculating the available energy,

Figure 2: Triangle Plots for a) Waldo, FL on 4/21/2008 and Big Cypress, FL on 4/23/2008



Source: Author

Figure 3: Comparison of Method 1 versus Method 2



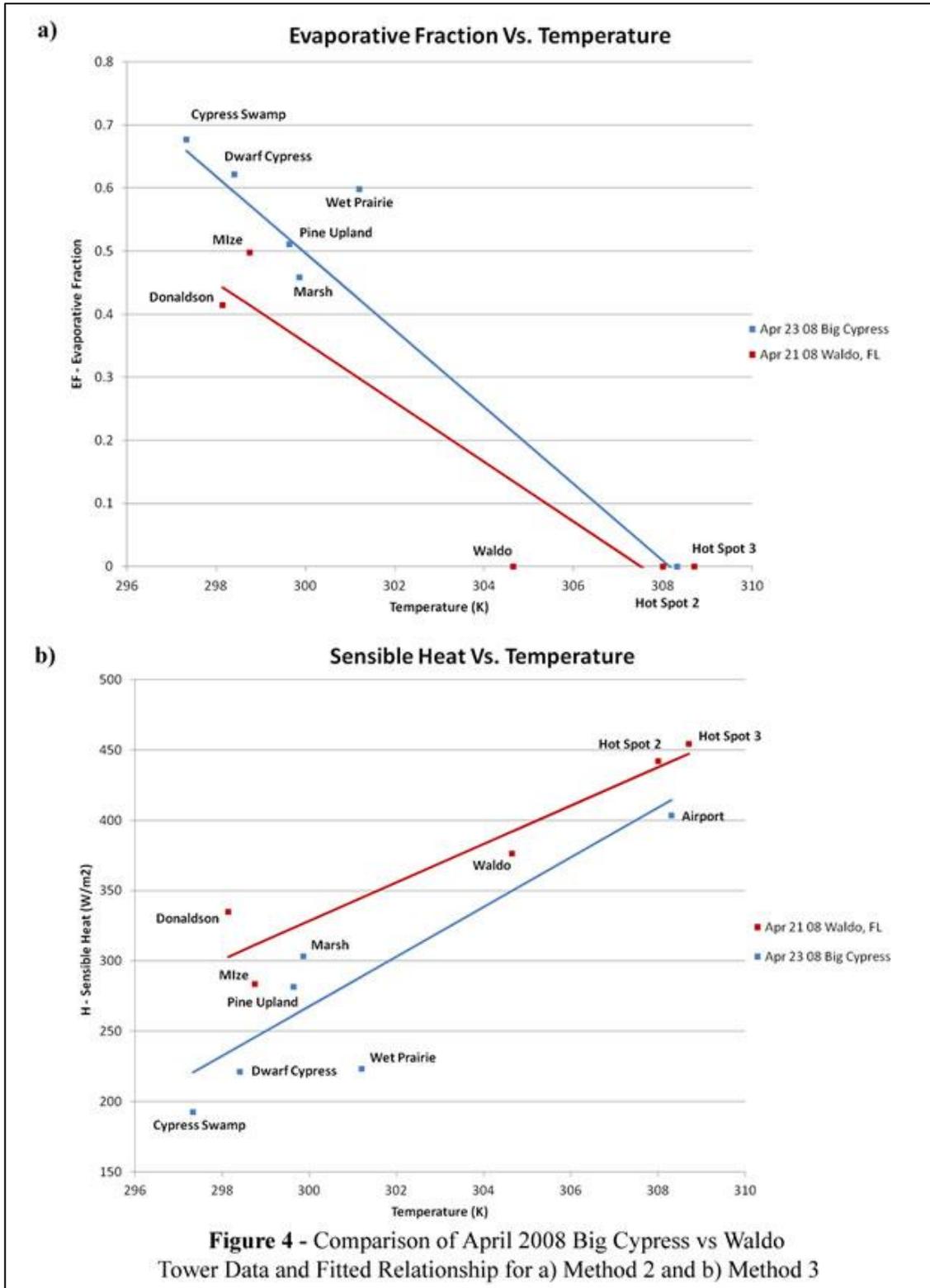
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especially the ground heat flux (or water heat flux). This was calculated from an empirical relationship with parameters that were not derived in the area of interest. For an area as unique as the Big Cypress, a locally derived relationship would be more desirable.

Table 1 reports the R2 and standard error for method 2 and 3 using all tower stations but also shows results of fits when some stations were omitted. Omitting wet prairie on 4/23/2008 increased R2 from 0.906/0.744 to 0.988/0.884 for method 2 / method 3. On 10/3/2009 omitting marsh changed R2 from 0.831/0.696 to 0.989/0.958. Omitting marsh and wet prairie 2/5/2010 changed R2 from 0.356/0.052 to 0.890/0.692. The marsh scene was wayward twice, possibly since it is so far away from the other sites and EF and H only varies linearly with T for a localized spatial extent. Along with the footprint effect, the isolation of this point could also cause problems.

It is rare to find consecutive clear sky LANDSAT images over south Florida therefore analyzing the Oct 3 and Oct 19 of 2009 images is valuable. Unless there was a large rain event, it can be assumed that the moisture levels have not changed too much, so that atmospheric changes can be analyzed. Figure 5a and 5b compare the relationship between EF and T and H and T respectively. It is noticeable that the temperatures of the hot spot and sites became colder for Oct 19. The available energy only reduced by less than 5% which would lead to only about 1 K

Figure 4: Comparison of April 2008 Big Cypress vs. Waldo Tower Data and Fitted Relationship for a) Method 2 and b) Method 3



Source: Author

Table 1: Linear Relationship Formed Using Methods 1, 2 and 3

Method 1						
Area	Date	EF _{cold}	a	b	T _{cold}	T _{hot}
Big Cypress	4/23/2008	0.887	17.43	-0.0559	295.7	311.6
Big Cypress	10/3/2009	0.896	25.79	-0.0840	296.4	307.0
Big Cypress	10/19/2009	0.837	23.13	-0.0763	292.4	303.3
Big Cypress	2/8/2010	0.749	20.02	-0.0672	287.0	298.1
Gainesville	4/21/2008	0.896	16.84	-0.0538	296.4	313.1

Method 2						
Area	Date	Omission	a	b	R ²	Std Error
Big Cypress	4/23/2008	None	18.52	-0.0600	0.906	0.0691
Big Cypress	4/23/2008	Wet Prairie	18.77	-0.0609	0.988	0.0262
Big Cypress	10/3/2009	None	19.55	-0.0638	0.831	0.0913
Big Cypress	10/3/2009	Marsh	23.76	-0.0778	0.989	0.0257
Big Cypress	10/19/2009	None	27.17	-0.0905	0.633	0.1722
Big Cypress	10/19/2009	Dwarf Cypress	20.85	-0.0693	0.778	0.0955
Big Cypress	2/8/2010	None	15.73	-0.0528	0.356	0.1609
Big Cypress	2/8/2010	Marsh/Wet Prairie	22.38	-0.0756	0.890	0.0621
Gainesville	4/21/2008	None	14.81	-0.0482	0.882	0.0706

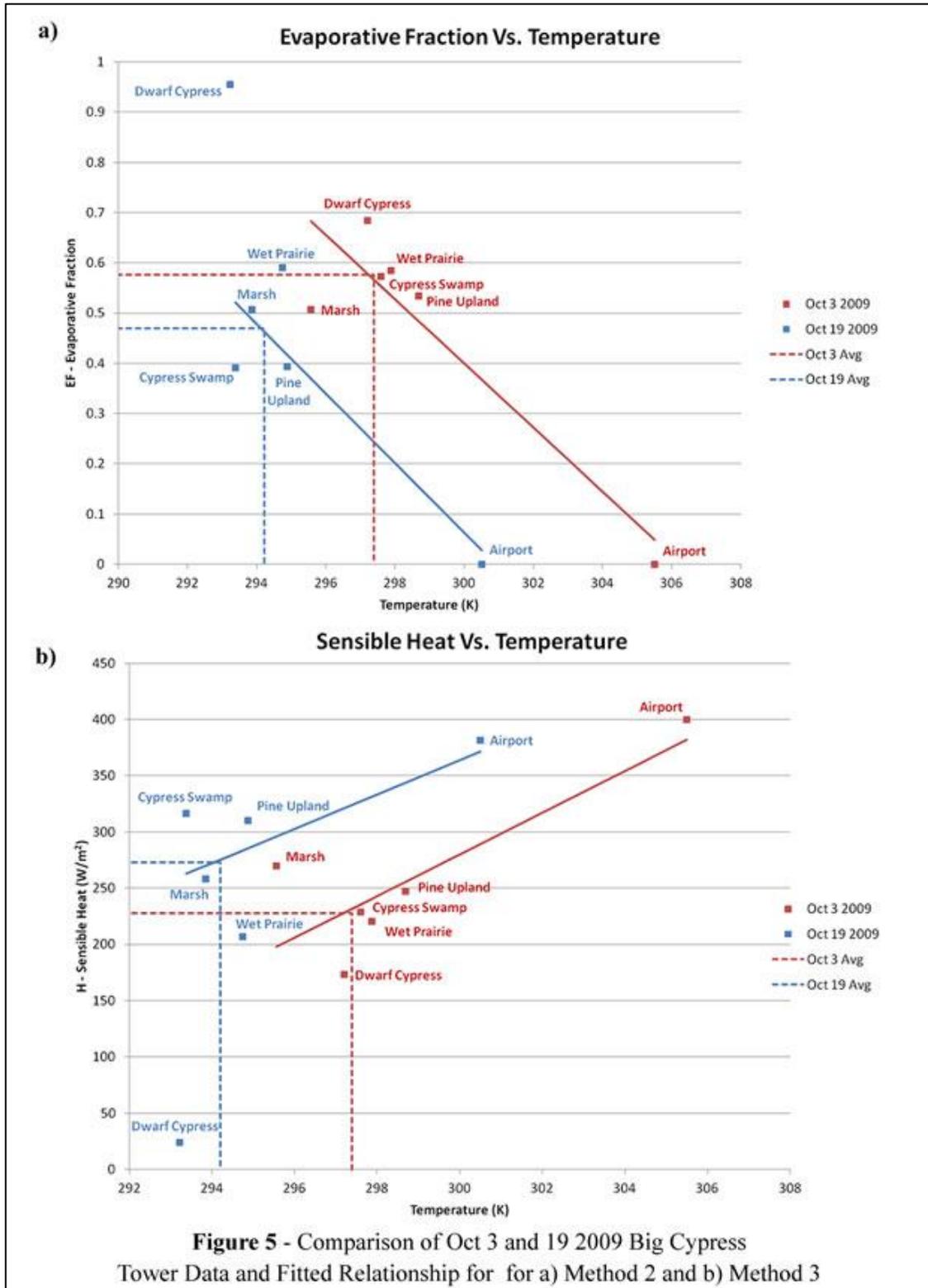
Method 3						
Area	Date	Omission	a	b	R ²	Std Error
Big Cypress	4/23/2008	None	-4928.2	17.28	0.774	33.41
Big Cypress	4/23/2008	Wet Prairie	-5023.1	17.64	0.884	24.96
Big Cypress	10/3/2009	None	-5281.7	18.54	0.696	38.84
Big Cypress	10/3/2009	Marsh	-7005.7	24.25	0.958	15.72
Big Cypress	10/19/2009	None	-7747.0	27.10	0.350	92.23
Big Cypress	10/19/2009	Dwarf Cypress	-4207.2	15.24	0.445	43.87
Big Cypress	2/8/2010	None	-1552.7	6.24	0.052	60.44
Big Cypress	2/8/2010	Marsh/Wet Prairie	-4319.2	15.73	0.692	24.52
Gainesville	4/21/2008	None	-3817.9	13.82	0.899	18.70

Source: Author

temperature change but there is 5 K cooling. Since $H = gA (T - T_A)$, the shift in the Oct 19 line to the left means that the temperature of mix layer has cooled. Since the two lines are close to parallel it means the atmospheric conductance gA is fairly constant. Another interesting point is that the average EF has reduced as shown by the dashed lines on Figure 5a because the lower temperature reduced the ET. Also the temperatures of the wet areas do not reduce as much as the dry hot spots since energy previously allocated to ET is used to warm the surface a bit.

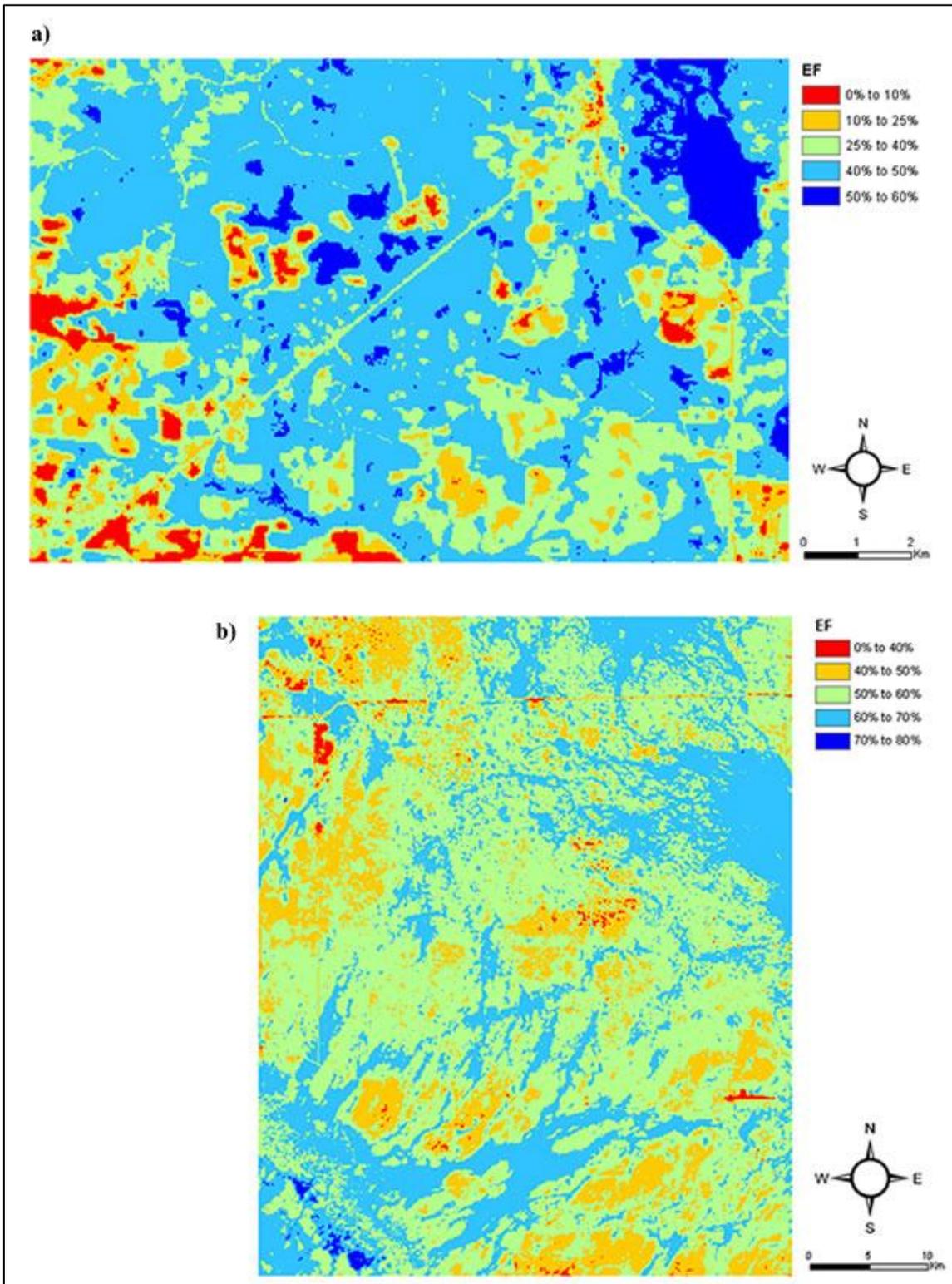
Figure 6a and 6b shows EF maps for Waldo on 4/21/2008 and Big Cypress on 4/23/2008 computed using method 3. As expected the Waldo area has less EF on average, but a much

Figure 5: Comparison of October 3 and 19 2009 for Big Cypress Tower Data and Fitted Relationship for a) Method 2 and b) Method 3



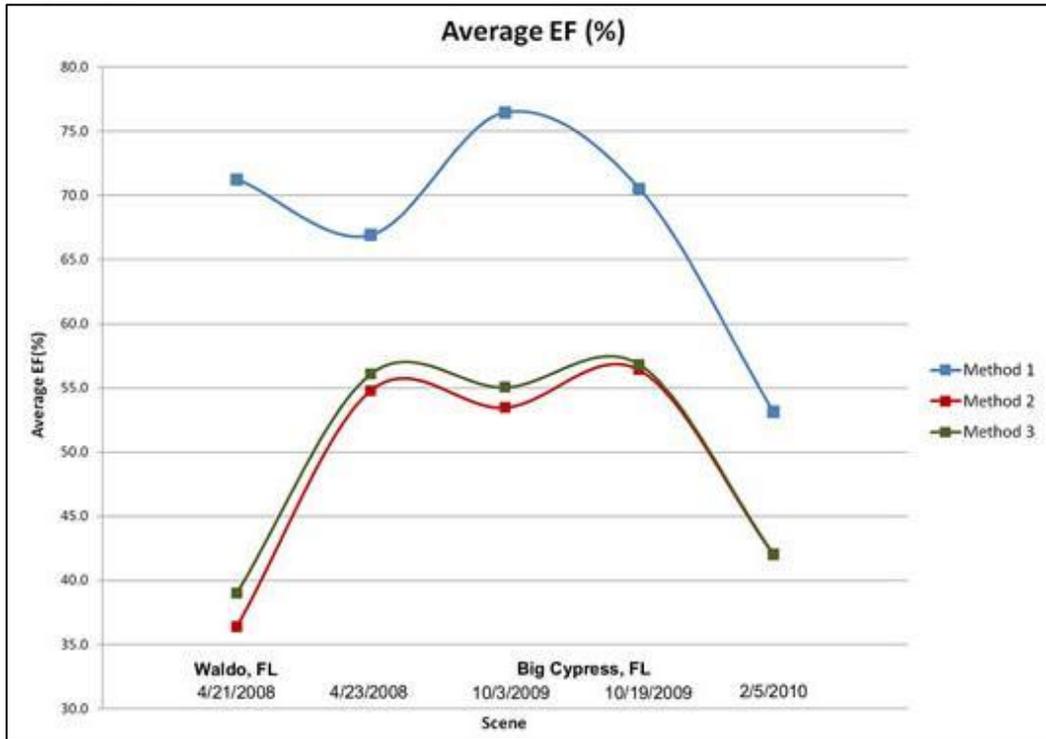
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Figure 6: EF maps for a) Waldo, FL on 4/21/2008 and b) Big Cypress on 4/23/2008



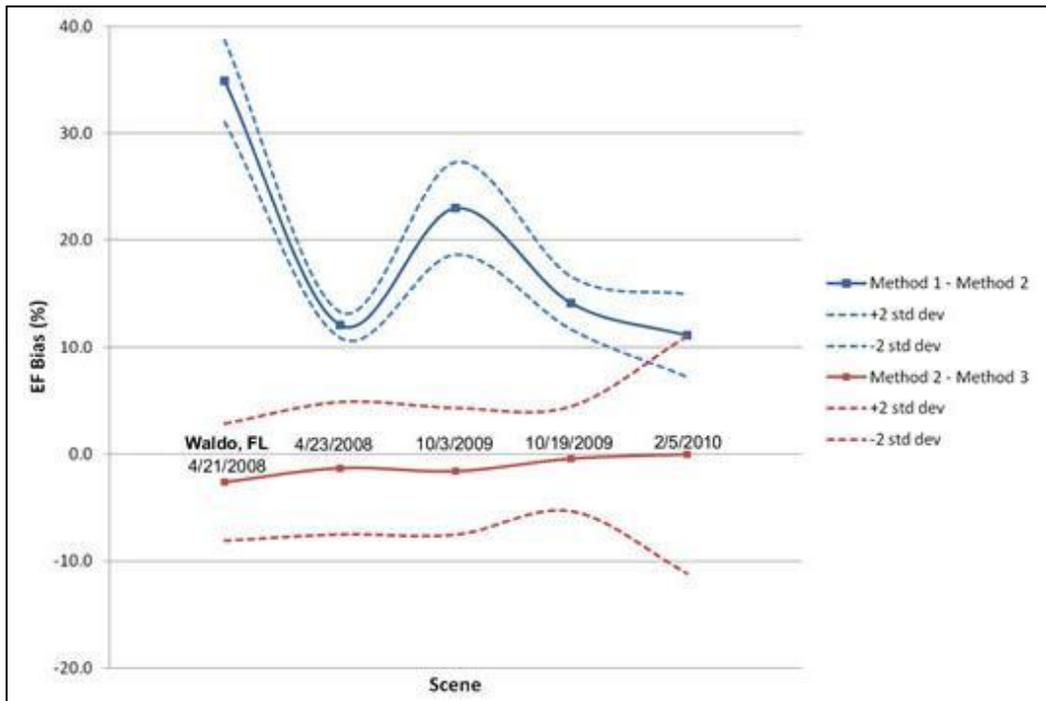
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Figure 7a: Average EF for Waldo and Big Cypress



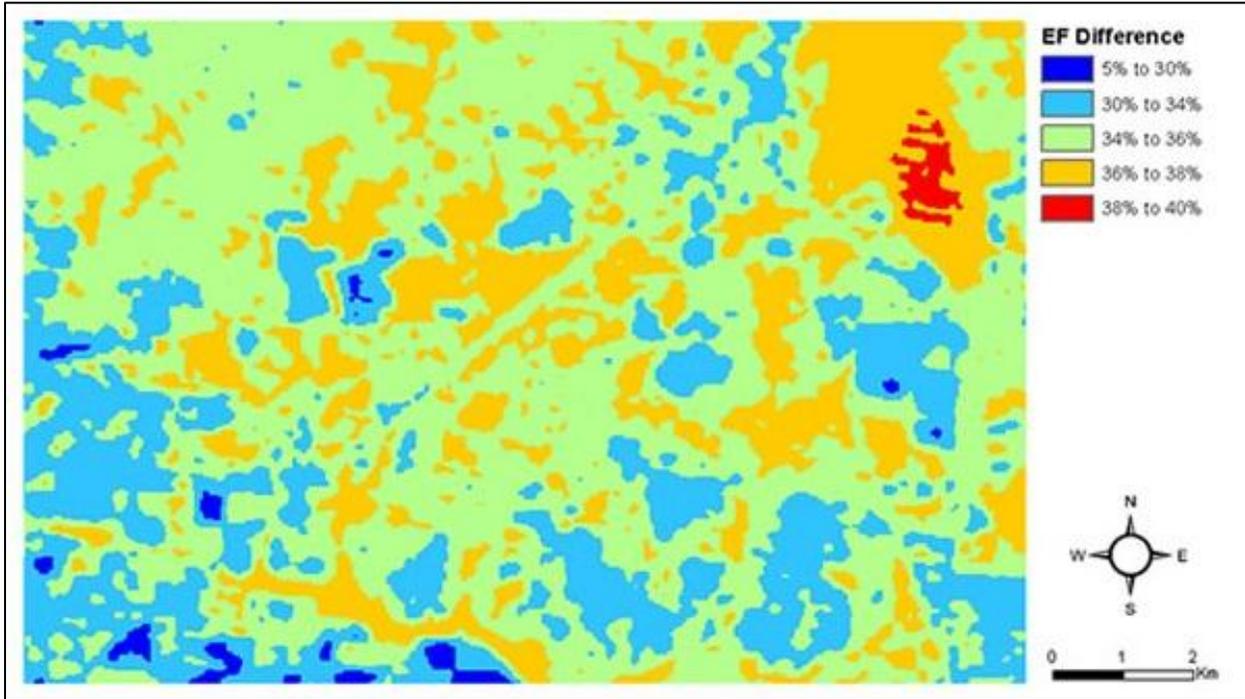
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Figure 7b: Bias and Standard Deviation between Methods



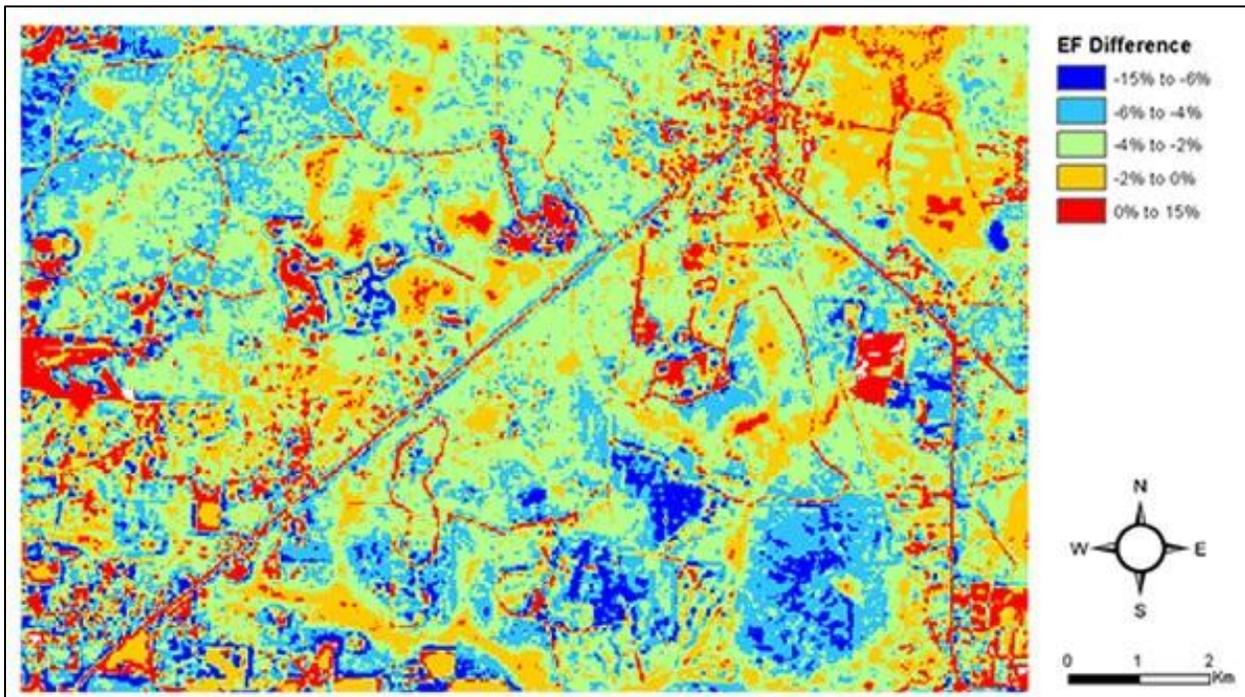
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Figure 8a: Method 1 minus Method 2 for Waldo, FL on 4/21/2008



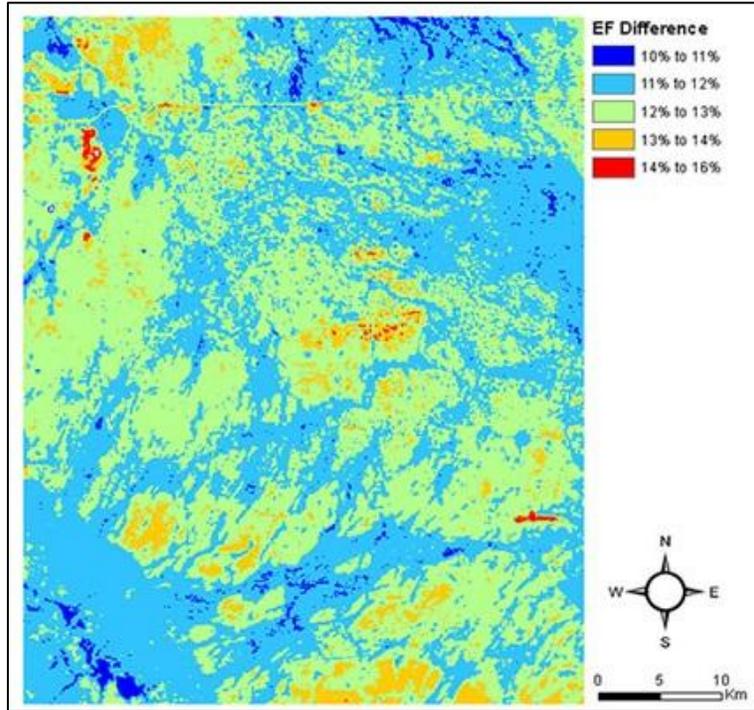
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Figure 8b: Method 2 minus Method 3 for Waldo, FL on 4/21/2008



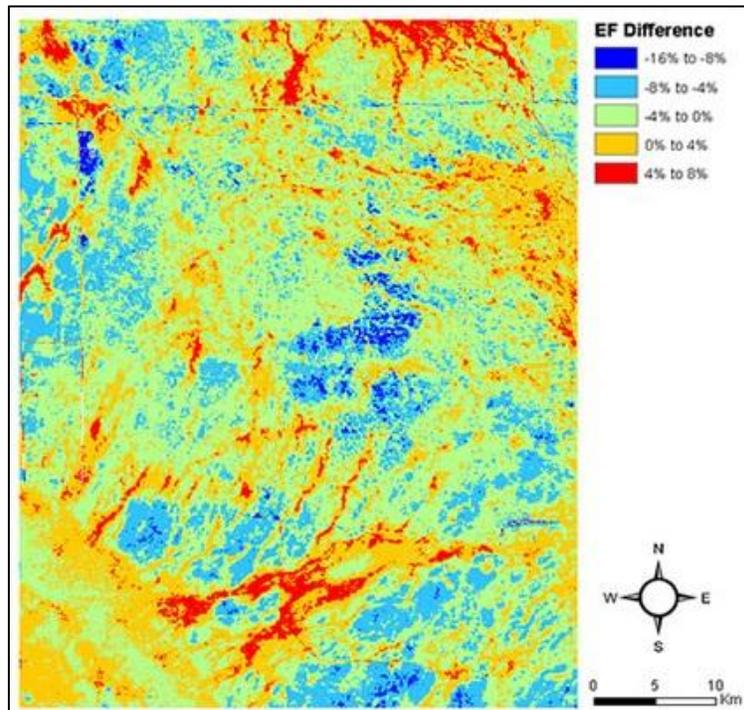
Source: Author

Figure 9a: Method 1 minus Method 2 for Big Cypress on 4/23/2008



Source: Author

Figure 9b: Method 2 minus Method 3 for Big Cypress on 4/23/2008



Source: Author

greater variation in EF because Big Cypress area is consistently wetter than human dominated areas around Waldo (mean = 39% vs. 56% and standard deviation = 11 % vs. 6%). In Big Cypress most areas have EF > 40% while for Waldo there is a mixture of cleared and vegetated areas. A large part of Big Cypress has EF > 60% while 60% is the limit of EF in Waldo. Fig 7a shows the variation in average EF over the various scenes for the 3 methods. This figure clearly shows the overestimation of EF using method 1. Method 2 and 3 produce an average EF that is very similar to each other. Since method 1 chose the maximum EF in an arbitrary fashion, methods 2 and 3 should be considered more reliable since they use ground measurements. Additionally, the variation in EF with scene makes more sense for method 2 and 3 vs. method 1. For example, method 1 predicts that Big Cypress has less EF on average compared to Waldo. Figure 7b reveals not only the bias or mean difference between the methods but also the variation of the differences. As expected, the bias between method 1 and 2 is high, but interestingly the bias between method 2 and 3 is low. Also interesting is that the variation in differences between method 2 and 3 is much larger than method 1 and 2. This can easily be explained by remembering that the only difference between method 1 and 2 is the choice of slope and intercept in the $EF = a + b T$ relationship. But method 3 accounts for variability of energy via albedo and ground flux which increases the variance of method 2 minus method 3. Also method 2 both overestimates and underestimates method 3 results.

It is important to understand where the overestimation and underestimation is occurring, so the differences between methods are shown in Figures 8 and 9. Figure 8a shows that for Waldo method 1 minus method 2 errors are greater in the wetter regions. Figure 8b which compares method 2 and method 3 is a bit more complex. In this map some dry areas overestimate while some underestimate depending on albedo. On the other end the lake is overestimated by method 2 but the vegetated areas are moderately underestimated and shown in green or orange. Most of the areas are underestimated on average which is evident in the bias = -2.6. Another interesting feature is the difference in resolution apparent on the maps. This is because method 1 and 2 only used temperature from the satellite which has 120 m resolution, but method 3 includes albedo and ground heat flux which uses bands 1-5 and 7 which have 30 m resolution. Figure 9a and 9b show a more balance variation for Big Cypress. For method 1 minus 2 the dry areas are now overestimated more. For method 2 minus 3 the wet areas are overestimated and drier areas are only underestimated. The difference here is that the dry areas in the Big Cypress are not really “dry” in the sense that they are cleared like Waldo.

Conclusions

Method 1 is clearly inconsistent and therefore method 2 or 3 should be chosen instead. Method 3 does not require any additional data compared to method 2 but it does require extra calculation. Determining whether the advantage of accounting for variations in available energy would offset the uncertainty of the calculation would require some type of validation data. The first step in determining why some sites did not follow the linear relationships would be to apply footprint modeling to create a weighted average over the footprint that accounts for wind direction and buoyancy of air (Korman and Meixner, 2001; Kim, et al., 2010). Next, method 3 should be conducted where ground flux is neglected or varied. Also allowable spatial extent must be examined. In reality the coefficients a and b should vary in space but finding this variation is difficult due to lack of data. Lastly, it should be determined how many hot spots should be used and possibly automate finding them.

It would also be very useful to introduce a Method 4 which is a variation of Method 3 which accounts for the variation of roughness length. In that case the vertical temperature gradient in boundary layer (equal to sensible heat divided by atmospheric conductance) would be assumed linear function of surface temperature. This would account for the cooling that is due to increased roughness of surface opposed to mistaking that for evaporative cooling. This is the standard procedure with SEBAL/METRIC, but it can be very difficult to estimate roughness length.

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