Annotated Bibliography on Accuracy of Evapotranspiration (ET) achievable from Landsat Thermal Infrared (TIR) and Required Spatial Resolution

REFEREED PUBLICATIONS

Accuracy of evapotranspiration achievable from Landsat TIR

1. Bastiaanssen, W.G., R. Chavez, A. Alsulaimain and M. Ahmad. 2007. Estimation of groundwater extraction on irrigated lands in arid zones from thermal infrared satellites. ***J. GeoHydrology***. (in press)
http://www.kimberly.uidaho.edu/water/papers/remote/J_GeoHydrology_2007_Bastiaanssen.pdf

"…overall accuracy of ET from SEBAL for single-day events and for scale of the order of 100 ha is +/- 15%. The seasonal differences are smaller (1 to 5%) due to reduction in the random error component. On occasion, the energy balance closure error is 15% or more (e.g. Baldocchi et al., 2000). The deviation on a daily basis is typically 1 to 13%, while for seasonal values the deviation is – without parameter tweaking – typically 5% or less. The higher accuracy for accumulated ET values can be explained by cancelling of the random errors that prevails during individual satellite flyover days. These random errors are caused by semi-empirical relationships that are imbedded in the SEBAL model. "

Table 1: Validation of SEBAL predictions of actual ET for irrigated crops at plot and supra-plot scale (from Bastiaanssen et al. 2007). ***(note by Allen: most of these applications were made using Landsat including Landsat thermal)***

Location	Scheme	Crop types	Field instruments	Validation duration	Year of eval.	ET meas. (mm)	ET SEBAL (mm)	Diff. (%)
Idaho, USA	Montpelier, USDA research station	Native sedge forage crop	Lysimeter	season	1985	388	405	+4
Idaho, USA	Kimberly, USDA research station	sugarbeet	Lysimeter	season	1989	716	702	-2
Castilla La Mancha, Spain	Barrax	maize	Eddy covariance	2 days	1991	10.2	10.1	-1
Gansu, China	Yangtse Oasis, Hei Basin	maize	Eddy covariance	1 day	1990	6.5	7.1	+9
Menemen, Turkey	Gediz Delta	cotton	Sigma-T	2 days	1999	7.8	6.8	-13
Menemen, Turkey	Gediz Basin	grapes, cotton, fruit trees	Scintillometer	2 days	1999	6.9	6.5	-6
France	Alpilles	wheat	Bowen ratio	4 days	1996	inst	inst	3
Morroco	Marrakech	olives	Scintillometer	season	2003	na	na	11
Rechna Doab, Pakistan	Pindi Bhattian	wheat	Bowen-ratio	season	2001	570	626	+10
Rechna Doab, Pakistan	Faisalabad	cotton-wheat	Bowen-ratio	annual	2001	992	1010	+2

Sonora State, Mexico	Yaqui Valley	wheat	Eddy covariance	season	2000	417	410	-2
Sri Lanka	Habantota	rice	Scintillometer	month	2000	107	108	0
California, USA	Fresno County, San Joaquin	peaches	Lysimeter	season	2002	1097	1021	-7
California, USA	Fresno County	alfalfa	Lysimeter	season	2002	1144	1168	+2
California, USA	Kern County, San Joaquin	almonds	Neutron probes	season	2002	838	843	+1
AVERAGE								4.9

2. Bastiaanssen , W.G.M., E.J.M. Noordman , H. Pelgrum, G. Davids, B.P. Thoreson and R.G. Allen. 2005. SEBAL model with remotely sensed data to improve water resources management under actual field conditions. *J. Irrig. and Drain. Engrg,* ASCE 131(1):85-93. http://www.kimberly.uidaho.edu/water/papers/remote/ASCE_JIDE_2005_Bastiaanssen et al_p85.pdf

"For a range of soil wetness and plant community conditions, the typical ***accuracy at field scale is 85% for 1 day and it increases to 95% on a seasonal basis****. The accuracy of annual ET of large watersheds was found to be 96% on average. SEBAL has been applied in more than 30 countries worldwide, and the 26 research studies that were conducted over the past 10 years are now gradually being replaced by application studies (17 studies finished).*

"SEBAL computes the sensible heat flux H in an alternative way, i.e., the so-called "self-calibration" procedure*. First, H is estimated at extreme dry (H~Rn−G) and wet locations (H~0), which are manually identified by the user on the image. This eliminates the need to install expensive in situ equipment to measure H. Then, by model inversion, a temperature difference dT that is required to match the range of H in given turbulent conditions is obtained for these two extreme dry and wet locations."*

Need for <= 120 m thermal pixel size for comparing ET with ground measurements:

3. Kustas, W. P., Anderson, M.C., French, A.N., Vickers, D. Using a remote sensing field experiment to investigate flux-footprint relations and flux sampling distributions for tower and aircraft-based observations. Advances in Water Resources. 29:355-368. 2006. http://www.kimberly.uidaho.edu/water/papers/remote/Adv_Wat_Res_2006_Kustas_et_al.pdf

The capability to assess the effects of model and flux measurement resolution and contributing source areas on flux distributions (pdfs) can provide a means to evaluate differences caused by a mismatch in model output resolution and the sampling area and resolution associated with the flux observations.

With a high-resolution remote sensing based energy balance model such as DisALEXI, fluxes from these patches of strong discontinuities capable of producing boundary layer scale atmospheric eddies can be mapped and analyzed

The capability of evaluating the impact of source area and model and measurement resolutions on *flux distributions provides very useful information for locating a network of tower measurements and[remote sensing] flight lines which can provide flux distributions similar to what is likely to exist over a particular landscape. In addition, this approach can also provide some insight to the effects of model and flux measurement resolution on the flux distributions being represented. Thus, the tower network does not appear to be sampling a full range of fluxes present in this landscape.*

(and thus the need for remote sensing-based energy balance to extend inadequate ground-based sampling over larger areas)

4. Tasumi, M., R. G. Allen, R. Trezza, J. L. Wright. 2005. Satellite-based energy balance to assess within-population variance of crop coefficient curves, *J. Irrig. and Drain. Engrg,* ASCE 131(1):94-109.
   http://www.kimberly.uidaho.edu/water/papers/remote/ASCE_JIDE_2005_Tasumi et al_p94.pdf

   "The 180 x 140 m lysimeter[1] research field was smaller than the minimum requirement of 240 x 240 m that would ensure at least one 120 x120 m thermal pixel of Landsat 5 to reside completely inside the field for all images. For this reason, the satellite observed surface temperatures for pixels over the lysimeter field were occasionally impacted by portions of pixels lying over adjacent plots having dissimilar field conditions and temperature.

   "The predicted K_c[2] by the EB model agreed well with the lysimeter measured values throughout the course of the growing season as the sugar beet field progressed from bare soil to full cover. Overall, the absolute difference between the EB model and lysimeter-derived Kc values averaged 0.05 with the exclusion of the three heavily contaminated dates for the thermal band pixel as noted previously.

   Ability to View Individual Fields
   "Characteristics of Kc and Vegetation Indices were sampled for 3,888 Classified Fields. Theoretically, a minimum field size of 240 x 240 m is required to ensure that at least one 120 m thermal pixel exists that is purely from the field area. The typical field sizes in the study area are on the order of 400 x 400 m–800 x 800 m. Therefore, the resolutions of the Landsat based ET images are fine enough to permit quantification of ET from most individual agricultural fields by sampling interiors of fields. Minor fields having sizes less than 400 x 400 m were rejected and were not used for the analysis."

Impact of bias in surface temperature (T_s) measurements:

5. Tasumi, M., R. Trezza , R.G. Allen and J. L. Wright. 2005. Operational aspects of satellite-based energy balance models for irrigated crops in the semi-arid U.S. *J. Irrigation and Drainage Systems.* 19:355-376.

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[1] A lysimeter is an automatically weighed container suspended with the top at ground level, where changes in weight over time are translated into depth of evapotranspiration.
[2] K_c is the 'crop coefficient', defined as the ratio of ET / ET_{ref}, where ET is the evapotranspiration from any particular location (pixel) and ET_{ref} is the reference, or potential ET, calculated from weather data. ET_{ref} generally is defined to represent ET from clipped, cool-season grass or from 0.5 m tall alfalfa. K_c is an ET index that is relatively stable from day to day.

http://www.kimberly.uidaho.edu/water/papers/remote/JIDS_2005_p355-376 tasumi et al.pdf

"Under southern Idaho summer conditions, uncorrected Ts had almost the same value as the corrected Ts for the cooler surfaces (at around 290 K), but was 5 Kelvin lower (underestimated) for hotter surfaces in the 320–330K range. Interestingly, this "bias" in Ts did not impact the ET estimation as shown in Figure 7 (right) because the automated, internal calibration of the "a + b Ts" relationship in SEBAL and METRIC eliminated the impacts of the linear temperature bias.

"The estimation biases in Ts and α transfer little impact to ET because the internal calibration procedure largely eliminates the biases. The SEBAL-type internal calibration procedure calibrates the energy balance at the two extreme pixels (cold and hot pixels) and determines the intensity of needed corrections at the extreme pixels."

From citation 3 above:

"Sensitivity studies with ALEXI have shown that the air temperature calculated at the blending height adjusts to instrumental biases in the surface radiometric temperature measurement, preserving the relationship between the observed temporal change in surface temperature and modeled heat flux-ABL evolution."

6. Allen, R.G., M.Tasumi, A.T. Morse, and R. Trezza. 2005. A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. *J. Irrigation and Drainage Systems.* 19:251-268.

http://www.kimberly.uidaho.edu/water/papers/remote/JIDS_2005_p251-268 allen et al.pdf

"In the Idaho applications, we have exclusively used Landsat imagery. The attractiveness of Landsat is the high resolution (30 m in the visible and near infrared bands and 60 to 120 m in the thermal band) so that ET from individual fields can be observed. Field-scale ET is very important for water rights regulation where proof of water consumption on a field by field basis is often required. Field-scale ET also permits using METRIC to define new crop coefficients for an area."

Benefits of frequent return times and multiple Landsat systems

"ET images were created for 12 dates during year 2000 and were integrated over the March–October period (Figure 3). Interpolation between image dates was done using ET_rF[3] from pixels of each image and multiplying these by ET_r computed for each day between images. A closeup of ET for an area of primarily center-pivot irrigated fields is shown in Figure 4 for a single satellite date. Images were purchased from both Landsat 5 and Landsat 7 archives to increase the number of images available for the Southern Idaho area. Often, images were available where the dates for adjacent Landsat paths were separated by only 1 day. This was made possible by obtaining Landsat 5 images for one path and Landsat 7 images for the adjacent path. We found Landsat 5 images to be of immense value in predicting ET between Landsat 7 dates, especially when Landsat 7 images were cloudy and during periods of rapid vegetation growth."

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[3] ET_rF is the 'fraction of reference ET' and is equivalent to the crop coefficient, K_c, defined in footnote 1 as the ratio of ET/ET_r where ET_r is reference ET, computed from weather data and ET is the ET from any pixel.

7. Allen, R.G., M. Tasumi and R. Trezza. 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. *ASCE J. Irrigation and Drainage Engineering* (in press).
http://www.kimberly.uidaho.edu/water/papers/remote/ASCE_JIDE_2007a_Allen et al.pdf

"Generally one satellite image per month is sufficient to construct an accurate ET_rF curve for purposes of estimating seasonal ET. During periods of rapid vegetation change, a more frequent image interval may be desirable…"

Calibration around inaccuracies and uncertainties in surface temperature of Landsat

"The calibration of the sensible heat process equations, and in essence the entire energy balance, to ET_r corrects the surface energy balance for lingering systematic computational biases associated with empirical functions used to estimate some components and uncertainties in other estimates as summarized by Allen et al. (2005), including:

atmospheric correction
albedo calculation
net radiation calculation
surface temperature from the satellite thermal band
air temperature gradient function used in sensible heat flux calculation
aerodynamic resistance including stability functions
soil heat flux function
wind speed field

This list of biases plagues essentially all surface energy balance computations that utilize satellite imagery as the primary spatial information resource."

(see also prior topics on impact of bias in T_s measurements)

Need for high resolution for Evapotranspiration

"METRIC is designed to produce high quality and accurate maps of ET for focused regions smaller than a few hundred kilometers in scale and at high resolution. This contrasts with some remote sensing models .... designed for routine application over large regions ..... The narrowed focus of METRIC is intended to provide relatively more accurate estimates of ET at higher resolution (~30 m) .... to account for impacts of regional advection. The narrowed focus does come at a cost, however, in the requirement for trained experts having good background in energy balance and radiation physics and adequate knowledge of vegetation characteristics as well as the requirement for high quality hourly (or shorter) weather data."

Using Landsat-based Energy Balance to Calibrate MODIS-based Energy Balance

"In applications with MODIS, it is often difficult to find 1000 m thermal pixels containing homogenous vegetation that are at sufficient ground cover to represent the 'cold pixel' condition (where ET ~ 1.05 ET_r). Under these conditions, one can use METRIC applications based on and calibrated using ***Landsat*** *to determine ET and ET_rF for specific MODIS-scale pixels and to develop associated ET_rF vs. NDVI relationships for a target region that can in turn be used to determine calibration for the coarse* ***MODIS****-based images (where pixels having ET_rF = 1.05 do not exist). "*

8. Allen, R.G., M. Tasumi, A.T. Morse, R. Trezza, W. Kramber, I. Lorite and C.W. Robison. 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. *ASCE J. Irrigation and Drainage Engineering* (in press).
   http://www.kimberly.uidaho.edu/water/papers/remote/ASCE_JIDE_2007b_Allen et al.pdf

Need for high resolution for comparing with measured ground data

> *"The small size of the lysimeter field (110 x 120 m) prevented procurement of Landsat based samples from the field for all image scenes that were free of any influence, in the 120-m thermal band of Landsat 5, from areas outside the fields. This "thermal contamination" of some sampled pixels from the small lysimeter field created some degree of bias in METRIC estimated ET that were not present in the lysimeter ET measurements, and would not occur for large fields, which are commonly on the order of 800 x 800 m in southern Idaho."*

Landsat scale TIR based ET required for high spatial variation in riparian ET

> *"METRIC was applied with Landsat 5 and 7 images during 2002 to spatially and temporally quantify ET from irrigated crops and riparian vegetation (native and invasive tree species and wetlands) along the Middle Rio Grande river of northern and central New Mexico. The high resolution of Landsat was extremely valuable for assessing ET on a field by field basis and for estimating ET from riparian (tree) systems that were often less than 100 m in width."*

Using Landsat-based Energy Balance to Calibrate MODIS-based Energy Balance

> *"Much of the utility of METRIC is with Landsat imagery or imagery having similar resolution (and a thermal band) so that field-level detail can be defined. Unfortunately, problems with Landsat 7 in 2003 and recent problems with the aging Landsat 5 have revealed the vulnerability of these two satellites with high resolution thermal bands….. Although the temporal frequency of MODIS is much vaunted by some, it is seriously compromised by large view angles on many days, causing blurring, and the spatial resolution of MODIS is insufficient to provide the same level of information as Landsat. MODIS images on at least two of every three days for a specific location are acquired from such a large, lateral distance (i.e., from a large view angle), that the pixel size for short-wave information stretches from the specified size of 0.5 x 0.5 km to an effective 1 km x 1.5 km size and thermal pixels stretch from the specified size of 1 x 1 km to an effective 2 km x 3 km size. This 'blurring' of the image is problematic for determining 'crisp' ET images from which individual land holdings (farms) can be identified. ….. These fields are not discernable from any of the MODIS images.*

> *"The potential accuracy of METRIC when applied with MODIS is nearly as good as with Landsat when ET is integrated over areas of at least 10 x 10 km (Hong et al., 2005). This type of resolution is useful for basin scale water balance and hydrologic studies, but is much less useful for water rights management and use in litigation. Allen et al., 2007 have used Landsat-based ET images, where calibration was based on readily identifiable anchor pixels at the 30 to 120 m scale, to determine energy balance components and vegetation index-based relationships at the 1000 m scale by which to calibrate MODIS-based METRIC applications."*

On spatial needs for ET from irrigated agriculture

9. Courault, D., B. Seguin and A. Olioso. 2005. Review on estimation of evapotranspiration from remote sensing data: From empirical to numerical modeling approaches. *Irrigation and Drainage Systems* 19: 223–249
   http://www.kimberly.uidaho.edu/water/papers/remote/JIDS_2005_p223-249 Courault et al.pdf

   "But more detailed observations would be needed for analyzing the spatial distribution of water use in the irrigation network. The NOAA resolution (1 km) is too coarse for that purpose. A higher resolution can be achieved by Landsat (120m in TIR for Landsat 5, 60m for Landsat 7), but both the frequency (every 16 days) and time acquisition (for example 10:00 over France) are limiting factors. Moreover the future of Landsat is uncertain, because the cooling techniques are too heavy and that makes the payload too expensive."

Annotated Bibliography on use of thermal remote sensing data in surface energy budget partitioning at multiple scales with the ALEXI/DisALEXI models

REFEREED PUBLICATIONS AND BOOK CHAPTERS:

Background information on thermal remote sensing of surface energy fluxes:

These are general review articles, discussing the shortcomings of early thermal-based ET modeling experiments. They motivate the need for robust model formulations that simultaneously accommodate both inevitable sensor biases due to errors in calibration and atmospheric corrections, and the wide range in vegetation cover/roughness/moistures stress conditions that are found in natural and agricultural landscapes, which can strongly influence the radiometric surface temperature – heat flux relationship. These considerations led to the development of the Two-Source Energy Balance (TSEB) landsurface model, and the Atmosphere-Land Exchange Inverse (ALEXI) model, which applies the TSEB to time-differential surface temperature measurements.

Norman, J. M., and F. Becker (1995), Terminology in thermal infrared remote sensing of natural surfaces, *Remote Sens. Rev.*, *12*, 159-173.

Norman, J. M., M. Divakarla, and N. S. Goel (1995), Algorithms for extracting information from remote thermal-IR observations of the earth's surface, *Remote Sens. Environ.*, *51*, 157-168.

Kustas, W. P., G. R. Diak, and J. M. Norman (2001), Time difference methods for monitoring regional scale heat fluxes with remote sensing, *Land Surface Hydrology, Meteorology, and Climate: Observations and Modeling*, *3*, 15-29.

Kustas, W. P., J. M. Norman, T. J. Schmugge, and M. C. Anderson (2004), Mapping surface energy fluxes with radiometric temperature, in *Thermal Remote Sensing in Land Surface Processes*, edited by D. A. Quattrochi and J. C. Luvall, pp. 205-253, CRC Press, Boca Raton, FL.

The Two-Source Energy Balance (TSEB) Model:

Early applications of thermal remote sensing to surface energy balance modeling used a "single-source" methodology, where the thermal pixel area was treated as a single homogeneous source of sensible and latent heat. In fact the soil and canopy components of a heterogeneous surface can be very differently coupled with the atmosphere, and do not necessarily contribute to the bulk sensible heat flux in proportion to their component temperatures. The soil tends to be hotter than the transpiring vegetation, and yet is less strongly coupled with the atmosphere – models that don't take this into account will tend to overestimate the sensible heat flux and underestimate evapotranspiration under conditions of partial canopy cover (see e.g., Hall et al, 1992). The Two-Source Energy Balance (TSEB) landsurface representation (Norman et al, 1995) explicitly treats the soil and canopy as coupled sources using physical principles. It is simple enough to embed in a remote sensing algorithm, but detailed enough to be applied over a range in surface vegetative and moisture conditions. Many *experiments have demonstrated significant improvement in energy budget partitioning provided by two-source vs. single-source approaches.*

Hall, F. G., K. F. Huemmrich, S. J. Goetz, P. J. Sellers, and J. E. Nickerson (1992), Satellite remote sensing of surface energy balance: success, failures and unresolved issues in FIFE, *J. Geophys. Res.*, *97*, 19,061-019,089.

Norman, J. M., W. P. Kustas, and K. S. Humes (1995), A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature, *Agric. For. Meteorol.*, *77*, 263-293

Kustas, W. P. (1990), Estimates of evapotranspiration with a one- and two-layer model of heat transfer over partial canopy cover, *J. Appl. Meteorol.*, *29*, 704-715.

Kustas, W. P., K. S. Humes, J. M. Norman, and M. S. Moran (1996), Single- and dual-source modeling of surface energy fluxes with radiometric surface temperature, *J. Appl. Meteorol.*, *35*, 110-121.

Kustas, W. P., and J. M. Norman (1997), A two-source approach for estimating turbulent fluxes using multiple angle thermal infrared obserations, *Water Resources Research*, *33*, 1495-1508.

Kustas, W. P., and J. M. Norman (1999), Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover, *Agric. For. Meteorol.*, *94*, 13-25.

Kustas, W. P., and J. M. Norman (1999), Reply to comments about the basic equations of dual-source vegetation-atmosphere transfer models, *Agric. For. Meteorol.*, *94*, 275-278.

Kustas, W. P., and J. M. Norman (2000), A two-source energy balance approach using directional radiometric temperature observations for sparse canopy covered surfaces, *Agronomy J.*, *92*, 847-854.

Li, F., W. P. Kustas, M. C. Anderson, T. J. Jackson, R. Bindlish, and J. Prueger (2006), Comparing the utility of microwave and thermal remote-sensing constraints in two-source energy balance modeling over an agricultural landscape, *Remote Sens. Environ.*, *101*, 315-328.

Regional applications of the TSEB - The ALEXI (Atmosphere-Land Exchange Inverse Model):

For regional applications, the upper boundary conditions in above-canopy air temperature required by the TSEB are difficult to obtain with adequate accuracy. The ALEXI model (Anderson et al., 1997) was developed to address this problem, allowing accurate assessment of surface fluxes over continental scales. ALEXI applies the TSEB using time-differential surface temperature measurements acquired by geostationary satellites along with a simple atmospheric boundary layer energy closure technique to estimate fluxes at 5-10km horizontal resolution. The use of time-differential temperatures significantly reduces model sensitivity to errors in sensor calibration, atmospheric corrections, and emissivity specifications. The TSEB intrinsically models variations in surface temperature due to sensor viewing angle – single-source models cannot easily be applied to GOES data at the continental scale.

Anderson et al. (2007a) describe a methodology for filling gaps in the model flux record under *cloudy conditions, when surface temperature data cannot be acquired by satellite. In comparison with measurements from a watershed-scale flux tower network, gap-filled fluxes from ALEXI have errors of ~15% at hourly timescales, and 10% at the daily timestep.*

The physical basis of the TSEB embedded in ALEXI allows the model to sense moisture stress signatures – where the landsurface is not evaporating at its potential rate. Anderson et al. (2007) demonstrated the ability of ALEXI to generate a thermal-based drought index over the US that shows very good correspondence with standard precipitation-based indices, but at considerably higher spatial resolution.

Anderson, M. C., J. M. Norman, G. R. Diak, W. P. Kustas, and J. R. Mecikalski (1997), A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing, *Remote Sens. Environ.*, *60*, 195-216.

Mecikalski, J. M., G. R. Diak, M. C. Anderson, and J. M. Norman (1999), Estimating fluxes on continental scales using remotely-sensed data in an atmosphere-land exchange model, *J. Applied Meteorol.*, *38*, 1352-1369.

Anderson, M. C., J. M. Norman, J. R. Mecikalski, J. P. Otkin, and W. P. Kustas (2007a), A climatological study of evapotranspiration and moisture stress across the continental U.S. based on thermal remote sensing: I. Model formulation, *J. Geophys. Res., (in press).*

Anderson, M. C., J. M. Norman, J. R. Mecikalski, J. P. Otkin, and W. P. Kustas (2007b), A climatological study of evapotranspiration and moisture stress across the continental U.S. based on thermal remote sensing: II. Surface moisture climatology, *J. Geophys. Res., (in press).*

Local to regional scale flux mapping using a flux disaggregation approach, DisALEXI:

Flux measurements at the 5-10km scale needed to validate regional models like ALEXI are typically collected only during intensive field experiments. Direct comparison between ALEXI fluxes and ground-based flux tower observations (sampling a ground area of ~100m) can be dominated by sub-pixel heterogeneity effects and do not give a good representation of intrinsic model accuracy (Anderson et al., 2007a). An ALEXI flux disaggregation approach (DisALEXI; Norman et al, 2003) applied to high resolution surface temperature imagery allows a more scale-appropriate comparison between modeled and observed fluxes. Anderson et al., (2007a) demonstrate that model-measurement errors are halved when ALEXI fluxes are disaggregated to the tower footprint scale. Two papers in the following section demonstrate that Landsat at 60-120m thermal resolution adequately resolves the tower footprint and gives excellent agreement with model fluxes, while MODIS at 1km thermal resolution is less effective in model validation.

With ALEXI/DisALEXI we can effectively model surface fluxes (sensible heat, latent heat or evapotranspiration, net radiation, and soil heat conduction) and evaporative stress at the field scale all the way up to continental scales. Anderson et al. (2007) suggest that such multi-scale modeling systems are essential for deriving continental scale water budgets from tower networks like FluxNet. Anderson et al. (2007b) describe how the TSEB can also be used for mapping carbon assimilation fluxes, additionally allowing upscaling of FluxNet carbon measurements.

Anderson, M. C., W. P. Kustas, and J. M. Norman (2003), Upscaling and downscaling - a regional view of the soil-plant-atmosphere continuum, *Agron. J.*, *95*, 1408-1423.

Anderson, M. C., J. M. Norman, J. R. Mecikalski, R. D. Torn, W. P. Kustas, and J. B. Basara (2004), A multi-scale remote sensing model for disaggregating regional fluxes to micrometeorological scales, *J. Hydrometeor.*, *5*, 343-363.

Anderson, M. C., J. M. Norman, W. P. Kustas, F. Li, J. H. Prueger, and J. M. Mecikalski (2005), Effects of vegetation clumping on two-source model estimates of surface energy fluxes from an agricultural landscape during SMACEX, *J. Hydrometeorol.*, *6*, 892-909.

Anderson, M. C., W. P. Kustas, and J. M. Norman (2007a), Upscaling tower and aircraft fluxes from local to continental scales using thermal remote sensing, *Agron. J.*, *99*, 240-254.

Anderson, M.C., Norman, J.M., and W.P. Kustas (2007b), A thermal remote sensing model for mapping carbon assimilation fluxes (*in preparation*).

French, A. N., et al. (2005), Surface energy fluxes with the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) at the Iowa 2002 SMACEX site (USA), *Remote Sens. Environ.*, *99*, 55-65.

Kustas, W. P., M. C. Anderson, A. N. French, and D. Vickers (2006), Using a remote sensing field experiment to investigate flux footprint relations and flux sampling distributions for tower and aircraft-based observations, *Adv. Water Res.*, *29*, 355-368.

Norman, J. M., M. C. Anderson, W. P. Kustas, A. N. French, J. R. Mecikalski, R. D. Torn, G. R. Diak, T. J. Schmugge, and B. C. W. Tanner (2003), Remote sensing of surface energy fluxes at 10^1-m pixel resolutions, *Water Resour. Res.*, *39*, DOI:10.1029/2002WR001775.

Impact of thermal image resolution on validation:

A couple of papers demonstrating how validation is compromised using coarse-scale thermal image data from MODIS in comparison with high-resolution Landsat imagery.

Kustas, W. P., F. Li, T. J. Jackson, J. H. Prueger, J. I. MacPherson, and M. Wolde (2004), Effects of remote sensing pixel resolution on modeled energy flux variability of croplands in Iowa, *Remote Sens. Environ.*, *94*, 535-547.

Li, F., W. P. Kustas, M. C. Anderson, J. H. Prueger, and R. L. Scott (2006), Effect of remote sensing spatial resolution on interpreting tower-based flux observations, *Remote Sens. Environ. 101*, 315-328.