MAPPING EVAPOTRANSPIRATION AND DROUGHT AT LOCAL TO CONTINENTAL SCALES WITH A THERMAL-BASED SURFACE ENERGY BALANCE MODEL

M. C. Anderson[1*] and W. P. Kustas[1]

[1] U.S. Dept. of Agriculture Hydrology and Remote Sensing Laboratory, Beltsville, MD

1. INTRODUCTION

Water lost to the atmosphere through evapotranspiration (ET) has the effect of cooling the Earth's surface. Land-surface temperature (LST), as mapped using thermal-infrared (TIR) band data, is therefore a valuable remote indicator of both ET and the surface moisture status (Moran, 2003). In partially vegetated landscapes, depletion of water from the soil surface layer (0-5 cm) causes the soil component of the scene to heat rapidly. Moisture deficiencies deeper in the soil profile, in the plant root zone (down to 1-2 m depth), lead to stomatal closure, reduced transpiration, and therefore elevated canopy temperatures, which can be effectively detected from space (Anderson et al., 2007c).

Given current trends in population growth and climate change, it will become increasingly critical to be able to accurately remotely monitor the earth's freshwater resources at local to global scales. The suite of thermal imaging sensors available over the U.S. currently provides this broad coverage. With the Geostationary Operational Environmental Satellites (GOES) we can obtain thermal images every 15min, but at fairly coarse spatial resolution (~5-10 km). At the other end of the spectrum, the aging Landsat-5 and -7 platforms provide thermal data at 60-120 m resolution, but only periodically (~monthly), and now with degraded coverage due to system failures. The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites provides moderate resolution (1 km) TIR snapshots of land-surface conditions a couple of times each day, depending on cloud cover. These various data sources have good potential to be used synergistically in a variety of applications, at field to watershed to national scales.

Proper interpretation of the TIR land-surface signal in terms of the underlying moisture status, however, requires ancillary information about vegetation amount, which can be related to vegetation indices (VIs) derived from shortwave satellite reflectance data, and information about the local energy constraints (radiative and meteorological forcings) on the combined soil-plant-atmosphere system. These factors can be accounted for in a physical way within the context of a surface energy balance model. The Atmosphere-Land Exchange Inverse (ALEXI) modeling scheme described below is an example of one possible framework for synthesizing multi-scale, multi-platform thermal imagery into useful end-products for operational monitoring of drought and evaporative water loss.

2. MODEL DESCRIPTION

The ALEXI model (Anderson et al., 1997; 2007b; 2007c) was originally developed for estimating surface fluxes, including ET, over large regions using primarily remote-sensing data. This type of approach is unique in that no information regarding antecedent precipitation or soil moisture storage capacity is required - the surface moisture status is deduced from a radiometric temperature change signal. Therefore, ALEXI can provide independent information for updating soil moisture variables in more complex regional models.

ALEXI consists of a two-source (soil and canopy) land-surface model (Norman et al., 1995) coupled with a 1-dimensional atmospheric boundary layer (ABL) model (McNaughton and Spriggs, 1986). The lower boundary conditions for the two-source model are provided by TIR observations taken at two times during the morning hours from a geostationary platform such as GOES. The ABL model then relates the rise in air temperature above the canopy during this interval and the growth of the ABL to the time-integrated influx of sensible heating from the surface, and ET is computed as a partial residual to the energy budget. Use of time-differential measurements of surface radiometric temperature reduces model sensitivity to errors in sensor calibration, and atmospheric and surface emissivity corrections.

ALEXI is constrained to operate on spatial scales of 5-10 km – scales at which atmospheric forcing

----

*Corresponding Author Address: M.C. Anderson, 10300 Baltimore Ave, Beltsville, MD 20705
e-mail: martha.anderson@ars.usda.gov

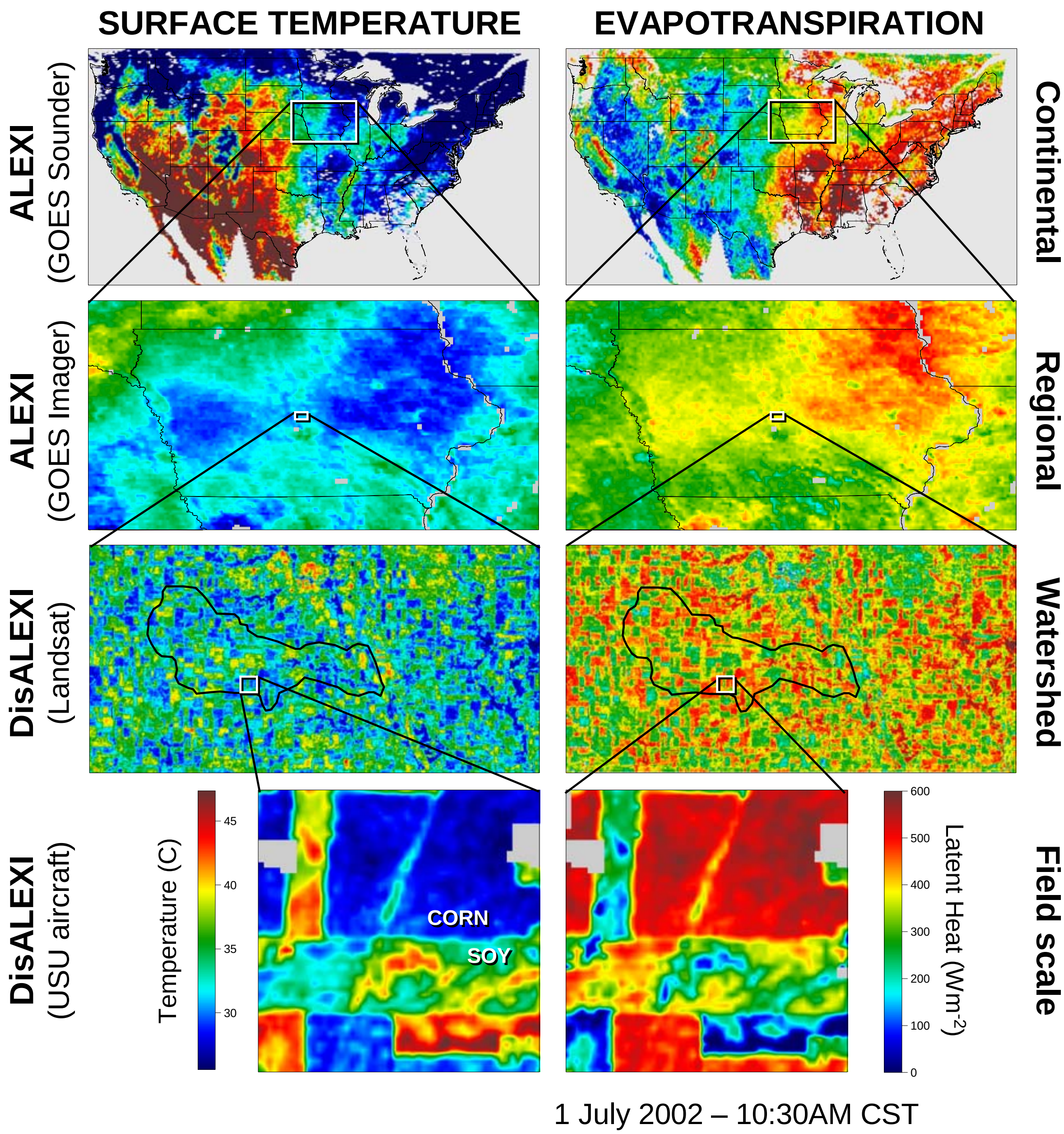

Figure 1: Multi-scale ET maps for 1 July 2002 produced with ALEXI/DisALEXI using surface temperature data from aircraft (30m resolution), Landsat (60m), GOES Imager (5km) and GOES Sounder (10km). The continental-scale ET map is a 14-day composite of clear-sky model estimates (Anderson et al., 2007a).

by uniform land-surface behavior becomes effective. This is also the typical resolution of a geostationary TIR sensor. To obtain finer resolution information, a flux disaggregation algorithm (DisALEXI; Norman et al., 2003) can be applied to ALEXI output fields, incorporating higher resolution (1-m to 1-km scale) thermal and shortwave imagery from satellite platforms like Landsat, ASTER and MODIS or from airborne imaging systems.

The ALEXI/DisALEXI package allows us to generate nested flux and moisture stress maps using thermal imagery from a combination of geostationary and polar orbiting satellites, zooming in from the national scale to sites of specific interest – providing scalable surface moisture information in the vein of Google Earth (Fig. 1; Anderson et al., 2007a).

3. EVAPORATIVE STRESS INDEX

Spatial and temporal variations in instantaneous ET at the continental scale are primarily due to variability in moisture availability (antecedent precipitation), radiative forcing (cloud cover, sun angle), vegetation amount, and local atmospheric conditions such as air temperature, wind speed and vapor pressure deficit. Potential ET describes the evaporation rate expected when soil moisture is non-limiting, ideally capturing response to all other forcing variables. To isolate effects due to spatially varying soil moisture availability, a simple Evaporative Stress Index (ESI) can be developed from model flux estimates, given by 1 minus the ratio of actual-to-potential ET (f_{PET}):

$$ESI = 1 - f_{PET} \quad (1)$$

The ESI has a value of 0 when there is ample moisture/no stress, and a value of 1 when evapotranspiration has been cut off due to stress-induced stomatal closure and/or complete drying of the soil surface. With the two-source land-surface representation in ALEXI, we can derive analogous stress indices for the soil and canopy, as well as for the bulk system. Anderson, et al., (2007b) demonstrates that these various indices are sensitive to moisture stress over different timescales. The soil surface responds quickly to moisture deficiencies, and therefore the soil index should be a better measure of meteorological drought, while the canopy index changes at a slower rate and is more appropriate for tracking agricultural drought conditions.

4. DROUGHT MAPPING

4.1 Continental scale product

The ALEXI model currently runs daily, in near-realtime, on a 10-km grid covering the contiguous U.S. (CONUS), generating hourly and daily fields of ET and ESI, as well as other surface fluxes. Assessments are currently limited to snow-free conditions, but a technique for filling gaps due to cloud cover has been implemented (Anderson et al., 2007b). Monthly anomalies in the ESI show good spatiotemporal correspondence with standard drought metrics such as the Palmer Drought Severity Index, and with patterns of antecedent precipitation, but at significantly higher spatial resolution due to ALEXI's limited reliance on ground observations (Fig. 2; Anderson et al., 2007c).

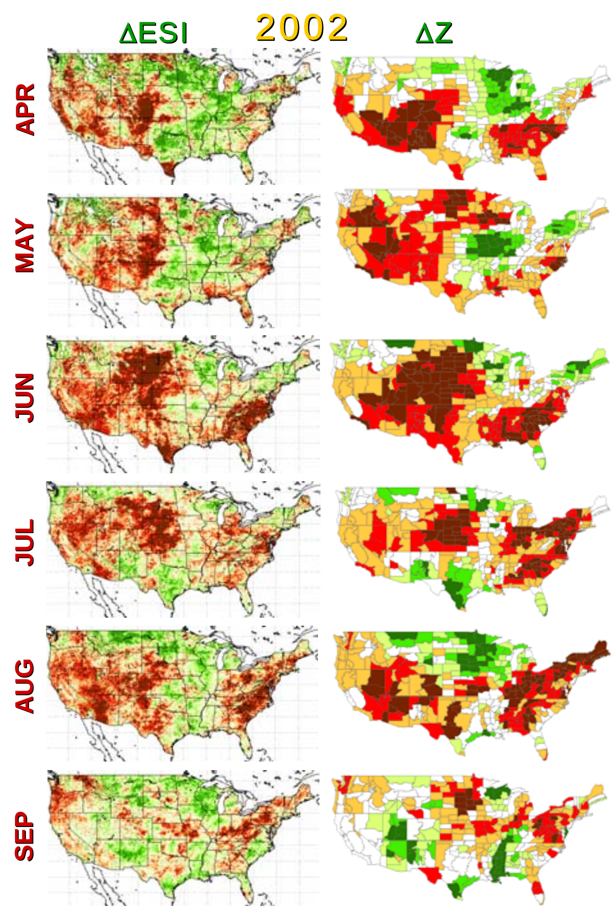

Figure 2: Anomalies in the ALEXI Evaporative Stress Index and in the Palmer Z Index, a precipitation-based metric of short-term meteorological drought for 2002-2005, computed with respect to 4 year monthly mean conditions. Note that ALEXI does not use precipitation as an input – the ALEXI stress signals are derived from the remotely sensed land-surface temperature (Anderson et al., 2007c).

4.2 Scalable mapping

By combining ALEXI with DisALEXI, a multi-scale drought monitoring approach becomes possible. Time-composites of the ALEXI ESI can be generated daily or weekly using geostationary satellite data, identifying areas at the continental scale that appear to be experiencing moisture stress. These areas can then be targeted for disaggregation using high-resolution imagery from polar orbiting satellites (Fig. 3). Landsat-resolution (~100 m) thermal data typically resolve individual fields, facilitating sub-county level assessments of vegetation health by crop type. MODIS at 1-km resolution is too coarse for crop-level analyses, since the typical field size in the U.S. is on the order of ~500 m. MODIS, on the other had, has good temporal resolution, which is a benefit to operational monitoring. A synergistic approach utilizing all three datastreams (GOES, MODIS, and Landsat) appears optimal.

Landsat, however, is the only commercially available satellite platform currently operated (or planned) by any nation that routinely provides ~100-m resolution TIR images. Plans by NASA to remove TIR imaging capabilities from the Landsat Data Continuity Mission (LDCM) jeopardize well-developed water management programs that have been implemented in the western US where this kind of information is desperately needed, and will derail ongoing development of new high-resolution applications in agriculture and drought monitoring.

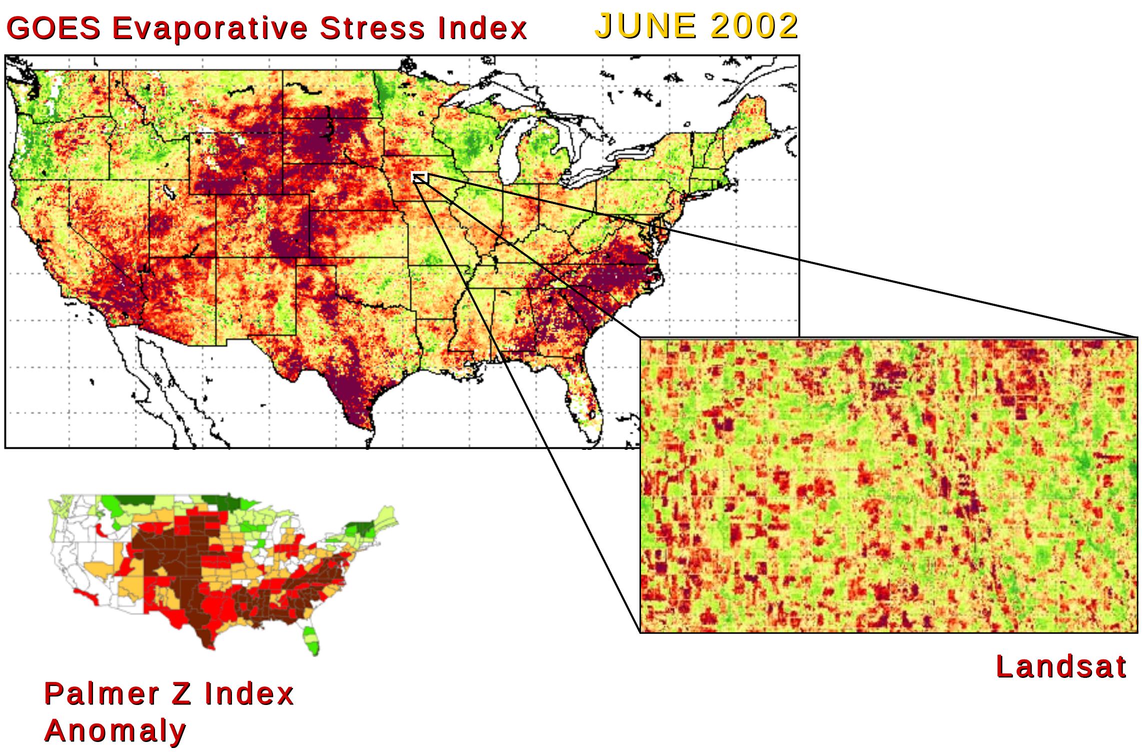

Figure 3: Multi-scale drought monitoring scheme, using GOES-TIR-based stress index to screen for drought-affected areas at the national scale, and Landsat TIR to provide stress information at the sub-field scale in areas of interest.

5. FUTURE WORK

Our immediate goals are to a) expand the spatial and temporal properties of the ESI archive, and to b) assess the practical utility of this remote sensing system for operational drought monitoring at the continental scale within the context of the U.S. Drought Monitor and the National Integrated Drought Information System.

By June 2008, the ALEXI ESI product will become operational and the archive will include daily 10-km CONUS grids for 2002-present (see Table 1). Potential enhancements to the archive include extension back to the mid-90's (limited by the extant GOES archive), and reimplementation on a 5-km grid. Introduction of a snow mask will enable year-round mapping at southern latitudes. In addition, an implementation of ALEXI over central Europe, using geostationary products from Meteosat, is in progress.

Table 1: Operational details for ESI product

Frequency of availability	Daily
Delay in availability	Near real-time (updated nightly)
Web access	http://www.soils.wisc.edu/alexi/ (soon to be transferred to USDA)
Geographic projection	Latitude/longitude
File format	Flat binary, GIF
Compatibility with GIS	To be determined

In terms of assessment, a rigorous quantitative comparison between the TIR-based ESI and other remote-sensing and precipitation-based drought indices at the CONUS scale is currently underway. This study will identify specific geographic, climatic and biotic conditions associated with varying levels of disagreement between a diverse set of drought indicators. The performance of the ESI will be investigated in detail over the Corn Belt in comparison with county-level yield data. Because signals of vegetation stress are first manifested in an elevated canopy temperature, even before any reduction of leaf area is realized, TIR-based indices have good potential for drought early warning screening. The relative detection lead-time will be assessed retrospectively over areas with documented drought impact.

Work is also underway to implement and validate robust techniques for successive downscaling of GOES-based ESI maps using higher resolution TIR data from a suite of polar-orbiting sensors, working toward a Google Earth approach to drought visualization. Without a Landsat-like TIR sensor, however, we lose our ability to provide the kind of spatially detailed surface moisture information that is ever increasingly being demanded of the U.S. Drought Monitor. The opportunity cost of eliminating TIR bands from future Landsat platforms is enormous and untimely, given the recent major advances in our understanding of how to effectively exploit thermal imaging capabilities at all spatial resolutions.

6. ACKNOWLEGEMENTS

Funding for this research was provided by the National Aeronautics and Space Administration under grant NNG04GK89G.

7. REFERENCES

Anderson, M.C., Kustas, W.P. and Norman, J.M., 2007a. Upscaling flux observations from local to continental scales using thermal remote sensing. *Agron. J.*, 99: 240-254.

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

Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.P. and Kustas, W.P., 2007b. A climatological study of evapotranspiration and moisture stress across the continental U.S. based on thermal remote sensing: I. Model formulation. *J. Geophys. Res.*: 112, D10117, doi:10.1029/2006JD007506.

Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.P. and Kustas, W.P., 2007c. 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.*: 112, D11112, doi:10.1029/2006JD007507.

McNaughton, K.G. and Spriggs, T.W., 1986. A mixed-layer model for regional evaporation. *Boundary-Layer Meteorol.*, 74: 262-288.

Moran, M.S., 2003. Thermal infrared measurement as an indicator of plant ecosystem health. In: D.A. Quattrochi and J. Luvall (Editors), Thermal Remote Sensing in Land Surface Processes. Taylor and Francis, pp. 257-282.

Norman, J.M. et al., 2003. Remote sensing of surface energy fluxes at 10^1-m pixel resolutions. *Water Resour. Res.*, 39: DOI:10.1029/2002WR001775.

Norman, J.M., Kustas, W.P. and Humes, K.S., 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.