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MAPPING DROUGHT AND SOIL MOISTURE WITH A THERMAL TWO-SOURCE SURFACE FLUX MODEL

Martha C. Anderson* and William P. Kustas
USDA-ARS 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 in the root zone (down to 1-2 m depth) lead to stomatal closure, reduced transpiration, and elevated canopy temperatures, which can be effectively detected from space [*Anderson, et al.*, 2007c].

Proper interpretation of the TIR land-surface signal in terms of the underlying moisture status requires ancillary information about vegetation amount and 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] consists of a two-source (soil and canopy) land-surface energy balance 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 [*Kustas, et al.*, 2001]..

ALEXI is constrained to operate on spatial scales of 5-10 km, where atmospheric forcing by uniform land-surface behavior becomes effective. 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. Disaggregation allows scale-appropriate validation with respect to flux tower observations, which typically sample a footprint on the land surface of order 10^2 m [*Anderson, et al.*, 2007a]. Together, ALEXI/DisALEXI facilitate scalable flux and moisture stress mapping using thermal imagery from a combination of geostationary and polar orbiting satellites, zooming in from the national scale to sites of specific interest [Fig. 1; *Anderson, et al.*, 2007a].

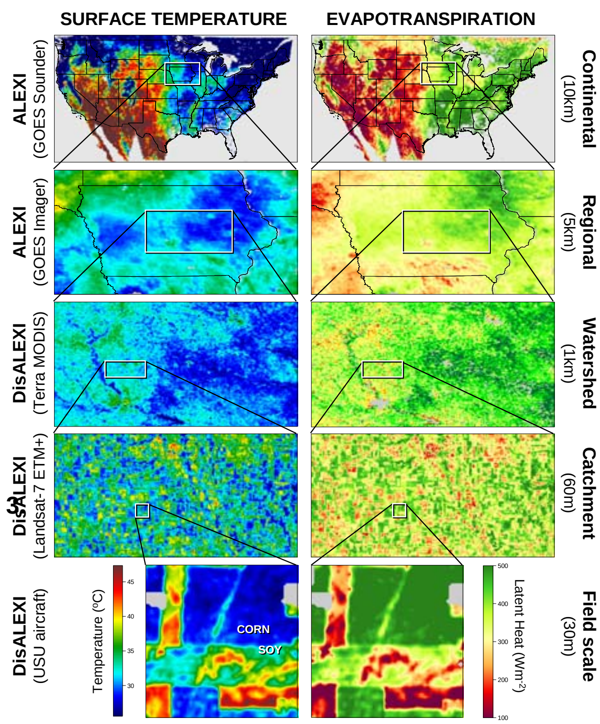

FIGURE 1: Multi-scale ET maps for 1 July 2002, focused over the corn and soybean production region of central Iowa, produced with the ALEXI/DisALEXI surface energy balance models [*Anderson, et al.*, 2007a] using surface temperature data from aircraft (30-m resolution), Landsat-7 ETM+ (60-m), Terra MODIS (1-km), GOES Imager (5-km) and GOES Sounder (10-km) instruments. The continental-scale ET map is a 14-day composite of clear-sky model estimates.

* *Corresponding author address:* Martha C. Anderson, Hydrology and Remote Sensing Lab, USDA-ARS, 10300 Baltimore Ave, Beltsville, MD 20705; Martha.Anderson@ars.usda.gov

3. DROUGHT MAPPING

3.1. 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. 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.

3.2. Continental Scale Product

The ALEXI model currently runs daily, in near-realtime, on a 10-km grid covering the contiguous U.S., 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 ALEXI ESI show good spatiotemporal correspondence with standard drought metrics such as the Palmer Drought Indices, and with patterns of antecedent precipitation, but at significantly higher spatial resolution due to limited reliance on ground observations [Fig. 2; *Anderson, et al.*, 2007c].

3.3. 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. 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. On the other hand, MODIS has good temporal resolution, which is a benefit to operational monitoring. A synergistic approach utilizing all three datastreams (GOES, MODIS, and Landsat) appears optimal (Fig 2).

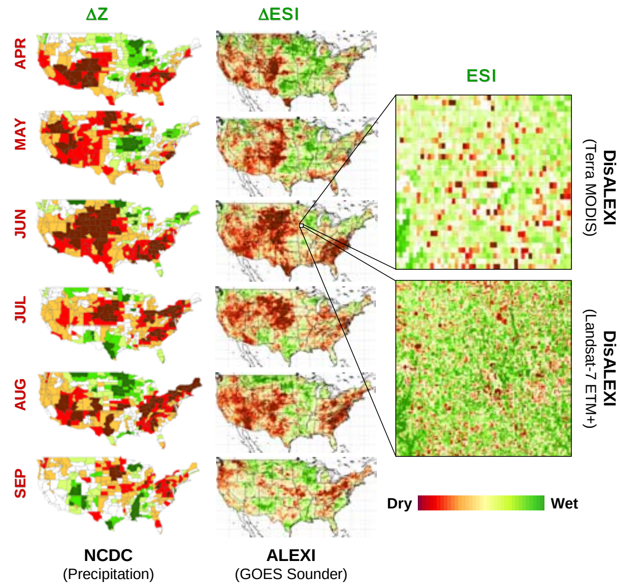

FIGURE 2. Anomalies in the GOES-based (10-km resolution) ALEXI Evaporative Stress Index [*Anderson, et al.*, 2007b] and in the National Climate Data Center (NCDC) Palmer Z Index, a precipitation-based metric of short-term meteorological drought. Both are computed for 2002 with respect to 4-year (2002-2005) monthly mean conditions. Also shown are ESI values over central Iowa from Terra MODIS (1-km) and Landsat-7 ETM+ (60-m). Note that precipitation is not an input to ALEXI/DisALEXI.

4. IMPORTANCE OF HIGH-RESOLUTION TIR IMAGING

Periodic high-resolution TIR data from Landsat add significant interpretive value to the MODIS/GOES ESI maps, allowing identification of satellite-derived stress signals with specific human activities: management of agricultural fields, water control and treatment structures, restoration projects, etc. These connections cannot be made at the GOES or MODIS resolutions – thus Landsat-scale thermal imagery is absolutely critical for actionable monitoring at the local scale.

Landsat is the only commercially available satellite platform currently operated (or planned) by any nation that routinely provides ~100-m resolution TIR images. The decision by NASA to descope TIR imaging capabilities from the Landsat Data Continuity Mission (LDCM) jeopardizes well-developed water management programs that have been implemented in the western US and other water-limited regions, and will derail ongoing development of new high-resolution applications in agriculture, and in river and weather forecasting.

5. REFERENCES

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

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.

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: I. Model formulation, *J. Geophys. Res.*, 112, D10117, doi:10110.11029/12006JD007506.

Anderson, M. C., J. M. Norman, J. R. Mecikalski, J. P. Otkin, and W. P. Kustas (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:11110.11029/12006JD007507.

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.

McNaughton, K. G., and T. W. Spriggs (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 *Thermal Remote Sensing in Land Surface Processes*, edited by D. A. Quattrochi and J. Luvall, pp. 257-282, Taylor and Francis.

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.

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.