Mapping Water Use and Drought with Satellite Remote Sensing

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We can’t manage what we can’t measure …

**WATER ACCOUNTING AND FOOD SECURITY**

- Improved accounting of current water use and crop water productivity
- Monitoring changes in water use with changing climate, land-use and population
- Improved hydrologic monitoring (flood, drought, runoff) to better cope with extremes
- Crop stress detection and yield estimation
Multi-scale monitoring toolkit

TOOLS
- ALEXI: Multi-scale ET modeling
- DMS: Thermal image sharpening
- STARFM: Multi-sensor data fusion

APPLICATIONS (daily/30 m to 10 km)
- Crop water use (Evapotranspiration)
- Crop phenology metrics
- Crop stress (drought early warning)

ASSETS
- GEO: Hourly 5km/5km
- MODIS: Daily 250m/1km
- Landsat: 16 day 30m/100m
- Lsat-like: ~20-60m/ --
MULTI-SCALE SATELLITE ET RETRIEVAL

... Surface energy balance
Approaches to mapping ET

**PRECIPIRATION**
- Precipitation
- Transpiration & evaporation
- Veg stress parms
- Sfc moisture
- Infiltration
- Soil hydraulic parms
- Rootzone moisture
- Root uptake
- Drainage
- Soil moisture holding capacity

**WATER BALANCE APPROACH**
(prognostic modeling)

**SURFACE TEMPERATURE**
- Surface temperature
- $T_{soil}$ & $T_{veg}$
- Transpiration & evaporation
- Bare soil evap parms
- Runoff
- Soil evaporation

**ENERGY BALANCE APPROACH**
(diagnostic modeling)

Given known radiative energy inputs, how much water loss is required to keep the soil and vegetation at the observed temperatures?
COMPARISON of ET from energy and water balance models

(Green indicates energy balance ET is persistently wetter than expected based on local water balance)

Differences are primarily related to:

- % Irrigation
- Depth to water table (m)

(as well as density of subpixel water bodies)

Hain, et al. (2014)
Two-Source Energy Balance (TSEB)

System, soil, canopy budgets
RN = H + LE + G
RN_S = H_S + LE_S + G
RN_C = H_C + LE_C

Two-source approximation
T_{RAD}(\theta)^4 \sim f_C(\theta) T_C^4 + [1-f_C(\theta)] T_S^4

Temperature constraint
H_C, H_S, RN_C, RN_S, G

PT, PM or LUE R_C model
LE_C

Residual
LE_S = RN - H - G - LE_C

SENSIBLE HEAT FLUX
\[ \text{ET} = (R_{\text{NET}} - G) - H \]

Two-Source Model

Regional scale

\[ \Delta T_{\text{RAD}} \quad \text{- Geostationary} \]
\[ T_a \quad \text{- ABL model} \]

Landscape scale

\[ T_{\text{RAD}} \quad \text{- Landsat, MODIS} \]
\[ T_a \quad \text{- ALEXI} \]
DATA FUSION: daily ET at field scale

SURFACE TEMPERATURE
- GEO (ISCCP) (Global) (25km)
- GEO (GOES Sounder) (Continental) (10km)
- GEO (GOES Imager) (Regional) (5km)
- Polar (MODIS) (Basin) (1km)
- Polar (Landsat) (Watershed) (30m)
- Airborne (USU aircraft) (Field scale) (30m)

EVAPOTRANSPIRATION
- 1 July 2002 – 10:30AM LST

Temperature (°C)
- corn
- soy

Latent Heat (Wm$^{-2}$)
- 1 LS – 16 day
- 2 LS – 8 day

Hourly
GOES/MODIS/Landsat FUSION

Daily Evapotranspiration – Orlando, FL, 2002

Spatial Temporal Adaptive Reflectance Fusion Model (STARFM) (Gao et al, 2006)
GOES/MODIS/Landsat FUSION

Daily Evapotranspiration – Orlando, FL, 2002

Spatial Temporal Adaptive Reflectance Fusion Model (STARFM) (Gao et al, 2006)

$L^2$: 0.83 (9% error)
Evaluation of fused ET fluxes

SMEX02
Soil Moisture Experiment 2002
Ames, Iowa
Rainfed corn and soybean

BEAREX08
Bushland ET and Remote sensing Experiment 2008
Bushland, Texas
Rainfed and irrigated cotton

MEAD
Ameriflux site (S. Verma)
Mead, NE
Rainfed and irrigated corn and soybean

InterDrought Workshop, Feb 2014
Model performance on Landsat dates

**SMEX02**

<table>
<thead>
<tr>
<th>Modeled Daily Fluxes (MJ m$^{-2}$ d$^{-1}$)</th>
<th>Observed Daily Fluxes (MJ m$^{-2}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.08 MJ m$^{-2}$ d$^{-1}$</td>
<td>8%</td>
</tr>
</tbody>
</table>

**BEAREX08**

<table>
<thead>
<tr>
<th>Modeled Daily Fluxes (MJ m$^{-2}$ d$^{-1}$)</th>
<th>Observed Daily Fluxes (MJ m$^{-2}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 MJ m$^{-2}$ d$^{-1}$</td>
<td>10%</td>
</tr>
</tbody>
</table>

**MEAD**

<table>
<thead>
<tr>
<th>Modeled Daily Fluxes (MJ m$^{-2}$ d$^{-1}$)</th>
<th>Observed Daily Fluxes (MJ m$^{-2}$ d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 MJ m$^{-2}$ d$^{-1}$</td>
<td>11%</td>
</tr>
</tbody>
</table>

InterDrought Workshop, Feb 2014
Validation using flux tower data

Rainfed soybean – SMEX02 (Iowa)
Validation using flux tower data

Reference ET
Observed ET
Landsat retrievals
Landsat-only

Rainfed soybean – SMEX02 (Iowa)
Validation using flux tower data

Rainfed soybean – SMEX02 (Iowa)
Validation using flux tower data

Rainfed soybean – SMEX02 (Iowa)

Reference ET
Observed ET
Landsat retrievals
Landsat-only
Landsat-MODIS fusion

Day of Year
Cumulative ET (mm)
Daily ET (mm per day)

0 150 160 170 180 190 200 210 220 230 240
0 2 4 6 8 10

0 150 160 170 180 190 200 210 220 230 240
0 2 4 6 8 10

Rainfall

InterDrought Workshop, Feb 2014
SMEX02: soybean and stunted corn

InterDrought Workshop, Feb 2014
SMEX02 cumulative fluxes

Modeled cumulative flux (mm)
Observed cumulative flux (mm)

Landsat-only
Landsat-MODIS
(7% RE)
(4% RE)

y = 1.0089x - 7.2676
R² = 0.8784

y = 1.2552x - 76.752
R² = 0.8699

InterDrought Workshop, Feb 2014
BEAREX08 and MEAD

InterDrought Workshop, Feb 2014
Daily ET at field scale (Landsat+MODIS)
Monitoring forest water/carbon flux

Collaborator R. Wynne
FIELD-SCALE DAILY EVAPOTRANSPIRATION

Daily Evapotranspiration

SW/TIR

GEO
MODIS
Landsat

STARFM
DMS
ALEXI

Daily 30 m ET maps

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CROP PHENOLOGY METRICS

... at field scale
FIELD-SCALE
PHENOLOGIC METRICS

SW reflectances

MODIS
Landsat
Lsat-like

Daily EVI timeseries

TimeSat:
• start of season
• end of season
• peak greenness
• start of senescence
Spatial and Temporal Adaptive Reflectance Fusion Model

STARFM: Multi-sensor data fusion

MODIS
Landsat

STARFM (30 m)

Observed pairs
Reconstructed images

5/24/01 (144) 6/4/01 (155) 7/4/01 (185) 7/11/01 (192)
Landsat/MODIS fused NDVI timeseries
TIMESAT fits to fused NDVI timeseries

Start of season

Peak greenness

Start of senescence

End of season

**CORN**
- Landsat
- STARFM
- Timesat

**SOYBEAN**
- Landsat
- STARFM
- Timesat

**FOREST**
- Landsat
- STARFM
- Timesat

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Phenological Metrics

Start of Season (day of year)

![Image showing start of season in different seasons for forest, corn, and soybean.]

Graph showing the percentage of forest, corn, and soybean across different days of the year.

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MONITORING DROUGHT

... Crop stress and yield impacts
FIELD-SCALE DROUGHT IMPACTS

Daily ET maps

Crop phenology

Stress signals

Yield impacts (with NASS)

GEO
MODIS
Landsat
Lsat-like

Drought/Crop Stress

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Satellite ET Drought Indicator

Atmosphere-Land Exchange Inverse Model (ALEXI)
(Anderson et al., 1997, 2007)
2012 FLASH DROUGHT

Figure 1. 2012 State Corn Yields as a Percent of Trend Yield.
Using ESI to project crop yields

ESI CORN YIELD CORRELATIONS
(10-km ESI vs. state level yields)

Correlation coefficient ($r$)

Correlation coefficient ($r$)

Day of year

Dave Johnson,
National Agricultural Statistics Service

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GOES Evaporative Stress Index

JUNE 2002

MODIS (1 km)

Landsat (60 m)
Variable crop response to stress

- **2009 – Good year**
- **2008 – Drought year**

*InterDrought Workshop, Feb 2014*
The Evaporative Stress Index (ESI) describes temporal anomalies in evapotranspiration (ET), highlighting areas with anomalously high or low rates of water use across the land surface. Here, ET is retrieved via energy balance using remotely sensed land-surface temperature (LST) time-change signals. LST is a fast-response variable, providing proxy information regarding rapidly evolving surface soil moisture and crop stress conditions at relatively high spatial resolution. The ESI also demonstrates capability for capturing early signals of “flash drought”, brought on by extended periods of hot, dry and windy conditions leading to rapid soil moisture depletion.
GLOBAL APPLICATIONS

... Monitoring drought and water use
Yield correlation study

Regions
- North
- Northeast
- Midwest
- Southeast
- South
Yield correlation study

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Using ESI to project crop yields

ESI SOYBEAN YIELD CORRELATIONS
(10-km ESI vs. state level yields)

Week of year

Correlation coefficient (r)

APPROXIMATE HARVEST
Weeks from Harvest

Bahia

Averaging Interval (weeks)

Correlation coefficient (r)

ESI

ΔLAI

ΔTRMM

ΔCHIRPS

ΔVHI
2009 APRIL-SEPTEMBER

Average ALEXI ET (MJ m⁻² d⁻¹)

Average ALEXI ET/PET
EUMETSAT
Monitoring weather and climate from space
Surveiller le temps et le climat depuis l’espace

0° Operational

Indian Ocean
MONTHLY AVERAGE LATENT HEAT

March 2009

Monthly average ET (MJ m² d⁻¹)
Austrian/Czech Republic border

~2km
JUNE 2011
12-week composite

ET/PET anomaly (2009-2012 baseline)
2004

Global monitoring (MODIS – 50km)

Annual average ET/PET

InterDrought Workshop, Feb 2014
APRIL 2010
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
JULY 2010
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
AUGUST 2010
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
MAY 2011
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
AUGUST 2011
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
MAY 2012
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
JUNE 2012
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
JULY 2012
12-week composite

ET/PET anomaly (2009-2012 baseline)

ET/PET standardized anomaly (2000-2011 baseline)
AUGUST 2012
12-week composite

ET/PET anomaly
(2009-2012 baseline)

ET/PET standardized anomaly
(2000-2011 baseline)
Satellite Evapotranspiration

- Monitoring water use at field to continental scales
- Land-surface temperature conveys early warning of vegetation stress
- Independent check on precipitation- and vegetation index-based drought indices
- Applications in global water and food security

hrsl.arsusda.gov/drought
**DRIVERS**

- Air temp
- Dewpoint depression
- Wind
- Cloud cover

**RESPONSES**

- USDМ
  - ESI – 2WK
  - ESI – 4WK
  - ESI – 8WK
  - Accum precip anomaly

*ESI Change over NE Oklahoma*

*InterDrought Workshop, Feb 2014*