Monitoring Evapotranspiration Over Arid Lands of the U.S. Southwest

Andrew N. French\textsuperscript{1}, Juan Manuel Sanchez\textsuperscript{2}, Vicente Garcia-Santos\textsuperscript{3}, Enric Valor\textsuperscript{3}, Cesar Coll\textsuperscript{3}, Kelly Thorp\textsuperscript{1} & Tom Schmugge\textsuperscript{4}

1. USDA/ARS Maricopa, AZ
2. Univ Castilla La Mancha
3. Univ Valencia
4. NMSU/ret.
Need for Arid Land Evapotranspiration Remote Sensing Research

- Increasing population in water scarce regions
- Drought & climate change exacerbating water supplies
- Irrigated agriculture in arid lands are highly productive but will be the first to sacrifice water use.
- Ag. Use 40% of freshwater withdrawals (Hutson et al. 2004)
- Irrigated crops 53% of market value on 17% of crop land (Clemmens et al., 2008)
- Trend: In Arizona annual water supply 2.4 M ac-ft; enough to support 8 M people with no agriculture (Watering the Sun Corridor, Morrison Inst. Public Policy 2011)
- Remote sensing is only way to synoptically observe & estimate land cover and water use changes.
Need for High Spatial & Temporal Resolution

• Arid Lands are highly heterogeneous in space and time
• For water use studies mixed-pixels poorly represent actual conditions
• Better than 100 m needed for VNIR and TIR
• Remote sensing cannot be part of a decision support system if land and water use changes are not up-to-date
• Daily to weekly estimates for croplands, weekly to monthly for rangelands.
Need for Multispectral/Hyperspectral Remote Sensing

- More accurate energy balance estimates
- Better land cover discrimination
- Observe land surface changes and states unobservable with single or several broadband channels
Energy Balance Modeling for Water Use Estimation

\[ R_n - G = H + LE \]

Available Turbulent Flux

- Physically based
  - Generality
  - Estimates closely linked to vegetation/soil/atmospheric processes & detects water stress vegetation
  - Complex & computationally demanding
- Empirical & Parameterized
  - Locally calibrated
  - Applies to standardized conditions

\[
LE = \frac{\Delta}{\Delta + \gamma} [R_n - G] + \frac{\gamma}{\Delta + \gamma} \rho c_p \left[ e^* - e_a \right] / r_a
\]

Penman-Monteith ET (N.B.- no surface temperature)
Available Energy: Net Radiation

\[ R_n = (1 - \text{albedo})R_{\text{solar}} + \varepsilon_{\text{air}} R_{L\downarrow} - \varepsilon_{\text{surface}} L_{BB,\uparrow} \]

- Single most important component of surface energy balance
- HyspIRI design can improve estimation of \( R_n \) beyond broadband sensors
- Error/uncertainty needs to be less than 10%
- Shortwave component dominant term & can be improved with hyperspectral VNIR
- Surface longwave component also important and dependent upon accurate land surface emissivities
Available Energy: Soil Heat Flux

Remote sensing can’t directly retrieve G
Typically estimated with Rn and vegetation index
Diurnally variable with time lag
Small : < 50 W m⁻²
G = c * Rn_soil
Turbulent Energy Flux: Sensible Heat

Energy flux due to surface temperature gradients
Can be estimated using remotely sensed thermal infrared
Sensible heat related to surface and sub-surface water content
Linked in a non-trivial way to radiometric temperature

\[ H = \rho \ c_p \ \Delta T / (r_a + r_s) \]
Turbulent Energy Flux: Latent Heat
-> Evapotranspiration <-

- Component of surface energy balance representing conversion of liquid water to vapor from soil and plants
- Indicator of plant water use and plant water stress
- Estimated from energy balance residual
- Current ET model examples: SEBAL/METRIC, SEBS, TSEB

\[ LE_C = f_g \alpha \left[ \frac{\Delta}{\Delta + \gamma} \right] R_{n,C} \]

\[ H \approx H_{soil}(\Delta T) + H_{canopy}(PT) \]

\[ LE_S = R_{n,S} - G - \rho c_p \frac{T_s - T_a}{r_a + r_s} \]

\[ LE = R_n - G - \rho c_p \left[ \frac{\Delta T}{r_a} \right] \]
Energy balance modeling to get daily ET

LST  NDVI  Emissivity

+Land Use
+Meteorology+

H  LE

ASTER 6 Oct 2002
## ET estimates at 90 m Resolution

<table>
<thead>
<tr>
<th>Site</th>
<th>H</th>
<th>LE</th>
<th>G</th>
<th>(R_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>411 (7)</td>
<td>0</td>
<td>92 (2)</td>
<td>505 (1)</td>
</tr>
<tr>
<td></td>
<td>377</td>
<td>8</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Transition (Bowen)</td>
<td>419 (7)</td>
<td>0</td>
<td>88 (2)</td>
<td>509 (1)</td>
</tr>
<tr>
<td></td>
<td>326</td>
<td>91</td>
<td>121</td>
<td>538</td>
</tr>
<tr>
<td>Mesquite</td>
<td>418 (35)</td>
<td>0</td>
<td>89 (8)</td>
<td>508 (7)</td>
</tr>
<tr>
<td></td>
<td>364</td>
<td>22</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

ASTER TSEB  Ground Observation
Emissivity Contrast at Jornada

Emissivity data are dynamic
Provide additional information about the land surface
Obtainable only from multispectral TIR

-May 15
-Aug 10
-Sep 20
-Oct 6

-Soil moisture effects
-Atmospheric correction errors
Remote Sensing of ET with Multispectral TIR Dynamic Emissivity & Land Cover Change

Jornada Emissivity Change

New Mexico State University Ranch

Emissivity Uncertainty Simulation

2001  2002  2003

200 m extract
MASTER Confirms Emissivity Changes

6-12 m resolution

May 2001  May 2002  May 2003
Importance of Spatial Resolution: Scaling of Land Surface Temperatures

- Most of LST dynamic range lost ~50m
- LST contrast loss mainly over cooler surfaces
- HyspIRI resolution will discriminate land used changes, but not individual shrubs
- Loss of range needs to be considered when modeling surface energy fluxes
NDVI an Unsatisfactory LST Estimator

Rangeland has limited NDVI range
Cropland has broad variance of LST
Cannot discriminate plant stress

Slope is time of day dependent
Emissivities May Help Disaggregation

\[ LST = k \left[ b_0 + b_1 \text{NDVI} \right] + (1 - k) \left[ c_0 + c_1 \text{Emiss} \right]. \]
ET Estimation for Croplands

- Integration of multiple sensors, ground-based information & models required
- Decision support tools require <weekly estimates & spatial resolution <
Remote Sensing of ET with Simulated HyspIRI

- Implement ET methodology at 60m using MASTER data (11 Flights 1999-2010) and AVIRIS (6 flights 1998-2002)
- Investigate ways to improve LST retrieval for low emissivity contrast surfaces
- Incorporate hyperspectral data to improve vegetation detection, classification and albedo
Conclusions

• Finding accurate ways to estimate ET is vital for monitoring water use & building decision support tools to manage freshwater supplies.

• Remote sensing essential for global scale studies

• HyspIRI will advance these goals by providing frequent high spectral & spatial resolution spanning multiple thermal bands & contiguous VSWIR bands needed for resolving the surface energy balance components.
ASTER Composite over Jornada 2001-2003
Update ET estimates beyond Remote Sensing Times

- Image data not available frequently enough, nor with sufficient resolution
- Background crop model constrains growth to physiological plausible ranges
- But process model not spatial, so need image data to map ET
- Update with observables such as LAI and LST
Land surface temperature modeling

7 Parameter Composite Diurnal Function
- Day length
- Time of maximum temperature
- Time of cosine/exp transition
- Newton cooling decay constant
- Residual temperature difference
- Temperature at sunrise
- Temperature amplitude

\[
T(t) = \begin{cases} 
T_0 + T_a \cos \left[ \frac{\pi}{\omega} (t - t_m) \right] & t < t_s \\
(T_0 + \delta T) + \left[ T_a \cos \left[ \frac{\pi}{\omega} (t_s - t_m) \right] - \delta T \right] \exp^{-\frac{(t-t_s)}{\kappa}} & t \geq t_s
\end{cases}
\]
How to extrapolate spatially distributed plant cover?

• Updates needed at least weekly
• Some (most?) process models don’t handle spatial effects
  • Extrapolation needed for 2-week periods
• Model needs to accommodate plot means and variabilities
LST Disaggregation & Diurnal LST/NDVI variability

19 hour (UTC)

LST = 329.78 - 41.85(NDVI)

DOMAIN: 91 - 126 W, 25 - 43 N

\[ \frac{d(LST)}{d(NDVI)} \]
How to Spatially Extrapolate Land Surface Temperatures?

• Empirical approach scales ground observations based on vegetative cover

LST’s observations from 2-min radiometric observations of plant/soil
Partitioning of Composite Radiometric Temperature

\[ T_4 = f \cdot T_{\text{veg}4} + (1-f) \cdot T_{\text{soil4}} \]

- Need additional information to solve
- Sensitive to errors when one fraction is < 0.2
- Some compensation due to corresponding decrease in component $R_n$