Evaluation of a MODIS Triangle-based Algorithm for Improving ET Estimates in the Northern Sierra Nevada Mountain Range

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Motivation

- Disturbances (urbanization, wildfire, and climate change) alter landscapes, land-atmosphere interactions and hydrologic behavior
- Remote sensing provides key information about pre- and post-disturbance environments
- Critical for spatial and temporal monitoring of long-term response

Goal

- Develop and test popular remote-sensing based ET methods to obtain an ET product feasible for operational use in altered systems where little gaged data exists
  - SSEB\textsubscript{op} (Operational Simplified Surface Energy Balance) (Senay et al., 2013)
  - MODIS MOD16* (Mu et al., 2007)
  - MODIS Triangle Method (Wang et al., 2001; Kim and Hogue, 2013)

Approach – MODIS Triangle Method

- MODIS products are used in developed independent, stand-alone algorithms and detection methods for:
  - Net Radiation (SW and LW parameters) (Kim and Hogue, 2008)
  - Evapotranspiration (ET) (Kim and Hogue, 2012a, 2012b, 2013)
- Algorithms and methods are applied over a small region in the Northern Sierra Nevada Mountain Range
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*Product downloaded from Montana’s Numerical Terradynamic Simulation Group (ftp.ntsg.umt.edu/pub/MODIS/Mirror/MOD16/)
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Estimation of ET (LE)

\[ EF = \frac{LE}{(R_n - G)} \]
Estimation of ET (LE)

\[ LE = EF(Rn - G) \]

All values can be estimated on a regional scale for all sky conditions using only satellite based data.
Estimation of ET (LE)

\[ \text{LE} = \text{EF} (\text{Rn} - G) \]

**MODIS Products**

- **MYD03**
  - Geolocation

- **MYD05**
  - Water Vapor

- **MYD06**
  - Cloud Fraction
  - Cloud Optical Thickness
  - Surface Temperature

- **MYD07**
  - Total Ozone
  - Air Temperature
  - Dew Point Temperature

- **MYD11**
  - Emissivity
  - LST

Net Radiation (Rn)

\[ \text{R}_\text{net} = \text{SW} \downarrow (1 - \text{Alb}) \text{CC} + \text{LW} \downarrow - \text{LW} \uparrow \]

(Bisht and Bras, 2010; Kim and Hogue, 2008, 2013)

\[ \frac{R_s(1 + \cos(2z))}{2(1.085 \cos(z) + 0.001e_0(2.7 + \cos(z)) + 0.2)} \]

\[ z = \text{zenith angle} \]
\[ e_0 = \text{water vapor pressure} \]
\[ f(\text{air temp., dew point temp.}) \]

\[ CC = (1 - C_f) + \left( C_f \exp \left( \frac{C_{opt}}{\cos(z)} \right) \right) \]

\[ C_f = \text{cloud fraction} \]
\[ C_{opt} = \text{cloud optical thickness} \]

\[ \text{LW} \downarrow = \varepsilon_a T_a^4 + (1 - \varepsilon_a) \varepsilon_c T_c^4 \]

\[ \varepsilon_a = \text{air emissivity} \]
\[ \varepsilon_c = \text{cloud emissivity} \]
\[ T_a = \text{air temperature} \]
\[ T_c = \text{cloud temperature} \]

\[ \text{LW} \uparrow = \varepsilon_s T_s^4 \]

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Estimation of ET (LE)

$$LE = \text{EF}(R_n - G)$$

### Net Radiation (Rn)

$$R_{\text{net}} = SW \downarrow (1 - \text{Alb})CC + LW \downarrow - LW \uparrow$$

*Bisht and Bras, 2010; Kim and Hogue, 2008, 2013*

$$SW \downarrow = \frac{R_s(1 + \cos(2z))}{2(1.085 \cos(z) + 0.001e_0(2.7 + \cos(z)) + 0.2)}$$

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$$LW \downarrow = \varepsilon_a T_a^4 + (1 - \varepsilon_a)\varepsilon_c T_c^4$$

$$\varepsilon_a = \text{air emissivity}$$

$$\varepsilon_c = \text{cloud emissivity}$$

$$T_a = \text{air temperature}$$

$$T_c = \text{cloud temperature}$$

### Ground Heat Flux (G)

$$G = \frac{T_s}{\text{Alb}}(0.0038\text{Alb} + 0.0074\text{Alb}^2)(1 - 0.98\text{NDVI}^4)$$

$$T_s = \text{surface temperature}$$

$$\text{Alb} = \text{Albedo}$$

### MODIS Products

- **MYD03** Geolocation
- **MYD05** Water Vapor
- **MYD06** Cloud Fraction
- **MYD07** Total Ozone
- **MYD11** Emissivity
- **MOD13/MYD13** NDVI
- **MYD43** Albedo
Estimation of ET (LE)

\[ \text{LE} = \text{EF}(\text{R}_n - G) \]

**Net Radiation (Rn)**

\[ R_{\text{net}} = \text{SW} \downarrow (1 - \text{Alb})\text{CC} + \text{LW} \downarrow - \text{LW} \uparrow \]

*Bisht and Bras, 2010; Kim and Hogue, 2008, 2013*

\[
\begin{align*}
\text{SW} \downarrow &= \frac{R_s(1 + \cos(2z))}{2(1.085 \cos(z) + 0.001e_0(2.7 + \cos(z)) + 0.2)} \\
&\quad \text{z = zenith angle} \\
&\quad e_0 = \text{water vapor pressure} \\
\text{f(air temp., dew point temp.)} &= f(T_a, T_{\text{dew}}) \\
\text{CC} &= (1 - C_f) + \left(C_f \exp\left(C_{\text{opt}}/\cos(z)\right)\right) \\
C_f &= \text{cloud fraction} \\
C_{\text{opt}} &= \text{cloud optical thickness} \\
\text{LW} \downarrow &= \varepsilon_a T_a^4 + (1 - \varepsilon_a)\varepsilon_c T_c^4 \\
&\quad \varepsilon_a = \text{air emissivity} \\
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\text{LW} \uparrow &= \varepsilon_s T_s^4 \\
&\quad \varepsilon_s = \text{surface emissivity} \\
&\quad T_s = \text{surface temperature} \\
\]

**Ground Heat Flux (G)**

*(SEBAL; Bastiaanssen et al., 1998)*

\[ G = \frac{T_s}{\text{Alb}} (0.0038\text{Alb} + 0.0074\text{Alb}^2(1 - 0.98\text{NDVI}^4)) \]

*Ts = surface temperature*  
*Alb = Albedo*

**Evaporative Fraction (EF)**

*(Wang et al., 2006; Kim and Hogue, 2013)*

\[ \text{EF} = \alpha \frac{\Delta}{\Delta + \gamma} \]

*\gamma = \text{psychrometric constant}*

\[
\Delta = \frac{26297.77}{(T_a - 29.65)^2} \exp\left(\frac{17.67(T_a - 273.15)}{T_a - 29.65}\right) \\
&\quad T_a = \text{air temperature} \]
Evaporative Fraction (EF) – Triangle Method

EF = $\frac{\Delta}{\Delta + \gamma}$

- $\Delta T_{max}$
- $\Delta T_{i}$
- $\Delta T_{min}$

$\alpha_{min} = 0$

Water Stressed Conditions in Root Zone Soil Water Content

Observed Dry Edge

Observed Wet Edge

Sufficient Water Conditions

$\alpha_{max} = 1.26$

+Tang et al., 2010
*Wang et al., 2006
**Jiang & Islam (2001)
Evaporative Fraction (EF) – Triangle Method

\[ EF = \frac{\Delta}{\Delta + \gamma} \]

\[ \alpha = \frac{\Delta T_{\text{max}} - \Delta T_i}{\Delta T_{\text{max}} - \Delta T_{\text{min}}} (\alpha_{\text{max}} - \alpha_{\text{min}}) + \alpha_{\text{min}} \]

\[ \alpha_{\text{min}} = 1.26 f_{\text{veg}} = 1.26 \frac{EVI_i - EVI_{\text{min}}}{EVI_{\text{max}} - EVI_{\text{min}}} \]

\[ \alpha_{\text{max}} = 1.26 \]

*Tang et al., 2010
*Wang et al., 2006
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Evaporative Fraction (EF) – *Triangle Method*

\[
EF = \alpha \frac{\Delta}{\Delta + \gamma}
\]

\[
T = \left( \frac{T_s^4}{\cos \gamma} \right)^{1/4}
\]

**Cosine Method:**
Corrects for terrain-induced angular effects

\[
\alpha_i = \frac{\Delta T_{max} - \Delta T_i}{\Delta T_{max} - \Delta T_{min}} \left( \alpha_{max} - \alpha_{min} \right) + \alpha_{min}
\]

\[
\alpha_{min} = 1.26 f_{\text{veg}} = 1.26 \frac{EVI_i - EVI_{min}}{EVI_{max} - EVI_{min}}
\]

\[
\alpha_{max} = 1.26
\]

8 Day-Night Temperature Difference*

\[\Delta T_{max}\]

\[\alpha_{min} = 0\]

\[\alpha_{min, i}\]

Water Stressed Conditions in Root Zone Soil Water Content

\[\Delta T_i\]

Observed Dry Edge

\[\Delta T_{min}\]

\[\alpha_{max, i}\]

Sufficient Water Conditions

\[\alpha_{max} = 1.26\]

\[\text{Observed Triangular Domain}\]

* Tang et al., 2010
* Wang et al., 2006
** Jiang & Islam (2001)
Study Area – Sagehen Watershed

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Vegetation</th>
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<tr>
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<td>39.43143</td>
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<td>Shrub/Scrub</td>
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<td>Site 8</td>
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<td>Site 11</td>
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<td>Shrub/Scrub</td>
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Snow Depth (NOAA NOHRSC)

<table>
<thead>
<tr>
<th>Water Year</th>
<th>Standardized Precipitation Index (SPI)</th>
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</thead>
<tbody>
<tr>
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<td>2005</td>
<td></td>
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<td>2010</td>
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</tr>
</tbody>
</table>
Study Area – *Sagehen Watershed*

- USFS GTR 237: Managing Sierra Nevada Forests to restore natural forest structure (North et al., 2012)
- Sagehen Experimental forest management prototype for the Sierra Nevada
  - Treatments started summer 2014
- Evaluate variability in fuel treatments and corresponding water yield response
- Understand altered annual and seasonal water budgets
Study Area – Sagehen Watershed

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Similar $R_n$, less canopy, and less interception will alter:

- Snow Regimes (melt & timing)
- Evapotranspiration (ET)
- Sublimation
- Runoff and Water Yield
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*Similar $R_n$, less canopy, and less interception will alter:*

- Snow Regimes (melt & timing)
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- Runoff and Water Yield
Validation - Net Radiation ($R_{\text{net}}$)

- Daily
- 250m Resolution
- Years 2010 - 2014

- Model systematically underestimates surface net radiation
Validation - Net Radiation ($R_{net}$)

**Kim and Hogue, 2013**
Validation – 8 day Average Actual ET

- Slight over-estimations (Sites 1 & 3)
- Fraval Sandy Loam – moderately deep and well-drained
Validation – 8 day Average Actual ET

**Kim and Hogue, 2013**
Validation – Monthly Actual ET

- Monthly total ET (mm/month)
- 1 km Resolution

- Poor Performance by MOD16
- SSEBop and MODIS Triangle Method show improved estimations to that of MOD16
Validation – Monthly Actual ET

- **Graphs**
  - Site 1: 2010-2013
  - Site 3: 2010-2013
  - Site 8: 2010-2013
  - Site 11: 2010-2013

- **Bar Charts**
  - RMSE (mm/month)
  - Correlation (R)
  - Bias (mm/month)

- **Legend**
  - MODIS Triangle
  - MOD16
  - SSEB<sub>op</sub>
Concluding Remarks

• ET is arguably one of the most difficult hydrologic components to estimate given its dependence on a range of climatological parameters (i.e. solar radiation, temperature, wind speed, vapor pressure, etc.).

• Methods show the ability to accurately estimate ET with improved spatial and temporal scale in remote data sparse regions.

• Methods also show promise in an ability to monitor land cover change and disturbances such as regional treatments using remotely sensed products.

• The continuation of rapid landscape alterations due to climate change, urbanization and forest fire, among others, provide the motivation to continue improving remote sensing techniques in estimation of ET and other hydro-meteorological parameters for operational use.
Thank You!

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Relevant Group Work


Additional Citations