Drought monitoring in the Sahel using Earth Observation data: Evaluation of two global process-based models

Monica García¹, ², Mu Qiaozhen³, Ceccato Pietro¹, Ardö⁴ Jonas., Mougin Eric⁵, Kergoat Laurent⁵, Timouk Franck⁵, Sandholt Inge², and Joshua Fisher⁶.

¹International Research Institute for Climate & Society. Columbia University, New York, USA. mggarcia@iri.columbia.edu
²Department of Geography & Geology, University of Copenhagen, Denmark
³Numerical Terradynamic Simulation Group, Department of Ecosystem and Conservation Sciences, The University of Montana, USA.
⁴Dept of Physical Geography. Lund University, Sweden.
⁵Géosciences Environnement Toulouse (GET), France.
⁶NASA-Jet Propulsion Laboratory, California Institute of Technology, USA.
Drylands: annual evaporative demand exceeds rainfall

In **arid and semiarid regions**, around 90% of annual rainfall is returned to the atmosphere through evapotranspiration (Glenn et al. 2007).

Cover more than 41% of the Earth surface and around 35% of the population, high vulnerable to droughts and climate changes
The Sahel region

The Sahel is the transition region between the Sahara desert and the more wetter savannas in the South (250-1000 mm)

Making spatial information available on evapotranspiration for hydrology, agriculture and warning systems...

Source: NOAA-GHCN

Huber et al., 2011
Danish project CalM: Earth Observation of land surface moisture in Africa

**Aim**: Develop an **evapotranspiration and a wetness index** product for the Sahel relying on optical and thermal data

Evapotranspiration $\Rightarrow$ EF = Evapotranspiration /Available Energy

**Requirements:**

- Daily/weekly time step
- No calibration with field data
- Consideration of soil and vegetation fluxes explicitly
- Minimal use of climatic inputs (reanalyses)
- Spatial resolution 1-4 km.
Global evapotranspiration model: MOD16.

Penman-Monteith evapotranspiration

Vegetation

Available Energy ($A$) partitioned proportionally to vegetation cover $f_c = f_{PAR}^{MODIS}$

$$A_c = A - A_{soil}$$

$$LE_c = \frac{sA_c + (\rho c_p D / r_a)}{s + \gamma (1 + r_c / r_a)}$$

Surface conductance

$$r_c = LAI \cdot [r_{min} \cdot m(T_{min}) \cdot m(VPD)]$$

Bare soil

$$A_{soil} = (1 - f_c) \cdot A$$

$$LE_s = LE_{Ps} \cdot f_{SM}$$

Soil moisture

$$f_{SM} = RH^{V_{PD} \beta}$$

New model version: nighttime evapotranspiration, ra, new interception evapotranspiration term based on Biome-BGC (Thornton, 1998)  

Mu et al., 2007, 2011
Model PT-JPL: Priestley-Taylor JPL model

Two layer Priestley-Taylor potential evapotranspiration equation is reduced according to multiple stresses.

\[
\lambda E = \lambda E_c + \lambda E_s
\]

\[
\lambda E_c = f_g \cdot f_T \cdot f_M \cdot \alpha \frac{\Delta}{\Delta + \gamma} (Rn - Rn_s)
\]

\[
\lambda E_s = f_{SM} \cdot \alpha \frac{\Delta}{\Delta + \gamma} (Rn \cdot \exp(-k_{Rn} \cdot LAI)) - G
\]

- Requires VPD and RH to estimate \( f_{SM} \).
- Evaluated already in 36 eddy-sites. None with rainfall below 400 mm
- Originally applied at monthly time step

(Fisher et al., 2008)
Two steps

1. **Field level:**
Adapt the PT-JPL model in dryland ecosystems: **in situ data**

   New soil moisture constraint: **Apparent thermal Inertia**

   \[ ATI = C \frac{1 - \alpha}{T_{R_{-DMax}} - T_{R_{-Dmin}}} \]

   Verstraeten et al., 2006

2. **Satellite level:**
Evaluate the JPL-PT and MOD16 models forced with same satellite and reanalyses data at eddy flux sites.
1. Field level: Adapting the JPL-PT model

Two semiarid sites with in–situ $T_R$ and different precipitation regimes

- **Agoufou (Mali)**
  - Grassland savanna ($fc=0.5$, $hc_{\text{max}}=0.4$)
  - Trees $<5\%$ fraction cover
  - Annual precipitation: 375 mm
  - Rainy season: June to Sept
  - In-situ $T_R$
    (thermal infrared Everest 4000)

- **Balsa Blanca (Spain)**
  - Mediterranean grassland ($fc=0.6$, $hc=0.7$)
  - Annual precipitation: 370 mm (highly variable)
  - In-situ $T_R$
    (thermal infrared Apogee IRTS-P)
1. Field level: JPL-PT model: model inputs

Sensor MODIS
(Terra & Aqua)

Sensor SEVIRI
(MSG Meteosat second generation)

Field data

NDVI: 16 days, pixel 250 m
LAI:

8 days, pixel 1 Km

\( f_{PAR} \):

\( T_R \): 15 minutes, pixel 3Km

\( \alpha \): daily average, pixel 3Km

\{ Rn, G, Tair, RH, T_{in-situ} \}

Interpolation to get daily
1. Field level: soil moisture constraint JPL-PT model

Using $f_{SM-SWC}$:

$$f_{SM-SWC} = 1 - \left( \frac{SWC - SWC_{min}}{SWC_{Max} - SWC_{min}} \right)$$

Mediterranean grassland

Grassland savanna

Eddy C: 20% uncertainty (daily)

Eddy C: 9% uncertainty (daily)

(Garcia et al., 2013, RSE)
1. Field level: soil moisture constraint JPL-PT model

Using $f_{SM-Fisher}$:

$$f_{SM-Fisher} = RH^{VPD} \beta$$

High sensitivity to:
- Value of $\beta$
- Temporal step of RH and VPD

**Mediterranean grassland**

$R^2 = 0.17$

$\beta = 0.1 \text{kPa}$

VPD and RH midday

$R^2 = 0.53$

**Grassland savanna**

$R^2 = 0.62$

$\beta = 1 \text{kPa}$

VPD and RH daily

$R^2 = 0.80$

(Garcia et al., 2013, RSE)
Using $f_{SM-ATI}$:

$$
    f_{SM-ATI} = \frac{ATI - ATI_{min}}{ATI_{Max} - ATI_{min}}
$$

Mediterranean grassland (Balsa Blanca)

Grassland savanna (Agoufou)

\[ R^2 = 0.57 \]

\[ R^2 = 0.83 \]

$T_R \gamma \alpha$ (in situ)

(Garcia et al., 2013, RSE)
2. Satellite level: JPL-PT and MOD16 comparison

Accuracy of the two models using only satellite and climatic reanalysis data

- To estimate evapotranspiration and evaporative fraction
- At daily and 8-time step

AGOUFOU (MALI)

DEMOKEYA (SUDAN)
2. Satellite level analyses in the Sahel

**Sudan (Demokeya)**

- **Site name (location):** Demokeya
- **Vegetation type:** Sparse savanna grassland
- **Mean annual rainfall:** 320 mm
- **Dominant herbaceous species:** Aristida pallida, Eragrostis tremula and Cenchrus biflorus
- **Dominant woody:** Acacia Senegal (5-10% the cover)
- **Years of field data:** 2007-2008-2009

**Mali (Agoufou)**

- **Site name (location):** Agoufou
- **Vegetation type:** Open woody savannah (natural grassland)
- **Mean annual rainfall:** 375 mm
- **Dominant herbaceous species:** Cenchrus biflorus, Aristida mutabilis
- **Dominant woody:** Acacia raddiana, (5% the cover)
- **Years of field data:** 2007-2008

<table>
<thead>
<tr>
<th>Site name (location)</th>
<th>Vegetation type</th>
<th>Mean annual rainfall</th>
<th>Dominant herbaceous species</th>
<th>Dominant woody</th>
<th>Years of field data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agoufou (Mali)</td>
<td>Open woody savannah (natural grassland)</td>
<td>375 mm</td>
<td>Cenchrus biflorus, Aristida mutabilis</td>
<td>Acacia raddiana, (5% the cover)</td>
<td>2007-2008</td>
</tr>
<tr>
<td>Demokeya (Sudan)</td>
<td>Sparse savanna grassland</td>
<td>320 mm</td>
<td>Aristida pallida, Eragrostis tremula and Cenchrus biflorus</td>
<td>Acacia Senegal (5-10% the cover)</td>
<td>2007-2008-2009</td>
</tr>
</tbody>
</table>
2. Satellite level analyses: Model inputs

- Climatic reanalyses data from MERRA GMAO (NASA reanalysis GEOS-5): *Tair, VPD, RH, SW incoming*

- Land Surface Temperature and emissivity (MODIS 8day MOD11A2)

- Vegetation products: MODIS NDVI, LAI/fPAR (MOD15A2), Albedo (MODIS MOD43C1) (10th band of White-Sky-Albedo)
## 2. Satellite level: model runs

<table>
<thead>
<tr>
<th>ALGORITHM</th>
<th>Forcing variables</th>
<th>MODEL NAME</th>
<th>Available energy</th>
<th>Tair, Swinc</th>
<th>$f_{SM}$ Soil moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOD16 (Mu et al., 2011)</td>
<td>Satellite</td>
<td>1. MOD16 (MERRA)</td>
<td>1. $f$(Tair, Swinc) Mu et al., 2011</td>
<td></td>
<td>$f$(VPD, RH)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. PT-JPL (moist. MODIS, MERRA, Rn Mu)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT-JPL $f_{SM-ATI}$ (Garcia et al., 2013)</td>
<td>satellite &amp; in situ</td>
<td>3. PT-JPL (moist. MODIS, MERRA, Rn Bisht)</td>
<td>2. $f$(Ts, $\alpha$, $\varepsilon$, Tair, Swinc, latlon) Bisht et al., 2008</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Satellite level results: Daily evapotranspiration

**MALI**
- LE_eddy
- MOD16 (MERRA) $r=0.79$
- PT-JPL (moist. MODIS, MERRA, Rn Mu) $r=0.77$

**SUDAN**
- LE eddy
- MOD16 (MERRA) $r=0.61$
- PT-JPL (moist. MODIS, MERRA, Rn Mu) $r=0.57$

---

**MALI**
- LE_eddy
- PT-JPL (moist. MODIS, field) $r=0.93$
- PT-JPL (moist. MODIS, MERRA, Rn Bisht) $r=0.76$

**SUDAN**
- LE eddy
- PT-JPL (moist. MODIS, field) $r=0.80$
- PT-JPL (moist. MODIS, MERRA, Rn Bisht) $r=0.79$

---

**MALI**
- LE_eddy
- PT-JPL (moist. MODIS, field) $r=0.93$
- PT-JPL (moist. field SWC, field) $r=0.83$

**SUDAN**
- LE eddy
- PT-JPL (moist. MODIS, field) $r=0.80$
- PT-JPL (moist. field SWC, field) $r=0.84$
2. Satellite level: evapotranspiration daily

Shaded = Not any field data inputs (only satellite and MERRA)
2. Satellite level. 8day evapotranspiration
Wetness index: Evaporative fraction $EF = \frac{LE}{A \cdot E}$.
Satellite level: relation with rainfall?

**SUDAN-Agoufou**

**MALI-Demokeya**

**SUDAN 8day**

**MALI 8-day**
Conclusions

• Potential for regionalization of LE (daily and 8day) and EF (8day) using the PT-JPL model with an Apparent Thermal Inertia index for soil moisture (1 km).
  
  No need of VPD. Meteorological inputs: Tair and Solar irradiance.

• MOD16 less robust than the PT-JPL model, especially for EF, but similar to PT-JPL evapotranspiration at 8day time scale.

• Both models better and more robust performance in Mali than Sudan, especially MOD16.
Future research

- Correct biases: Incoming radiation, cloudy days, soil moisture non-linear relationships.
- Model intercomparisons: participation in ALMIP validation (AMMA)
- Incorporate new spectral information: SWIR, PRI
- Regionalization and new sites (Dahra, Senegal)
Acknowledgements

- **CaLM project.** Danish Council for Independent Research and Technology and Production Sciences (FTP)
- **CARBORAD project** CGL2011-27493 (Plan Nacional MICINN, pain).
- Field data for the savanna site in Mali were collected within the frame of the **AMMA project** ([www.amma-eu.org](http://www.amma-eu.org)). The Malian site belongs to the **AMMA-CATCH observatory** ([www.amma-catch.org](http://www.amma-catch.org)). Field data from the Sudan site were collected within the EU-funded **CARBOAFRICA** project (contract 037137)
- **MODIS data** were obtained through the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science Center, Sioux Falls, South Dakota ([http://lpdaac.usgs.gov/get_data](http://lpdaac.usgs.gov/get_data)).
- **MSG-SEVIRI data** were provided by EUMETSAT
- We acknowledge Rado Gucinski, Simon Proud, Hector Nieto, Marc Ridler and Paula Gonzalez for their help during this work.
Thanks!

Dahra 2011, Senegal
1. Field analyses: Sensitivity analyses
Field level: Adapting the JPL-PT model

Which are the key model parameters? Sensitivity analyses

Extended Fourier Amplitude Sensitivity Test (EFAST)
Allows input variables to vary simultaneously considering interactions. A Fourier decomposition is used to obtain the contribution of the factors to the variance (Saltelli et al., 1999).

(Garcia et al., 2013, RSE)
COMPARISON MERRA AND FIELD VARIABLES
year: 2007 : \( r^2 = 0.8338; \ r = 0.9131, \ p = 00.0000; \ y = -1.9723 + 1.042\times \)
year: 2008 : \( r^2 = 0.8500; \ r = 0.9220, \ p = 00.0000; \ y = -3.6377 + 1.0798\times \)
year: 2009 : \( r^2 = 0.8806; \ r = 0.9384, \ p = 00.0000; \ y = -0.817 + 0.9766\times \)
1. Field analyses: $T_s$ in-situ and SEVIRI

**Sahelian savanna**

$r^2 = 0.86$; 
MAE=1.56 °C; bias=-0.42 °C

**Mediterranean grassland**

$r^2 = 0.88$; 
MAE=2.43 °C; bias=1.44 °C
Incoming solar radiation
Comparison with other models in savanna ecosystems

<table>
<thead>
<tr>
<th>Country</th>
<th>Lat °</th>
<th>Lon °</th>
<th>Climate type</th>
<th>Model type</th>
<th>r²</th>
<th>MAE</th>
<th>RMSE</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mali</td>
<td>15.34, -1.48</td>
<td>BWh</td>
<td>Fisher-daily ( f_{SM} )</td>
<td>0.80</td>
<td>20.21</td>
<td>26.53</td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>15.34, -1.48</td>
<td>BWh</td>
<td>SVAT in-situ calibration</td>
<td>0.81</td>
<td>16.57</td>
<td>9.90</td>
<td>Ridler et al., 2012</td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>15.34, -1.48</td>
<td>BWh</td>
<td>SVAT satellite calibration</td>
<td>0.63</td>
<td>39.24</td>
<td>46.66</td>
<td>Ridler et al., 2012</td>
<td></td>
</tr>
<tr>
<td>Senegal</td>
<td>15.41, -15.47</td>
<td>BWh</td>
<td>Triangle using SEVIRI/MODIS</td>
<td>0.75</td>
<td>-</td>
<td>31.00</td>
<td>Stisen et al., 2007</td>
<td></td>
</tr>
<tr>
<td>Sudan</td>
<td>13.28, -0.48</td>
<td>BWh</td>
<td>Sim-ReSET using SEVIRI/MODIS</td>
<td>0.73</td>
<td>26.00</td>
<td>-</td>
<td>Sun et al., 2011</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>146.55, -19.88</td>
<td>Aw</td>
<td>PM- in situ meteorological calibration</td>
<td>0.23</td>
<td>-</td>
<td>112.1</td>
<td>Cleugh et al., 2007</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>146.55, -19.88</td>
<td>Aw</td>
<td>PML-optimized with hydrological model</td>
<td>0.49</td>
<td>-</td>
<td>15.94</td>
<td>Zhang et al., 2010</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>-12.50, 131.15</td>
<td>Aw</td>
<td>PML-optimized with hydrological model</td>
<td>0.53</td>
<td>-</td>
<td>32.18</td>
<td>Zhang et al., 2010</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>35.40, -111.80</td>
<td>Csb</td>
<td>MOD16. PM new version (old version)</td>
<td>0.06</td>
<td>- (0.42)</td>
<td>23.92 (18.51)</td>
<td>Mu et al., 2011</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>29.9, -98.0</td>
<td>Cfa</td>
<td>MOD16. PM new version (old version)</td>
<td>0.48</td>
<td>- (0.52)</td>
<td>25.91 (30.76)</td>
<td>Mu et al., 2011</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>38.4, -121.0</td>
<td>Csa</td>
<td>MOD16. PM new version (old version)</td>
<td>0.61</td>
<td>- (0.53)</td>
<td>19.08 (21.36)</td>
<td>Mu et al., 2011</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>38.4, -121.0</td>
<td>Csa</td>
<td>PM (field eddy calibration)</td>
<td>0.57</td>
<td>-</td>
<td>19.08</td>
<td>Yuan et al., 2010</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>38.4</td>
<td>Csa</td>
<td>Fisher-daily ( \tau )</td>
<td>0.74</td>
<td>-</td>
<td>19.39</td>
<td>Vinukollu et al., 2011</td>
<td></td>
</tr>
</tbody>
</table>

SVAT MIKE-SHE: data assimilation LST and AMSR-E \( r^2=0.63: \) MAE=39.24 Wm⁻²

![Graph showing LE SVAT MIKE-SHE and LE in situ (eddy) data](image)