Monitoring of evapotranspiration using microwave and optical remote sensing observations: rate limiting factors under different climate conditions

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Outline

• Introduction

• Remote Sensing for Evapotranspiration: algorithms

• Application and requirement

• Summary
Terrestrial Water Cycle
Terrestrial Water Cycle

Simplified Terrestrial Water Balance (from green field geography)
Climate Change Relevance

• “Climate change is expected to intensify the hydrological cycle and to alter ET, but direct observational evidence of a positive trend in global ET is lacking.” (Jung et al., 2010)

Rate ET increased by \(7.1 \pm 1.0\ mm/\text{year/decade}\) for 1982-1997, consistent with expected ‘acceleration’ of hydrological cycle.

Trend becomes negative during 1998-2008 at \(-7.9 \ mm/\text{year/decade}\).
Climate Change Relevance

(Jung et al., 2010)
Basic Concept

• Evapotranspiration (\(ET\)) =
  + Evaporation from bare soil and water surface
  + Transpiration from dry surface of plant
  + Interception (Evaporation from wet surface)
Determining Factors

- **Water supply** (water availability in the soil)
  - Wetness/Dryness of land

- **Water demand** (absorbability of atmosphere)
  - Wetness/Dryness of atmosphere

Jung et al. (2010, Nature): Figure S2. Inferred supply and demand limitation of ET.

A vapor pressure gradient between the evaporating surface and the air.

The rate and quantity of water vapor entering into the atmosphere both become higher in drier air.
Determining Factors

• **Water supply** (water availability in the soil)
  ➔ Wetness/Dryness of land

• **Water demand** (absorbability of atmosphere)
  ➔ Wetness/Dryness of atmosphere

• Sufficient **energy** for phase change (from liquid to vapor)
  ➔ More than half of the solar energy absorbed by land surfaces is used to evaporate water.

• **Aerodynamic forcing** for vapor movement
  ➔ Keep the atmospheric layer above surface unsaturated

• **Plant geometry and physiology:**
  ➔ Total leaf surface area/Plant height
  ➔ Root suction / Stomatal response to environment

Jung et al. (2010, Nature): Figure S2. Inferred supply and demand limitation of ET.
Governing Processes

- ET is a term involving **Surface Energy Balance (SEB)** and **Surface Water Balance (SWB)**

More than 50% of the solar energy absorbed by land surfaces is currently used to evaporate water.

Global land evapotranspiration (ET) returns about 60% of annual land precipitation to the atmosphere.
From remote sensing to ET

**SATELLITE OBSERVATIONS**

Satellites measure:
Radiation coming up from the earth system (surface + atmosphere)

→ ET
## From remote sensing to ET

### SATELLITE OBSERVATIONS

**Optical remote sensing:**
- albedo
- LAI, NDVI, Fc
- LST
- LULC

**Microwave remote sensing:**
- Surface soil moisture

**Radar (and IR):**
- Precipitation

**Hybrid/multi-sensors:**
- Snow cover/snow water equivalent
- Lake area

### Satellites measure:
Radiation coming up from the earth system (surface + atmosphere)
From remote sensing to ET

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Satellites measure:
Radiation coming up from the earth system (surface + atmosphere)

Land surface fluxes, so to ET, do not have a unique signature/signal that can be remotely detected by satellite sensors, so satellite observations need to be combined to infer them.
Governing Equations

• Surface Energy Balance and Energy partitioning:

\[ R_n = H + \lambda E + G_0 \]

\[ H = \rho c_p \frac{T_s - T_a}{R_a} \]

\[ \lambda E = \frac{\rho c_p}{\gamma} \frac{e_s - e_a}{R_a + R_s} \]

- \( R_n \): net radiation flux
- \( H \): sensible heat flux
- \( \lambda E \): Latent heat flux
- \( G_0 \): soil heat flux

- \( R_a \): aerodynamic resistance
- \( R_s \): surface resistance to vapor

- \( T_a, T_s \): aerodynamic temperature of air and surface

- \( e_a, e_s \): water vapor pressure of air and at evaporating surface

- \( u, u_c \): wind speed at reference height above canopy and at canopy average flow height
**Penman-Monteith Equation**

**Potential evaporation**

\[ \lambda E_p = \frac{\Delta (R_n - G_0) + \rho_a c_p (e_s - e) r_e^{-1}}{\Delta + \gamma} \]

**Maximum Evaporation**

\[ \lambda E_{\text{max}} = \frac{\Delta (R_n - G_0) + \rho_a c_p (e_s - e) r_e^{-1}}{\Delta + \gamma (1 + r_{i_{\text{min}}} r_e^{-1})} \]

**Actual evaporation**

\[ \lambda E_a = \frac{\Delta (R_n - G_0) + \rho_a c_p (e_s - e) r_e^{-1}}{\Delta + \gamma (1 + r_i r_e^{-1})} \]

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**Energy constrain**

- \( r_i = 0 \) 
- \( r_i = r_{i_{\text{min}}} \)
- \( r_i \geq r_{i_{\text{min}}} \)
- \( r_i \rightarrow \infty \)

**Available water**

- Climatic water requirements
- Optimal water supply
- Limited water supply

**Water constrain**

- Water stress

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G-WADI workshop: Remote Sensing and Eco-hydrology in Arid Regions
16-20 September, 2013, Beijing, China
Remote Sensing of ET

SATELLITE OBSERVATIONS

Optical remote sensing:
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- LULC

Microwave remote sensing:
- Surface soil moisture

Radar (and IR)
- Precipitation

Governing Equations

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Penman-Monteith Equation

Algorithms/ Models

- **Land Surface Energy Balance (SEB) based methods:**
  
  H is calculated from LST, LE (ET) is calculated as residual of SEB

- **Combined method: Energy Balance + Plant physiology (Penman-Monteith type):**
  
  LE is directly calculated from equations involving evapotranspiration processes (P-M)

- **Contextual method + Energy/water balance**

- **Empirical methods: linking surface heat fluxes to relevant atmospheric/surface observations**
Remote Sensing of ET

A: Land Surface Energy Balance (SEB) based methods:

H is calculated from LST:

\[ H = \rho C_p \frac{(LST - Tair)}{r_{ah}} \]

\[ = f(LST, Tair, windspeed, surface roughness length, atmospheric stability) \]

LE (ET) is calculated as residual of SEB: \[ LE = Rn - G0 - H \]

- SEBI (Menenti and Choudhury, 1993)
- SEBAL (Bastiaanssen, 1995)
- SEBS (Su, 2001)
- TSEB (Norman et al, 1995; Jia 2004)
- Etc

**Land Surface Temperature (LST):** dominant variable

**Soil moisture:** not involved directly but via implication of LST

**Single-source SEB method:**
Soil and vegetation are treated as one entity

**Dual-source SEB method:**
Soil and vegetation are treated separately
Flowchart of Large Scale ET Modeling by SEBS

input

Forcing: Meteorological conditions

RS input

Albedo
NDVI
LAI
Surface temperature

RS/GIS input

Land use map
Vegetation map

Developed by Alterra (ref. Su 2002; Jia et al. 2003)

SEBS model

- SEBI
- Roughness length for momentum z0m
- Roughness length for heat transfer z0h
- MOS
- BAS

output

Instantaneous ET
Vegetation conditions

Daily ET
Gap-filling
Monthly ET
Method A: RS-ET based on SEB

Single-source model

Forcing the inherently 3-D vegetation-soil system to a single layer (source) parameterization of heat and water exchanges with the atmosphere.

Single-source parameterization

Semi-arid environment
(Barrax, Spain, 2004 July)
Method A: RS-ET based on SEB

Single-source model

Error in Sensible Heat Flux due to Uncertainty in Aerodynamic Resistance

Heihe River Basin, north-western China, arid region
Method A: RS-ET based on SEB

Single-source model

Error in Sensible Heat Flux due to Uncertainty in Aerodynamic Resistance

Possible solutions to reduce the error:

Improve Parameterization of resistance for heat transfer using bi-angular satellite observations to capture the thermal anisotropy

ATSR, AATSR (ESA) sensors
(1995 - 2010)

Sentinel-3 (ESA)
(2014 - )
Method A: RS-ET based on SEB

Single-source model

Error in Sensible Heat Flux due to Uncertainty in Aerodynamic Resistance

Possible solutions to reduce the error:

Improve Parameterization of resistance for heat transfer using bi-angular satellite observations to capture the thermal anisotropy

From aerodynamic based algorithm ➔ Thermodynamic based algorithm
Method A: RS-ET based on SEB

Single-source model

Error in Sensible Heat Flux due to Uncertainty in Aerodynamic Resistance

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Improve Parameterization of resistance for heat transfer using bi-angular satellite observations to capture the thermal anisotropy

From aerodynamic based algorithm \(\rightarrow\) Thermodynamic based algorithm

Resistances from

- Aerodynamic based algorithm
- Thermodynamic based algorithm
Method A: RS-ET based on SEB

Single-source model

Resistance: aerodynamic based vs. thermodynamic based algorithm

Heihe River Basin + Qinghai-Tibetan Plateau, north-western China
Arid, semi-arid, semi-humid region

Sensible Heat Flux estimated from AATSR

Aerodynamic based algorithm

Thermodynamic based algorithm

Frequency (%) vs. $k_B^{-1}$ for 2008-06-02
Method A: RS-ET based on SEB

Single-source model

Resistance: aerodynamic based vs. thermodynamic based algorithm

Heihe River Basin + Qinghai-Tibetan Plateau, north-western China
Arid, semi-arid, semi-humid region

Overestimated over arid/semi-arid region

Sensible Heat Flux

Underestimate ET
Method A: RS-ET based on SEB

Dual-source model

TSEB: with component temperatures resolved from energy balance equation (Norman et al, 1995)

DualN95

Dual-source model with component temperatures retrieved from bi-angular radiance measurements (Jia 2004)

DualJia2004

Reference height above canopy $z_{ref}$

Reference height within canopy $z_0$
Method A: RS-ET based on SEB

Energy or water limitations
Remote Sensing of ET (cont.)

B: Combined method: Energy Balance + Plant physiology (Penman-Monteith type):
LE is directly calculated from equations involving evapotranspiration processes (P-M)

\[ LE = f(Rn, Tair, windspeed, roughness length, VPD, soil moisture) \]

- Cleugh et al. (2007)
- Running et al. (2008)
- Mu et al. (2007, 2011) - MODIS MOD16 ET products
- Jia et al, 2013 – ET-Monitor
- Etc

**Soil moisture:** can be explicit dominant variable controlling soil evaporation (via surface soil moisture) and plant transpiration (via root zone soil water content).

**LST:** implicit or can be neglected on daily time step
MOD16 ET

**Method B: RS-ET based on P-M**

**MOD16 ET**

- Land cover, LAI
- Air pressure, air temperature, humidity
- Albedo, FPAR
- Radiation, Air temperature
- Land cover
- Radiation, air temperature

**Net radiation to the plant**
- Canopy surface
  - Wet canopy surface
  - Canopy transpiration
- Dry canopy surface
  - Plant transpiration
- Canopy conductance
- Scalar
- Moisture soil surface
  - Potential soil evaporation
  - Potential soil evaporation
- Actual soil evaporation
- Soil evaporation

**Soil evaporation**

**Evapotranspiration (ET)**

**Legend for the evapotranspiration (ET) flowchart**

- 8-day, 16-day: Remote Sensing inputs
- Daily: Meteorological inputs
- Daily: Intermediate algorithm calculations
- 8-day, monthly, annual: Final algorithm output

*(Mu et al., 2011)*
Method B: RS-ET based on P-M

ET-Monitor

Method combining surface energy balance with soil water availability and plant physiology

Input data
- Meteo data
  - Wind speed
  - Air temperature
  - Humidity
  - Radiation
  - Precipitation
  - albedo
  - LAI/NDVI/Fc
  - Soil moisture
  - Land surface temperature
- Satellite data
- LULC
- Soil map

Input variables/parameters
- Actual Evapotranspiration (ETa)
- ET Deficit
- Plant Transpiration
- Soil Evaporation
- Interception

Output maps

Daily 1km, 25km spatial resolution
Method B: RS-ET based on P-M

MOD16 vs ETMonitor

MODIS MOD16 ET

ETMonitor
Method B: RS-ET based on P-M

MOD16 vs ETMonitor

Heihe River Basin, North-western China
Arid/Semi-arid region
Method B: RS-ET based on P-M

Plant physiology based methods (e.g. MODIS ET product MOD16): photosynthesis limited only, no consideration of soil water content
Method B: RS-ET based on P-M

Heihe River Basin in China
ETMonitor 12 years time series (daily, 1km)

ET 2009

ET 2010

ET 2011
Method B: RS-ET based on P-M

Case in The Netherlands
Humid region, high latitude interception is important

2012-05-25, cloudfree day

2012-05-30, rainy day

2012-07-25, cloudfree day
Remote Sensing of ET (cont.)

C: Contextual method + Energy/water balance:

- SSEBI (Roerink et al., 2001)
- Priestly-Taylor Equation + LST-NDVI (Fc) space feature (Jiang and Islam, 1999; Tang et al., 2010)
- Priestly-Taylor Equation + LST-NDVI (Fc) space feature + soil water balance (Miralles, et al. 2011)

\[
LE = \phi \left( R_n - G \right) \frac{\Delta}{\Delta + \gamma}
\]

Scaled in LST-Fc diagram by actual position;

Require “wet” and “dry” pixels in the image;

Similar weather conditions;

Region is flat

\( (Tang\ et\ al.\ 2010) \)
Method C: RS-ET from Contexture of LST-Fc

Contexture based method: ET calculation depends on area used to construct the “triangle” space of LST & Fc → changing with the area considered

![Diagram showing triangle of the map and its coefficients](image-url)
Method C: RS-ET from Contexture of LST-Fc

• The diagram of RS_PT method is not only dependent on the size of the area to build the TS-Fc feature space, but also on the ranges of the land surface vegetation cover and soil moisture conditions.

• LST cannot reflect sufficiently the root zone soil moisture conditions
Application Requirements

• Different applications have different requirements on:
  – Spatial resolution
  – Temporal sampling step
  – Accuracy

• At current available satellite sensors, it is difficult to satisfy all user requirements with a single ET product
Drought Monitoring Applications

- 2009 drought in Inner-Mongolia of China

**Drought Monitoring Applications**

- 2009 drought in Inner-Mongolia of China

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Evapotranspiration Deficit
July 2009

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- Evapotranspiration Deficit

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Evapotranspiration Deficit
July 2009

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- Evapotranspiration Deficit

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Evapotranspiration Deficit
July 2009

```

- Evapotranspiration Deficit
Summary

- Processes that control water vapor exchanges with terrestrial objects are complicated (Transpiration, Evaporation, Interception, and more: Sublimation).

- Under different conditions the dominant process is different (energy control or water control), so the parameterization.

- Need to observe the most specific state variables for each process.

- At current available satellite sensors, it is difficult to satisfy all user requirements with a single ET product.
Thank you for your attention!

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