METRIC: High Resolution Satellite Quantification of Evapotranspiration

University of Idaho, Kimberly, Idaho

Part One – Introduction
Co-developers and collaborators

- A. Morse; W. Kramber, IDWR
- M. Garcia, Univ. LaPaz, Bolivia; Ignacio Torres, IFAPA, Spain; Aureo Oliveira, Univ. Bahia, Brazil; Boyd Burnett, UI; Eric Kra, Univ. Ghana
- W. Bastiaanssen, Waterwatch; J. Wright, USDA-ARS
- J. Hendrickx, NM Tech
- Ayse Irmak, Univ. Nebraska
- Justin Huntington, Desert Research Institute
- Riverside Technology, Inc.
A few applications that helped to shape METRIC
Imperial Valley, CA via Landsat 7

Imperial Valley

ET during January – March, 2003
Product of METRIC™ for Southeastern Idaho

Seasonal Evapotranspiration during 2000
Eastern Snake River Plain, Idaho

3 million acres with 30 m resolution
Product- Monthly ET

Summed ET for the Mission Valley, MT for during July, 2008
Seasonal ET from Irrigated Areas for S. Idaho

Evapotranspiration from Irrigated Land in Southern Idaho
March 1, 2000 to October 31, 2000

The map shows the distribution of evapotranspiration from irrigated land in Southern Idaho for the specified period.
Annual ET for all of California

Created by SEBAL-North America for 2002 using MODIS satellite imagery (resolution = 1 km)

http://www.sebal.us
Background on the ET mapping procedure
Evapotranspiration “mapping” with SEBAL and METRIC™

Surface Energy Balance Algorithm for Land
Dr. Wim Bastiaanssen, WaterWatch, The Netherlands
– beginning in 1990
– SEBAL is commercially applied in the U.S.A. by SEBAL-North America

Mapping EvapoTranspiration with high Resolution and Internalized Calibration
Allen, Tasumi, University of Idaho, Kimberly
– beginning in 2000
– rooted in SEBAL²⁰⁰⁰

METRIC™ is energy-balance-based ET mapping tied down and partly calibrated using ground-based reference ET (from weather data)

METRIC™ works well in advective conditions of the western U.S.
Energy balance gives us “actual” ET

Surface Energy Balance:

ET is calculated as a “residual” of the energy balance

\[
ET = R_n - G - H
\]

Basic Truth:
Evaporation consumes Energy

The energy balance includes all major sources (R_n) and consumers (ET, G, H) of energy

University of Idaho
Via the Energy Balance we can “see” reduction in ET caused by

- soil water shortage (stress)
- plant density
  - low plant population or size
  - planting skips
  - wide row spacings
- soil salinity
- fertility deficiencies
- disease
- insect pressures
- weeds
- senescence
- tillage/traffic
- hail/frost
ET from *individual* Fields is *Critical* for Water Rights, Water Transfers, Farm Water Management.

Minidoka County, Idaho
Sharpening of Thermal Band of Landsat 5 from 120 m to 30 m using NDVI

Landsat 5 -- Albacete, Spain, 07/15/2003

ET ratio before sharpening

ET ratio after sharpening
Why use High Resolution Imagery?

Riparian vegetation and small fields along the Middle Rio Grande, New Mexico
Why use High Resolution Imagery?

Landsat False Color (MRG)

MODIS False Color (MRG)

Landsat vs MODIS
Need for ET Maps in Idaho

- Quantify Net Depletion from Ground-water Pumping \(\text{(unmeasured)}\)
- Compare actual ET with Water Right
- Calculate Natural and Irrigation-Induced Recharge to Aquifers \(\text{(via water balance to calibrate MODFLOW)}\)
- Determine “Actual” ET for Developing better Crop Coefficient Curves
**Uses of ET maps**

ET from individual fields is essential for: Water Rights, Water Transfers, Farm Water Management, verification of pumping records

---Barrax, Spain, Allen and Trezza, 2004
Other Applications

- ET from natural systems
  - wetlands
  - rangeland
  - forests/mountainous areas
  - hazardous waste sites

- ET from cities
  - changes in ET as land use changes
Definition of Remote Sensing:
The art and science of acquiring information using a non-contact device

Landsat 5

Landsat 7
Why Satellites?

**Typical method for ET:**
- **weather data** are gathered from fixed points -- assumed to extrapolate over large areas
- “crop coefficients” assume “well-watered” situation *(impacts of stress are difficult to quantify)*

**Satellite imagery:**
- **energy balance** is applied at each “pixel” to map spatial variation
- areas where **water shortage reduces ET** are identified
- little or no ground data are required
- valid for **natural vegetation**
Components of the Energy Balance and those retrieved via satellite

- **Net Radiation** ($R_n$) = function of:
  - date and time
  - *reflectance* (brightness) of surface
  - *surface temperature*
  - humidity (minor effect)

- **Heat to Air** ($H$) = function of:
  - *surface temperature*
  - wind speed
  - *vegetation* type and “roughness”
  - surface to air temperature difference:
    - $H$ at the “cold” pixel = $R_n - G - ET_{\text{reference}}$
    - $H$ at the “hot” pixel = $R_n - G - 0$

- **Heat to Ground** ($G$) = function of:
  - *amount of vegetation*
  - *Net radiation*
  - *surface temperature, reflectance*
Landsat – Polar Orbiting

A new image each 16 days for a specific location
Landsat – Polar Orbiting

The map to launch an Access search represent Landsat 7 scene center points --
What Landsat sees

Visible → Near Infrared

Transmissivity of atmosphere

Wavelength in Microns:

0 0.4 0.6 0.8 1.2 1.6 2.0 2.4

(Band 6 is the surface temperature band (not shown))

Various amounts of reflection

(Between land surface and sun)
MODIS – Polar Orbiting
705 km, 10:30 a.m. (Terra) and 1:30 p.m. (Aqua)

36 bands -- most at 1 km resolution
A new image each day for a region

University of Idaho
MODIS – Polar Orbiting

Many “products” at 1 km (0.62 mile) resolution

BIOMASS Net Primary Productivity for North America

Surface Temperature, Southern California, Record Weather, May 2, 2004
Landsat vs MODIS

Landsat False Color (MRG) 8/26/2002 10:33am

MODIS False Color (MRG) 8/26/2002 11:02am
Landsat vs MODIS

Landsat False Color (MRG) 8/26/2002 10:33am

MODIS False Color (MRG) 8/26/2002 11:02am
Satellite Compatibility

METRIC™ needs both short wave and thermal bands.

METRIC™ can use images from:

- NASA-Landsat (30 m and 60 to 120 m resolution each 8 or 16 days) since 1982
- NOAA-AVHRR (advanced very high resolution radiometer) (1 km, daily) - since 1980’s
- NASA-MODIS (moderate resolution imaging spectroradiometer) (500 m to 1000 m daily) - since 1999
- NASA-ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (15 m, 8 days) - since 1999
Why Use METRIC\textsuperscript{tm} or SEBAL?

- ET via Satellite using METRIC\textsuperscript{tm} or SEBAL can provide dependable (i.e. accurate) information
- ET can be determined remotely
- ET can be determined over large spatial scales
- ET can be aggregated over space and time
- In METRIC, the ET surface can be ‘tied down’ using reference ET (accounting for advection)
Accuracy of ET by Satellite Energy Balance

What can we expect?

- Satellite is 705 km above the earth
- Besides energy "seen" by satellite, ET is impacted by aerodynamics *invisible* to the satellite
- Need to key aerodynamic characterizations off image
- Design of SEBAL and METRIC make process relatively *insensitive* to the parameterization of aerodynamics
- "Magic" of the temperature difference (dT) vs. surface temperature function of SEBAL (Bastiaanssen 1995, 1998) provides internal and relatively automatic calibration
How METRIC™ Works

METRIC™ keys off:

- reflectance of light energy
- vegetation indices
- surface temperature
- relative variation in surface temperature
- general wind speed *(from ground station)*
Accuracy of ET by Satellite Energy Balance

What can we expect?

- **METRIC** is an “engineer’s tool”
- Focus is on a ‘small’ region of interest (100 miles x 100 miles) (i.e., not the world, not 17 western states)

- **METRIC combines** the strengths of energy balance from satellite and accuracy of ground-based reference ET calculation:
  - satellite-based energy balance provides the spatial information and distribution for a large area (and does most of the “heavy lifting”)
  - reference ET calculation “anchors” the energy balance surface and provides “reality” to the product.
What is the Alternative to Satellite Energy Balance?

**ET = Crop Coefficient x Reference ET**
(i.e., $K_c \times ET_r$)
-- note that $K_c$ is synonymous with $ET_r F$
(fraction of $ET_r$)

**$K_c$ curve** is a continuous ratio of ET to $ET_r$ over the life of a crop.
- General curves are available from only five or six experimental sites.
- Accuracy of the $K_c$ estimate for any specific field is probably $\pm 10\%$ at best.

The ASCE-EWRI standardized **Reference ET** method, if used with high quality weather data, is $\pm 10\%$ for a given location.

The **$K_c ET_r$ product** is probably $\pm 15\%$ for any specific field and perhaps $\pm 10\%$ over an area *(if done well).*
Accuracy of ET by Satellite Energy Balance

What can we expect?

Because **METRIC** uses $ET_r$ to tie to and by which to integrate ET over time, ET from METRIC incorporates any errors and bias of the $ET_r$ calculation.

Extrapolation over an area is similar to $K_c ET_r$ approach

- Use $ET_r$ surface to represent climatic demand
- **Whereas**: Satellite energy balance incorporates effects of vegetation density, water availability (via $T_s$) etc. in the calculation of **specific ET by field** ($K_c$ curve usually does not)

**Accuracy** of ET by **METRIC** is probably

- +/- 10 to 20% for a specific field on a specific day
- +/- 10 to 15% for many fields on a specific day
- +/- 10 to 15% for a specific field over a season *(if done well)*
Why we selected the SEBAL Model and evolved the METRIC™ Model

CIMEC: The energy balance and ET predictions are **internally calibrated** to two known ET rates:

An internalized calibration function for “H”

is constructed within SEBAL (and METRIC)

In Classical **SEBAL**:
1. ~zero ET → bare, dry agricultural soil
2. ET ~ $R_n - G - (H\sim0)$ → “wetter” vegetated pixels (or $H_{20}$)

In **METRIC**:
2. alfalfa reference ET → “wetter” cropped pixels

Much less need to apply extensive atmospheric corrections or depend upon absolute temperature gradients (because of the internal calibration)
Why we selected the SEBAL Model and evolved the METRIC™ Model

METRIC and SEBAL are “crop classification free”

- No need to perform an extensive, expensive crop classification (may be required to apply ET_f vs. vegetation index relations)
- A crop classification might cost more than applying the full energy balance of METRIC or SEBAL

METRIC™: Mapping Evapotranspiration with High Resolution and Internalized Calibration
**METRIC** is tied down to *everything we know* about ET that is *straightforward* and *good* (i.e., ET<sub>r</sub>)

ET<sub>r</sub> contains information on:

- Direct impact of wind speed on ET process
  - at image time
  - during the day (*for extrapolation*)
- Impact of vapor pressure deficit and other advective factors
  - at image time
  - over the course of the day (*for extrapolation*)
- Impact of afternoon clouding on daily ET (*for extrapolation*)

*Plus, the approach is congruent with the alternative (K<sub>c</sub> ET<sub>r</sub>)*
SEBAL and METRIC\textsuperscript{tm} are complementary:

use SEBAL when high quality hourly electronic weather data are not available.

use METRIC\textsuperscript{tm} otherwise for improved accuracy under advective conditions.
Image Processing

ERDAS Imagine used to process Landsat images

- METRIC™ equations programmed and edited in Model Maker function
- 8 functions / steps run per image
METRIC™ Level One

- **Robust** set of equations and procedures
- For general application
- **Applications manual** includes instructions and recommendations
- Includes algorithms for application in mountainous terrain (Appendix 12)
- Accuracy requires
  - **Intelligence**
  - **Insight**
  - **Iterative Review**

METRIC™ is an Engineering Tool

University of Idaho
METRIC™ Level Two

Equations and procedures (potentially) modified and customized for each application area:

- Multiple dT functions (calibrations) for complex subareas
- Limits on dT function
- Customized albedo and three source $T_s$ estimation
- Modification of soil heat flux computation
- Refined selection of hot pixel
- Excess aerodynamic resistance for sparse vegetation
- Available energy for water bodies
METRIC™ Level Two

- Customized modifications rely as much on operator behavior, care, understanding and judgment as in modification of equations.

- Level Two requires even more
  - *Experience*
  - *Understanding (of physics and processes)*
  - *Insight*
  - *Iterative Review*

- Level two is not for general release.
METRIC™ Level One
Operator requirements

◆ **Background in:**
  - *Hydrologic science or engineering* *(to know behavior of soil, vegetation and water systems)*
  - *Environmental physics*
    - Radiation
    - Aerodynamics
    - Heat transfer

◆ **Familiarity with**
  - *Vegetation systems* *(to know what one is looking at and growth and canopy characteristics)*
  - *Specific human activities* *(agriculture, irrigation, etc.)*
  - *Remote Sensing Science and Applications*
  - *Image Processing*
Next Section: More Background