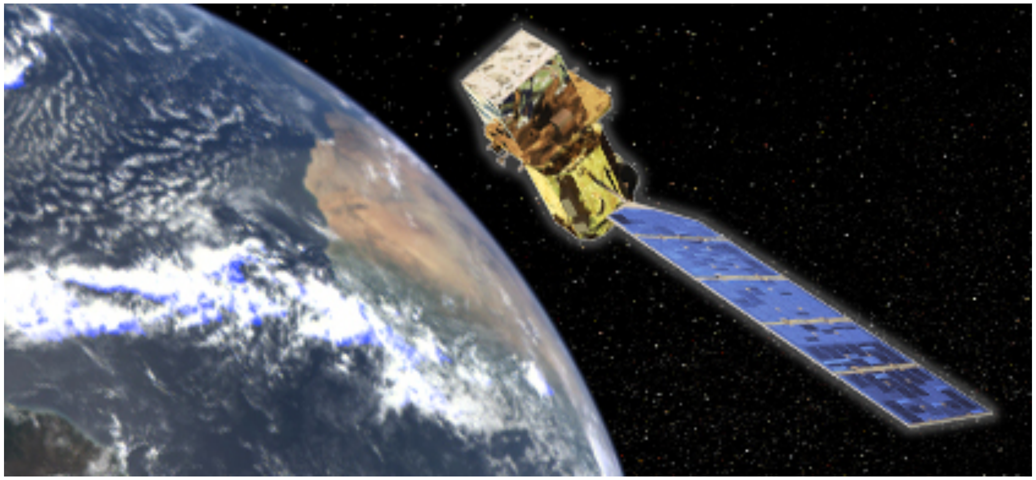
METRIC^{tm}



Mapping Evapotranspiration at high Resolution with Internalized Calibration

WASHINGTON STATE UNIVERSITY
World Class. Face to Face.

Shifa Dinesh

Outline

- Introduction
- Background of METRIC^{tm}
- Surface Energy Balance
- Image Processing
- Estimation of Energy Fluxes
- Instantaneous ET, 24-hour ET and Seasonal ET
- Applications
- Acknowledgements
- Questions

Introduction

- Evapotranspiration transfers large volumes of water from soil (evaporation) and vegetation (transpiration) to the atmosphere.
- Water consumption by crops - largest use of freshwater resources on Earth.
- Quantifying ET from irrigated fields is vital for management of water resources in areas of water scarcity
  - mitigation of impacts of reduced streamflow
  - establishment of hydrologic water balance
  - water rights management and water regulation
- Satellite data – ideally suited for deriving spatially continuous fields of ET using energy balance techniques

Why Satellites ?

Conventional Methods for ET

- "weather data" – gathered from fixed points – extrapolated over large areas
- "Crop coefficients" – assume well watered situation (difficult to quantify the impacts of stress)

Satellite imagery

- Little or no ground data are required
- Major advantage : ET can be computed without quantifying other complex hydrological processes.
- Evaporation and transpiration consumes energy.
- Energy balance applied at each pixel in to estimate how much water a particular field of crops can consume on any particular day

METRIC[tm]

METRIC^{tm}

- Satellite based image processing tool for calculating ET as "residual"of energy balance at the Earth's Surface
- Focus is on "small" region of interest – 100 miles x 100 miles
- Based on model "SEBAL" – Surface Energy Balance Algorithm
  - Dr.Wim Bastiaanssen (beginning in 1990)
    (WaterWatch, The Netherlands)
  - Uses a near surface temperature gradient (dT) indexed to radiometric surface temperature
- Dr. Allen, Dr. Trezza and Dr. Tasumi
  - University of Idaho, Kimberly (beginning in 2000)
  - METRIC^{tm} uses SEBAL technique to estimate dT

Satellite Compatability

METRIC^{tm} needs both short wave and thermal bands

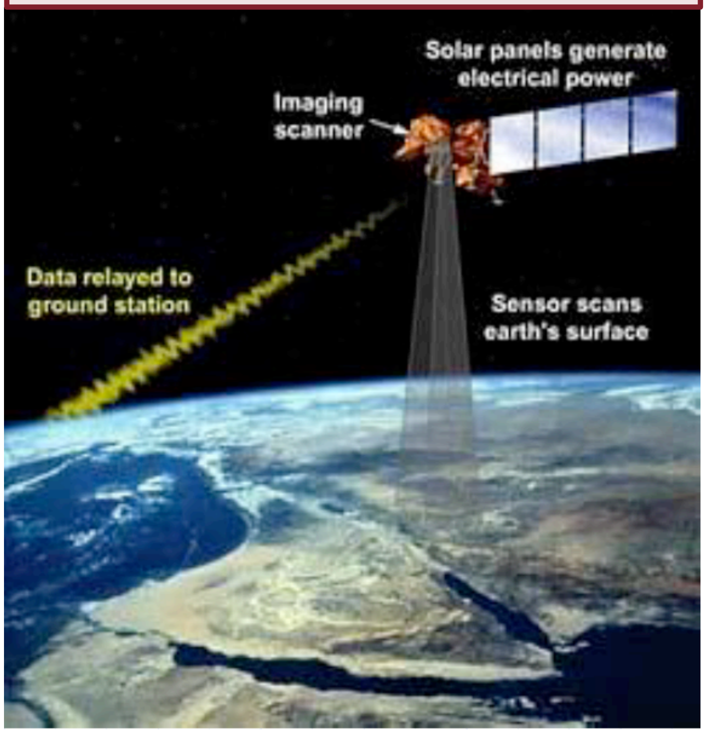
METRIC^{tm} can use images from

Satellite	Spatial Resolution	Revisit period
NASA - Landsat	30 m, 60 to 120 m	16 days
NASA - MODIS	500 m to 1000 m	daily
NASA -ASTER	15 m	8 days
NOAA -AVHRR	8 or 16 days	daily

Landsat – Polar Orbiting

Landsat is the only operational satellite with a "thermal band" and a pixel size small enough to map ET for individual fields.

Swath = 180 km
Scene size = 180 km x 170km



A new image each 16 days for a specific location

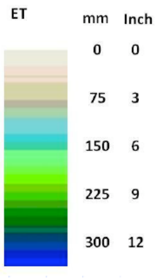
LANDSAT 7 ETM+

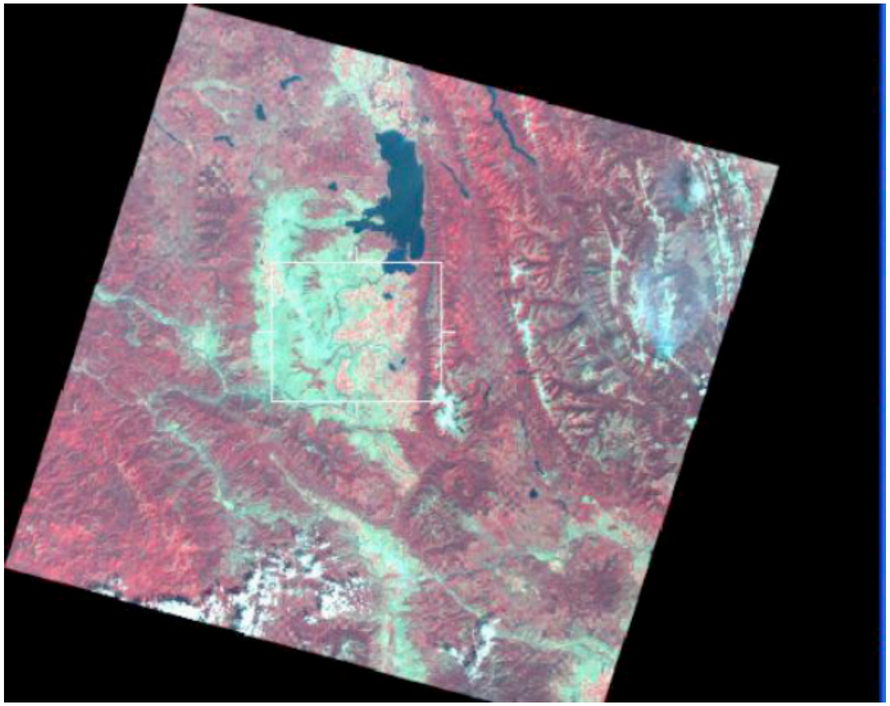
Spectral Resolution (μm)	Band	Spatial Resolution (m)
Band 1 : 0.450-0.515	Blue	30
Band 2: 0.525-0.690	Green	30
Band 3: 0.630-0.690	Red	30
Band 4: 0.760-.900	Near IR	30
Band 5 : 1.550-1.750	Mid IR	30
Band 6: 10.40-12.50	Thermal	60
Band 7 : 2.080 -2.35	Mid IR	30

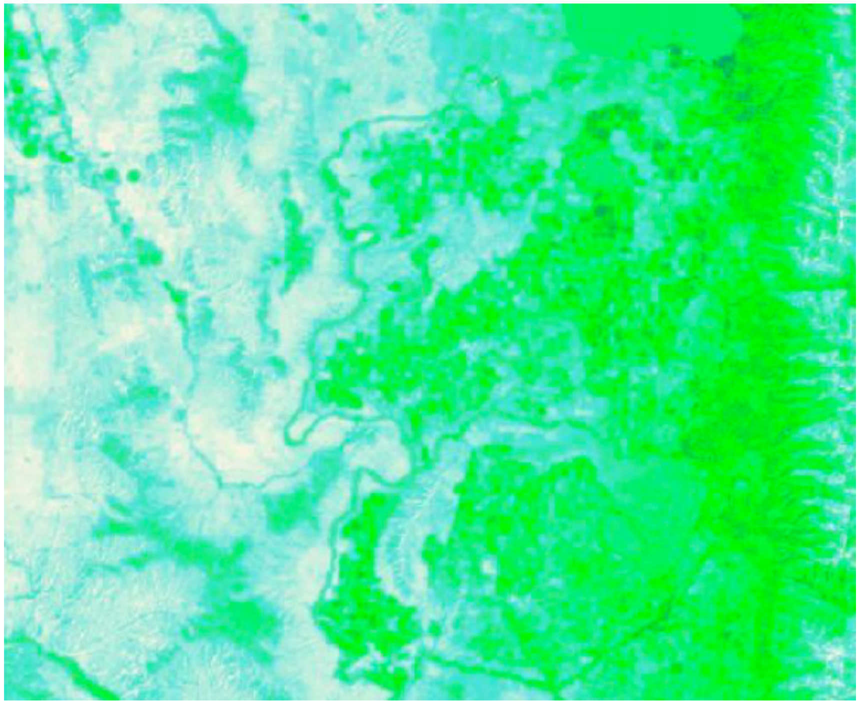
http://landsat.gsfc.nasa.gov/about/L7_td.html

Product - Monthly ET

Summed ET for the Mission Valley, MT for during July 2008







Primary Inputs for METRIC

- Short wave and long wave (thermal) satellite images
- Digital Elevation Model (DEM)
- Weather Data from within or near the area of interest- windspeed, vapour pressure and reference ET
- Land Use Map

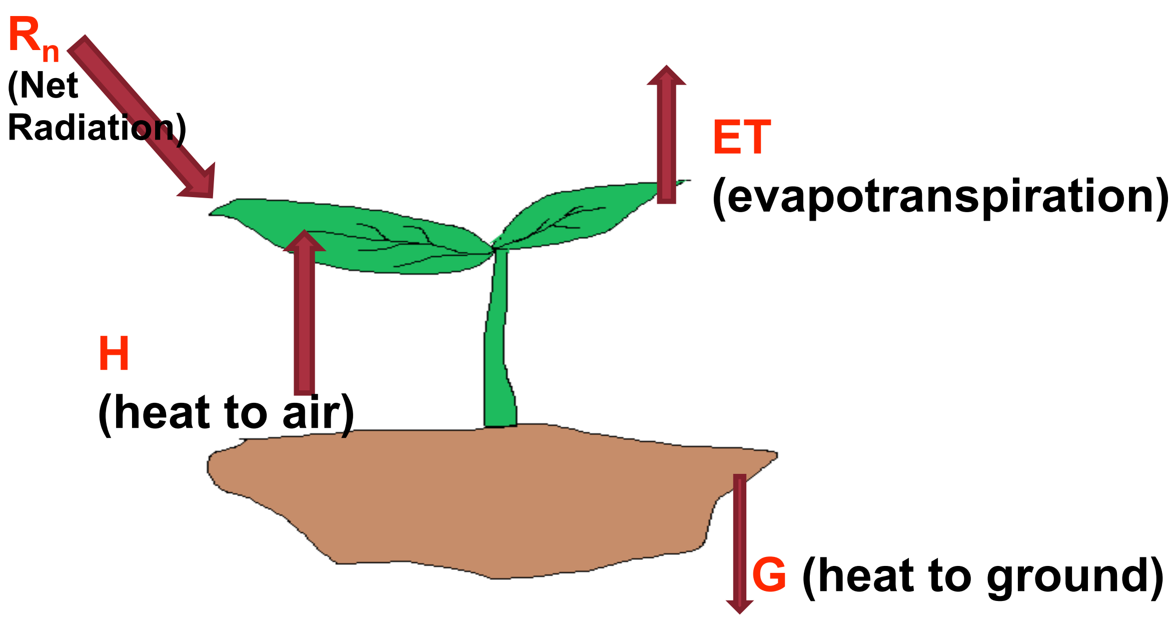
Concept of Surface Energy Balance

Surface Energy Balance

- ET flux is calculated as "residual" of the energy balance

$$LE = R_n - H - G$$

Retrieved via satellite



Components of Energy Balance

Net Radiation (R_n)	• Date and time • Reflectance (brightness of surface) • Surface temperature
Heat to Air (H)	• Surface temperature • Windspeed • Vegetation type and roughness • Surface to air temperature difference (dT)
Heat to Ground (G)	• Amount of vegetation • Net radiation • Surface temperature • Reflectance

Image Processing

Models in METRIC

Eight sub-models

Radiance
Reflectance
Model 1

Surface
Albedo
Transmittance
Model 2

Vegetation
Indices –
NDVI,
LAI,NDWI
Model 3

Surface Temperature
Surface Emissivity
Model 4

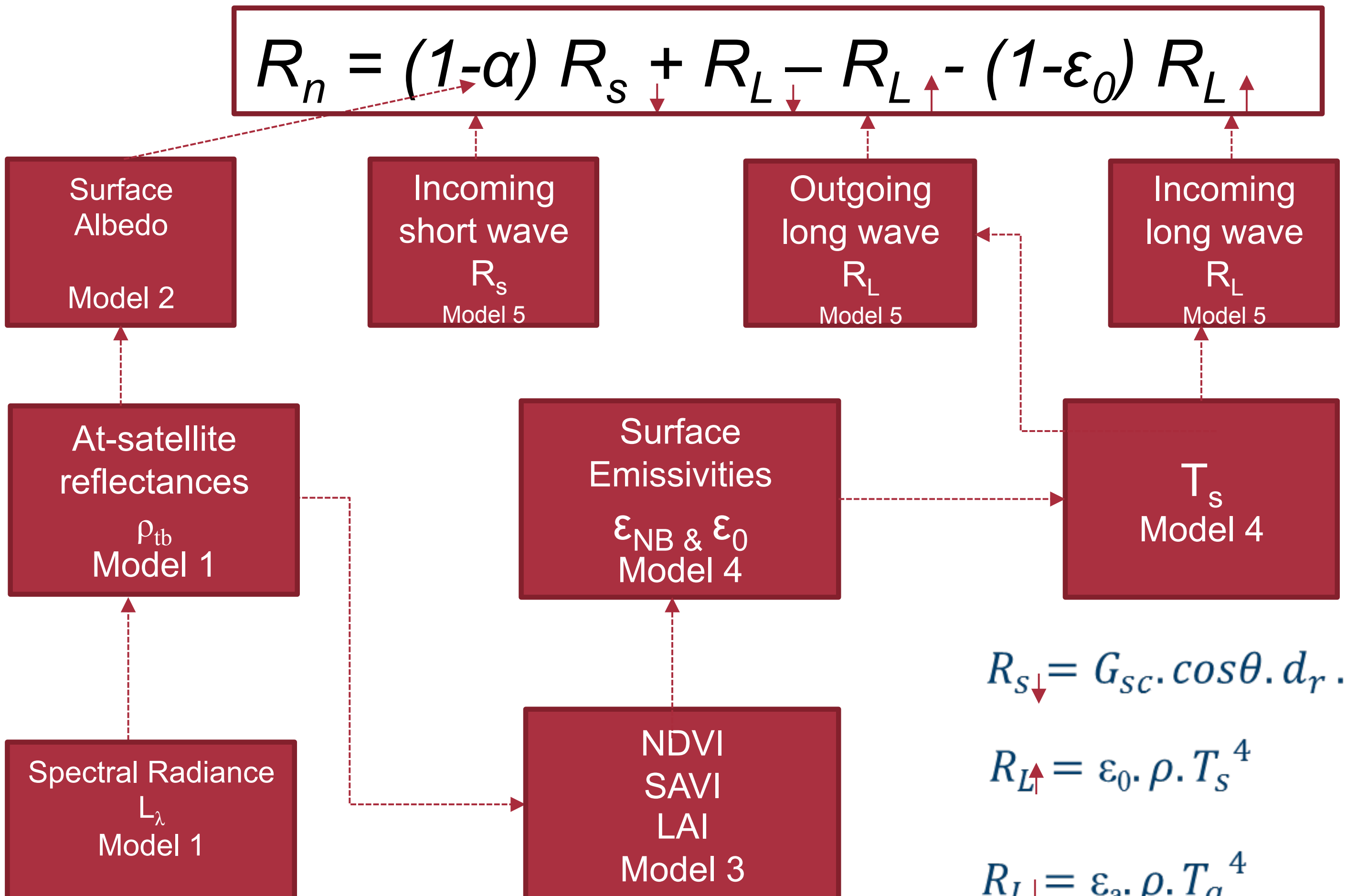
Zom,
Excess
resistance
Model 5

H (W/m^2)
Model 6

Rn (W/m^2)
G (W/m^2)
Model 7

ETrF24
ET24 (mm/day)
Model 8

Net Radiation (R_n)



$$R_{s\downarrow} = G_{sc} . \cos\theta . d_r . \tau_{sw}$$

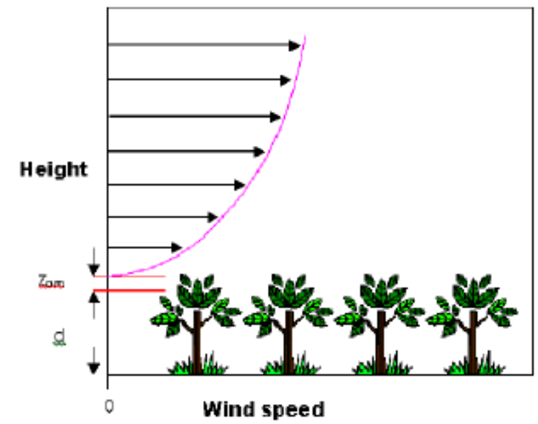
$$R_{L\uparrow} = \varepsilon_0 . \rho . T_s^{\,4}$$

$$R_{L\downarrow} = \varepsilon_a . \rho . T_a^{\,4}$$

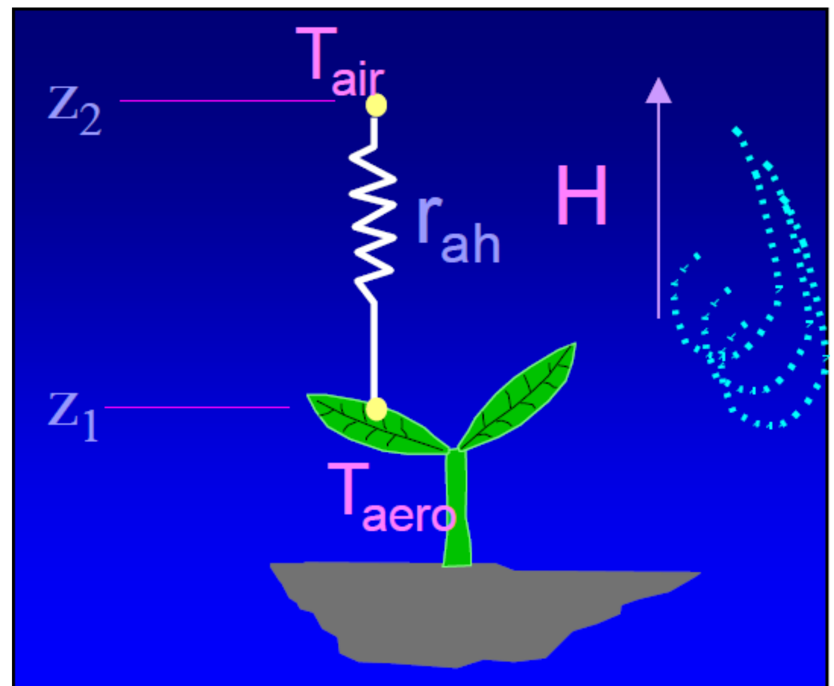
Sensible Heat Flux

$$H = \frac{\rho C_p dT}{r_{ah}}$$

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \psi_{h(z2)} + \psi_{h(z1)}}{u_* k}$$



r_{ah} = aerodynamic resistance
u* = friction velocity (m/s)
z_1, z_2 = height in meters above the zero plane displacement



Two "anchor pixels" utilized where reliable values of H are estimated and solve for dT

Near Surface Temperature difference (dT)

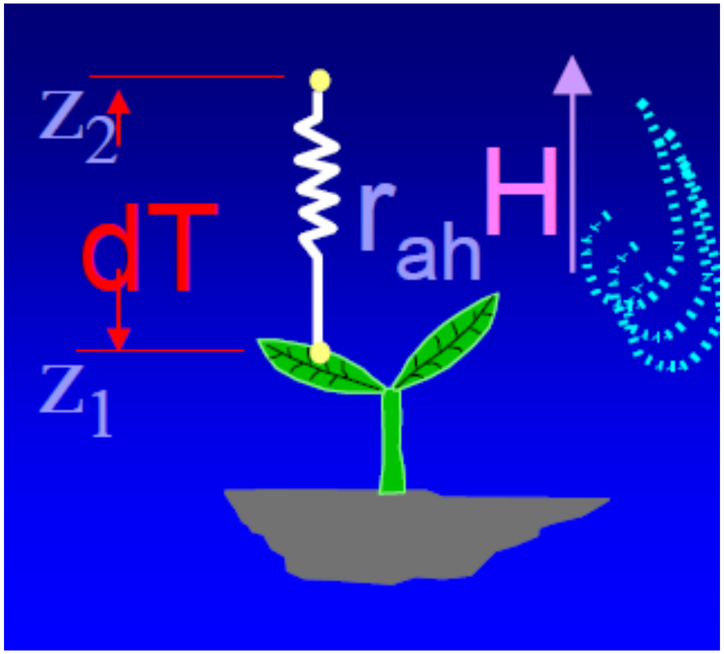
- To compute sensible heat flux (H), define dT for each pixel

  $dT = T_{near\ surface} - T_{air}$

  $dT = T_{z1} - T_{z2}$

- T_{air} is unknown
- SEBAL and METRIC[tm] assume a linear relationship between T_s and dT

$$dT = b + aT_{s\_dem}$$



T_{s_dem} is the delapsed surface temperature

Development of dT Vs Ts_dem

Cold Pixel

- $H_{cold} = R_n - G - LE_{cold}$

$LE_{cold} = 1.05$ ETr

$$dT_{cold} = \frac{H_{cold} r_{ah\_cold}}{\rho_{cold} C_p}$$

- a well irrigated water surface with full cover where $T_s \sim T_{air}$

(In SEBAL, $H_{cold} = 0$)

Hot Pixel

- $H_{hot} = R_n - G - LE_{hot}$

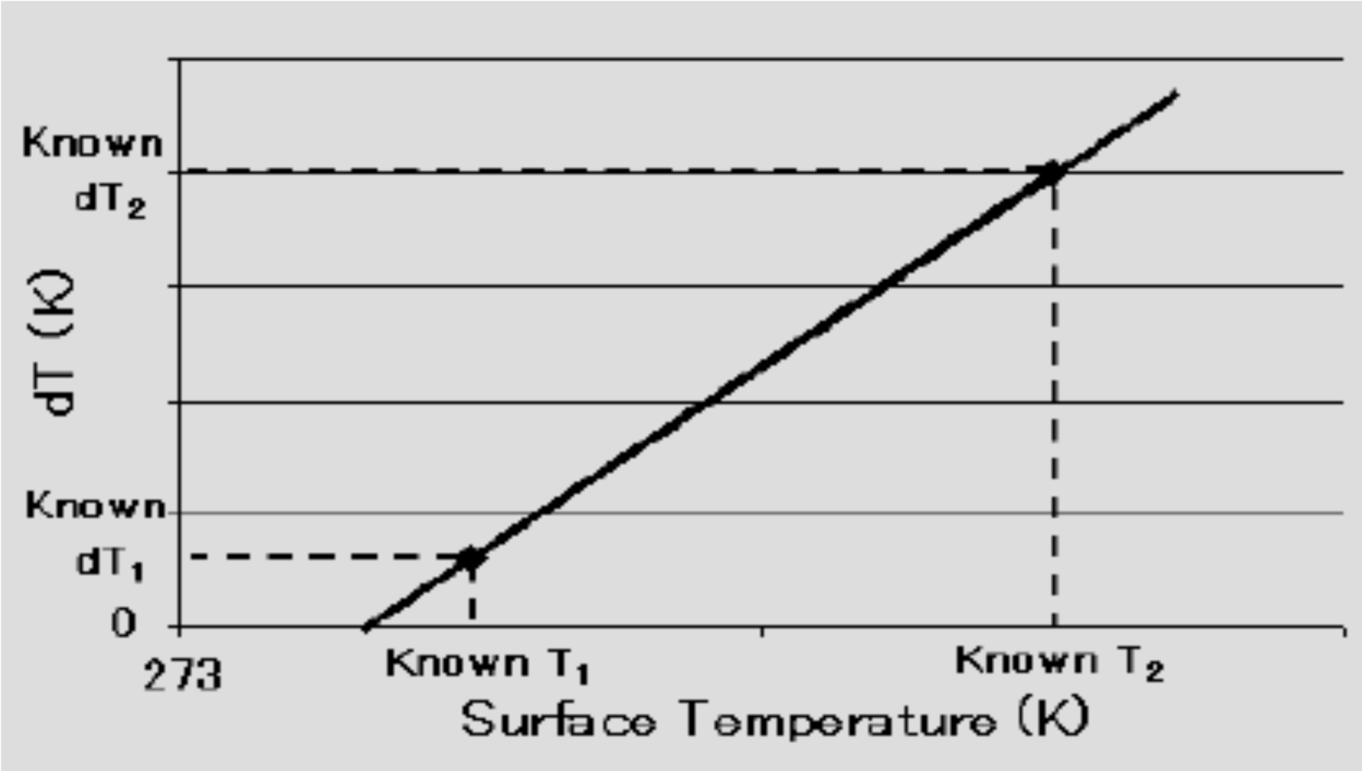
$LE_{hot} \sim 0$

$$dT_{hot} = \frac{H_{hot} r_{ah\_hot}}{\rho_{hot} C_p}$$

- dry bare soil

Training of METRIC^{tm}

Once Ts and dT are determined for the cold and hot pixels, the relationship between Ts and dT is defined as linear



Iterative Process to Compute H

Weather station

u, z_x, z_{om}, u_*

wind speed at 200 meters

$$u_{200} = u_* \frac{\ln\left(\frac{z_{200}}{z_{0m}}\right)}{k}$$

$Z_{om}=0.12h$

friction velocity at each pixel

$$u_* = \frac{k u_{200}}{\ln\left(\frac{z_{200}}{z_{0m}}\right)}$$

Land use map

$Z_{om} = 0.018\ LAI$

NDVI and albedo data

r_{ah} for each pixel

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right)}{u_* \times k}$$

Cold Pixel	**Hot Pixel**
$H_{cold}=Rn-G-\lambda ET_{cold}$	$H_{hot}=Rn-G-\lambda ET_{hot}$
$dT_{cold}=H_{cold}*r_{ah}/(\rho Cp)$	$dT_{hot} = H_{hot}*r_{ah}/(\rho Cp)$

dT for each pixel

$$dT=aT_s+b$$

H for each pixel

$$H = \rho Cp \frac{dT}{r_{ah}}$$

$$L = -\frac{\rho\ Cp\ u_*^3 T_s}{k\, g\, H}$$

$\Psi_{m\ (blending)}$

$\Psi_{h\ (z1)}$ $\Psi_{h\ (z2)}$

$$u_* = \frac{k\ u_{200}}{\ln\left(\frac{z_{200}}{z_{0m}}\right) - \Psi_{m(200)}}$$

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

Soil Heat Flux (G)

- Empirical equation developed by Bastiaansen (1995) :

$$\frac{G}{R_n} = T_s\left(0.0038 + 0.0074\alpha\right)\left(1 - 0.98NDVI^4\right)$$

- An alternative equation was developed by Tasumi et al (2003) using soil heat flux data developed by Dr. J. L Wright (USDA) for irrigated crops near Kimberly, ID.

$$\frac{G}{R_n} = 0.05 + 0.18e^{-.52LAI}$$ LAI ≥ 0.5

$$\frac{G}{R_n} = 1.80(T_s - 273.16)/R_n + 0.084$$ LAI < 0.5

$$\frac{G}{R_n} = G.R_n$$

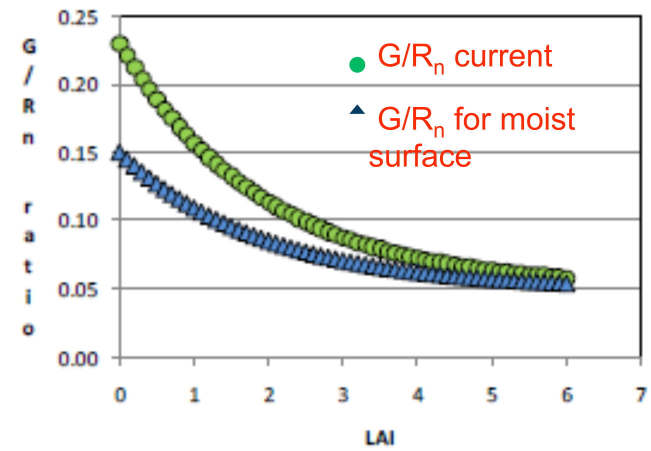
Current G functions

$$\frac{G}{R_n} = 0.05 + 0.10e^{-.52LAI}$$

LAI ≥ 0.5

$$G = \max(0.4H, 0.15R_n)$$

LAI < 0.5



- G = fn(H) after suggestion of Stull (1988) and development of Allen (2010, memo)
- For water (NDVI<0):
  - On average for deep clear water, $G/R_n = 0.5$
  - For shallow turbid water, $G/R_n < 0.5$
- For snow:
  - If $\alpha > .47$, assume $G/R_n = 0.5$

Solving for ET and computing LE for longer periods

Calculation of Instantaneous ET

- Applying the energy balance equation, calculate LE:

$$LE = R_n - G - H$$

- This ET rate expressed as latent heat (W/m2) is converted into depth of liquid evaporated as :

$$ET_{inst} = \frac{3600LE}{\rho_w \lambda}$$ where, $\lambda = (2.501 - 0.00236(T_s - 273))10^6$

What about the rest of the day?
Month? and year ???

ET_rF

- For longer time periods, METRIC uses Reference ET fraction (ET_rF) to extrapolate in time –synonymous with Kc

$$ET_rF = \frac{ET_{inst}}{ET_r}$$

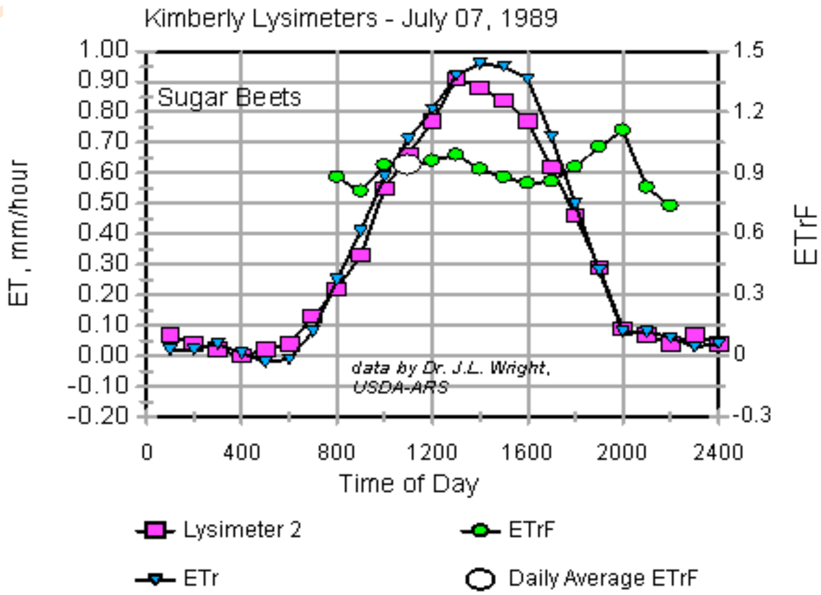
- ET_r is the reference ET calculated for the time of the image

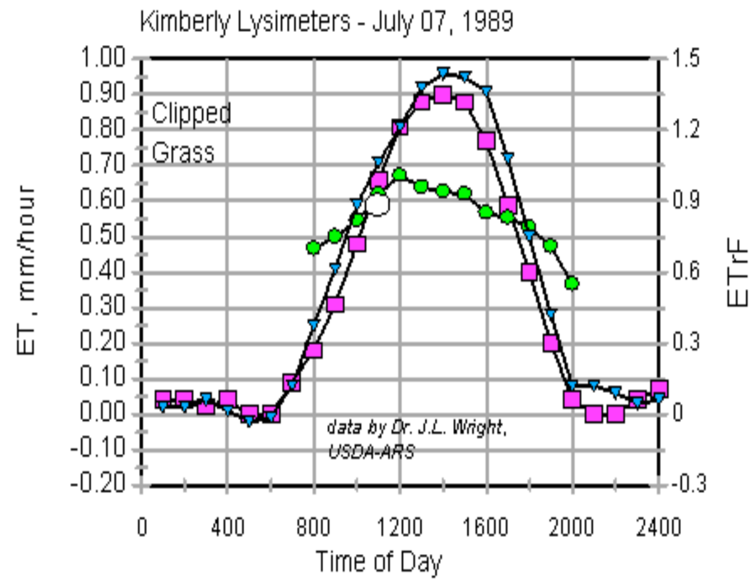
Assumptions:

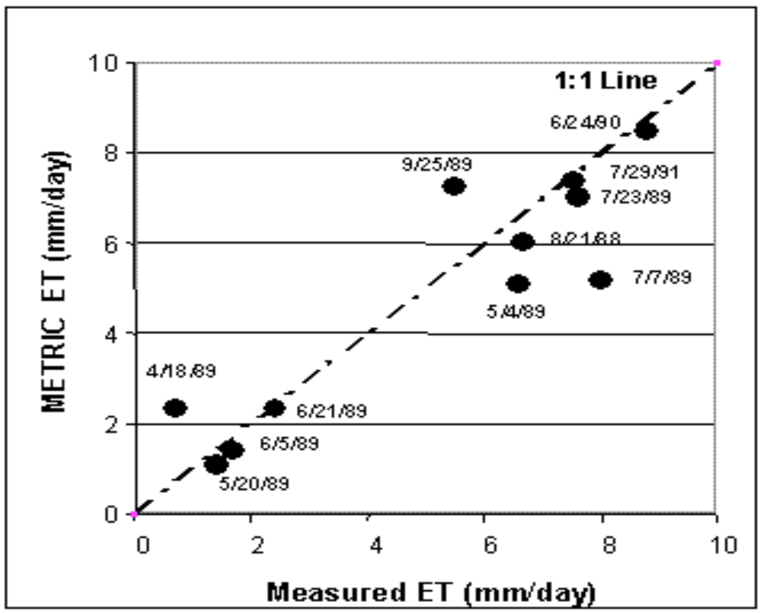
- The fraction ET_rF is nearly constant for the day
- ET_r provides a good estimate of the climatic demands placed on each pixel.

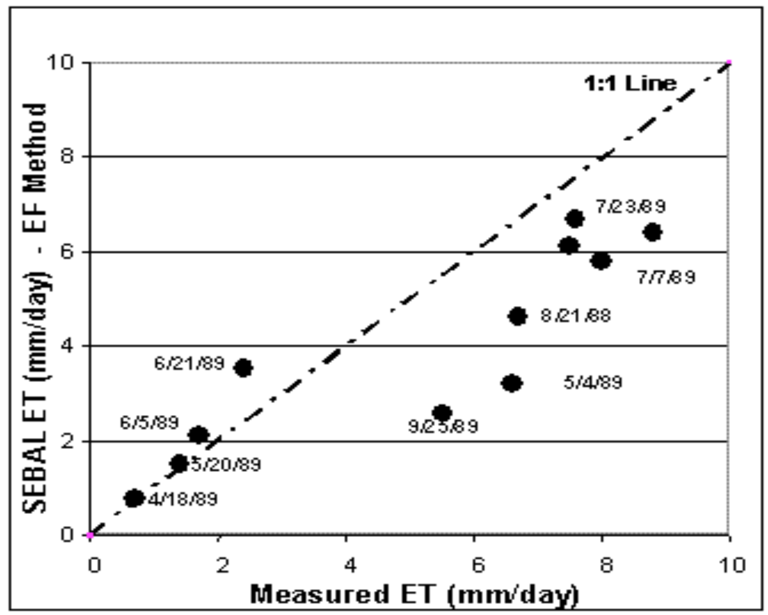
$$ET_{24}\ (mm/day) = ET_rF \times ET_{r-24}$$

- ET_{r_24} is the cumulative 24-hour ET_r for the day of the image



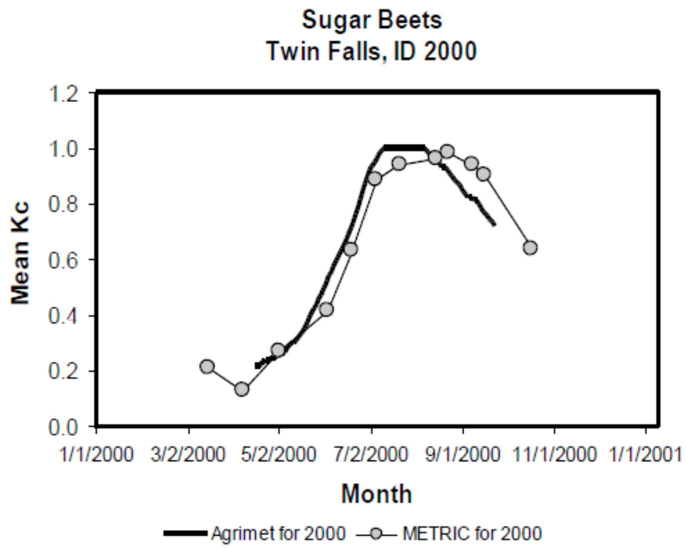


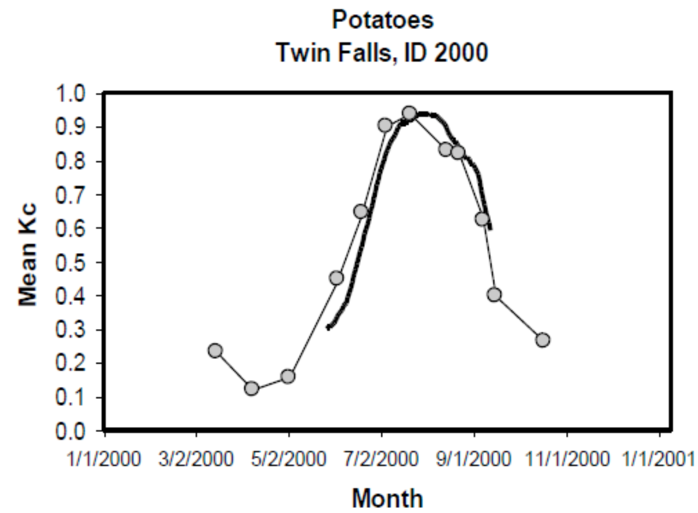


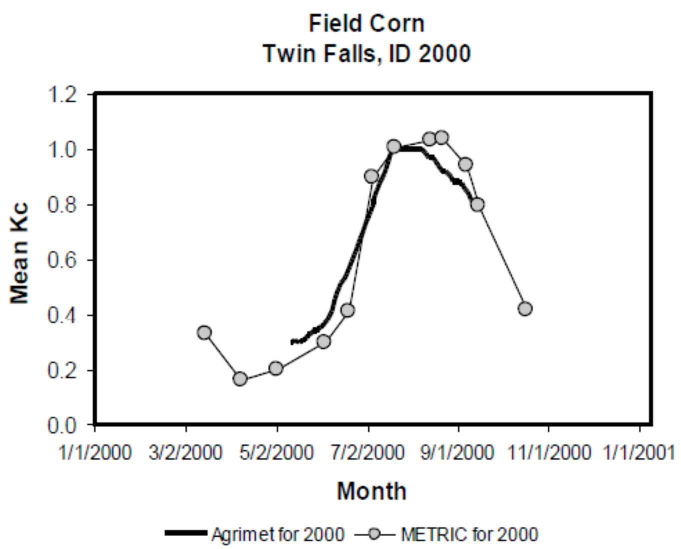


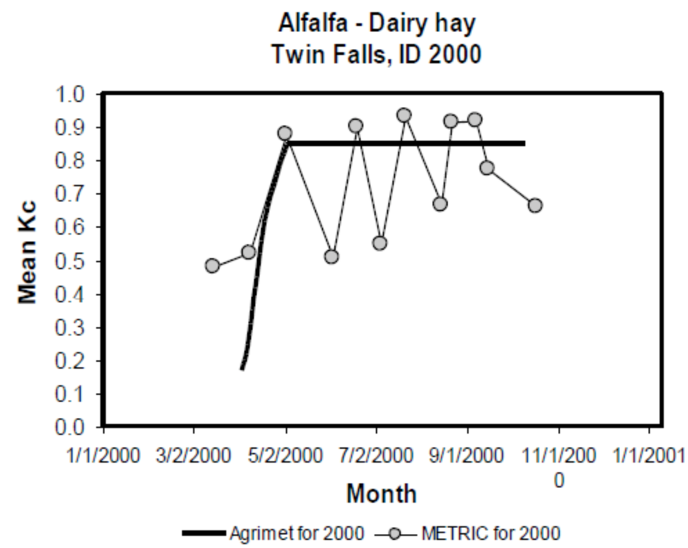
Allen et al.,2005

Comparison with local K_c curves

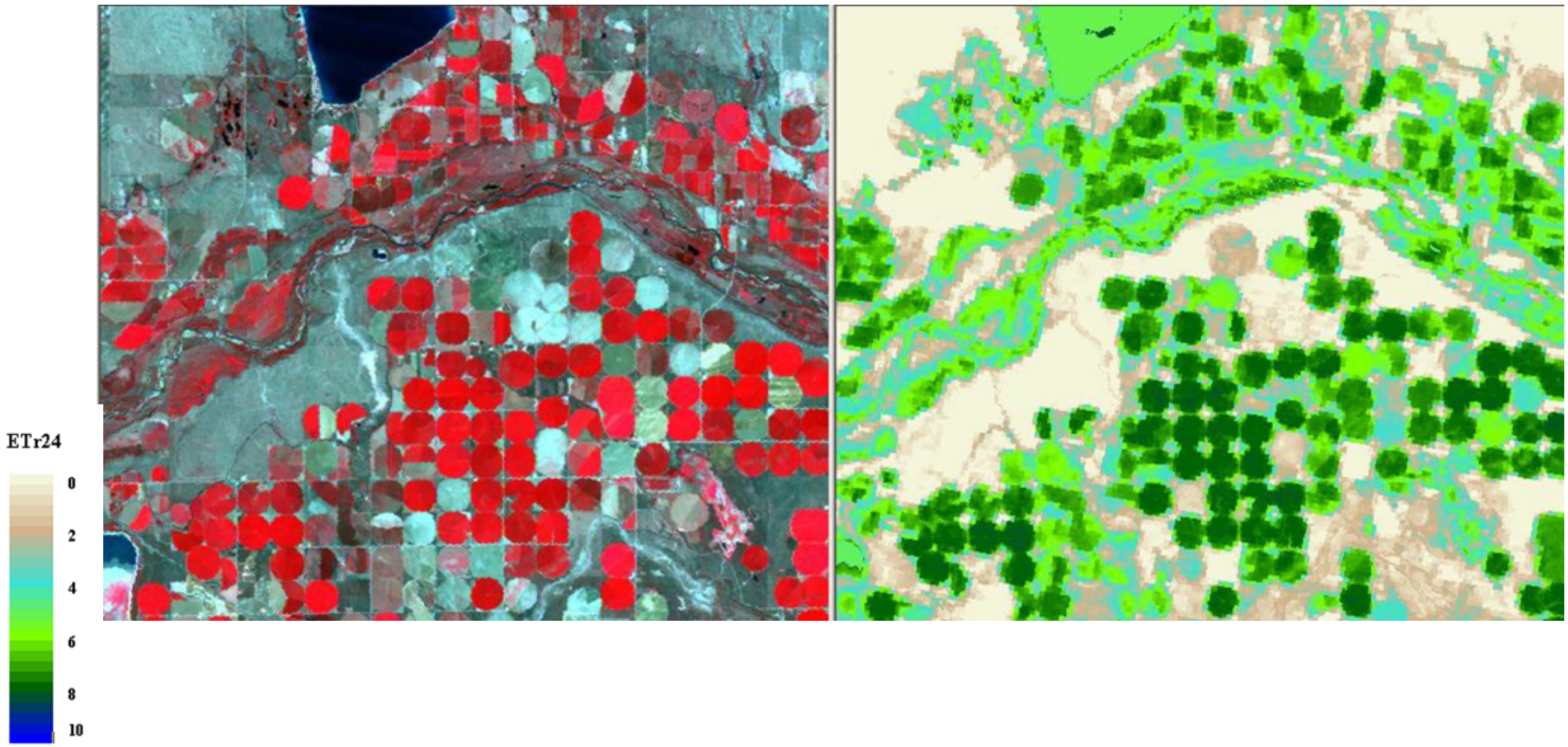








24-Hour Evapotranspiration (ET_{24})



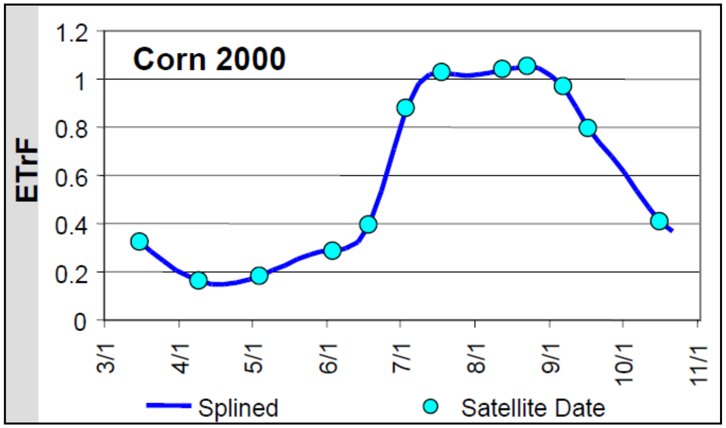
Seasonal ET

- Seasonal ET map is desired which covers an entire growing season for quantifying water consumption
- Derived from ETrF images by interpolating between processed images

$$ET_{period} = \int ET_rF_t \,.\, ET_{r24t} dt$$

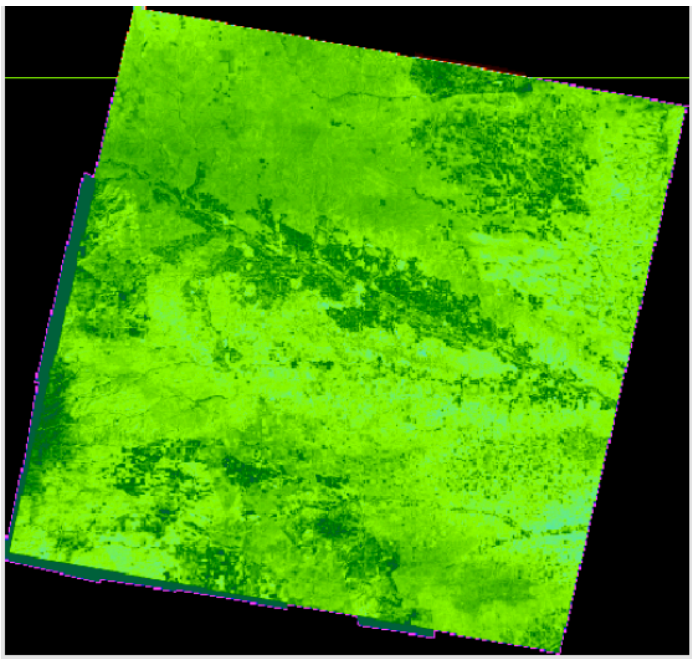
- Assumption: ET for the entire area of interest changes in proportion to changes in the ET_r at the weather station

$$ET_{seasonal} = \sum ET_{period}$$

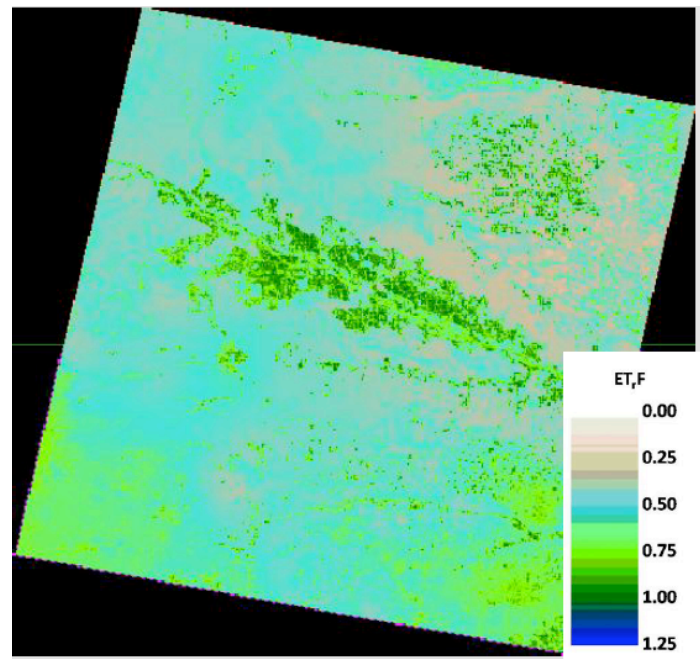


Generally, one image per month is sufficient

Adjustment for background evaporation to account for Inter –image Rainfall

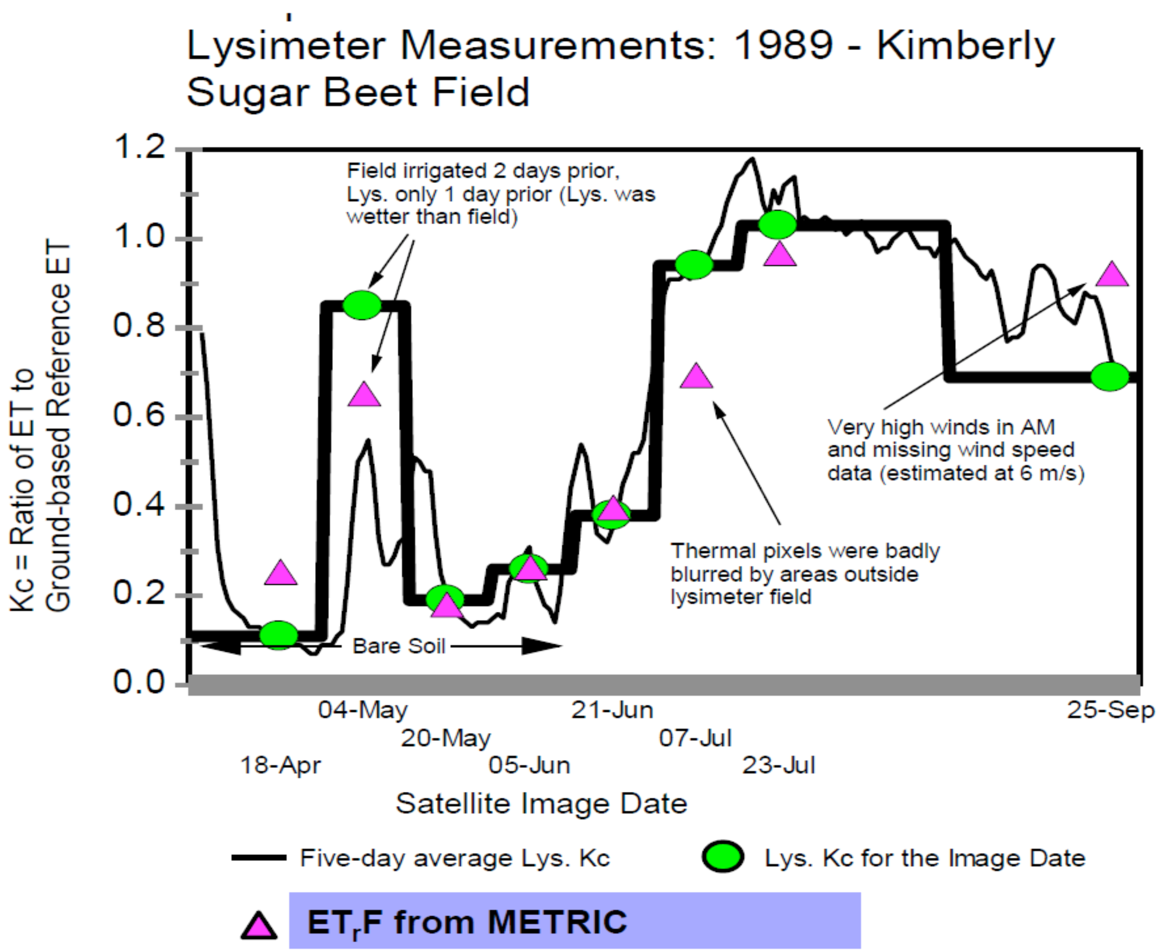


ET from August13,1997 not adjusted for background soil evaporation



ET from August13,1997 adjusted for background soil evaporation

Kimberly, Idaho (Snake River Basin)



Validation of ET estimates

- Confirmation of ET from remote sensing with independent measurement is highly desirable
- Estimate of H includes internal biases that account for biases in R_n, G, T_s etc.
  - Therefore, comparisons are best made between measured and estimated ET, not H
- Ground data must be accurate

biased H

biased R_n, G

$$H = R_n - G - LE$$

$$LE = R_n - G - H$$

Less biased LE

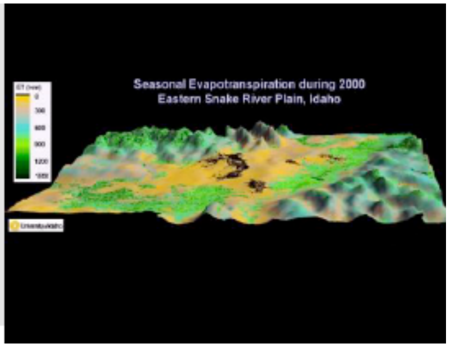
Accuracy of ET

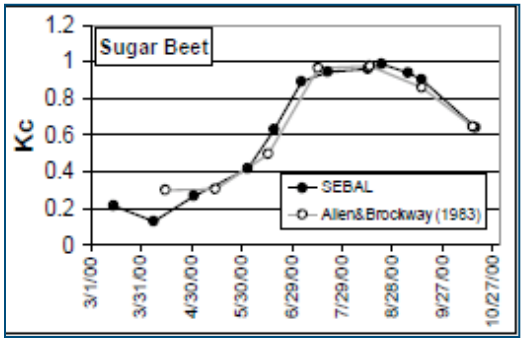
- Satellite is 705 km above the earth
- ET is impacted by aerodynamics invisible to the satellite
- Design of SEBAL and METRIC make process relatively insensitive to the parameterization of aerodynamics
- "Magic" of the dT Vs T_s provides internal and relatively automatic calibration
- METRIC combines the strengths of energy balance from satellite and accuracy of ground-based reference ET calculation

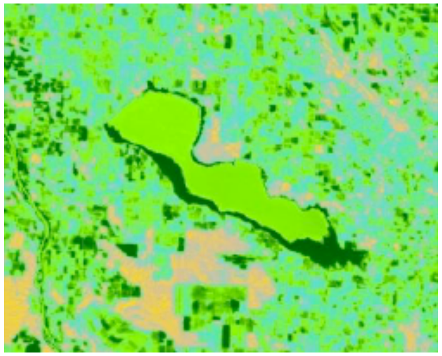
Applications

ET maps are valuable for:

- Determining actual ET
- Ground Water Depletions
- Water Right Conflicts
- Refining crop coefficient curves
- Evaluation of regional and global climate models







Acknowlegements

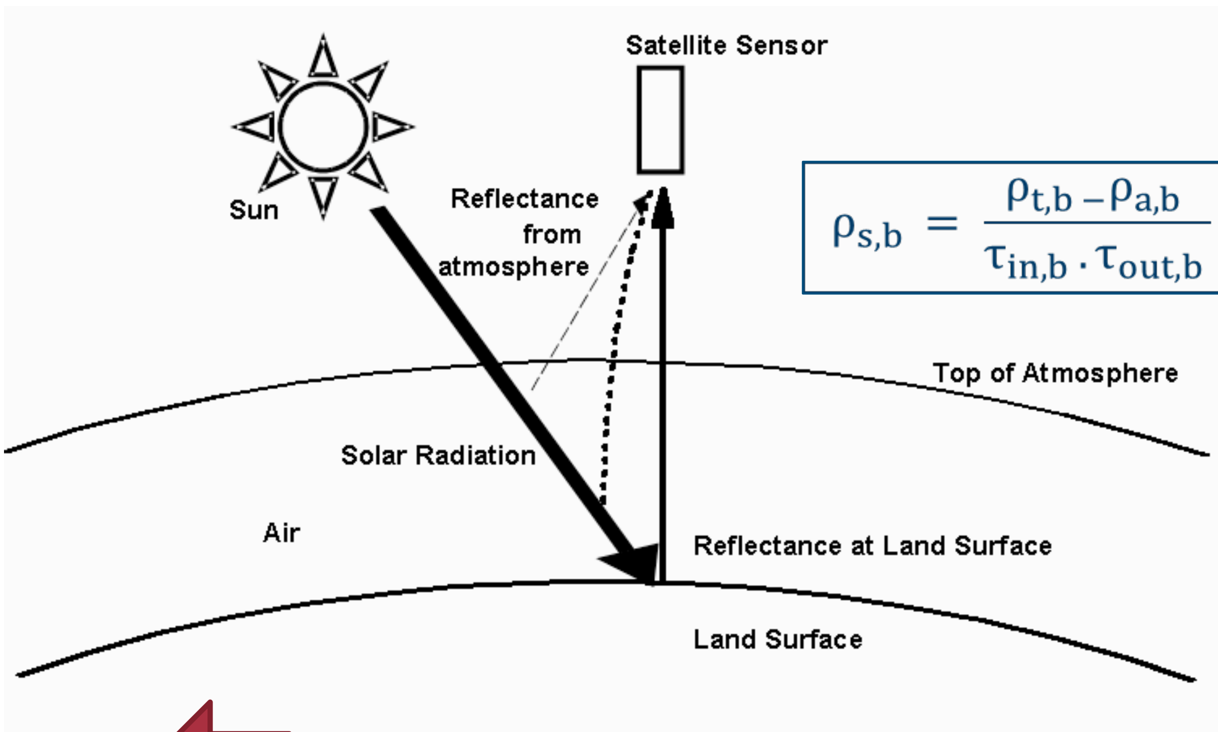
Adapted from workshop presentation by Dr. Richard Allen, University of Idaho.

Questions ?

Additional Slides

Solar Radiation and Reflectance

"non-reflected" radiation is what is absorbed at the surface and part of the energy balance. Therefore it is important to calculate it accurately



$$\rho_{s,b} = \frac{\rho_{t,b} - \rho_{a,b}}{\tau_{in,b} \cdot \tau_{out,b}}$$

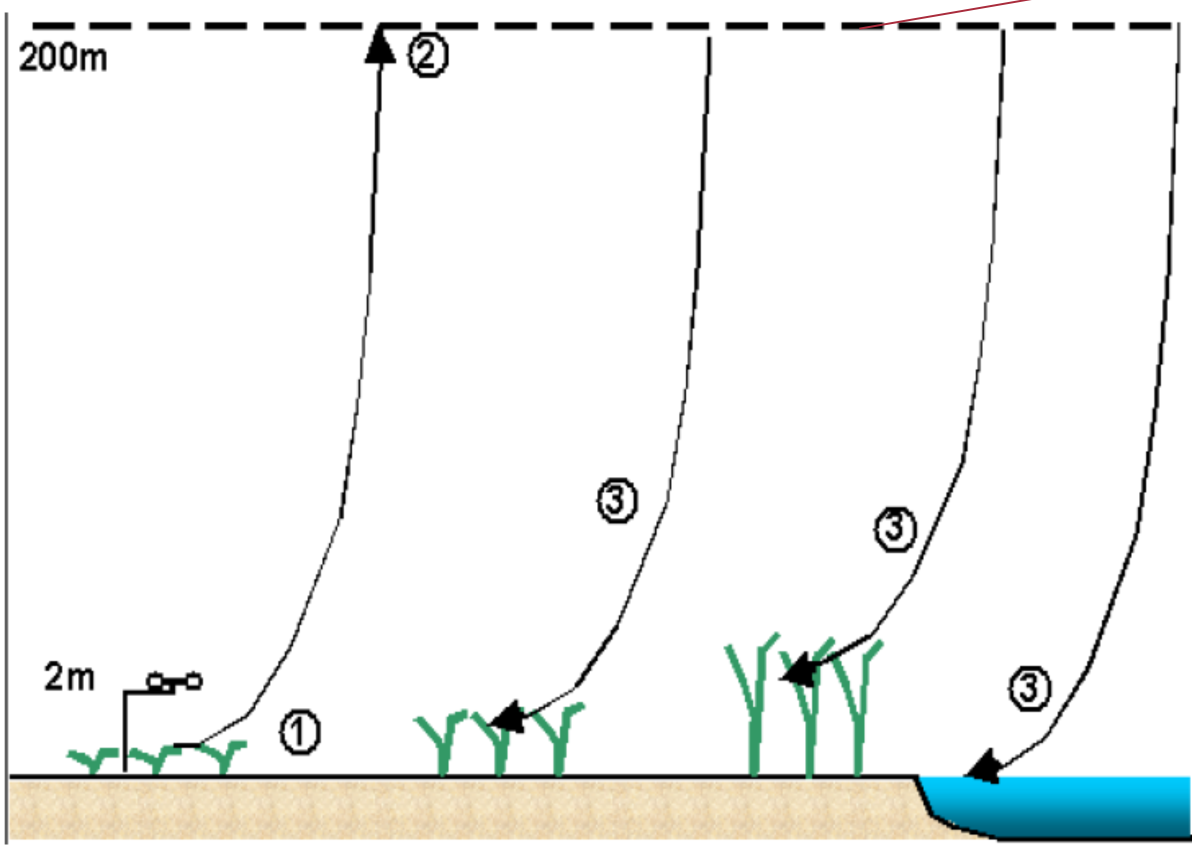
$\rho_{t,b}$ = at-satellite reflectance for band "b"

$\rho_{a,b}$ = path reflectance for band "b

$\tau_{in,b}$ and $\tau_{out,b}$ are narrowband transmittances for incoming solar radiation and for surface reflected shortwave radiation

Friction Velocity

$$u_* = \frac{u_x k}{\ln(\frac{x}{z_{om}}) - \Psi_{m(x)}}$$



Assume windspeed at 200m is constant