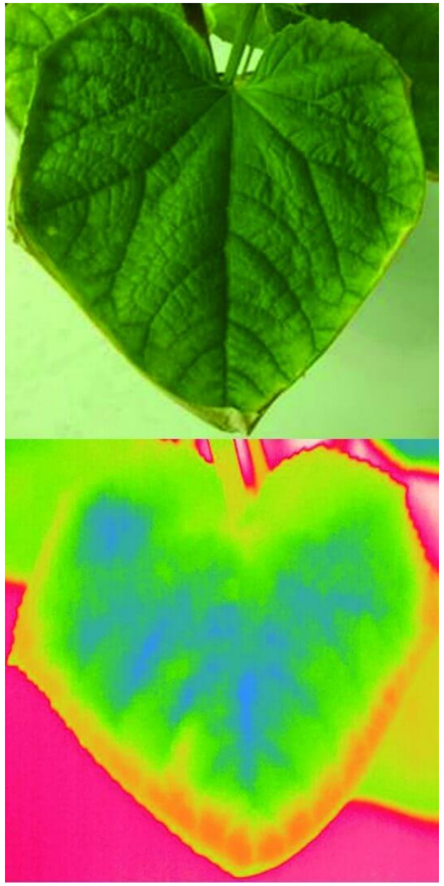
Radiation Use Efficiency-based ET Modelling

20 December 2021



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Learning Objectives of this Course

- Interpret problems in agricultural monitoring considering the scale of observation and information requirements

- Compare observation and remote sensing-based estimates of crop yield

- Analyze observation and remote sensing-based estimates of evapotranspiration

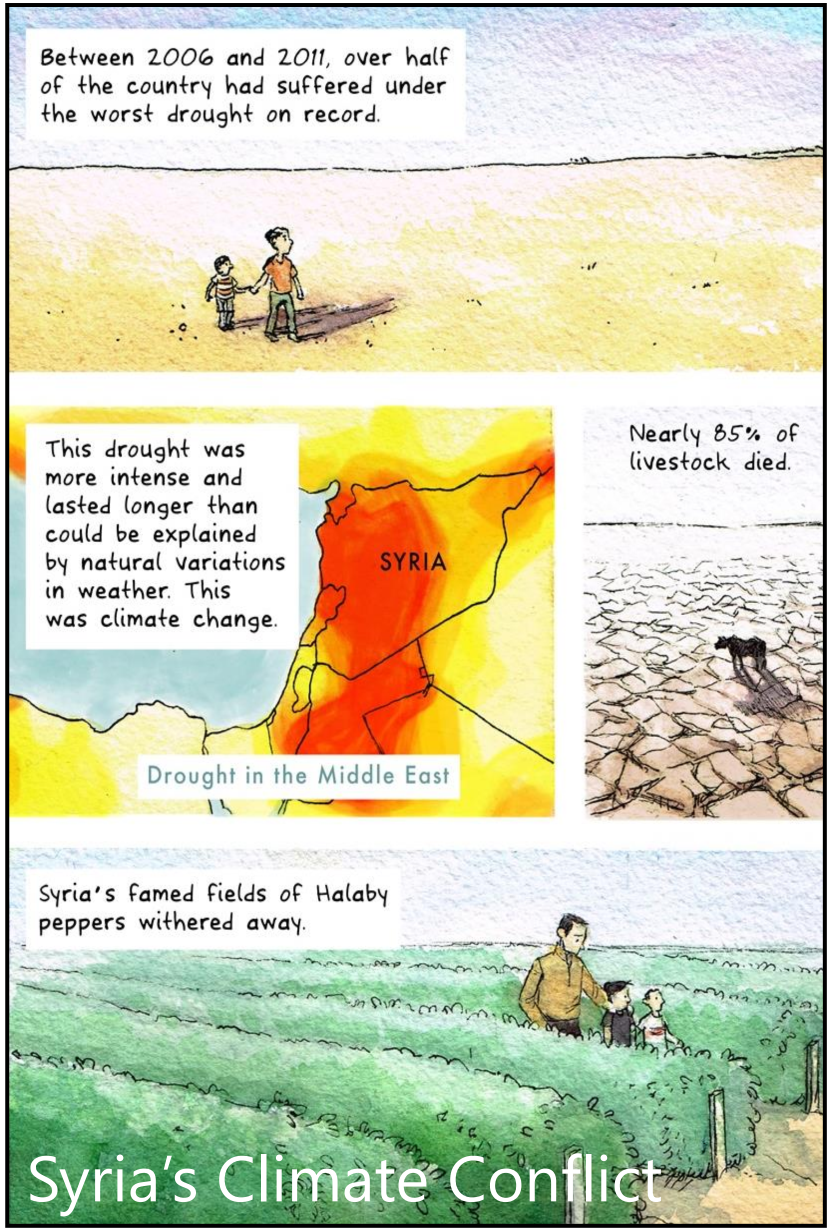
Learning Objectives

- Define evapotranspiration (ET) using land surface energy balance
- Calculate at-sensor (top-of-atmosphere) brightness temperature and land surface temperature (LST)
- Examine the relationship between LST and ET

“Food security has many dimensions, but the question of whether there will be enough food in the future should immediately be followed by the question: Will there be enough water to produce enough food?” Fereres et al. (2011)

Impending Water Crisis

- Population growth
- Dry areas getting drier
- Irrigation insufficient by mid-21st century
- Agriculture ~85% of water use
  - Biofuels
  - Middle class and meat consumption
  - Water pollution
  - Urbanization
- How to we grow more food with less water?



Syria's Climate Conflict

Blue-Green Revolution

- Crop type and variety selection
- Coordinated surface and groundwater supplies
- Precision agriculture
  - Deficit irrigation
  - Drip irrigation
  - Irrigation application and timing
  - Soil salinity
- Water markets
- Multidisciplinary integrated assessments

Crop Water Productivity ("More Crop Per Drop")

Enables scientists and decision-makers to analyze the trade-offs between food and water

$$\text{CWP}_1 = \frac{\text{Grain or seed yield (kg)}}{\text{Water applied to field (cm)}}$$

$$\text{CWP}_2 = \frac{\text{Total dry matter yield (kg)}}{\text{Water applied to field (cm)}}$$

$$\text{CWP}_3 = \frac{\text{Total dry matter yield (€)}}{\text{Water applied to field (cm)}}$$

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Evapotranspiration

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Evapotranspiration

$$CWP_3 = \frac{\text{Total dry matter yield (€)}}{\text{Water applied to field (cm)}}$$

Not to be confused with water use efficiency, irrigation efficiency or water footprint

Evapotranspiration (ET)

When crops assimilate CO_2, they lose moisture used to maintain plant functions. We call this transpiration. Water that falls on the leaf or soil that is lost to the atmosphere following a rain or irrigation event is called evaporation.

We can express ET in units of

water mass

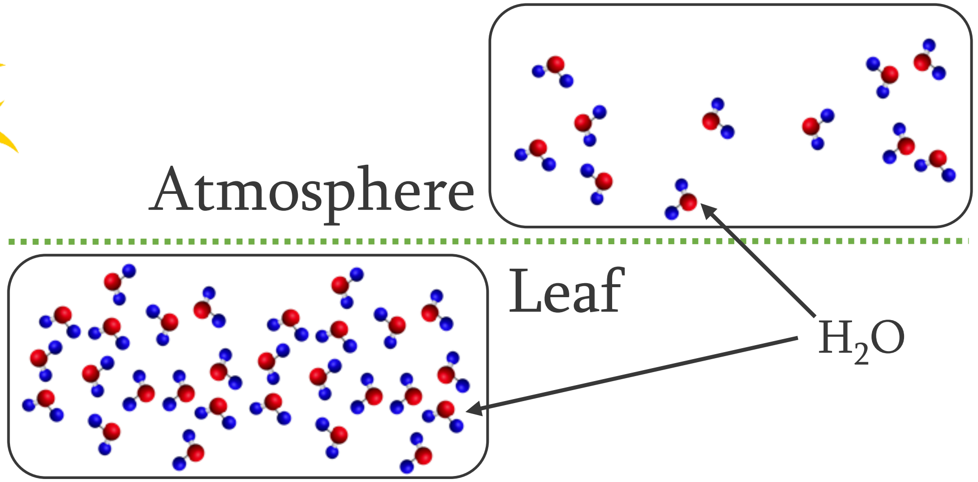
energy as latent heat (LE)

Biology of Evapotranspiration

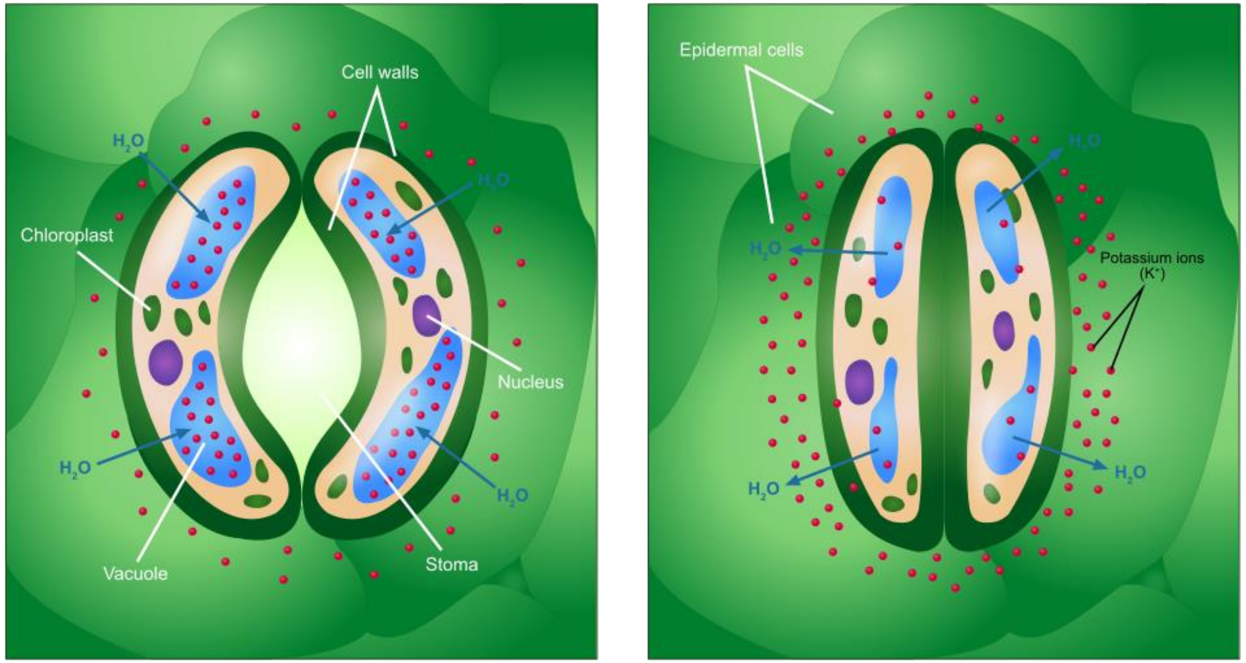
Photosynthesis

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

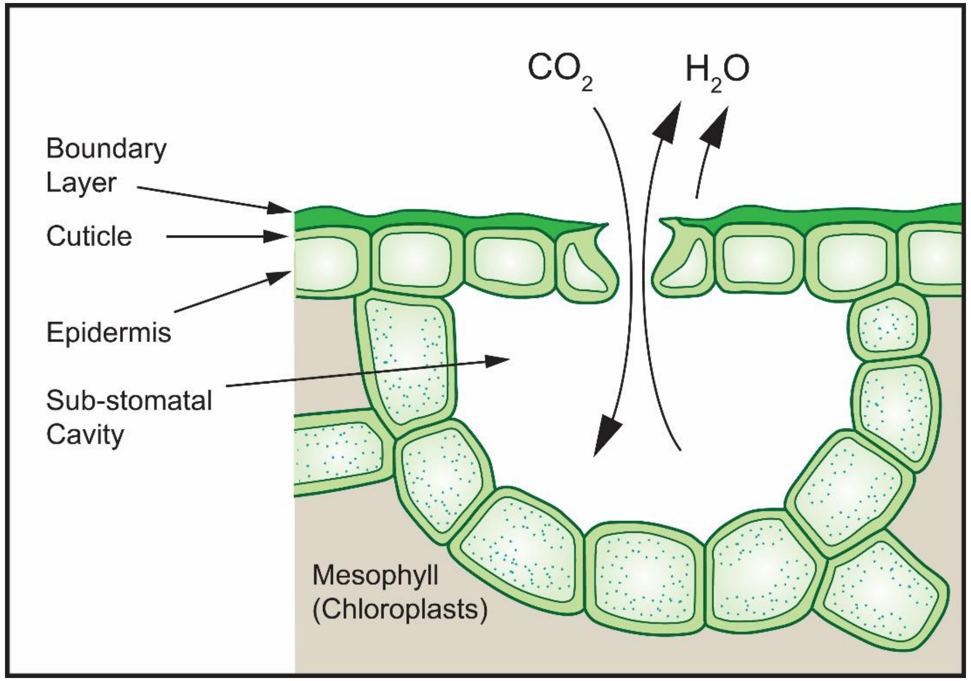
carbon dioxide + water → glucose + oxygen

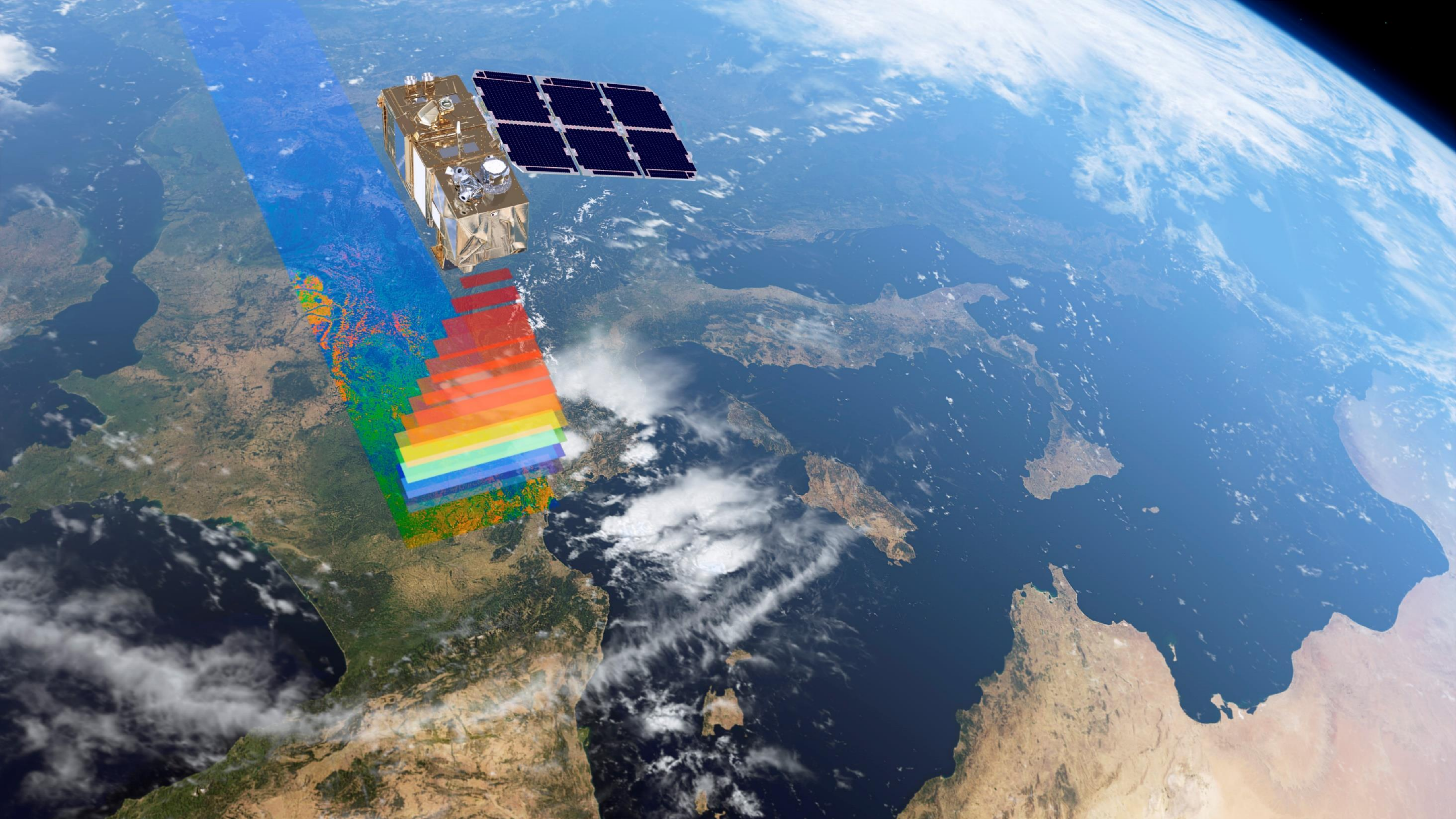


Guard cells (swollen) **Guard cells (shrunken)**

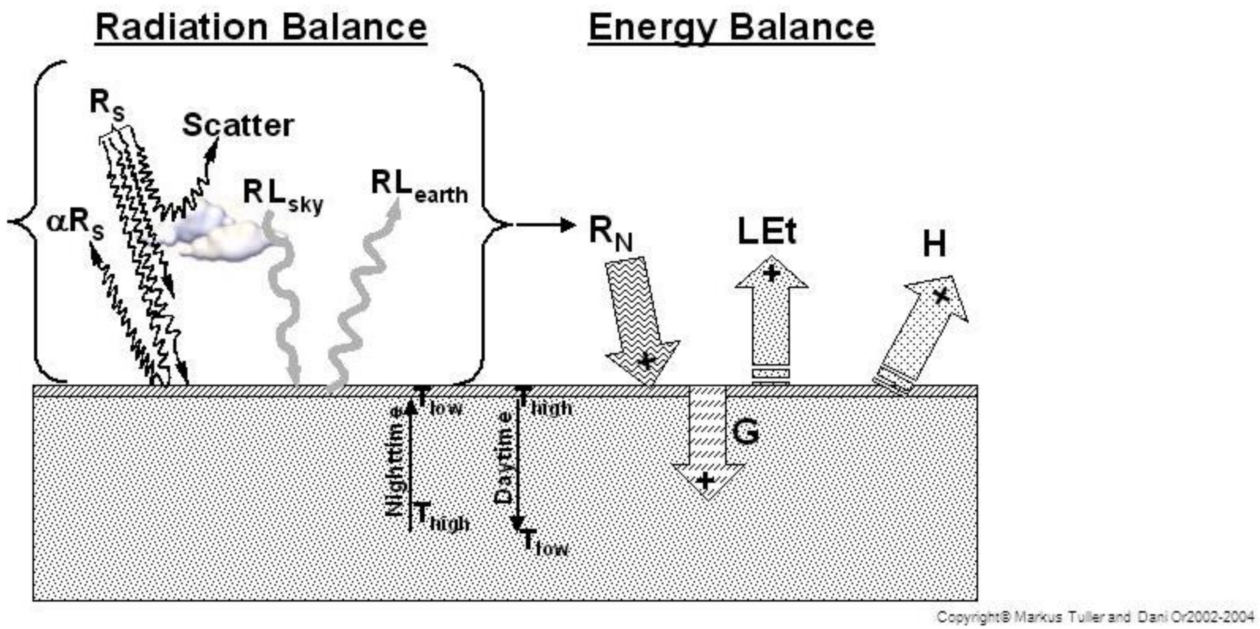


Stoma opening **Stoma closing**



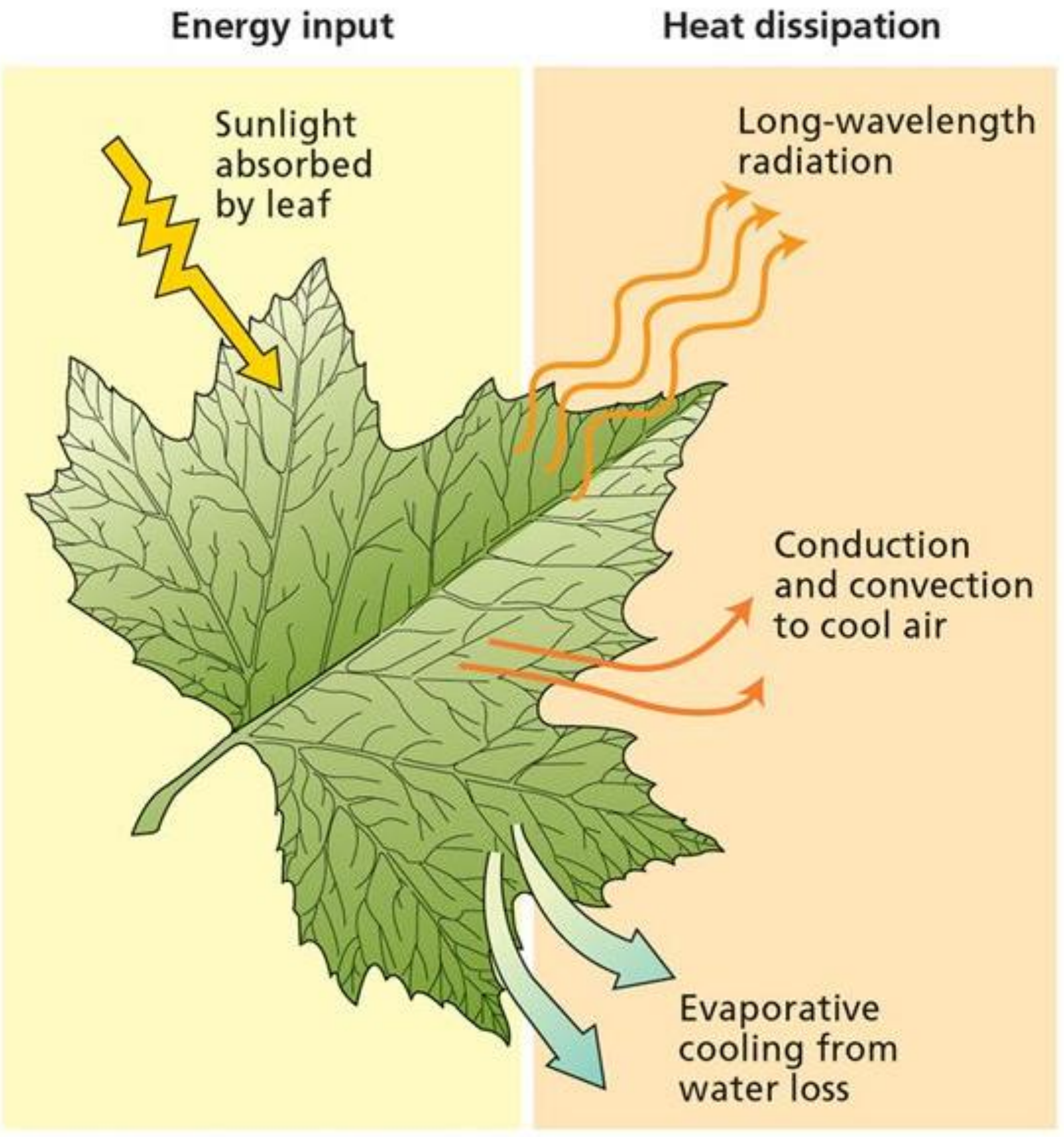


Surface Energy Balance



$$R_N = LE + G + H$$

Net Radiation | Latent Heat | Soil Heat | Sensible Heat



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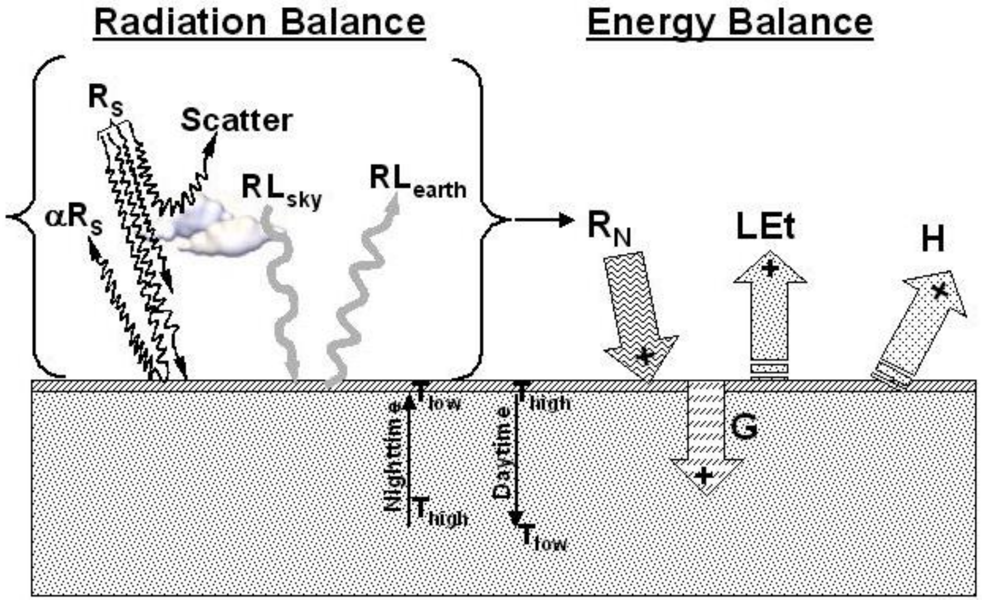
Surface Energy Balance



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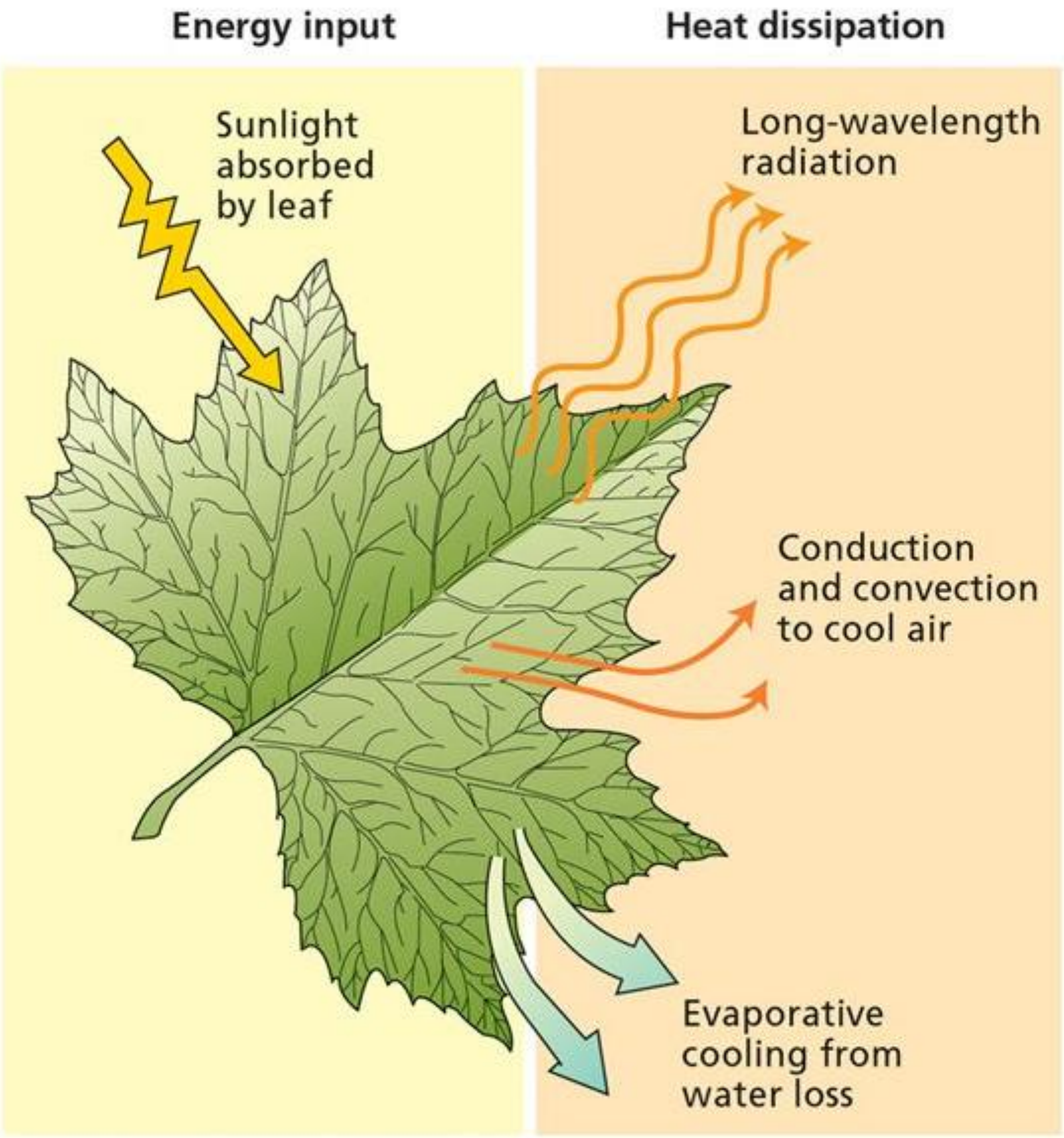

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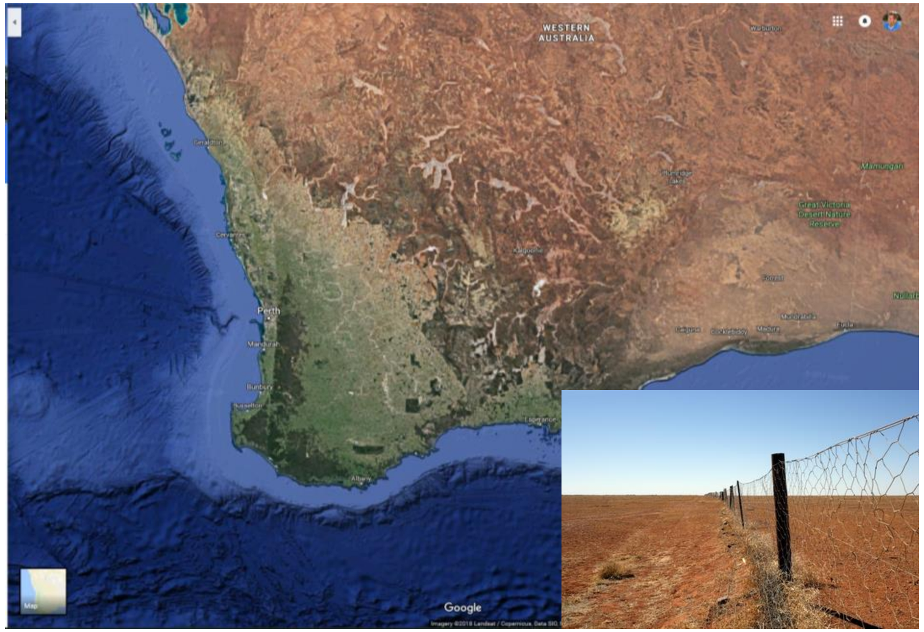
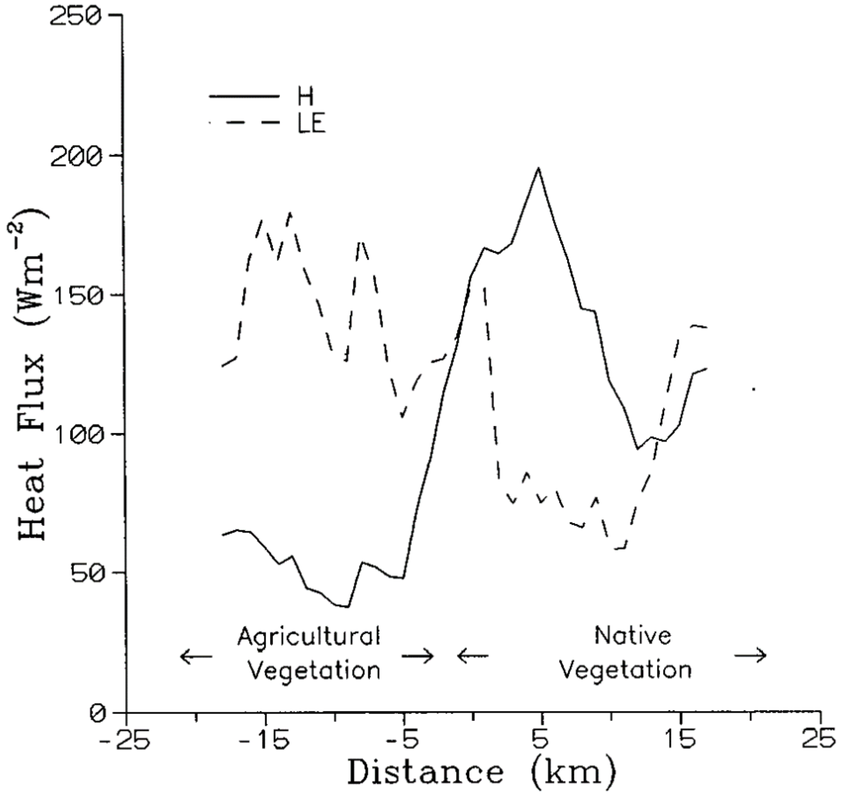
Question

The rabbit-proof fence stretches across several areas in western Australia. In southwestern Australia, the fence clearly separates wet irrigated crops near the coast from native vegetation and desert in the interior. In a famous experiment (Lyons et al., 1993), the intensity and frequency of thunderstorm activity was seen to be much higher on the drier side of the fence.





Question

Why is there more thunderstorm activity on the drier side of the fence?

a) Latent heat (ET) is much higher on the drier side

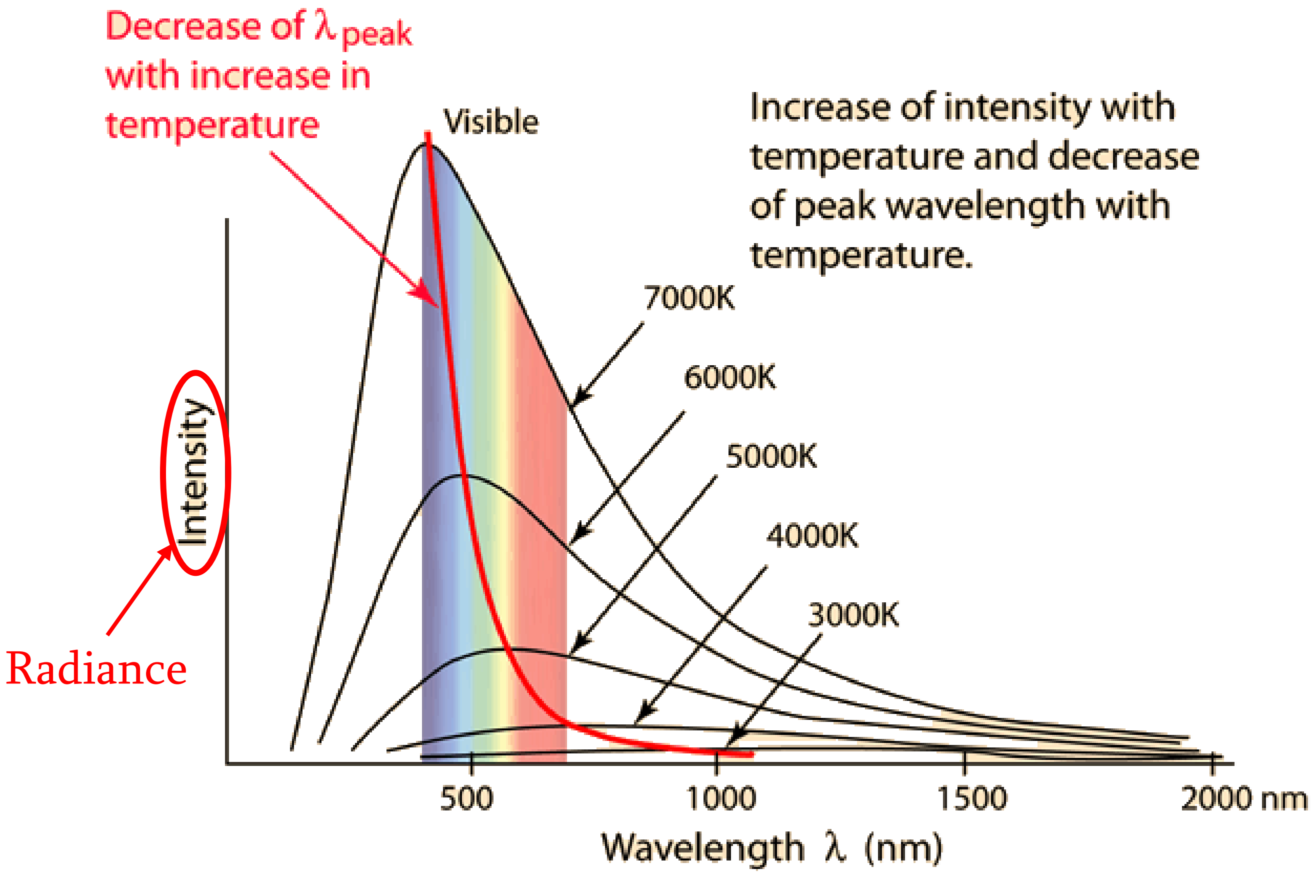
b) Sensible heat (H) is much higher on the drier side

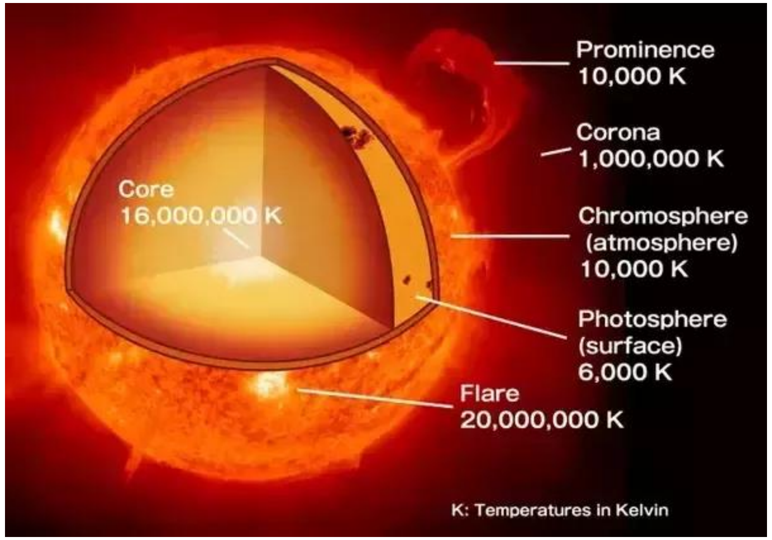
c) Sensible heat is much higher on the wetter side

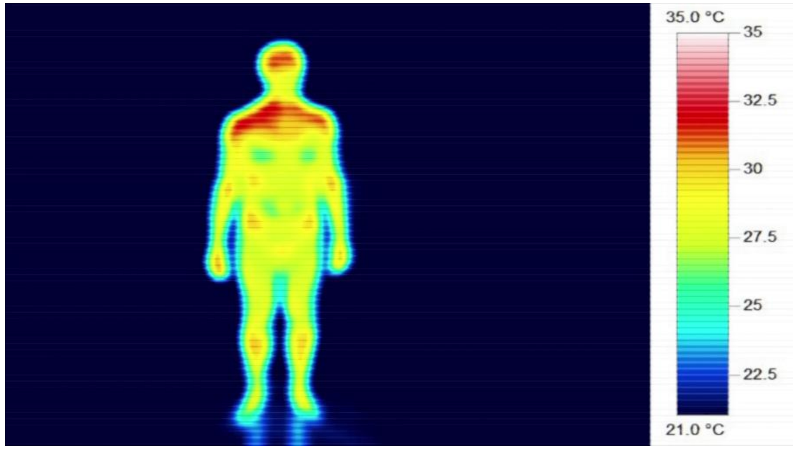
d) Land cover has no impact

Sensible Heat (H) and Radiant Temperature

Wien’s Displacement Law for “Black Bodies”







<u>Cooler objects emit less energy at longer wavelengths</u>

Sensible Heat (H) and Radiant Temperature

Radiance to At-Sensor or TOA Brightness Temperature

$$B_\lambda(T) = \frac{C_1}{\lambda^5(e^{C_2/\lambda T} - 1)}$$ Planck's Radiance Function (PRF)

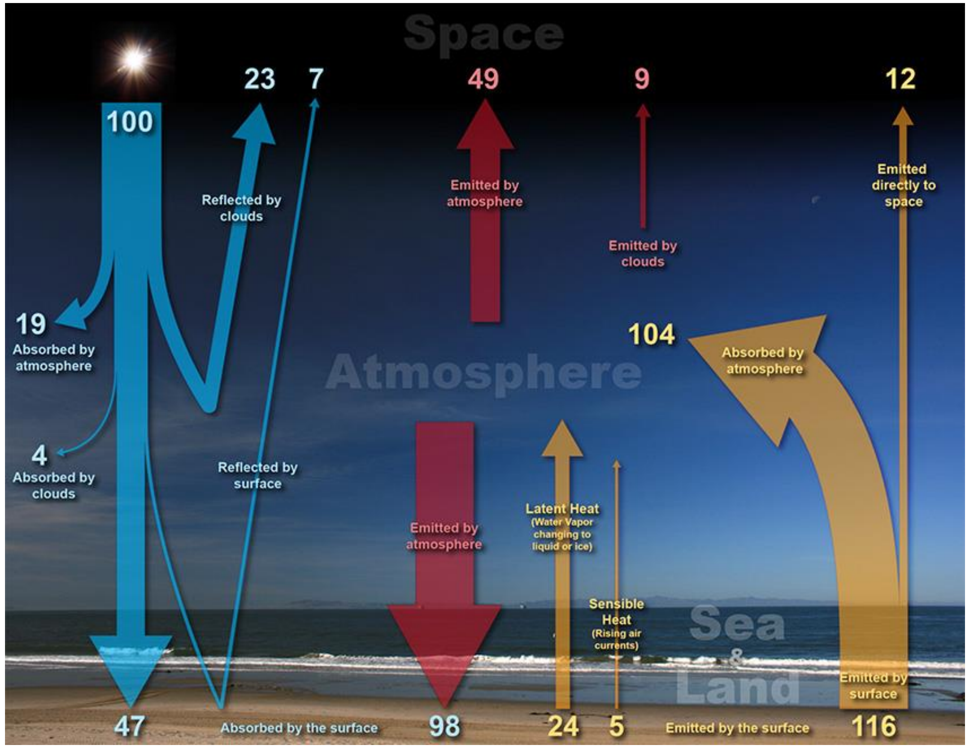
$$T = \frac{\frac{C_2}{\lambda}}{\ln\left(\frac{C_1}{\lambda}\frac{1}{B_\lambda(T)}+1\right)}$$ Inverted PRF

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_{TOA}}+1\right)}$$ Inverted PRF adapted for remote sensing

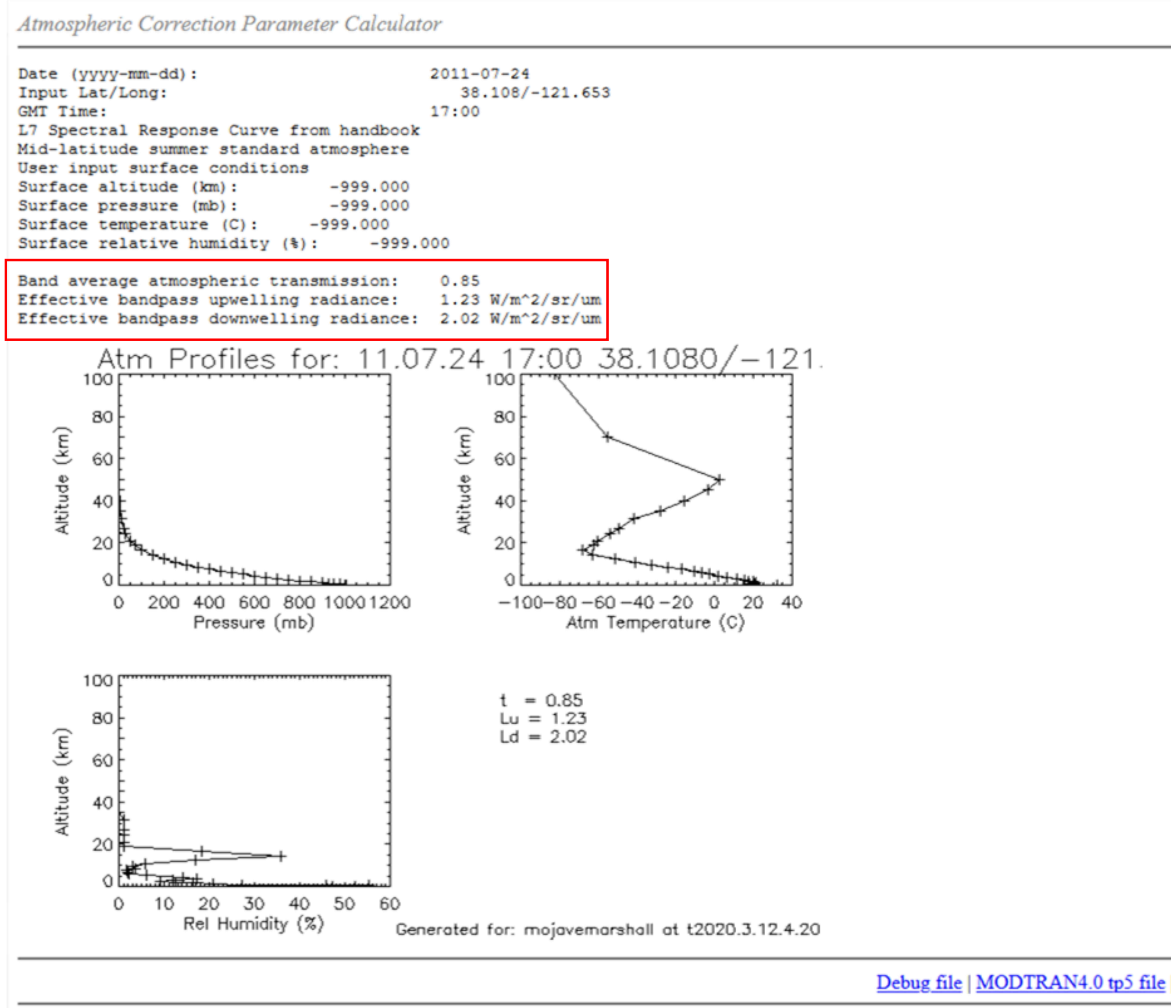
T is the TOA brightness temperature, K_1 and K_2 are coefficients corresponding to the effective wavelength (λ) of a sensor, and L_{TOA} is the TOA radiance

Sensible Heat (H) and Radiant Temperature

Radiance to Land Surface Temperature (LST)



$$L_\lambda = \left[\left(\frac{L_{TOA} - LW^{\uparrow}}{\tau}\right) - (1 - \varepsilon) \cdot LW^{\downarrow}\right] \cdot \left(\frac{1}{\varepsilon}\right)$$



Atmospheric Correction Parameter Calculator

```
Date (yyyy-mm-dd):                          2011-07-24
Input Lat/Long:                               38.108/-121.653
GMT Time:                                   17:00
L7 Spectral Response Curve from handbook
Mid-latitude summer standard atmosphere
User input surface conditions
Surface altitude (km):            -999.000
Surface pressure (mb):            -999.000
Surface temperature (C):       -999.000
Surface relative humidity (%):       -999.000

Band average atmospheric transmission:     0.85
Effective bandpass upwelling radiance:     1.23 W/m^2/sr/um
Effective bandpass downwelling radiance:   2.02 W/m^2/sr/um
```


Debug file | MODTRAN4.0 tp5 file

https://atmcorr.gsfc.nasa.gov/

Surface Energy Balance (SEB) Models

The energy used to evaporate water from the soil and vegetation is inversely related to H

$$LE = R_N + G + H$$

$$H = \frac{\rho C_p (T_0 - T_a)}{r_a}$$

ρ is the air density, C_p is the specific heat of air, T_0 is the aerodynamic temperature and T_a is the near surface air temperature

Surface Energy Balance (SEB) Models

The energy used to evaporate water from the soil and vegetation is inversely related to H

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Approximated from LST (Landsat, ASTER, MODIS, etc.)

ρ is the air density, C_p is the specific heat of air, T_0 is the aerodynamic temperature and T_a is the near surface air temperature

How do we measure ET from LST?

- Empirical methods
- Single source models (SEBAL, METRIC and SEBS)
- Scatterplot-based methods (triangle and trapezoid)
- Two-source models (ALEXI/DisALEXI)

How do we measure ET from LST?

- Empirical methods
- Single source models (SEBAL, METRIC and SEBS)
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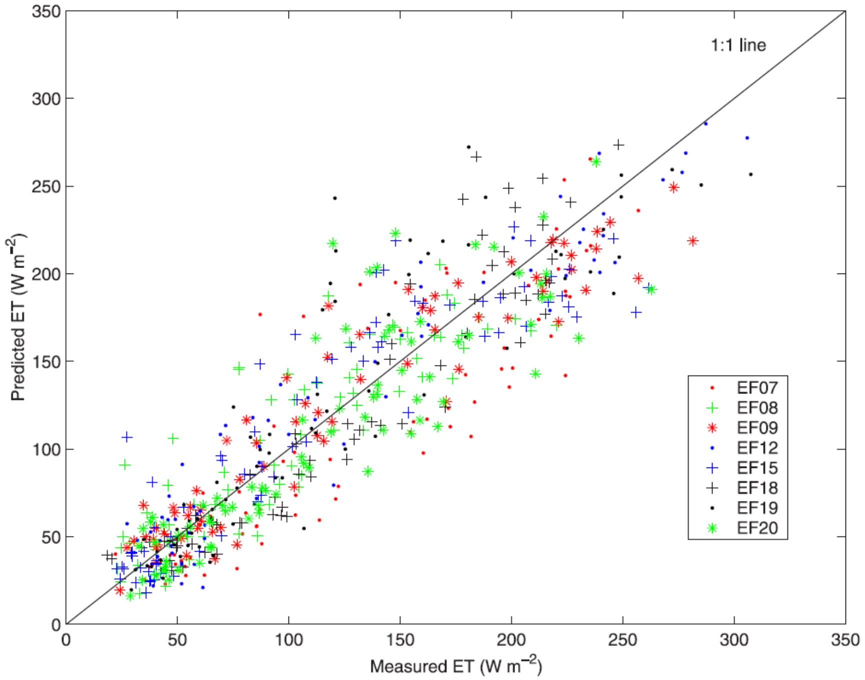
Each address SEB approach limitations

Empirical Methods

Early methods used linear relationships between ET and T_0-T_a. R_N was used to normalize the relationship. Later methods incorporated VIs such as NDVI and EVI:

$$LE = R_N \cdot (a_0 + a_1 \cdot VI + a_2 \cdot LST)$$

a_0 = intercept and $a_{1,2}$ = slope coefficients



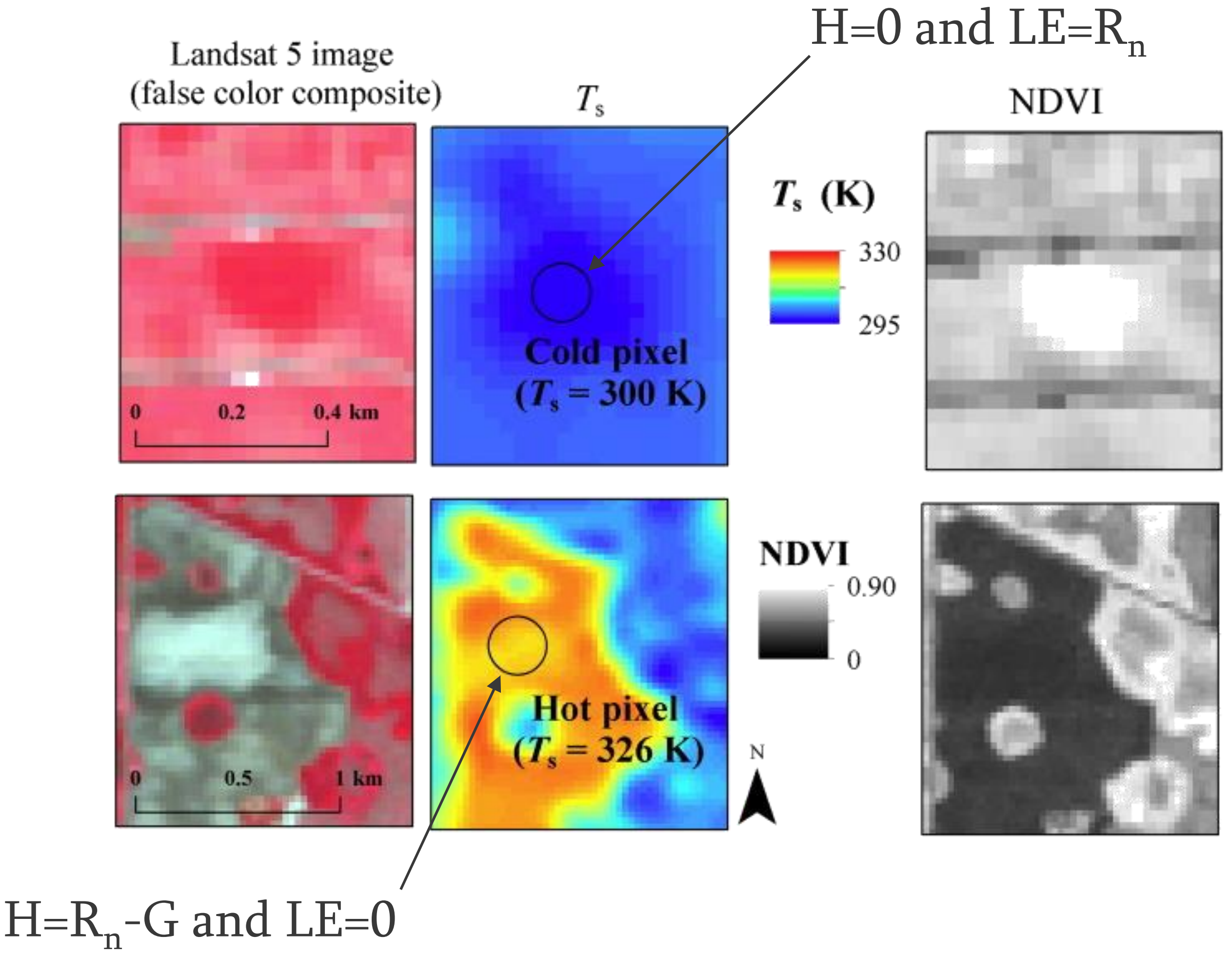
Wang, K., Wang P., Li Z., Cribb M., and Sparrow M. 2007. A simple method to estimate actual evapotranspiration from a combination of net radiation, vegetation index, and temperature. *Journal of Geophysical Research* 112: D15107, doi:10.1029/2006JD008351.

SEB Model Uncertainties

- Difficulties estimating T_0 - T_a
  - LST sensitive to water vapor
    - Multi-angle or split-window correction
  - Surface is not a perfect black body
    - Emissivity
  - Atmospheric correction
  - Spatial heterogeneity
- Transport Coefficient (r_a)
  - Highly sensitive to canopy conditions and the canopy itself
- One-time satellite overpass
  - Evaporative fraction

Single source models

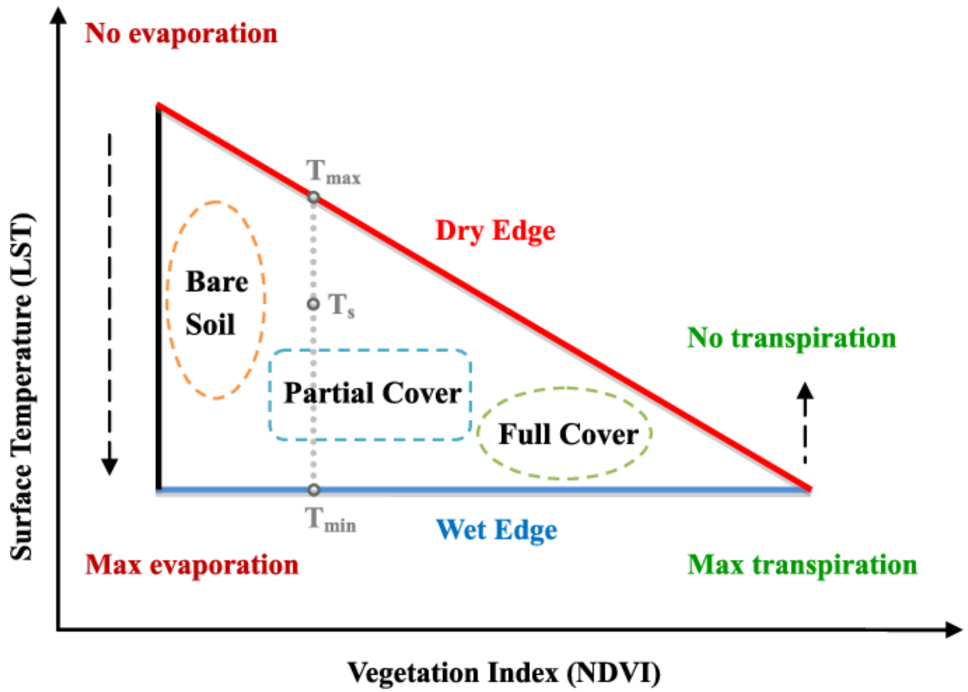
- Appropriate for moderate resolution (~30m) imagery
- Assumes soil and vegetation are one source
- Self calibrate for T_0 and T_a
- Still requires r_a
- Evaporative fraction still a problem

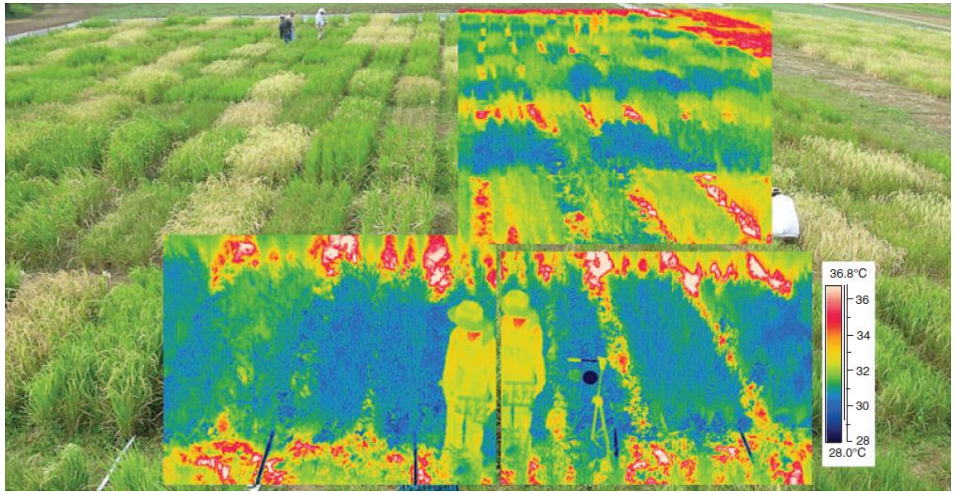


Bastiaanssen, W. 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. *Journal of Hydrology* 229: 87-100.

Scatterplot-Based Methods
NDVI-LST Feature Space

- Triangle (LST)
- Trapezoid (LST & T_a)
- Position in feature space determines evaporative fraction
- Soil moisture a limiting factor?
- Cloud contamination
- Edges determined from image
  - Spatial heterogeneity

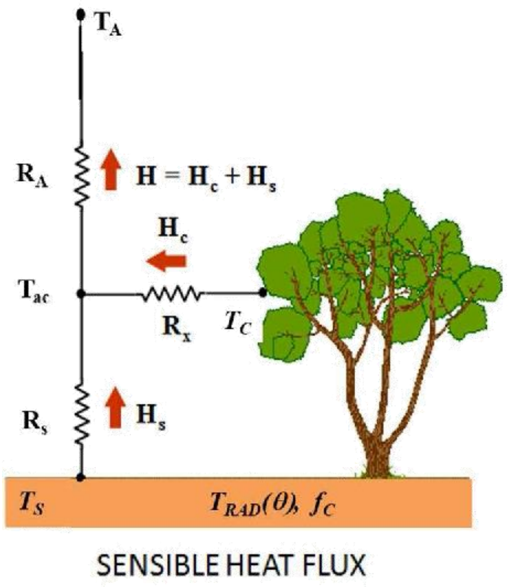




Moran, M., Clarke,T., Inoue, U., and Vidal, A. 1994. Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Remote Sensing of Environment 49: 246–263.

Two-source models

- Coarse resolution
  - DisALEXI
- Soil and vegetation are considered separately
  - Vegetation determined from potential evapotranspiration
  - Soil determined from T_0 and T_a
- Still requires r_a
- Geostationary weather satellites



System, soil, canopy budgets

$R_n = H + \lambda E + G$

$R_{n,s} = H_S + \lambda E_S + G$

$R_{n,c} = H_C + \lambda E_C$

Two-source approximation

$T_{RAD}(\theta)^4 \sim f_C(\theta)\, T_C^4 + [1 - f_C(\theta)]\, T_S^4$

Temperature constraint

H_C, H_S, $R_{n,c}$, $R_{n,s}$, G

PT, PM or LUE R_C model

λE_C

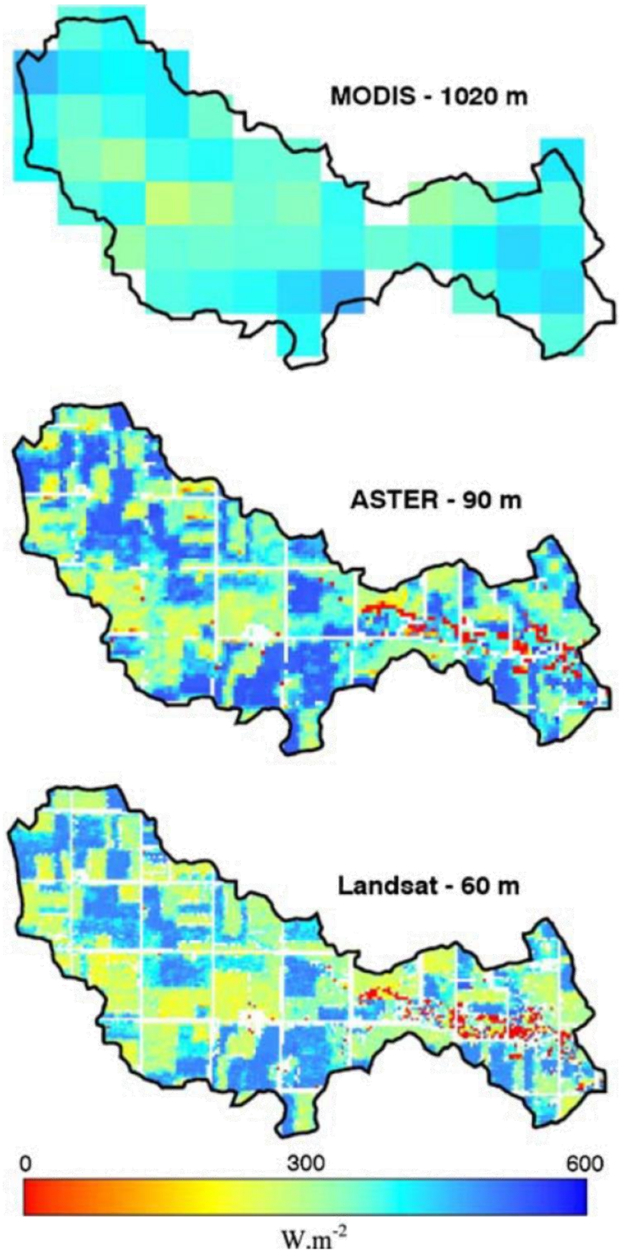
Residual

$\lambda E_S = R_n - H - G - \lambda E_C$

Norman, J.,Kustas,W., and Humes, K. 1995. A two-source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. Agriculture and Forest Meteorology 77: 263–293.

Persistent Issues with SEB Models

- LST is NOT scale-invariant
- Satellite coverage
- Equifinality
- R_N – G uncertainties
- Windspeed and aerodynamic surface conditions
- Nighttime transpiration
- Diffuse (cloudy) daylight conditions
- Poor validation data
- 15-30% uncertainty with ground data



Other Methods to Measure ET

- Empirical crop coefficient (FAO-56)
- Direct ET (PT-JPL, MOD16)
- Water-balance (hydrologic or SVAT models)

Question

On a previous slide, I showed parameters from the Atmospheric Correction Parameter Calculator for a target within a Landsat-7 ETM+ scene where thermal data was collected:

- The radiance at TOA (L_{TOA}) = 10.53 W m^{-2} sr^{-1} μm^{-1}
- Atmospheric transmission (τ) = 0.85
- Upwelling longwave radiation ($LW\uparrow$) = 1.23 W m^{-2} sr^{-1} μm^{-1}
- Downwelling longwave radiation ($LW\downarrow$) = 2.02 W m^{-2} sr^{-1} μm^{-1}
- Emissivity (ε) can be approximated with NDVI: $1.0094+0.047\cdot\ln(NDVI)$. The value of the target has an NDVI of 0.7

Question

How many degrees Celsius are lost between the surface and the Landsat sensor?

a) 3.17 $^\circ$C

b) 3.27 $^\circ$C

c) 26.69 $^\circ$C

d) 2.17 $^\circ$C

Summary

- Thermal infrared imagery has many agricultural applications
  - Irrigation management
- Evapotranspiration links the surface to the atmosphere
  - Water balance
  - Energy balance
- "Warmer" drier surfaces (bare) tend to radiate more sensible heat
- "Cooler" wetter surfaces (vegetated) tend to emit more latent heat
- SEB models all loosely based on LST-NDVI

Practical

Estimating evapotranspiration (ET) with top of atmosphere brightness temperature (TOA)

- San Joaquin/Sacramento River Delta (California)
- Download Landsat-7 (level 2) data
- Eddy covariance flux tower ET
- Build statistical relationships between ET and TOA