Evapotranspiration modelling with satellite data

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DHI

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Agenda

1. Introduction
2. What is evapotranspiration and why is it important
3. Modelling of evapotranspiration
4. Application with satellite / Copernicus data
5. Conclusions and perspectives
6. Exercise

Introduction

Introduction

About me:

- Bachelor of Computer Science at University of Adelaide
- Master in Physical Geography and Ecosystem Modelling from Lund University
- PhD in Geography and Remote Sensing from Copenhagen University
  - Advancements in Modelling of Land Surface Energy Fluxes with Remote Sensing at Different Spatial Scales
- 2-year Research Fellowship at European Space Agency
- Working at DHI for over 10 years
  - Focus on physical and machine learning models of biophysical parameters in agricultural and natural ecosystems

DHI at a glance

Global advisory company with deep domain knowledge, strong technology and continuous innovation

Independent, private, not-for-profit

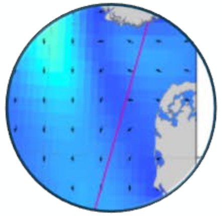
Supports sustainability in water environments

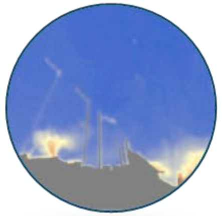
1000+ employees, 80% with an MSc or PhD degree

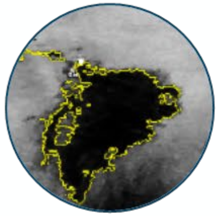
Representing 50+ years of dedicated research and real-life experiences

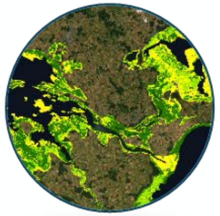
DHI at a glance

Providing a satellite perspective on water data for over 20 years

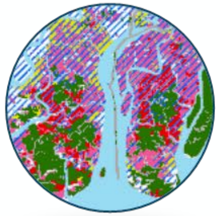

MetOcean data

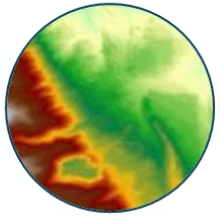

Sea Surface Temperature


Oil Spill


Marine Habitat Maps

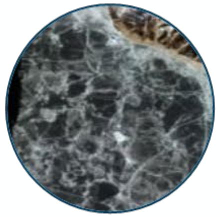

Satellite Images

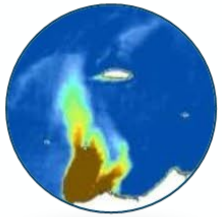

Coastal Vegetation

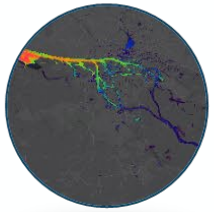

Digital Elevation

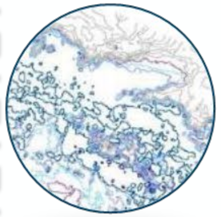

Urban Mapping

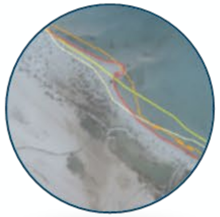

Vegetation Health

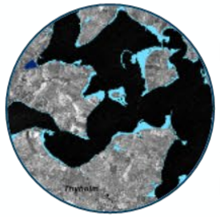

Sea Ice and Icebergs

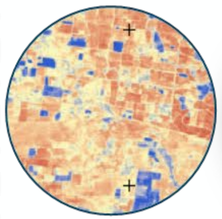

Dredge Plumes


Water Quality

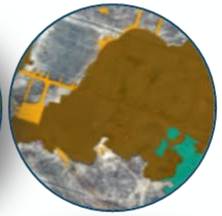

Bathymetry


Coastal Dynamics


Flooding


ET and drought


Freshwater Monitoring

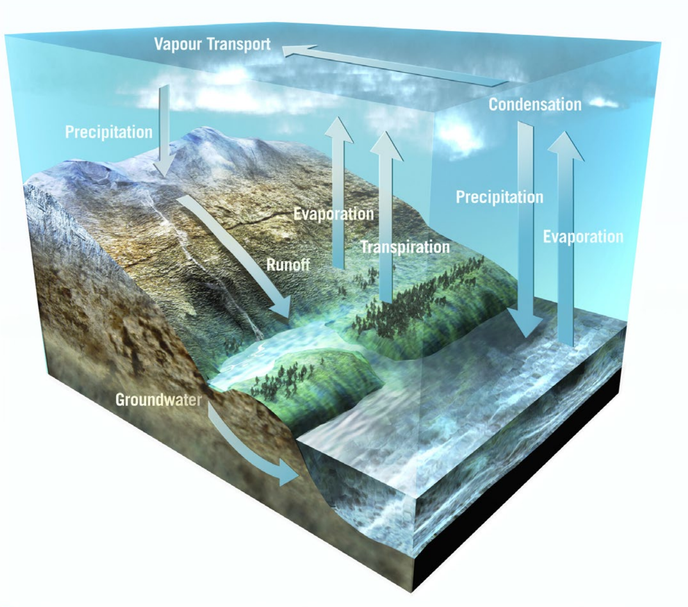

Land Cover - Land Use

Offshore and Near shore → Coastal Zone → Onshore and inland

What is evaporation and why is it important

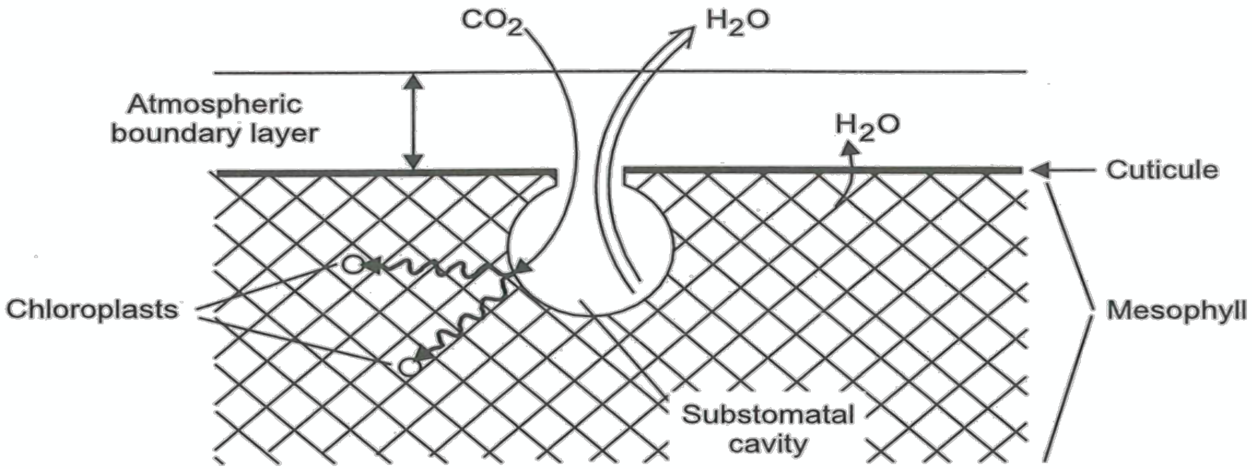
What is evapotranspiration (ET)

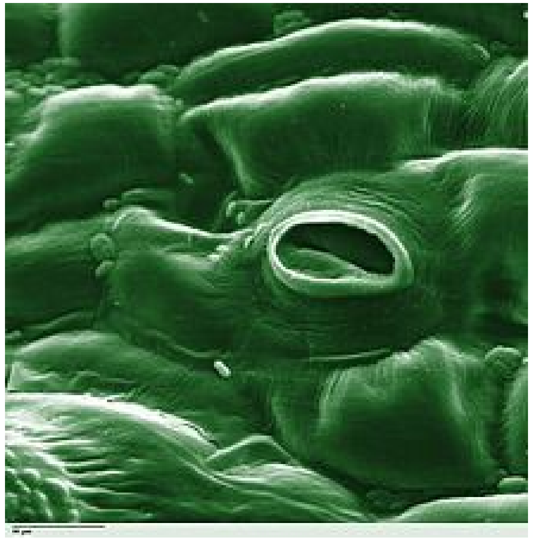
- The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants – *Oxford*
    - Evaporation – from top-soil soil moisture, water bodies and ponded water
    - Transpiration – through leaf stomata, i.e. from the root-zone
- Integral part of water cycle:



Leaf stomata

- Stoma - pore found in the epidermis of leaves, stems, and other plant organs, that controls the rate of gas exchange





- Gas exchange cools the plant and allows for photosynthesis
- Water stress -> stomata close -> transpiration and photosynthesis decrease -> leaf temperature increases

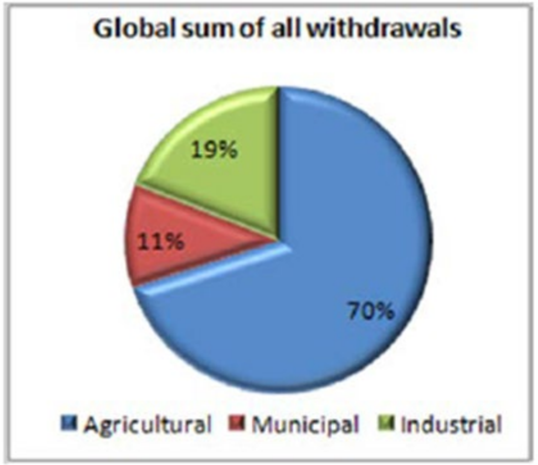
Importance of ET in water management

- 70 % of global water withdrawals are used in agriculture
  - Irrigation is main use of agricultural water
- Sustainable Development Goal indicator 6.4.1
  - Change in Water Use Efficiency (WUE) over time

$$WUE = A_{we} \times P_A + M_{we} \times P_M + S_{we} \times P_S$$

$$A_{we} = \frac{GVA_a \times (1 - C_r)}{V_a}$$

V_a = Volume of water used by the agricultural sector (including irrigation, livestock and aquaculture) [m^3]

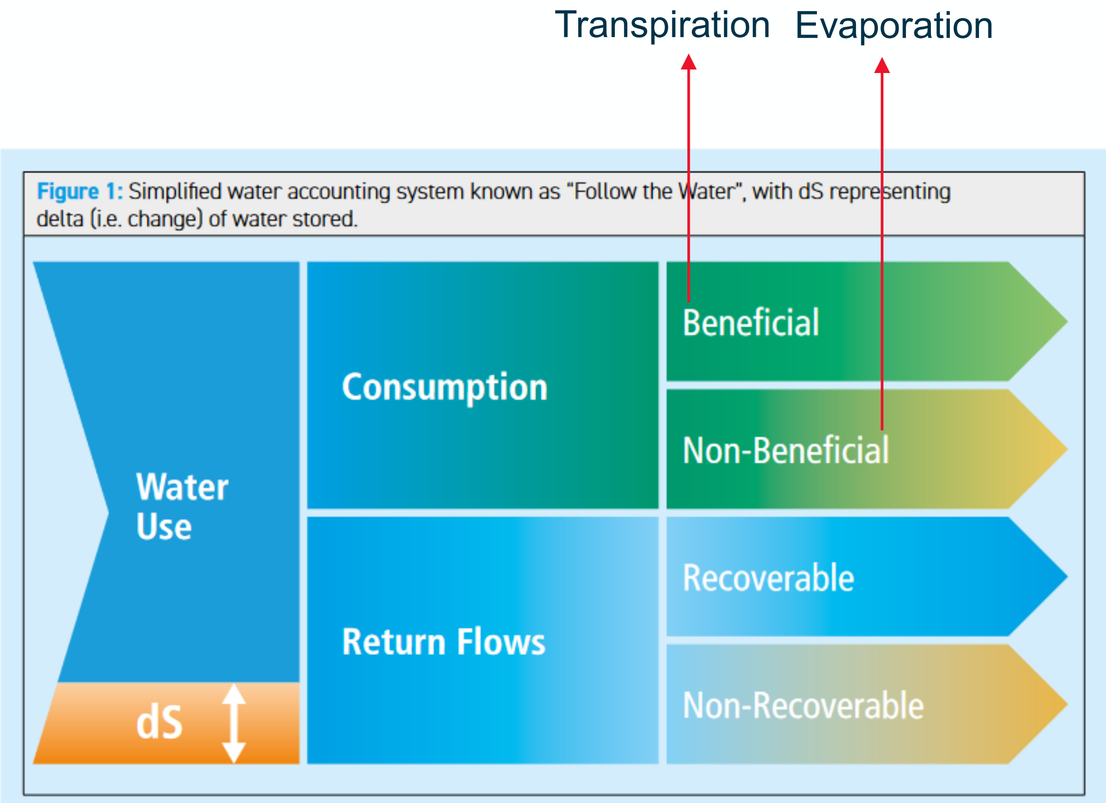


FAO Aquastat

- Actual evapotranspiration is a proxy of irrigation water use
  - With earth observation spatial and temporal patterns can be captured
  - Impartial and consistent view across political and natural boundaries

Real water savings in agriculture – water accounting

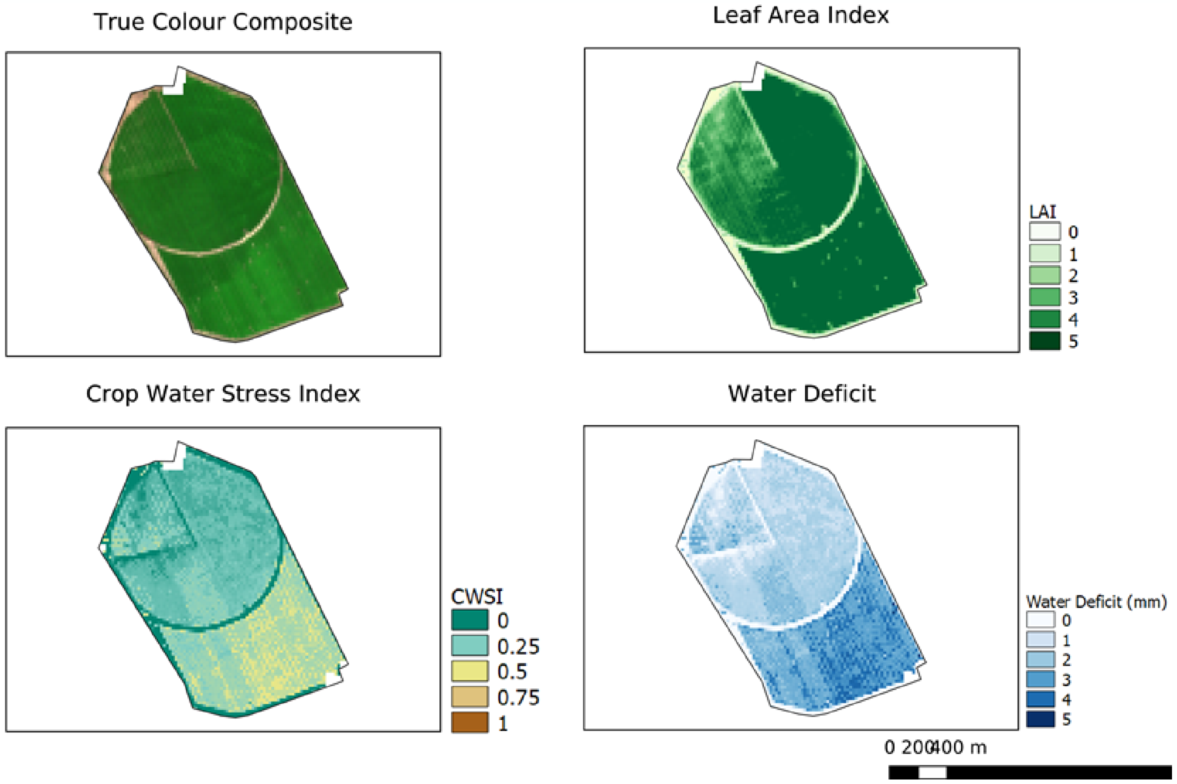
- FAO Water Management Policy Brief - https://www.fao.org/3/cc1771en/cc1771en.pdf
  - "In reality, it is more often the case that increasing water use efficiency also increases water consumption…which ultimately makes water scarcity worse."
  - "Water accounting should also increasingly be part of a long-term monitoring and evaluation programme aimed at improving sustainable water resources management."
  - "Real water savings can only be achieved if the amount of water supplied is reduced accordingly and reallocated elsewhere via a water allocation system."



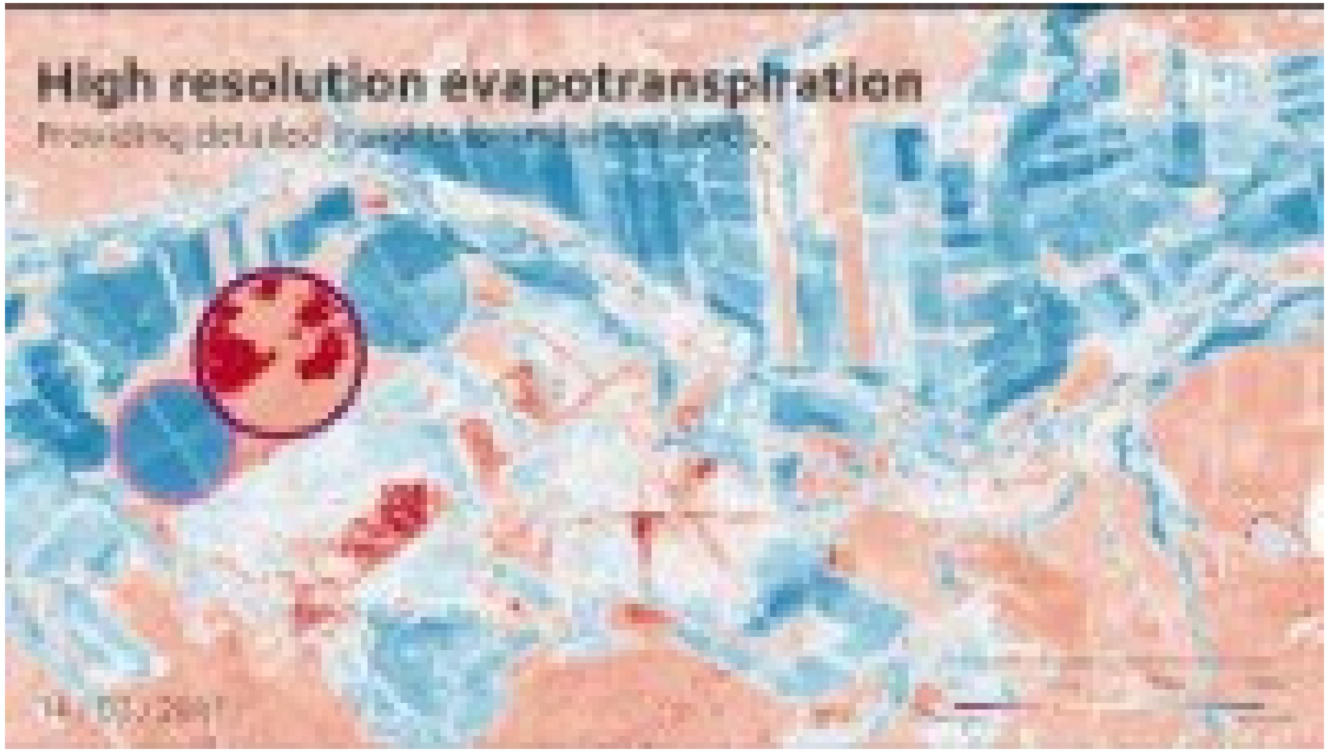
Source: Van Opstal, J., Droogers, P., Kaune, A., Steduto, P. & Perry, C. 2021. *Guidance on realizing real water savings with crop water productivity interventions*. Wageningen. FAO and FutureWater, doi: 10. 4060/cb3844en. Ruane, J., & Food and Agriculture Organization of the United Nations (FAO). 2013. *Coping with water scarcity: An action framework for agriculture and food security*. Rome.

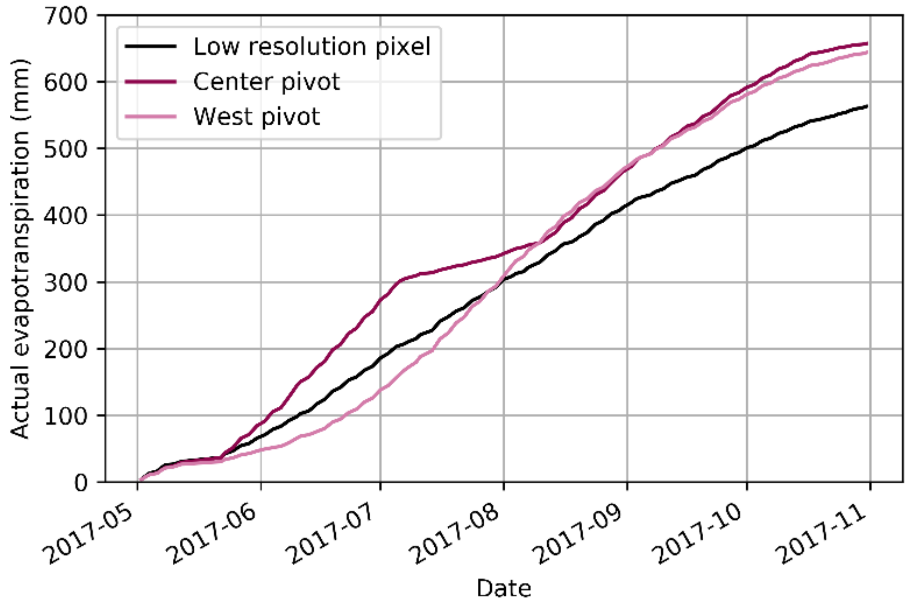
Early detection of water stress and efficient irrigation

- Stomata reacts to water stress immediately
  - Before crop damage occurs
  - Before stress becomes visible due to pigment changes
- Amount of water can be quantified
  - Irrigation advice and forecasting
    - Irrigation scheduling
    - Planning of water and equipment allocation
    - Variable irrigation



Importance of field-scale ET monitoring





Modelling of evapotranspiration

Modelling of evapotranspiration

- Remote sensing measures electromagnetic radiation
- ET therefore must be estimated from energy perspective
  - Latent heat flux – energy used to turn water from liquid to gas

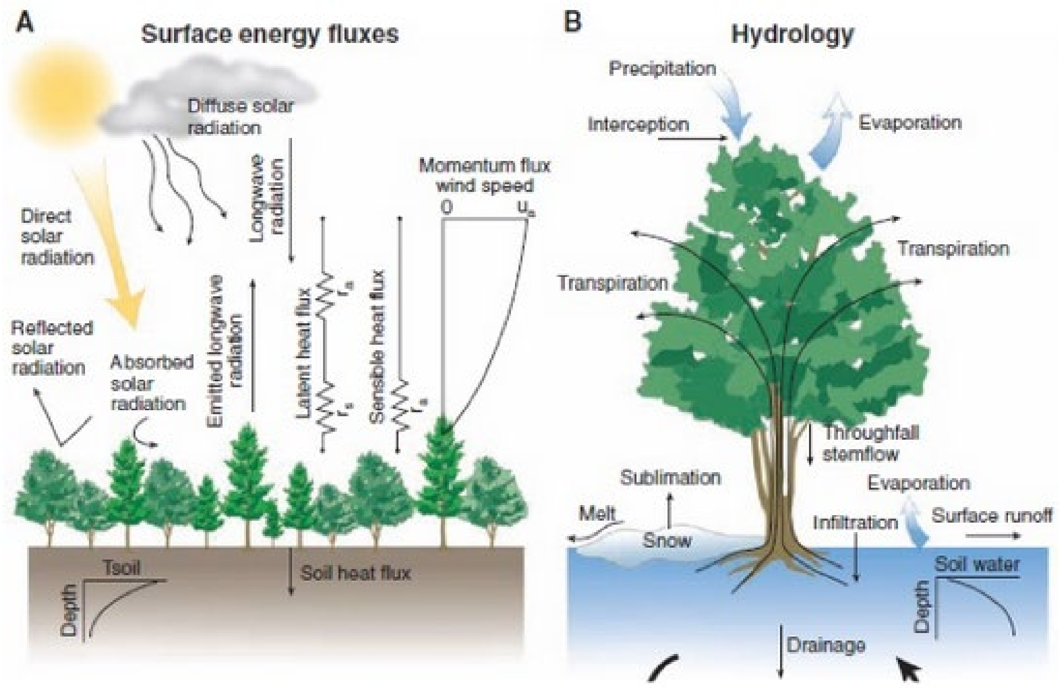
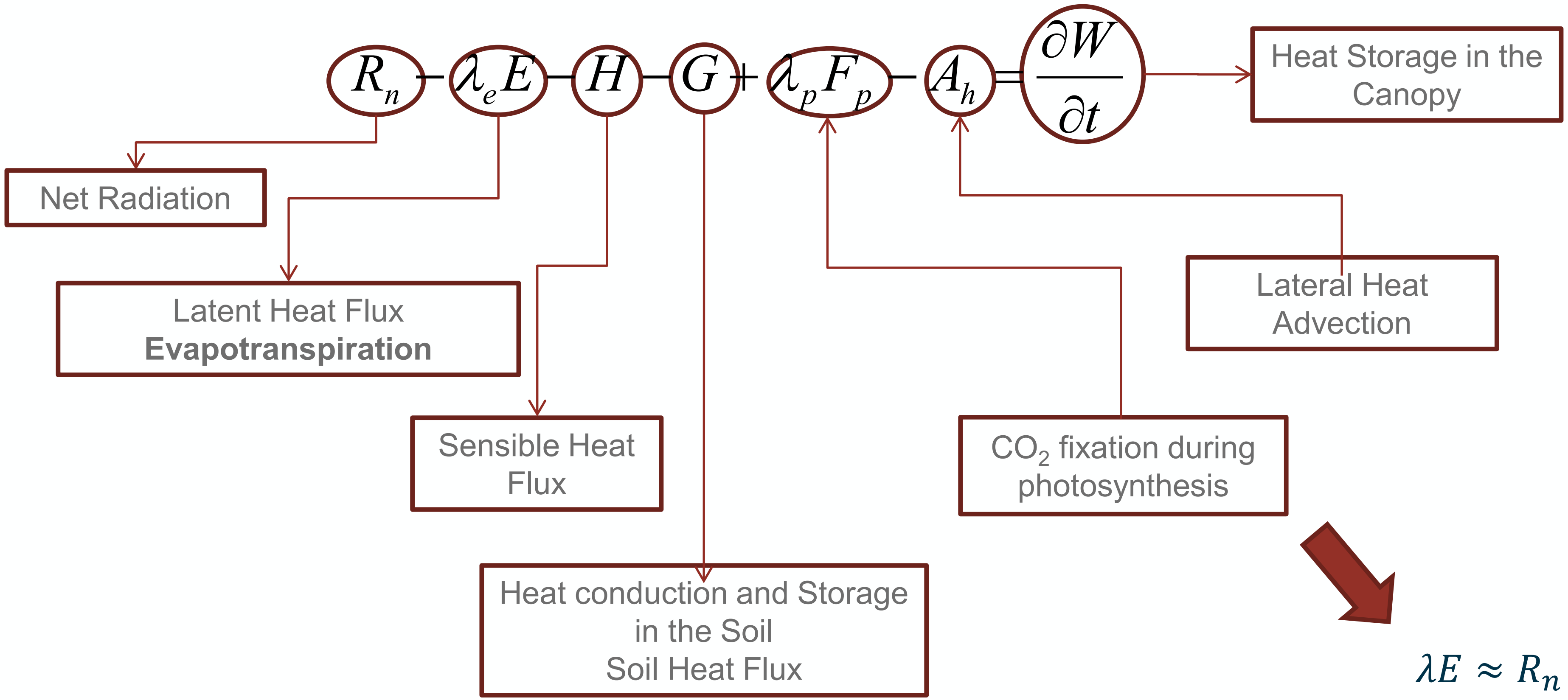


Figure source:
Bonan, G.B. Science, 320,1444-1449 (2008)

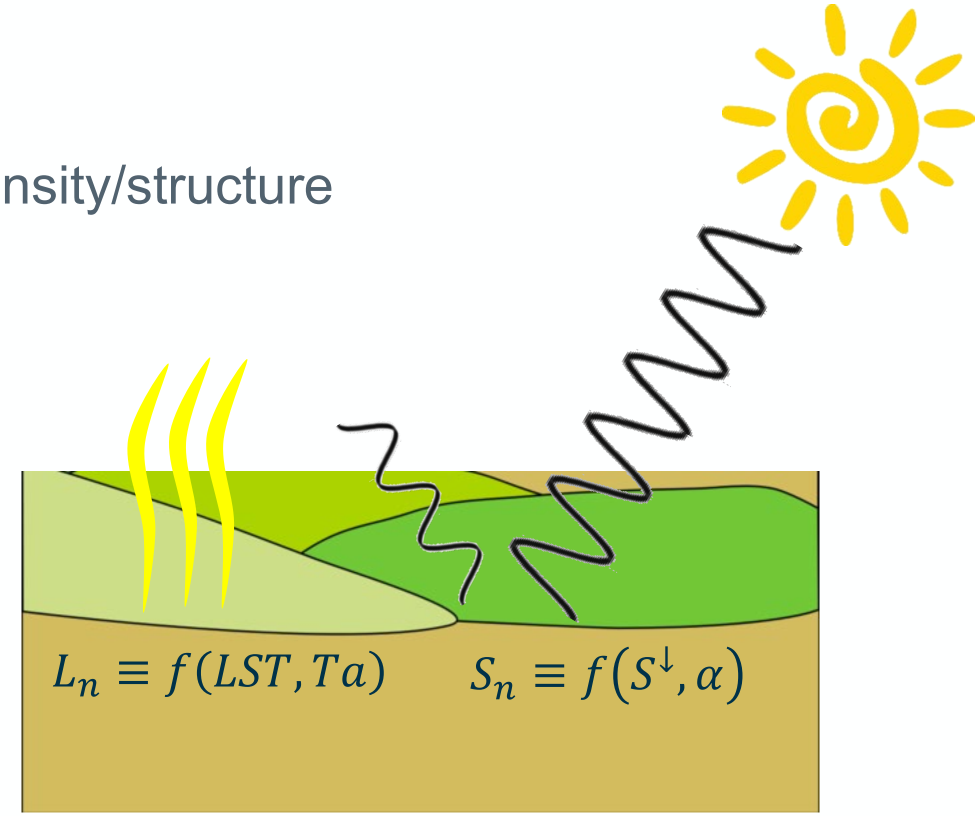
Surface energy balance



$$\lambda E \approx R_n - G - H$$

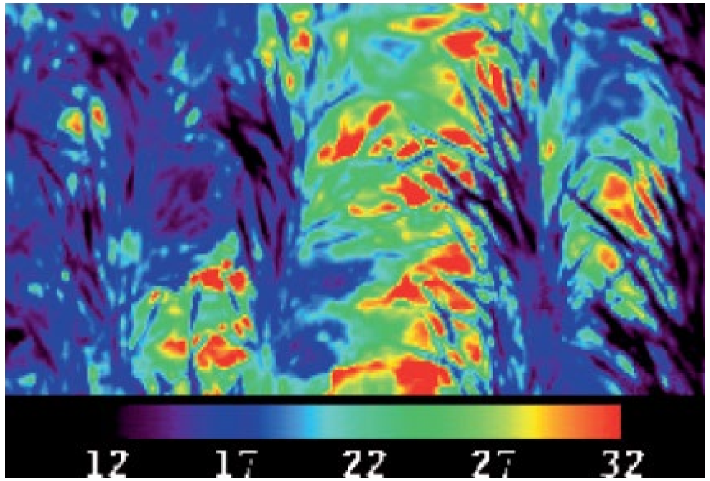
Net radiation and soil heat flux

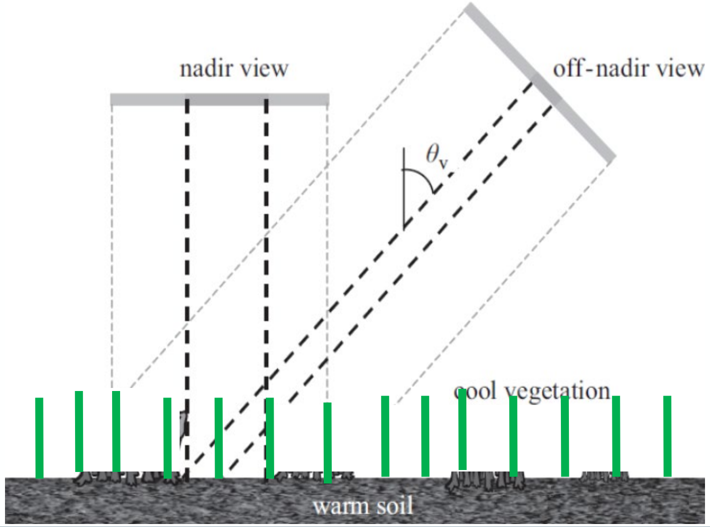
- Net radiation – incoming and outgoing shortwave and thermal radiation
  - Net shortwave radiation
    - Solar irradiance
    - Surface albedo
      - Leaf biochemistry (pigments) and canopy density/structure (LAI/fAPAR)
    - Soil albedo
  - Net longwave radiation depends on:
    - Surface and air temperature
    - Surface and air emissivity
- Ground heat flux has smaller magnitude
  - Function of (soil) net radiation



Sensible heat flux

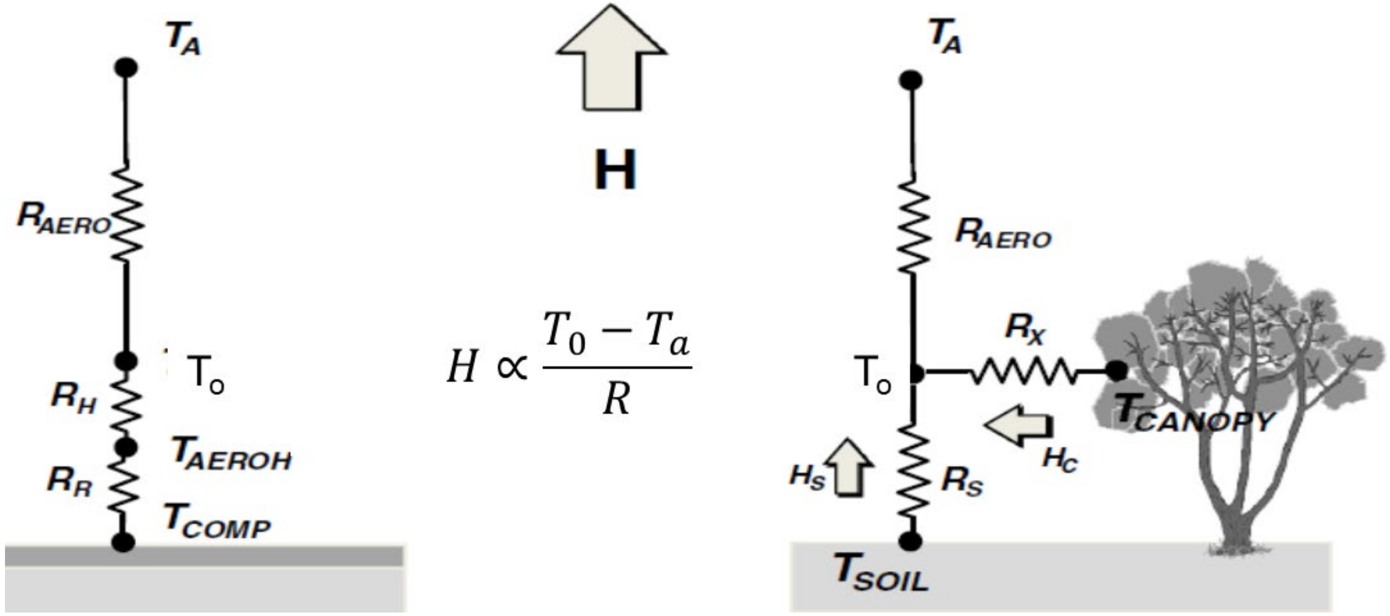
- Vertical transport/exchange of heat
  - Driven by a gradient of temperatures (aerodynamic vs. air)
- Do not confuse aerodynamic temperature with radiometric surface temperature (also called Land Surface Temperature – LST)
  - Aerodynamic temperature
    - Temperature at the canopy-air space
    - Satisfies the bulk resistance formulation for sensible heat transport
  - Radiometric surface temperature
    - Weighted soil and vegetation temperature





Sensible heat flux

- Sensible heat flux is modulated by
  - Wind – surface interaction
  - Atmospheric stability and convective turbulence
- Those interactions can be simplified by concept of aerodynamic resistances
  - Analogy to Ohm's Law

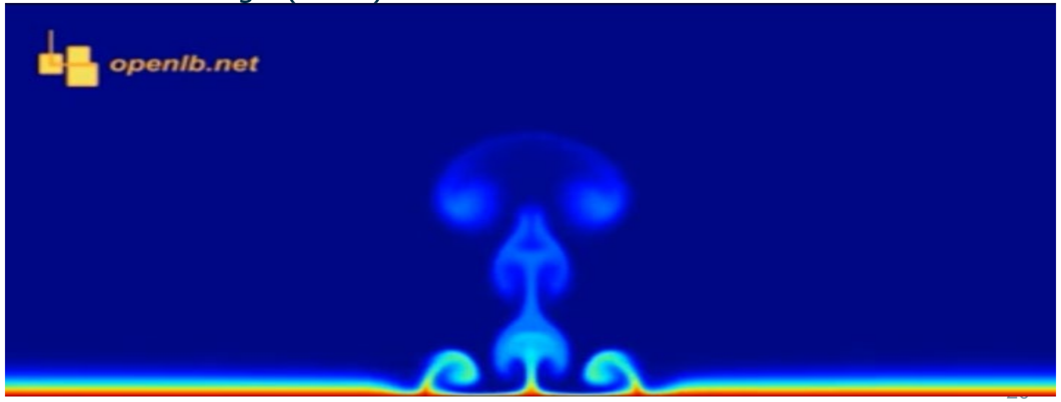


$$H \propto \frac{T_0 - T_a}{R}$$

Aerodynamic resistance

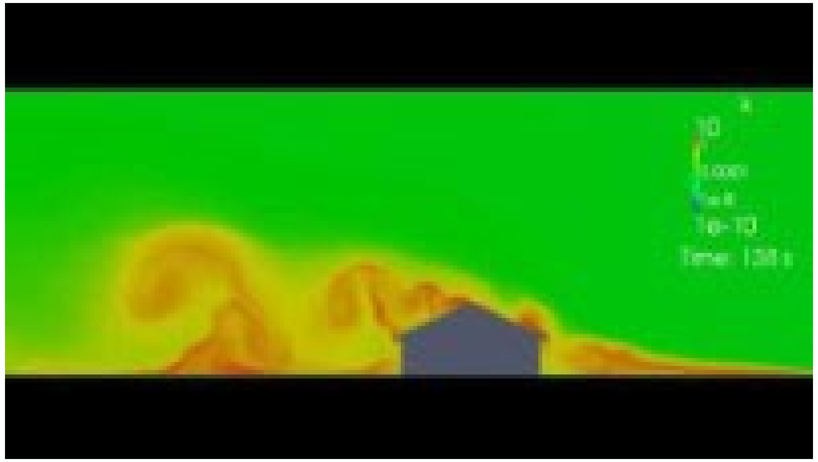
- Wind is a fluid
  - … usually under a turbulent regime
    - Mechanical turbulence driven by surface roughness
    - Thermal turbulence driven by convection (gradient of temperatures)
  - This turbulence produces eddies:
    - ↑ vertical transport ↓ lower resistance ↑ H

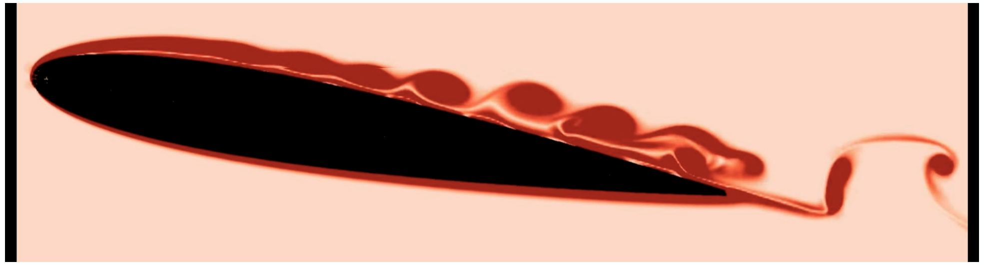
Source: Van Gogh (1889)

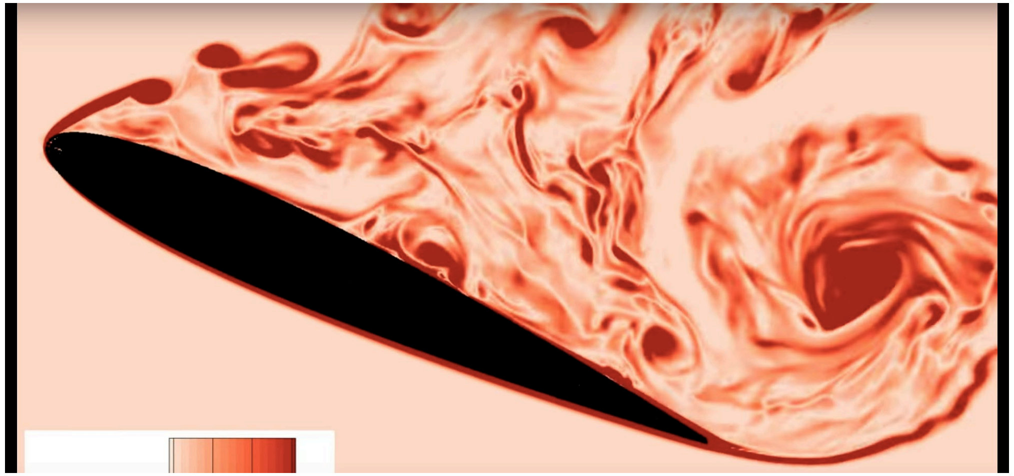


Aerodynamic roughness

- Depends on
  - Obstacle height
    - Canopy height
  - Canopy density
    - Leaf Area Index
  - Horizontal and vertical heterogeneity
    - Canopy structure





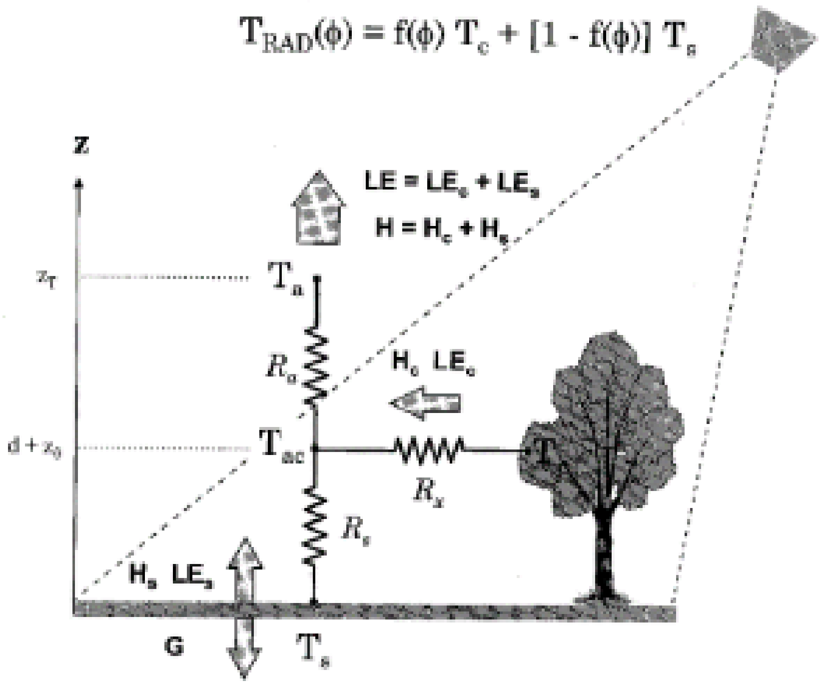


Remote sensing ET models

- One-source energy balance:
  - SEBS: https://github.com/jvdkwast/PySEBS
  - STIC
  - SEBAL
  - ...
- Two-source energy balance:
  - ETLook: https://bitbucket.org/cioapps/wapor-et-look/
  - TSEB: https://github.com/hectornieto/pyTSEB
  - ALEXI/Dis-ALEXI
  - 3SEB: https://github.com/VicenteBurchard/3SEB
  - ...
- Contextual
  - Triangle / trapezoid

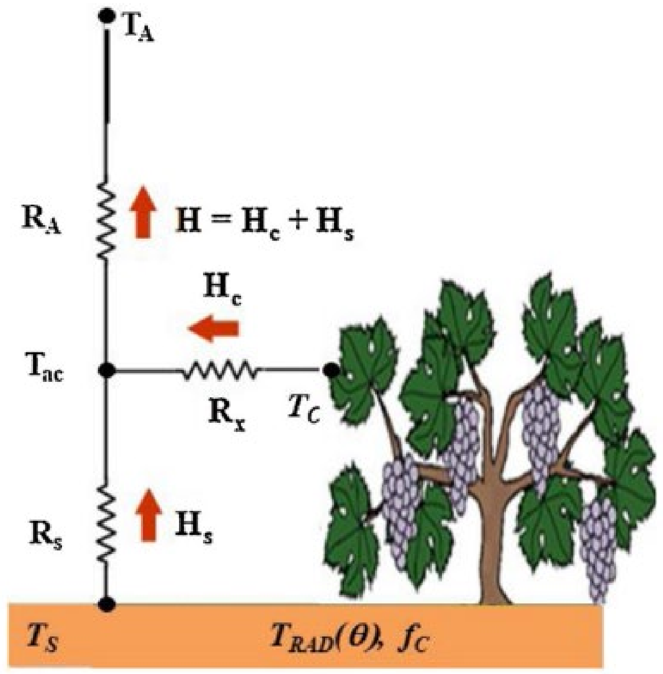
Model example - TSEB

- Two Source Energy Balance
  - Physical model
  - Models instantaneous land-surface energy fluxes (W/m2)
  - Partitions Evaporation and Transpiration with resistances in series
  - Flux interaction between canopy and soil
  - Robust in many environments
  - Continually developed
- Extrapolation to daily ET (mm/day)



Source: Mecikalski et al., 1999

Model example - TSEB



SENSIBLE HEAT FLUX

Norman and Kustas, et al. (1995)

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 model

λE_C

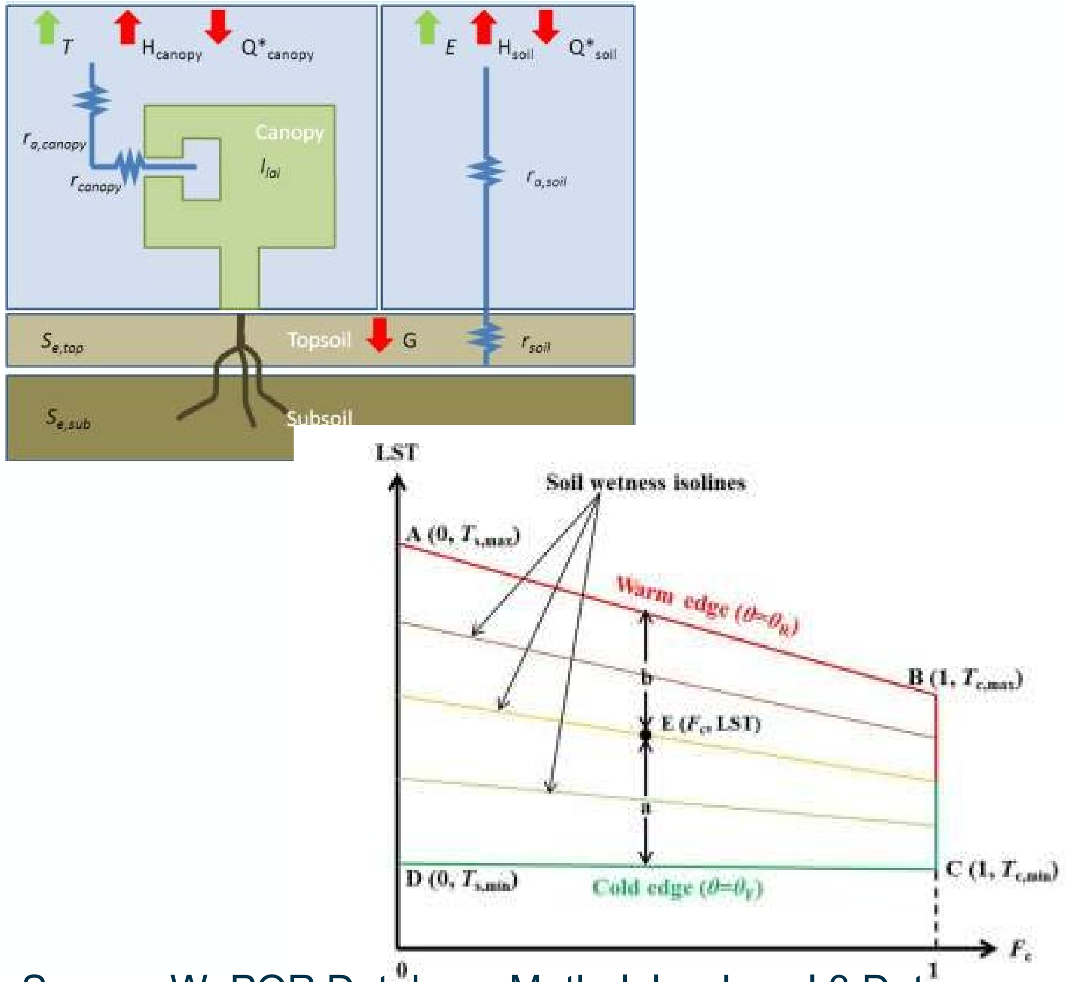
Residual

$\lambda E_s = R_n - H - G - \lambda E_c$

Iterative solution

Model example - ETLook

- ETLook
  - Physical/contextual model
  - Models daily land-surface energy fluxes (W/m2)
  - Partitions Evaporation and Transpiration by radiation partitioning
  - No flux interaction between canopy and soil
  - Requires definition/calculation of extreme temperatures
  - Less sensitive to input uncertainty

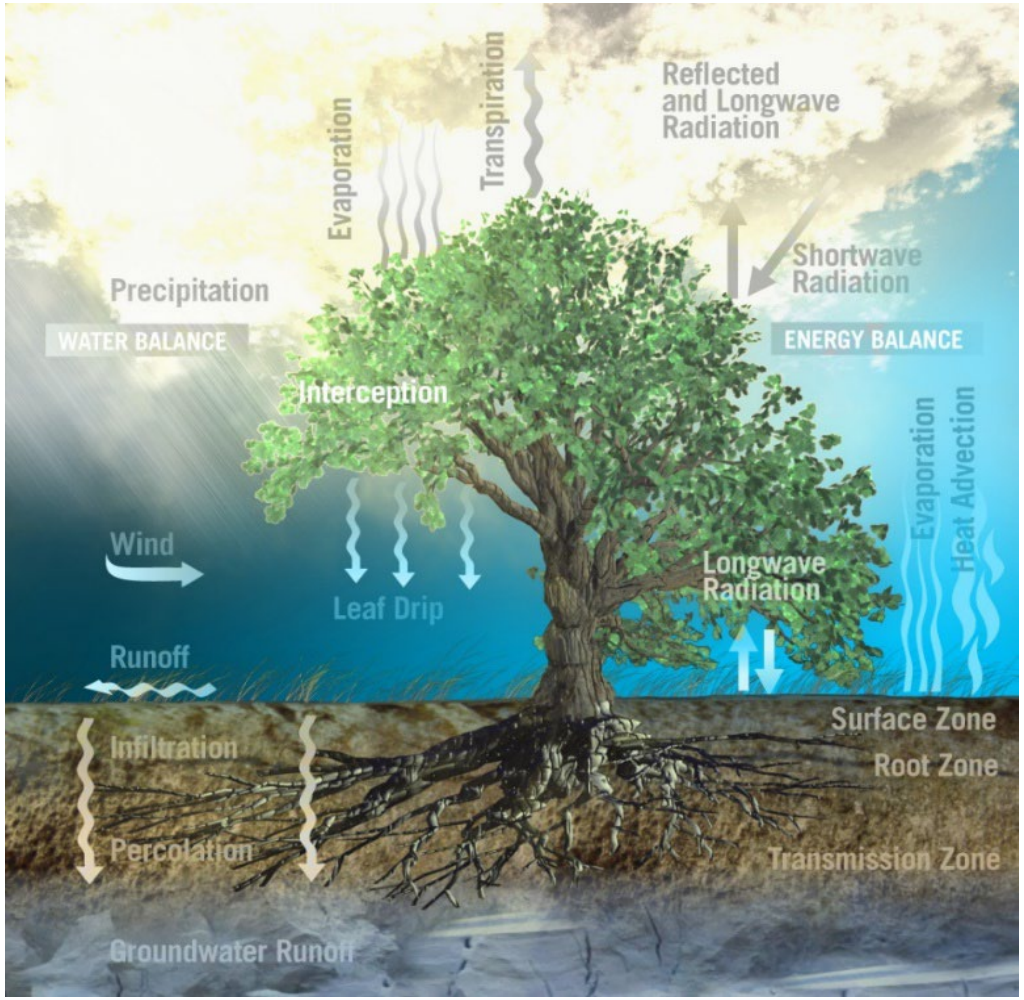


Source: WaPOR Database Metholoolgy, Level 3 Data

Application with satellite / Copernicus data

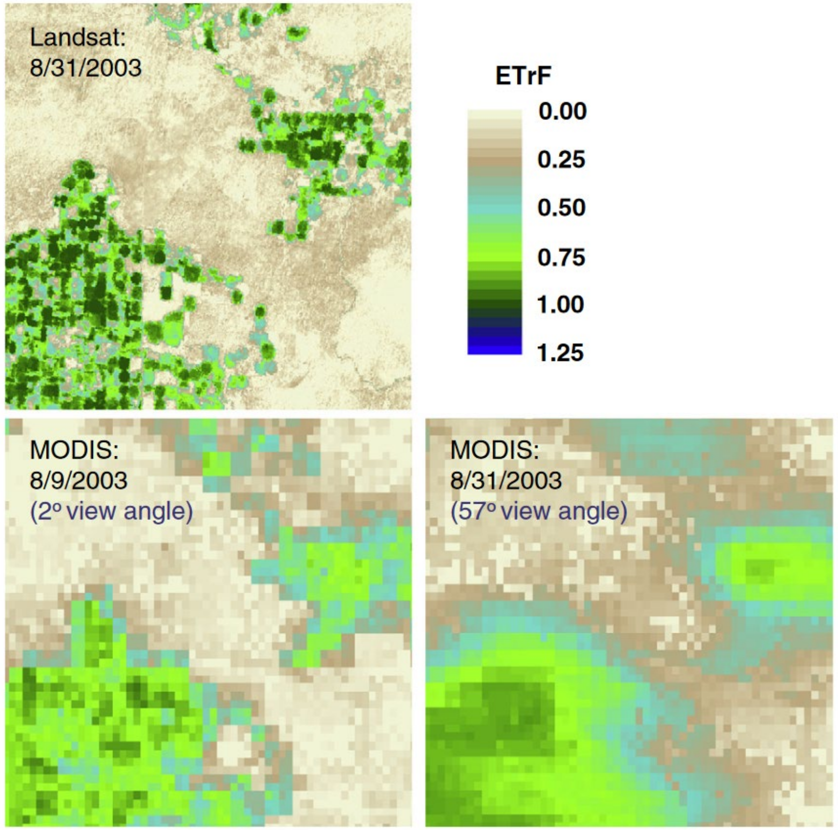
Satellite based ET monitoring

- ET is often modeled from energy perspective
  - Latent heat flux from the surface (W/m2)
  - No need to obtain surface water balance
    - Rainfall, run-off, infiltration, etc. can be ignored
- Input data
  - Shortwave optical – biophysical properties of the surface (leaf area index, albedo)
  - Thermal infrared – lower boundary condition for surface-air energy exchange
  - Meteorological data – drives and modulates energy exchange between surface and air
  - Ancillary data – vegetation / obstacle height, other biophysical properties



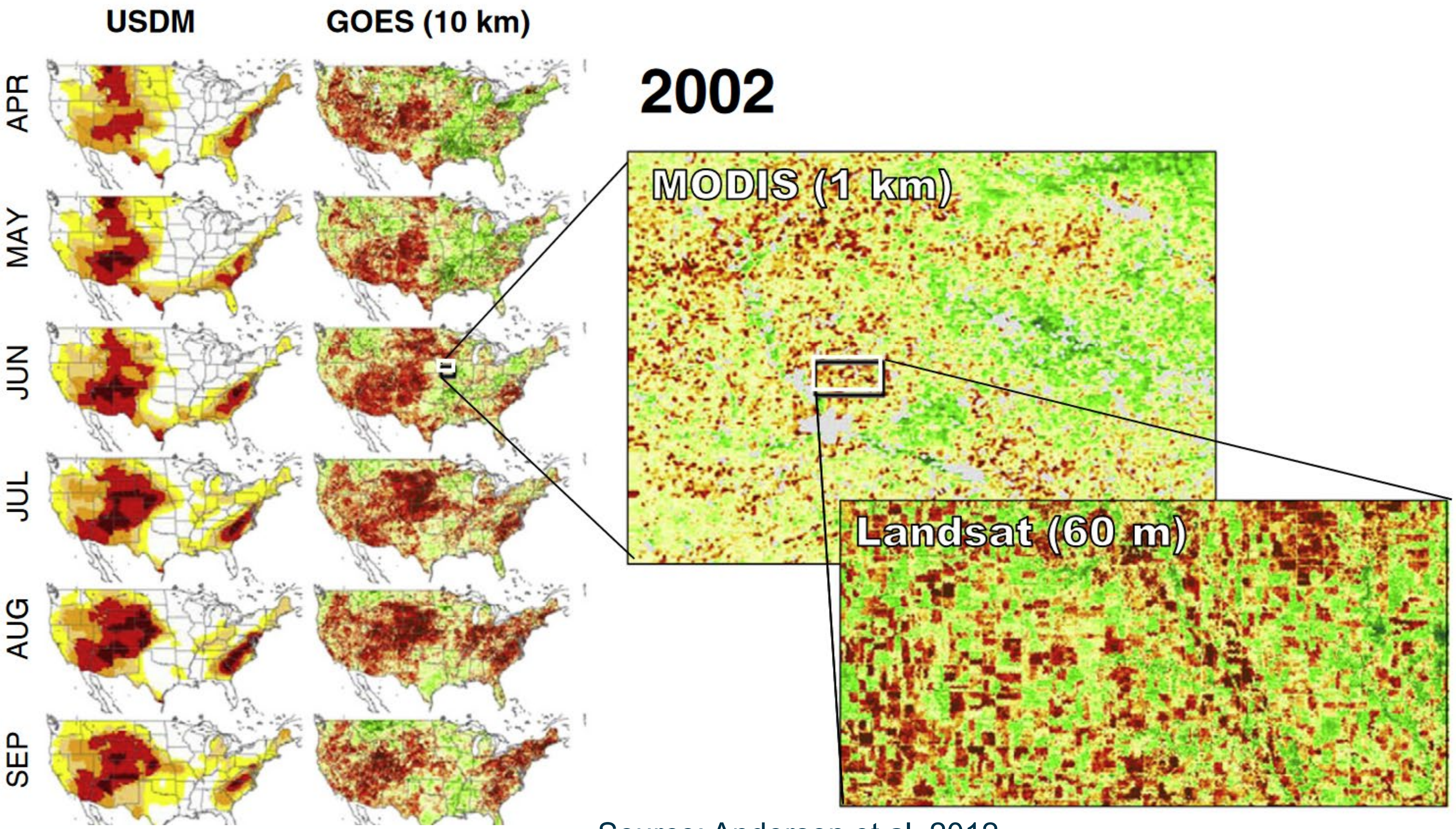
MODIS – Landsat data

- Landsat
  - Shortwave and thermal infrared observations
  - 30 m and 60 – 120 m respectively
  - 8-16 days temporal resolution
- MODIS
  - Shortwave and thermal infrared observations
  - 250 m and 1000 m respectively
  - Daily temporal resolution



Source: Anderson et al, 2012

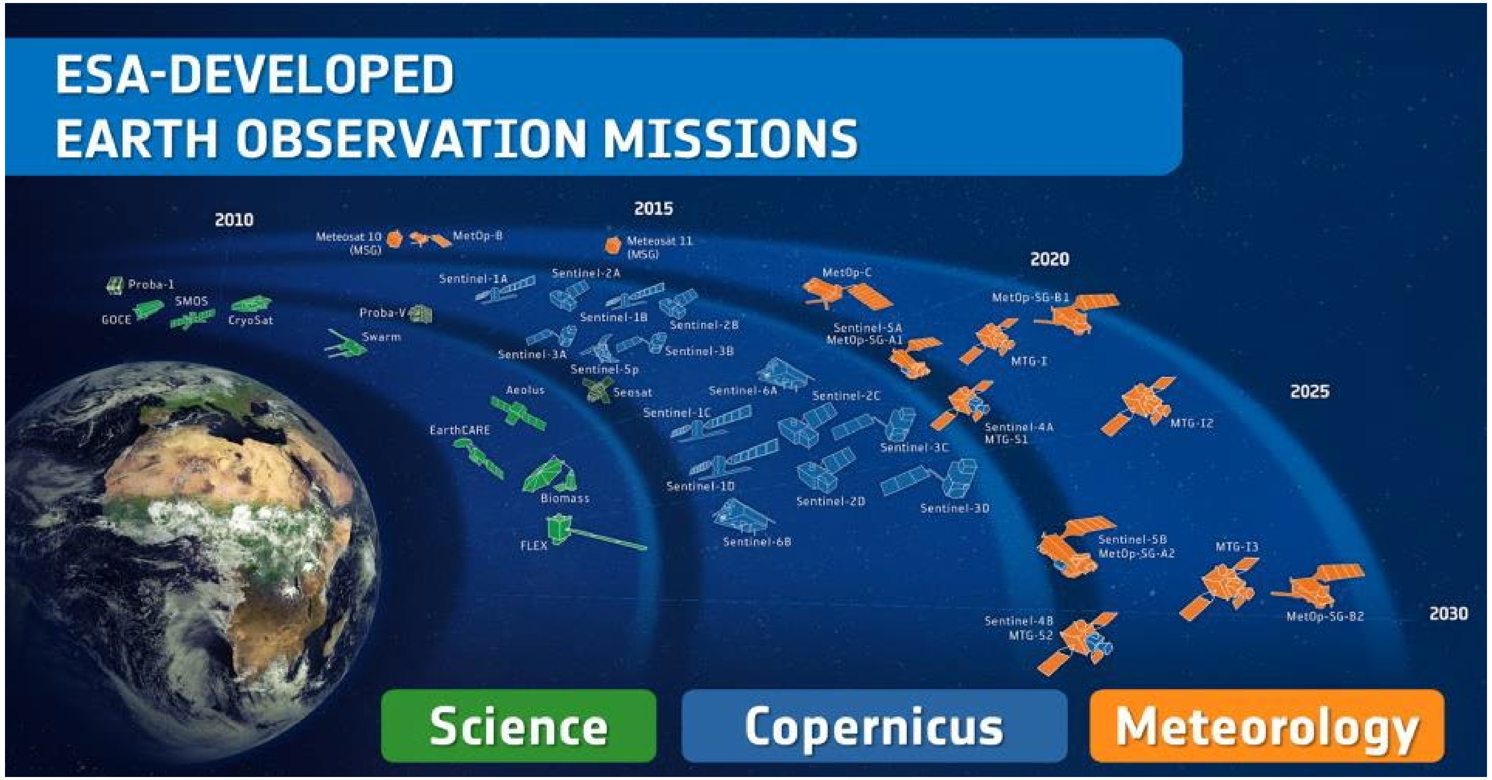
ALEXI – disALEXI modelling scheme



Source: Anderson et al, 2012

Why use Copernicus data?

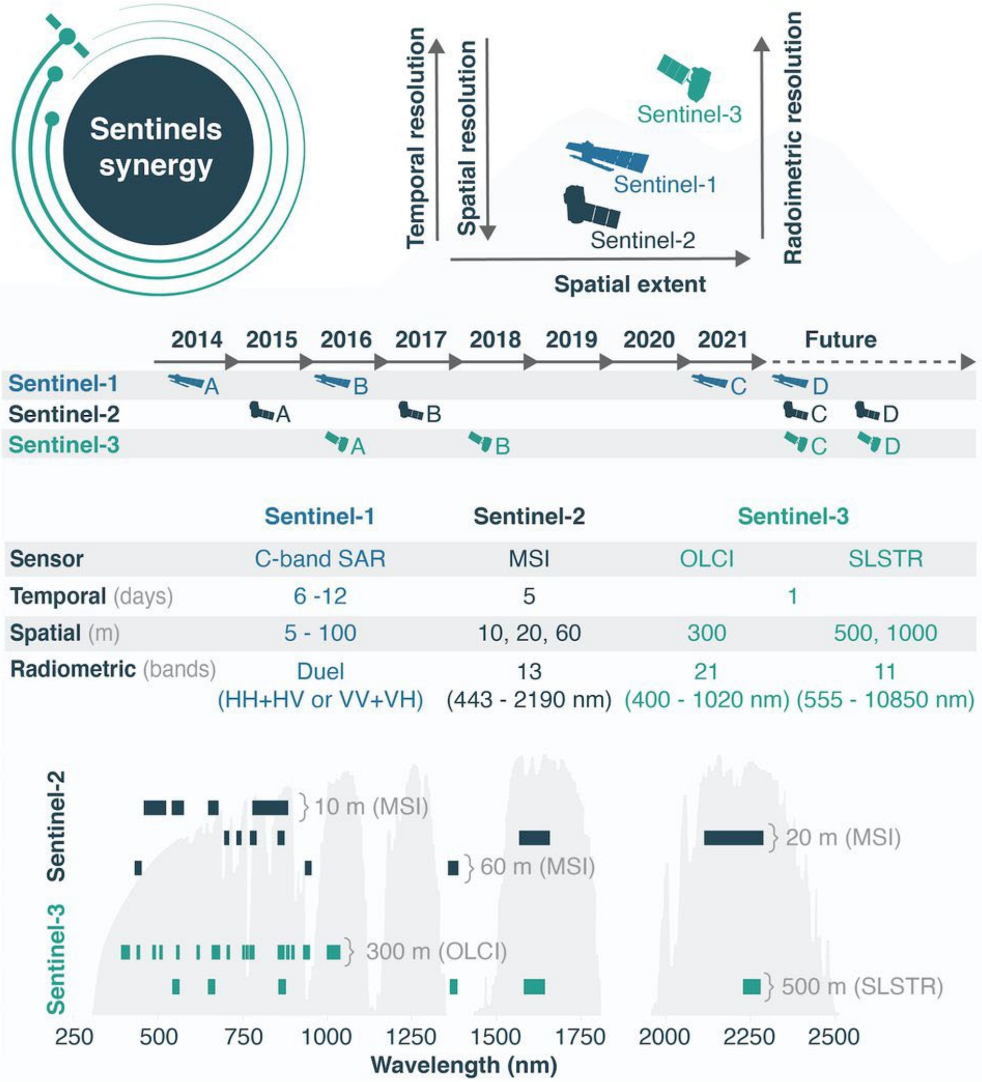
- Developed with operational mindset
  - High data quality
  - Long-term continuity
- Free and open access
- Space component
  - Sentinel Earth observation satellites
- Copernicus Services
  - Climate Change
  - Land Monitoring



Copernicus Sentinel Data

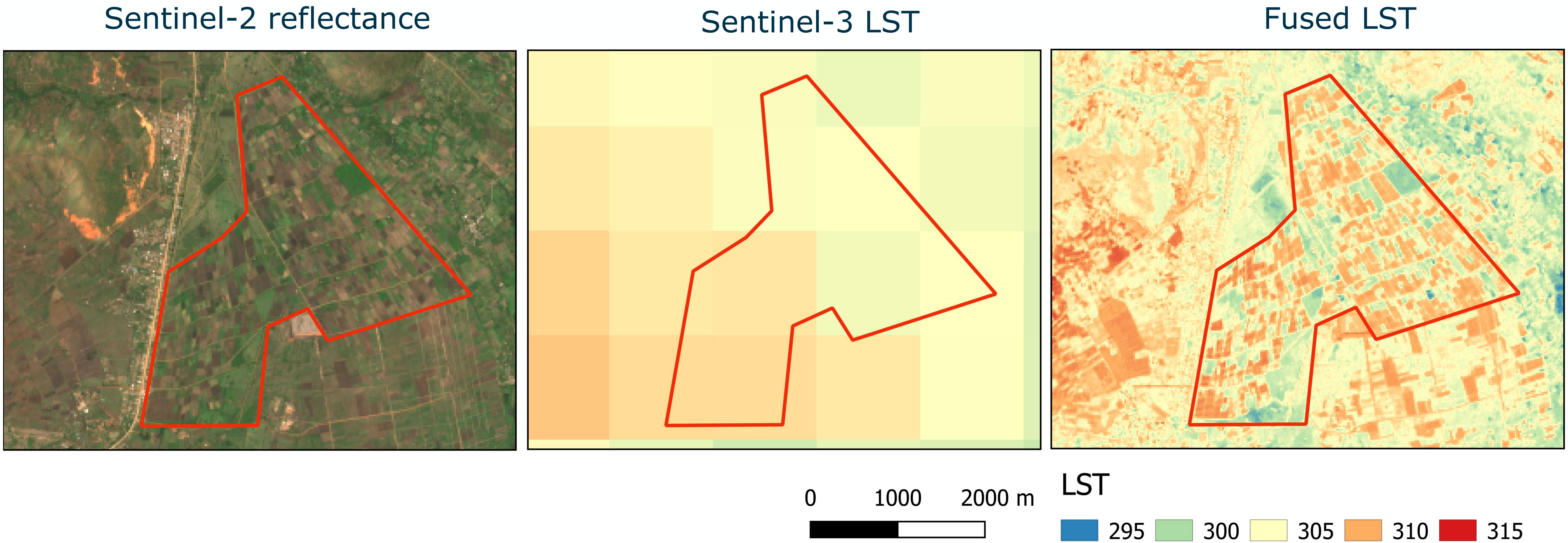
Sentinel constellation highly suitable for parcel-scale agricultural monitoring

Satellite	Sentinel-2	Sentinel-3	Constellation
Spatial resolution	10 m - 60 m	300 m – 1 km	10 m
Temporal resolution	1 – 5 days	Daily	Daily
Spectral coverage	VIS, NIR, SWIR	VIS, NIR, SWIR, TIR	VIS, NIR, SWIR, TIR

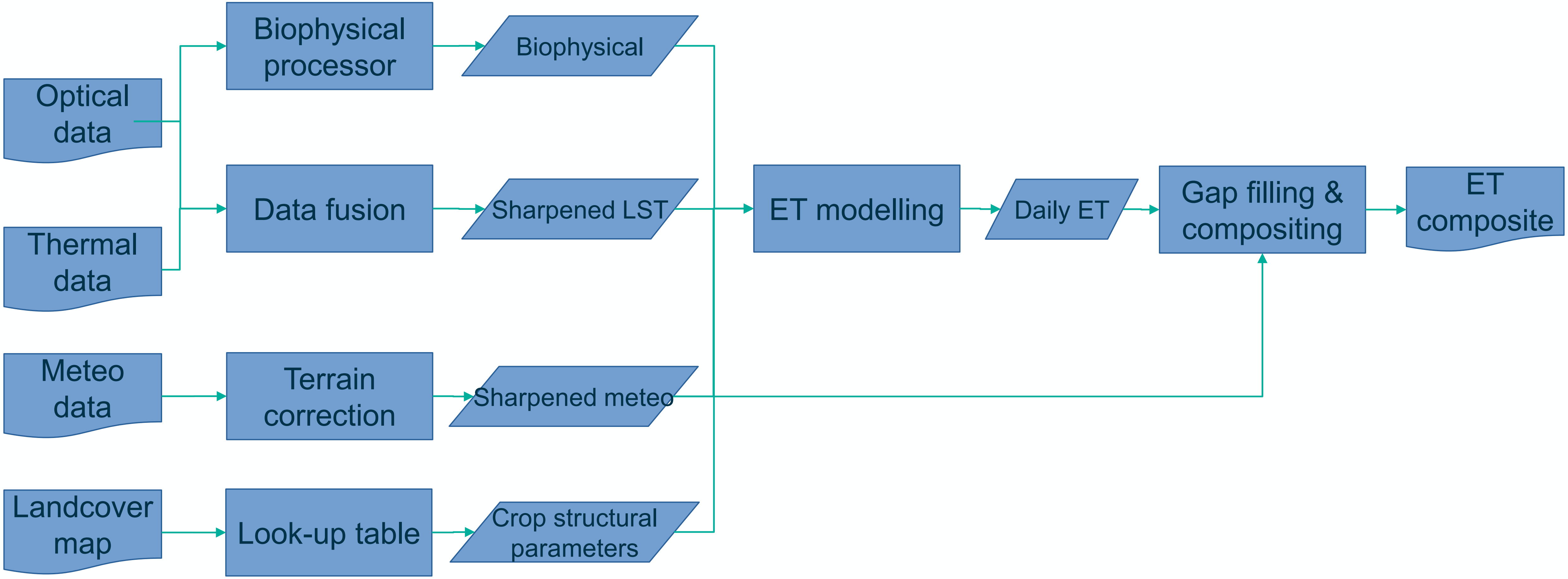


Challenge with Copernicus

Lack of high-resolution thermal data



ET Processing chain



Biophysical processing – Sentinel-2

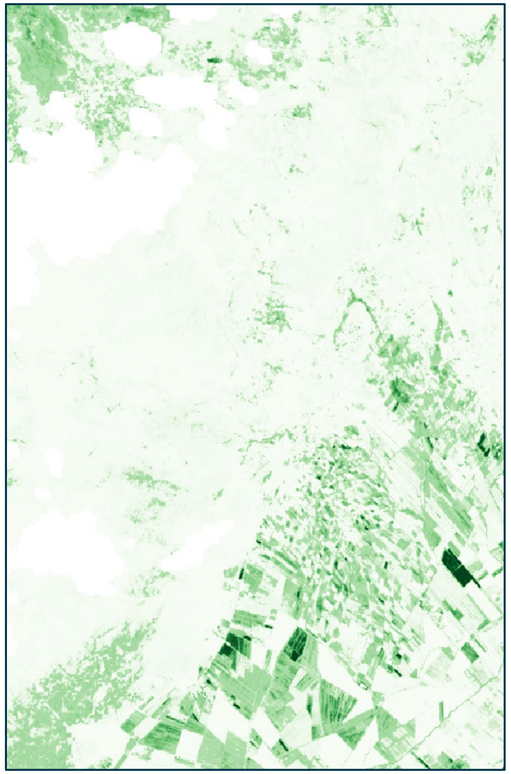
L1C

Download

L2A

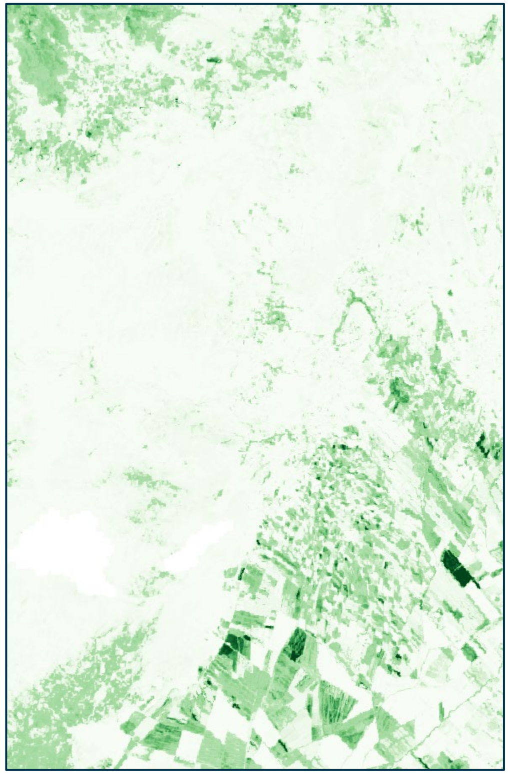
Sen2Cor & Fmask

L2B - LAI



SNAP & Python

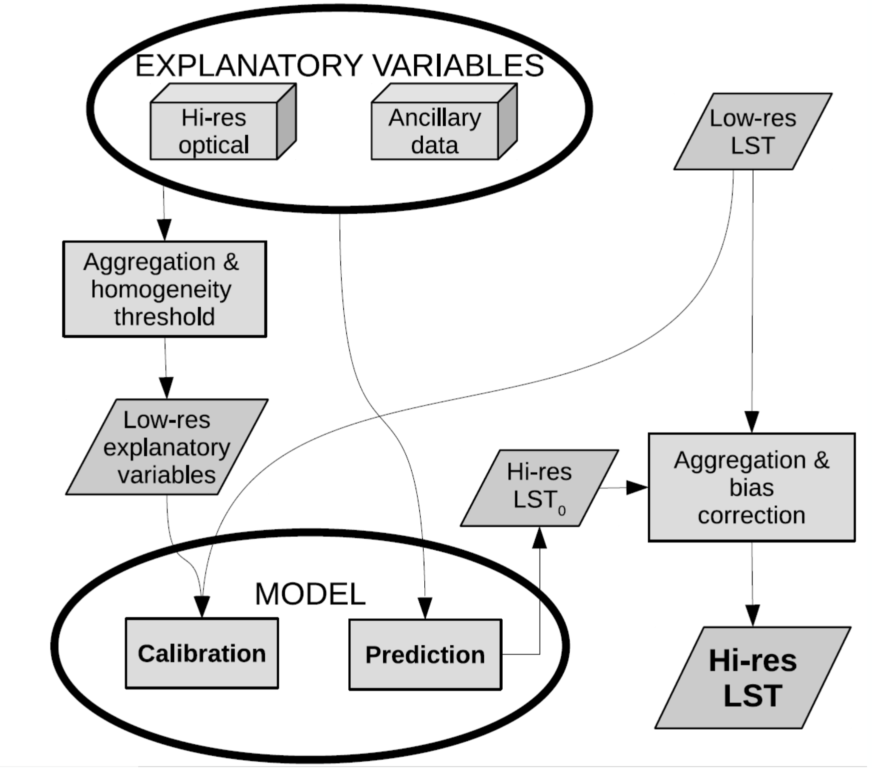
L3



SNAP / Python

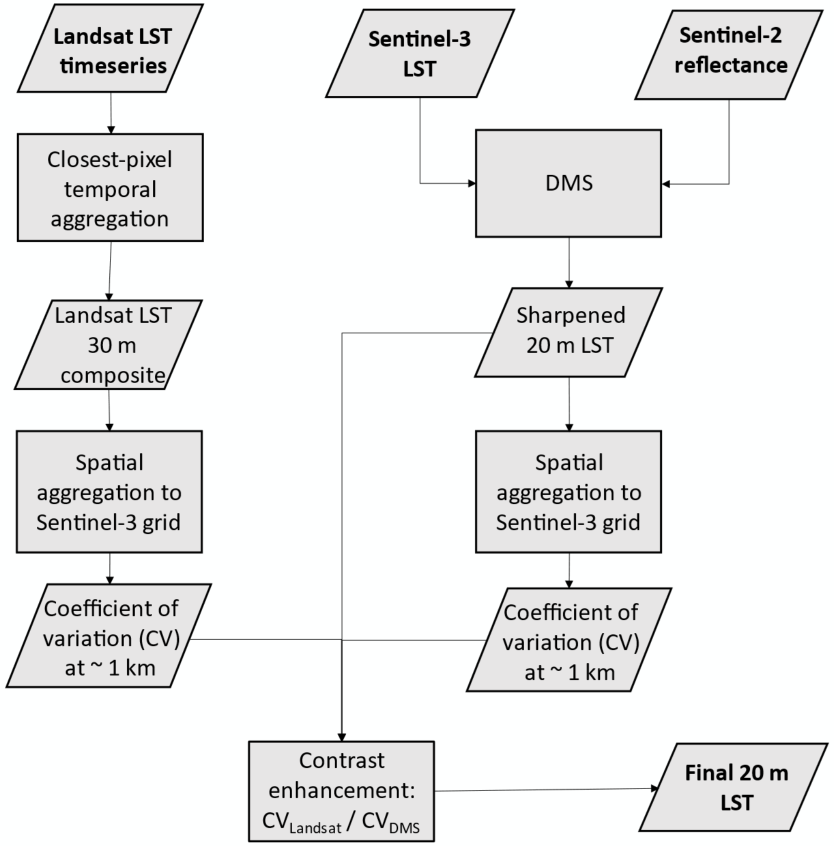
Data fusion – thermal sharpening

- Data Mining Sharpener - based on Gao et al (2012) - https://doi.org/10.3390/rs4113287
- Implementation: https://github.com/radosuav/pyDMS
- Bagging ensembles of modified decision trees
- Works on pairs on optical and thermal images
  - Up to 10-days offset
  - Unique model trained and applied for each pair
- Conservation of thermal energy
- Assumptions:
  - Relation exists between optical and thermal images
  - This relation is scale-independent
- Limitations:
  - Temporal offset between thermal and optical
  - LST range

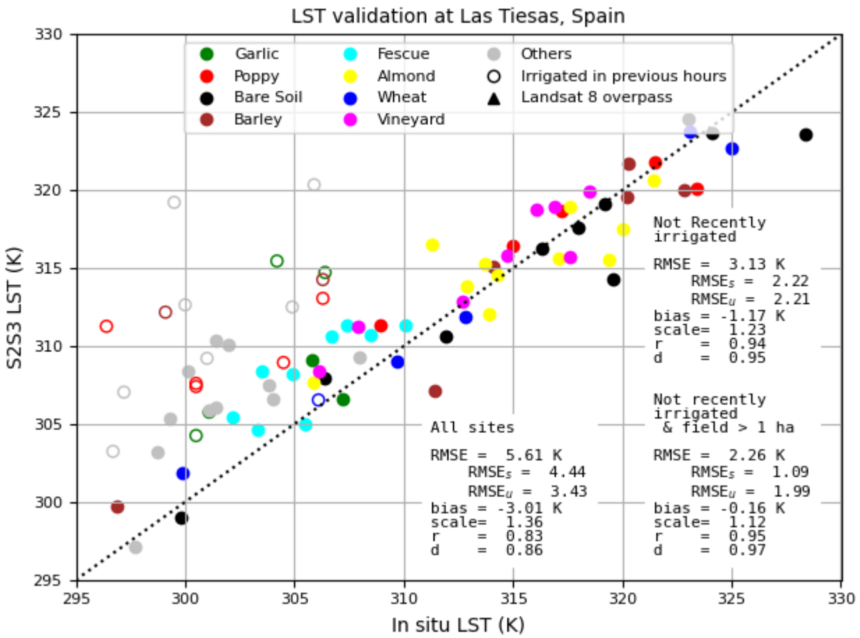


Thermal contrast enhancement

- Enhancing the thermal contrast (spatial variability) within the sharpened scene using the thermal contrast present within Landsat observations.

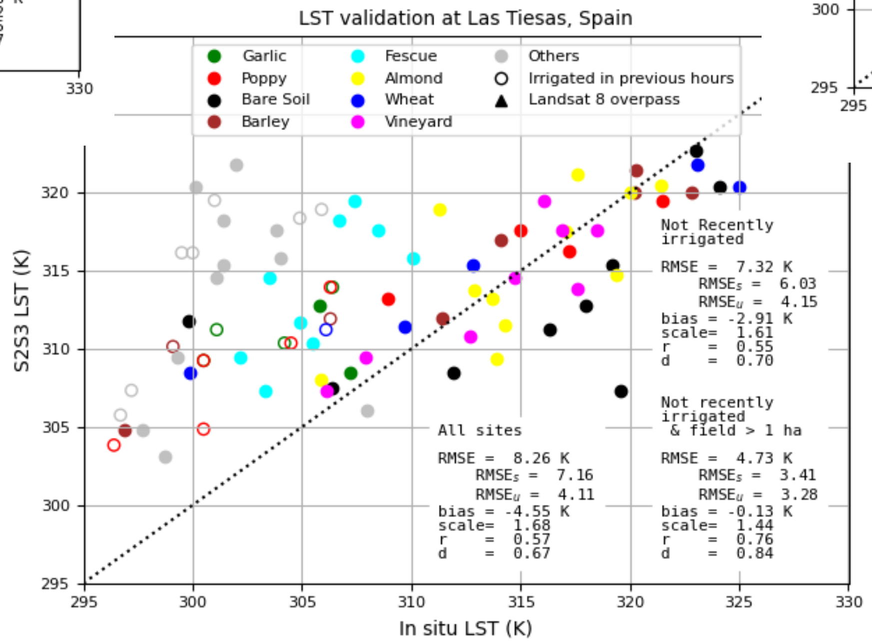


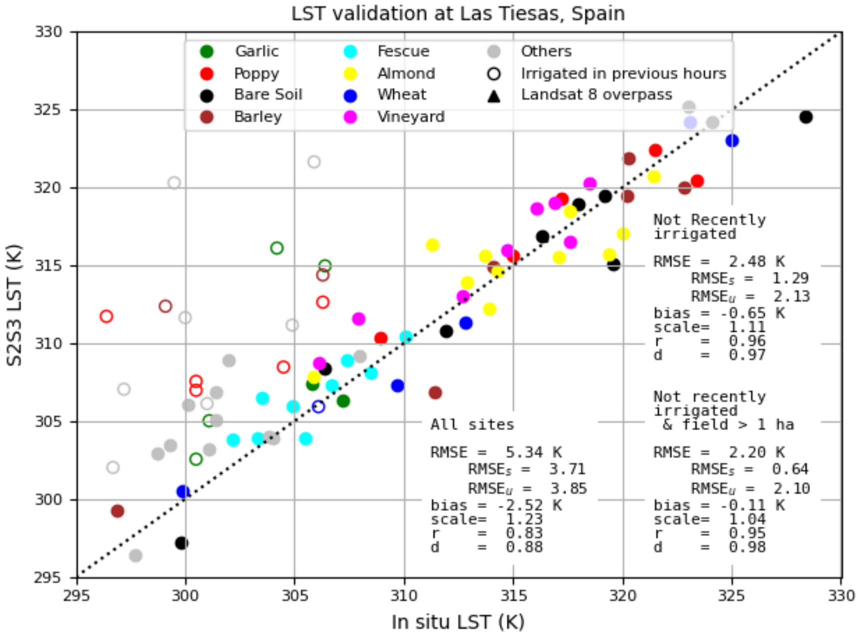
Thermal sharpening results



DMS sharpening

Sentinel-3

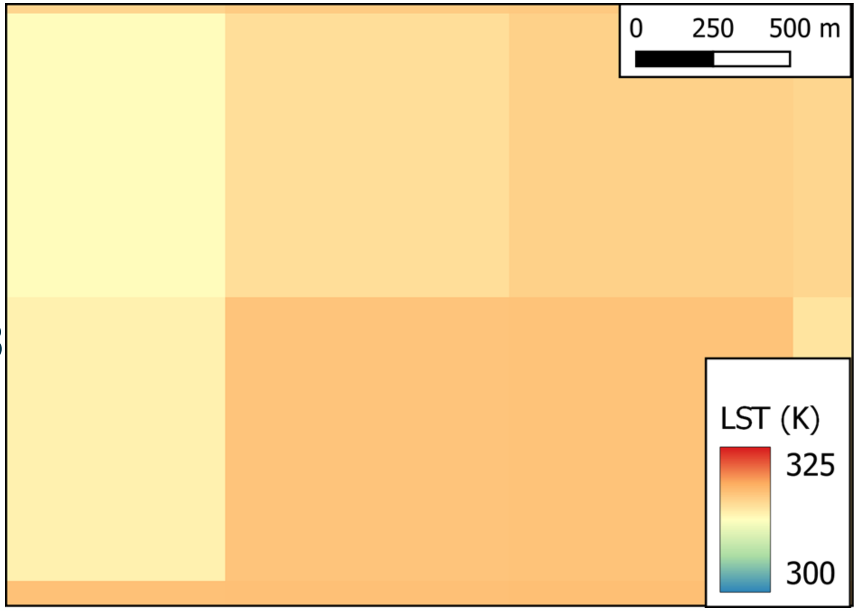




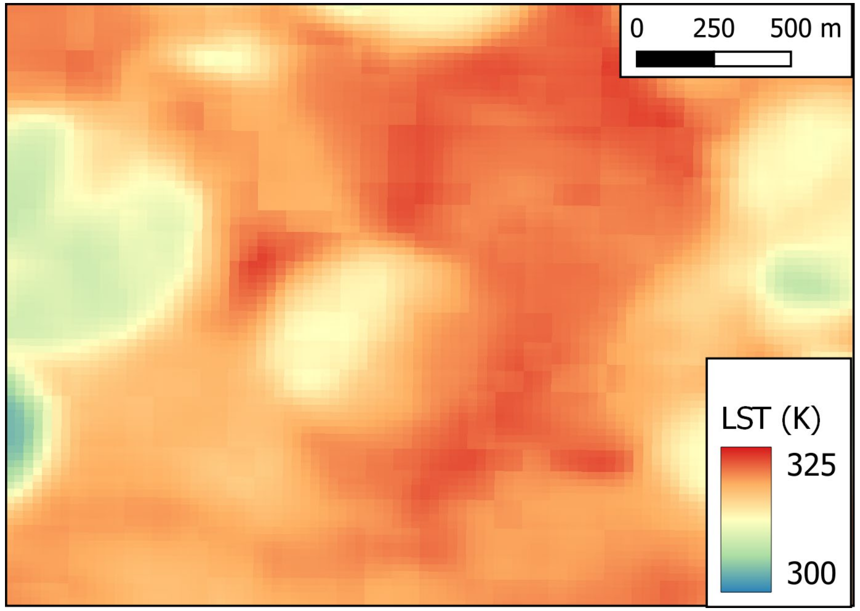
DMS sharpening and contrast enhancement

Thermal sharpening results

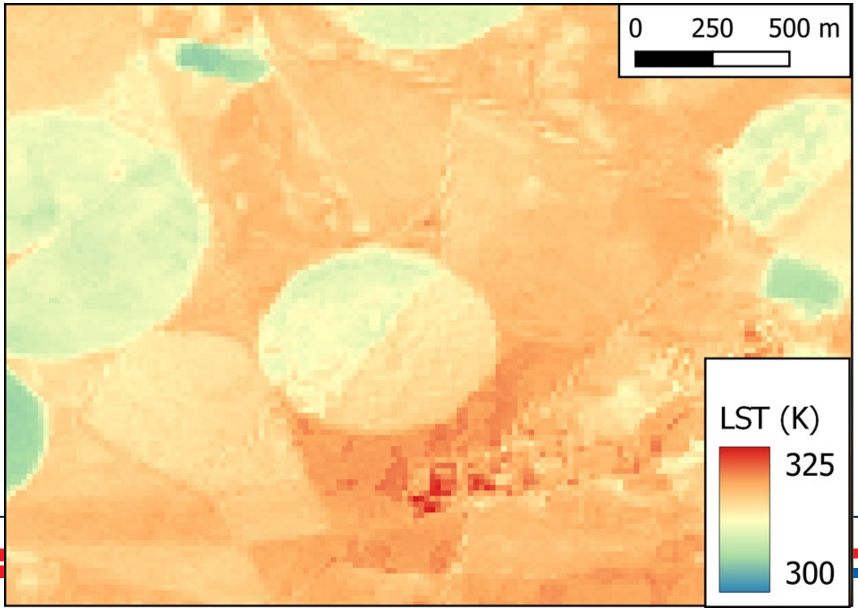
Sentinel-3



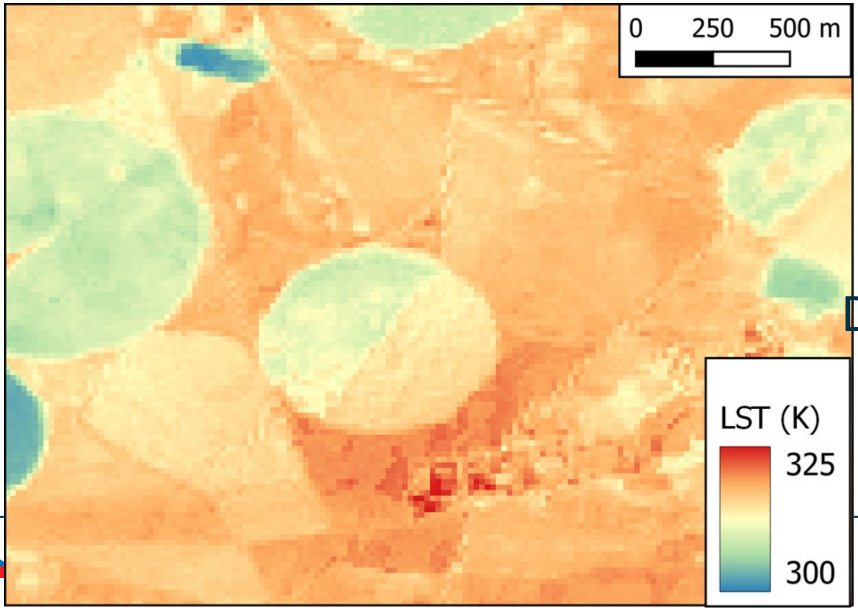
Landsat



DMS

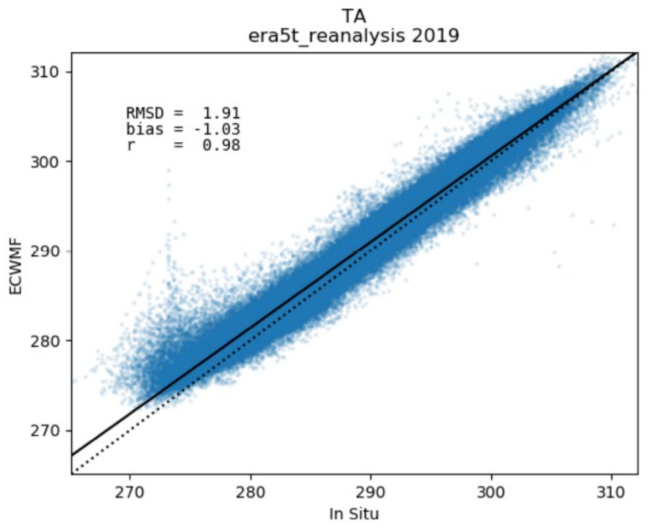


DMS + contrast

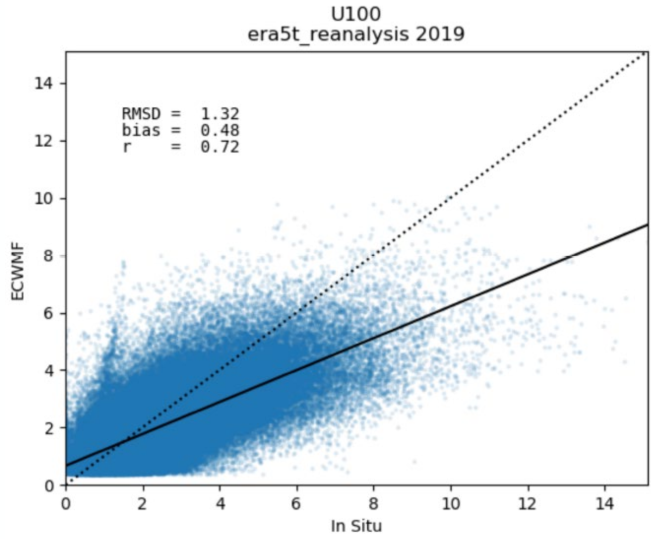


Copernicus meteorological data

- Available from Copernicus Climate Data Store

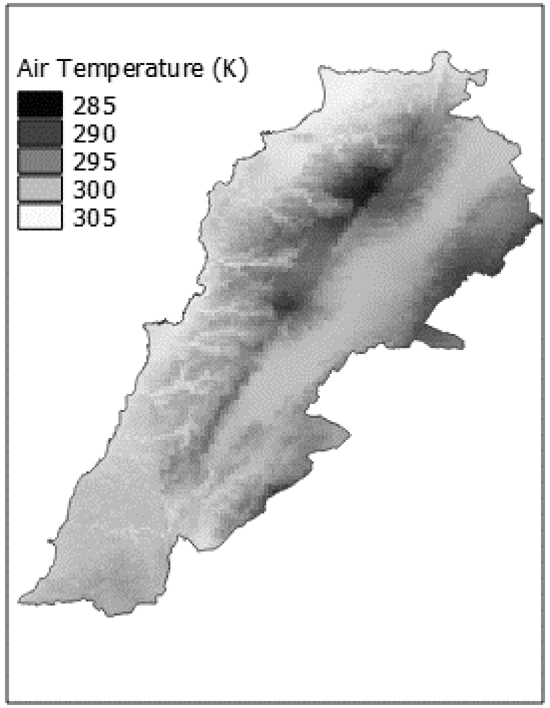


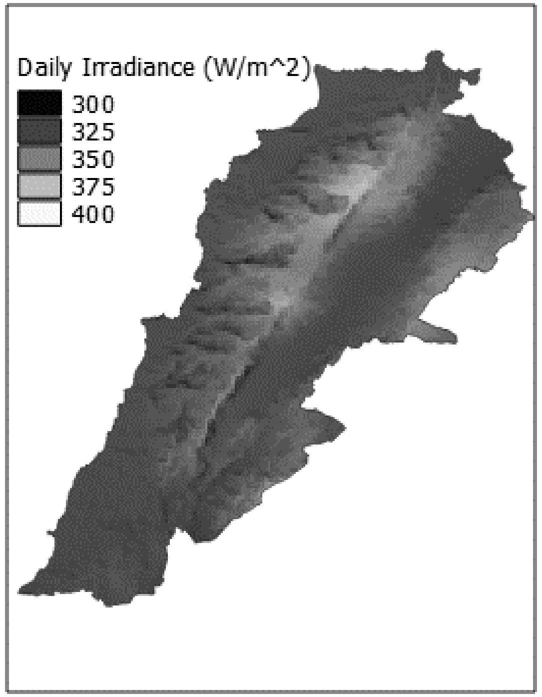
- ERA5 climate model
  - Land-surface meteorological parameters
  - 30 km spatial resolution
  - Hourly temporal resolution
  - 5-day timeliness (ERA5T)
  - Global coverage
- Also available
  - ERA5-Land – 10 km spatial resolution
  - AgERA5 – daily values tailored for agriculture



Terrain correction of meteorological data

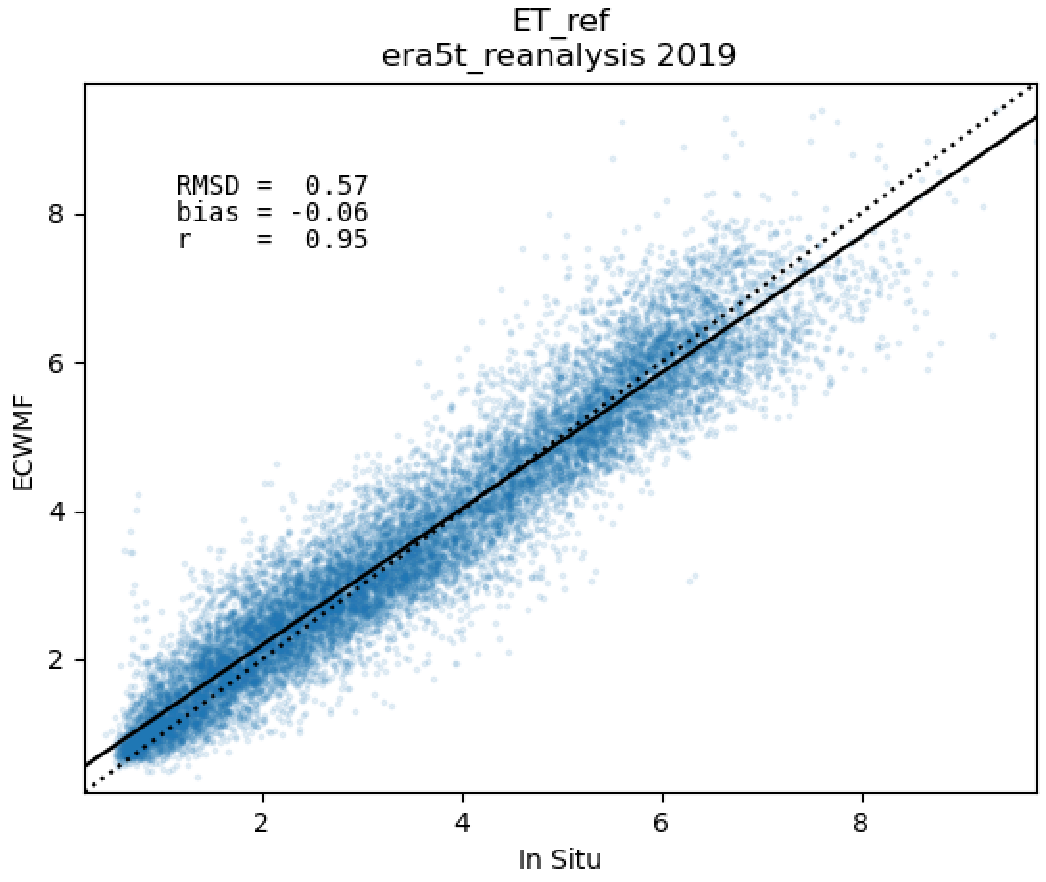
- Using a Digital Elevation Model (DEM)
  - Air temperature – lapse rate correction
  - Humidity/dew temperature – lapse rate correction
  - Wind speed – no correction
  - Pressure – lapse rate correction
  - Solar irradiance (inst. and daily) – elevation and solar illumination (slope, aspect, shadowing) corrections



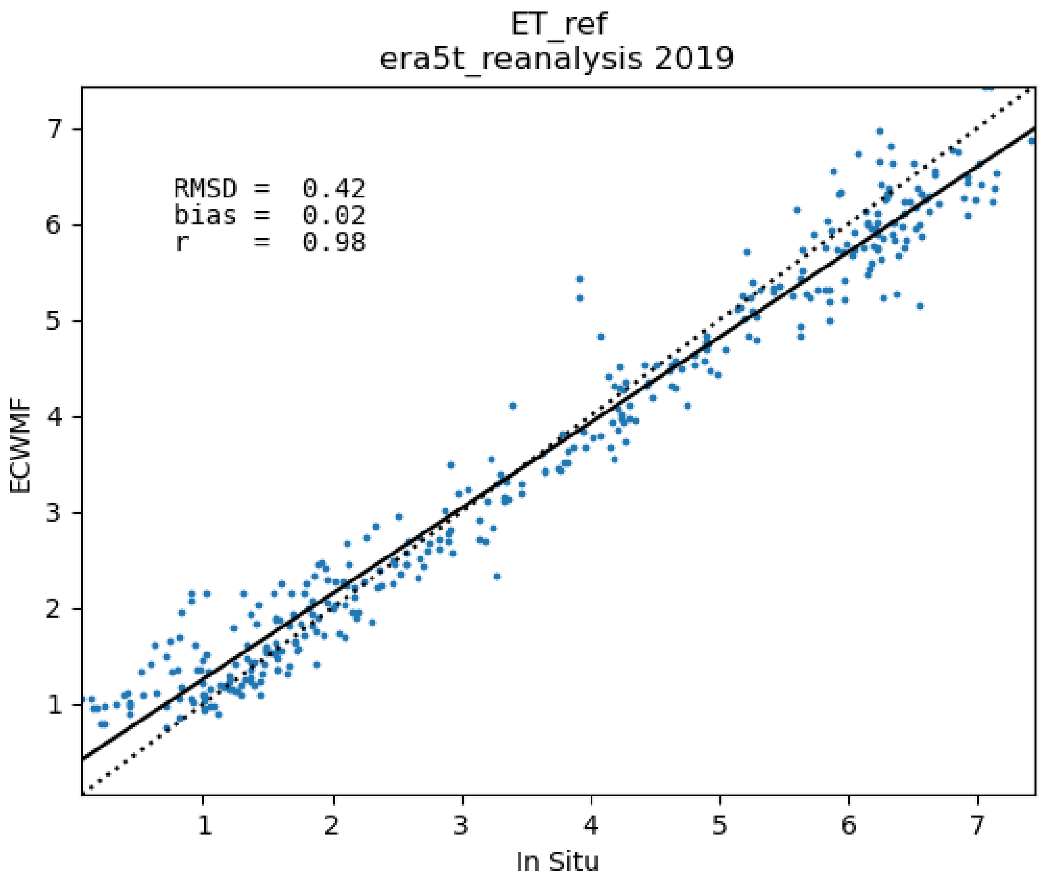


Validation of meteorological data

Reference ET
Murcia (SE Spain)

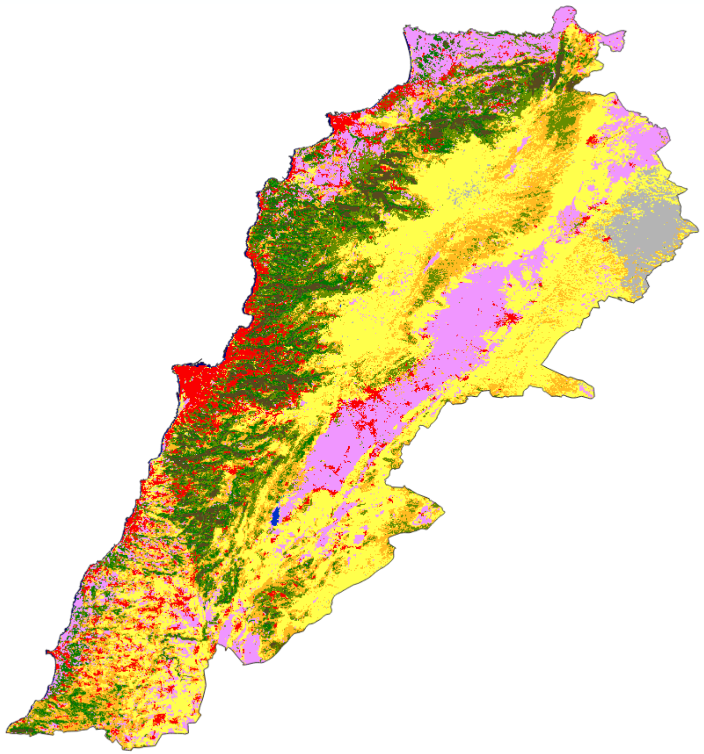


Reference ET
Tal Amara (Lebanon)



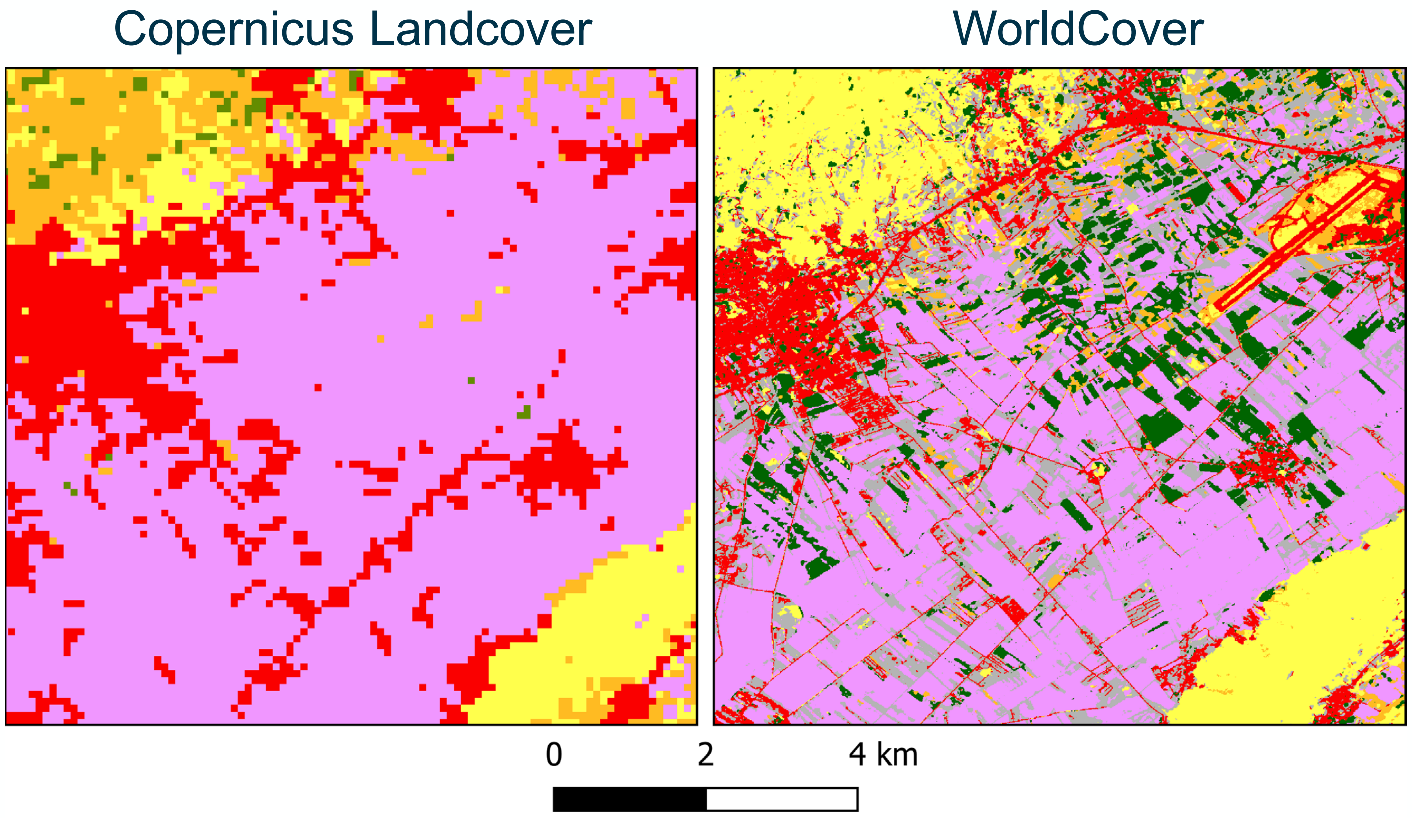
Copernicus landcover map

- Used to set ancillary model parameters
  - E.g. vegetation / obstacle height, leaf orientation
- Produced by Copernicus Land Monitoring Service
- Global, high-resolution landcover map
  - 100 m spatial resolution
  - Yearly temporal resolution
  - Overall mapping accuracy – 80 %
- Limitations
  - Only one cropland class
    - No distinction between orchards, vineyards, herbaceous crops
  - Spatial resolution still too low

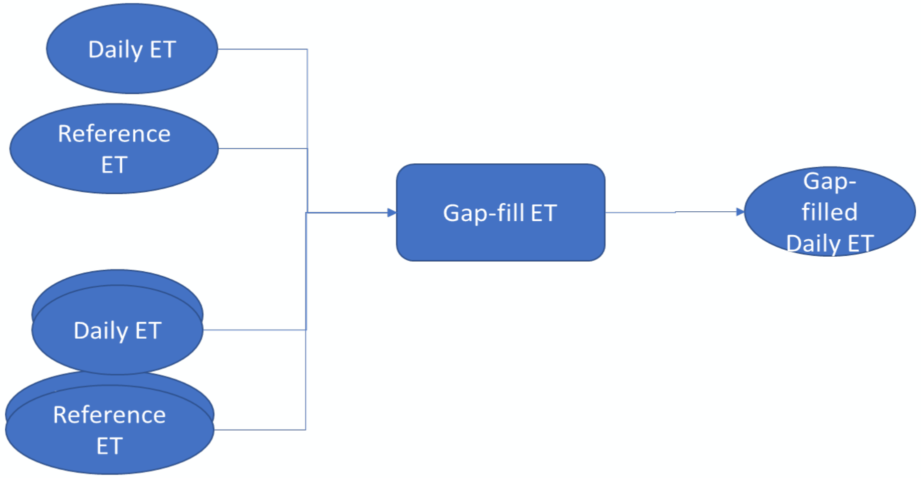


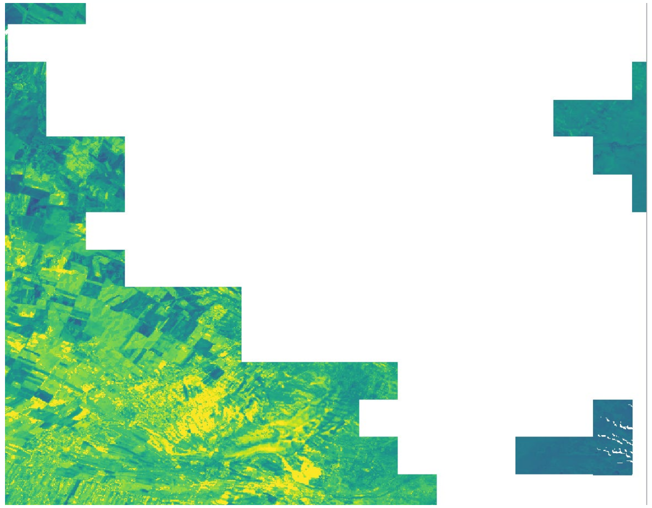
WorldCover Map

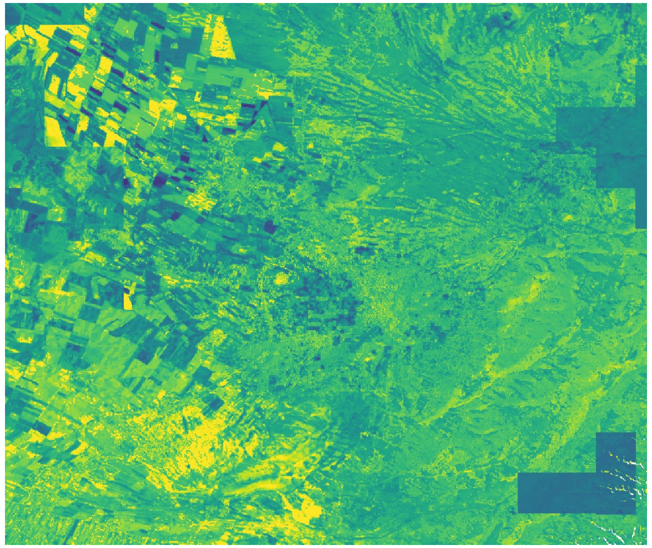
- Produced by ESA
- Global, very-high-resolution landcover map
  - 10 m spatial resolution
  - 75 % – 77 % overall accuracy
  - Two versions – 2020 and 2021
- Limitations
  - Only one cropland class
  - No distinction between orchards, vineyards, herbaceous crops



ET gap-filling



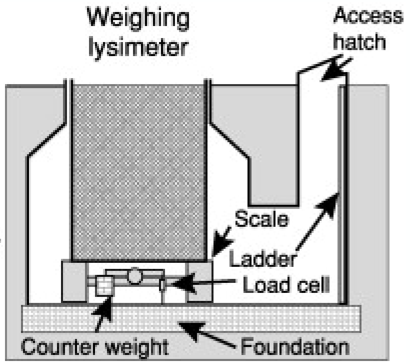




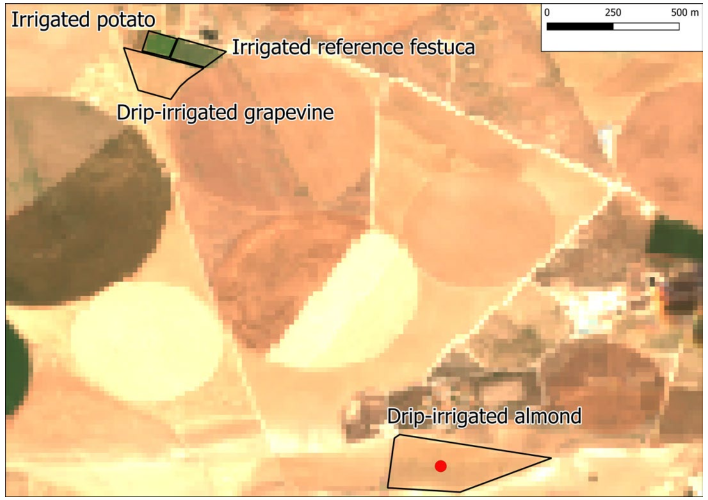
- Method
  1. Identify gaps in ET on a given date
  2. Starting with images closest in time calculate ratio reference to actual ET (Kcs)
  3. Use this ratio and reference ET on a given date to produce gap-free ET image

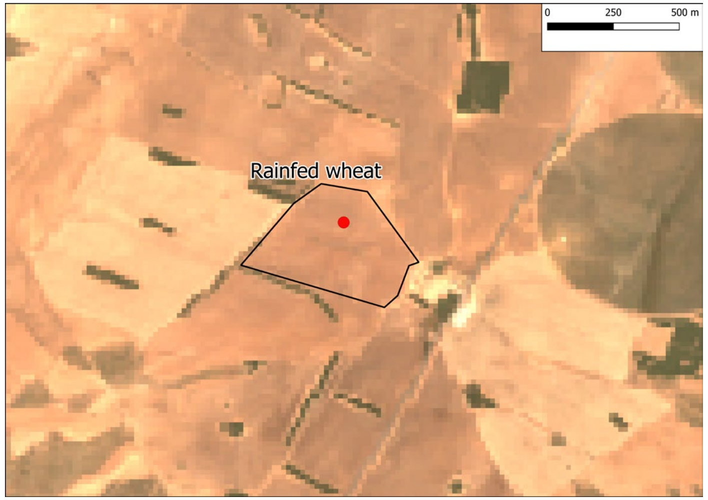
Field measurements of ET

- Two main methods
  - (Weighing) Lysimeters
    - Measure the change in weight of soil column
    - The change is caused by water input and output
    - Accurate but very localized
  - Eddy covariance towers
    - Measure wind speed and direction
    - Measure changes in temperature and humidity
    - Based on this the flux of temperature (sensible heat) and water (evapotranspiration – latent heat) can be estimated
    - Larger footprint but up to 20-30% uncertainty



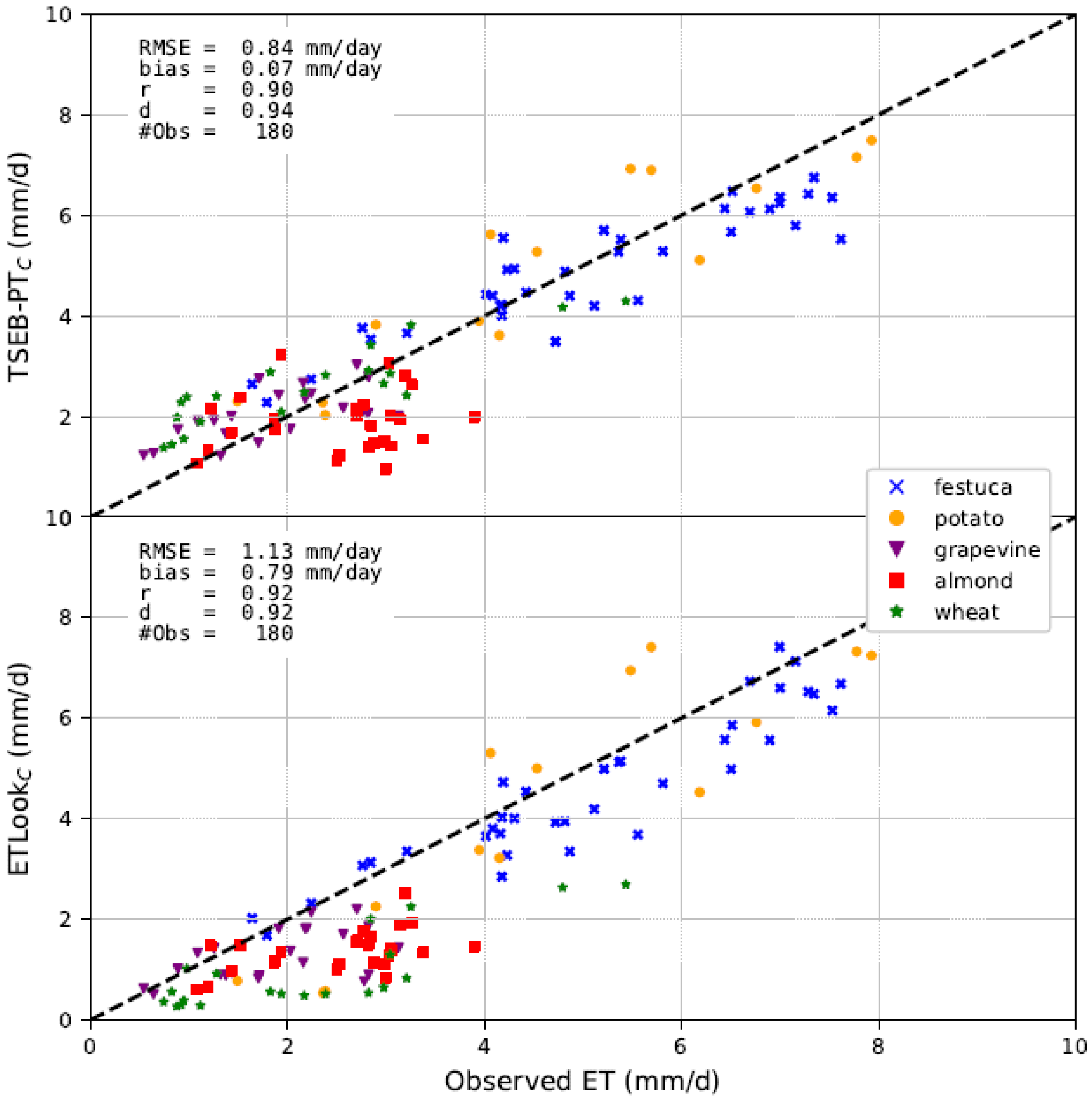
Validation sites – ET4FAO project

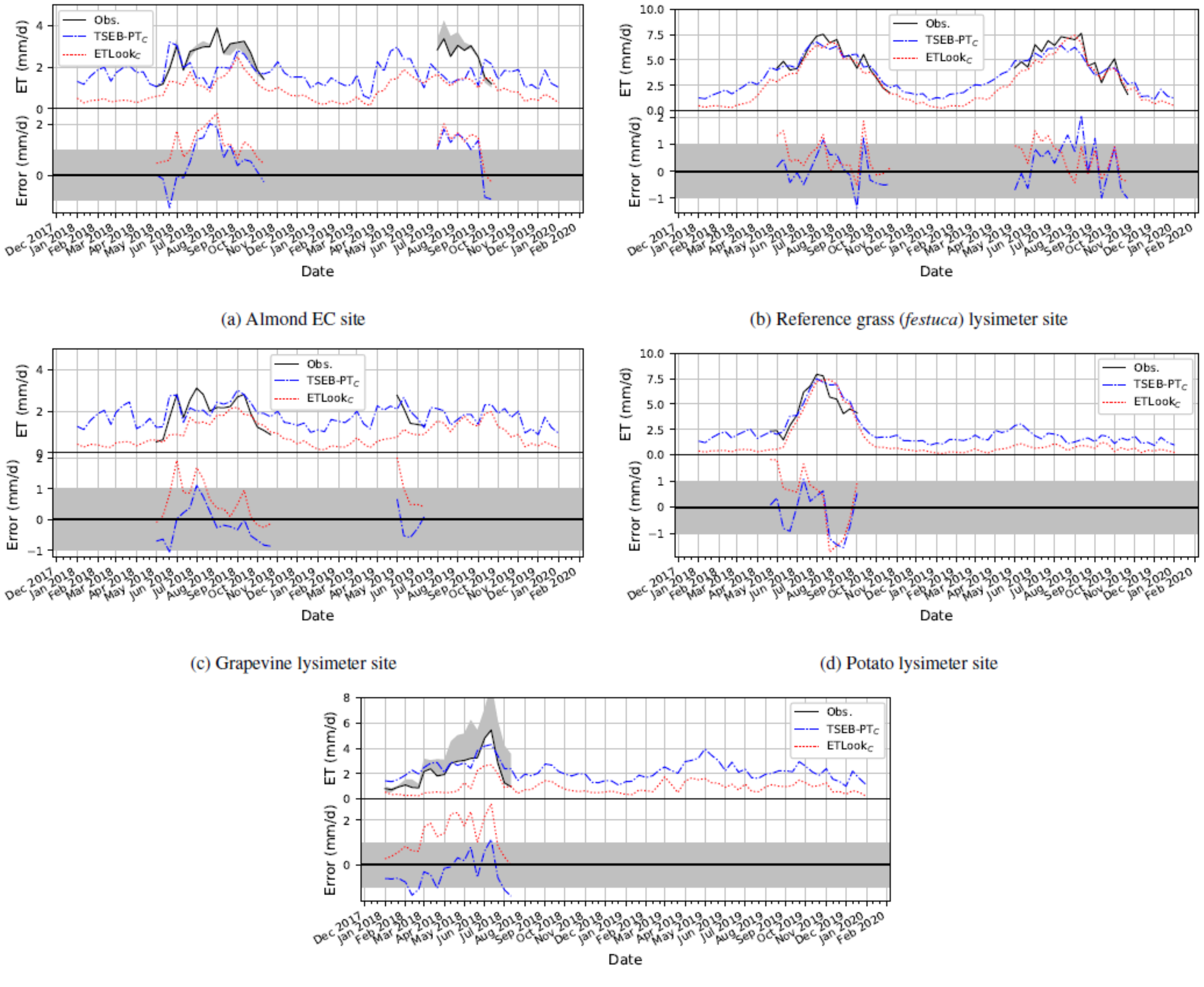




Site	Irrigation	Measurement	Notes
Potato	Sprinkler	Lysimeter	Small parcel
Festuca / reference grass	Sprinkler	Lysimeter	Small parcel Frequently irrigated Clipped to 12 cm
Vineyard	Drip	Lysimeter	
Almond	Drip	EC tower	Residual assigned to latent heat
Wheat	None	EC tower	No residual correction

Validation – ET4FAO project





(a) Almond EC site

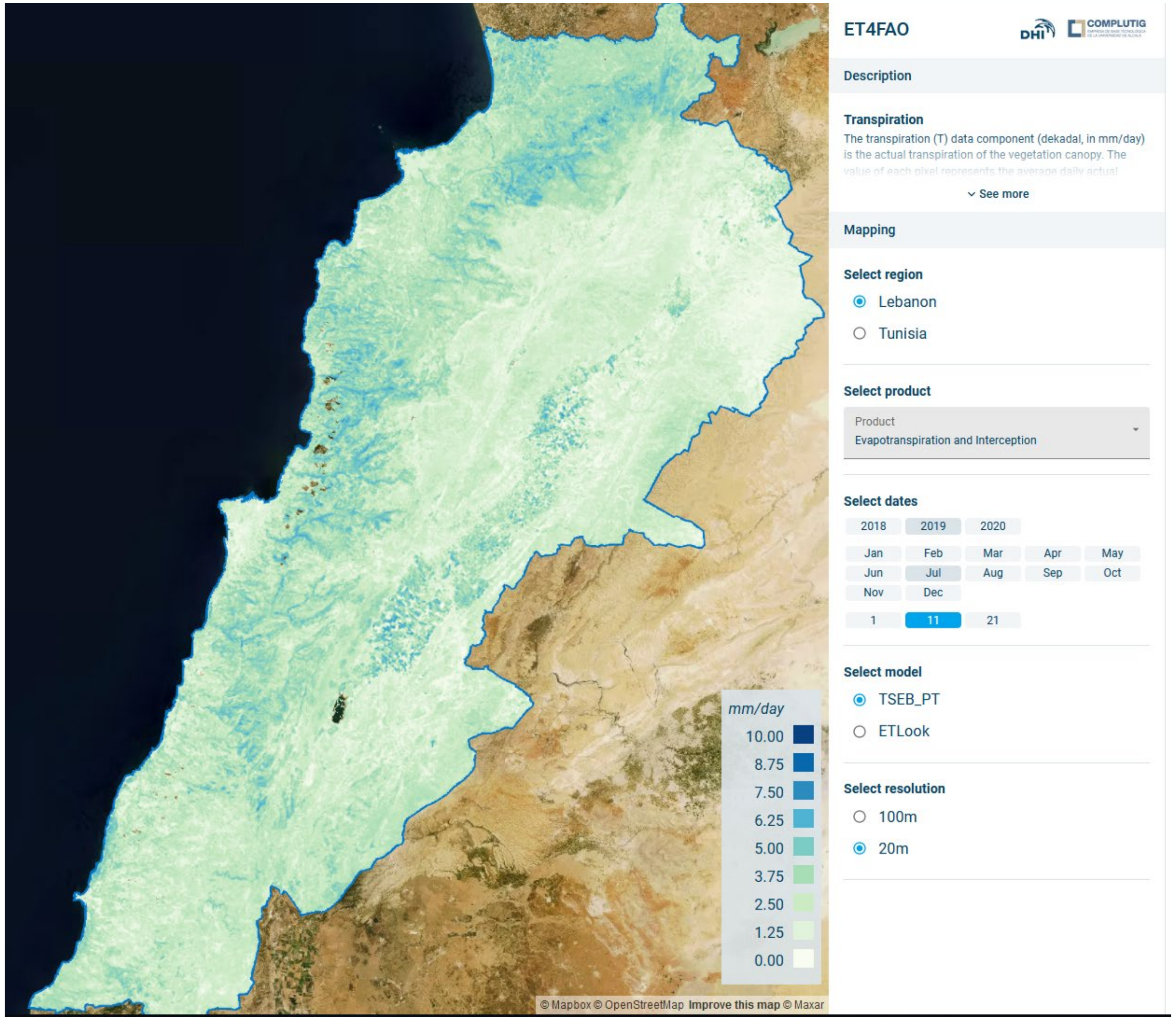
(b) Reference grass (*festuca*) lysimeter site

(c) Grapevine lysimeter site

(d) Potato lysimeter site

(e) Winter wheat EC site

ET4FAO project outputs



et4fao.dhigroup.com

Guzinski, Radoslaw, Hector Nieto, Juan Manuel Sánchez, Ramón López-Urrea, Dalenda Mahjoub Boujnah, and Gilles Boulet. 2021. "Utility of Copernicus-Based Inputs for Actual Evapotranspiration Modeling in Support of Sustainable Water Use in Agriculture." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 14: 11466–84. https://doi.org/10.1109/JSTARS.2021.3122573.

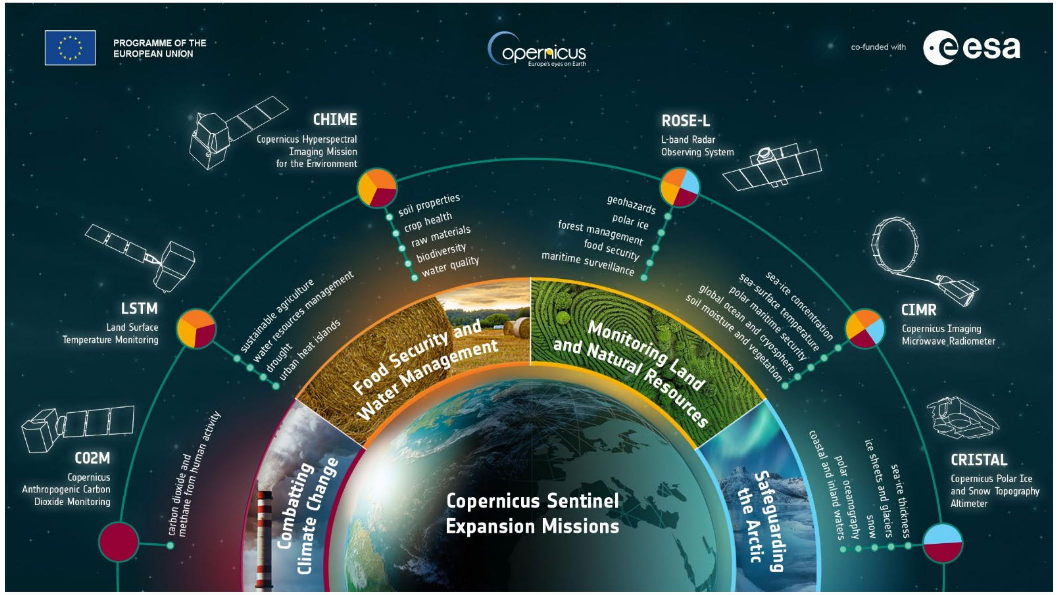
Conclusions and perspectives

Summary

- Modelling of evapotranspiration is essential for water resources management and improved water utilization in agriculture
  - SDG reporting, water rights monitoring, irrigation advice
- ET is usually modelled from energy perspective when using remote sensing data
  - Latent heat – energy used in the evapotranspiration process
  - Modelling of land-surface energy balance
    - Complex biophysical processes
- Satellite data, and in particular Copernicus data, is highly suitable for operational field-scale ET monitoring
  - RMSE of < 1 mm day and bias of < 0.1 mm day is possible with Copernicus data
- Lack of high-spatio temporal thermal sensor is a limitation but not a block
  - Thermal sharpening approach (S2 – S3 data fusion) can capture variability of small parcels

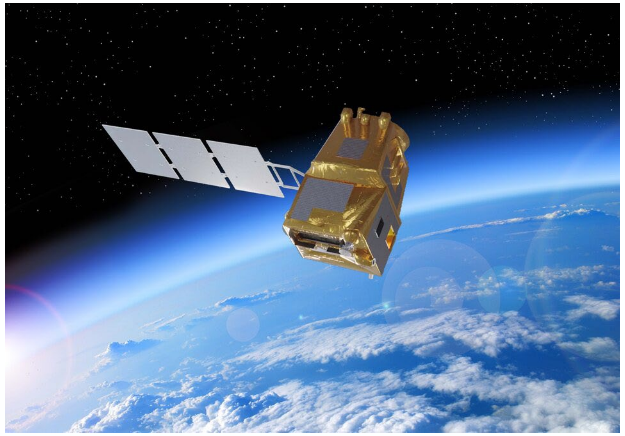
Upcoming thermal missions

- Many high spatio-temporal resolution thermal missions are in the pipeline
  - ESA / Copernicus LSTM
  - Trishna
  - SBG
  - Landsat-Next
  - Commercial providers
- Focus on evapotranspiration and other thermal domains
- Presentation from recent workshop: https://thermal2023.esa.int/



LSTM mission

- Copernicus Land Surface Temperature Monitoring
  - High priority Copernicus expansion candidate mission
  - “Primary objective: to support monitoring evapotranspiration (ET) rate at European field scale by capturing the variability of Land Surface Temperature (LST) (and hence ET) enabling more robust estimates of field-scale water productivity.”
- Requirements
  - Spatial resolution 30 – 50 m
  - Temporal resolution 1 – 3 days
  - Observation time ~13:00 local time
  - Maximum view angle 30 – 35 degrees
  - Accuracy of LST > 1 – 1.5 K
- Potential launch towards the end of the decade



Mission requirements document:

https://esamultimedia.esa.int/docs/EarthObservation/Copernicus_LSTM_MRD_v2.0_Issued20190308.pdf

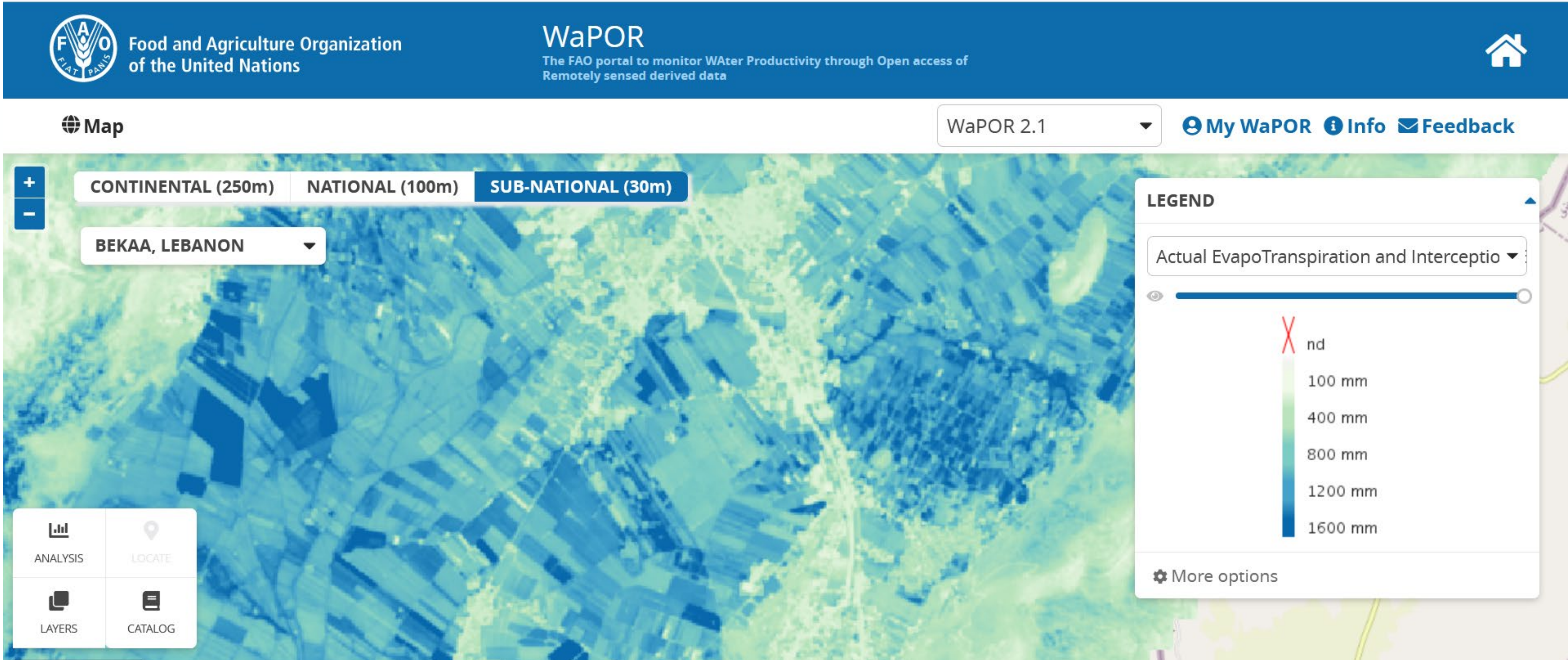
Copernicus ET

- ET product is included in the just-starting Copernicus Global Land Monitoring framework contract
- Specifications
  - Spatial resolution: 300 m
  - Temporal resolution: 10 days
  - Coverage: global
  - Timeliness: near-real time (4-5 days after compositing period)
- Based on TSEB and ETLook ET models
- Timeline
  - Still to be finalized
  - Product design and validation: 2023 – 2024
  - Product launch: 2025

WaPOR portal

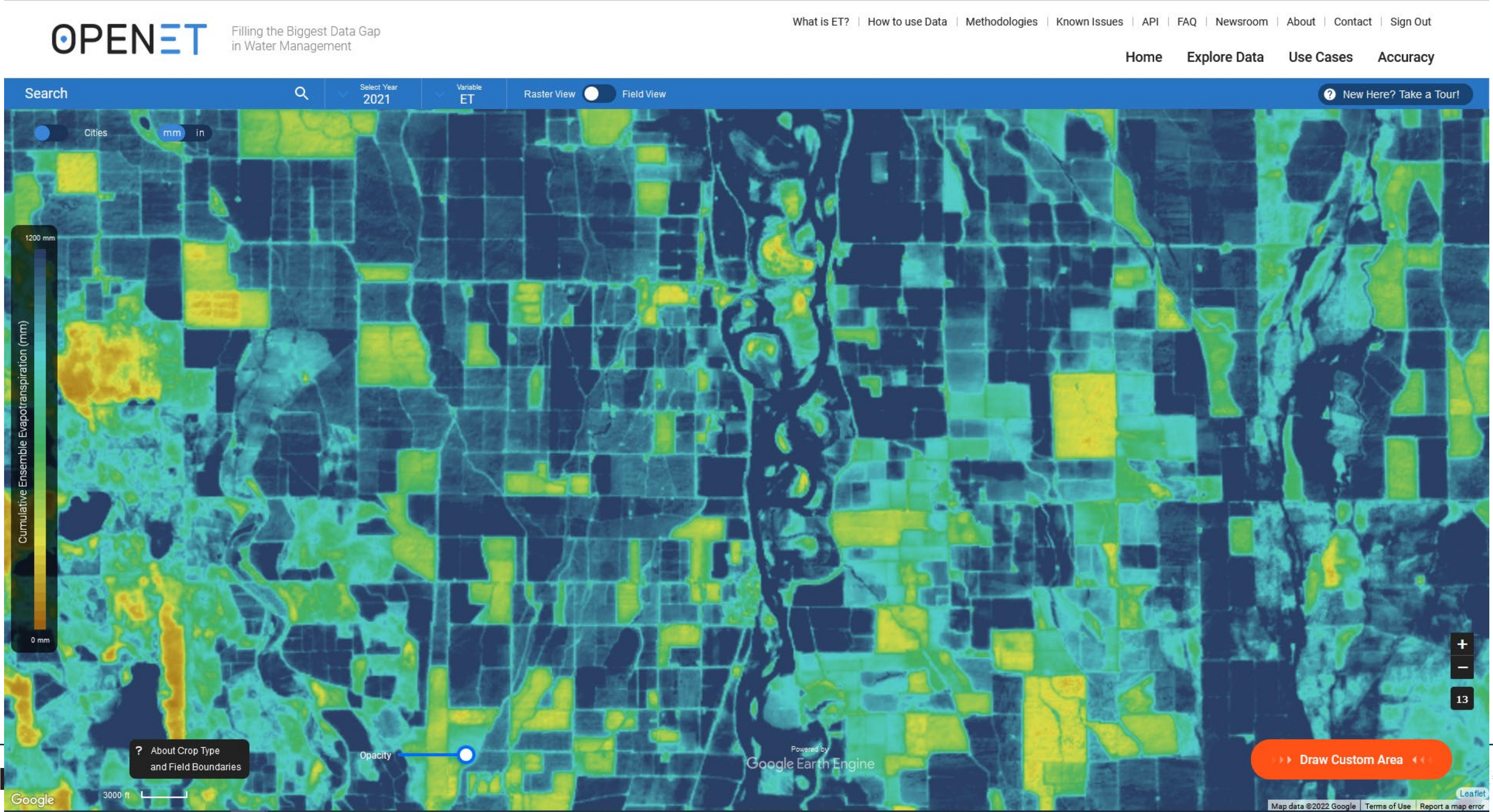
esa

wapor.apps.fao.org



OpenET portal

openetdata.org



Exercise

Exercise

- In the afternoon
- Aim: get better understanding of the physics behind the ET models and importance of different model inputs and parameters
- Interactive Jupyter Notebooks
  - Accessible online through MyBinder.org
  - Two notebooks:
    - Net radiation - https://mybinder.org/v2/gh/hectornieto/Curso-WUE/esa?labpath=EN_net_radiation.ipynb
    - Turbulence, sensible heat flux and ET - https://mybinder.org/v2/gh/hectornieto/Curso-WUE/esa?labpath=EN_turbulence_and_sensible_heat_flux.ipynb

Thank you

Radoslaw Guzinski
DHI