Hungarian Space Office

SZENT ISTVÁN UNIVERSITY

esa

→ 7th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

4–9 September 2017 | Szent István University | Gödöllő, Hungary

SURFACE ENERGY BALANCE SYSTEM (SEBS) - EVAPOTRANSPIRATION

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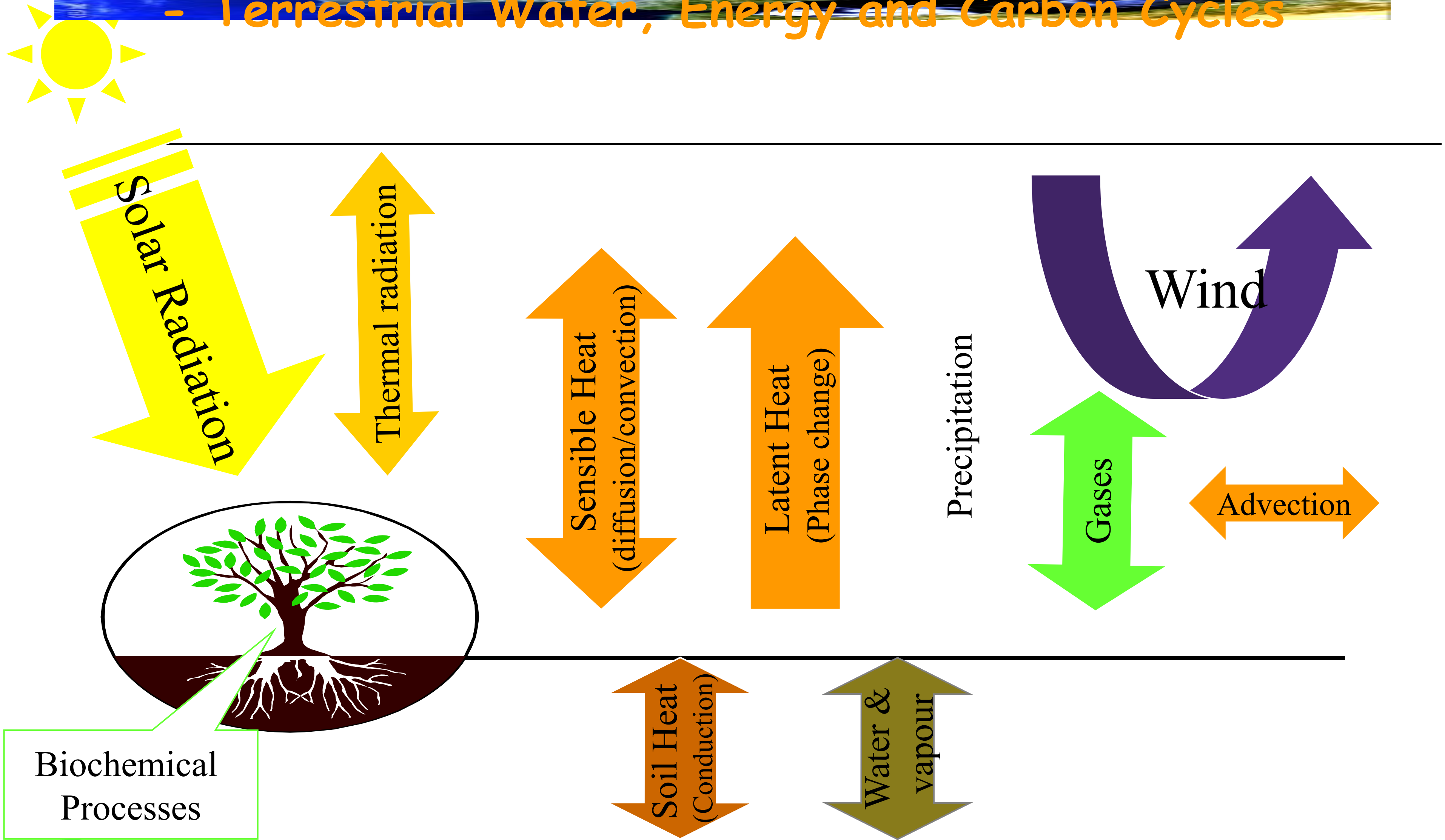
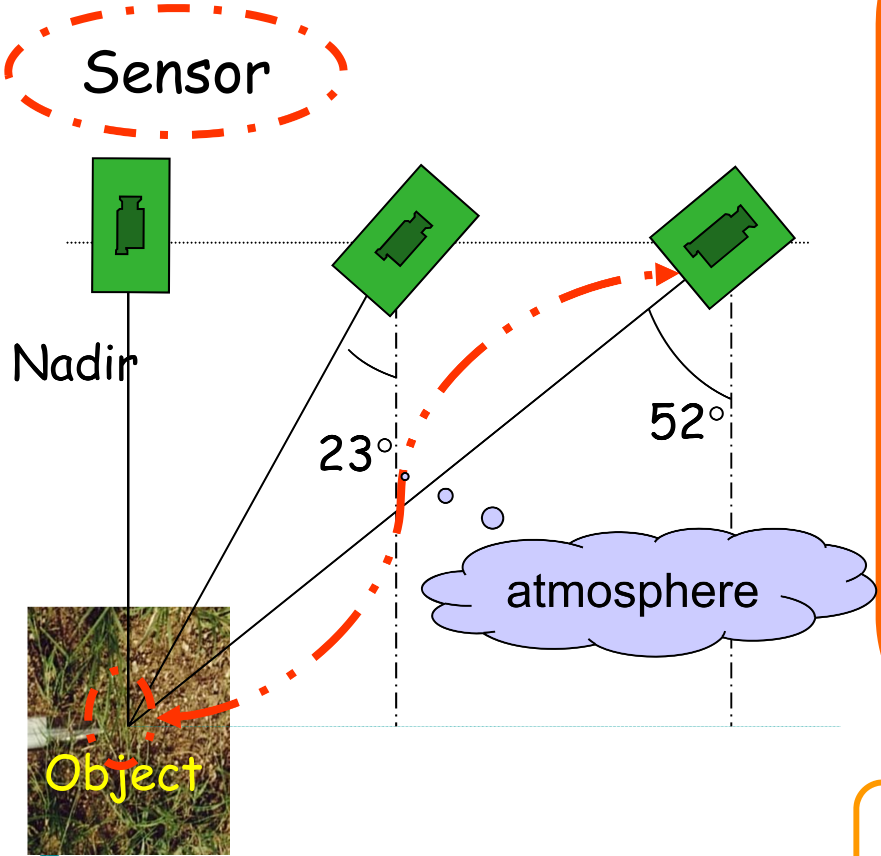
Learning Objectives

1. To understand basic ideas of advanced thermal remote sensing
2. To understand the most critical processes in surface energy balance
3. To be able to use SEBS for deriving different flux terms and evapotranspiration
4. To be able to develop applications of SEBS

Land-Atmosphere Interactions
- Terrestrial Water, Energy and Carbon Cycles





Sensor Response

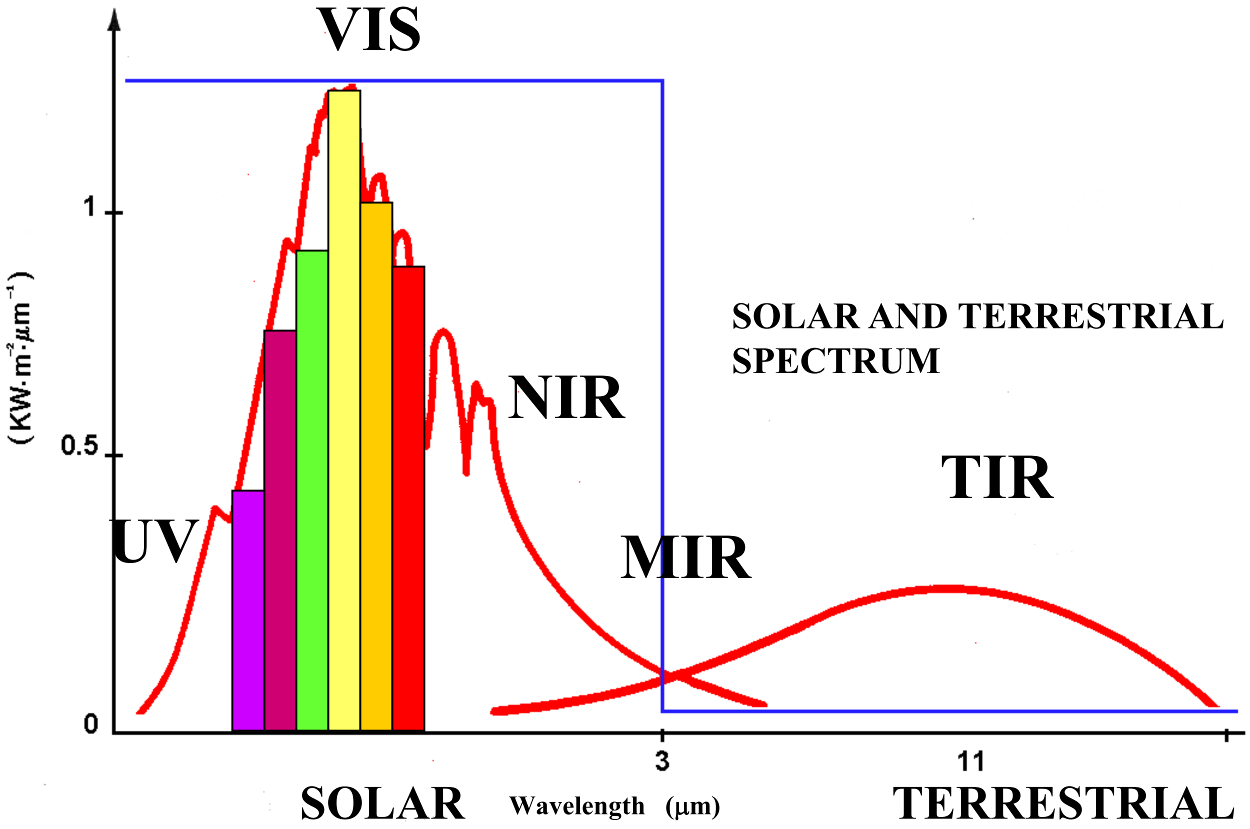
A. How much radiation is detected?
B. When does it arrive?

Object Properties:

Its range, its combined temperature & emissivity (or reflectivity) at different times, at different spatial resolution, at different wavelengths, at different direction, at different polarization

A: A Passive Sensor System
A+B: An Active Sensor System

THERMAL INFRARED RADIATION is a form of electromagnetic radiation with a wavelength between 3 to 14 micrometers (µm). Its flux is much lower than visible flux.



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Source: J.-L. Casanova

The Fundamental of Earth Observation

(from radiometric observations to quantification of processes in turbulence, thermodynamics and fluid dynamics at different scales in space and time)

Credits:

Editors:
Lee Balick &
Chris Jeffery

Camera:
Alan Gillespie

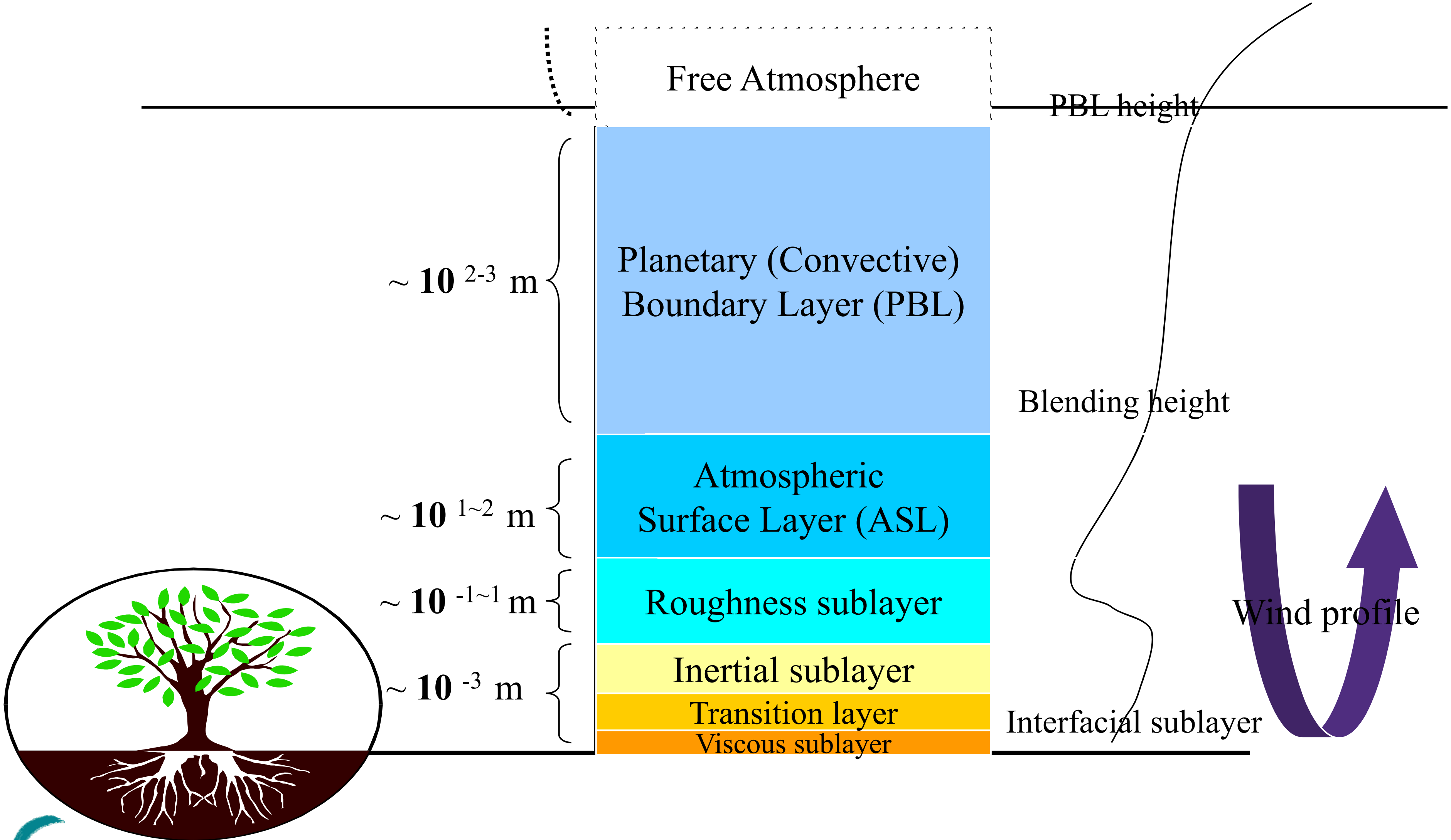
Director:
Lee Balick

Actors:
the wheat field et al. in Barrax, Castilla - la Mancha, Spain

Producer:
University of Valencia (Spain) & ESA

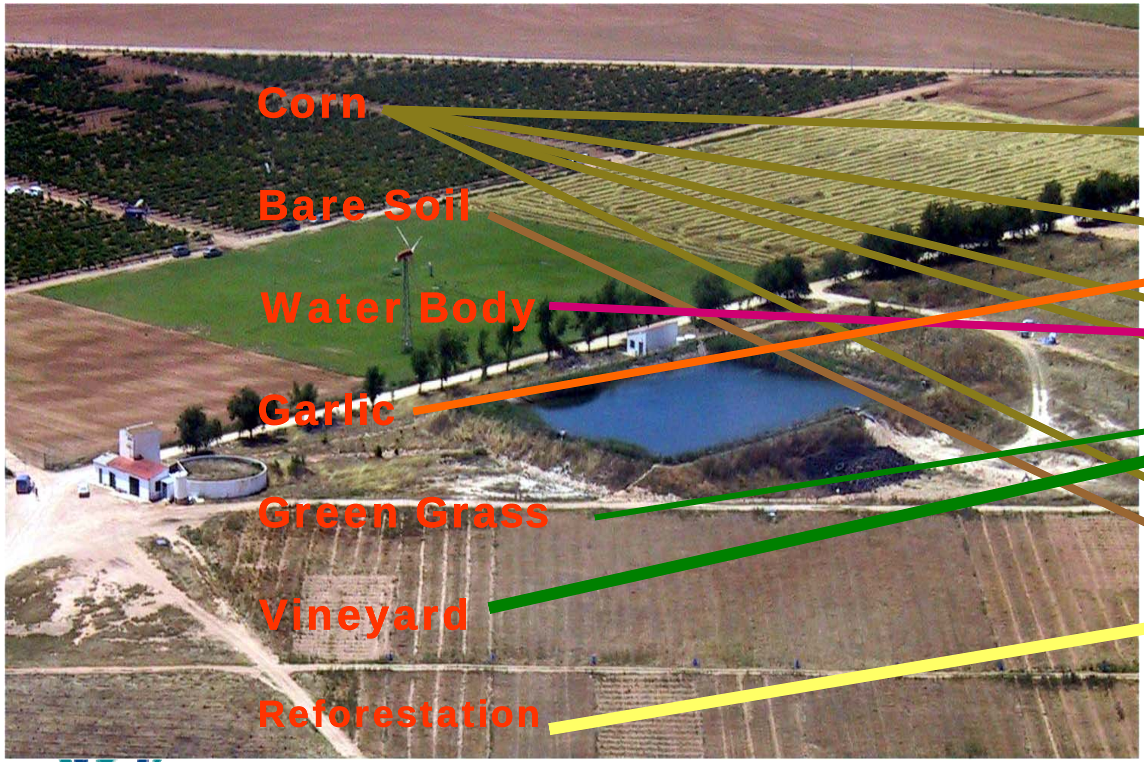
(Su et al., 2008, IJRS)

Structure of the atmospheric boundary layer considered in SEBS

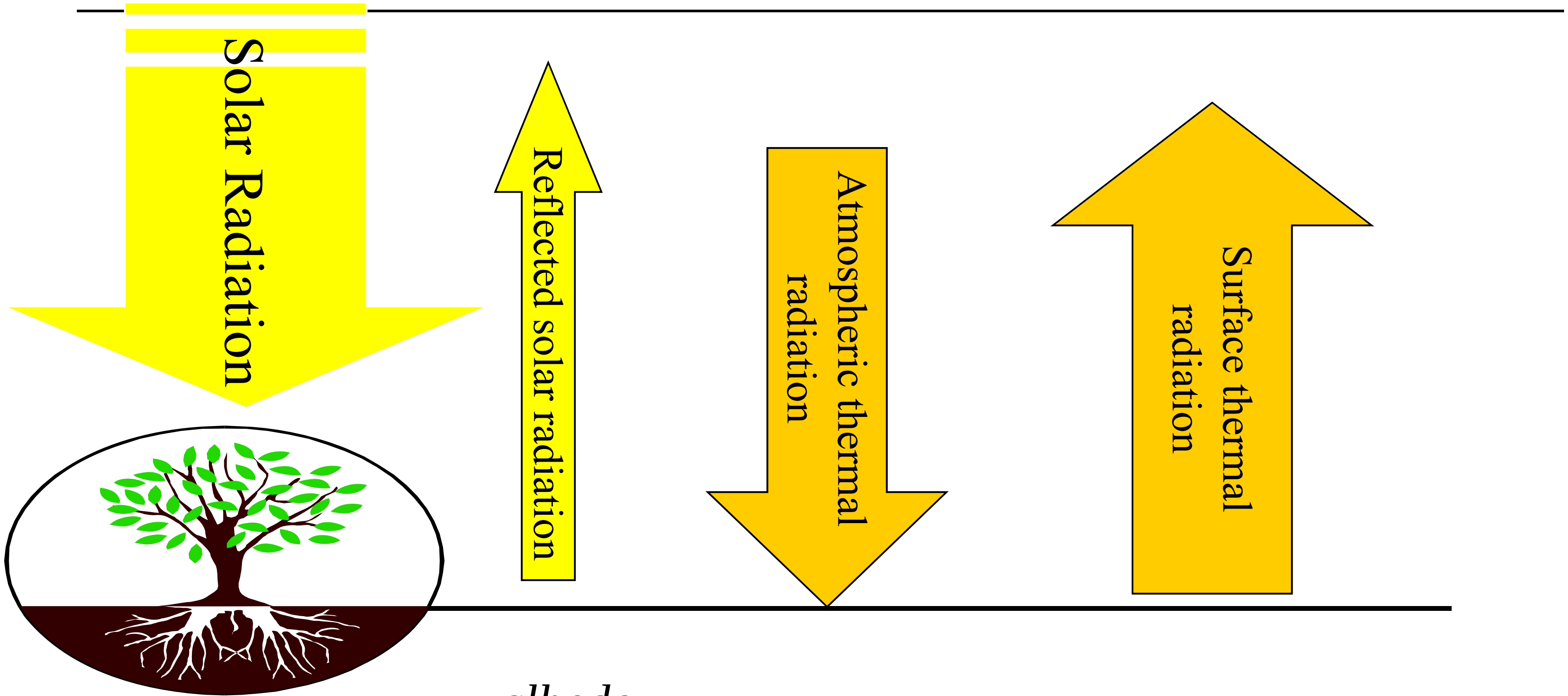


Barrax Test Site, Spain

- Situated in the area of La Mancha, in the west of the province of Albacete, 28 km from Albacete
- Geographic coordinates: 39º 3’ N; 2º 6’ W
- Altitude (above sea level): 700 m



Surface Radiation Balance



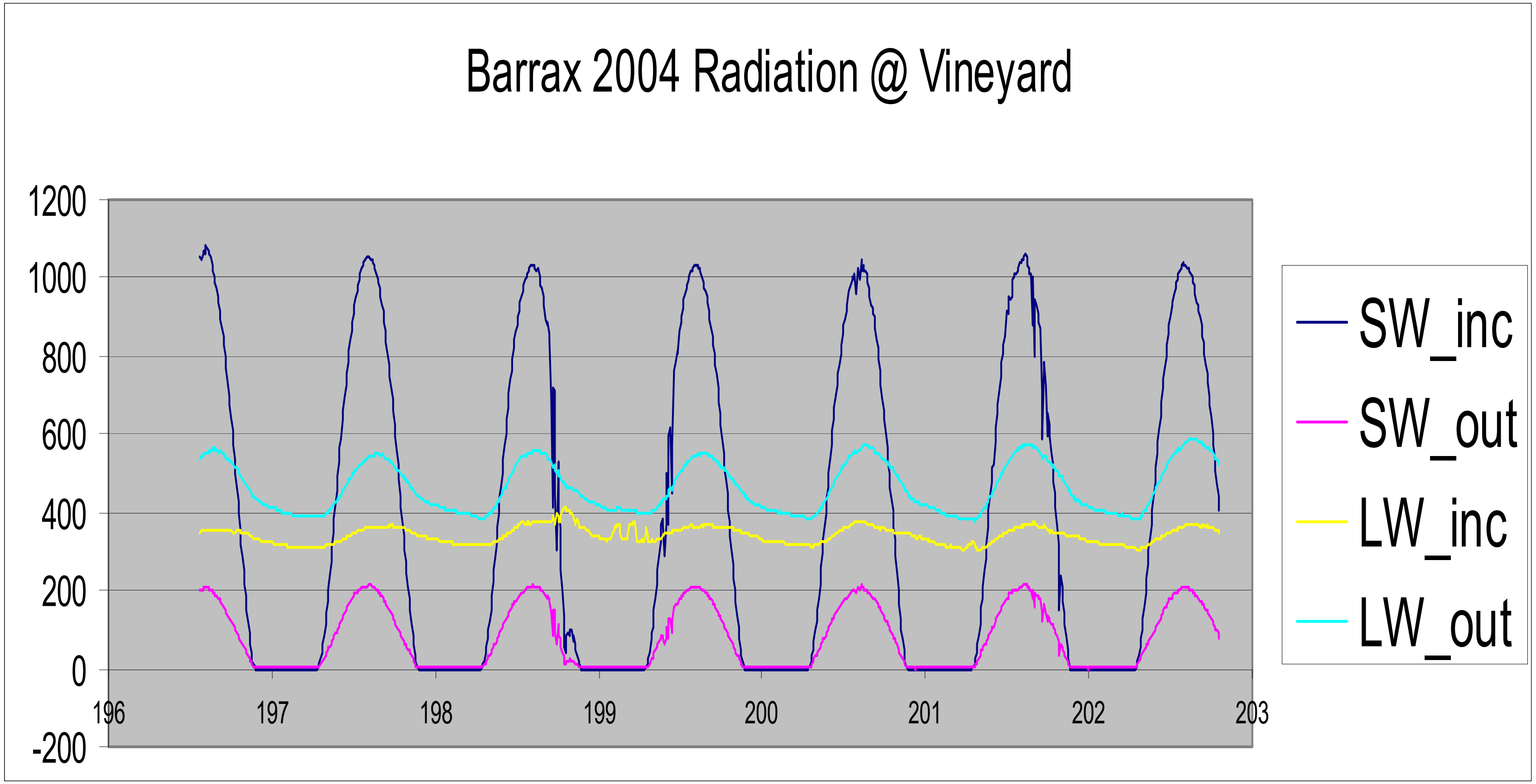
α : *albedo*

ε : *emissivity*

T_0 : *Surface Temperature*

$$R_n = (1-\alpha)\cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4$$

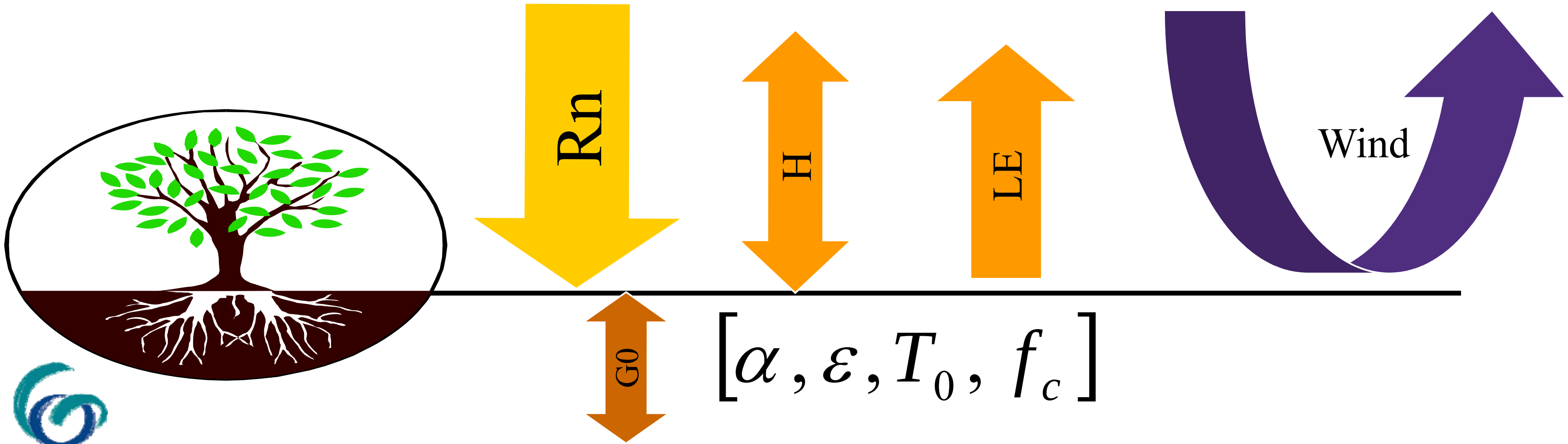
Data from EAGLE/SPARC Campaign 2004, Barrax, Spain



Surface Energy Balance Terms

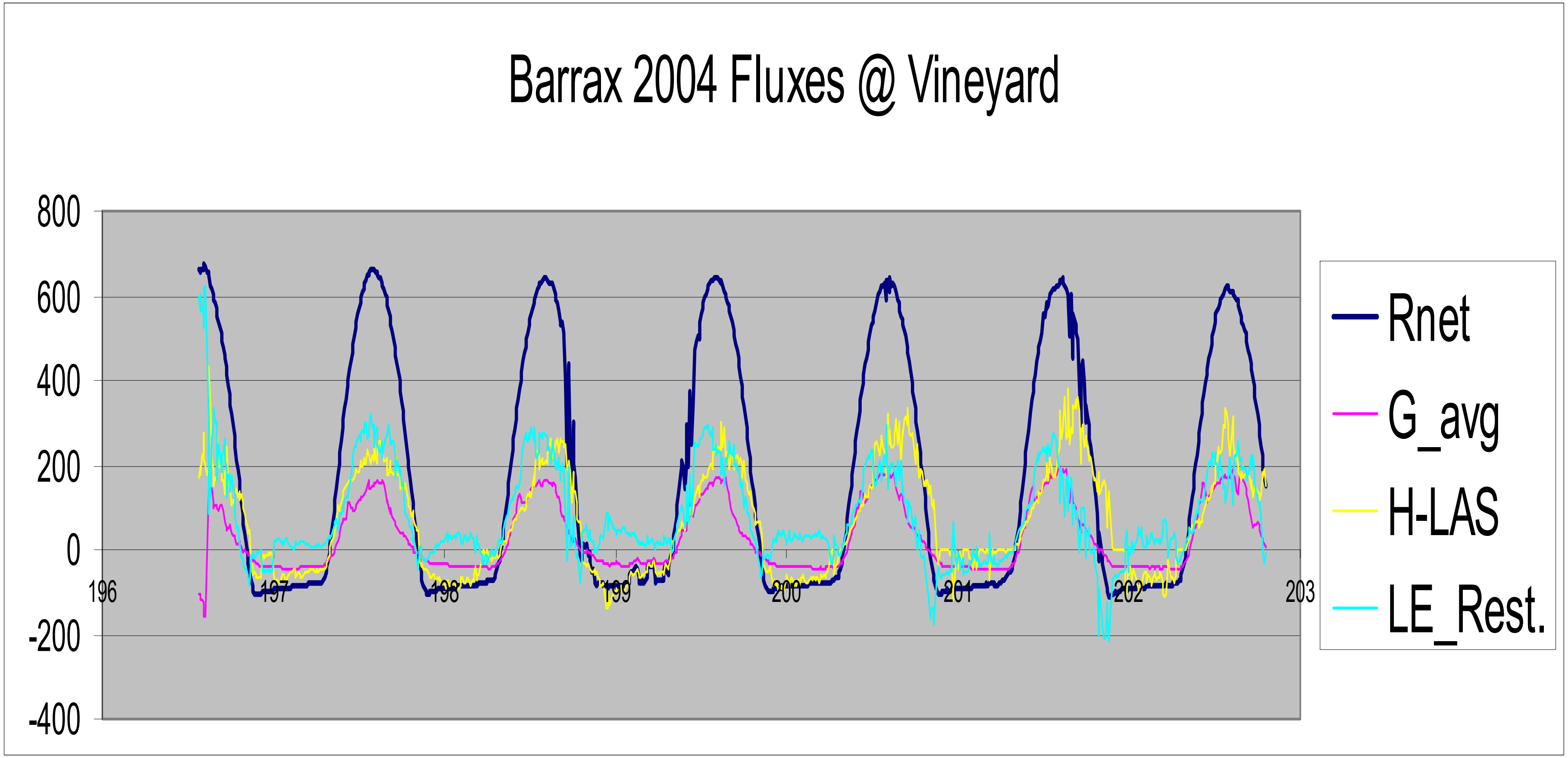
$$R_n = G_0 + H + LE$$

$$G_0 = R_n \cdot \left[f_c \cdot \Gamma_c + (1 - f_c) \cdot \Gamma_s \right]$$



$$\left[\alpha, \varepsilon, T_0, f_c \right]$$

Scintillometer Data from EAGLE/SPARC Campaign 2004, Barrax, Spain



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Schematic representation of SEBS

(Radiometric observables) (r_0, T_0),

(RS observables or estimates) (f_c, LAI, h_c),

(Surface observation, radiosonds, NWP fields) (T_{PBL}, V_{PBL}, P_{PBL}, q_{PBL}, R_s, R_{ld})

Preprocessing to derive radiation balance terms

Submodel to derive roughness length for heat transfer
(Su, Schmugge, Kustas, Massman, 2001)

Submodel to derive stability parameters
(ASL scaling or PBL scaling, Brutsaert, 1999)

Energy balance at limiting cases
(Menenti, Choudhury,1993)

Energy balance terms
(R_n, G_0, H, λE, Λ)

SEBS Basic Equations, Su, 2002, HESS, 6(1),85-99

$$R_n = G_0 + H + \lambda E$$

$$\lambda E_{dry} = R_n - G_0 - H_{dry} \equiv 0, \quad or$$
$$H_{dry} = R_n - G_0$$

$$\lambda E_{wet} = R_n - G_0 - H_{wet}, \quad or$$
$$H_{wet} = R_n - G_0 - \lambda E_{wet}$$

$$H_{wet} = \left((R_n - G_0) - \frac{\rho C_p}{r_{ew}} \cdot \frac{e_s - e}{\gamma} \right) \Big/ \left(1 + \frac{\Delta}{\gamma} \right)$$

$$\Lambda_r = \frac{\lambda E}{\lambda E_{wet}} = 1 - \frac{\lambda E_{wet} - \lambda E}{\lambda E_{wet}}$$

$$\Lambda_r = 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}}$$

$$\Lambda = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \cdot \lambda E_{wet}}{R_n - G}$$

$$H = (1 - \Lambda) \cdot (R_n - G)$$
$$\lambda E = \Lambda \cdot (R_n - G)$$

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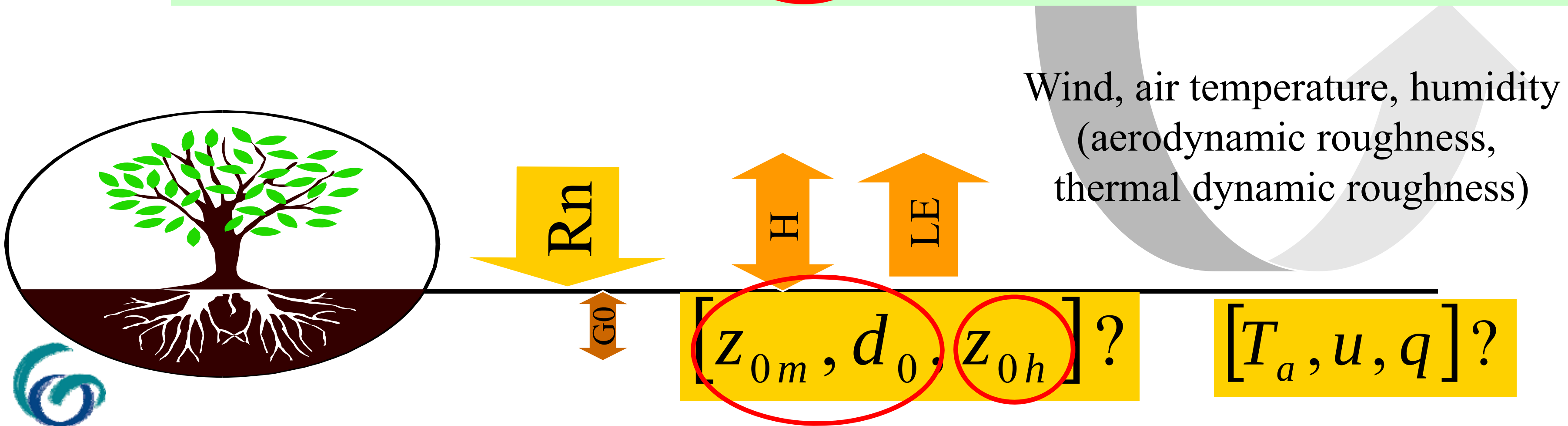
Turbulence parameterisation
– wind, stability and sensible heat flux

$$
\begin{cases}
u = \dfrac{\boxed{u_*}}{k}\left[\ln\left(\dfrac{z-d_0}{z_{0m}}\right) - \Psi_m\left(\dfrac{z-d_0}{L}\right) + \Psi_m\left(\dfrac{z_{0m}}{L}\right)\right] \\[2ex]
\boxed{L} = -\dfrac{\rho C_p u_*^3 \theta_v}{kgH} \\[2ex]
\boxed{H} = k u_* \rho C_p (\theta_0 - \theta_a)\left[\ln\left(\dfrac{z-d_0}{z_{0h}}\right) - \Psi_h\left(\dfrac{z-d_0}{L}\right) + \Psi_h\left(\dfrac{z_{0h}}{L}\right)\right]^{-1}
\end{cases}
$$



The scalar roughness height for heat transfer

$$z_{0h} = z_{0m} / \exp\left(kB^{-1}\right)$$

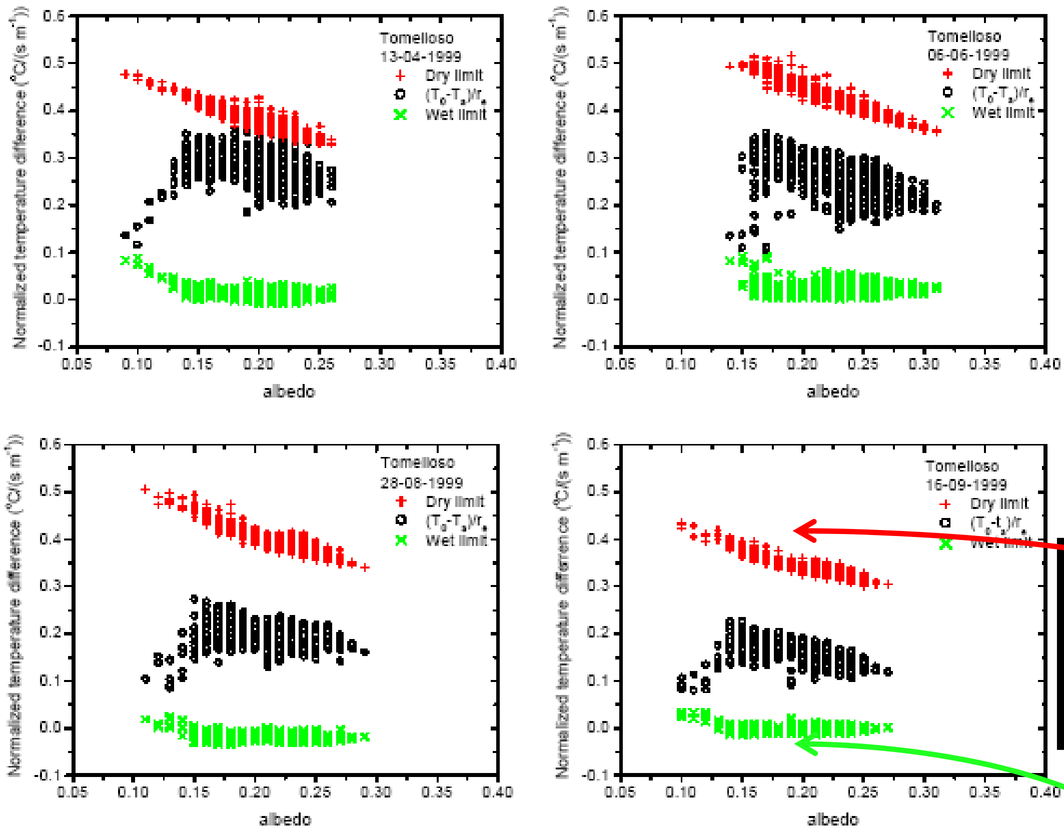
The within-canopy wind speed profile extinction coefficient,

$$n_{ec} = \frac{C_d \cdot LAI}{2u_*^2 / u(h)^2}$$

$$kB^{-1} = \frac{kC_d}{4C_t \frac{u_*}{u(h)}\left(1 - e^{-n_{ec}/2}\right)} f_c^2 + 2 f_c f_s \frac{k \cdot {u_*}/{u(h)} \cdot {z_{0m}}/{h}}{C_t^*} + kB_s^{-1} f_s^2$$

$$kB_s^{-1} = 2.46\left(\mathrm{Re}_*\right)^{1/4} - \ln[7.4]$$

Graphical representation of the SEBS equations

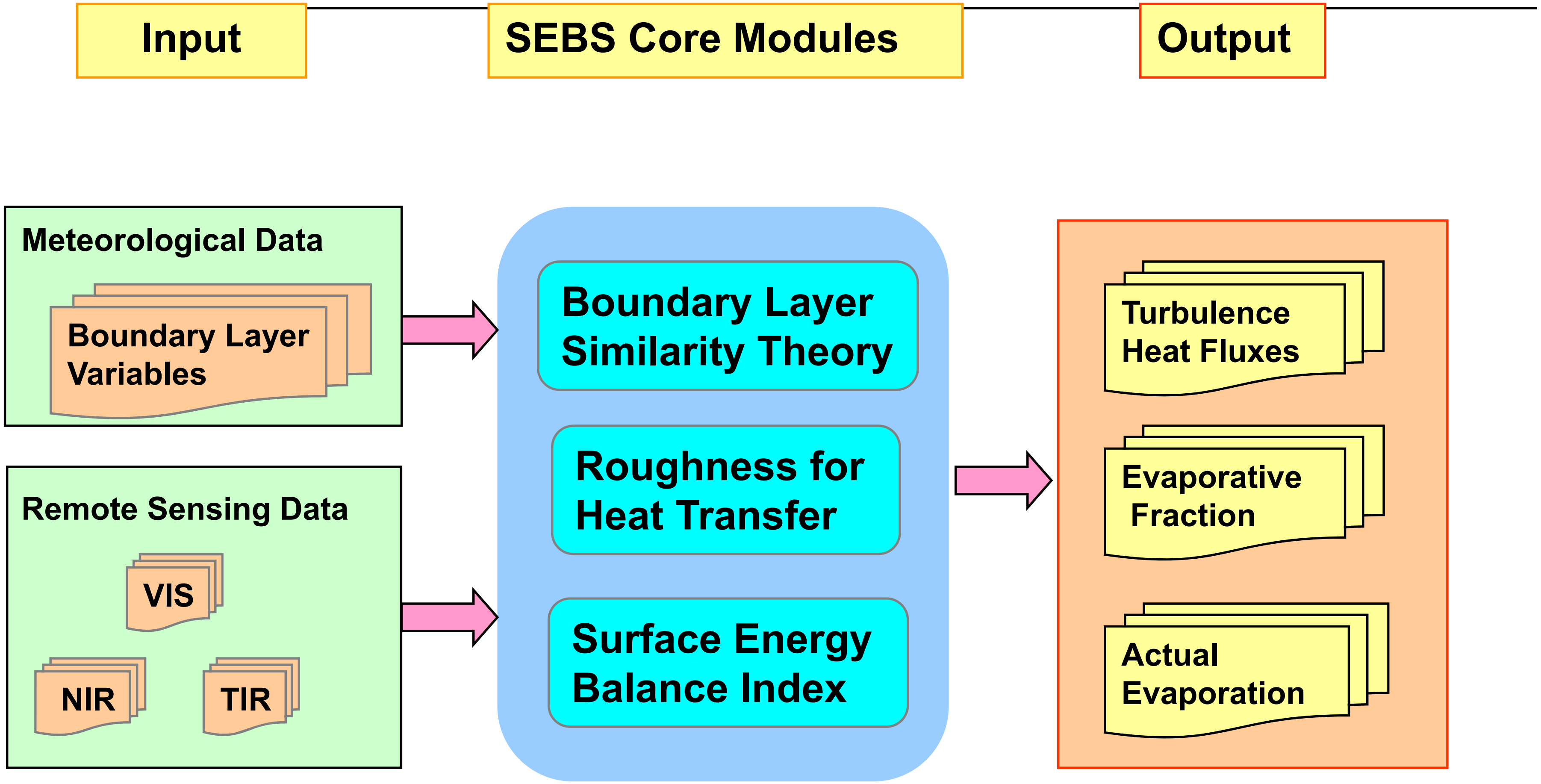


$$\Lambda_r = 1 - \frac{H - H_{wet}}{\boxed{H_{dry}} - \boxed{H_{wet}}}$$

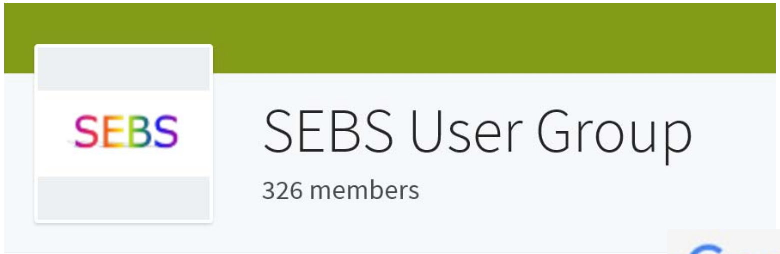
Dry limits

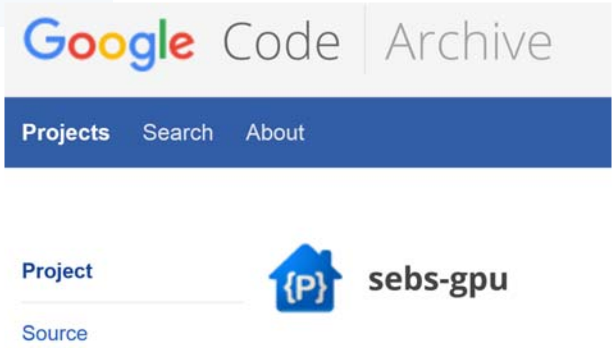
Wet limits

SEBS - The Surface Energy Balance System

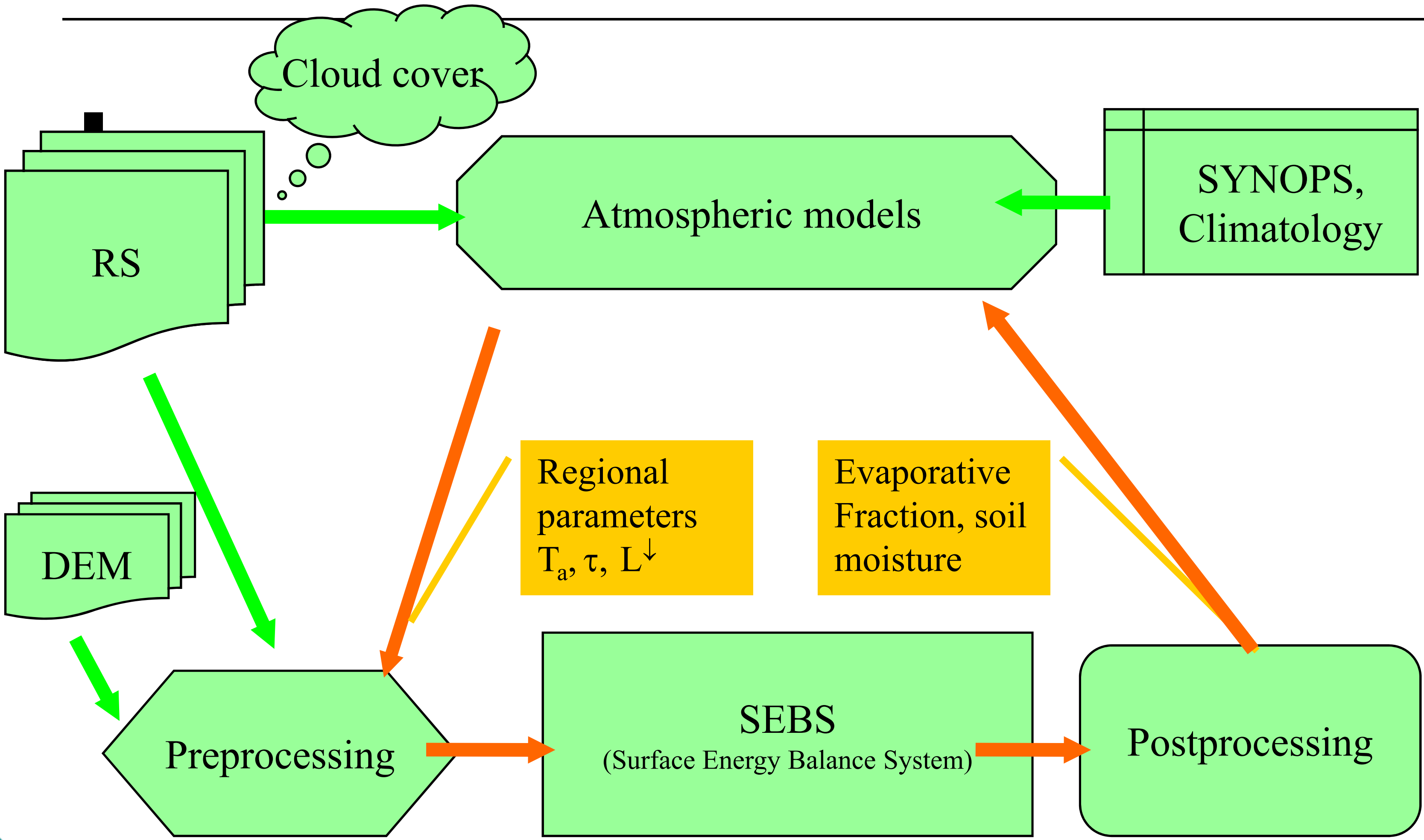


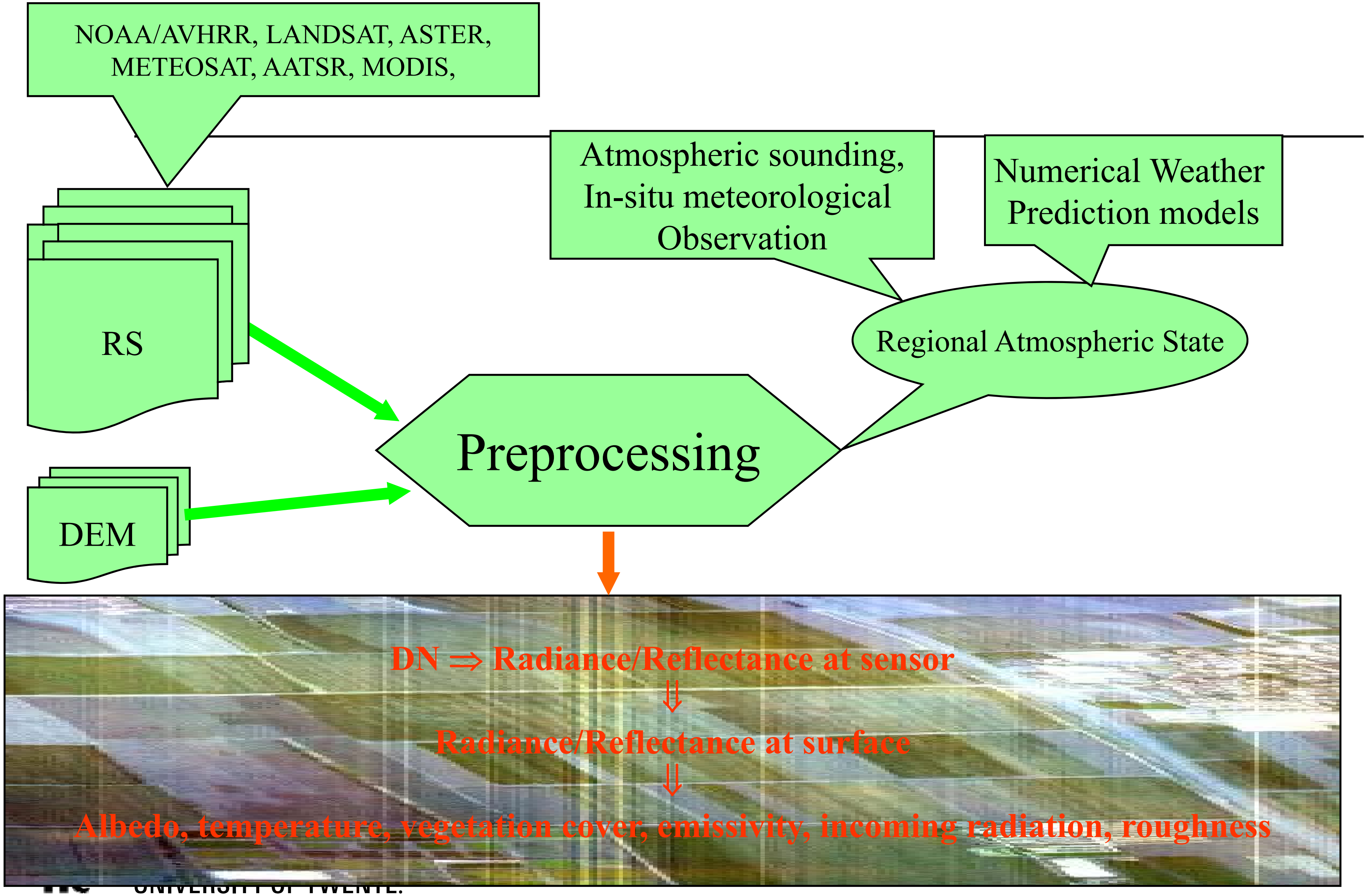
Software implementation





General Methodology




NOAA/AVHRR, LANDSAT, ASTER,
METEOSAT, AATSR, MODIS,
Atmospheric sounding,
In-situ meteorological
Observation
Numerical Weather
Prediction models
Regional Atmospheric State
RS
Preprocessing
DEM
DN ⇒ Radiance/Reflectance at sensor
⇓
Radiance/Reflectance at surface
⇓
Albedo, temperature, vegetation cover, emissivity, incoming radiation, roughness

Some examples

(Su et al., 2008 IJRS)

Barrax Test Site, Spain

- Situated in the area of La Mancha, in the west of the province of Albacete, 28 km from Albacete
- Geographic coordinates: 39° 3’ N; 2° 6’ W
- Altitude (above sea level): 700 m

EAGLE2006

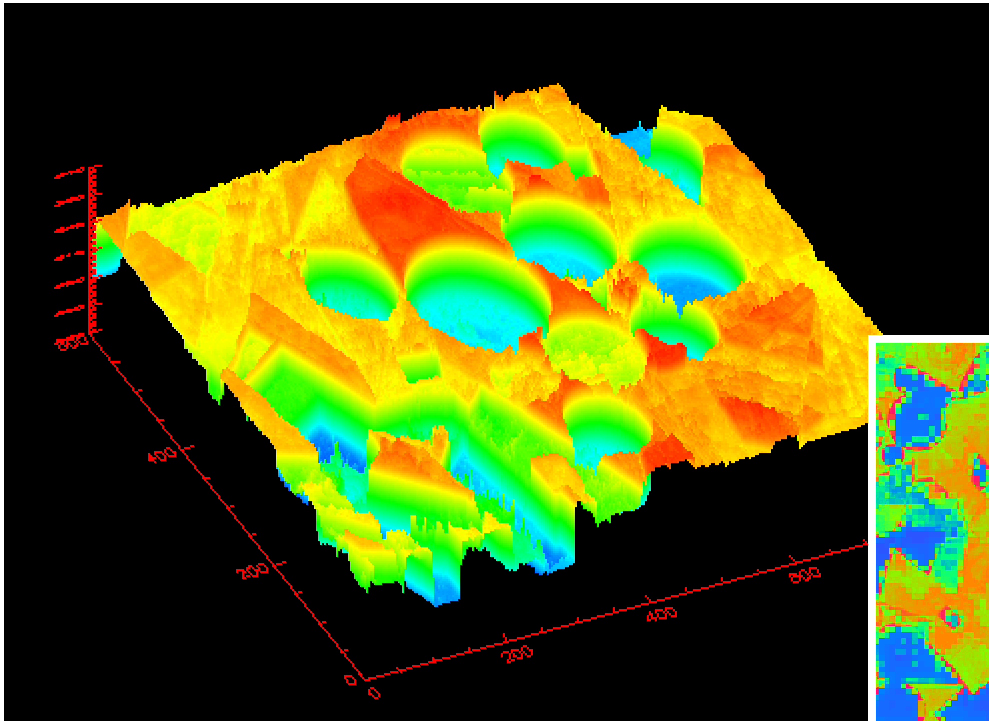
(Su et al., 2009, HESS)

EAGLE Netherlands Multi-purpose, Multi-Angle and Multi-sensor,

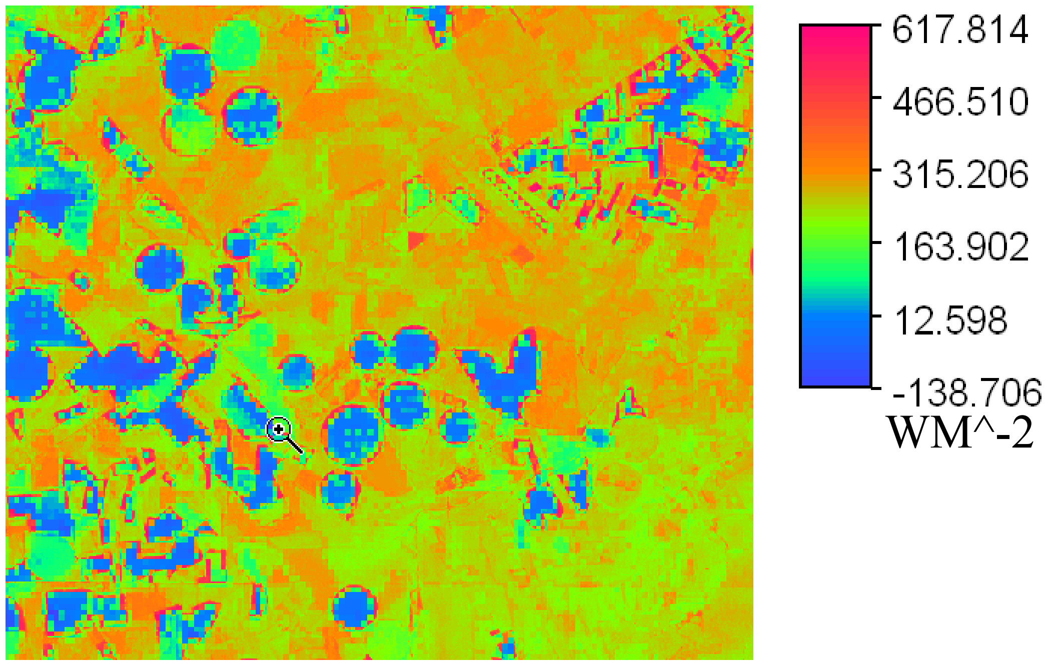
In-situ, Airborne and Space Borne Campaigns over Grassland and Forest

esa NWO SRON

Results from SEBS

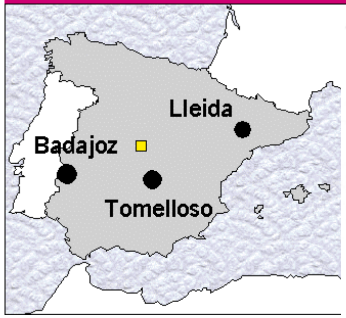


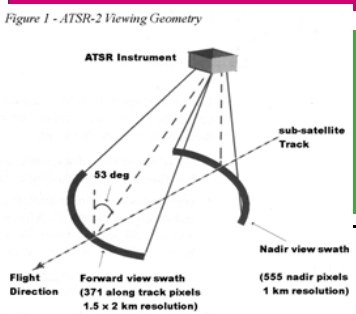
Sensible Heat
AHS 15 July 2004
(A. Gieske)



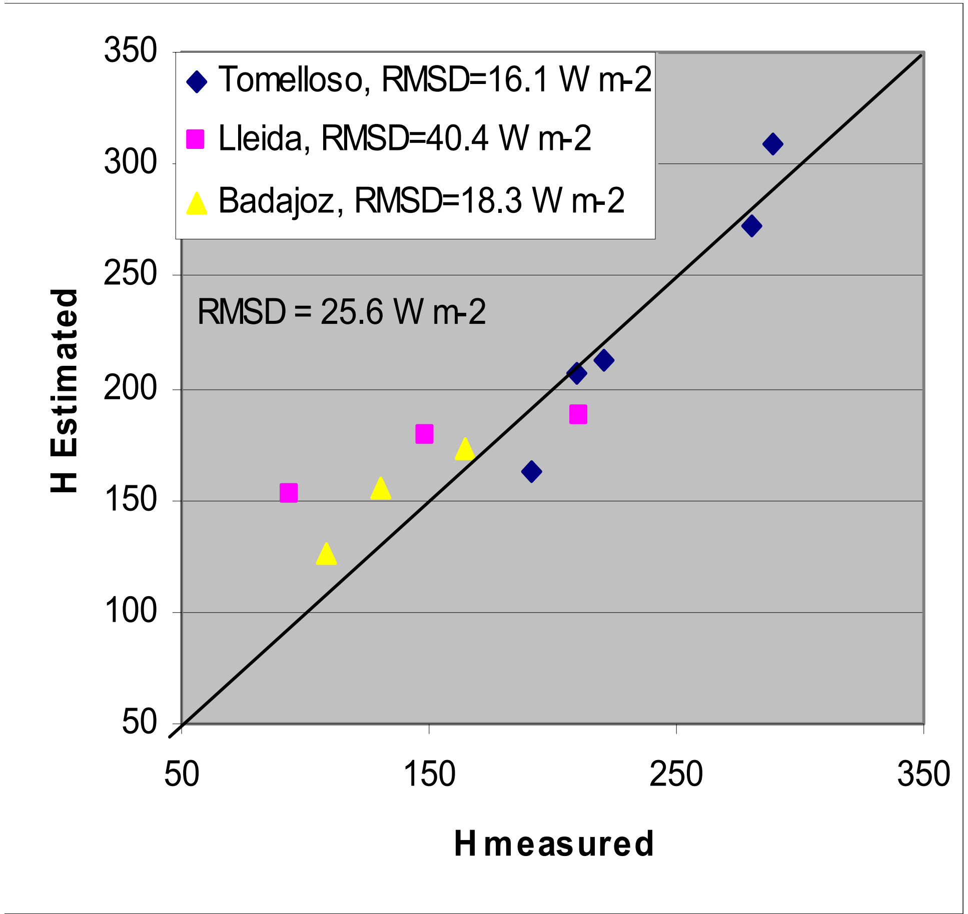
Sensible Heat
ASTER 18 July 2004

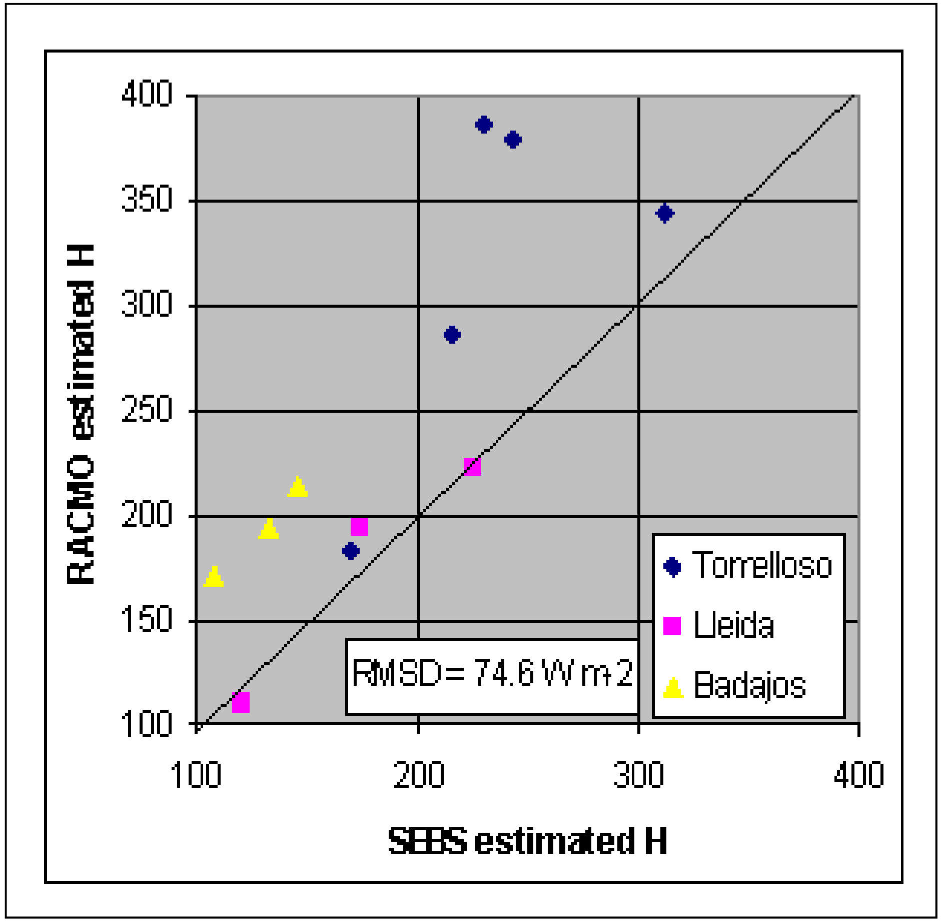
Validation of Atmospheric Models at Regional Scales



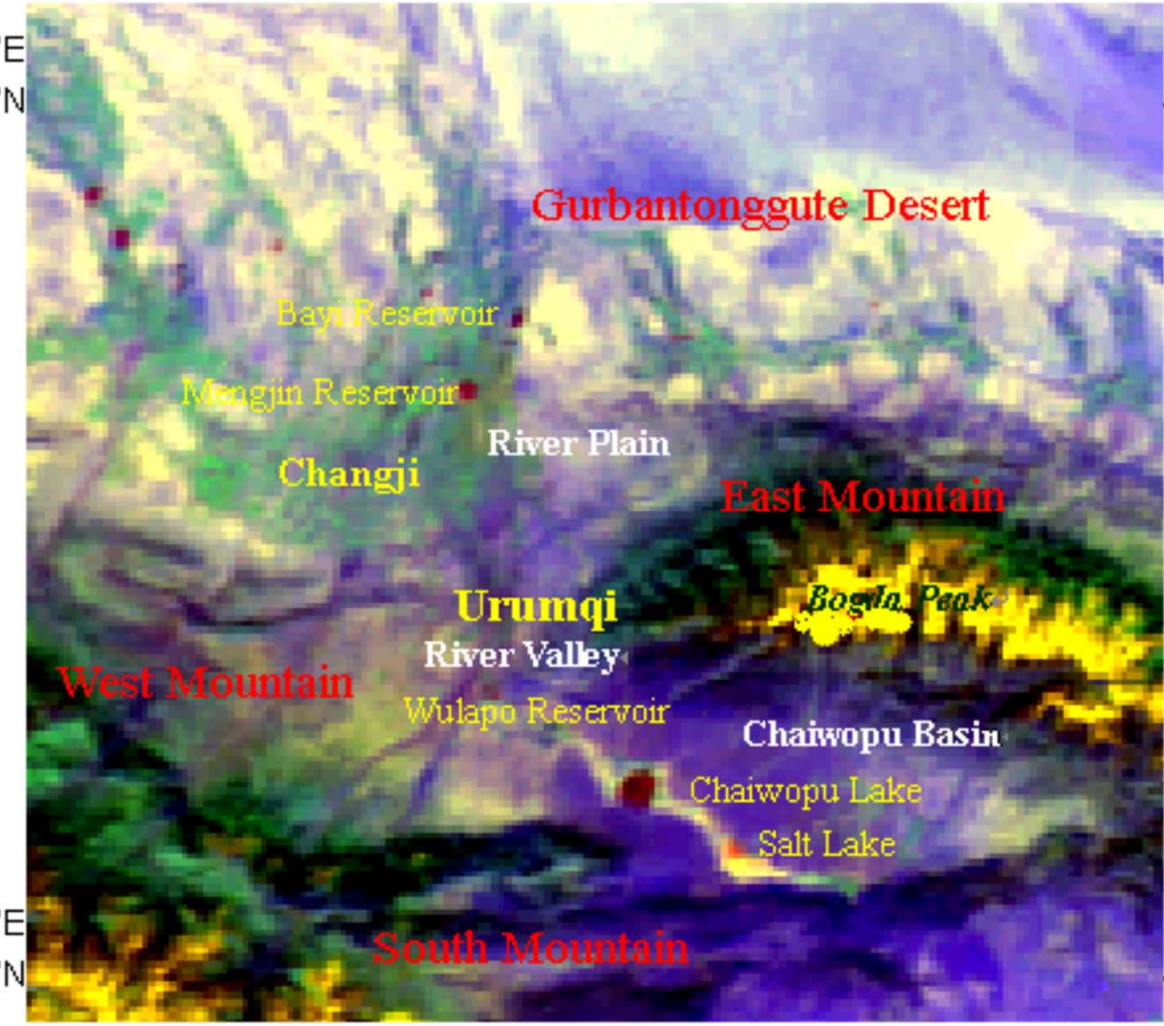


Scintillometer measurements, retrievals by SEBS using ATSR data and RACMO PBL fields, and simulation by RACMO (Jia, et al., 2002, PCE)

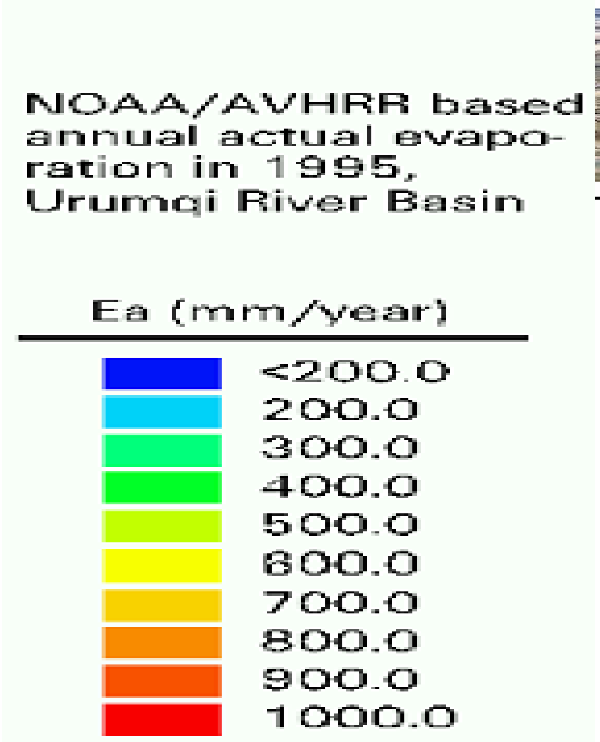


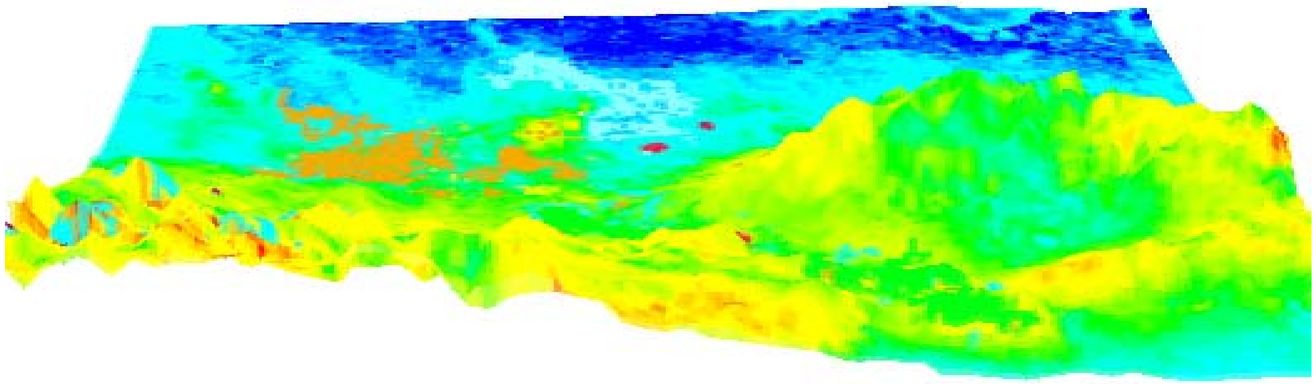


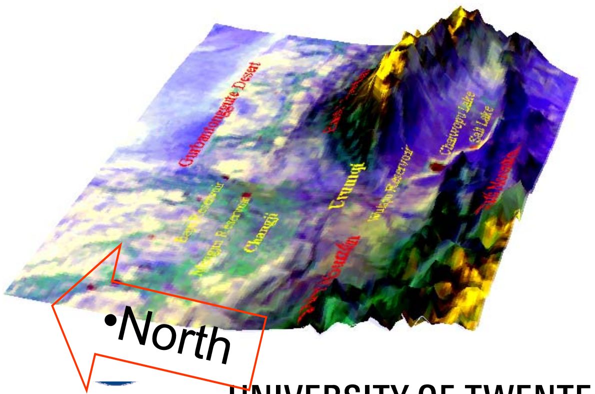
Application to the Urumqi River Basin, NW China

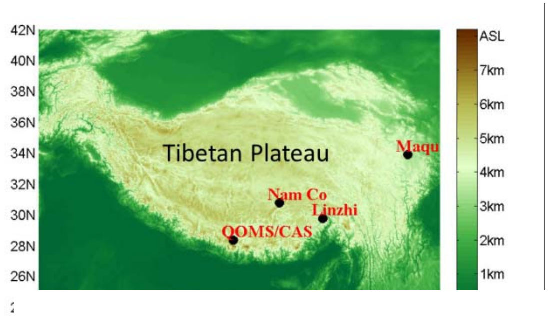


Spatial Distribution of Annual Evaporation over the Urumqi River Basin

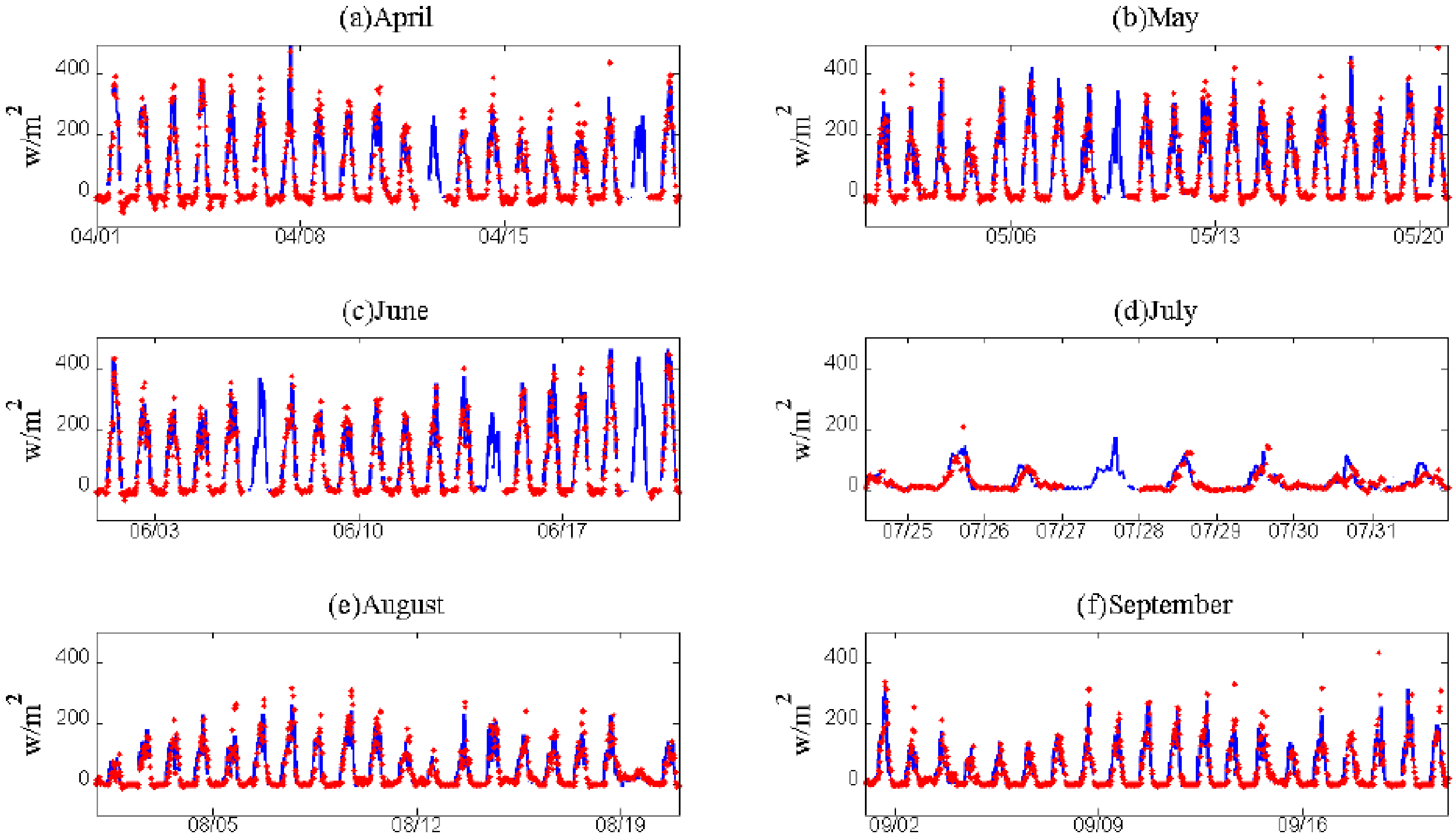




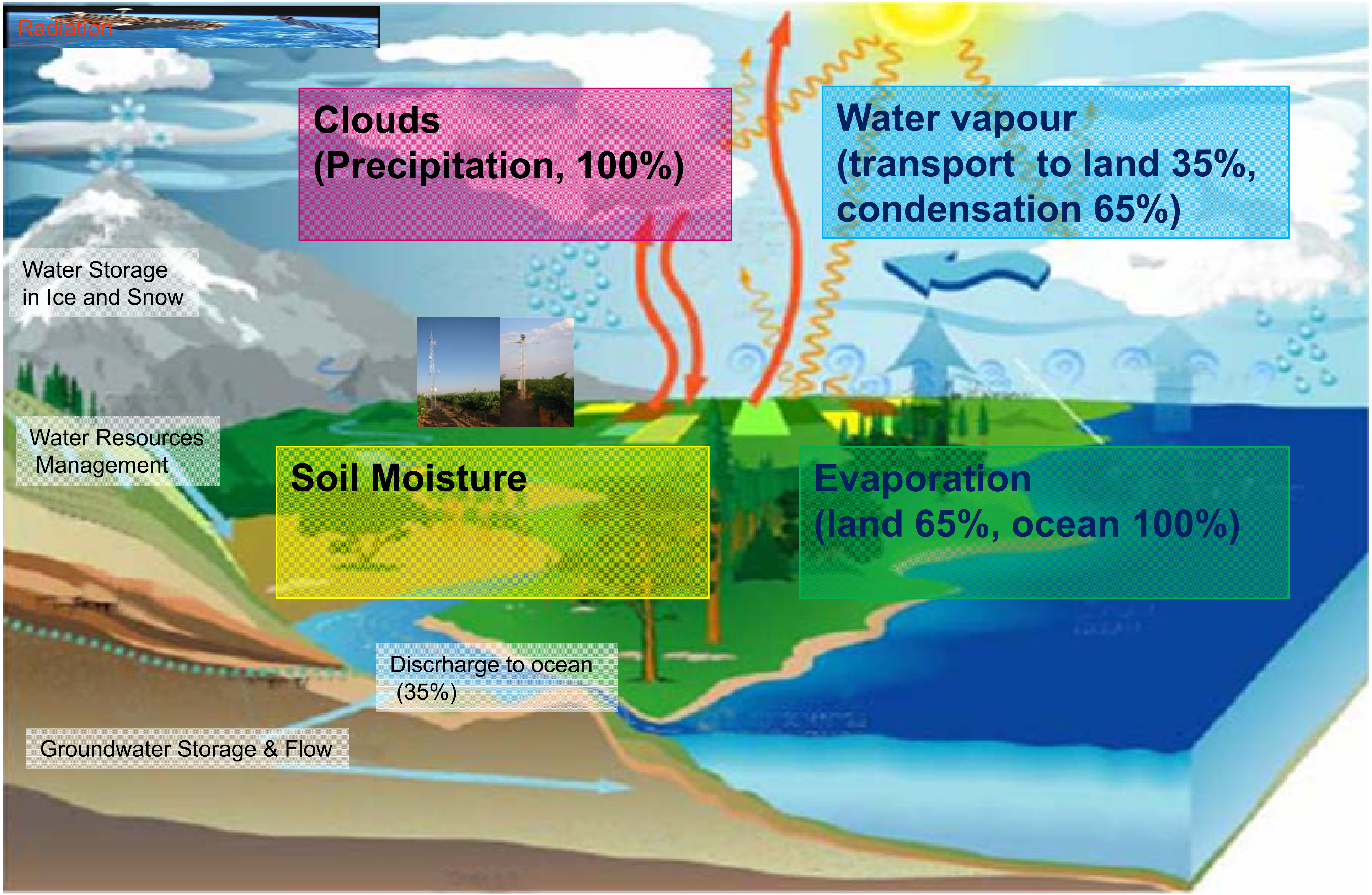




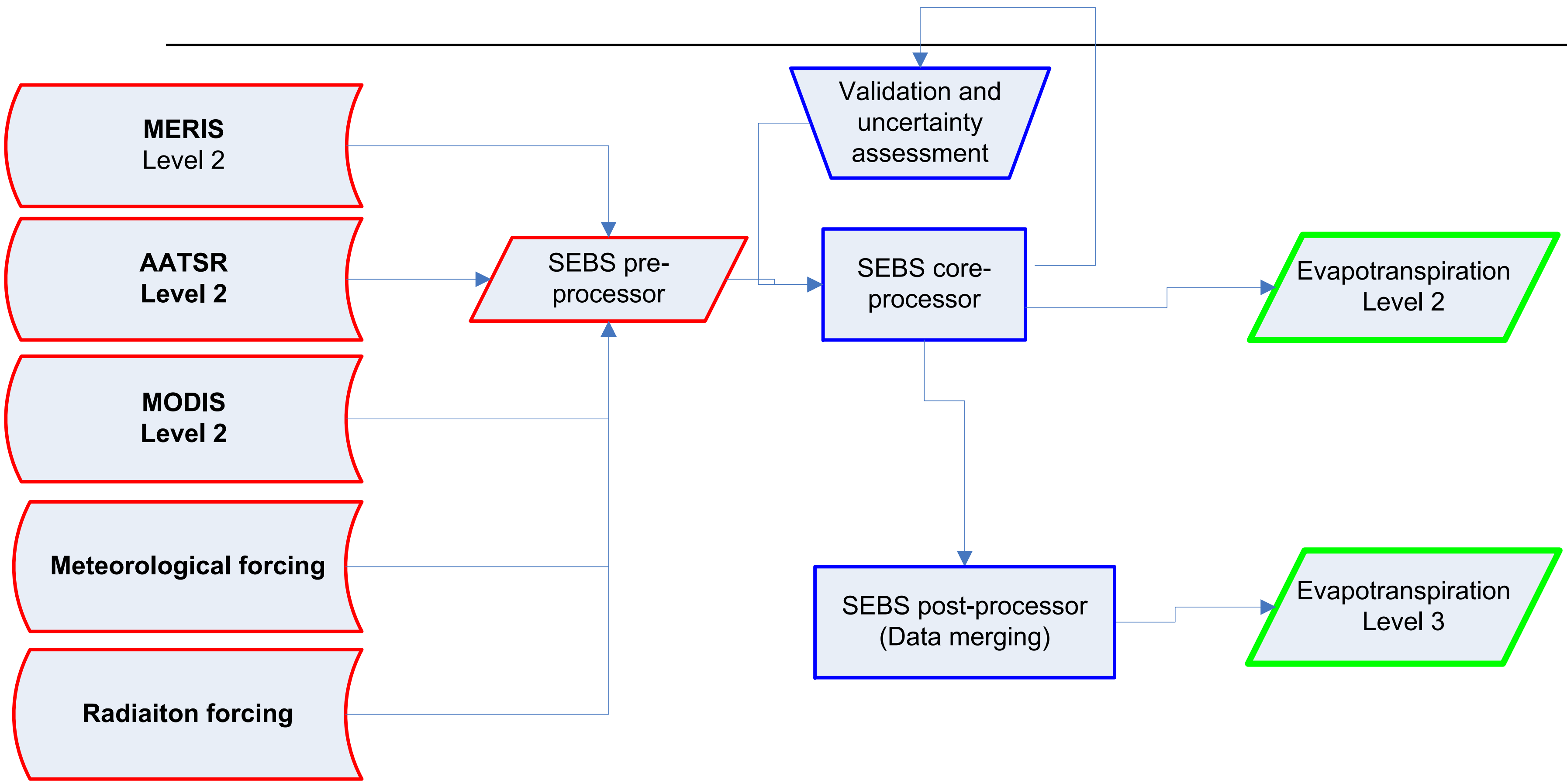
(Chen et al., 2012, JAMC)



Earth Observation of Water Cycle

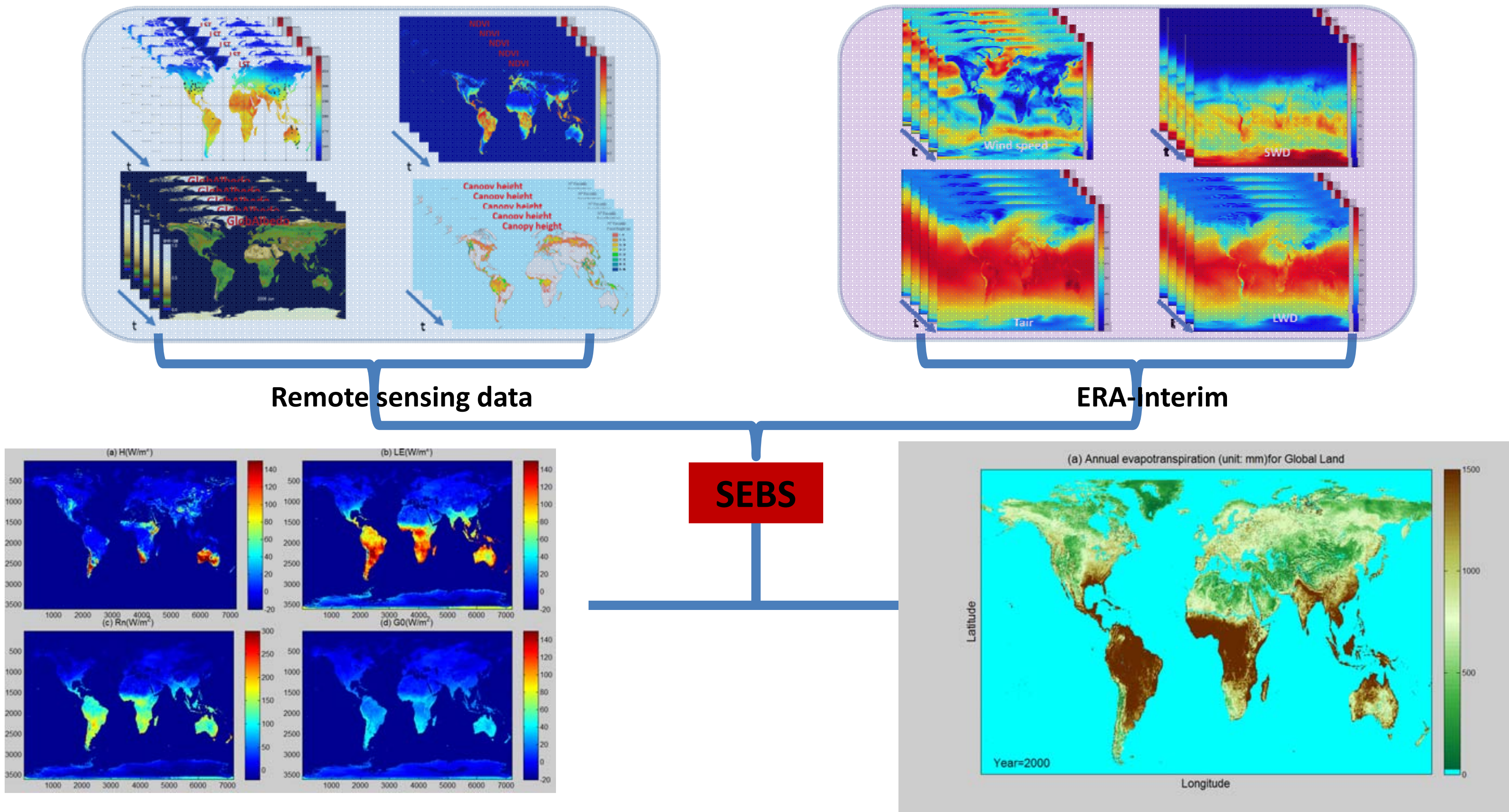


Evapotranspiration - Technical specification: SEBS data flow



(Su, 2002, HESS; Oku et al., 2005, JAMC; Su et al., 2005, JHM; Su et al., 2007, JMSJ)

Remote Sensing based global land surface flux and ET data

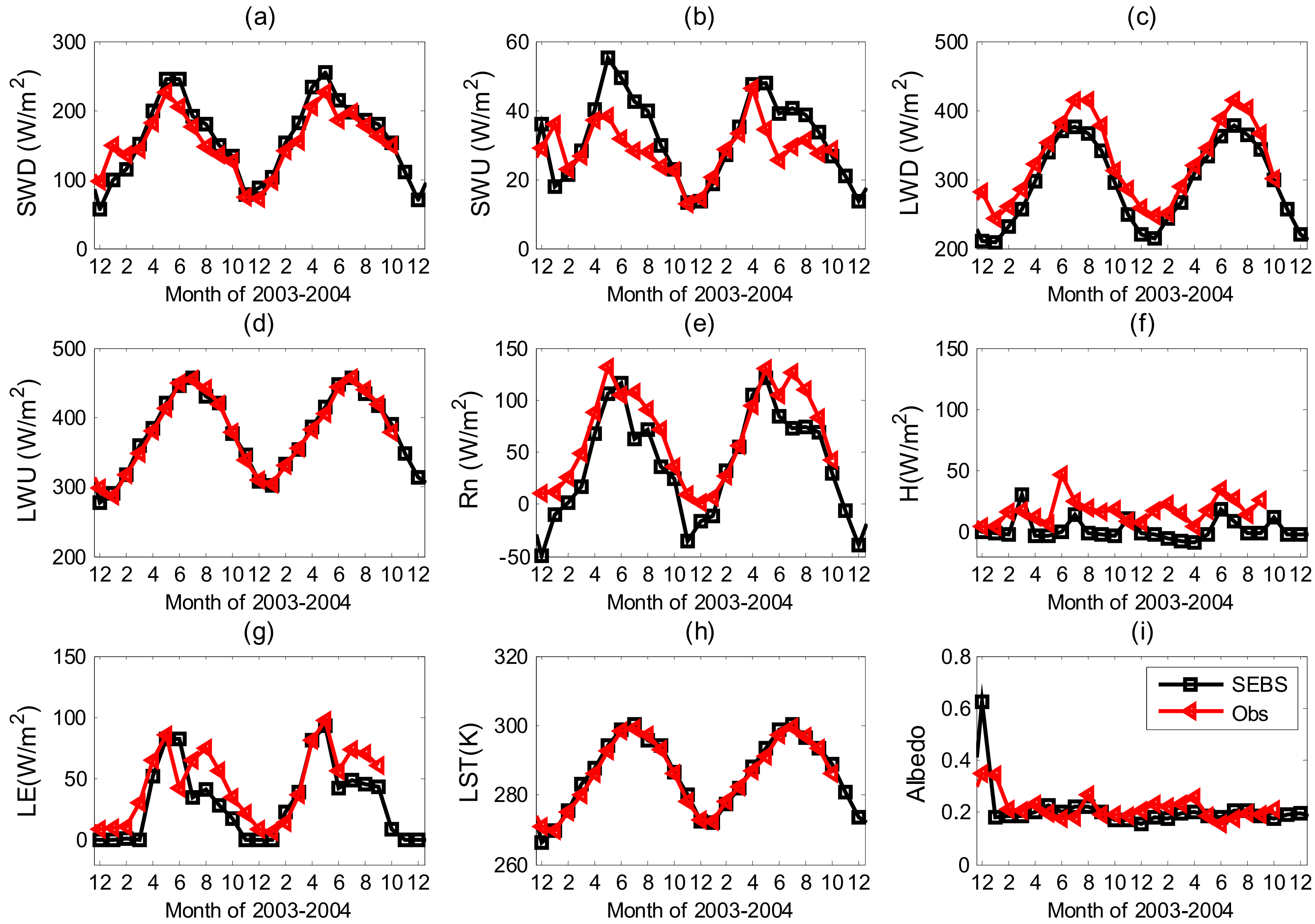


Global land fluxes 2001-2015

Global land ET 2001-2015

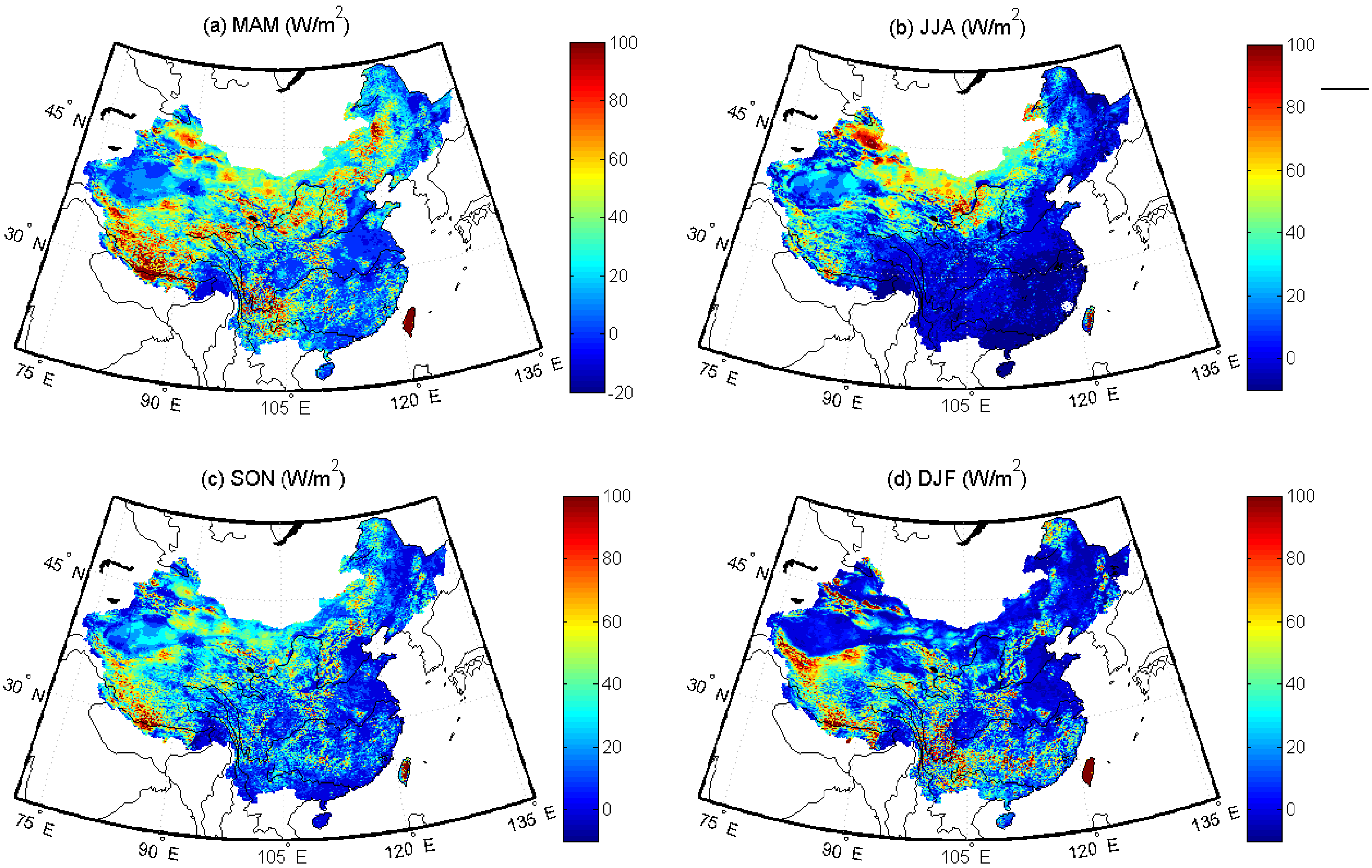
SEBS input and output variables vs measurement

(winter wheat and summer maize at Yucheng station)



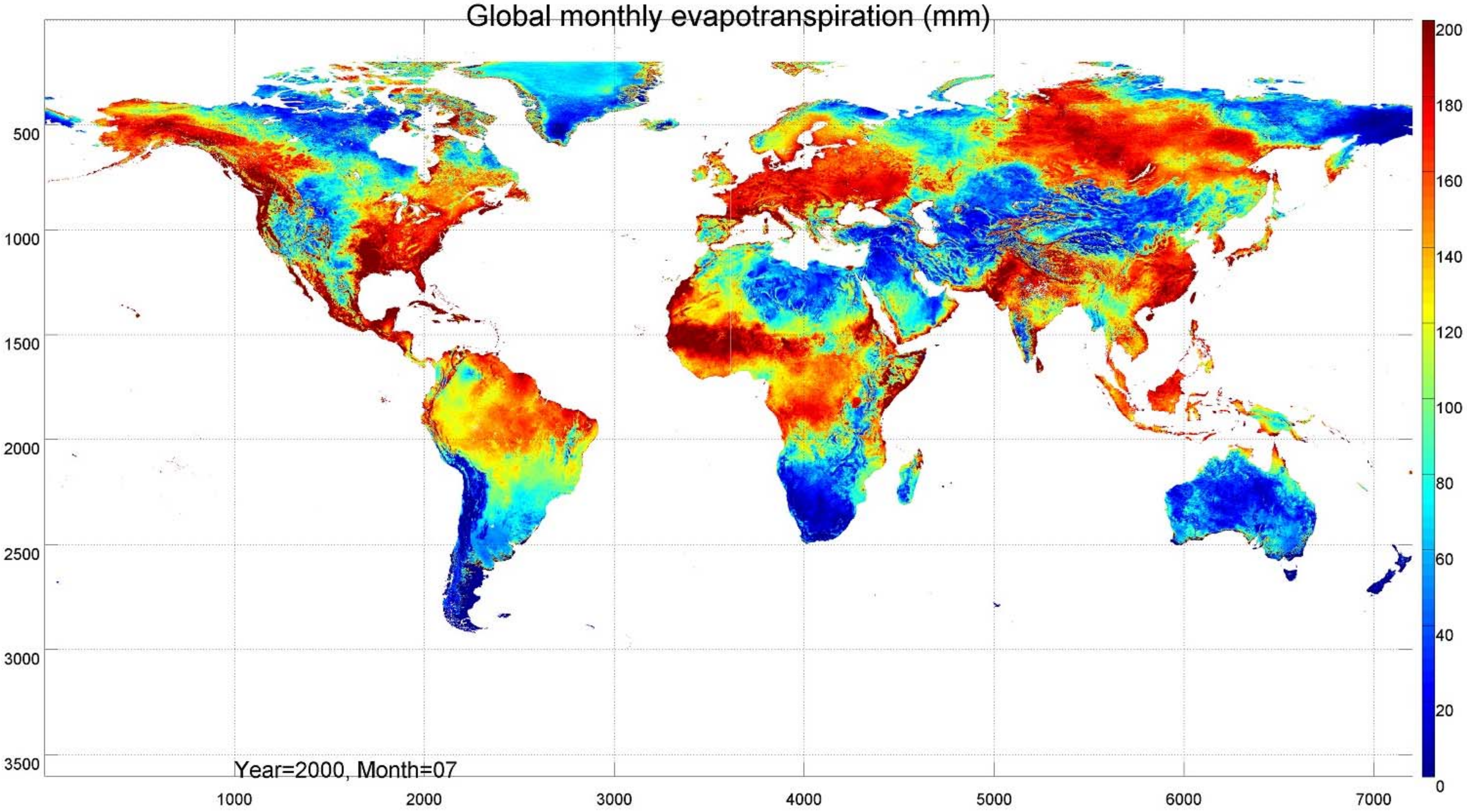
Seasonal average maps of sensible heat flux (H)

(a) Mar-May, (b) Jun-Aug,(c) Sep-Nov, (d) Dec-Feb

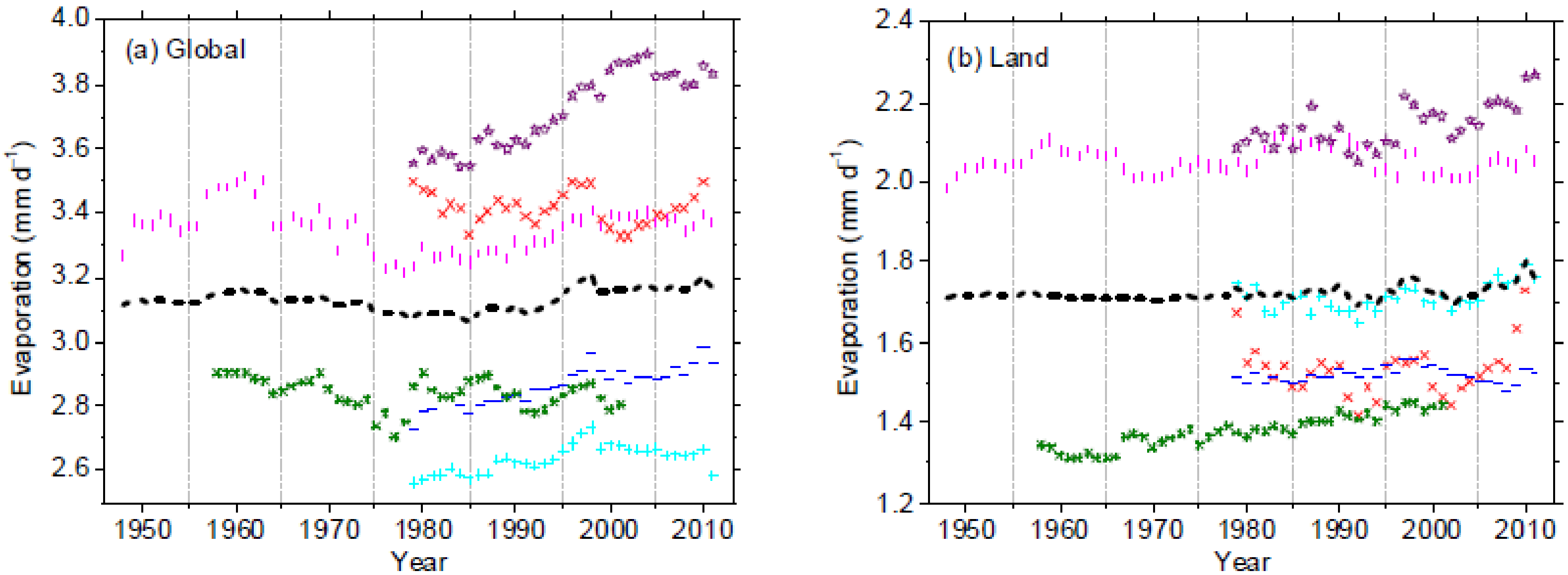


ITC SEBS DERIVED GLOBAL ENERGY & ET FLUXES

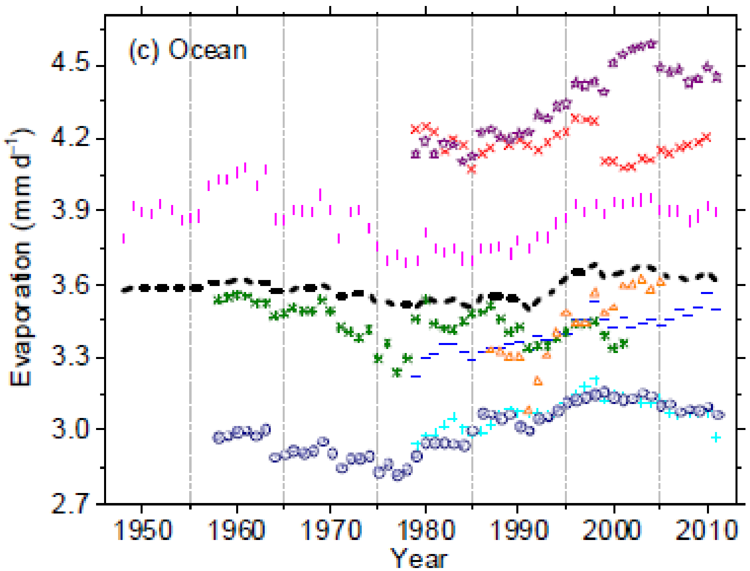
(2000 to near present at 5 km*5 km spatial resolution), data access: linkendin SEBS group



Global ET from land surface models in reanalysis data



Black dashed lines
indicate the average value.



Su et al. 2015

A global turbulent exchange parameterization scheme Momentum roughness length (z_{0m})

(a) z_{0m} scheme *without* vertical foliage density profile

$$\frac{z_{0m}}{h} = \left(\frac{1}{2n_{ec}} \times (1 - e^{-2n_{ec}})\right) \times e^{\frac{-k}{\frac{u_*}{u(h)}}}$$

$$n_{ec} = \frac{0.2 \times LAI}{2 \times (C_1 - C_2 \times \exp(-C_3 \times 0.2 \times LAI))}$$

$$\frac{u_*}{u(h)} = C_1 - C_2 \times \exp(-C_3 \times 0.2 \times LAI)$$

Input canopy information:
h: canopy height; LAI: leaf area index

Su, HESS 2002

(b) z_{0m} scheme *with* vertical foliage density profile

$$\frac{z_{0m}}{h} = \left(\frac{1}{2n_{ec}} \times (1 - e^{-2n_{ec}})\right) \times e^{\frac{-k}{\frac{u_*}{u(h)}}}$$

$$n_{ec} = \frac{\zeta(h)}{2 \times (C_1 - C_2 \times \exp(-C_3 \times \zeta(h)))}$$

$$\frac{u_*}{u(h)} = C_1 - C_2 \times \exp(-C_3 \times \zeta(h))$$

$$\zeta(z) = \int_0^z [C_d(z')a(z')/P_m(z')]dz'$$

Input canopy information:
h: canopy height; a: vertical foliage density

Massman, JH, 1999

Heat roughness length (z_{0h})

$$z_{0h} = \frac{z_{0m}}{\exp(kB^{-1})},$$

$$kB^{-1} = \underbrace{f_c{}^2 * kB_c^{-1}}_{\text{Canopy}} + \underbrace{f_s{}^2 * kB_s^{-1}}_{\text{Soil}} + 2 * \underbrace{f_c * f_s * kB_m^{-1}}_{\text{Canopy+Soil}},$$

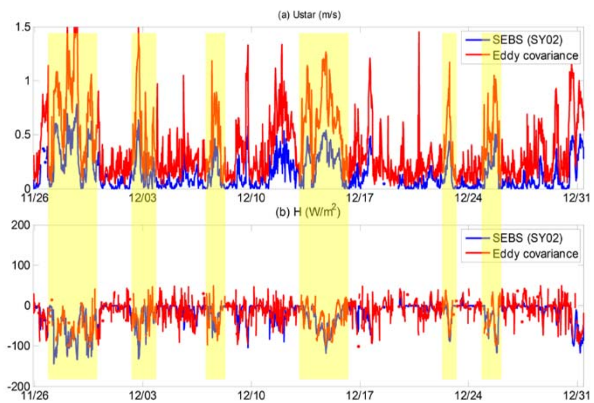
Su02
(Su, 2002,HESS)

$$z_{0hs} = \frac{70\,\vartheta}{u_*}\exp\left(-7.2\, u_*{}^{0.5}\theta_*{}^{0.25}\right),$$

$$kB_s^{-1} = \log\left(\frac{z_{0ms}}{z_{0hs}}\right),$$

Yang 02
(Yang et al.,2002,QJRMS)

Chen13
(Chen et al. 2013, JAMC)



kB_c^{-1} scheme (*with* vertical foliage density profile)

1

$$kB_c^{-1} = \frac{k \times C_d}{4C_t \frac{u_*}{u(h)}(1 - e^{-n_{ec}/2})}$$

$$\frac{u_*}{u(h)} = C_1 - C_2 \times \exp(-C_3 \times \zeta(h))$$

$$n_{ec} = \frac{\zeta(h)}{2 \times (C_1 - C_2 \times \exp(-C_3 \times \zeta(h)))}$$

$$\zeta(z) = \int_0^z [C_d(z')a(z')/P_m(z')]dz'$$

$$C_d(z) = C_d e^{-A2(1-z/h)}$$

$$P_m(z) = 1/(1 + 0.4\, h\, a(z))$$

$$a(z) = \frac{LAI}{h} \frac{\beta(\xi)}{\int_0^1 \beta(\xi)d\xi}$$

Su et al. 2001

$$\beta(\xi) = a1(1-\xi)(\xi - a2)exp(-a3(1-\xi))$$

2

$$kB_m^{-1} = \frac{k \frac{u_*}{u(h)} \times \frac{z_{0m}}{h}}{C_t^*}$$

$$\frac{z_{0m}}{h} = \left(\frac{1}{2n_{ec}} \times (1 - e^{-2n_{ec}})\right) \times e^{\frac{-k}{\frac{u_*}{u(h)}}}$$

$$C_t^* = \mathrm{P_r}^{-2/3} \times \mathrm{Re_*}^{-1/2}$$

$$\mathrm{Re}_* = h_s \times u_*/\vartheta$$

$$\vartheta = 1.327 \times 10^{-5}(p_0/p)(T/T_0)^{1.81}$$

$$\mathrm{P_r} = 0.71$$

Su et al. 2001

$$kB_s^{-1} = 2.46 \times (\mathrm{Re}_*)^{1/4} - \ln(7.4)$$

Su et al. 2001

3

$$kB_s^{-1} = \log\left(\frac{z_{0m\_s}}{z_{0h\_s}}\right)$$

$$z_{0h\_s} = \frac{70\,\vartheta}{u_*} \exp(-\beta * u_*^{0.5} * \theta_*^{0.25})$$

$$z_{0m\_s} = h_s$$

Chen et al. 2013

$$C_1, C_2, C_3, C_d, C_t, A2, a1, a2, a3, h_s$$

kB_c^{-1} scheme (*without* vertical foliage density profile)

1

$$kB_c^{-1} = \frac{k \times C_d}{4C_t \frac{u_*}{u(h)}(1 - e^{-n_{ec}/2})}$$

$$\frac{u_*}{u(h)} = C_1 - C_2 \times \exp(-C_3 \times 0.2 \times LAI)$$

$$n_{ec} = \frac{0.2 \times LAI}{2 \times (C_1 - C_2 \times \exp(-C_3 \times 0.2 \times LAI))}$$

Su 2002

2

$$kB_m^{-1} = \frac{k \frac{u_*}{u(h)} \times \frac{z_{0m}}{h}}{C_t^*}$$

$$\frac{z_{0m}}{h} = \left(\frac{1}{2n_{ec}} \times (1 - e^{-2n_{ec}})\right) \times e^{\frac{-k}{\frac{u_*}{u(h)}}}$$

$$C_t^* = \mathrm{P_r}^{-2/3} \times \mathrm{Re}_*^{-1/2}$$

$$\mathrm{Re}_* = h_s \times u_*/\vartheta$$

$$\vartheta = 1.327 \times 10^{-5}(p_0/p)(T/T_0)^{1.81}$$

$$\mathrm{P_r} = 0.71$$

Su 2002

$$kB_s^{-1} = 2.46 \times (\mathrm{Re}_*)^{1/4} - \ln(7.4)$$

Su 2002

3

$$kB_s^{-1} = \log\left(\frac{z_{0m\_s}}{z_{0h\_s}}\right)$$

$$z_{0h\_s} = \frac{70\,\vartheta}{u_*} \exp(-\beta * u_*^{0.5} * \theta_*^{0.25})$$

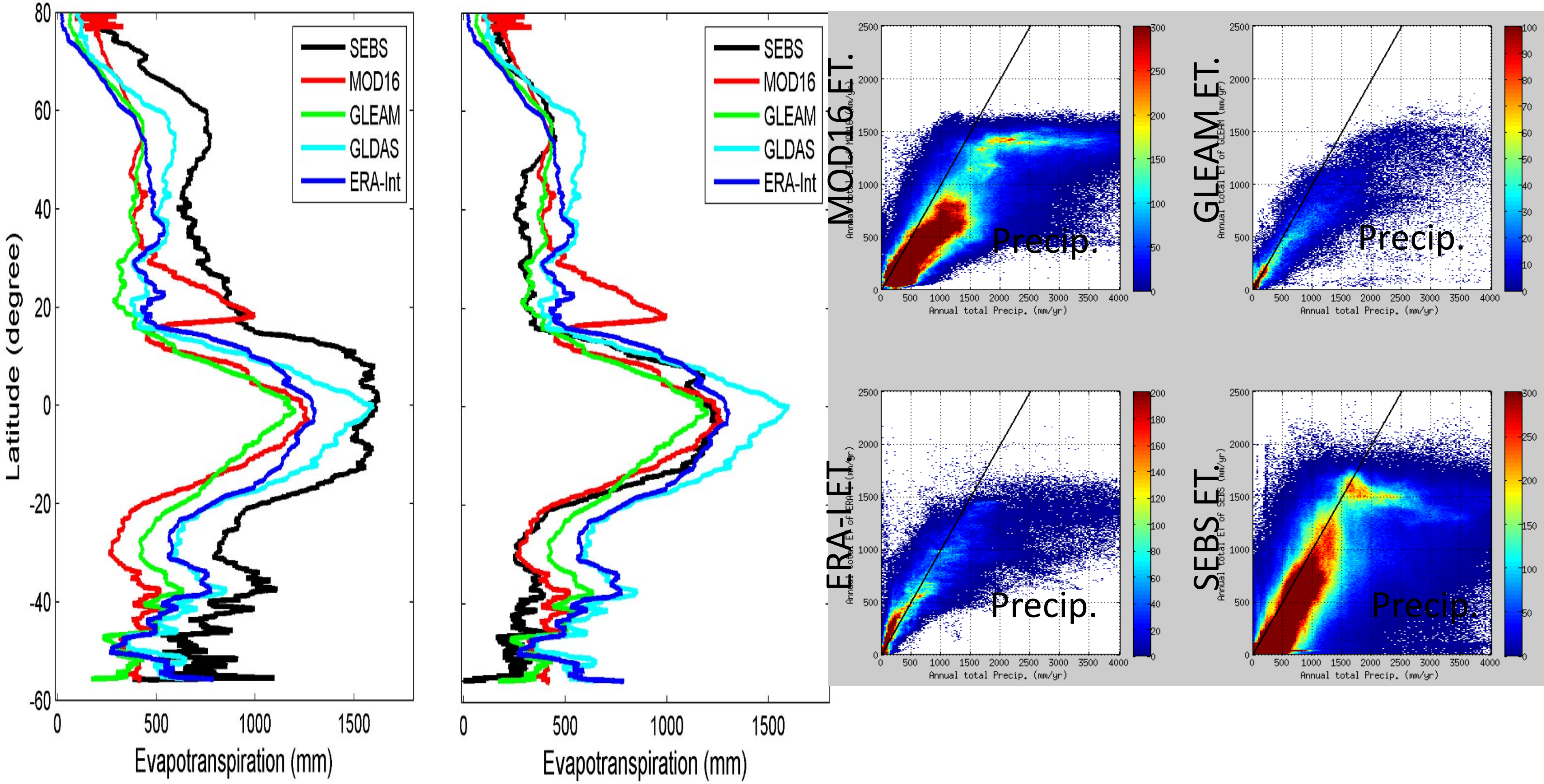
$$z_{0m\_s} = h_s$$

Chen et al. 2013

$C_1, C_2, C_3, C_d, C_t, h_s$

Global ET evaluation

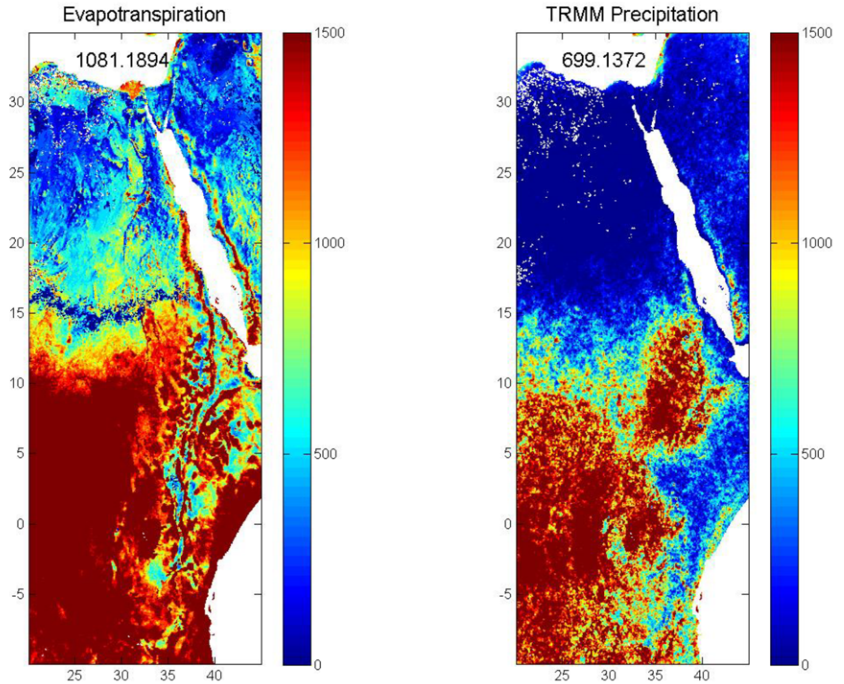
Old version　　　　Version 1



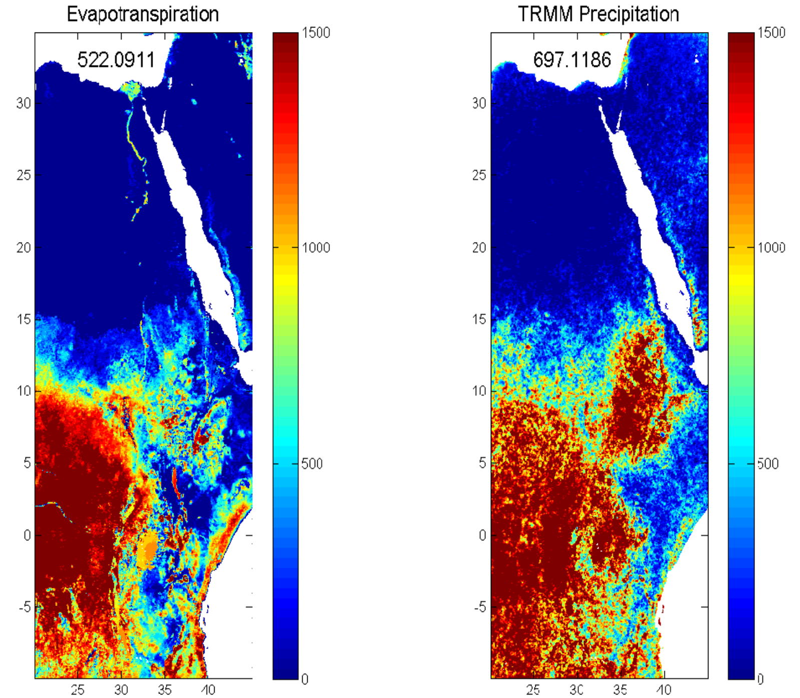
Old version—turbulent exchange parameterization scheme in Chen et al. 2013

Version 1—optimized turbulent exchange parameterization scheme (Chen et al. 2017)

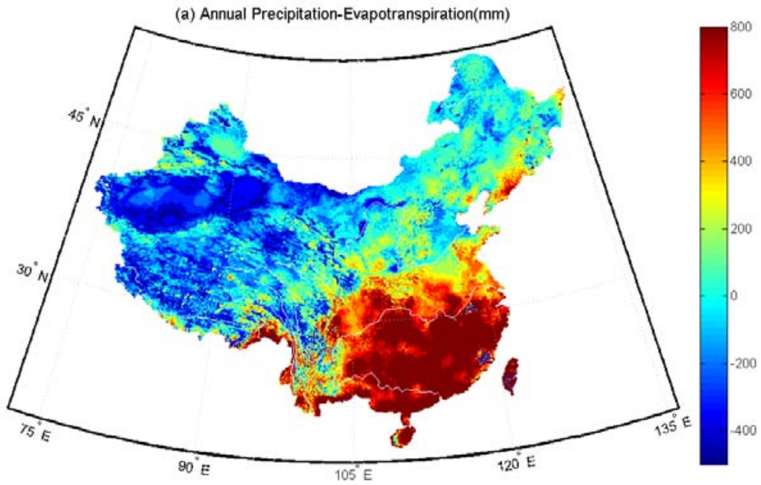
Old version



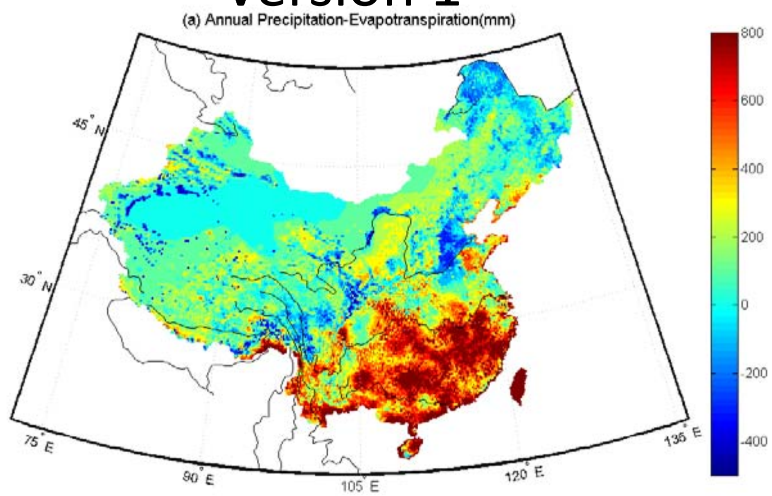
Version 1



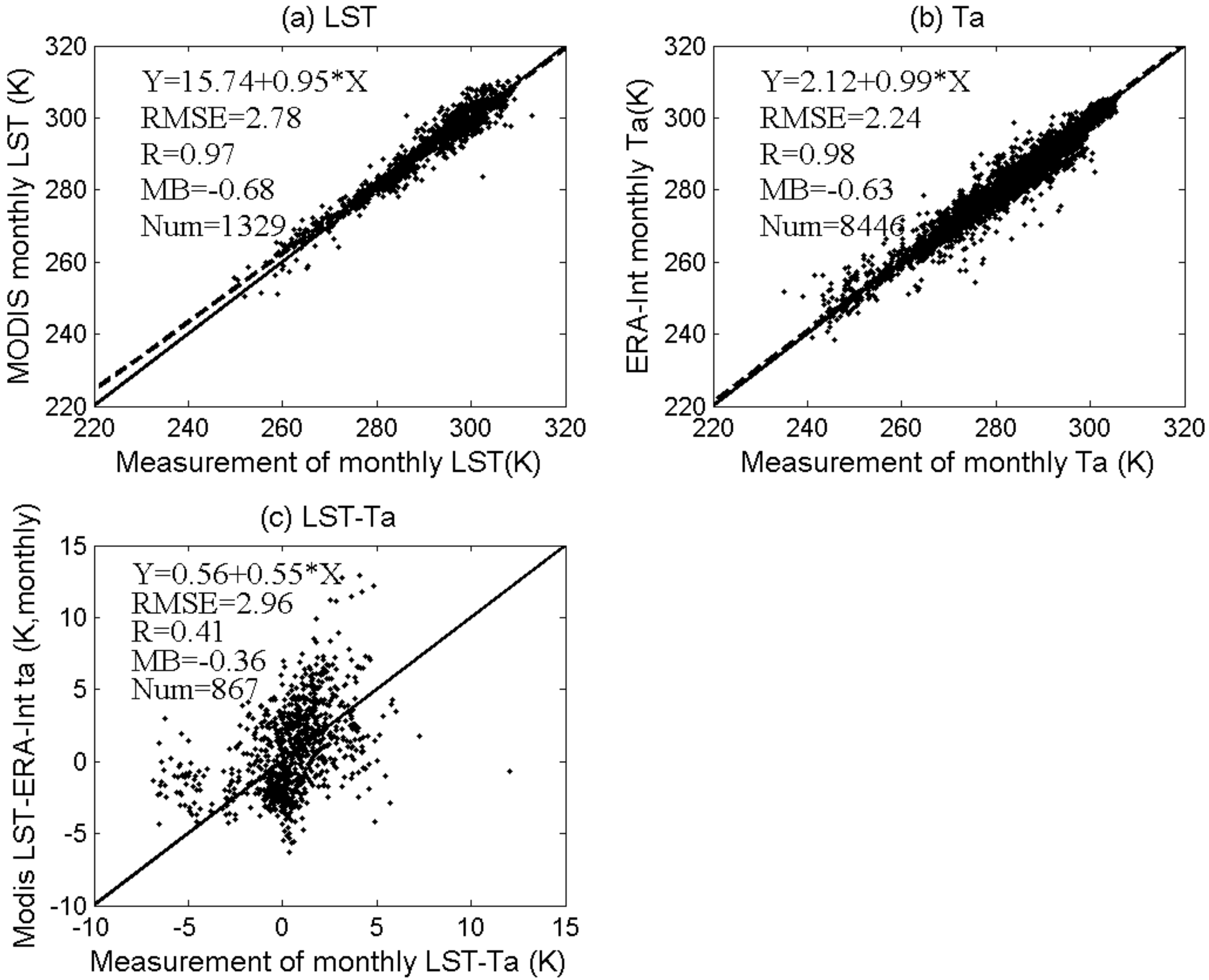
Old version



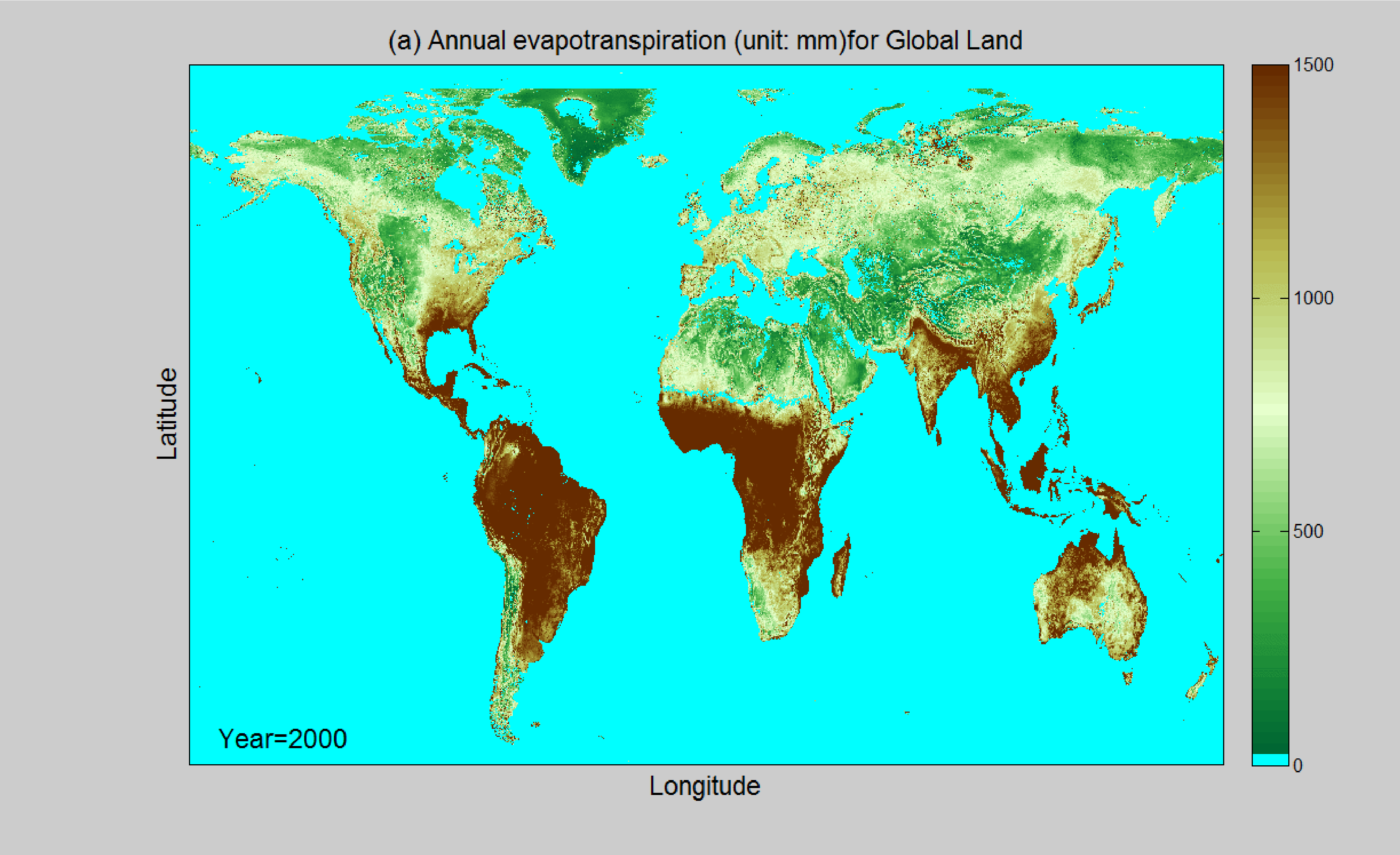
Version 1



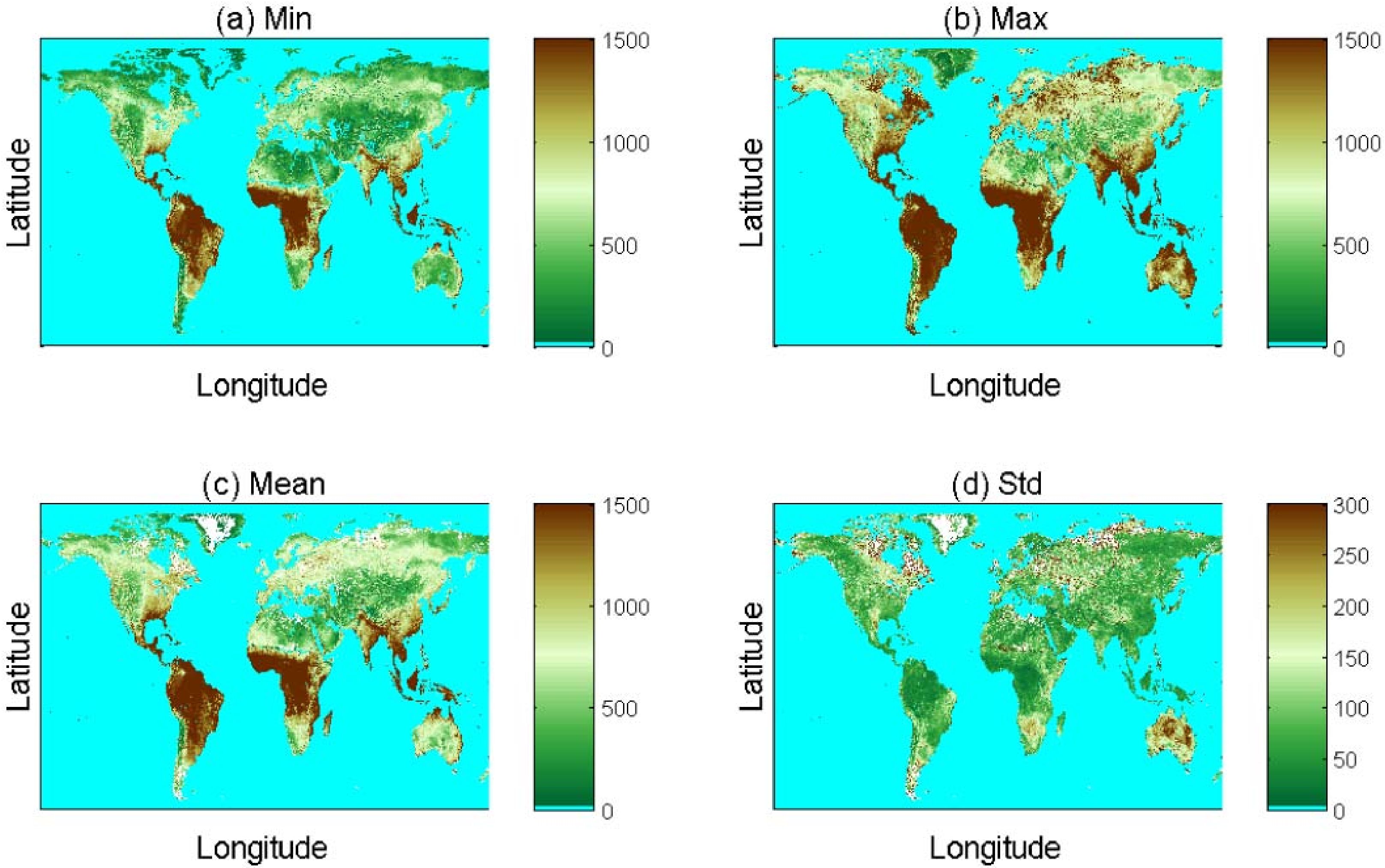
Source of uncertainty in the global flux data



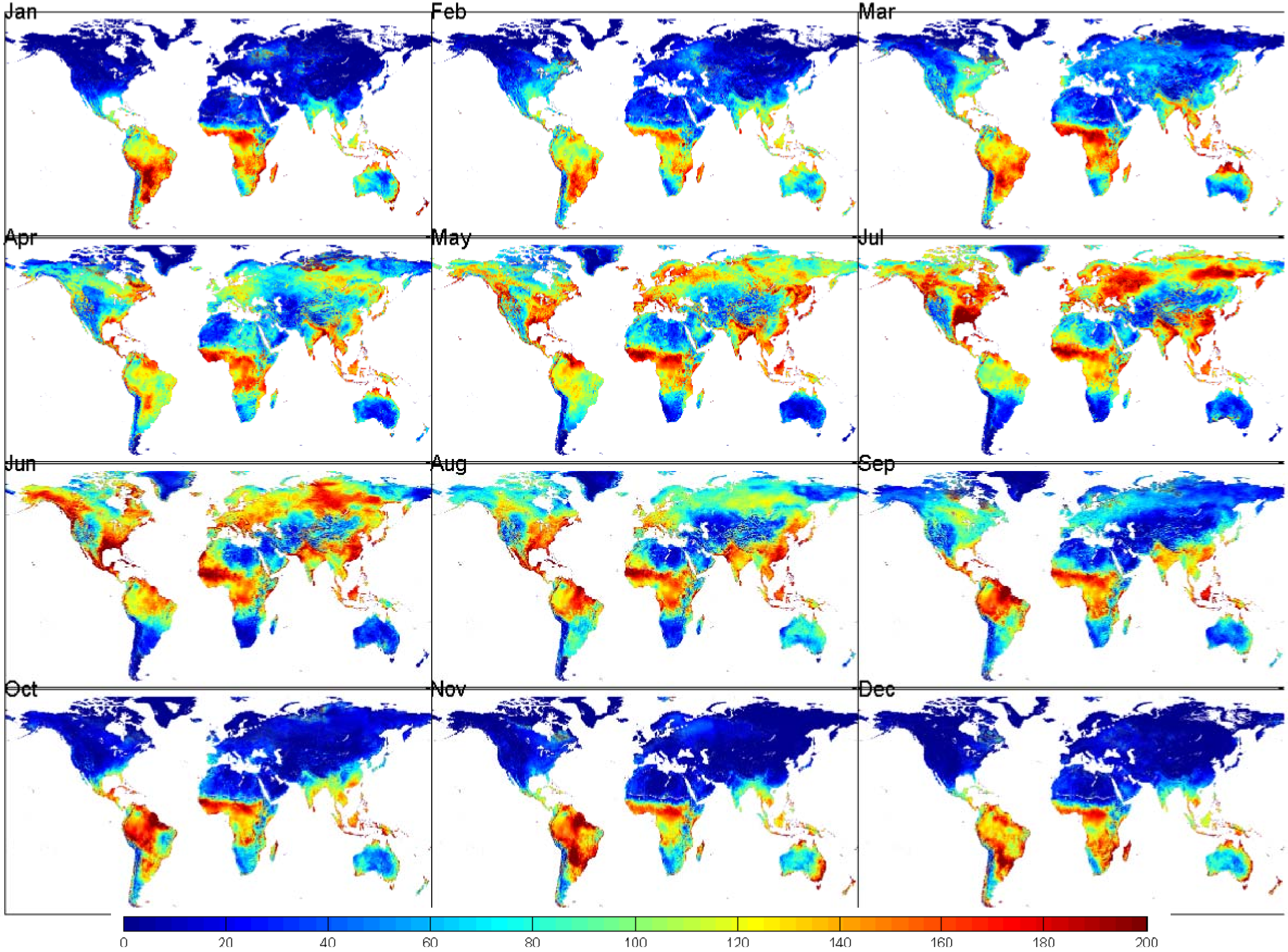
Global ET estimate



Multi-year statistical analysis (2001-2010) of annual evapotranspiration for global land



Global land monthly ET(mm) in 2008



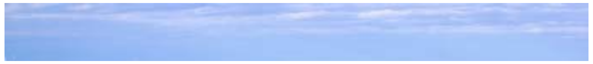
Hot or Not? WATER CYCLE & URBAN CLIMATE CHANGE

- **Improving the quality of life by improving understanding of water cycle and urban energy cycle processes**
- Twente site(s): measurements over a “coulissen” landscape:

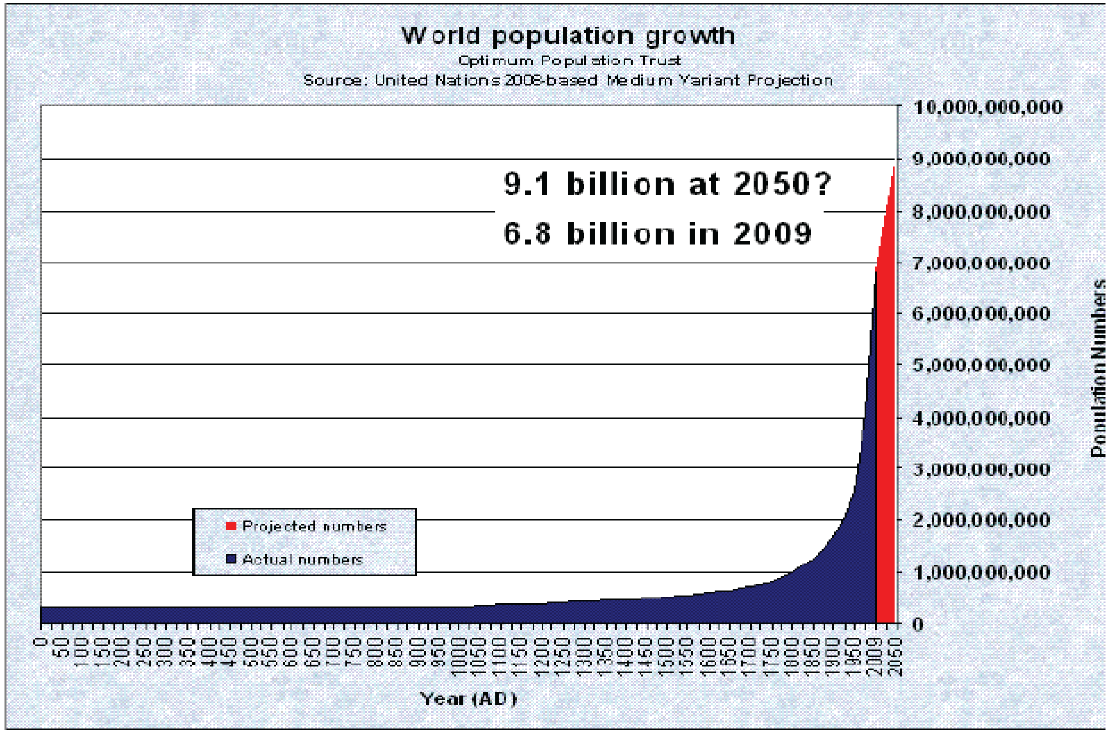
“typical landscape patterns”

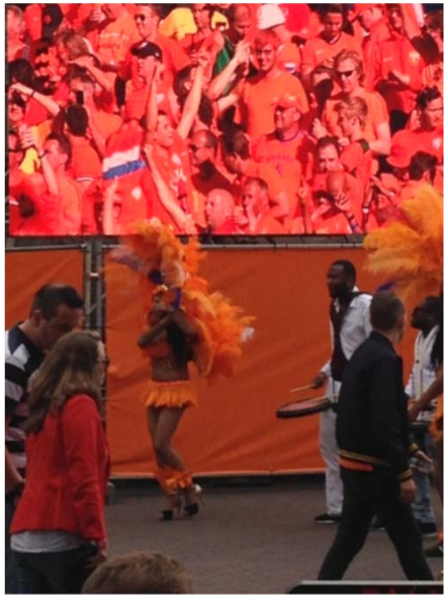
- Over an urban area:

urban heat (island)



1AD	0.3b
1650	0.5b
1800	1.0b
1927	2.0b
1960	3.0b
1975	4.0b
1987	5.0b
1998	6.0b
2011	7.0b





(W. Timmermans)

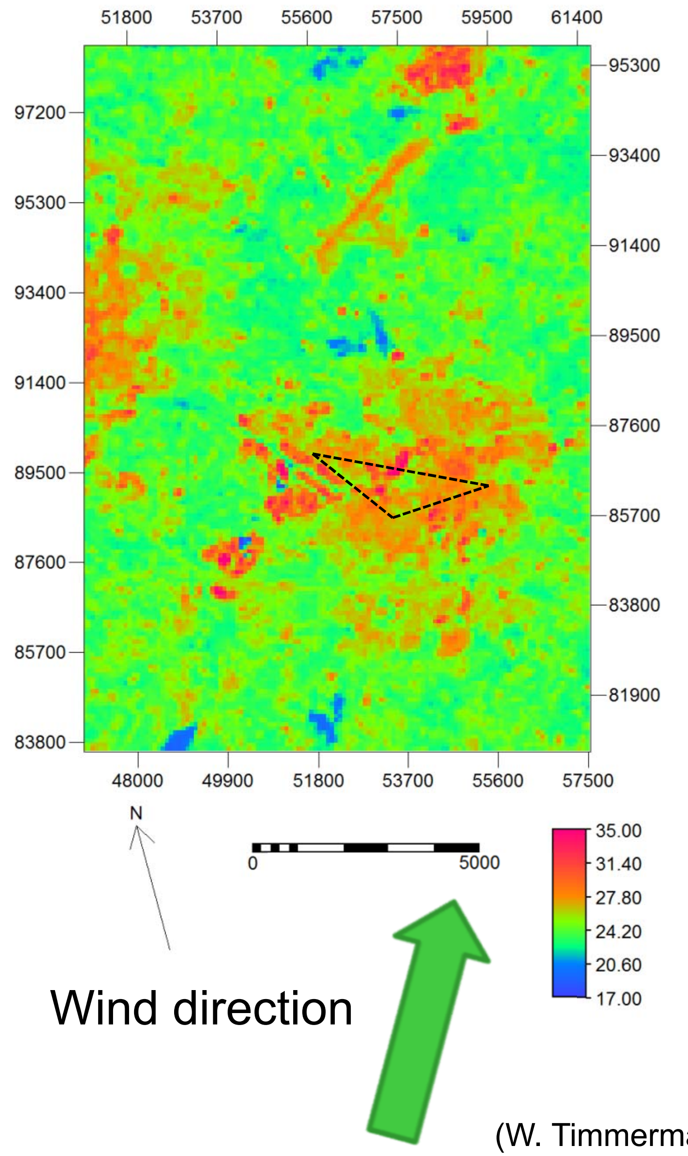
EO sites: why, where & what?

Drivers

- Rapid urbanization, e.s. in devel. countries.
- 70% of the projected 9 billion population by 2050 in cities.
- More intensive land, water and other resources use in cities.
- Climate change posts extra challenges in the urban water and climate
- Adaption to climate change and enhanced human activities

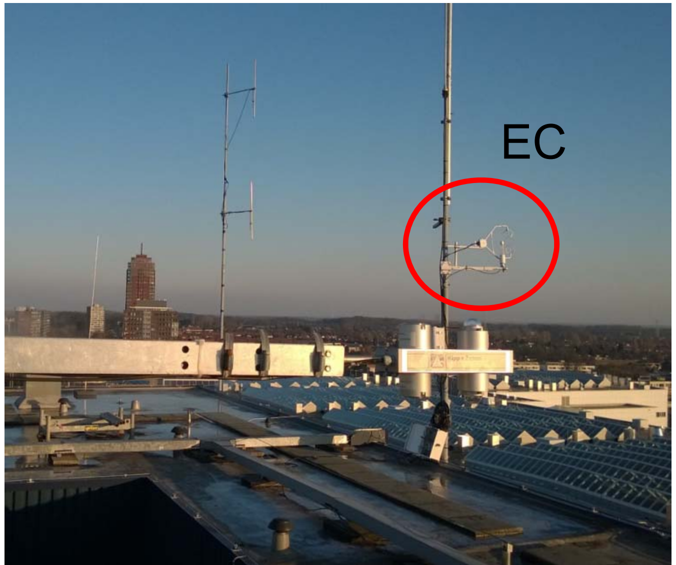
Demand: better water management, land use/city planning and env. Manag., all require fundamental knowledge of the water and energy cycle in cities.

- LST Enschede and surroundings - ASTER image, 12 Sept 2006, (11:45 LT)



(W. Timmermans)

Instruments at ITC Hotel



Twente sites: Where/What?

U01: ITC Hotel (85 m)

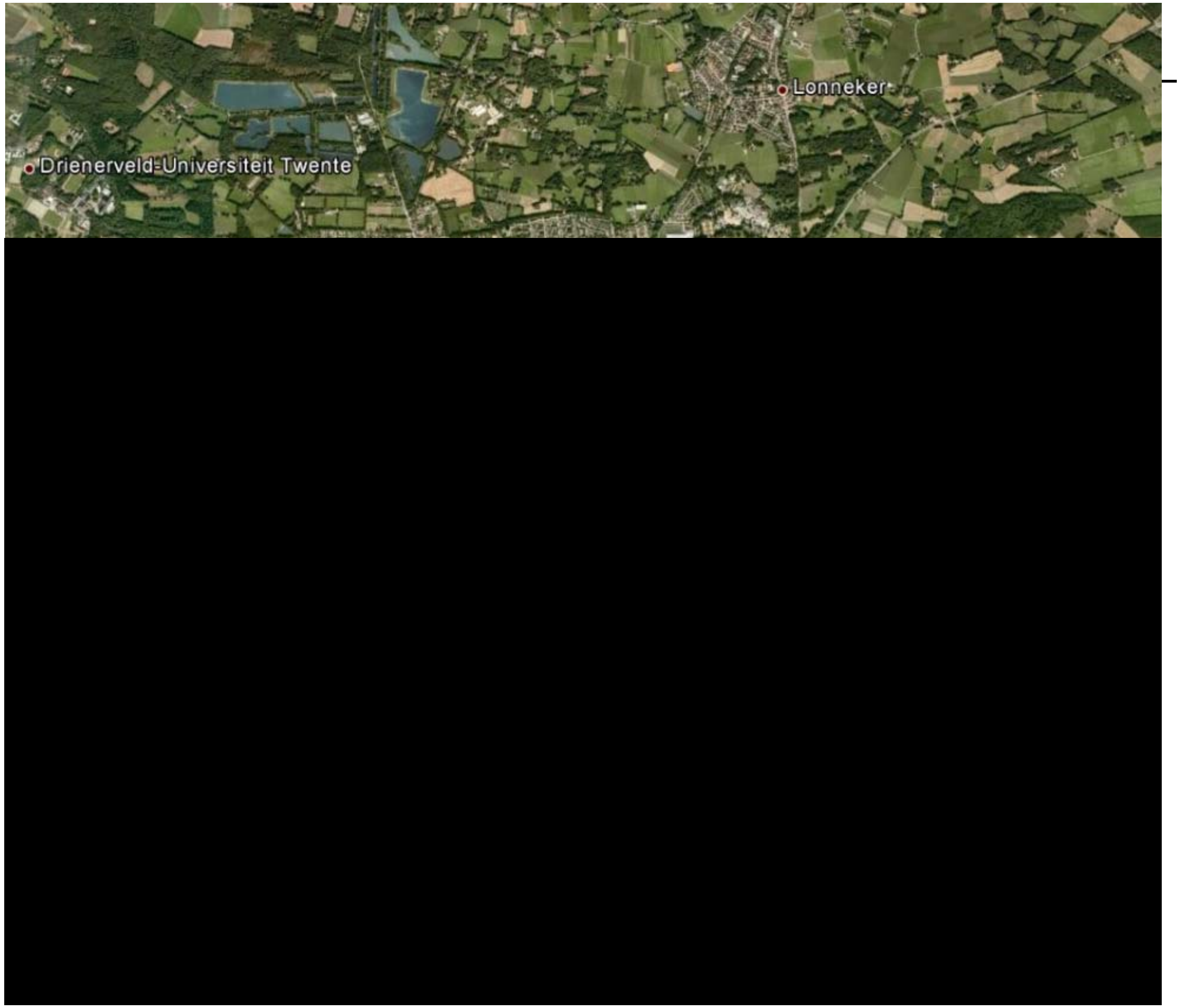
- ❑ Instrument:
- ✓ EC: CSAT3+Li-7500
- ✓ Net-Radiometer:CNR1
- ✓ Weather Station:WXT520
- ✓ Thermal Camera: NEC TH9100
- ✓ Data logger: CR5000

U02: Horst (82 m)

- ❑ Instrument:
- ✓ XLAS Receiver
- ✓ Wind Sonic 1
- ✓ Data logger: CR3000

U03: Esmarke (84m)

- ❑ Instrument:
- ✓ XLAS Transmitter



20150218 15:12 to 16:16

UNIVERSITY OF TWENTE.

(J. Du &W. Timmermans)

Conclusions

– The Surface Energy Balance System (SEBS) for estimation of heat fluxes and evaporation is briefly introduced.
– SEBS is scale invariant, so that it can be applied easily to different scales. Data of high or low spatial resolution from all sensors in the visible, near-infrared and thermal infrared frequency ranges can be used in the system.
– Based on a set of case studies, SEBS has proven to be capable to estimate turbulent heat fluxes and evaporation from point to continental (global) scale with acceptable accuracy.
– Some recent experiments are introduced – the data are accessible.
– The new urban hydroclimate study is introduced.

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