Multi-site modeling of land surface-atmosphere exchanges at the extent of an agricultural Mediterranean region

Carlo Montes

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March 18, 2015

Results from the PhD Thesis presented at University of Montpellier, France

Background

2015: NPP research fellow
"Evaluating vegetation albedo for a clumped, multi-level canopy radiative transfer scheme and impacts on simulated primary productivity and GISS GCM climate"

2014: **PhD. Environmental Physics,** University of Montpellier, France
Institute of Research for Development (IRD)

2011: **MSc. Terrestrial Biosphere Sciences,** University of Paris VI (UPMC), France

2008: **MSc. Atmospheric Sciences,** University of Chile

2006: **Agricultural Engineer,** University of Chile

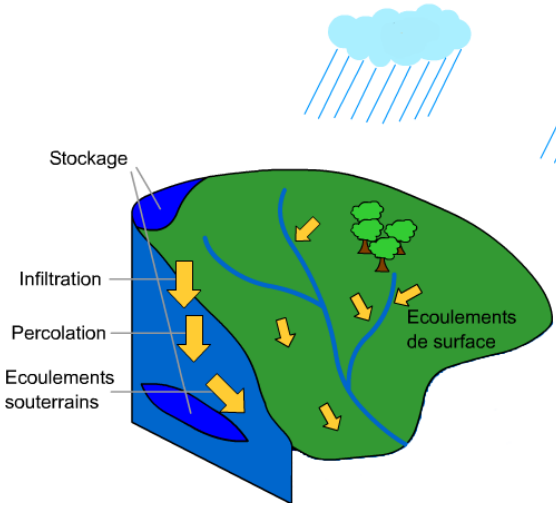
2004: **BSc. Agronomy (Soil Sciences),** University of Chile

Research interests: Biometeorology; Biosphere-Atmosphere Coupling; Land Surface Modeling; Remote Sensing Data Assimilation; Agriculture and Climate Variability

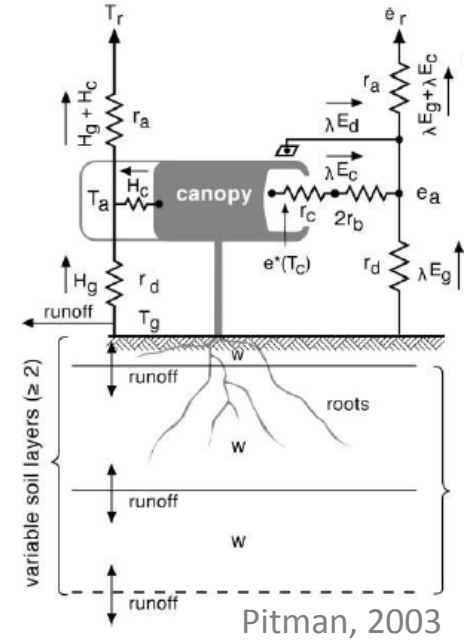
General motivation

Understanding of processes at the Soil-Vegetation-Atmosphere interface

- **Hydrology**
  - Surface water content: runoff/infiltration/floods
  - Root zone: soil/groundwater
  - Semiarid climate: ET ≈ 2/3 annual rainfall
- **Agriculture and ecosystems**
  - Link CO_2 and transpiration
  - Productivity: quantity and quality
- **Meteorology/climatology**
  - Surface boundary conditions
  - Land surface/atmosphere coupling
- **Climate change**
  - Pressure on water use: competition



Land surface in climate/hydrology modeling



Pitman, 2003

Representation of:

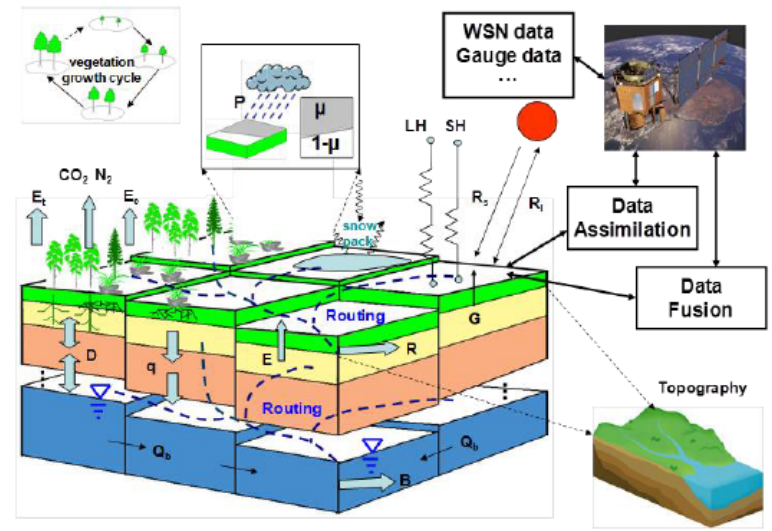
- Surface energy balance (LE, H, G)
- Surface water balance (ET, runoff, storage)
- Momentum balance (wind)
- Carbon and VOC fluxes

Feedbacks in terms of:

- Ecosystems/agriculture and water resources
- Atmospheric composition

Varying complexity:

- Processes: e.g. H20 and/or CO_2
- Number of exchange sources: vegetation, soil…
- Coupling: meteorology/hydrology models



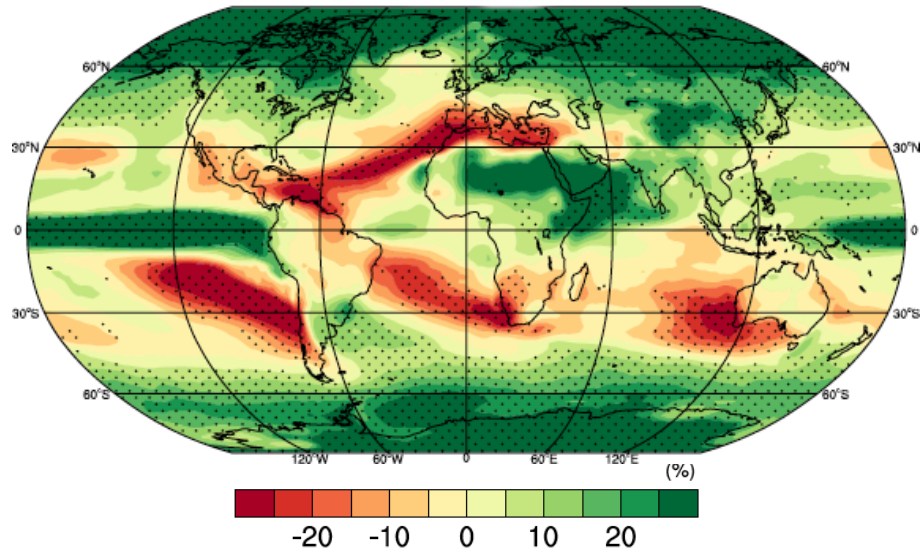
Prentice et al., 2014

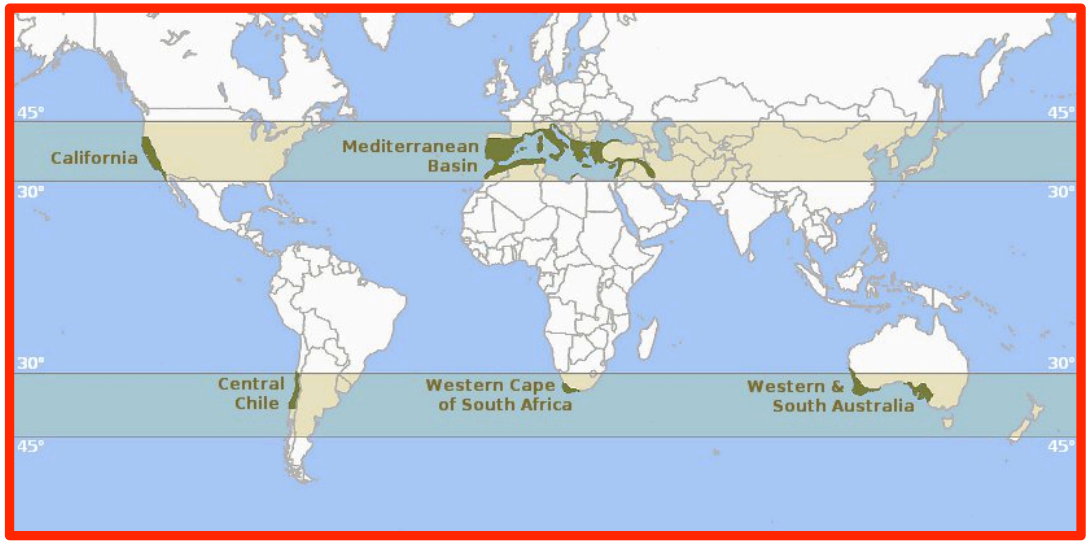
Importance for Mediterranean regions

Hot/dry season
Cool/wet season
5% Earth surface
Biodiversity hotspots
Dense population
Intense agriculture

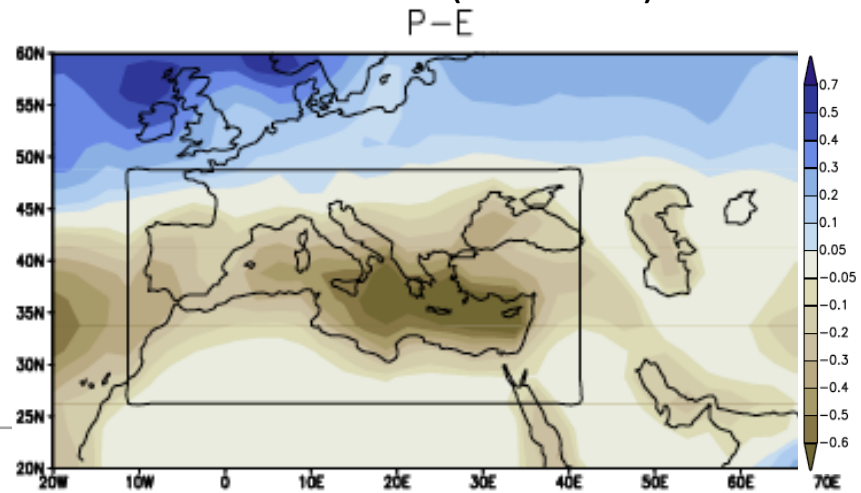
Mediterranean Basin
California
Central Chile
Southern Africa
Southern Australia

Multi-model ensemble: annual precipitation change (end c.XXI)





Annual water balance
Wet season (end c.XXI)



Objective and research questions

Quantify the water flow in the soil-plant-atmosphere
over a Mediterranean agricultural region,
considering the vegetation cycle and in a multi-site perspective

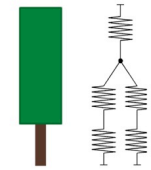
Research questions:

- Modeling approach/formalism for the study area?
- What model to be used in a multi-site perspective and for the vegetaiton cycle?
- How to get realistic simulations?
- How to spatialize (multi-site) simulations by using remote sensing?

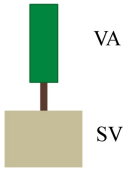
Approach

1

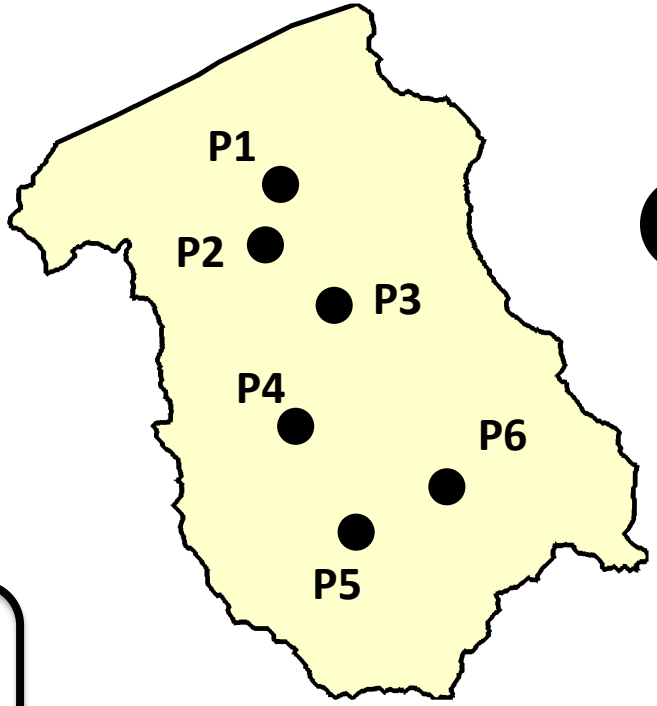
Plot scale :
Model development



Question 1: formalism

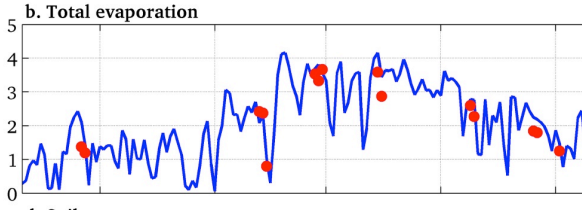


Question 2: modeling



2

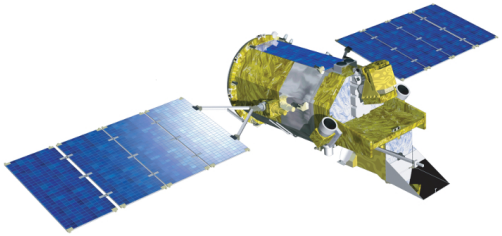
Plot scale : stochastic calibration



Question 3: realistic simulations

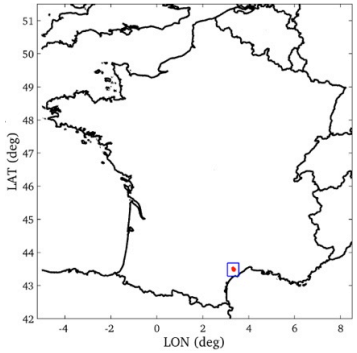
3

Regional extension

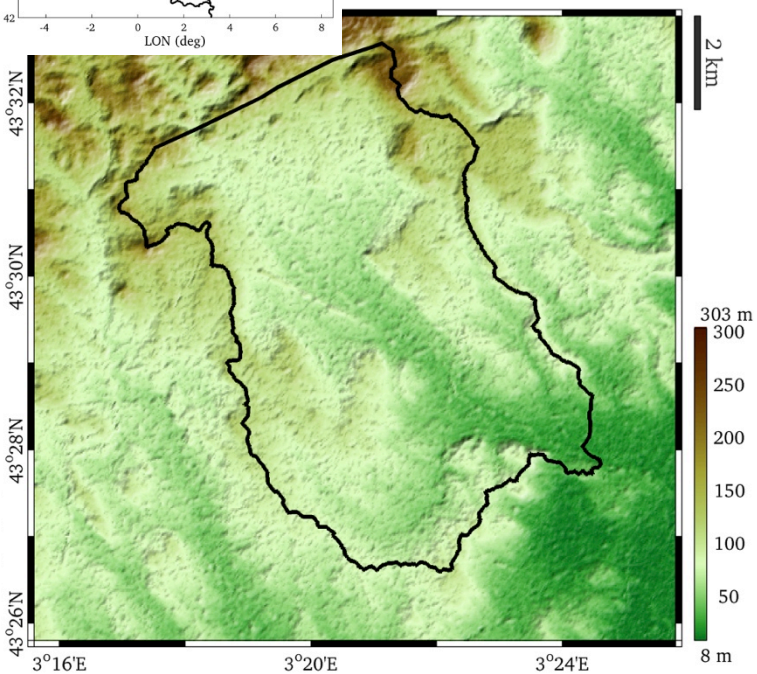


Question 4: spatial extent by remote sensing

Materials: study site location

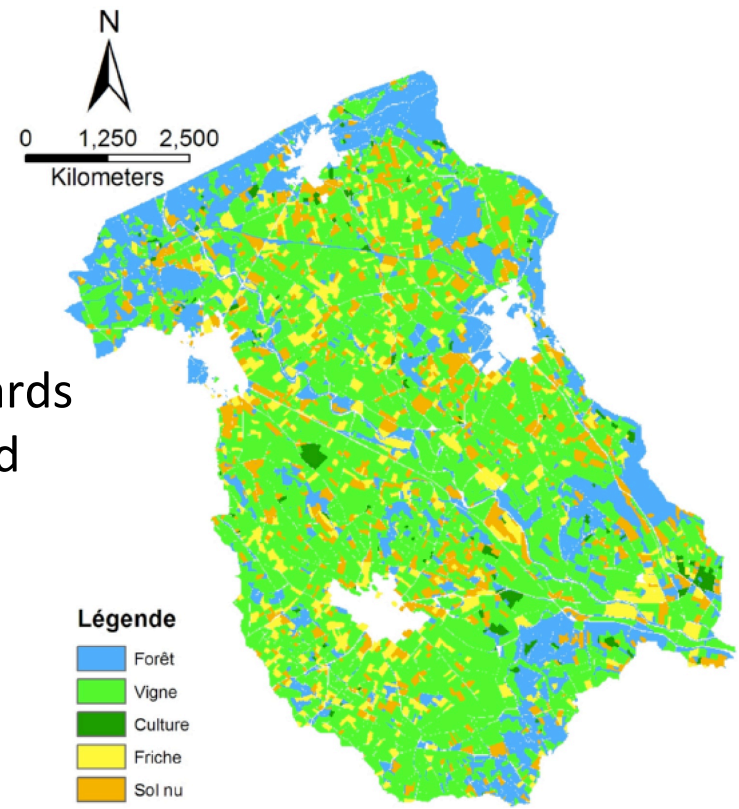


La Peyne watershed (65 km^2)
Département de l'Hérault
Southern France



Sub-humid Mediterranean climate
Rainfall = 720 mm y^{-1}
ETP = 1270 mm y^{-1}

70% vineyards
90% rainfed



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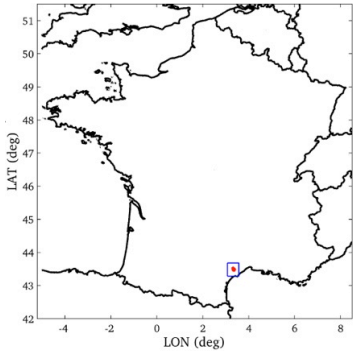

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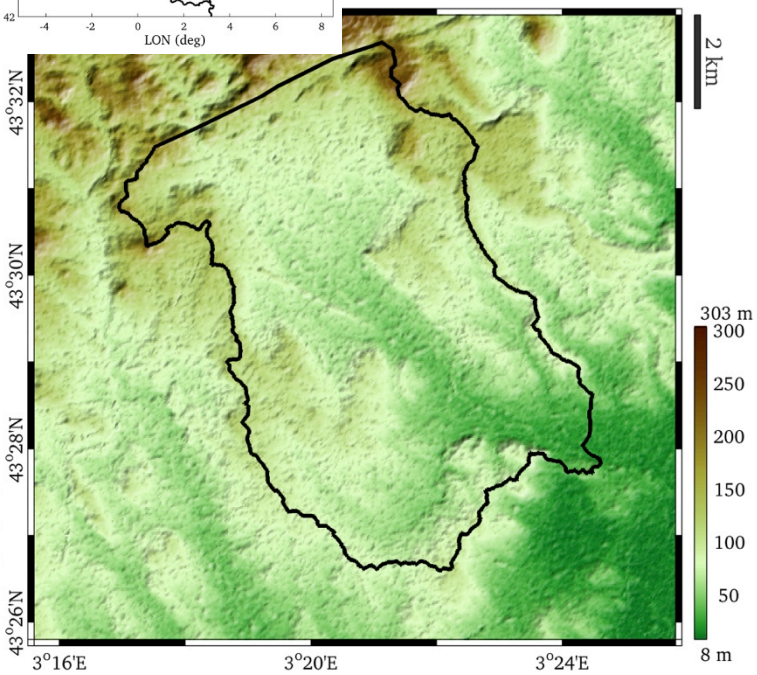

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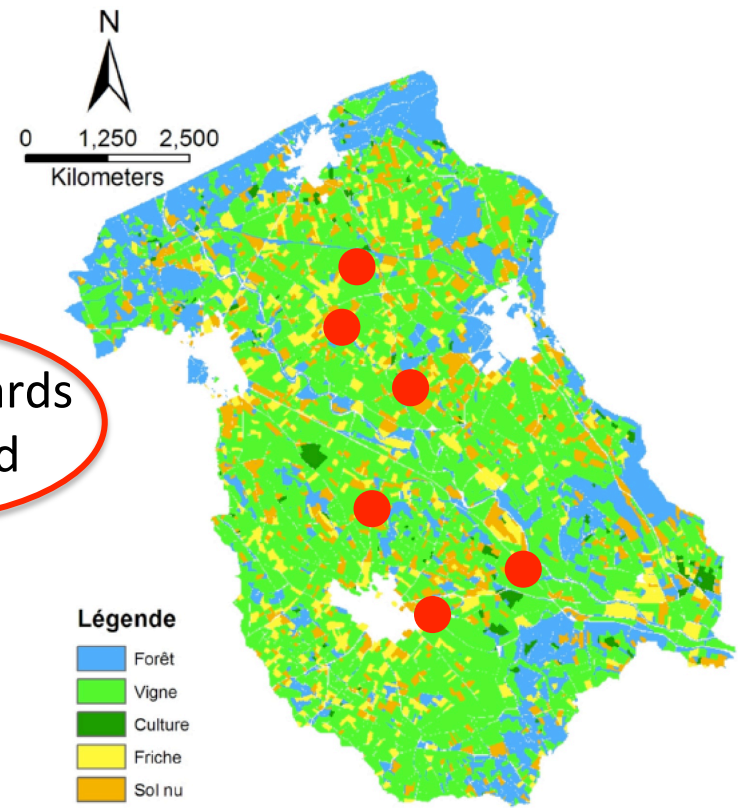


Materials: study site and water conditions

Moderately deep soils

Intermittent watertable

2 sites intermediate conditions

Shallow soils

Absent watertable

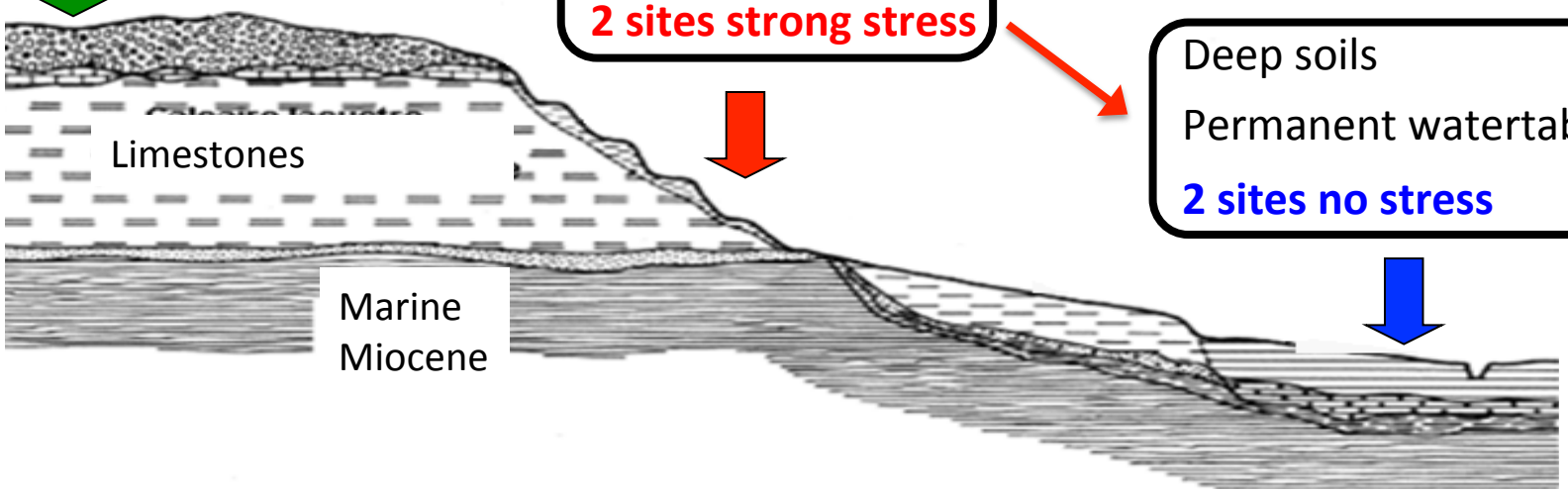
2 sites strong stress

Deep soils

Permanent watertable

2 sites no stress

Topo-séquence typique

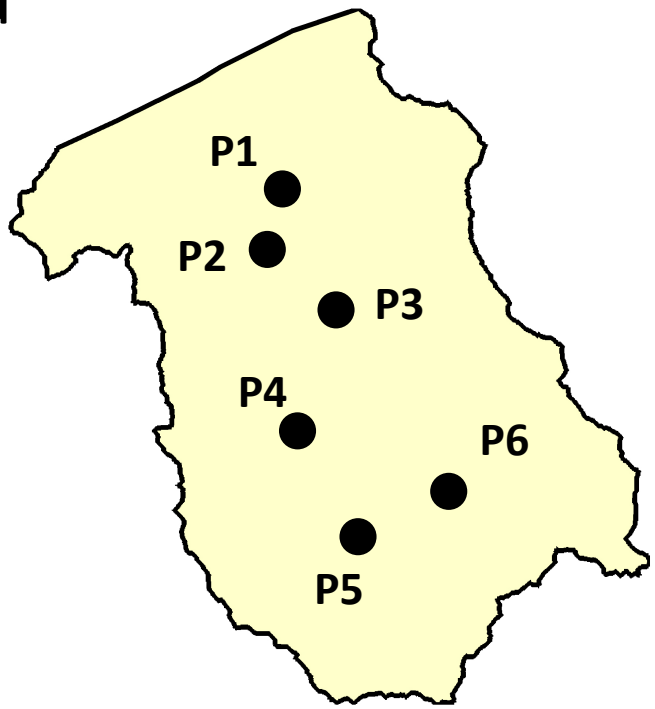


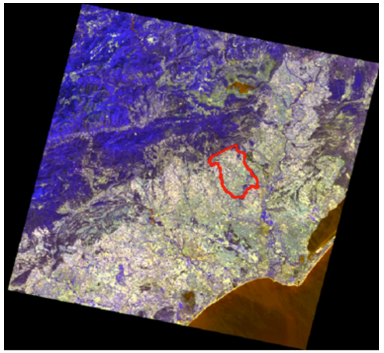
Materials: in-situ data

1) Meteorological data: **P4**
2) Eddy covariance station: **P6**
3) Soil moisture, vegetation (height, LAI), watertable: **P1-P6**
4) Satellite data

   ASTER 11 images 2007-2008 (90 m TIR)

   Landsat 7 ETM+ 12 images 2007-2008 (60 m TIR)

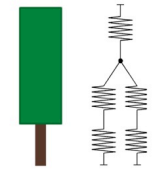




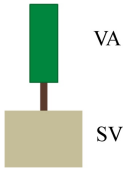
Modeling: implementation and results

1

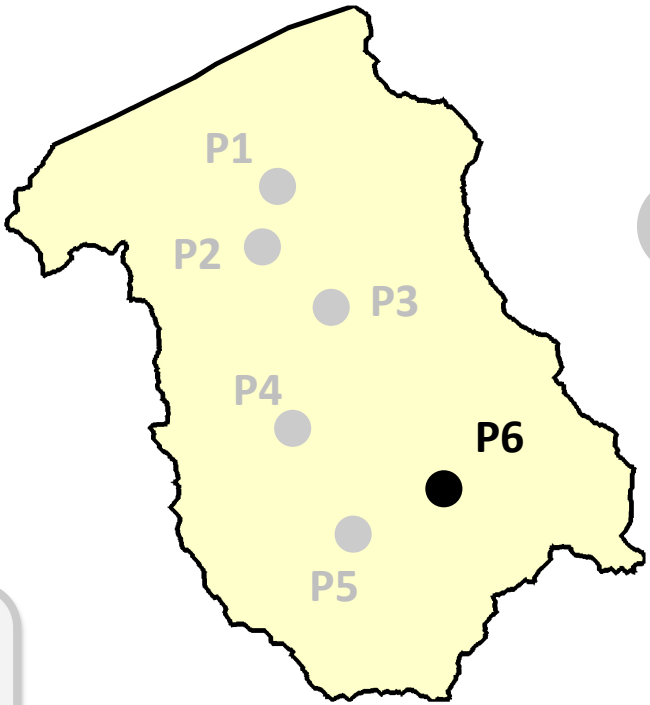
Plot scale :
Model development



Question 1: formalism



Question 2: modeling



2

Plot scale: stochastic calibration

Question 3: realistic simulations

3

Regional extension

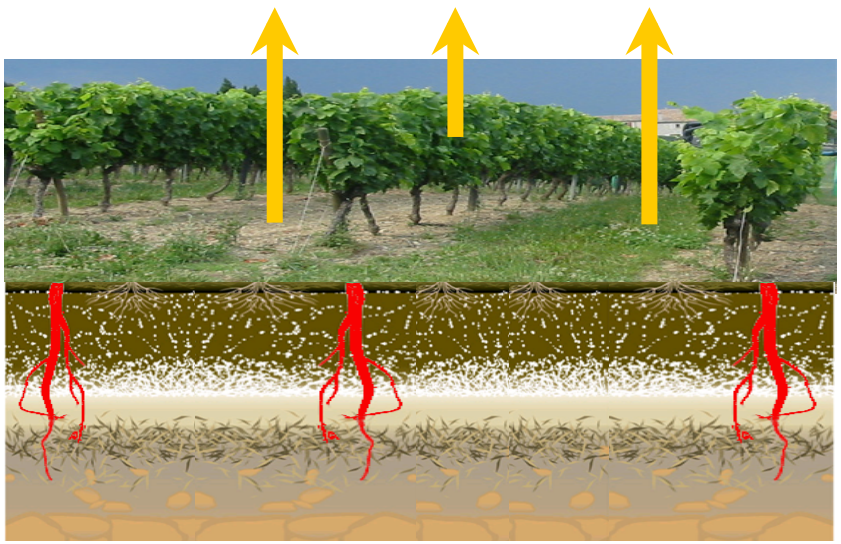
Question 4: remote sensing

Modeling approach

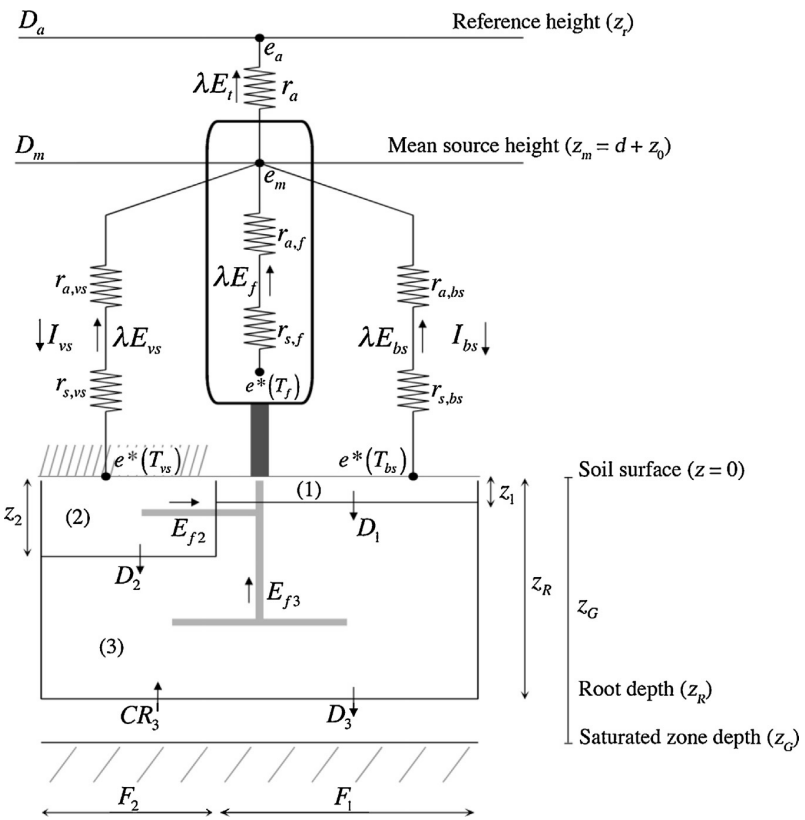
Discontinuous plant structures

- Bare soil / grazing / main foliage
- Deep rooting
- Seasonality in SPA fluxes

ET main component to simulate

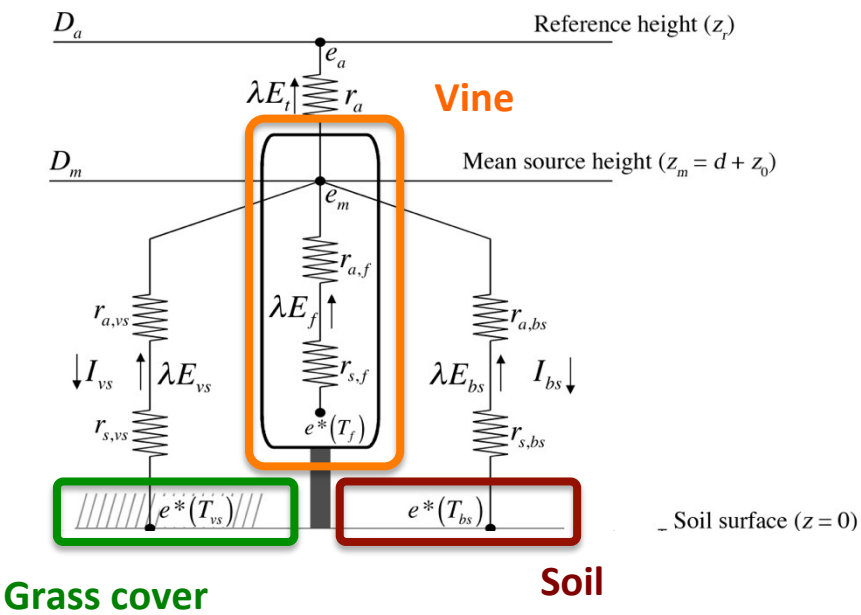


Multi-source Formalism



- Parsimonious modeling: compromise
- Module vegetation / atmosphere
- Module sol / végétation

Model: vegetation/atmosphere



- Energy balance: 3 sources

$$R_n - G = H + \lambda E$$

- Rn and G: F(relative area)
- ET: Penman-Monteith eqs. 3 sources

$$\lambda E_i = \frac{\Delta A_i + \rho c_p D_m / r_i}{\Delta + \gamma(n + r_{s,i}/r_{s,i})}$$

- At reference-level: F(total ET)

$$D_m = D_a + \frac{[\Delta A - \lambda E_t(\gamma + \Delta)]\, r_a}{\rho c_p}$$

Evapotranspiration model

Formulation for total evapotranspiration

- Some errors in literature: layer v/s patch approach
- Foliage characteristics
- Climatic demand (λE_p)
- P_i resistance combinations

$$\lambda E_t = \left(\frac{\Delta + \gamma}{\gamma}\right)(P_f + P_{vs} + P_{bs})\lambda E_p + \frac{\Delta}{\gamma}\frac{(P_f r_{a,f,h} A_f + P_{vs} r_{a,vs} A_{vs} + P_{bs} r_{a,bs} A_{bs})}{r_a}$$

- Generalized to *n* exchanging sources

$$\lambda E^n = R_0 \left(\sum_{i=1}^{n} P_i\right) \lambda E_p + \left(\frac{\Delta}{\gamma}\right) \sum_{i=1}^{n} P_i A_i r_{a,i}$$

JH, 2013

Model: revisiting evapotranspiration formalism

Stomatal distribution

- Hypo- v/s amphistomatic foliage
- Different formulations

Example 2-source model: PM equations applied to foliage (*f*) and soil (*s*)

$$\lambda E_t = \lambda E_f + \lambda E_s$$

$$\lambda E_t = \frac{\Delta A_f + \rho C_p D_m / r^f_{a,h}}{\Delta + \gamma(n + r^f_s / r^f_{a,h})} + \frac{\Delta A_s + \rho C_p D_m / r^s_a}{\Delta + \gamma(1 + r^s_s / r^s_a)}$$

n = 1 amphistomatic

n = 2 hypostomatic

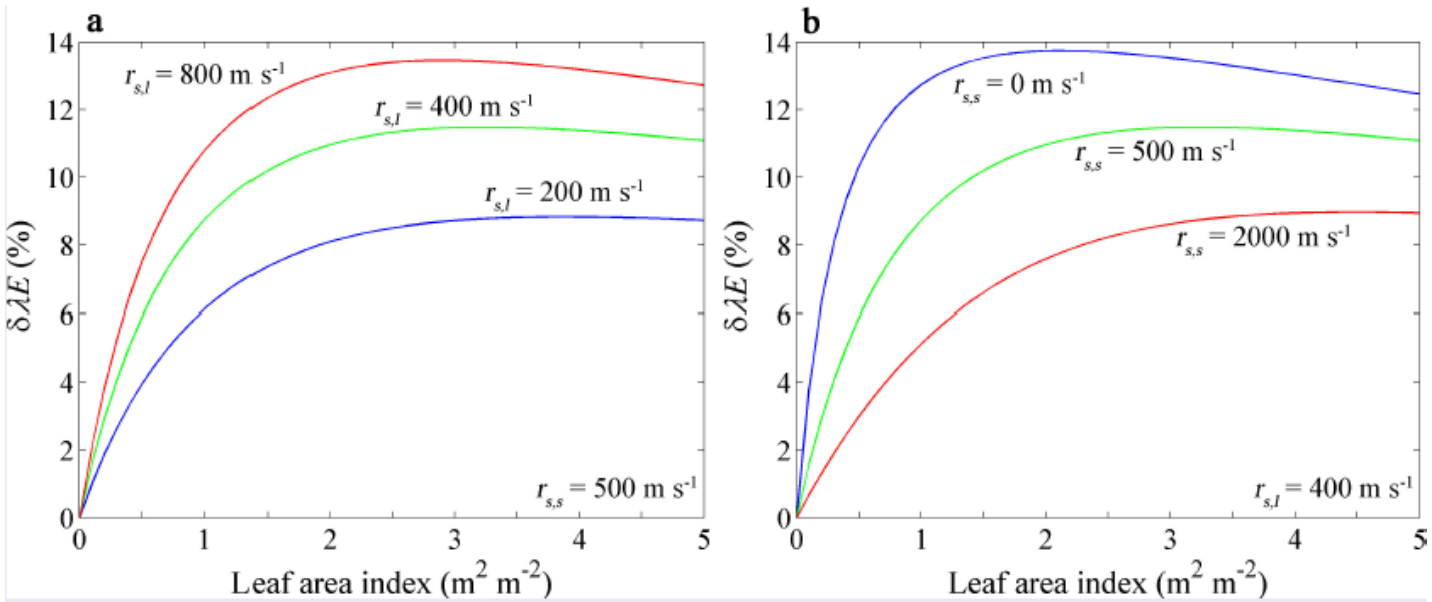
BLM, 2013

Model: revisiting evapotranspiration formalism

Case of vines

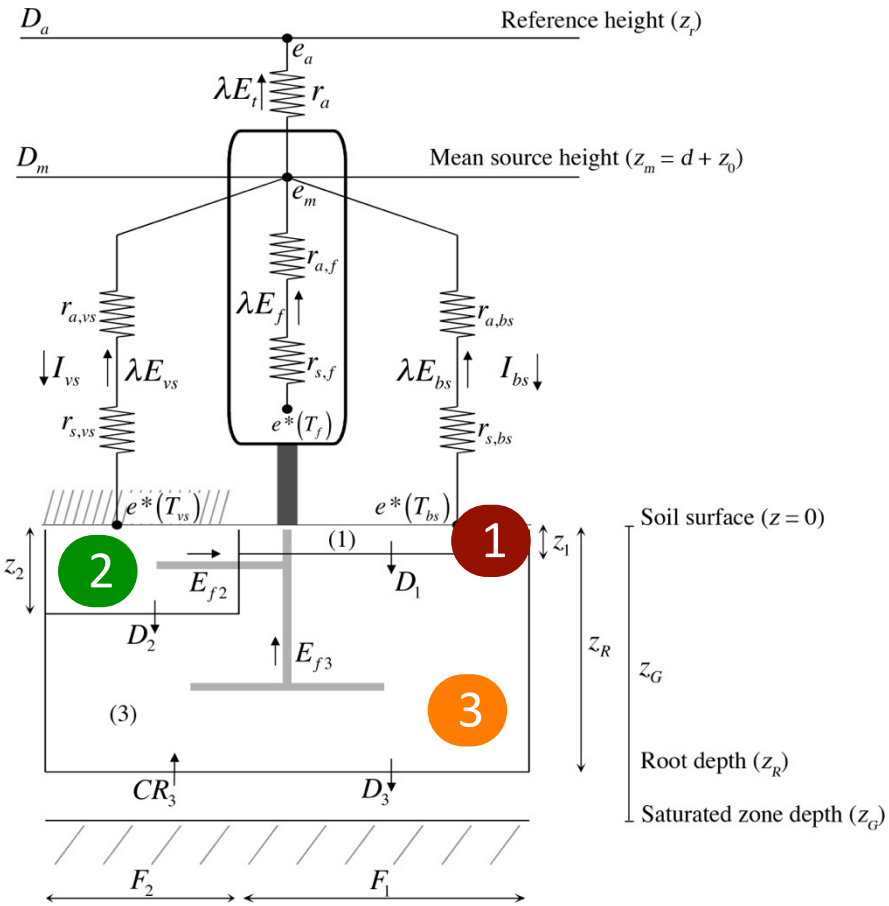
- Hypostomatique foliage considered as amphistomatic
- Relative error of ~10% for *LAI* ≈ 3 m^2 m^{-2}

Numerical simulation



BLM, 2013

Model : soil-plant-atmosphere



AFM, 2013

ET model coupled with soil module

- Three reservoirs:
  - Bare soil (1)
  - Grass cover (2)
  - Deep soil (3)

- Vine roots: reservoir (2) and (3)
- Infiltration F(rainfall), neglecting runoff
- Drainage: excess relative to retention capacity
- Capillary rise: Darcy's law

Dynamic water balance: daily time-step

$$ASW_j = ASW_{j-1} + I_j \pm CR_j - \sum_{h=1}^{24} E_j \pm D_j$$

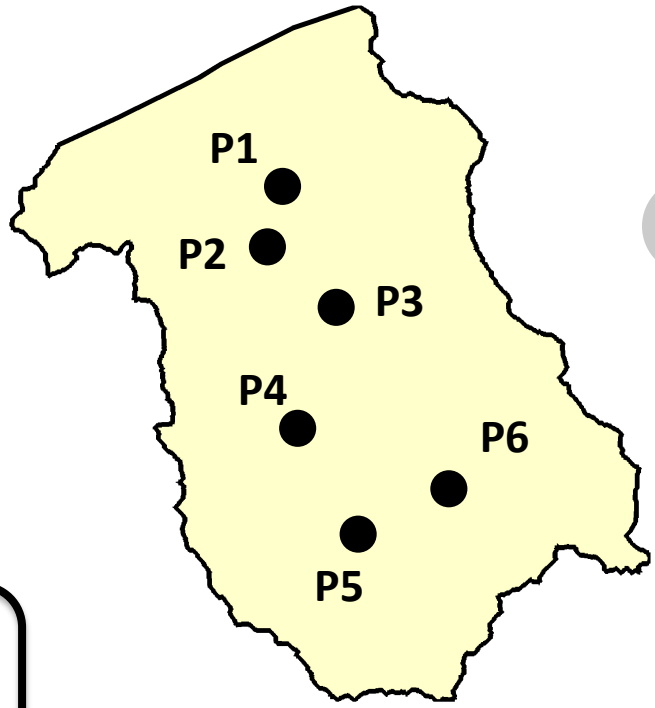
Approach

1

Plot scale :
Model development

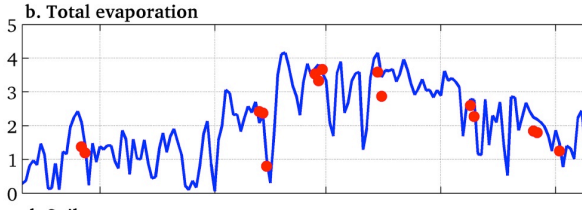
Question 1:
formalism

Question 2:
modeling



2

Plot scale : stochastic calibration



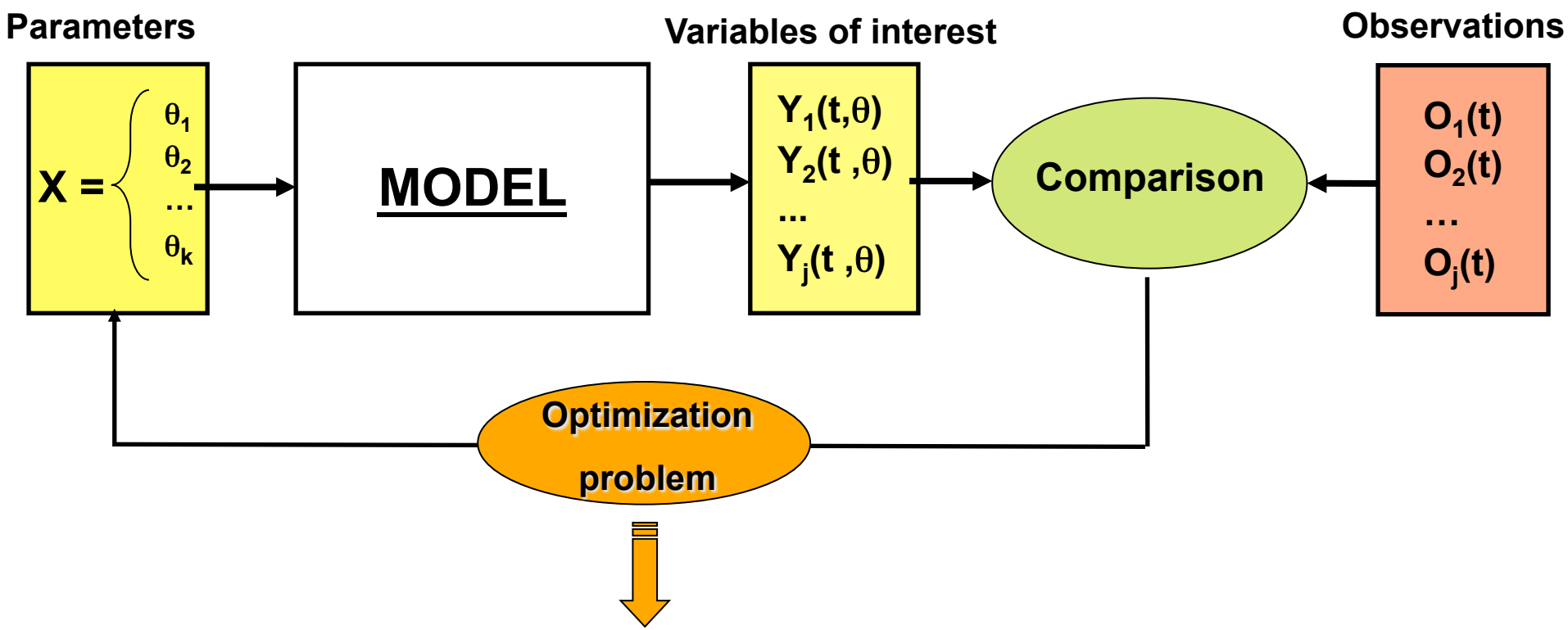
Question 3: realistic simulations

3

Regional extension

Question 4: spatial extent
by remote sensing

Site scale calibration: approach



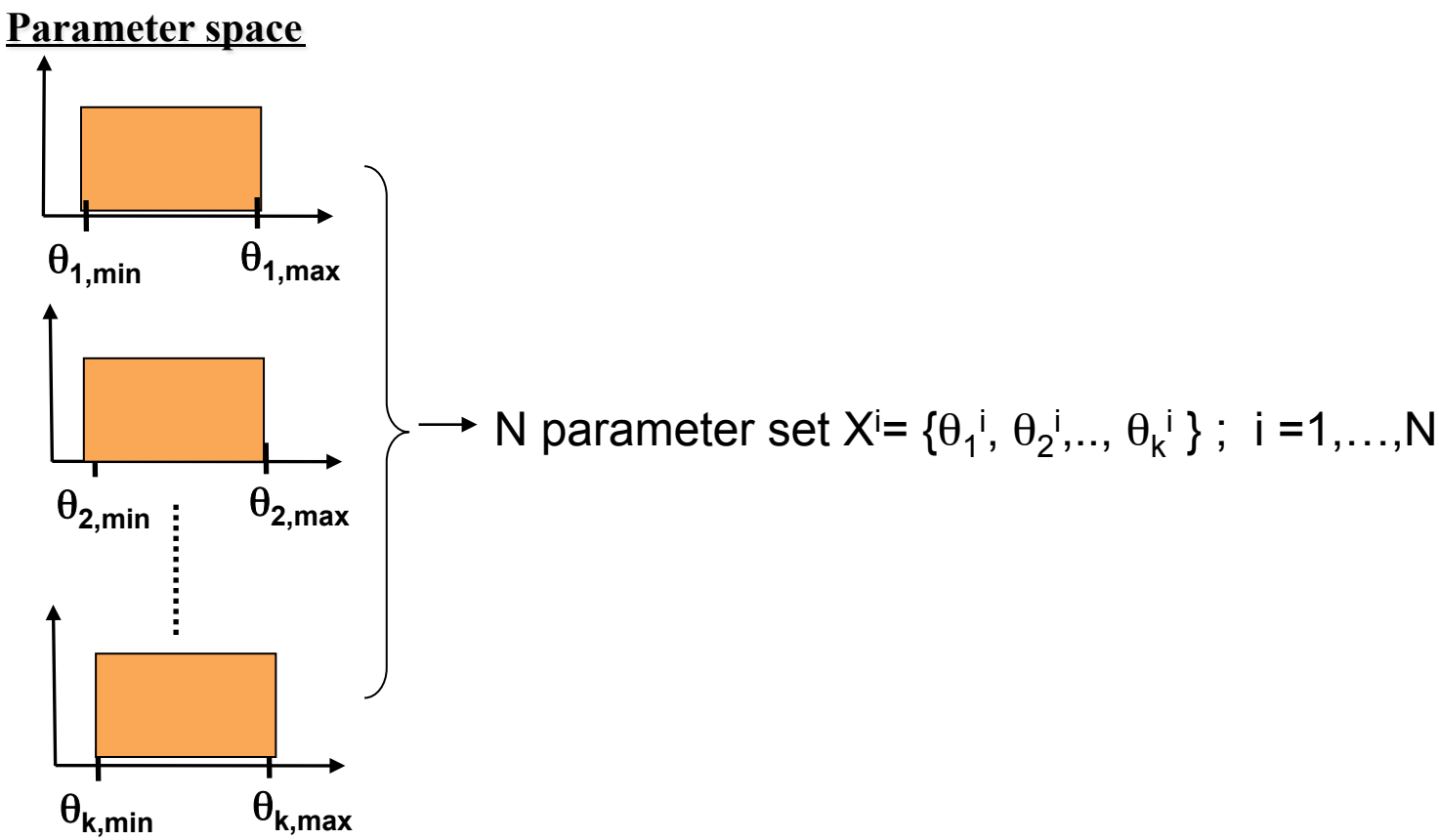
Stochastic and **multi-objective methods**

Multi-objective calibration procedure MCIP: (Demarty *et al.*, WWR, 2003)

(iterative sensitivity analysis)

Site scale calibration: approach

① - Random samplig of k model parameters

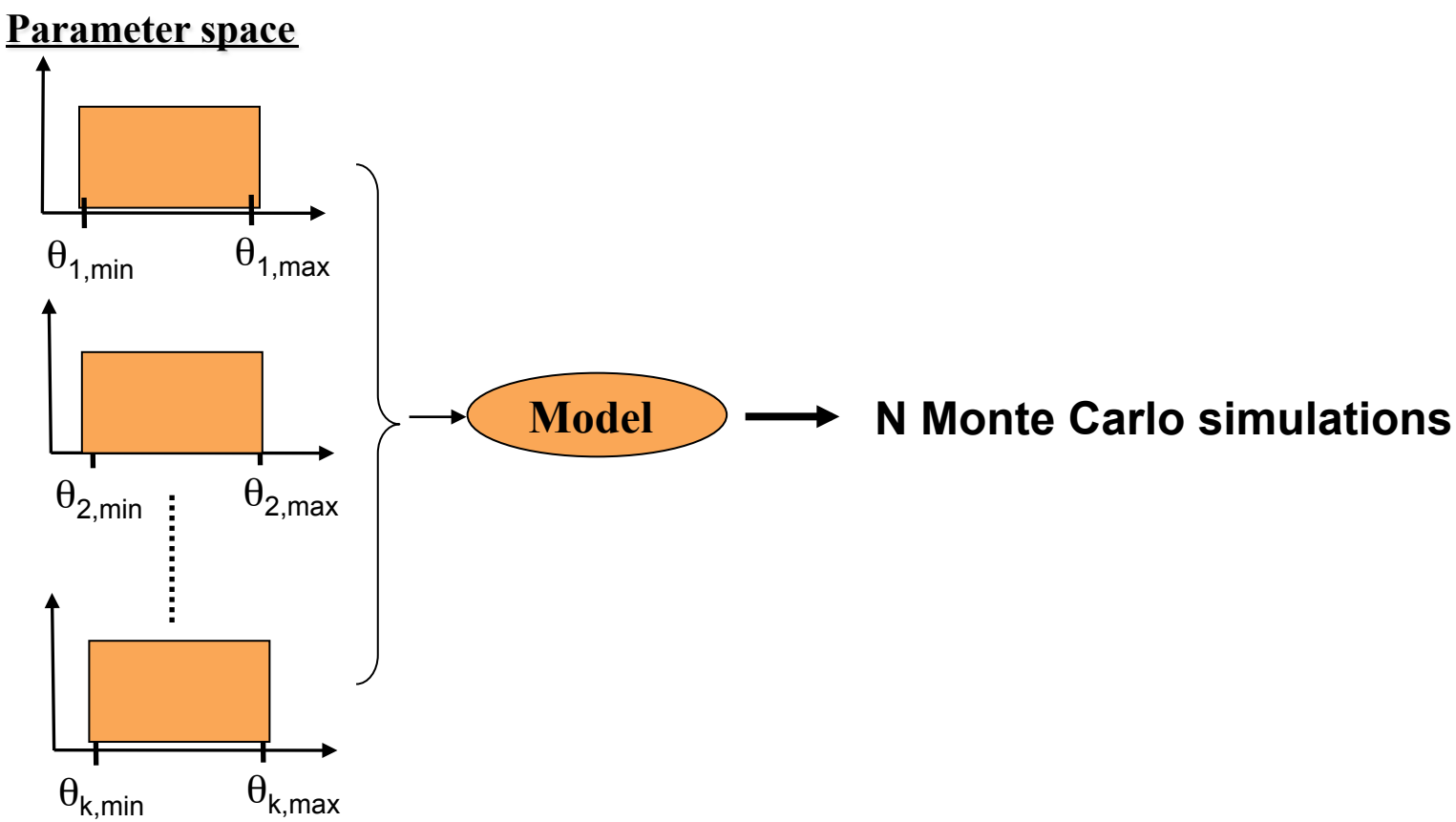


Site scale calibration: approach

① - Random samplig of k model parameters

② - N simulations generation

Stochastic approach

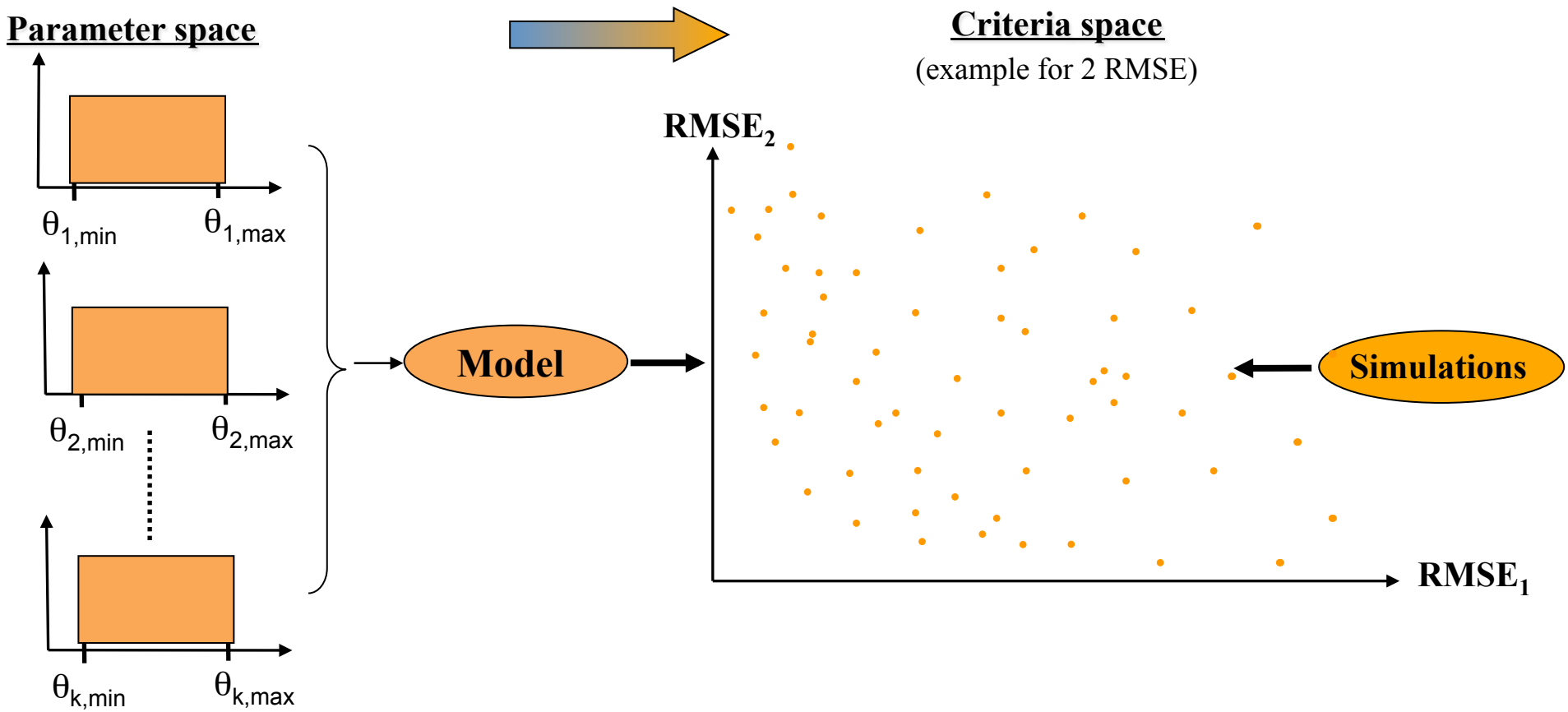


Site scale calibration: approach

① - Random samplig of k model parameters

② - N simulations generation

③ - **Performance evaluation (objective functions)**



Site scale calibration: approach

① - Random samplig of k model parameters

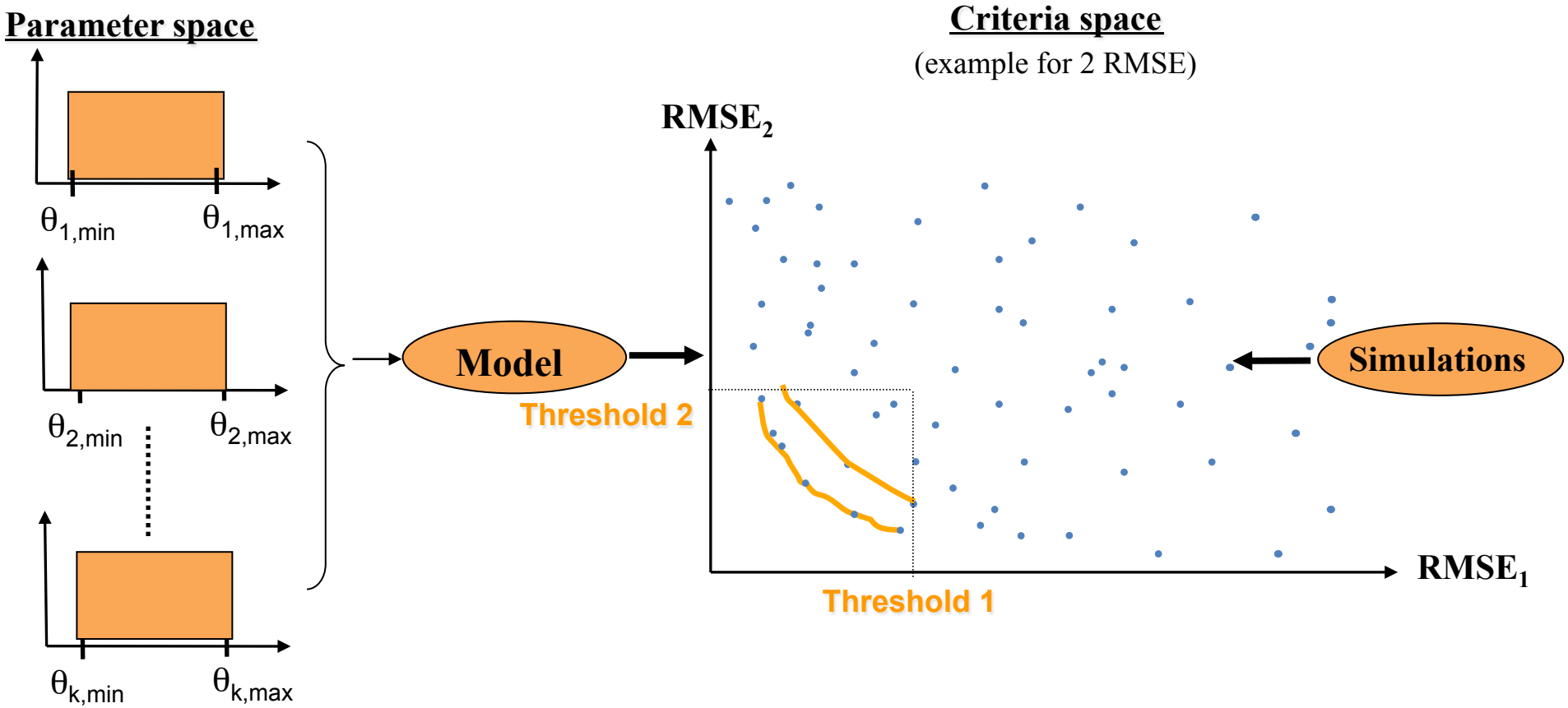
② - N simulations generation

③ - Performance evaluation (objective functions)

④ - **Selection of "best" simulations**

➔ Thresholding + Pareto solution

Multi-objectif approach



Site scale calibration: approach

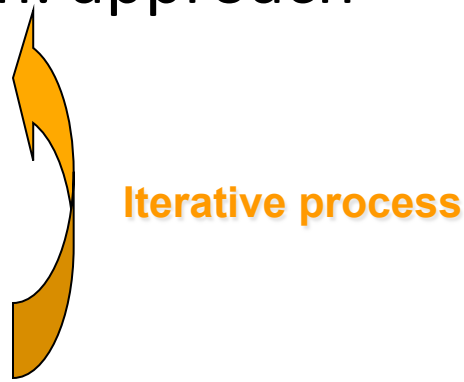
① - Random samplig of k model parameters

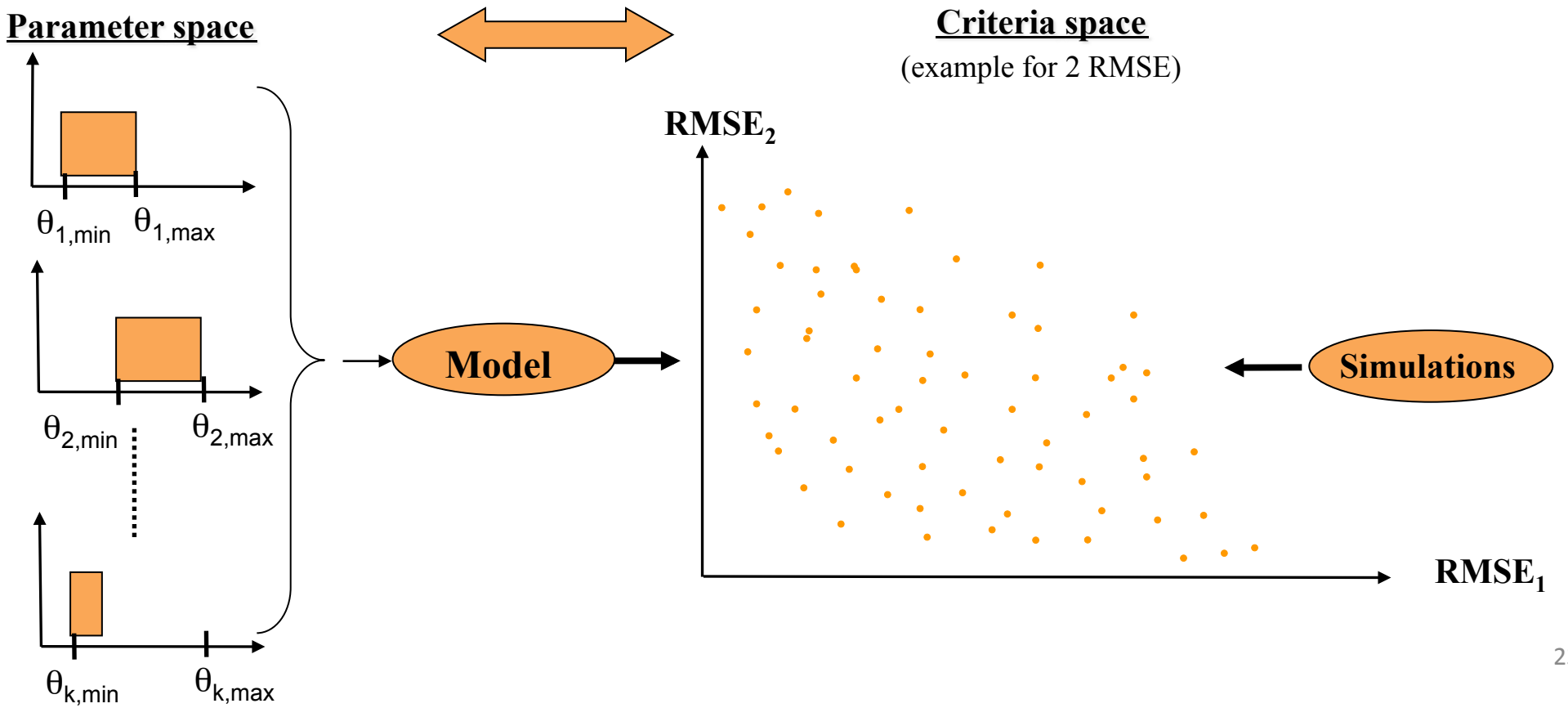
② - N simulations generation

③ - Performance evaluation (objective functions)

④ - Selection of "best" simulations

⑤ - Reduction of uncertainty intervals of parameters





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① - Random samplig of k model parameters

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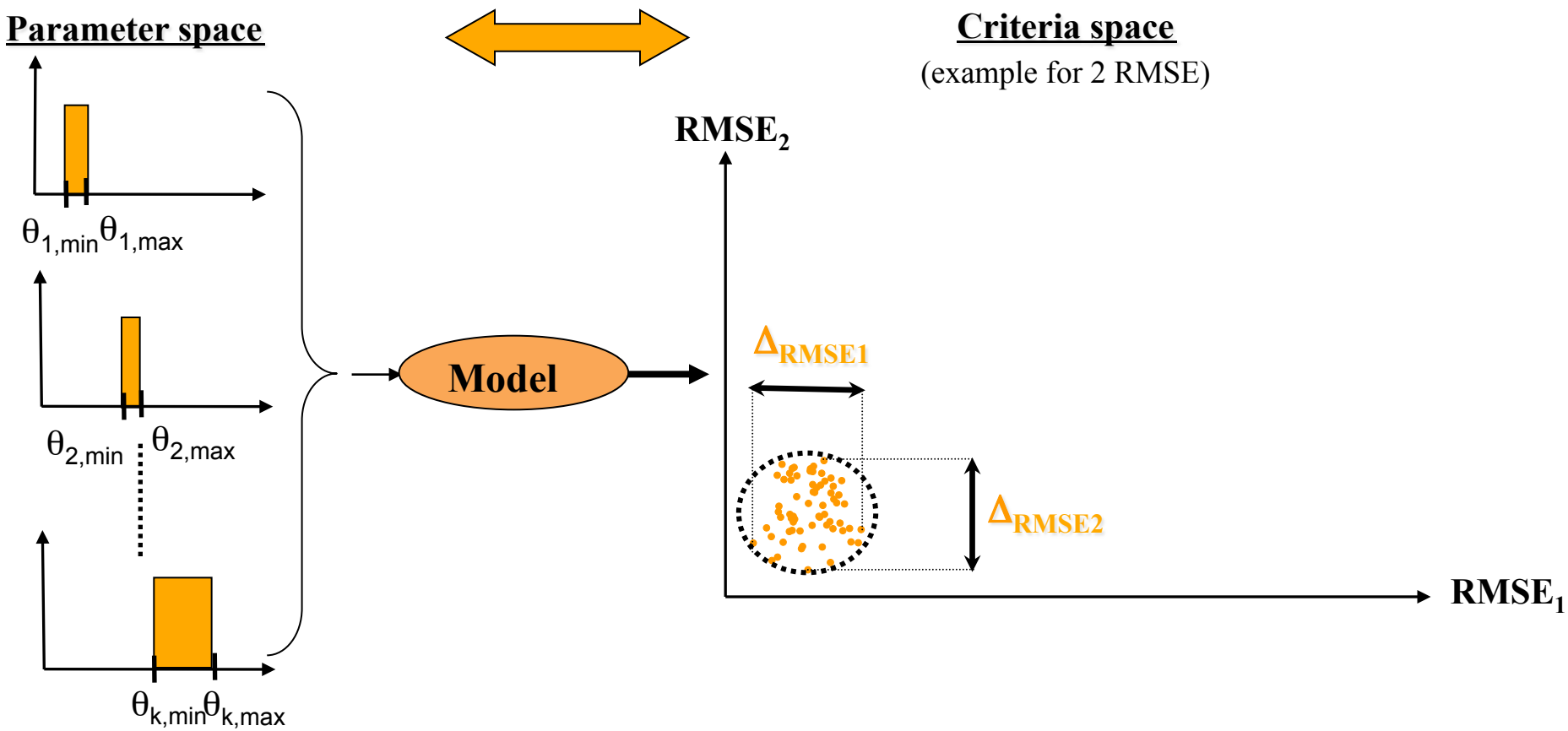
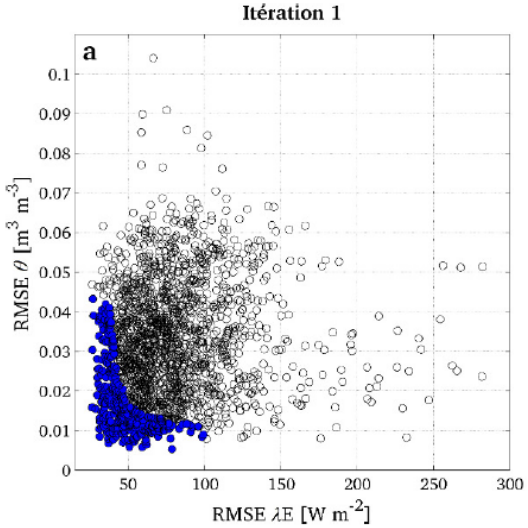
Iterative process

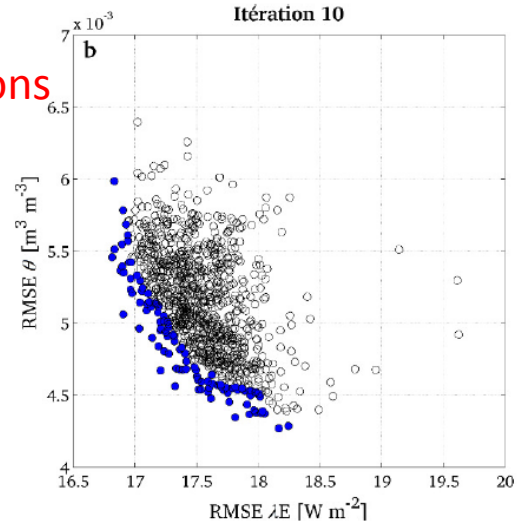


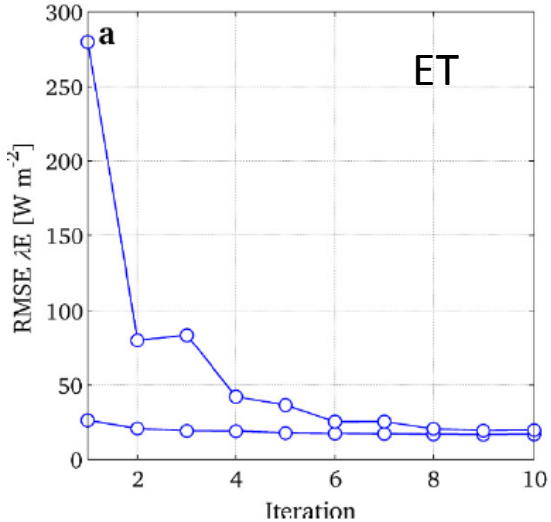
Site scale calibration: approach



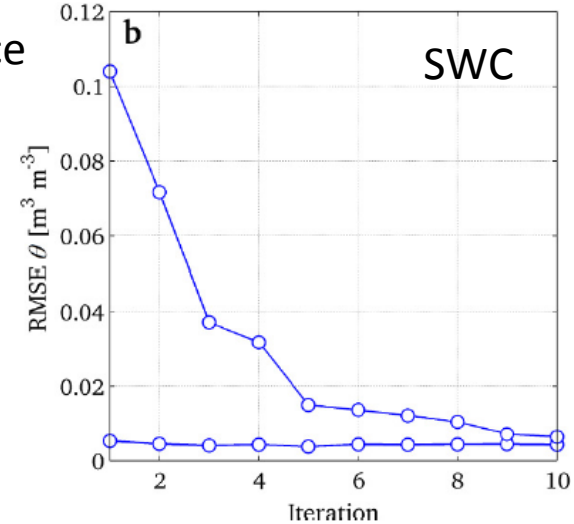
10x2.000 simulations

Parameter space

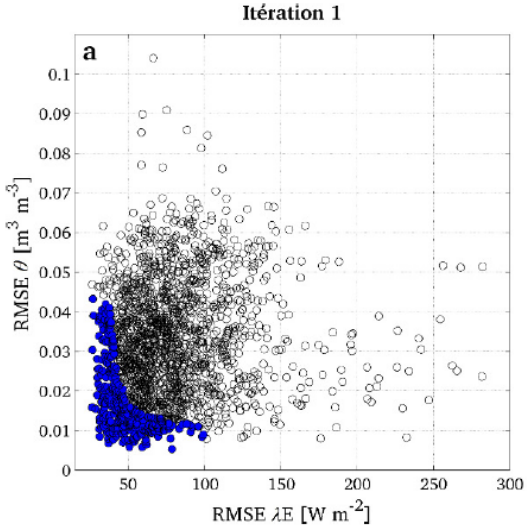




Error convergence

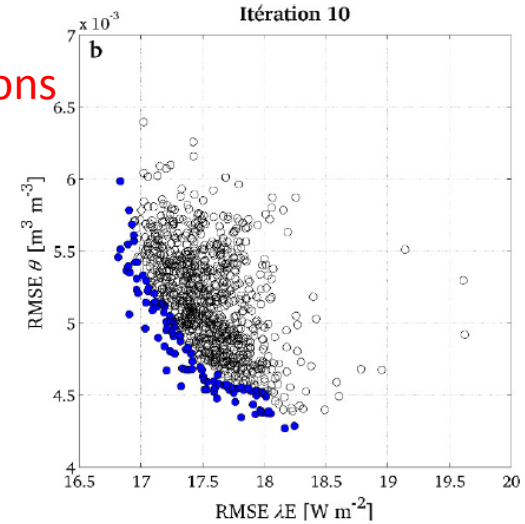


Site scale calibration: approach

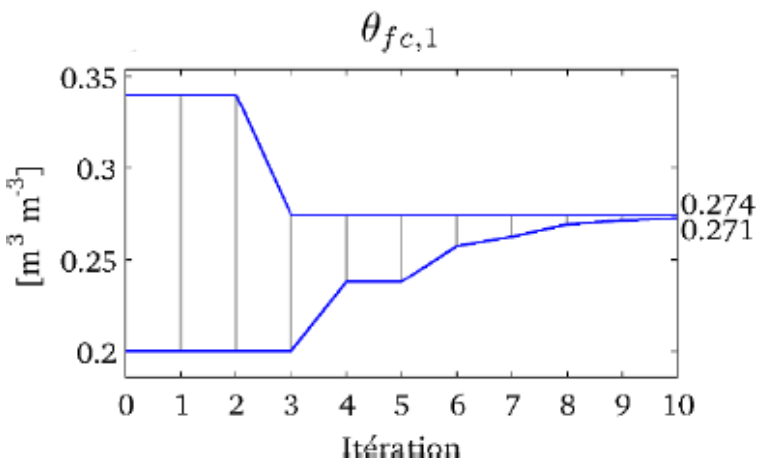


10x2.000 simulations

Parameter space



Example parameter evolution

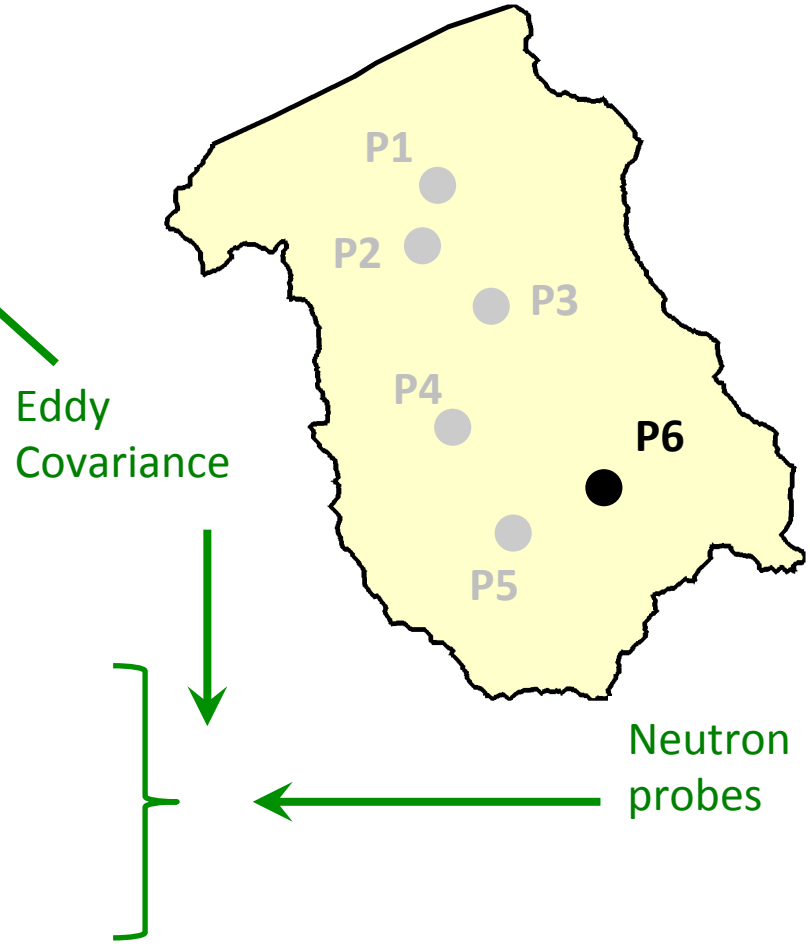


Model results: site simulations

1) Calibration of vegetation/atmosphere module
- Evapotranspiration (Eddy Covariance)
- Hourly time-step

2) Coupled calibration: ET and SWC
- Prescribed soil parameters (local measurements)
- Daily time-step
- Validation: evapotranspiration and soil moisture

3) Coupled calibration: ET and SWC
- Vegetation and soil parameters
- Daily time-step
- Validation: evapotranspiration and soil moisture

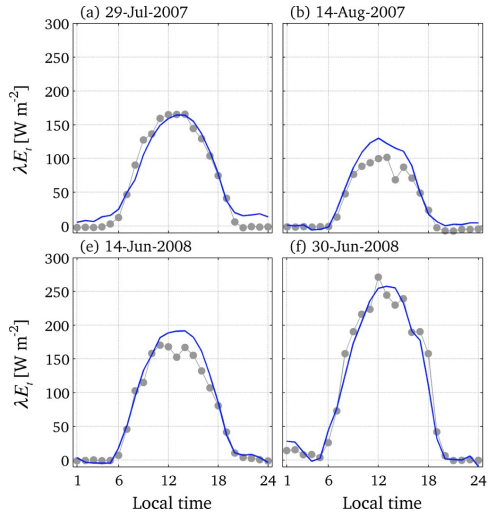


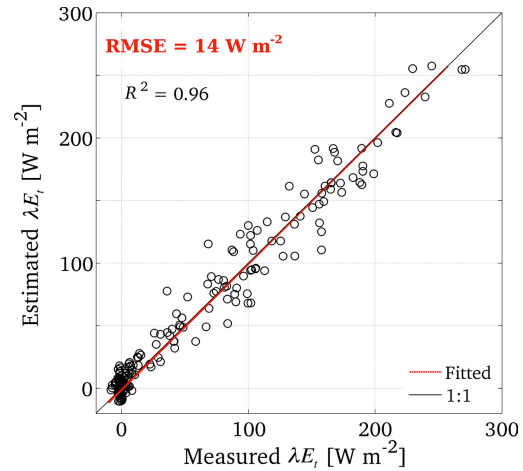
Model results: site simulations

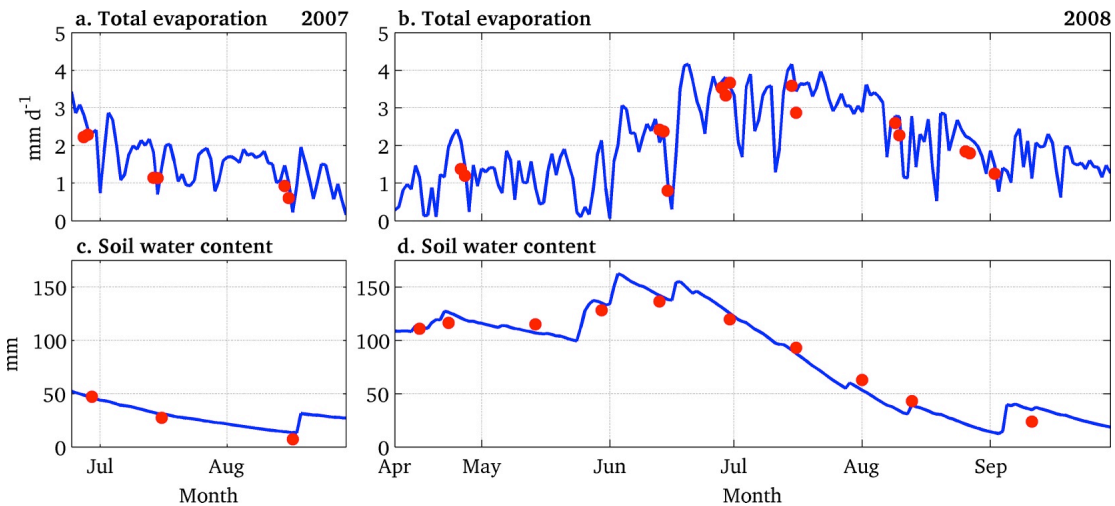
Vegetation/atmosphere module: ET daily cycle

- RMSE = 14 W m^{-2} = 0.5 mm d^{-1}
- Bias = 1.1 W m^{-2} = 0.04 mm d^{-1}

  → Low residual error







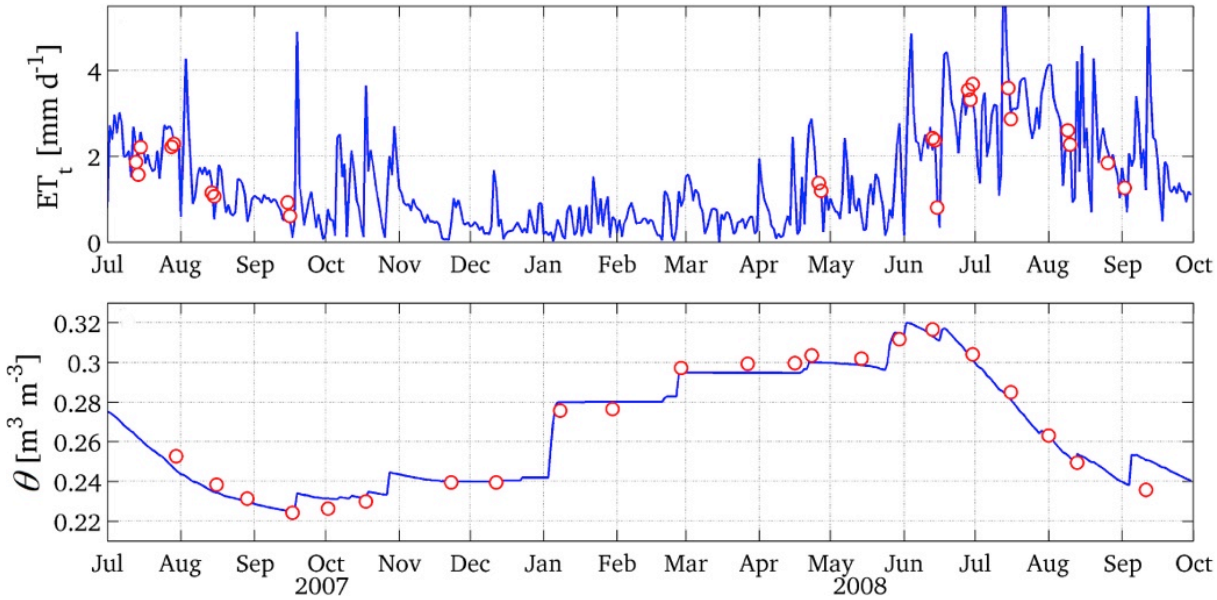
Coupled simulation

- ET RMSE = 0.43 mm d^{-1}
- SWC RMSE = 7 mm

Model results: site simulations

Coupled calibration: Vegetation and soil parameters

- Daily time-step
- Evapotranspiration and soil moisture



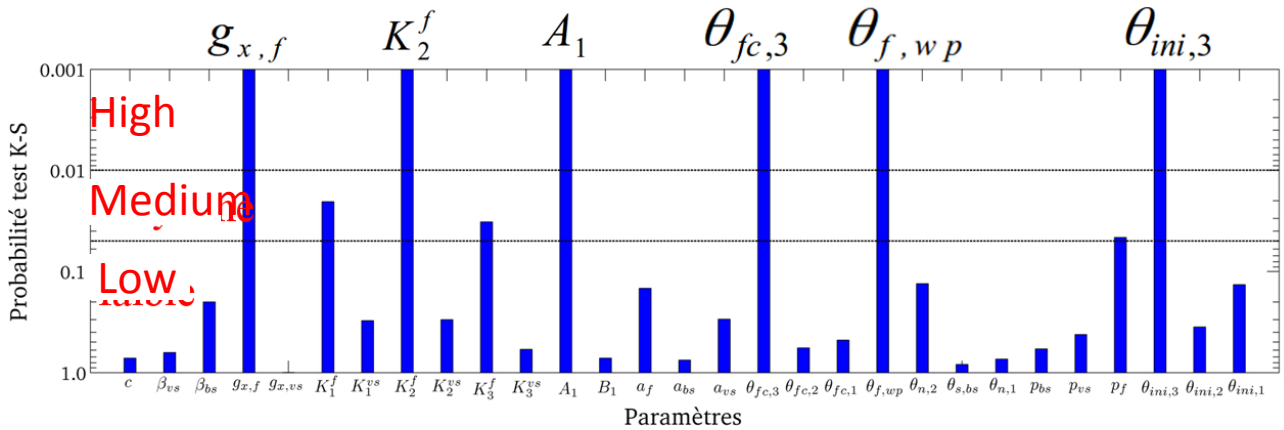
ET RMSE 0.26 mm d^{-1}

SWC RMSE 0.005 m^3 m^{-3}

Restitution of seasonal/interannual dynamics
Low residual error

Model results: site simulations

Relative sensitivity to each parameter (29)



1st iteration

High sensitivity:

- $g_{x,f}$: maximal stomatal conductance
- K^f_2 : stomatal conductance (VPD)
- A_1 : bare soil resistance
- $\theta_{fc,3}$: deep soil field capacity
- $\theta_{wp,3}$: deep soil wilting point
- $\theta_{ini,3}$: deep soil initial SWC

Medium sensitivity

- K^f_1 : stomatal conductance (PAR)
- K^f_3 : stomatal conductance (SWC)
- p_f : stone content

Approach

1

Plot scale :
Model development

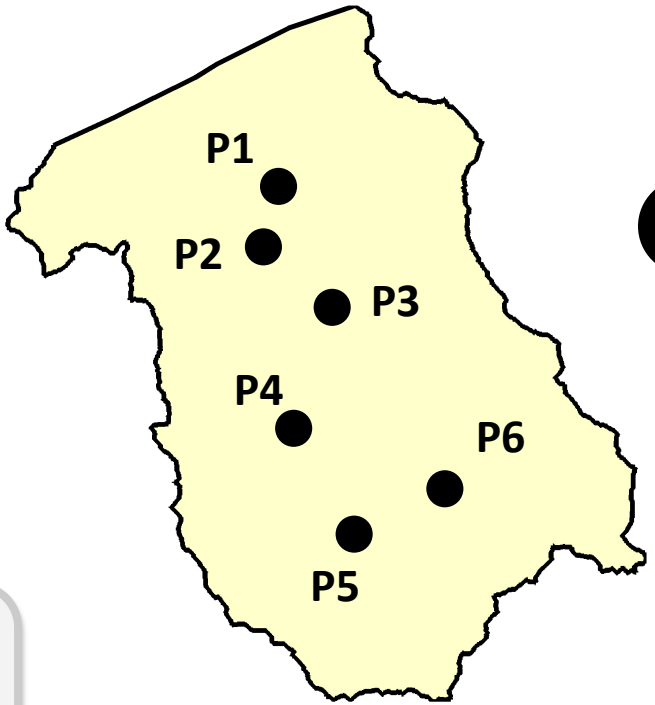
Question 1: formalism

Question 2: modeling

2

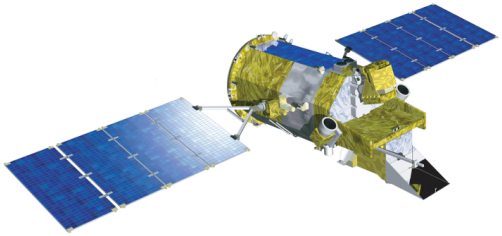
Plot scale : calibration

Question 3: realistic simulations



3

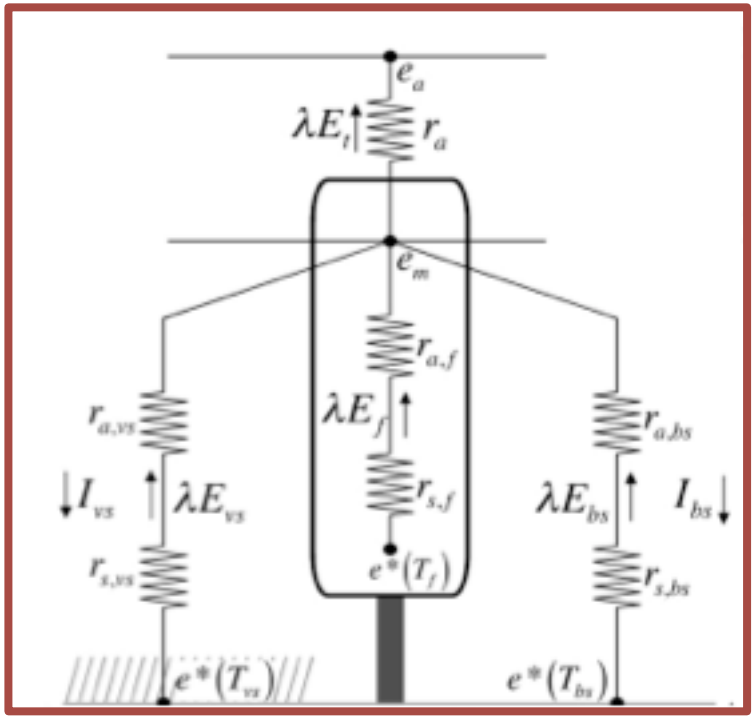
Regional extension



Question 4: spatial extent by remote sensing

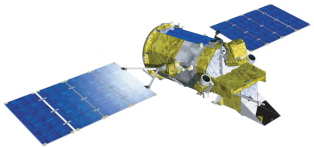
Remote sensing ET: approach

Model calibration by using remote sensing



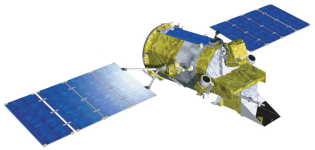
MCIP

Evapo-transpiration



Satellite reflectance

Satellite surface température

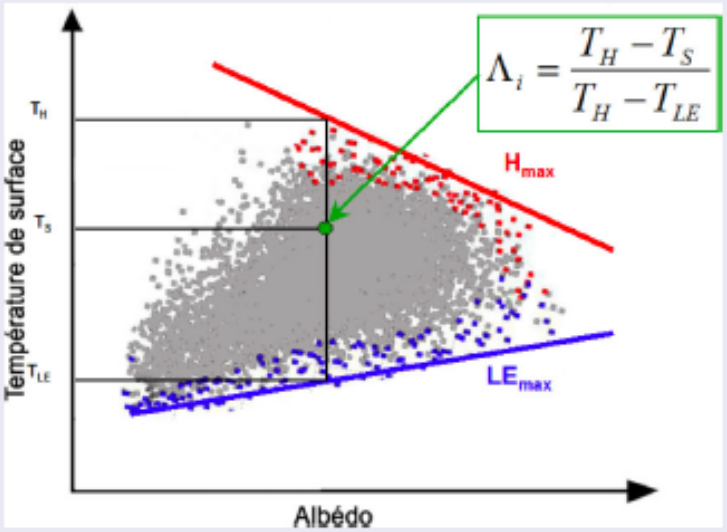


Remote sensing ET: approach

- Thermal remote sensing (TIR)
- Surface radiative temperature T_s associated with surface water conditions
- Energy balance: T_s equilibrium term

$$(1-\alpha_s)R_g + \varepsilon_s R_a - \varepsilon_s \sigma T_s^{\,4} = \rho Cp \frac{T_s - T_a}{r_a} + \frac{\rho Cp}{\gamma}\frac{e_{sat}(T_s) - e_a}{r_c} + \bar{\lambda}\frac{T_s - T_0}{\Delta z}$$

S-SEBI: Simplified Surface Energy Balance Index (Roerink et al., 2000)



Evaporative fraction

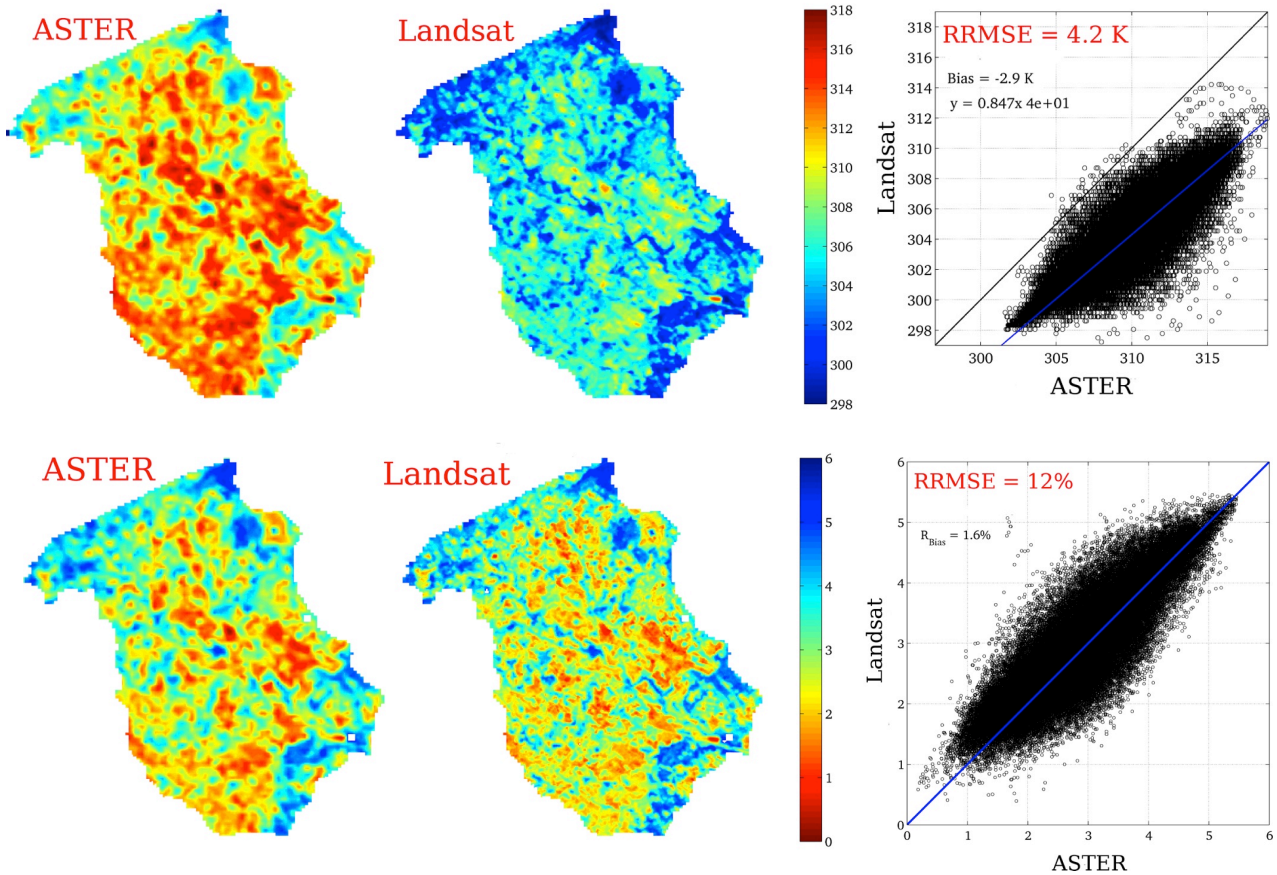
$$\Lambda = \frac{\lambda E}{\lambda E + H} = \frac{T_H - T_S}{T_H - T_{LE}}$$

Daily ET

$$\lambda E_d = \Lambda R_n$$

Remote sensing ET: approach

1) S-SEBI validation for ASTER imagery against HYDRUS model → RMSE 0.83 mm d^{-1} for all sites
2) S-SEBI Landsat? Lower radiometric quality/higher data availability



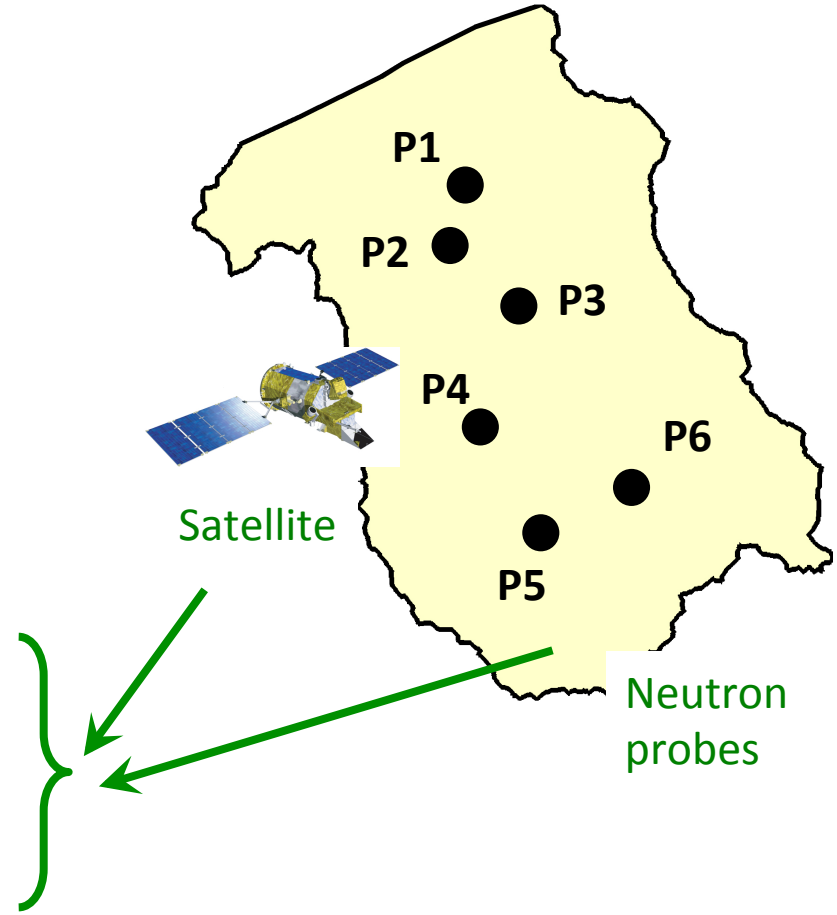
High temperature dispersion

Temperature difference

Low dispersion in evapotranspiration

Multi-site simulations: approach

- Forcing
  - Meteorological (interpolated rainfall)
  - LAI
  - Watertable
- Model calibration 2007 – 2008 (450 days)
  - 10 parameters soil / vegetation
  - 16 parameters vegetation/ atmosphere
  - 3 initial conditions
- Calibration method : MCIP
  - Remote sensing ET + SWC
- Comparison of Landsat and ASTER performance
  - Model parameters



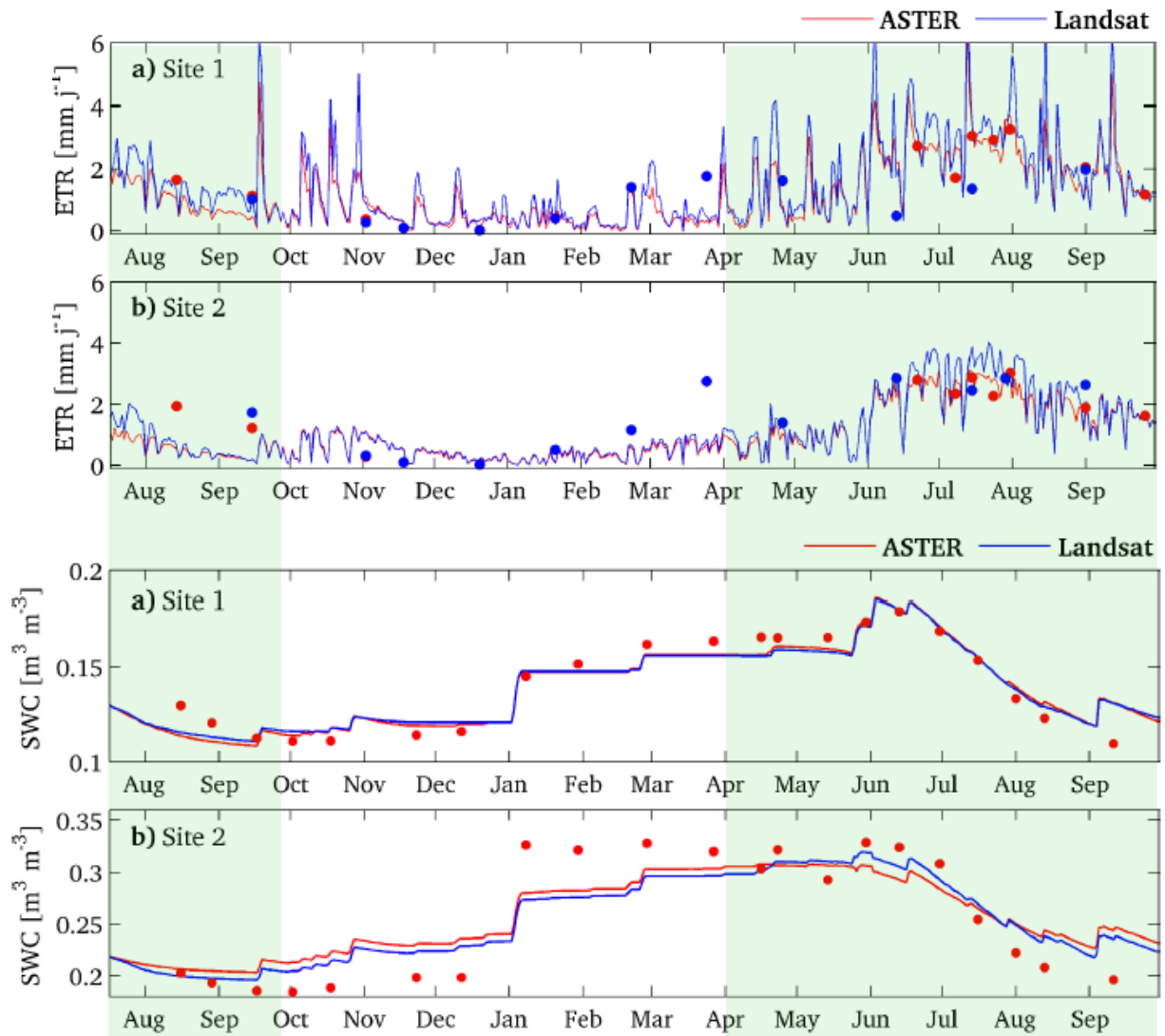
Multi-site simulations: results

ET and SWC for 2 contrasting sites in terms of soil water content

Overall 6 sites

ASTER
ET RRMSE 25%
SWC RRMSE 5%

Landsat
ET RRMSE 65%
SWC RRMSE 6%

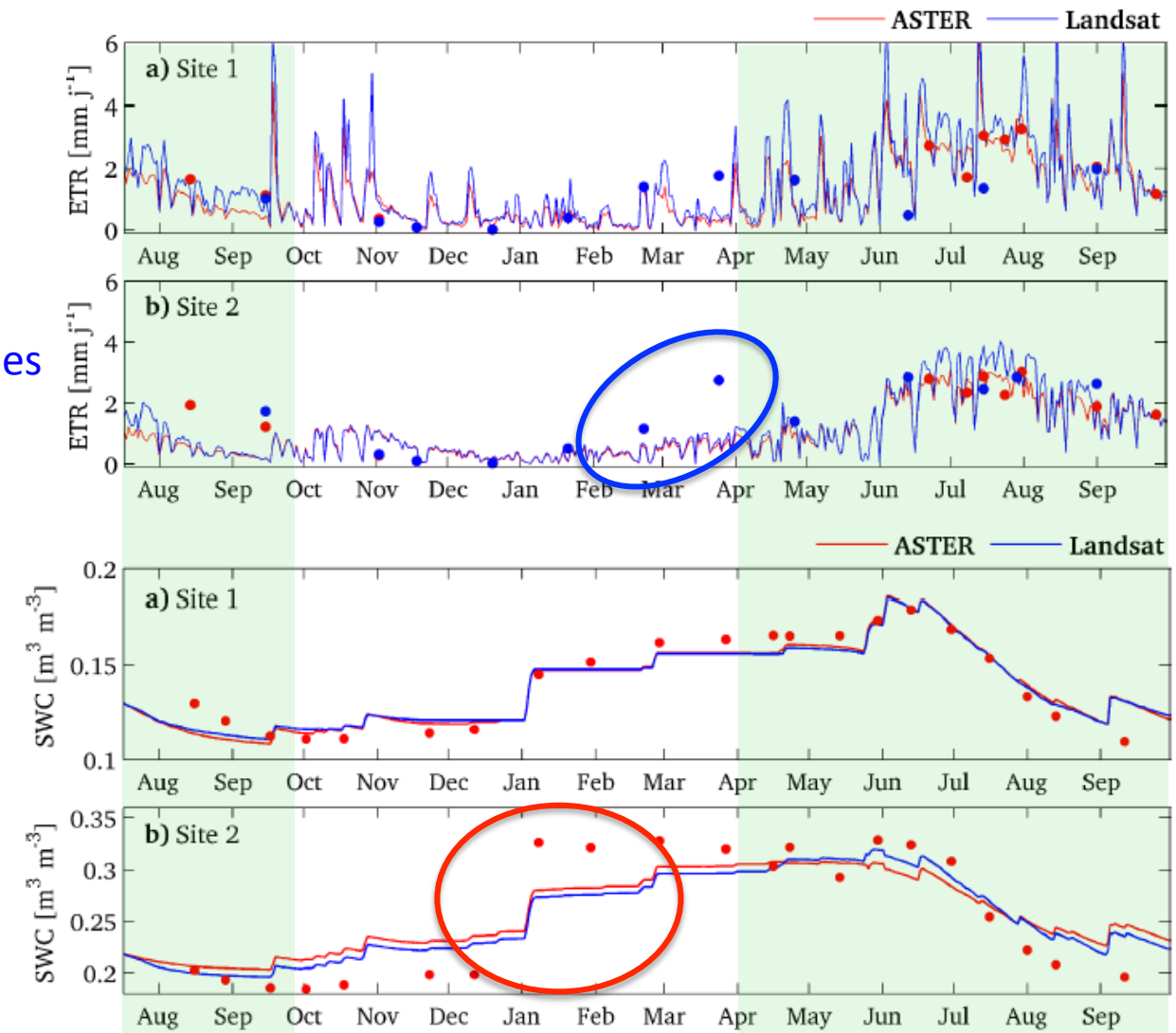


Multi-site simulations: results

Sources of uncertainty

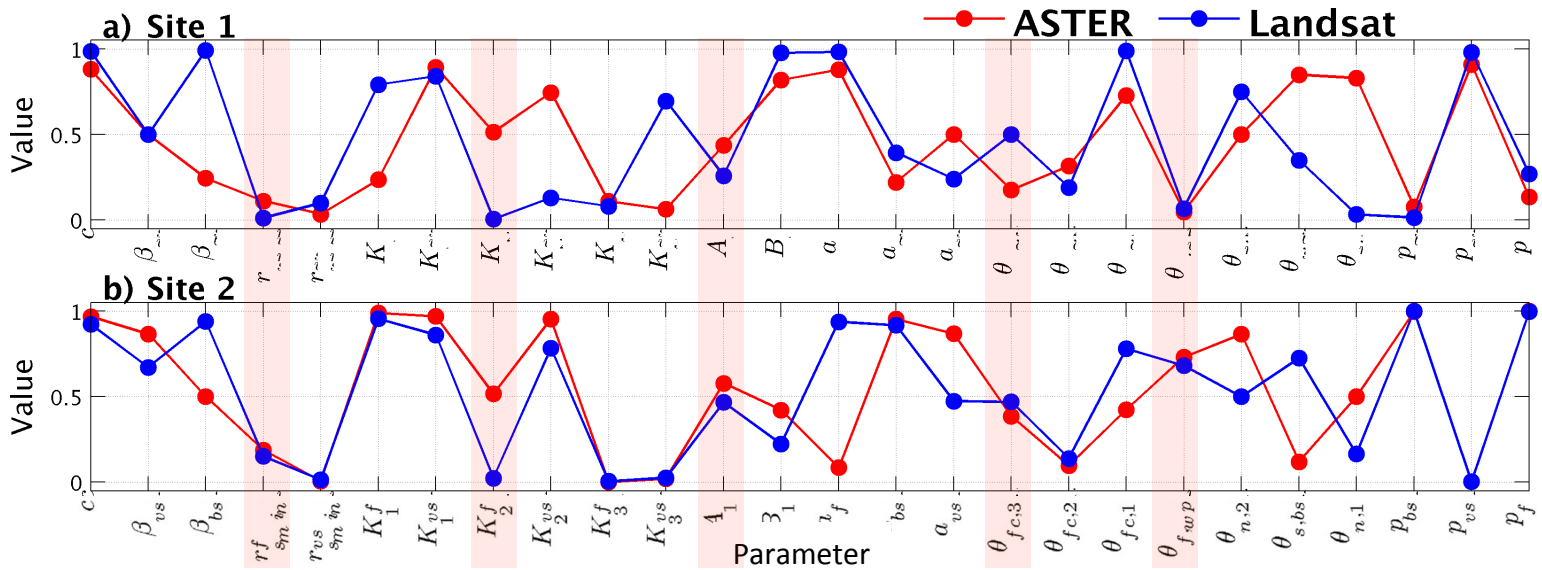
Landsat period:
- Spring semi-cloudy days: filtering
- Time distribution: surface properties
  - Higher complexity

Watertable presence
- Capillary rise parameterization?
- Impacts on ET



Multi-site simulations: results

Parameter comparison



Similar values

r^f_{min} : min. stomatal resistance

A_1 : bare soil resistance

Different values

K^f_2 : stomatal conductance (VPD): simulation periods

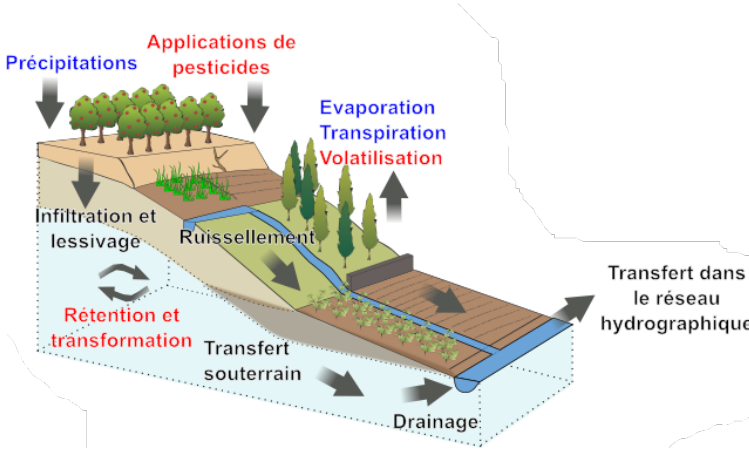
$\theta_{f,,wp}$: deep soil wilting point: 2 different sites

"High" sensitivity parameters

"Optimal" parameters are case dependent (equifinality)
Some degree of correspondence between sites and parameters

General conclusions

- Preliminary results:
  - Simulation platform for agricultural watersheds
- Obtaining interannual simulations (450 days)
  - Interannual dynamics
- Parsimonious model with MOGSA / MCIP
  - Restitution of local process
  - Possibility of obtaining parameters at the plot scale
  - Watertable during winter -> model not suitable
- Multi-site approach possible with limitations
  - Use of in-situ measurements



General conclusions

Further research

- Review local calibration
  - Different phenological stages
  - Soil moisture of first soil layer (instead 0-2 m)
  - Available by high spatial resolution radar
  - Data assimilation: surface and deep SWC

- Analysis of calibration results
  - Parameter values according to pedology
  - Comparing with literature

Perspectives

Spatial dimension

- 6 experimental plots → agricultural surface → watershed

Time dimension

- Satellite missions e.g. CNES/NASA THIRSTY mission: calibration considering different time-steps

Synergy with digital soil mapping

- Comparison of estimated parameters
- Joint use for calibration for patches

Coupling with other processes

- Hydrological modeling: taking into account lateral transfers and watertable
- Vegetation modeling : dynamics, processes

Papers resulting from this work

Montes, C., W. Ma and F. Jacob. Intercomparison of ASTER and Landsat 7 +ETM to retrieve evapotranspiration by using a contextual method. In prep. for *IEEE Geosci. Remote Sens. L.*

Montes, C., F. Jacob, J. Demarty and J.P. Lhomme. Spatialized modeling of land surface-atmosphere exchanges at the extent of an agricultural Mediterranean region. In prep. for *Agric. Forest Meteorol.*

Lhomme, J.P. and **C. Montes**. 2014. Generalized combination equations for canopy evaporation under dry and wet conditions. *Hydrol. Earth Syst. Sci*. 18, 1137-1149.

Montes, C., J.P. Lhomme, J. Demarty, L. Prévot and F. Jacob. 2014. A three-source SVAT modeling of evaporation: application to the seasonal dynamics of a grassed vineyard. *Agric. Forest Meteorol*. 191, 64-80.

Lhomme, J.P., **C. Montes**, F. Jacob and L. Prévot. 2013. Evaporation from multi-component canopies: generalized formulations. *J. Hydrol*. 486, 315-320.

Lhomme, J.P., **C. Montes**, F. Jacob and L. Prévot. 2012. Evaporation from heterogeneous and sparse canopies: on the formulations related to multi-source representations. *Bound.-Lay. Meteorol*. 144, 243-262.

Thank you

Carlo Montes

NASA GISS Seminar
March 18, 2015

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