Uncertainties in simulated evapotranspiration from Land Surface Model over a 14-year Mediterranean crop succession

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Outline

1) Introduction

2) Avignon crop succession dataset

3) Modelling experiment design

4) Results

5) Conclusions
1. Introduction
Introduction (1/2)

Evapotranspiration (ET) : key variable of the energy & water balance (Seneviratne et al., 2006)

ET: most uncertain term of the water balance of Mediterranean regions (Dolman et al., 2010; Orlowsky et al., 2013)
- ET dynamics and soil/vegetation partitioning (Sutanto et al., 2014)
- Large departure between models (Mueller and Seneviratne, 2014)

Sources of modelling uncertainties (Vrugt et al., 2009):
- Forcing variables (e.g. climate, vegetation dynamic, land-use)
- Model parameters (e.g. soil hydrodynamic properties)
- Model structure (e.g. water transfer scheme, energy balance, crop phenology, irrigation...)
Q.1) How crop succession drives the dynamics of ET, ET soil/vegetation partitioning and drainage?

Q.2) What are the most influential sources of uncertainties

- climate,
- vegetation dynamic,
- irrigation,
- soil parameters.

on ET simulation over a crop succession?

Q.3) What are the impacts of water transfer scheme: Force-Restore vs multi-layer soil diffusion scheme, on ET simulation over a crop succession?
2. Avignon dataset
Representation of crop succession

- Explicit representation of crop succession in the simulation
- Succession of winter (wheat) and summer (maize, sorghum, sunflower) crops
- Long period (9 months) of bare soil between winter and summer crops
Avignon Site

- **lower Rhone Valley region**, France (43°55'00" N, 4°52'47" E, 32m)
- **Mediterranean climate** (mean annual T°C=14°C and mean precip=~650 mm)
- Texture: 15% of sand, 35% of clay
- Crops: maize, wheat, sorghum, peas, sunflower

14 years of continuous measurements:

- **Fluxes**: Eddy, radiative and soil heat fluxes
- **Soil moisture vertical profiles**
- **Micrometeorological variables**
- **Vegetation**: LAI, height, agricultural practices
3. Modelling experiment design
The ISBA-A-gs model

Noilhan and Planton, 1989
Calvet et al., 1998
Masson et al., 2013

SURFEX/ISBA-A-gs model

- Version 8.0 of SURFEX
- **Single energy balance** of soil-vegetation composite (a new Multi-Energy Balance scheme is under testing)
- Detailed multi-layer **radiative transfer canopy scheme**
- **Force restore/Multi-layer soil diffusion** for heat and water soil transfers
- A-gs:
  - **Coupled photosynthesis-stomatal conductance scheme**
  - Driven by in situ LAI time series in this work
- ECOCLIMAP-II parameters: 1 km, global scale, ~270 land cover types over Europe

Implementation at the Avignon site

- Continuous simulations from **25 April 2001 to 1 March 2015**
- **Explicit representation of crop succession**
  - Crop periods: C3, C4 crop model patch,
  - Inter-crop periods: bare soil model patch.
4. RESULTS
Q1) How crop succession drives the dynamics of ET, ET soil/vegetation partitioning and drainage?

Garrigues et al., HESS, 2015
Influence of crop rotation on ET and soil moisture dynamics

Daily ET:
- meas
- sim

Crop cycle

Inter-crop

Root-zone soil moisture
- meas
- sim

Plant water stress
Influence of crop rotation on the water balance dynamic

- **Transpiration**: large flux, short period of time
- **Soil evaporation**: lower value but steadier over the crop succession
- **Drainage**: intermediate values during autumn and winter rainy season

Winter crop

Inter-crop (bare soil)

Summer crop
Soil evaporation represents 70% of cumulative evapotranspiration over 9 years of crop succession.

Soil evaporation main source of uncertainty in ET.
Q.2) What is the most influential source of uncertainties

- climate,
- vegetation dynamic,
- irrigation,
- soil parameters

on ET simulation over a crop succession?

Garrigues et al., GMD, 2015
## Experiment design

Experiments with **local** vs **standard/large-scale** drivers

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Climate</th>
<th>Vegetation</th>
<th>Soil parameters</th>
<th>Irrigation</th>
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</thead>
<tbody>
<tr>
<td>CTL</td>
<td>Local</td>
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<td>SAFRAN</td>
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<td>ERA-I</td>
<td>ERA-I+GPCC rainfall</td>
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<td>SAFRAN+MSG</td>
<td>SAFRAN+MSG radiation</td>
<td>Local</td>
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<td>NO IRRIG</td>
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<td>LAI-ECOCLIMAP</td>
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<td>ECOCLIMAP</td>
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<td>PTF-SOIL</td>
<td>Local</td>
<td>Local</td>
<td>ISBA Pedotransfer</td>
<td>Local</td>
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</table>
Sensitivity of ET to driver uncertainties

Difference in cumulative ET between each experiment and the control run (CTL)

Sources of uncertainties

Vegetation: LAI (6%)

Climate (5-7%)

No Irrigation (15%)

Soil parameters (20%)

Errors in soil parameters and having no irrigation are the most influential drivers on ET
Impact of uncertainties in irrigation

Lack of irrigation generates larger variations than differences in rainfall between climate data sets.

Inaccurate timing of modeled irrigation:
- underestimation in early stage of the crop cycle
- overestimation during senescence
Impact of errors in soil hydrodynamic parameters

Pedotransfer (PTF) versus in situ soil parameters (derived from soil moisture meas.)

- PTF parameters: ~800 mm deficit (20%) in cumulative ET over 9 years
- In situ soil parameters: bias reduced by 98%
- Errors in:
  - Available soil water content for the plant → plant transpiration
  - Soil moisture at saturation and field capacity → soil evaporation
Sensitivity to uncertainties in soil parameters

Monte-Carlo analysis

FORCE-RESTORE

962 mm
Q.3) What are the impacts of

- errors in soil parameters,
- water transfer scheme: Force-Restore vs multi-layer soil diffusion scheme,

on ET simulation over a crop succession?

Garrigues et al., HESS, 2015

Garrigues et al., JHM, 2017, under revision
Experiment design

4 Experiments derived using either:

- **Soil parameters**: pedotransfer (PTF) vs local estimates
- **Water transfer schemes**: Force-Restore (FR) vs multi-layer soil diffusion (DIF)

<table>
<thead>
<tr>
<th>Experiments</th>
<th>model</th>
<th>Soil parameters</th>
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<tbody>
<tr>
<td>FR&lt;sub&gt;PTF&lt;/sub&gt;</td>
<td>Force-Restore</td>
<td>pedotransfer</td>
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<tr>
<td>DIF&lt;sub&gt;PTF&lt;/sub&gt;</td>
<td>Multi-layer soil diffusion</td>
<td>pedotransfer</td>
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<td>FR&lt;sub&gt;LOC&lt;/sub&gt;</td>
<td>Force-restore</td>
<td>local</td>
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<td>DIF&lt;sub&gt;LOC&lt;/sub&gt;</td>
<td>Multi-layer soil diffusion</td>
<td>local</td>
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</tbody>
</table>

Soil parameters driving ET uncertainties (Garrigues et al., 2015):

- **Soil moisture at saturation, field capacity, wilting point**
- **Rooting depth, root profile parameters**
Evaluation over bare soil period

**Evapotranspiration**

**Root-zone soil moisture**

DIF: Accurate simulation of soil evaporation

Accurate simulation of soil moisture
5. CONCLUSIONS
Impact of Mediterranean crop succession on ET dynamics:

- Soil evaporation is the main ET component
- Uncertainties mainly driven by soil evaporation parameters

Most influential sources of uncertainties on ET:

- First order:
  - soil hydrodynamic parameters
  - Irrigation

- Second order:
  - vegetation dynamic
  - climate.
Impact of errors in soil parameters and water transfer scheme

- Multi-layer soil diffusion scheme more robust to uncertainties in soil parameters
- Force-Restore easier to calibrate at local scale
- Soil evaporation
  - DIF: accurate simulation of soil evaporation
  - FR: highly sensitive to soil moisture at field capacity and saturation
- Transpiration
  - DIF,FR: sensitive to available water content for the plant
  - DIF: Influence of root-profile parametrization on simulation of water stress
Future work

➔ Evaluation of JULES-crop over the Avignon data set
  - Jules irrigation module

  - Jules crop phenology

  - comparison with ISBAAd STICS crop model as reference

➔ Evaluation of water balance simulation over Europe
  - ISBA, JULES and reanalysis products intercomparison

  - Impact of uncertainty in irrigation on water balance long-term evolution
ISBA/JULES comparison over Europe

ISBA and JULES LE (W/m²) monthly time course for FRANCE

Month 2008-2009

LE (W/m²)

Jules
Isba
Additional slides
Mean seasonal ISBA and JULES T (°C) in FRANCE

Jan-Mar

Apr-Jun

Jul-Sept

Oct-Dec

T (°C)

Time of the day

Jules

Isba
Introduction (1/3): climate change context

Likely increase in evaporative demand (rise in temperature and radiations)

Likely decrease in soil moisture availability (5 to 30% decrease in rainfall)

Adaptations of agricultural practices:
- irrigation calendar
- early sowing date
- Intermediate crop in winter

Changes in vegetation processes:
- stomatal conductance
- crop phenology

Modifications of long-term dynamics of evapotranspiration (ET)

How improving the representation of ET in land surface models?
Sources of uncertainties in modelled ET

- **Representation of crop phenology**
  - Emergence date
  - Winter/summer crops
- **Water stress**:
  - Type of stress function
  - Implementation in the A-gs model
- **Energy budget**:
  - Single source vs dual source
  - Heterogeneous crops
- **Soil water transfer**
  - Force-restore vs Multi-layer soil diffusion scheme
  - Hydraulic parameters
  - Spatial distribution
- **Irrigation**:
  - Timing
  - Variability of practices
Bulk reservoir scheme with 2 or 3 reservoirs

Force-restore approach from Deardorff (1977):
- Based on by Bhumralkar (1975) and Blackadar (1976) approach for heat transfer
- The superficial soil moisture content is forced by the soil evaporation minus precipitation and restored toward the total moisture content of the soil reservoir.

Water transfers simulated according to moisture content gradient

Main assumption: homogeneous soil profile

Few parameters: advantage for coupling with atmospheric models
Multi-layer soil diffusion model

- Multi-layer (N) soil discretization

- Explicit representation of mass-diffusive equations (Richard's equation)

- Representation of soil vertical heterogeneity
  - Vertical gradient in soil texture and soil texture: impact on evaporation and infiltration
  - Account for upward diffusion from shallow water table: impact on soil evaporation
  - Root profile: improve the representation of the plant response to soil water stress
Multi-layer soil diffusion model

\[
\frac{\partial w_i}{\partial t} = \frac{1}{\Delta z_i} \left[ F_{i-i} - F_i + \frac{S_i}{\rho_w} \right]
\]

with

\[
F_i = \bar{k}_i \left( \frac{\psi_i - \psi_{i+1}}{\Delta \tilde{z}_i} + 1 \right) + \bar{v}_i \left( \frac{\psi_i - \psi_{i+1}}{\Delta \tilde{z}_i} \right),
\]

Layer width

Mean hydraulic conductivity

Matric potential gradient between 2 layers

Mean isothermal vapor conductivity

Source/sink term

Soil moisture tendency

Root profile:
- e.g. exponential model from Jackson et al. model (1996)

Cumulative root fraction between surface and depth \(d_k\)

Root extinction coefficient

\[
Y(d_k) = \left( 1 - R_e^{100 \times d_k} \right) / \left( 1 - R_e^{100 \times d_R} \right).
\]
Soil hydraulic characteristics

- Soil water-retention curve and soil water conductivity curve: van Genuchten, (1980); Brooks and Corey. (1966)
  
e.g. Brooks and Corey, 1966 (residual soil moisture=0)

\[
\psi(w) = \psi_{\text{sat}} \left( \frac{w}{w_{\text{sat}}} \right)^{-b} \quad \text{and} \quad k(\psi) = k_{\text{sat}} \left( \frac{\psi}{\psi_{\text{sat}}} \right)^{-\frac{2\alpha+3}{\beta}}
\]

- Model coefficients and hydraulic properties estimated using pedotransfer functions (PTF) of soil texture
  
e.g ISBA: continuous relationships derived from the Brooks and Corey. (1966) model and the Clapp and Hornberger (1978) parameters
Multi-layer soil diffusion model

- Multi-layer soil discretization
- Explicit solve mass-diffusive equations (Darcy's law and Richard's equation)
- Representation of soil vertical heterogeneity
  - Vertical gradient in soil texture and soil texture: impact on evaporation and infiltration
  - Root profile: improve the representation of the plant response to soil water stress

\[
\frac{\partial w_i}{\partial t} = \frac{1}{\Delta z_i} \left[ F_{i-1} - F_i + \frac{S_i}{\rho_w} \right] \quad \text{with} \quad F_i = \bar{k}_i \left( \frac{\psi_i - \psi_{i+1}}{\Delta z_i} + 1 \right) + \bar{\nu} \left( \frac{\psi_i - \psi_{i+1}}{\Delta z_i} \right),
\]

- Source/sink term
- Matric potential gradient between 2 layers
- Soil moisture tendency
- Layer width
- Mean hydraulic conductivity
- Mean isothermal vapor conductivity
Experiment design

**Control run (CTL):**
- Local climate
- Local LAI
- Local soil parameters (FC, WP, SAT) derived from soil moisture measurements
- Irrigation added to rainfall

**7 Experiments derived from CTL** by replacing local values by:
- **Climate**
  - SAFRAN reanalysis (8km, 1-h)
  - ERA-I/GPCC reanalysis (0.5°, 3-h)
  - SAFRAN&MSG radiations (3 km, 0.5 h)
- **Irrigation**
  - No irrigation
  - Simulated irrigation
- **ECOCLIMAP-II LAI**: monthly climatology derived from MODIS data (Faroux et al, 2013)
- **Soil parameters**: derived from ISBA pedotransfer functions using soil texture
ET performances for different LAI ranges

FORCE-RESTORE: strong reduction of the bias at large LAI in response to the use of more accurate estimate of the soil water content reservoir available for the crop.

DIFFUSION SCHEME: large bias despite the use of the proper water content reservoir.
Results

Sources of uncertainties

- LAI (6 %)
- Modeled Irrig (0 %)
- ERA-I
- SAFRAN
- SAFRAN+
- MSG

Climate (5-7%)

- No Irrigation (15%)
- Soil parameters (20%)

Errors in soil parameters and having no irrigation are the most influential drivers on ET
Impact of uncertainties in irrigation

Lack of irrigation generates larger variations than differences in rainfall between climate data sets.

Inaccurate timing of modeled irrigation:
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- overestimation during senescence
Sources of uncertainties in modelled ET

- **Representation of crop phenology**
  - emergence date
  - winter/summer crops

- **Water stress**
  - stress function
  - implementation in the A-gs model

- **Energy budget**
  - sparse vegetation
  - single source vs dual source

- **Soil water transfer**
  - Force-restore vs Multi-layer soil diffusion scheme
  - spatial distribution of hydraulic parameters

- **Irrigation**
  - timing
  - variability of practices
Impact of exponential vs homogeneous root distribution

Evapotranspiration

Root-zone soil moisture

Slight impact of root-profile parametrization
Smaller impact than the differences between FR and DIF
Evaluation over crop period

Evapotranspiration

Root-zone soil moisture

Underestimation of transpiration by DIF with local soil parameters

Uncertainties in root-profile parametrization
Differences in cumulated soil evaporation, transpiration and drainage between experiments

- **Drainage (D):**
  - FR: decrease
  - DIF: no impact

- **Soil evaporation (E):**
  - FR: increase
  - DIF: no changes

- **Transpiration (T):**
  - FR: increase
  - DIF: slight decrease

Impact of soil parameters: PTF vs local

**Soil evaporation (E):**
- FR: increase
- DIF: no changes

**Transpiration (T):**
- FR: increase
- DIF: slight decrease

**Drainage (D):**
- FR: decrease
- DIF: no impact
Daily evapotranspiration (mm.day\(^{-1}\))

Overall performances of experiments

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<tr>
<th></th>
<th>r</th>
<th>bias</th>
<th>SDD</th>
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<tbody>
<tr>
<td>FR(_{PTF})</td>
<td>0.77</td>
<td>-0.26</td>
<td>0.85</td>
</tr>
<tr>
<td>DIF(_{PTF})</td>
<td>0.80</td>
<td>0.15</td>
<td>0.81</td>
</tr>
<tr>
<td>FR(_{LOC})</td>
<td>0.80</td>
<td>0.05</td>
<td>0.84</td>
</tr>
<tr>
<td>DIF(_{LOC})</td>
<td>0.78</td>
<td>0.09</td>
<td>0.82</td>
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- When pedotransfer estimates are used:
  Best performances for DIF

- When local parameters are used:
  Best performances for FR
Sensitivity to uncertainties in soil parameters

MULTI-LAYER SOIL DIFFUSION SCHEME

Monte-Carlo analysis

Cumulative evapotranspiration (mm)

Time

MC sim  Sim 95% PI  $DIF_{LOC}$  Meas

374 mm