Parameterization of land-surface processes in NWP

Gianpaolo Balsamo

Introductory lecture
**Few words about me...**

**RESEARCH INTERESTS**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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<tr>
<td>2012</td>
<td>HDR (Habilitation) in Meteorology from University UPS–TOULOUSE III, France.</td>
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<td>2003</td>
<td>PHD (Doctorate) in Meteorology from University UPS–TOULOUSE III, and University of Genoa, Italy (co-tutored).</td>
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<td>1999</td>
<td>« Laurea in Fisica » General Physics Degree (4-year, with Atmospheric Physics spec.) University of Turin, Italy.</td>
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<td>Meteorology (BSc/MSc courses as ERASMUS student) Department of Meteorology, University of Reading, UK.</td>
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**UNIVERSITY PATHWAY**

<table>
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**PROFESSIONAL PATHWAY**

<table>
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<th>Year</th>
<th>Description</th>
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<tbody>
<tr>
<td>2009</td>
<td>Senior Scientist, ECMWF, U.K. : Responsible for the land surface modelling in NWP</td>
</tr>
<tr>
<td>2006</td>
<td>Scientist, ECMWF, U.K. : Land Surface Modelling in NWP</td>
</tr>
<tr>
<td>2004</td>
<td>Visiting Scientist Canadian Meteorological Centre, Montréal: Land Data Assimilation System in NWP</td>
</tr>
<tr>
<td>1999</td>
<td>Forecaster for the Piedmont Regional Meteorological Centre (ARPA-Piemonte), Turin, Italy.</td>
</tr>
</tbody>
</table>
Layout of these lectures

- Introduction
- General remarks
- Model development and validation
- The surface energy budget
- The surface water budget
- Soil heat transfer
- Soil water transfer
- Snow
- Initial conditions
- Conclusions and a look ahead
The challenges for Land Surface Modeling

- Capture natural diversity of land surfaces (heterogeneity) via a simple set of equations

- Focus on elements which affects more directly weather and climate (i.e. soil moisture, snow cover).
Today's satellite images are very informative not only about natural land surface...
Methodology

- Plant and soil science (a bite)
- ECMWF model and its evolution
- Justification and examples

Further readings

- Terrestrial Hydrometeorology, by W.J. Shuttleworth
- Environmental Soil Physics, by D. Hillel
- and few links to lecture notes by P. Viterbo

http://www.ecmwf.int/newsevents/training/lecture_notes/pdf_files/PARAM/Land_surf.pdf
http://www.ecmwf.int/newsevents/training/lecture_notes/pdf_files/PARAM/Rol_land.pdf
http://www.ecmwf.int/newsevents/training/lecture_notes/pdf_files/PARAM/Surf_ass.pdf
Earth energy cascade

- The sun emits $4 \times 10^{26}$ W
- The Earth intercepts 1.37 kW/m$^2$
- This energy is distributed between
  - Direct reflection (~30%)
  - Conversion to heat, mostly by surface absorption (~43%), re-radiated in the infrared
  - Evaporation, Precipitation, Runoff (~22%)
  - Rest of the processes (~5%, Winds, Waves, Convection, Currents, Photosynthesis, Organic decay, tides, ...)

Robinson & Henderson-Sellers, 1999
Role of land surface (1)

Atmospheric general circulation models need **boundary conditions** for the enthalpy, moisture (and momentum) equations: Fluxes of energy, water at the surface.

Trenberth *et al.* 2009: Earth’s global energy budget

ERA-Interim 1989-2008

ERA-40 1989-2001
### Role of land surface at ECMWF

**ECMWF model(s) and resolutions**

<table>
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<tr>
<th>Remarks</th>
<th>Length</th>
<th>Horizontal</th>
<th>Vertical</th>
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<tbody>
<tr>
<td>Deterministic</td>
<td>10 d</td>
<td>T1279 (16 km)</td>
<td>L137 00+12 UTC</td>
</tr>
<tr>
<td>Monthly/VarEPS (N=51)</td>
<td>0-10d</td>
<td>T639 (30 km)</td>
<td>L91</td>
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<tr>
<td></td>
<td>(SST tendency)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-32d</td>
<td>T399 (60 km)</td>
<td>L91</td>
</tr>
<tr>
<td></td>
<td>(Ocean coupled)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seasonal forecast</td>
<td>6 m</td>
<td>T159 (125 km)</td>
<td>L62</td>
</tr>
<tr>
<td></td>
<td>(Ocean coupled)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assimilation physics</td>
<td>12 h</td>
<td>T255 (80 km)</td>
<td>L137</td>
</tr>
<tr>
<td></td>
<td>T95 (200 km) inner</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>T159 (125 km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERA-40 Reanalysis 1958-2002</td>
<td>T159 (125 km)</td>
<td>3D-Var+surface OI</td>
<td>L60</td>
</tr>
<tr>
<td>ERA-Interim Reanalysis</td>
<td>1989-today T255 (80 km)</td>
<td>4D-Var+surface OI</td>
<td>L91</td>
</tr>
</tbody>
</table>

Land surface modelling (and data assimilation systems) need flexibility & upscalability (conservation) properties to be used by at a wide range of spatial resolutions in spite of natural heterogeneity of land surfaces. Errors in the treatment of land surface are likely to affect all forecasts products.
ECMWF deterministic model

Horizontal resolution upgrades:
- T511 ~ 40km (21 Nov 2000)
- T799 ~ 25 km (1 Feb 2006)
- T1279 ~ 16 km (26 Jan 2010)
- T2047 ~ 10 km (in 2015, TBC)

Vertical resolution upgrades:
- L60 (21 Nov 2000)
- L91 (1 Feb 2006)
- L137 (June 2013)
- <850 hPa
Role of land surface (3)

- **Feedback mechanisms for other physical processes, e.g.**:
  - Surface evaporative fraction\(^1\) \((EF)\), impacting on low level cloudiness, impacting on surface radiation, impacting on …
  - Bowen ratio\(^2\) \((Bo)\), impacting on cloud base, impacting on intensity of convection, impacting on soil water, impacting on …

\[ EF = \frac{\text{Latent heat}}{\text{Net radiation}} \]
\[ Bo = \frac{\text{Sensible heat}}{\text{Latent heat}} \]
Role of land surface (4)

- Partitioning between sensible heat and latent heat determines soil wetness, acting as one of the forcings of low frequency variability (e.g. extended drought periods).

- At higher latitudes, soil water only becomes available for evaporation after the ground melts. The soil thermal balance and the timing of snow melt (snow insulates the ground) also controls the seasonal cycle of evaporation.

- The outgoing surface fluxes depend on the albedo, which in turn depends on snow cover, vegetation type and season.

- Surface (skin) temperatures of sufficient accuracy to be used in the assimilation of TOVS satellite radiances (over land there is no measured input field analogous to the sea surface temperature)
**Systematic errors 850 hPa T**

1996 operational bias

1997 operational bias

*Viterbo and Betts, 1999*

- **A smaller albedo of snow in the boreal forests (1997)** reduces dramatically the **spring** (March-April) error in day 5 temperature at 850 hPa
Near surface atmospheric errors

- In the French forecast model (~10km) local soil moisture patterns anomalies at time $t_0$ are shown to correlate well with large 2m temperature forecast errors (2-days later)
Global budgets (1)

- **Mean surface energy fluxes** (Wm\(^{-2}\)) in the ERA40 atmospheric reanalysis (1958-2001); positive fluxes downward

\[
\begin{array}{cccccc}
R_S & R_T & H & LE & G & Bo = H/LE \\
\hline
\text{Land} & 134 & -65 & -27 & -40 & 2 & 0.7 \\
\text{Sea} & 166 & -50 & -12 & -102 & 3 & 0.1 \\
\end{array}
\]

- **Land surface**
  - The net radiative flux at the surface \((R_S + R_T)\) is downward. Small storage at the surface \((G)\) implies upward sensible and latent heat fluxes.

- **Bowen ratio: Land vs Sea**
  - Different physical mechanisms controlling the exchanges at the surface
    - **Continents:** Fast responsive surface; Surface temperature adjusts quickly to maintain zero ground heat flux
    - **Oceans:** Large thermal inertia; Small variations of surface temperature allowing imbalances on a much longer time scale
Global budgets (2)

- **Surface fluxes and the atmosphere**
  - **Sensible heat** \((H)\) at the bottom means energy **immediately** available close to the surface.
  - **Latent heat** \((LE)\) means **delayed availability** through condensation processes, for the whole tropospheric column.
  - The net radiative cooling of the whole atmosphere is balanced by condensation and the sensible heat flux at the surface. Land surface processes affect **directly** \((H)\) or **indirectly** (condensation, radiative cooling, ...) this balance.
Terrestrial atmosphere time scales

- Atmosphere recycling time scales associated with land reservoir

- Precipitation: \( \frac{4.5}{10^7} = 15 \) days
- Evaporation: \( \frac{4.5}{71} = 23 \) days

Chahine, 1992

\([\text{[\(\bullet\)]]} = 10^{15} \text{ kg} = \text{ teratons}\)

\([\text{[\(\bullet\)]]} = 10^{15} \text{ kg yr}^{-1}\)
Surface time scales (memory) (1)

- **Diurnal time scale**
  - Forcing time scale determined by the quasi-sinusoidal radiation modulated by clouds

Betts et al 1998
Surface time scales (memory) (2)

- **Diurnal/weekly time scale**
  - Forcing time scale determined by the “quasi-random” precipitation (synoptic/mesoscale)

![Graph showing solar radiation (S) and precipitation data over time](image)

Betts et al. 1998
Surface time scales (memory) (3)

- **Weekly/monthly** time scale
  - Internal time scale determined by the physics of soil water exchanges/transfer

![Graph showing soil moisture and rainfall over time](Betts et al 1998)
Surface time scales (memory) (4)

- Weekly/monthly time scale
  - Evaporation time scale determined by the ratio (net radiative forcing)/(available soil water)

\[ R_n = 150 \text{ Wm}^{-2} \sim (5 \text{ mmd}^{-1}) \]

Soil water = 150 mm

\[ (5 \text{ mmd}^{-1})/(150 \text{ mm}) = 30 \text{ days} \]
The hydrological rosette

Driver

Water exchange

Soil state

Rate

Soil Control

Atmosphere Control

EVAPORATION DURING DRY PERIODS

WATER BELOW CAPACITY

FIELD CAPACITY

ROOT SOIL WATER AT OR ABOVE

INfiltration during WET PERIODS

$E < E_{pol}$

$I_r = P$

$I_r < P$

$E = E_{pol}$

Dooge, 1992
A diversity of land models !!!

<table>
<thead>
<tr>
<th>Key Model</th>
<th>Number of Canopy Layers</th>
<th>Intercepted Treated</th>
<th>Number of Layers Included for</th>
<th>Canopy</th>
<th>Rationale for Temperature</th>
<th>Rationale for Soil moisture</th>
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<td>2</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
<td>Philip-de Vries</td>
<td>Pitman et al (1991)</td>
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<tr>
<td>C BUCKET</td>
<td>0</td>
<td>no</td>
<td>1</td>
<td>-</td>
<td>instantaneous surface heat balance</td>
<td>bucket + variation</td>
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<tr>
<td>D CLASS</td>
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<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Darcy's Law</td>
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<tr>
<td>G ISBA</td>
<td>1</td>
<td>yes</td>
<td>2-3</td>
<td>aerodynamic</td>
<td>force-restore</td>
<td>force-restore</td>
<td>Noilhan and Planton (1989)</td>
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<tr>
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<td>1</td>
<td>Penman/Monteith</td>
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<td>Philip-de Vries</td>
<td>Famiglietti and Wood (1995)</td>
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<td>7</td>
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<td>heat diffusion</td>
<td>Darcy's Law</td>
<td>Avisar and Pielke (1989)</td>
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<td>6</td>
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<td>bucket</td>
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<td>bucket</td>
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<td>Darcy's Law</td>
<td>Entekhabi and Eagleson (1989)</td>
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<td>O NMC-MRF</td>
<td>1</td>
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<td>1</td>
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<td>-</td>
<td>-</td>
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<td>Penman/Monteith</td>
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<td>diffusion</td>
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<td>30</td>
<td>Ohm's law analogy</td>
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<td>0</td>
<td>-</td>
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<td>bucket + variation</td>
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<td>2</td>
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<td>Choisnel</td>
<td>Ducoudré et al (1993)</td>
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<td>2</td>
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<td>force-restore</td>
<td>diffusion</td>
<td>Xue et al (1991)</td>
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<td>diffusion</td>
<td>Warrilow et al (1986)</td>
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<td>heat diffusion</td>
<td>Philip-de Vries</td>
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<td>1</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
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</tbody>
</table>

Table 3.1 Characteristics of several land surface parametrization schemes

Pitman et al 1993, with modifications
The Water, Energy and Carbon cycle

- Numerical Weather Prediction models have considerably evolved over time with respect to how they represent the land surface and its interaction with the atmosphere.

  - Precipitation forecasts improvements support (1 day/decade in skill gain) refined LSMs.

  - The needs of unification of NWP and Climated model are a driver to develop land surface schemes with increased realism.

Evolving towards Earth System Models.
Strategy for land surface model development at ECMWF

- Site runs (Offline)
- 2D runs (Offline)
- Global (Offline)
- Coupled GCM
- Coupled GCM + DA

Generality

Complexity/Cost
The combined verification of multiple processes permit to avoid tuning in favor of a more physically-based development.
Ground-based conventional observations

SYNOP/METAR/SHIP stations

Proximity map for 50000 inhabitants settlement. Source: JRC, World-Bank)

Satellite Remote Sensing

SMOS ESA

METOP ESA

METEOSAT (MSG) EUMETSAT
Europe 2m forecast errors for March 2001

72 H FC verifying at 12 UTC
Soil moisture verification

International Soil Moisture Network (ISMN) TU-Wien
http://www.ipf.tuwien.ac.at/insitu/
From Albergel et al. (2012).
Soil temperature verification

Averaged over Germany stations 26 April 2001

Verifying at 15 UTC
Verifying at 21 UTC
Verifying at 06 UTC
Land Fluxes (E, H$_2$O, CO$_2$) verification

**FLUXNET tower sites:**

http://www.fluxdata.org/

**GRDC**
(Global Runoff Data Centre):

http://www.gewex.org/grdc.html
ECMWF surface model milestones

- Vegetation based evaporation • 1989
- CY48 (4 layers + …) • 1993 / ERA15
- Initial conditions for soil water • 1994
- Stable BL/soil water freezing • 1996
- Albedo of snow forests • 1996
- OI increments of soil water • 1999
- TESSEL, new snow and sea ice • 2000 / ERA40
- HTESSEL, revised soil hydrology • 2007
- HTESSEL+SNOw, revised snow • 2009
- HTESSEL+SNOw+LAI, seasonal vegetation • 2010
- CHTESSEL (carbon-land surface) • 2012
- LAKETESSEL (addition of lake tile) • 2013
TESSEL model and validation

● Model Description

● 1D validation
  - Cabauw
  - FIFE
  - ARME
  - SEBEX
  - All the above + HAPEX-MOBIHLY+BOREAS

● US Summer 1993

● Soil water initial conditions
  Viterbo, 1996.

● Soil freezing
  Viterbo et al., 1999. QJRMS, 125, 2401-2426.

● Snow forest albedo
  Viterbo and Betts, 1999. JGR, 104D, 27,803-27,810.

● Mississippi river basins

● Mackenzie river basin
  Betts and Viterbo, 2000: J. Hydrometeor, 1, 47-60.

● Impact of land on weather
  Viterbo and Beljaars, 2002: Springer.
(CH)TESSEL scheme in a nutshell

- Tiled ECMWF Scheme for Surface Exchanges over Land

Revised canopy resistances, including air humidity stress on forest

High and low vegetation treated separately

Variable root depth

New treatment of snow under high vegetation

No root extraction or deep percolation in frozen soils

High vegetation

Low vegetation

Interception reservoir

Bare ground

Snow on ground & low vegetation

Snow under high vegetation

Land surface tiles in ERA40 surface scheme

+ 2 tiles (ocean & sea-ice)
**Land surface model evolution**

<table>
<thead>
<tr>
<th></th>
<th>2000/06</th>
<th>2007/11</th>
<th>2009/03</th>
<th>2009/09</th>
<th>2010</th>
</tr>
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<tbody>
<tr>
<td><strong>NEW SNOW</strong></td>
<td>Dutra et al. (2010)</td>
<td>Revised snow density</td>
<td>Liquid water reservoir</td>
<td>Revision of Albedo and sub-grid snow cover</td>
<td></td>
</tr>
<tr>
<td><strong>NEW LAI</strong></td>
<td>Boussetta et al. (2010)</td>
<td>New satellite-based</td>
<td>Leaf-Area-Index</td>
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</tbody>
</table>

- **TESSEL**
- **Hydrology-TESSEL**
- **NEW SNOW**
- **NEW LAI**
- **SOIL Evaporation**

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PA Surface I of IV - training course 2014  
Slide 35
Strategy for land surface model development at ECMWF (applied)

- Site runs (Offline)
- 2D runs (Offline)
- Global (Offline)
- Coupled GCM
- Coupled GCM + DA

Examples:
- SEBEX
- BERMS
- SNOWMIP2
- FLUXNET
- RhoneAGG
- AMMA
- GSWP2
- GLACE2
- ERA40, ERA-Interim
- ERA-Clim

Generality

Complexity/Cost
Soil hydrology
(Balsamo et al. 2009)
New snow scheme
(Dutra et al. 2010)
Forecasts (+36-h) impact

Forecast sensitivity

- Cooling 2m temperature
- Warming 2m temperature

Forecast Impact

- Improving temperature
- Degrade 2m temperature
Climate simulation impact

- Simulations colder than ERA-Interim
- Warmer than ERA-Interim
Perspectives for the land surface in Earth System Prediction

Modularity of the land system is a key to ESP model integrations and inter-operability of parameterizations.

- Better characterisation of the vertical profiles
- Complexity needs a step-wise approach
- The assimilation methods are integral part of the model diagnostics
- Unification of processes (cryosphere)
- A better coupling between sub-systems is the ultimate goal, achievable by enhanced knowledge on each sub-system and the mutual interactions
- Better representation on heterogeneity and ecosystems interaction

PA Surface I of IV - training course 2014

Slide 41
Parameterization of land-surface processes

...modelling should be always guided by observations...but in case of land surface your senses are also amazing instruments 😊

http://www.youtube.com/watch?v=jfa29pq6NFs