Parameterization of land-surface processes in NWP

Gianpaolo Balsamo

Introductory lecture
Few words about me...

RESEARCH INTERESTS


Land-Atmosphere predictability studies

UNIVERSITY PATHWAY

2012 HDR (Habilitation) in Meteorology from University UPS–TOULOUSE III, France.

2003 PHD (Doctorate) in Meteorology from University UPS–TOULOUSE III, and University of Genoa, Italy (co-tutored).

1999 « Laurea in Fisica » General Physics Degree (4-year, with Atmospheric Physics spec.) University of Turin, Italy.

1997, Meteorology (BSc/MSc courses as ERASMUS student) Department of Meteorology, University of Reading, UK.

PROFESSIONAL PATHWAY

2009 Senior Scientist, ECMWF, U.K.: Responsible for the land surface modelling in NWP

2006 Scientist, ECMWF, U.K.: Land Surface Modelling in NWP

2004 Visiting Scientist Canadian Meteorological Centre, Montréal: Land Data Assimilation System in NWP


1999 Forecaster for the Piedmont Regional Meteorological Centre (ARPA-Piemonte), Turin, Italy.
Layout of these lectures

- Introduction
- General remarks
- Model development and validation
- The Earth energy budget
- Soil/Water contrasts
- Snow hydrology
- Snow atmosphere coupling
- Vegetation cycle
- Carbon dioxide
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

Global Energy Flows W m⁻²
## Role of land surface at ECMWF

**ECMWF model(s) and resolutions**

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

Vertical resolution:
- L60 (12 levels) <850 hPa
- L91 (15 levels) <850 hPa

PA Surface I of IV - training course 2015
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 …

\(1\ EF = \frac{\text{Latent heat}}{\text{Net radiation}} \)

\(2\ Bo = \frac{\text{Sensible heat}}{\text{Latent heat}} \)
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

March-April 1996 850 hPa T day 5 error

1997 operational bias

March-April 1997 850 hPa T day 5 error

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

Viterbo and Betts, 1999
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)

Balsamo, 2003
Global budgets (1)

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

<table>
<thead>
<tr>
<th></th>
<th>(R_S)</th>
<th>(R_T)</th>
<th>(H)</th>
<th>(LE)</th>
<th>(G)</th>
<th>(Bo=H/LE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>134</td>
<td>-65</td>
<td>-27</td>
<td>-40</td>
<td>2</td>
<td>0.7</td>
</tr>
<tr>
<td>Sea</td>
<td>166</td>
<td>-50</td>
<td>-12</td>
<td>-102</td>
<td>3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- 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: \( \frac{4.5}{107} = 15 \) days
- Evaporation: \( \frac{4.5}{71} = 23 \) days

\[
\begin{align*}
\text{Evaporation} & \quad 71 \\
\text{Rain} & \quad 107 \\
\text{Runoff} & \quad 36 \\
\text{Land} & \quad \text{Chahine, 1992}
\end{align*}
\]

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

\( [\bullet] = 10^{15} \text{ kg yr}^{-1} \)
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 surface time scales with precipitation and Betts et al 1998 reference](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

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

Dooge, 1992
### A diversity of land models !!!

#### Table 3.1 Characteristics of several land surface parametrization schemes

<table>
<thead>
<tr>
<th>Key Model</th>
<th>Number Canopy Layers</th>
<th>Interception Treated</th>
<th>Number of Layers Included for</th>
<th>Canopy Rationale for Temperature</th>
<th>Rationale for Soil moisture</th>
<th>Reference</th>
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<tbody>
<tr>
<td>A BATS1E</td>
<td>1</td>
<td>yes</td>
<td>2 3 2</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
<td>Dickinson et al (1986, 1993)</td>
</tr>
<tr>
<td>B BEST</td>
<td>1</td>
<td>yes</td>
<td>3 2 2</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
<td>Pitman et al (1991)</td>
</tr>
<tr>
<td>C BUCKET</td>
<td>0</td>
<td>no</td>
<td>0 1 1</td>
<td>instantaneous surface</td>
<td>bucket + variation</td>
<td>Robock et al (1995)</td>
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<tr>
<td>D CLASS</td>
<td>1</td>
<td>yes</td>
<td>3 3 3</td>
<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Verseghy (1991)</td>
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<tr>
<td>E CSIRO</td>
<td>1</td>
<td>yes</td>
<td>3 2 1</td>
<td>aerodynamic</td>
<td>force-restore</td>
<td>Kowalczyk et al (1991)</td>
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<tr>
<td>F GISS</td>
<td>1</td>
<td>yes</td>
<td>6 6 6</td>
<td>aerodynamic</td>
<td>force-restore</td>
<td>Abramopoulos et al (1988)</td>
</tr>
<tr>
<td>G ISBA</td>
<td>1</td>
<td>yes</td>
<td>2 3 2</td>
<td>aerodynamic</td>
<td>force-restore</td>
<td>Noilhan and Planton (1989)</td>
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<td>H TOPPLATS</td>
<td>1</td>
<td>yes</td>
<td>1 2 1</td>
<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Famiglietti and Wood (1995)</td>
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<tr>
<td>I LEAF</td>
<td>1</td>
<td>yes</td>
<td>7 7 3</td>
<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Darcy's Law</td>
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<tr>
<td>J LSX</td>
<td>2</td>
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<td>6 6 6</td>
<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Avissar and Pielke (1989)</td>
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<tr>
<td>K MAN69</td>
<td>0</td>
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<td>heat diffusion</td>
<td>Darcy's Law</td>
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<td>N MOSAIC</td>
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<td>2 3 2</td>
<td>Penman/Monteith</td>
<td>-</td>
<td>Abramopoulos et al (1988)</td>
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<tr>
<td>O NMC-MRF</td>
<td>1</td>
<td>yes</td>
<td>1 1 1</td>
<td>lumped with soil</td>
<td>-</td>
<td>Entekhabi and Eagleson (1989)</td>
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<tr>
<td>P CAPS</td>
<td>1</td>
<td>yes</td>
<td>2 2 1</td>
<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Mahrt and Pan (1984)</td>
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<tr>
<td>Q PLACE</td>
<td>1</td>
<td>yes</td>
<td>30 30 2</td>
<td>Ohm's law analogy</td>
<td>force-restore</td>
<td>Wetzel and Chang (1988)</td>
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<tr>
<td>R RSTOM</td>
<td>-</td>
<td>no</td>
<td>0 1 1</td>
<td>-</td>
<td>-</td>
<td>Milly (1992)</td>
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<tr>
<td>S SECHIBA</td>
<td>1</td>
<td>yes</td>
<td>2 2 1</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
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<td>2 3 1</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
<td>Ducoudré et al (1993)</td>
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<tr>
<td>U UKMO</td>
<td>1</td>
<td>yes</td>
<td>4 1 1</td>
<td>Penman/Monteith or full energy balance</td>
<td>heat diffusion</td>
<td>Philip-de Vries</td>
</tr>
<tr>
<td>V VIC</td>
<td>1</td>
<td>yes</td>
<td>1 2 1</td>
<td>Penman/Monteith</td>
<td>heat diffusion</td>
<td>Liang et al (1994)</td>
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<tr>
<td>W BIOME</td>
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<td>1 1 1</td>
<td>Penman/Monteith</td>
<td>force-restore</td>
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</tr>
</tbody>
</table>

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
An Integrated & Process-oriented verification to support development

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

PA Surface I of IV - training course 2015
Europe 2m forecast errors for March 2001

72 H FC verifying at 12 UTC

[Maps showing 2m specific humidity and temperature forecast errors for Europe]
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

Soil temperature [°C]

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**

+ 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>
</thead>
<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>Revised snow density</td>
<td>New satellite-based</td>
<td>Leaf-Area-Index</td>
<td></td>
</tr>
<tr>
<td><strong>SOIL Evaporation</strong></td>
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<td></td>
<td></td>
<td></td>
<td>Mahfouf and Noilhan (1991)</td>
</tr>
</tbody>
</table>
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

PA Surface I of IV - training course 2015
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

- Better characterisation of the vertical profiles
- Better representation on heterogeneity and ecosystems interaction
- Unification of processes (cryosphere)

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

- Complexity needs a step-wise approach
- The assimilation methods are integral part of the model diagnostics
- A better coupling between sub-systems is the ultimate goal, achievable by enhanced knowledge on each sub-system and the mutual interactions
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