Land surface-atmosphere interaction approaching high resolution

Patrick Samuelsson
SMHI
patrick.samuelsson@smhi.se

With acknowledgements to NWP and SURFEX colleagues!
Outline

● Status and plans of surface modelling (SURFEX), its physiography (ECOCLIMAP), and assimilation (SODA) in the ALADIN-HIRLAM NWP system.

● State of the art NWP land-surface models

   i. are often based on the tiling approach where the tiles are independent of each other.

   ii. the lowest atmospheric level is considered as the upper boundary condition for the surface layers for prognostic variables, fluxes and diagnostic quantities

   iii. the Monin-Obukov similarity theory is used for the surface layer

   iv. are still happy with quite empirical 1D hydrology...

   v. the horizontal resolution is the same throughout the atmospheric column

● Concluding remarks
Outline

• Status and plans of surface modelling (SURFEX), its physiography (ECOCLIMAP), and assimilation (SODA) in the ALADIN-HIRLAM NWP system.
SURFEX/SODA and their options

[Image of a diagram illustrating the different components of SURFEX: Land, Town, Sea, and Lake, with processes such as orographic friction, land surface energy, water, and carbon fluxes, hydrological and vegetation processes, town energy balance, and sea and lake models.

http://www.umr-cnrm.fr/surfex/

SURFEX is designed to work from ESM scale to very high resolution and offline. The exact combination of options depends on application!

SURFEX physics

4 tiles:
- Land, Town, Sea, Lake

Land tile:
- 1-19 patches (land use)
- 4 snow schemes
- Force-restore and diffusion soil
- Explicit canopy (MEB)
- Several hydrological options
- Phenology (LAI) and carbon

Town:
- Town Energy Balance (TEB)

Sea:
- A few flux formulations
- Sea ice (GELATO & SICE)
- 1D ocean column model

Lake:
- FLake

Data assimilation (SODA)

Optimum Interpolation:
Operational

Extended Kalman Filter (EKF):
Applied in projects. Operational in near future in HARMONIE-AROME

Ensemble Kalman Filter (EnKF):
Under development
SURFEX8.0 patches (sub-tiles) for the land tile

Rules of parameter aggregation

ECOCLIMAP 19 vegetation types

- Bare soil
- Rocks
- Permanent snow/ice
- C3 crops
- C4 crops
- Grassland
- Boreal grass
- Tropical grass
- Irrigated crops
- Wetlands, parks, irrigated grass
- Temperate broadl. cold-dec. summergr
  - Tropical broadleaf deciduous
  - Temperate broadleaf evergreen
- Boreal broadl. cold-dec. summergr.
- Shrubs
  - Tropical broadleaf evergreen
  - Boreal needleleaf evergreen
  - Temperate needleleaf evergreen
- Boreal needlel. cold-dec. summergr.
SURFEX8.0 patches (sub-tiles) for the land tile

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ECOCLIMAP 19 vegetation types

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A number of parameters are associated with each vegetation type (e.g. LAI, albedo, root depth, Rmin,...)
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From Stéphanie Faroux (Météo-France):

- A global land cover map at 300m (1/360°) resolution.
- Each grid point stands for only ONE surface / vegetation / urban type.
- The building of the land cover map aims at being mainly automatic so that it could be updated quite easily and regularly over the years.
- The basemap chosen to build the ECOCLIMAP-SG new land cover map is the ESA CCI Land Cover product (Version 1.6.1, 28/01/2016)
ECOCLIMAP 2nd generation (SG) (in SURFEX8.1)

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To this land cover map will be associated global maps of primary parameters:
- 10-day LAI
- Root, soil and ice depths
- Height of trees
- Soil and 10-day vegetation albedo
- Parameters for towns (to be defined)
From Stéphanie Faroux (Météo-France):

- A global land cover map at **300m** (1/360°) resolution.
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To this land cover map will be associated global maps of **primary parameters:**
- 10-day LAI
- Root, soil and ice depths
- Height of trees
- Soil and 10-day vegetation albedo
- Parameters for towns (to be defined)

**The difficulty to build the map lies in:**
- **Translating** the ESA-CCI LC original cover types into our new ECOCLIMAP-SG land cover types
- Doing it **automatically enough** to be able to repeat it when a new version of ESACCI-LC will be released.
Details in physical processes

**1st generation**
Manabe (1969)

- Sensible heat $T_r$
- Latent heat $e_r$
- Reference height
- Aerodynamic pathway in lower atmosphere
- Fixed surface properties
- Bucket hydrology
- $W_{\text{max}} = 150$ mm
- Runoff

**2nd generation with explicit canopy**
Deardorff (1978)

**3rd generation with carbon**
Collatz et al. (1991); Sellers et al. (1992)

Latest HIRLAM at 5km resolution
Details in physical processes

1\textsuperscript{st} generation
Manabe (1969)

2\textsuperscript{nd} generation
with explicit canopy
Deardorff (1978)

3\textsuperscript{rd} generation
with carbon

Latest HIRLAM at 5km resolution
cy40t/h uses SURFEXv7.3 at 1.3/2.5 km resolution
Details in physical processes

1st generation
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3rd generation with carbon
Collatz et al. (1991); Sellers et al. (1992)

cy40t/h uses SURFEXv7.3 at 1.3/2.5 km resolution

cy43t uses SURFEXv8 as 1.5 generation

cy43h will use SURFEXv8 as 2nd generation

Arpege ESM uses SURFEXv8 as 3rd generation
Details in physical processes

1\textsuperscript{st} generation

Manabe (1969)

- Sensible heat $T_r$
- Latent heat $e_r$
- $r_a$

2\textsuperscript{nd} generation with explicit canopy

Deardorff (1978)

- Aerodynamic pathway in lower atmosphere
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3\textsuperscript{rd} generation with carbon

Collatz et al. (1991); Sellers et al. (1992)

SURFEXv8

Latest HIRLAM at 5km resolution

arpege ESM uses SURFEXv8 as 3\textsuperscript{rd} generation

cy40t/h uses SURFEXv7.3 at 1.3/2.5 km resolution

cy43t uses SURFEXv8 as 1.5 generation

cy43h will use SURFEXv8 as 2\textsuperscript{nd} generation

ECMWF (H-TESSEL)

ECMWF (C-TESSEL)
The ALADIN-HIRLAM system: HARMONIE-AROME

The ALADIN-HIRLAM NWP system (based on IFS) includes a few configurations: ALARO, AROME-France, HARMONIE-AROME, Climate

The latest release of the HARMONIE-AROME configuration is based on cy40h.

The surface perspective of the cycles:

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<tr>
<th></th>
<th>cy40h</th>
<th>cyxxh (long term ambition)</th>
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<tr>
<td>Patches</td>
<td>1 or 2</td>
<td>2-4 patches with explicit canopy</td>
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<td>Soil</td>
<td>Force-restore</td>
<td>Diffusion (14 layers)</td>
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<td>Snow</td>
<td>D95</td>
<td>Explicit snow (12 layers)</td>
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<td>Glacier</td>
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<td>Explicit snow as glacier</td>
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<td><strong>Sea</strong></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>SICE</td>
<td>Sea ice (SICE)</td>
</tr>
<tr>
<td><strong>Lake</strong></td>
<td>FLake (optional)</td>
<td>FLake (later with EKF)</td>
</tr>
<tr>
<td><strong>Town</strong></td>
<td>TEB</td>
<td>TEB (more options) as presented by Valéry Masson</td>
</tr>
<tr>
<td><strong>Physiog.</strong></td>
<td>ECOCLIMAP-II</td>
<td>ECOCLIMAP 2\textsuperscript{nd} generation</td>
</tr>
<tr>
<td></td>
<td>1 km resolution</td>
<td>300 m resolution</td>
</tr>
</tbody>
</table>
Outline

- Status and plans of surface modelling (SURFEX), its physiography (ECOCLIMAP), and assimilation (SODA) in the ALADIN-HIRLAM NWP system.

- State of the art NWP land-surface models
  
  i. are often based on the tiling approach where the tiles are independent of each other.
Shao et al. (2013) say that it is now understood that land-surface heterogeneity has two major effects on surface fluxes:

- **The aggregation effect** means that an aggregated surface will not produce the correct fluxes since it does not account for the non-linear combination of transfer processes and surface heterogeneity.

- **The dynamic effect** occurs because contrasts in surface conditions generate turbulence and horizontal advection that leads to spatial variations in turbulent transfer. To date, no theoretical framework exists, equivalent to Monin–Obukhov similarity theory, which effectively represents the dynamic effect.
Okay, the tiling approach is good! But the tiles become less and less independent the higher the horizontal resolution, and the more heterogeneous the landscape is. Take TESSEL as an example...

Aerodynamic resistance, \( r_a \), for each tile:

When the grid size is >10 km and the characteristic scale of tiles is >1 km it is reasonable to assume that the \( r_a \)s are independent of each other (local conditions of \( z_0 \), \( T_s \), ... dominate).
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When the grid size is $>10$ km and the characteristic scale of tiles is $>1$ km it is reasonable to assume that the $r_a$'s are independent of each other (local conditions of $z_0$, $T_s$, ... dominate).

But, when the grid size is $<5$ km and the characteristic scale of tiles is $<1$ km this assumption is less and less valid.
The tiling approach and surface fluxes

With $O(1)$ km tiles the turbulence is probably pretty unique over each tile and the tiles are characterized by their individual $r_a$'s (forest, open, lake).

E.g., momentum flux is expressed as

$$
\tau_0 = -\rho_a u' w' = \rho_a C_D U_r^2 = \rho_a \frac{U_r}{r_a}
$$
But, when tile size is $O(100 \text{ m})$ the turbulence is probably dominated by the most rough surface (forest) and therefore $a_r$ weighted towards the forest $r_a$ should be the relevant aerodynamic resistance for all tiles, right? Imagine for example small lakes in a forested landscape. Ok, with a very low lowest model level today's approximation is less problematic...

Thus, we should take into account the degree of sub-grid heterogeneity in physiography. Requires physiography resolution $>>$ grid resolution.
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The lowest atmospheric level

HARMONIE-AROME experience when introducing 2 patches over land...

- Lowest model level: 12 m
- Grid size: 2.5 km

NPATH=1 (N1), i.e. all veg parameters averaged to one value.

NPATH=2 (N2), i.e. forest and open land separated
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Lower BL wind N1 > Lower BL wind N2
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Z_{0eff} N1 < Z_{0eff} N2
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\[ U_{10mN1} > U_{10mN2\_open} \]

\[ \text{Lower BL wind N1} > \text{Lower BL wind N2} \]

\[ Z_{0\text{eff N1}} < Z_{0\text{eff N2}} \]

\[ U_{10mN2\_forest} \sim U_{10mN2\_open} \]
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Lower BL wind N1 > Lower BL wind N2

\[ Z_{0\_eff N1} < Z_{0\_eff N2}\]

NPATH=2 (N2), i.e. forest and open land separated

\[ U_{10mN2\_forest} \sim U_{10mN2\_open}\]

Hmhm, it is not realistic to enforce horizontally homogeneous conditions close to the surface, independent on surface/atmospheric conditions … what to do?
The lowest atmospheric level

As stated by Essery et al. (2003), in principle, the lowest model level should be set to the “blending height”;

- This is an approximate height scale (Mason 1988), high enough above the surface, that the temperature, humidity, and wind speed are nearly homogeneous but low enough that their profiles are nearly in equilibrium with the local surface.

- Blending heights depend on surface roughness, atmospheric stability, and heterogeneity length scales (degree of sub-grid heterogeneity in physiography).

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Shao et al. (2013) used a LES atmosphere–land model system at 60 m horizontal resolution to study the effect of heterogeneous land surface on atmospheric fluxes.

- Near the surface (below ~10 m), the flux patterns are closely correlated with the land-use patterns and remains identifiable to a level of over 60 m.
- Above, on average, the correlation between the flux and land-use pattern is quite strong and persistent in at least the lower half of the atmospheric boundary layer.

Idea... worth testing....??

High blending height:

- NLEV-4
- NLEV-3
- NLEV-2
- NLEV-1
- NLEV

Low blending height:

- NLEV-4
- NLEV-3
- NLEV-2
- NLEV-1
- NLEV

- Use the **blending height** $u,v,q,T$ as upper boundary condition (BC) for the surface model.
The lowest atmospheric level

Idea... worth testing....??

High blending height:

NLEV-4

NLEV-3

NLEV-2

NLEV-1

NLEV

Low blending height:

Constant flux layer

Constant flux layer

- Use the **blending height** $u,v,q,T$ as upper boundary condition (BC) for the surface model.
- Assume constant flux layer below **blending height** which means that fluxes (momentum, heat, moisture) can still be used as lower BC for the atmosphere at NLEV.
The lowest atmospheric level

Idea... worth testing....??

- Use the blending height u,v,q,T as upper boundary condition (BC) for the surface model.
- Assume constant flux layer below blending height which means that fluxes (momentum, heat, moisture) can still be used as lower BC for the atmosphere at NLEV.
- Separate profiles below blending height over each patch, forest and open land, respectively.
The lowest atmospheric level

Using the coupled system ECHAM6/JSBACH de Vrese et al. (2016) have investigated the influence of surface heterogeneity on the turbulent mixing process, using the newly developed VERTEX scheme.

By taking into account horizontal heterogeneity, not only at the surface, but also at the lowest levels of the atmosphere, the scheme allows resolution of the turbulent mixing process with respect to the surface tiles.

Left: surface temperature difference (VERTEX – tiled scheme, range -0.4 – 0.4 K)
Right: The p value of statistical significance in mean difference.

Although VERTEX represents a more accurate physical model, especially for regions with strongly contrasting surface characteristics, it did not result in a clear improvement of the simulated global climate.

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  - the Monin-Obukov similarity theory is used for the surface layer
Obstacles and challenges according to Bierkens et al. (2015):

When moving from O(50 km) to O(1 km) many concepts that have been designed to resolve small-scale processes at the sub-grid scale break down, e.g.:

- It is generally assumed that sensible and latent heat fluxes are proportional to the vertical gradient of potential temperature and specific humidity.

  This only holds true if vertical gradients are much larger than horizontal gradients, for example, when using average fluxes over large horizontal domains.

However, for spatial resolutions <100 m horizontal advection becomes important, and new theories to correctly model land-atmosphere heat and moisture exchange are needed.

At high resolution, a rough upwind grid box (forest) will affect $U$, $T$, $q$, (TKE) downwind, but the Monin-Obukov formulation (only considering $U$, $T$, $q$) will not correctly account for upwind generated turbulent intensity to parametrise aerodynamic resistances over downwind smoother grid boxes (open/lake).

Thus, traditional Monin-Obukov formulation is not a good enough approximation and e.g. TKE should be accounted for in parametrisation of aerodynamic resistances, right?
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  iv. are still happy with quite empirical 1D hydrology...
Obstacles and challenges according to Bierkens et al. (2015):

When moving from O(50 km) to O(1 km) many concepts that have been designed to resolve small-scale processes at the sub-grid scale break down, e.g.:

- Surface runoff at 50 km can be associated with a distribution of soil storage within a cell. However, when moving to higher resolutions, the explicit spatial distribution of saturated/non-saturated soils has to be accounted for, e.g. by using concepts related to the topographic index.

Scale related hydrological processes

SURFEX coupled to the hydrological TOPMODEL applied for a hilly French landscape in the Cèze river basin

Left: Soil moisture difference (coupled – uncoupled). In coupled mode, with lateral water transport, hills become drier and valleys wetter
Obstacles and challenges according to Bierkens et al. (2015):

When moving from O(50 km) to O(1 km) many concepts that have been designed to resolve small-scale processes at the sub-grid scale break down, e.g.:

- Surface runoff at 50 km can be associated with a distribution of soil storage within a cell. However, when moving to higher resolutions, the explicit spatial distribution of saturated/non-saturated soils has to be accounted for, e.g. by using concepts related to the topographic index.

- At 50 km, water stress assessments are based on the assumption that water demand is satisfied by available surface water and groundwater within the same grid cell. This works well, however, at resolutions of <10 km, inter-cell redistribution of water from abstraction points to hotspots of water consumption, or from lateral groundwater flow, need to be taken into account.
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  iii. the **Monin-Obukov similarity theory** is used for the surface layer

  iv. are still happy with quite **empirical 1D hydrology**...

  v. the **horizontal resolution** is the same throughout the atmospheric column
Question: Beyond cloud-resolving resolution, is it realistic/meaningful to increase resolution homogeneously at all vertical levels?

Idea / point made: Resolution should be high where processes require so (like close to the surface) while it can be lower where the characteristic scales are larger (like mid-upper troposphere). In other words, use computer resources where they are needed the most.

Numerical possibilities / challenges are investigated by Marco Kupiainen (SMHI) and mathematicians at Uppsala University (Sweden).
Horizontal resolution = $f(\text{scale of relevant processes})$

- Close to the surface the horizontal resolution is high, e.g. comparable to the resolution of available physiography information.
- Going upward, the horizontal resolution gradually decreases.
- A minimum horizontal resolution is kept within some atmospheric layers like the mid-upper troposphere or lower stratosphere.
Mathematical / numerical theories and methods do exist to tackle this problem, e.g. how to handle **hanging nodes**. Challenges include e.g. stability, accuracy, efficiency, ...
Horizontal resolution = $f(\text{scale of relevant processes})$

Parametrisations of atmospheric processes need to be revisited and reformulated!!
Concluding remarks

• With physiography at higher resolution than grid resolution, and with estimation of the degree of heterogeneity, we can adjust e.g. sub-tile surface resistances to the character of each grid box. (reduce horizontal gradients)

• We may also utilize e.g. the sub-grid variability of fluxes for triggering of convection...

• Use the blending height concept to define the actual lowest model level (increase horizontal gradients). Provides more realistic vertical profiles of wind, temperature, humidity.

• Consider alternatives to Monin-Obukov formulation for the surface layer.

• Revisit hydrological formulations and include new processes at higher resolution (lateral water transport).