Land surface-atmosphere interaction approaching high resolution

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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...**

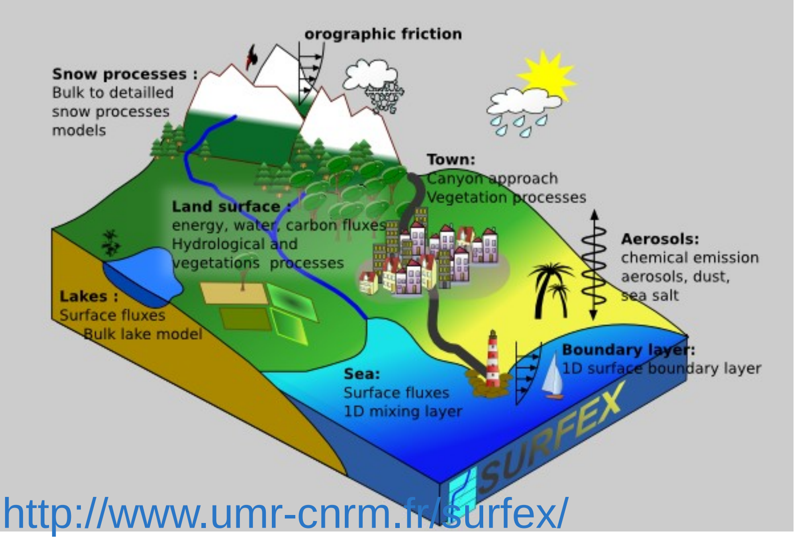
  v. **the horizontal resolution is the same throughout the atmospheric column**

- **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



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!

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

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

SURFEX8.0 patches (sub-tiles) for the land tile

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Rules of parameter aggregation

ECOCLIMAP 19 vegetation types

A number of parameters are associated with each vegetation type (e.g. LAI, albedo, root depth, Rsmin,...)

- 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

Rules of parameter aggregation

ECOCLIMAP 19 vegetation types

Number of patches specified (NPATCH)	19	12	11	10	9	8	7	6	5	4	3	2	1
Bare soil	1	1	1	1	1	1	1	1	1	1	1	2	1
Rocks	2	2	2	1	1	1	1	1	1	1	1	2	1
Permanent snow/ice	3	3	3	2	2	2	2	1	1	1	1	2	1
C3 crops	7	7	7	6	5	4	4	3	3	3	3	2	1
C4 crops	8	8	8	7	6	5	4	3	3	3	3	2	1
Grassland	10	10	10	9	8	7	6	5	5	3	3	2	1
Boreal grass	18	10	10	9	8	7	6	5	5	3	3	2	1
Tropical grass	11	11	10	9	8	7	6	5	5	3	3	2	1
Irrigated crops	9	9	9	8	7	6	5	4	4	4	3	2	1
Wetlands, parks, irrigated grass	12	12	11	10	9	8	7	6	4	4	3	2	1
Temperate broadl. cold-dec. summergr	4	4	4	3	3	3	3	2	2	2	2	1	1
Tropical broadleaf deciduous	13	4	4	3	3	3	3	2	2	2	2	1	1
Temperate broadleaf evergreen	14	4	4	3	3	3	3	2	2	2	2	1	1
Boreal broadl. cold-dec. summergr.	16	4	4	3	3	3	3	2	2	2	2	1	1
Shrubs	19	4	4	3	3	3	3	2	2	2	2	1	1
Tropical broadleaf evergreen	6	6	6	5	3	3	3	2	2	2	2	1	1
Boreal needleleaf evergreen	5	5	5	4	4	3	3	2	2	2	2	1	1
Temperate needleleaf evergreen	15	5	5	4	4	3	3	2	2	2	2	1	1
Boreal needlel. cold-dec. summergr.	17	5	5	4	4	3	3	2	2	2	2	1	1

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Arpege climate(?)

New NWP cyxxh setup

NWP operational

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ECOCLIMAP 2nd generation (SG) (in SURFEX8.1)

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)**

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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)

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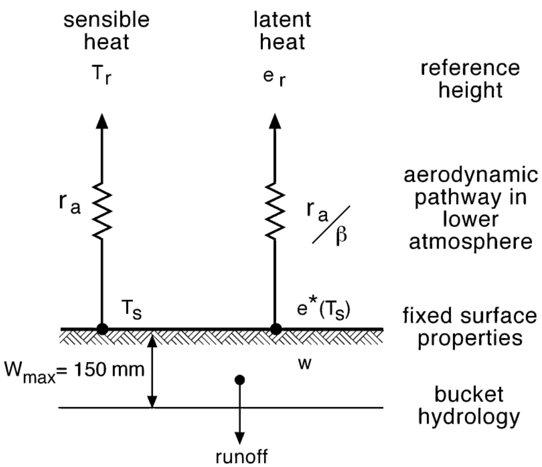
The difficulty to build the map lies in:

- 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

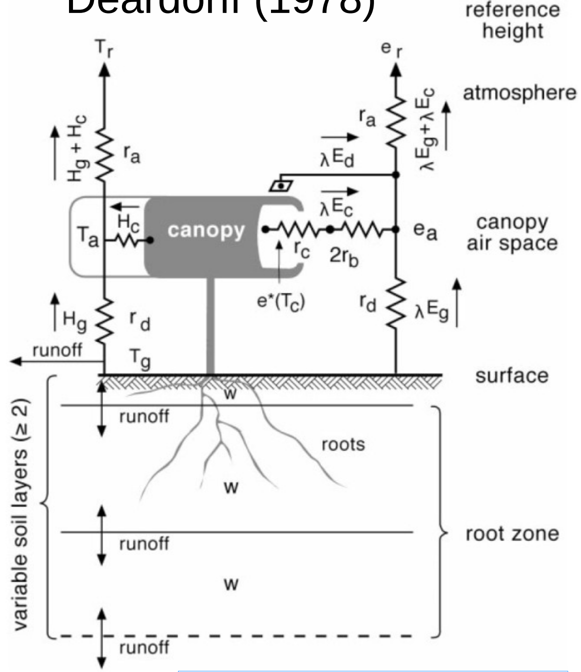
Manabe (1969)



2nd generation

with explicit canopy

Deardorff (1978)

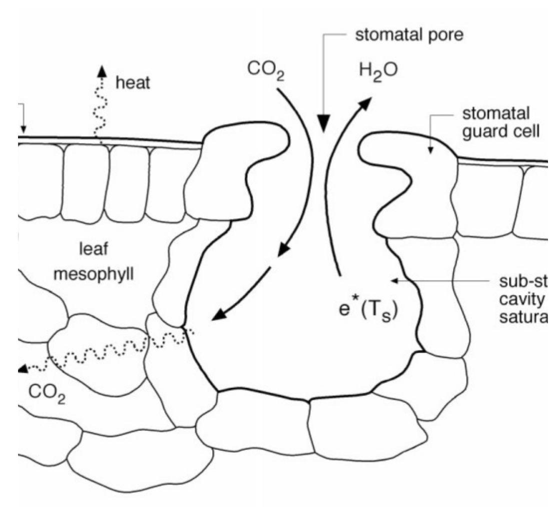


Latest HIRLAM at 5km resolution

3rd generation

with carbon

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



Details in physical processes

1st generation

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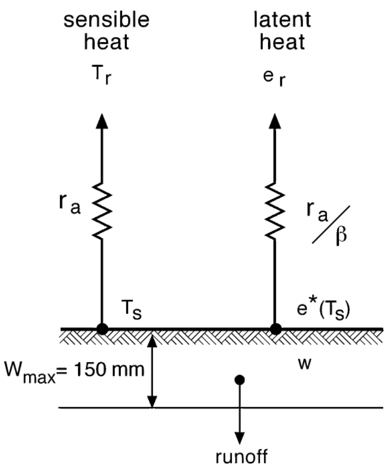

2nd generation
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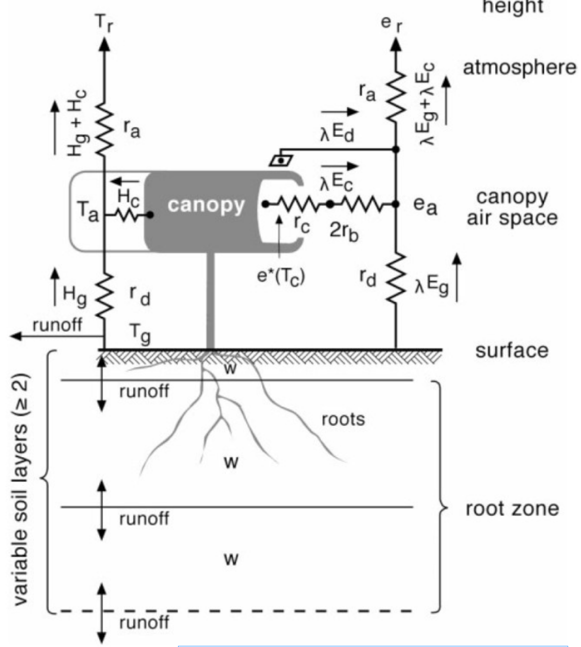

3rd generation
with carbon

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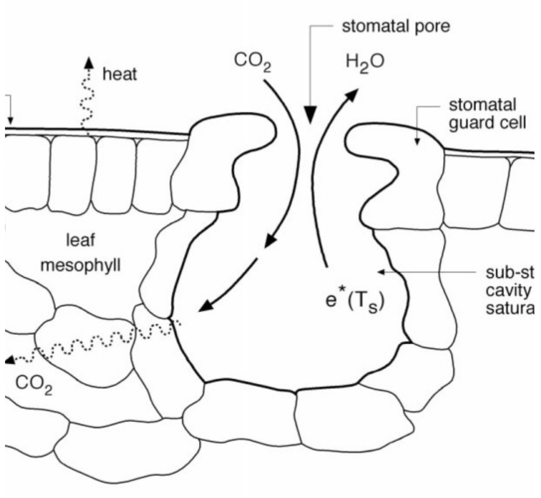

Latest HIRLAM at 5km resolution

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

Details in physical processes

1^{st} generation

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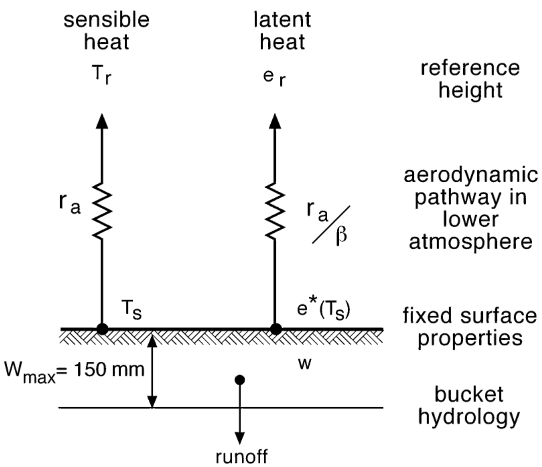
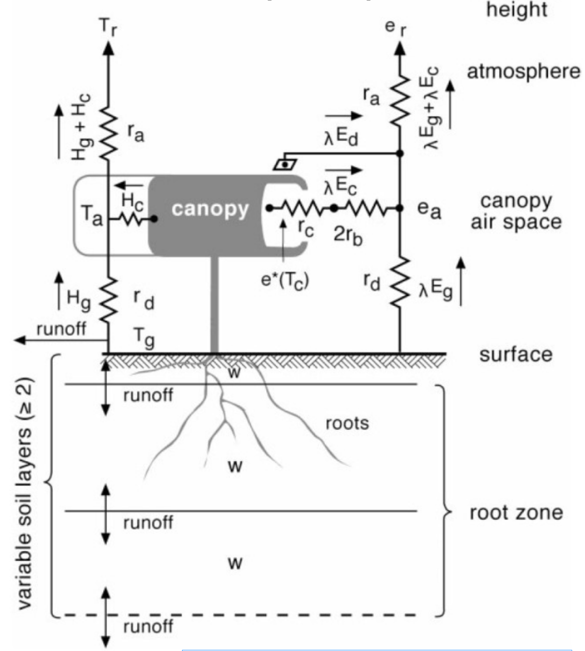


2^{nd} generation

with explicit canopy

Deardorff (1978)



3^{rd} generation

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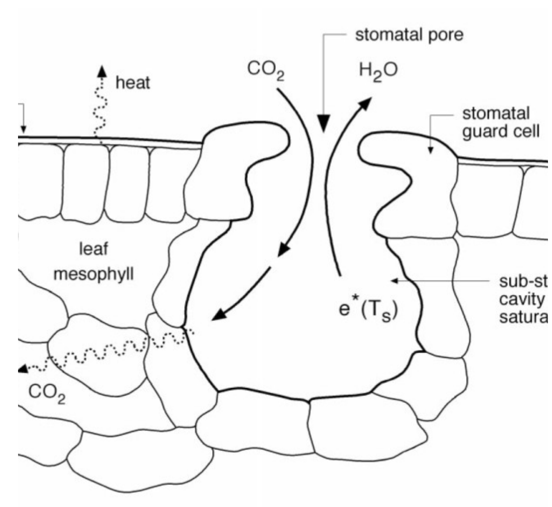

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cy40t/h uses SURFEXv7.3 at 1.3/2.5 km resolution

SURFEXv8

cy43t uses SURFEXv8 as 1.5 generation

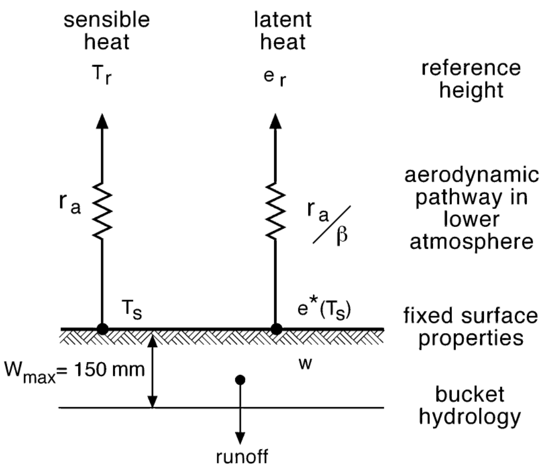
cy43h will use SURFEXv8 as 2^{nd} generation

Arpege ESM uses SURFEXv8 as 3^{rd} generation

Details in physical processes

1st generation

Manabe (1969)



2nd generation

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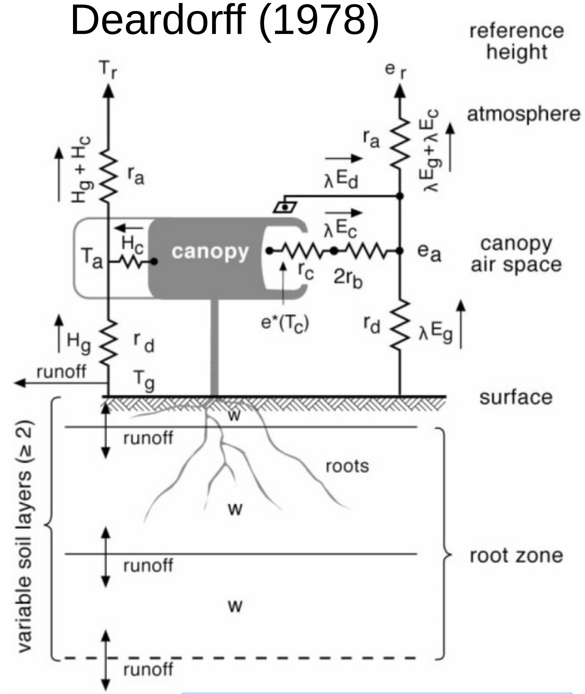

3rd generation

with carbon

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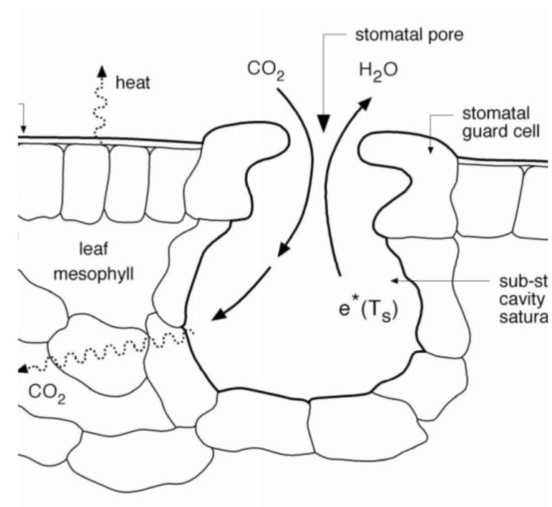

Latest HIRLAM at 5km resolution

ECMWF (H-TESSEL)

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

SURFEXv8

ECMWF (C-TESSEL)

Arpege ESM uses SURFEXv8 as 3rd generation

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:

	cy40h	**cyxxh (long term ambition)**
Land		
Patches	1 or 2	2-4 patches with explicit canopy
Soil	Force-restore	Diffusion (14 layers)
Snow	D95	Explicit snow (12 layers)
Glacier	-	Explicit snow as glacier
Assimilation	CANARI-OI	MESCAN-EKF/EnKF
Sea	SICE	Sea ice (SICE)
Lake	FLake (optional)	FLake (later with EKF)
Town	TEB	TEB (more options) as presented by Valéry Masson
Physiog.	ECOCLIMAP-II	ECOCLIMAP 2^{nd} generation
	1 km resolution	300 m resolution

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- **State of the art NWP land-surface models**

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

The tiling approach and surface fluxes

Shao et al. (2013) say that it is now understood that land-surface heterogeneity has two major effects on surface fluxes:

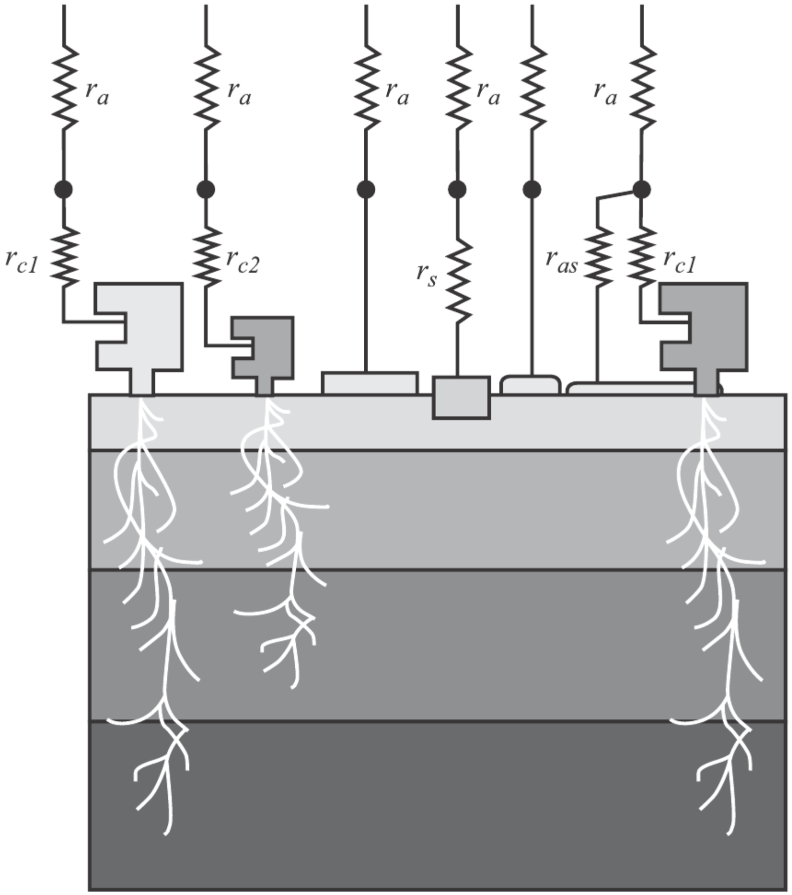
- **The aggregation effect** means that an aggregated surface will not produce the correct fluxes since it does not account for the non-linear combination of transfer processes and surface heterogeneity.
- **The dynamic effect** occurs because contrasts in surface conditions generate turbulence and horizontal 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.

Shao, Y., Liu, S., Schween, J.H. and Crewell, S., 2013. Large-eddy atmosphere–land-surface modelling over heterogeneous surfaces: Model development and comparison with measurements. Boundary-layer meteorology, 148(2), pp.333-356.

The tiling approach and surface fluxes

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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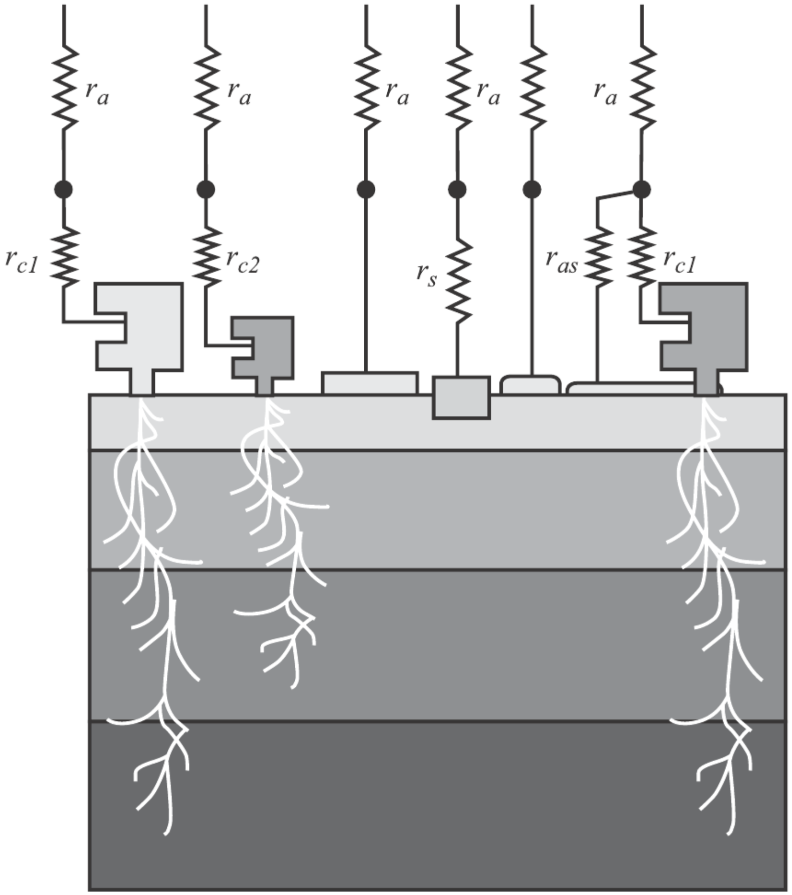
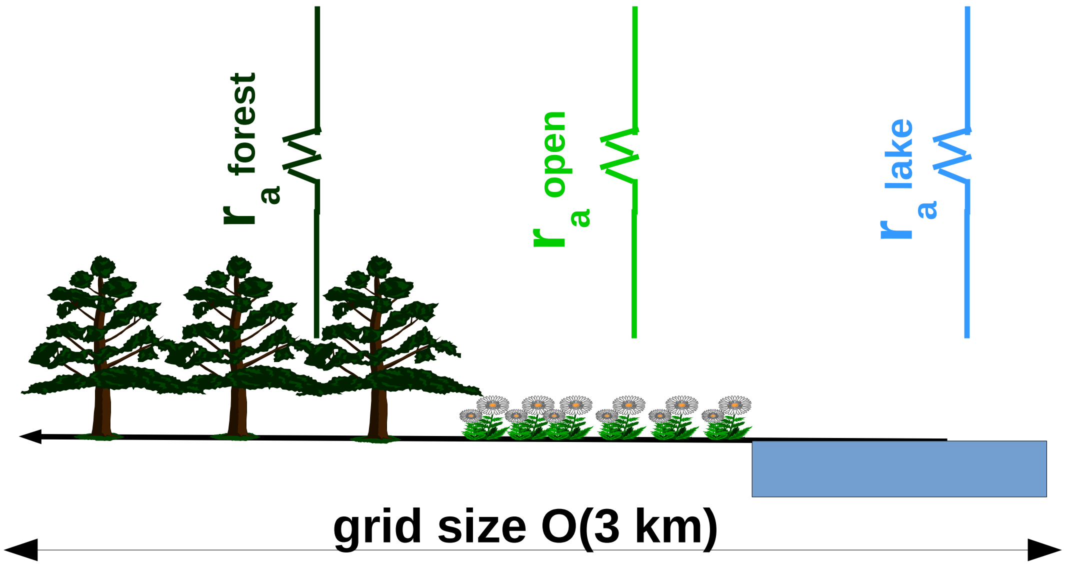


When the grid size is >10 km and the characteristic scale of tiles is >1 km it is reasonable to assume that the r_a:s are independent of each other (local conditions of z_0, T_s, ... dominate).

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

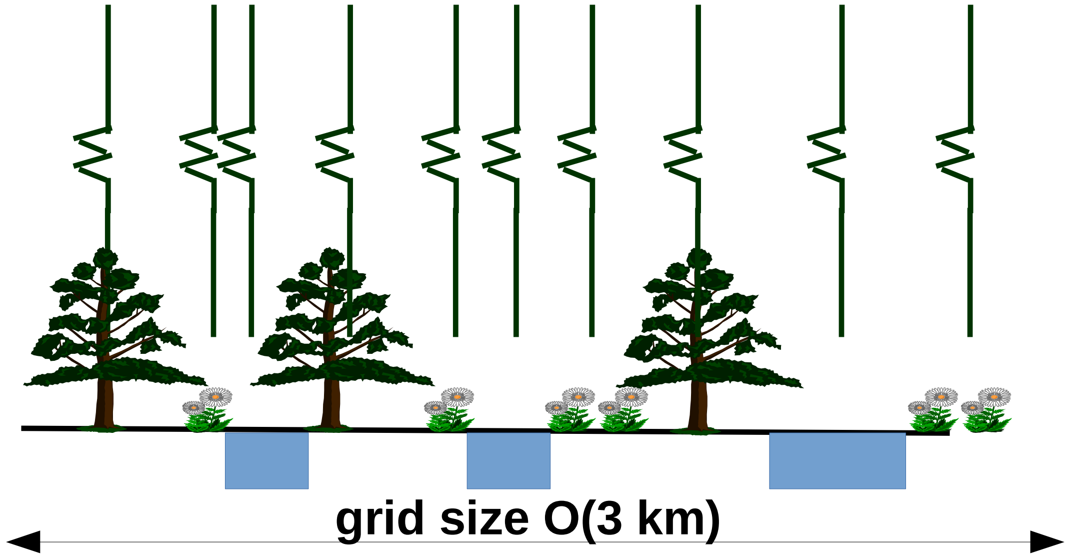


With O(1 km) tiles the turbulence is probably pretty unique over each tile and the tiles are characterized by their individual r_a:s (forest, open, lake).

E.g., momentum flux is expressed as

$$\tau_0 = -\rho_a \overline{u'w'} = \rho_a C_D U_r^2 = \rho_a \frac{U_r}{r_a}$$

The tiling approach and surface fluxes



But, when tile size is O(100 m) the turbulence is probably dominated by the most rough surface (forest) and therefore a r_a 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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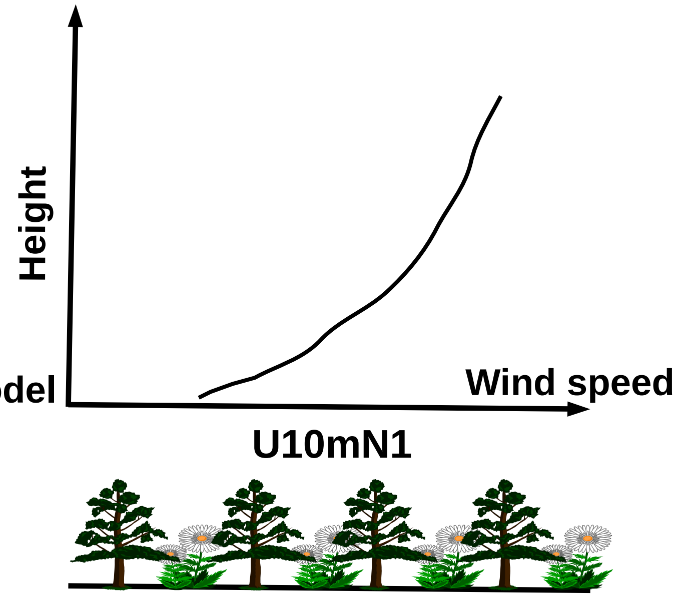
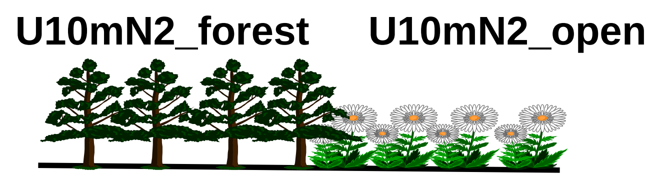
The lowest atmospheric level

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

Lowest model level:
12 m
Grid size:
2.5km



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



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

The lowest atmospheric level

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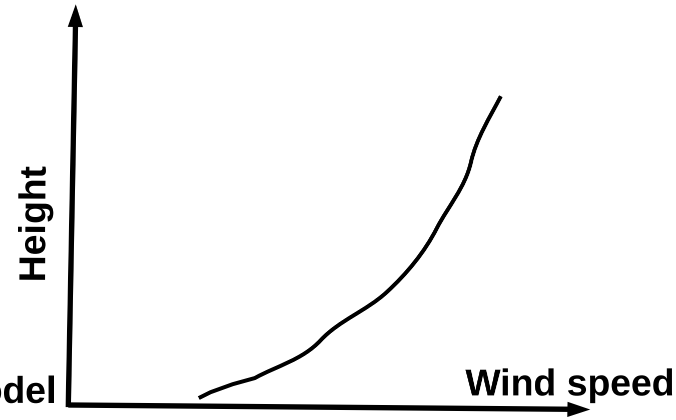

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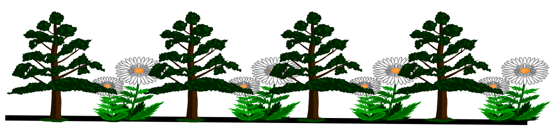
U10mN1



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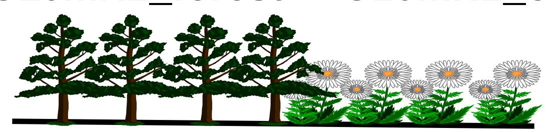
U10mN2_forest **U10mN2_open**



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U10mN1 > U10mN2_open

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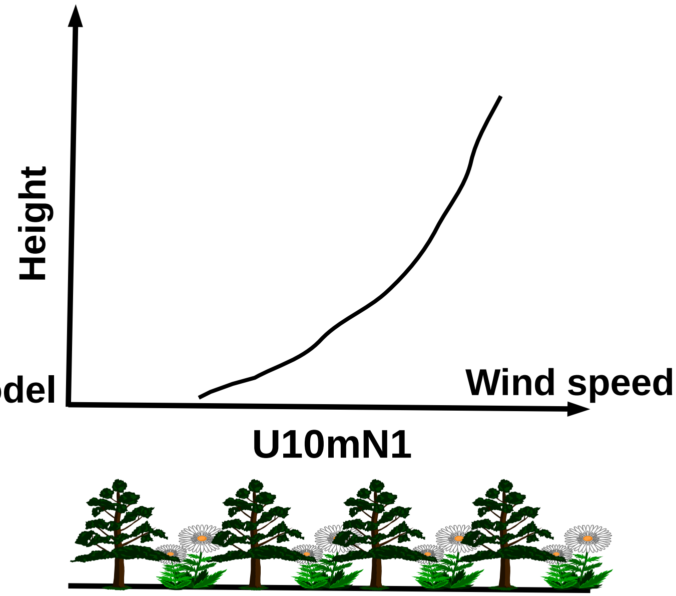

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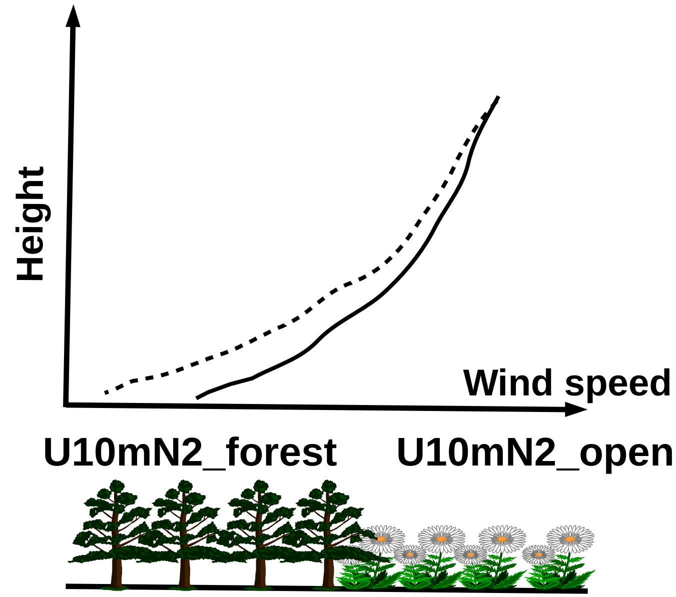

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U10mN1 > U10mN2_open

Lower BL wind N1 > Lower BL wind N2

The lowest atmospheric level

SMHI

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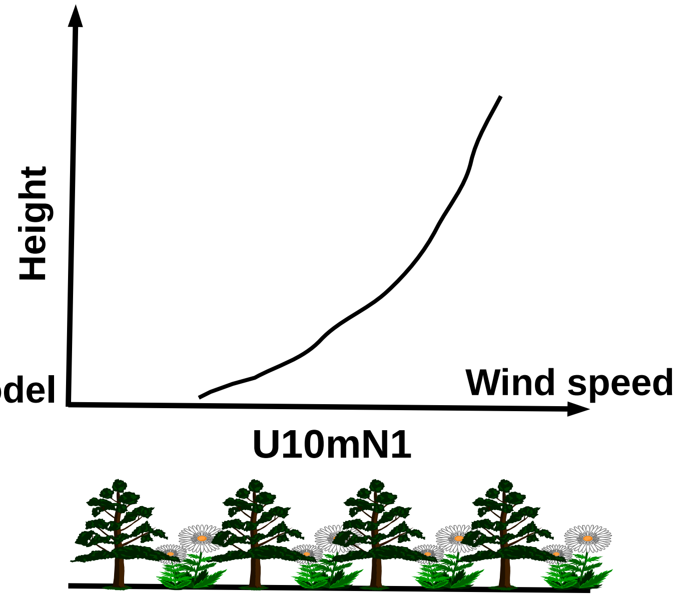

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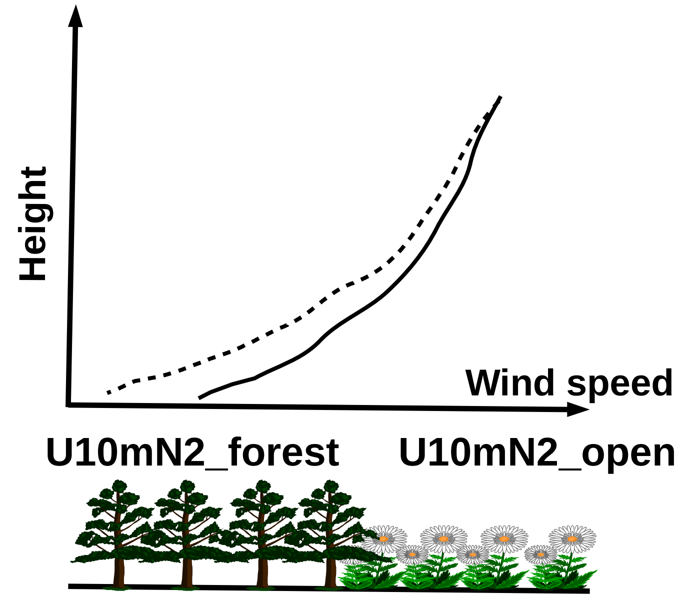

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U10mN1 > U10mN2_open

Lower BL wind N1 > Lower BL wind N2

$Z_{0eff}N1 < Z_{0eff}N2$

The lowest atmospheric level

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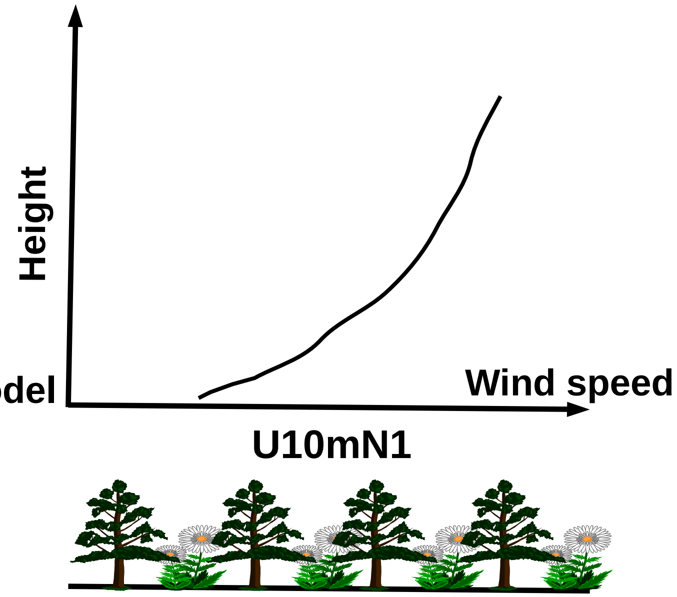

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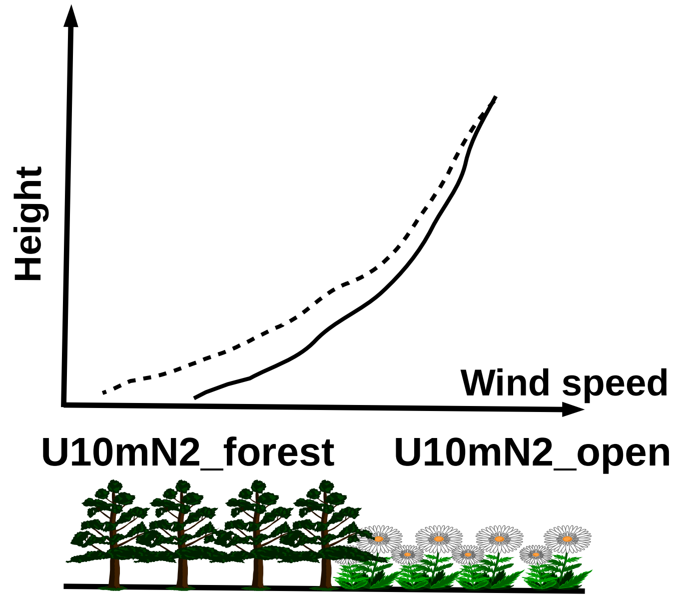

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Lower BL wind N1 > Lower BL wind N2

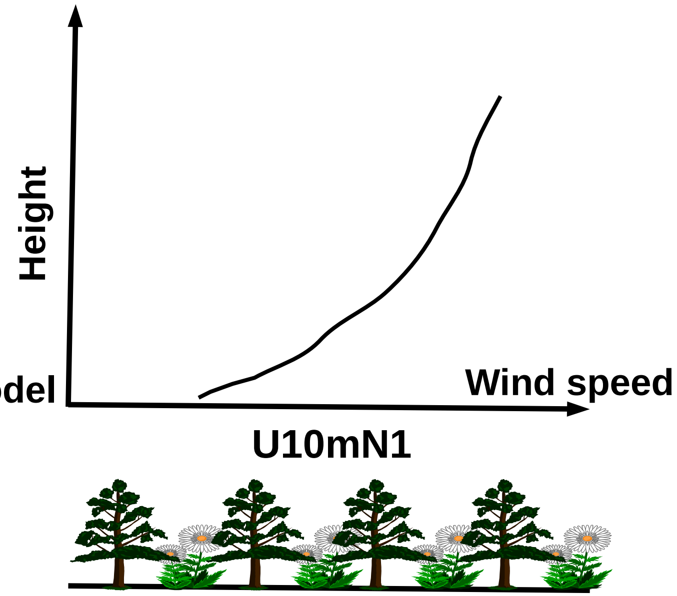
Z_{0eff}N1 < Z_{0eff}N2

U10mN2_forest ~ U10mN2_open

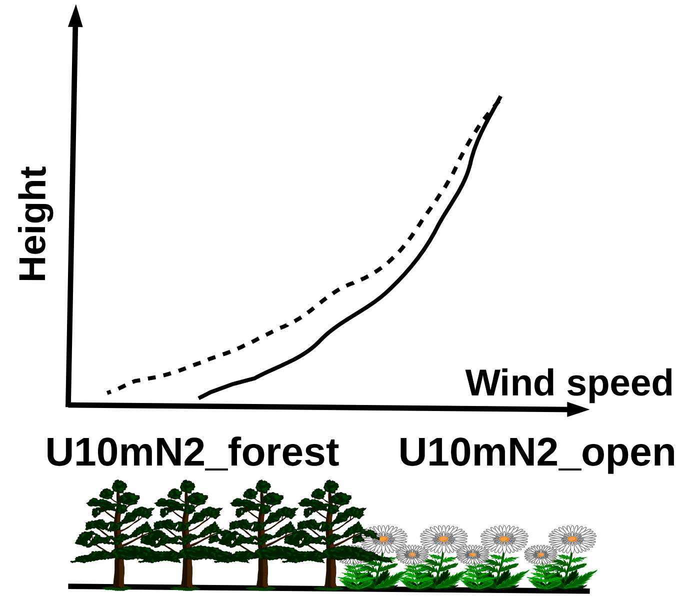
The lowest atmospheric level

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

Lowest model level:
12 m
Grid size:
2.5km



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



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

U10mN1 > U10mN2_open

Lower BL wind N1 > Lower BL wind N2

Z_{0eff}N1 < Z_{0eff}N2

U10mN2_forest ~ U10mN2_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).

Mason, P.J., 1988. The formation of areally-averaged roughness lengths. Quarterly Journal of the Royal Meteorological Society, 114(480), pp.399-420.

Essery, R.L.H., Best, M.J., Betts, R.A., Cox, P.M. and Taylor, C.M., 2003. Explicit representation of subgrid heterogeneity in a GCM land surface scheme. Journal of Hydrometeorology, 4(3), pp.530-543.

Shao, Y., Liu, S., Schween, J.H. and Crewell, S., 2013. Large-eddy atmosphere–land-surface modelling over heterogeneous surfaces: Model development and comparison with measurements. Boundary-layer meteorology, 148(2), pp.333-356.

The lowest atmospheric level

SMHI

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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.

Mason, P.J., 1988. The formation of areally-averaged roughness lengths. Quarterly Journal of the Royal Meteorological Society, 114(480), pp.399-420.
Essery, R.L.H., Best, M.J., Betts, R.A., Cox, P.M. and Taylor, C.M., 2003. Explicit representation of subgrid heterogeneity in a GCM land surface scheme. Journal of Hydrometeorology, 4(3), pp.530-543.
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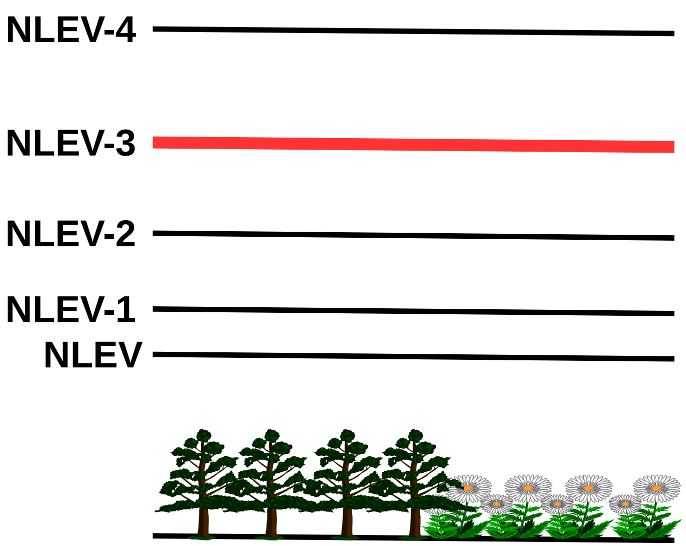
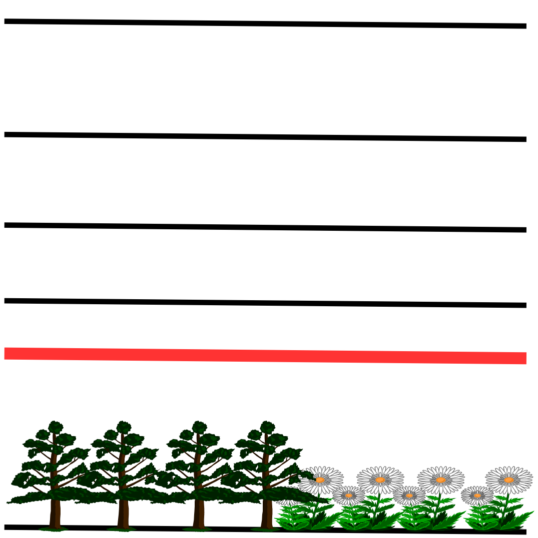
The lowest atmospheric level

Idea… worth testing….??

High blending height:



Low blending height:



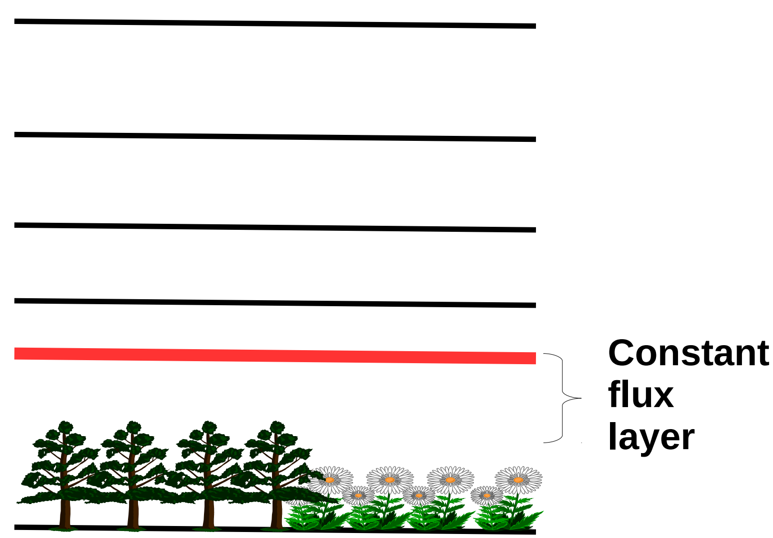
- Use the blending height u,v,q,T as upper boundary condition (BC) for the surface model.

The lowest atmospheric level

Idea… worth testing….??

High blending height:

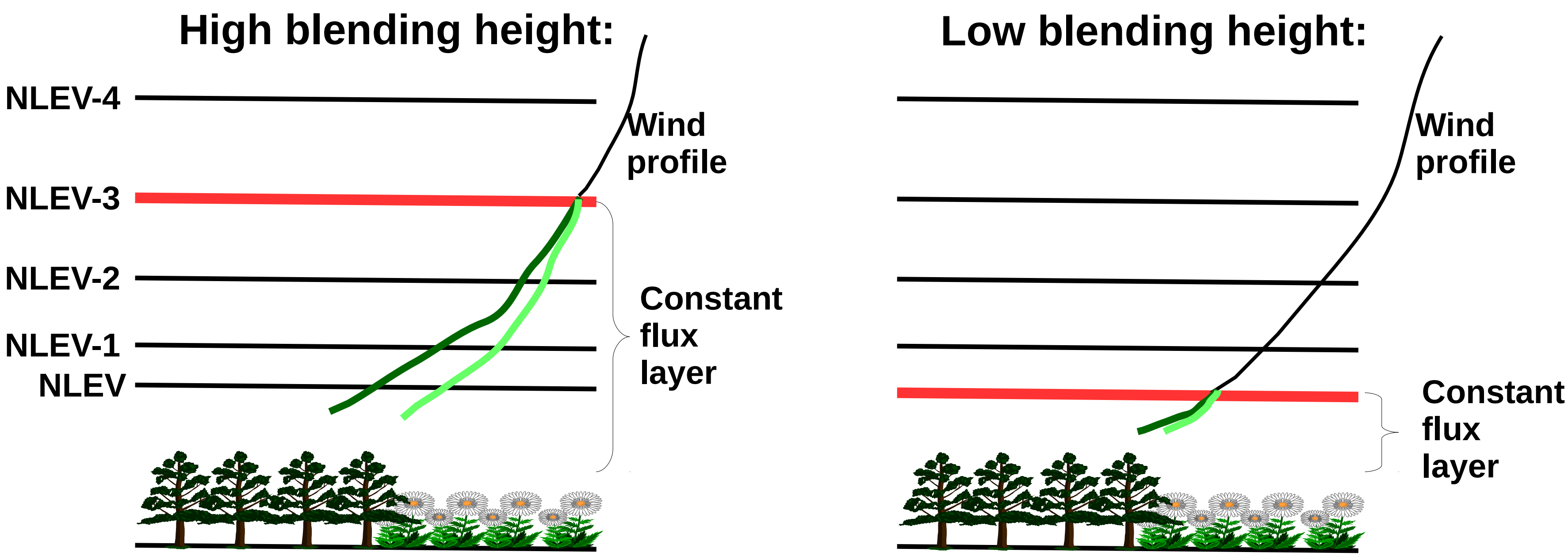
Low blending height:



- 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….??



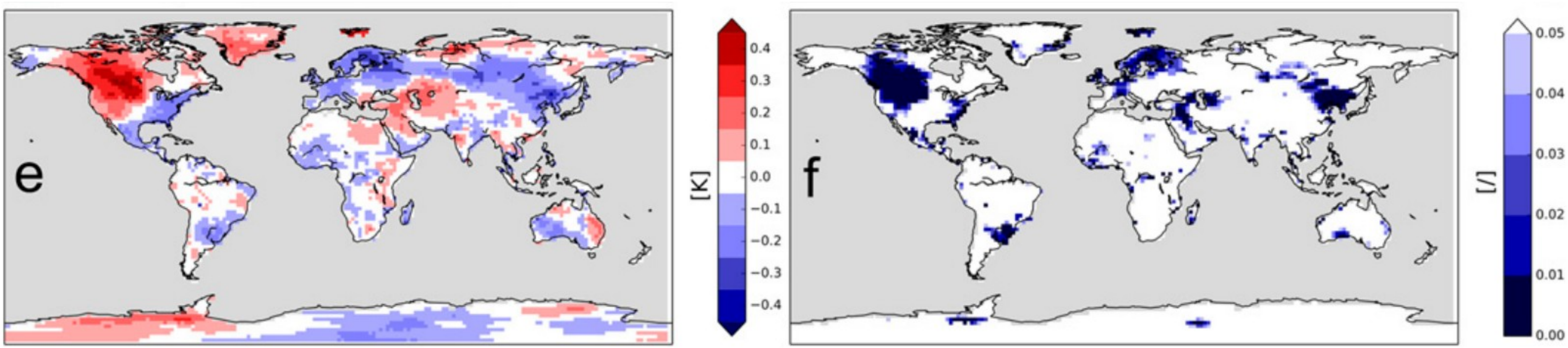
- Use the blending height u,v,q,T as upper boundary condition (BC) for the surface model.
- Assume constant flux layer below blending height which means that fluxes (momentum, heat, moisture) can still be used as lower BC for the atmosphere at NLEV.
- Sparate profiles below blending height over each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

The lowest atmospheric level

SMHI

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.

de Vrese, P., Schulz, J.P. and Hagemann, S., 2016. On the representation of heterogeneity in land-surface–atmosphere coupling. Boundary-Layer Meteorology, 160(1), pp.157-183.

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

Monin-Obukov similarity theory

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.:

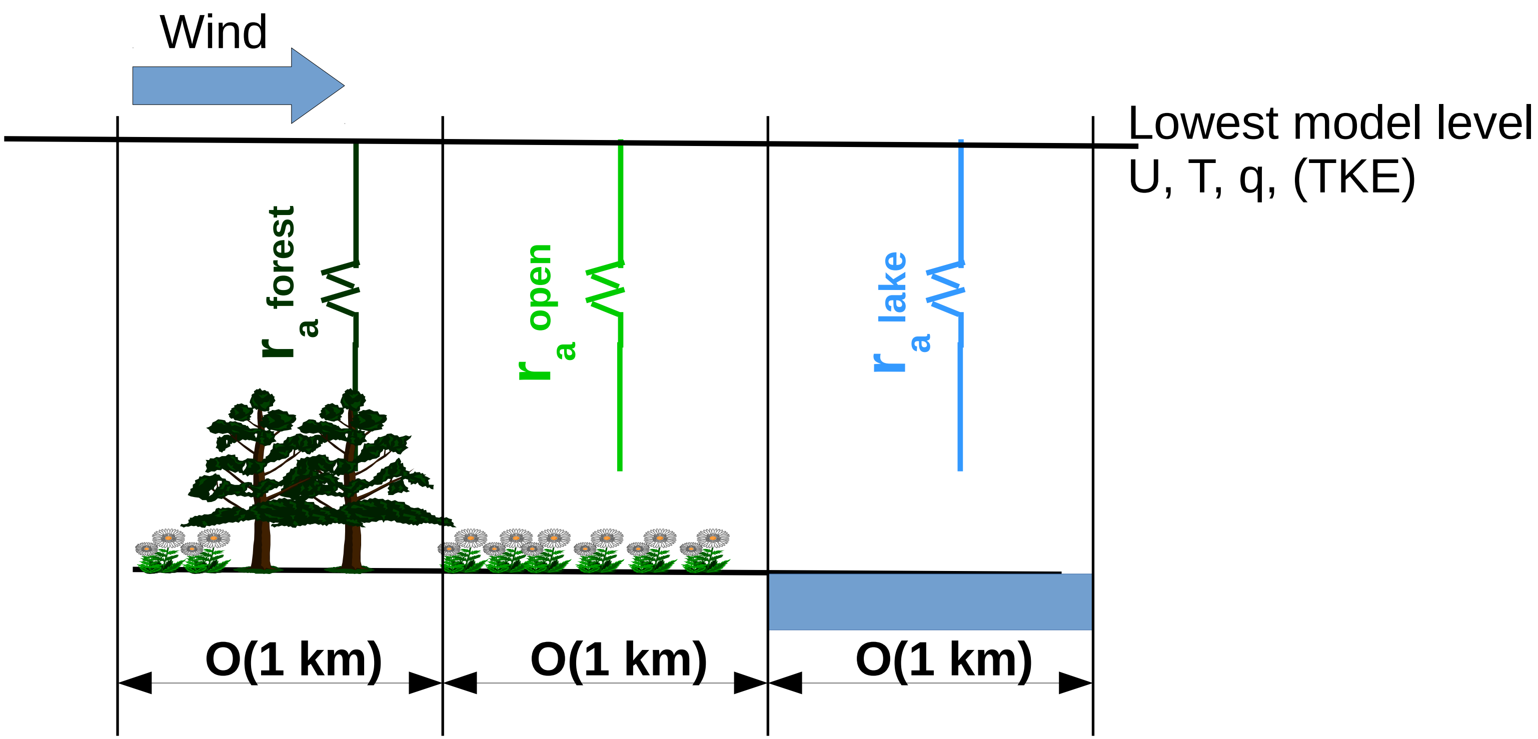
- It is generally assumed that sensible and latent heat fluxes are proportional to the vertical gradient of potential temperature and specific humidity.

  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.

Bierkens, M.F., Bell, V.A., Burek, P., Chaney, N., Condon, L.E., David, C.H., de Roo, A., Döll, P., Drost, N., Famiglietti, J.S. and Flörke, M., 2015. Hyper-resolution global hydrological modelling: What is next? Everywhere and locally relevant. Hydrol Process, 29(2), pp.310-320.

Monin-Obukov similarity theory



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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Scale related hydrological processes

Obstacles and challenges according to Bierkens et al. (2015):

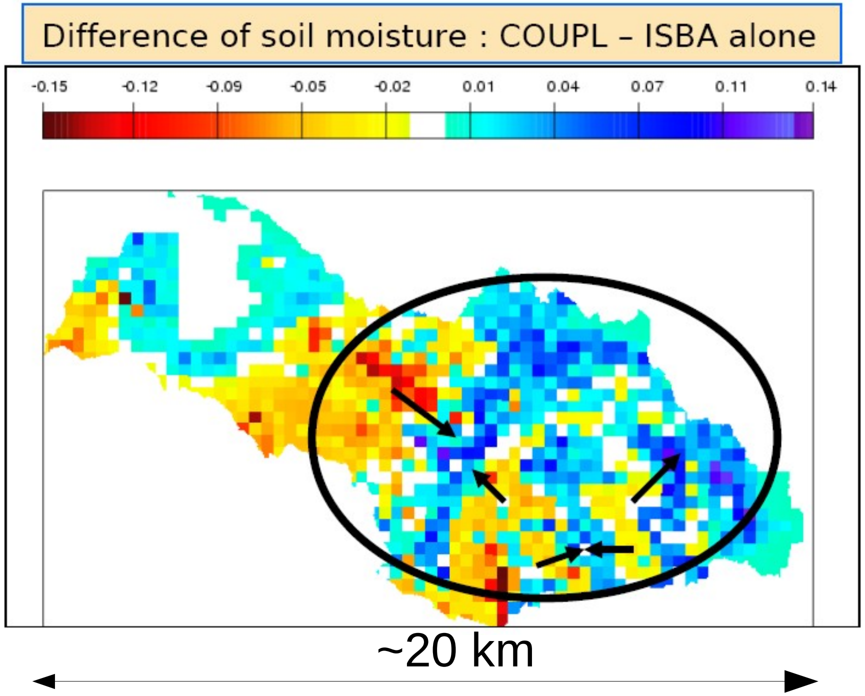
When moving from O(50 km) to O(1 km) many concepts that have been designed to resolve small-scale processes at the sub-grid scale break down, e.g.:

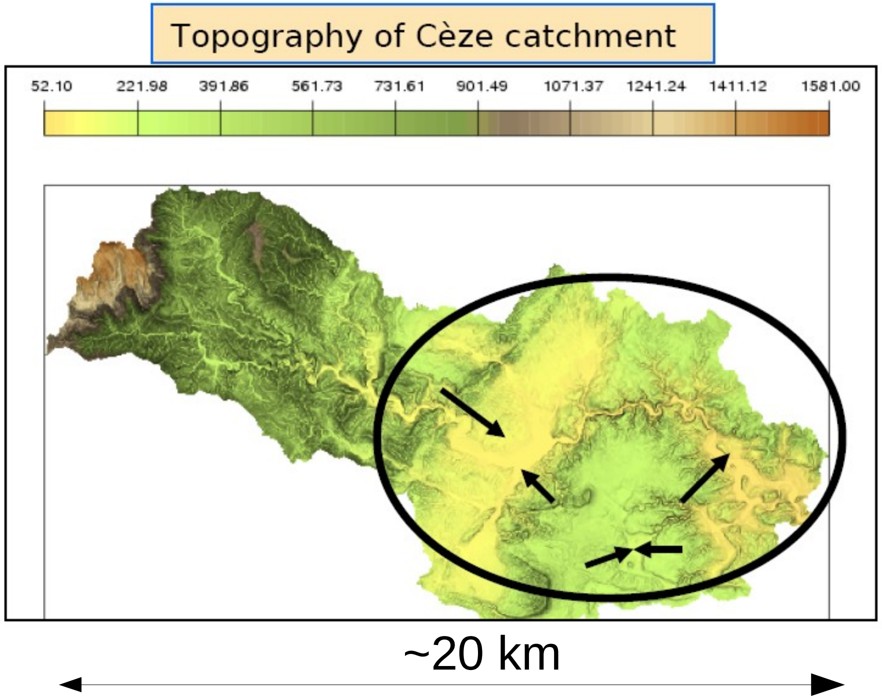
- Surface runoff at 50 km can be associated with a distribution of soil storage within a cell.
  However, when moving to higher resolutions, the explicit spatial distribution of saturated/non-saturated soils has to be accounted for, e.g. by using concepts related to the topographic index.

Bierkens, M.F., Bell, V.A., Burek, P., Chaney, N., Condon, L.E., David, C.H., de Roo, A., Döll, P., Drost, N., Famiglietti, J.S. and Flörke, M., 2015. Hyper-resolution global hydrological modelling: What is next? Everywhere and locally relevant. Hydrol Process, 29(2), pp.310-320.

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

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- 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.

Bierkens, M.F., Bell, V.A., Burek, P., Chaney, N., Condon, L.E., David, C.H., de Roo, A., Döll, P., Drost, N., Famiglietti, J.S. and Flörke, M., 2015. Hyper-resolution global hydrological modelling: What is next? Everywhere and locally relevant. Hydrol Process, 29(2), pp.310-320.

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

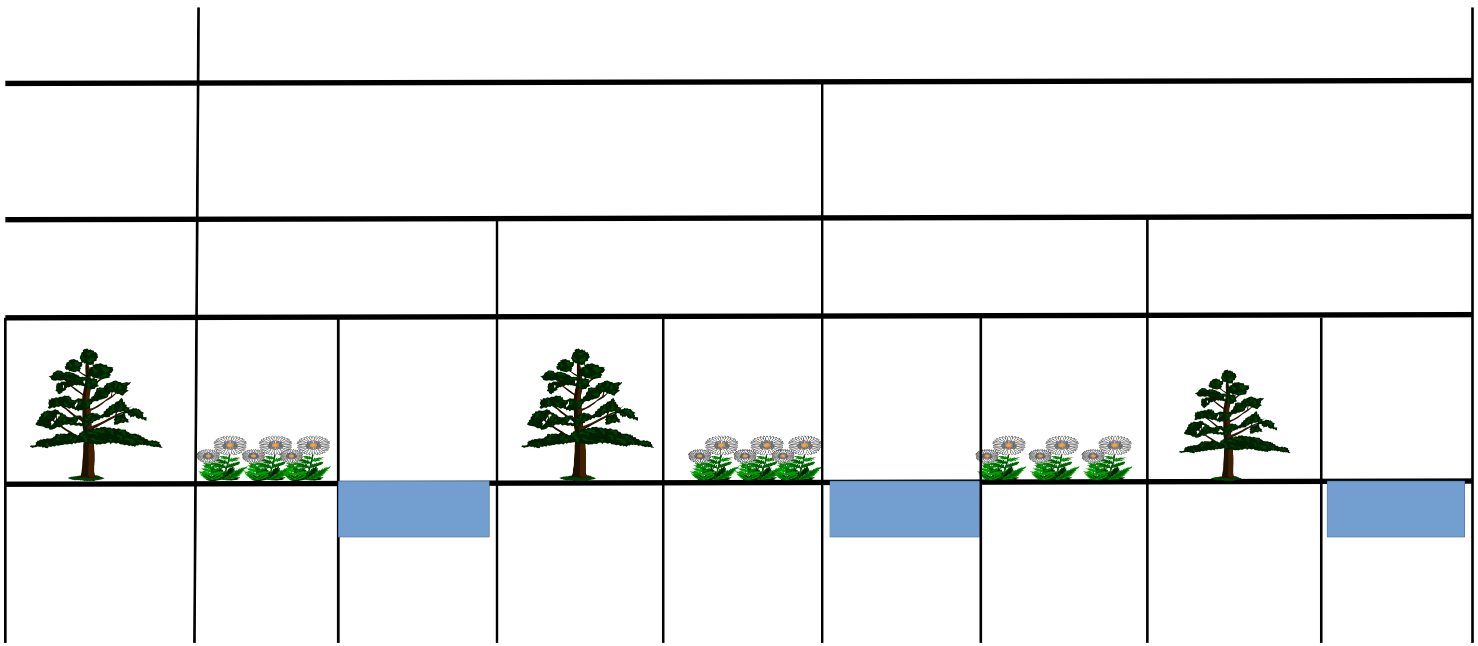
  v. **the horizontal resolution is the same throughout the atmospheric column**

Horizontal resolution = f(scale of relevant processes)

Question: Beyond cloud-resolving resolution, is it realistic/meaningful to increase resolution homogeneously at all vertical levels?

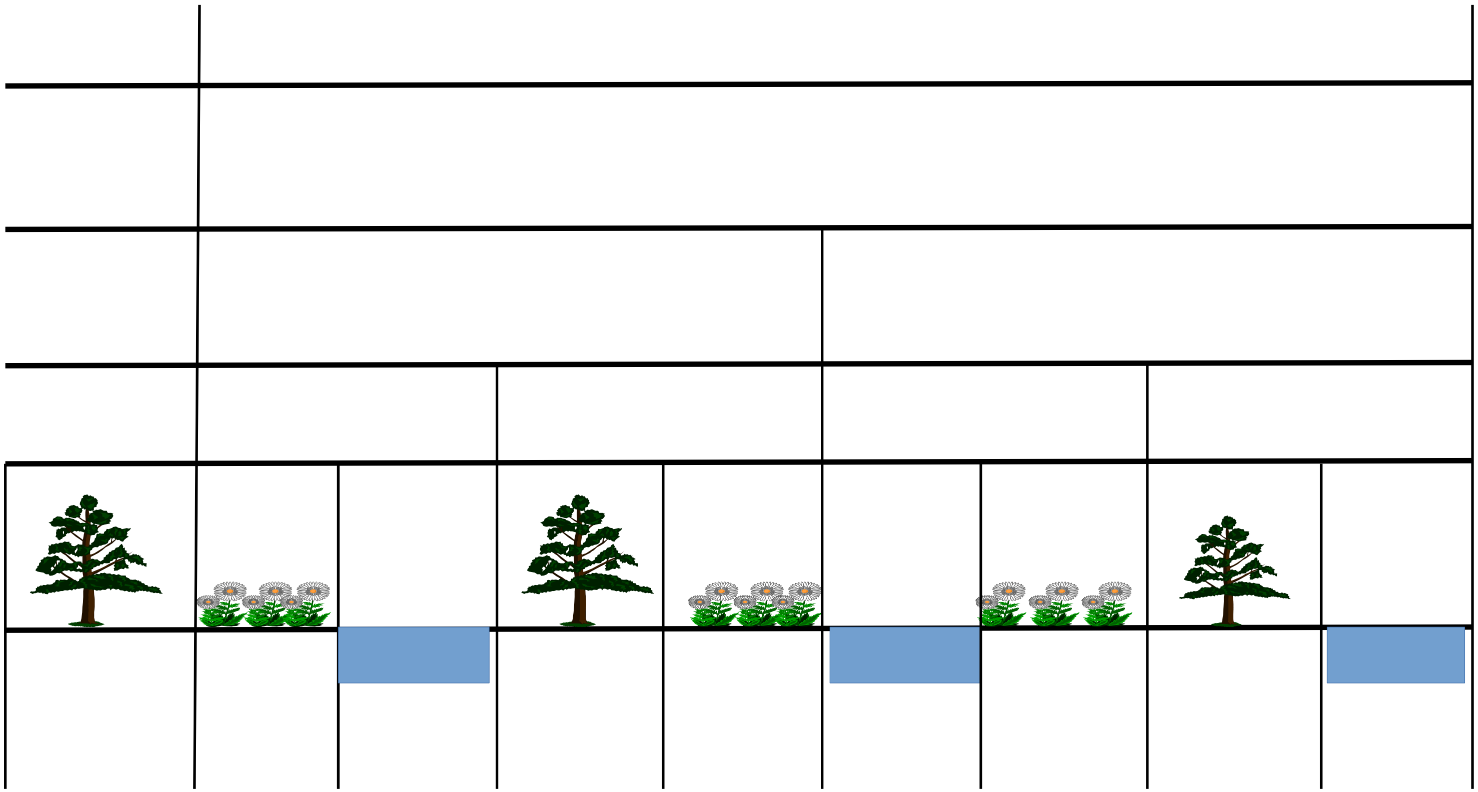
Idea / point made: Resolution should be high where processes require so (like close the surface) while it can be lower where the characteristic scales are larger (like mid-upper troposphere). In other words, use computer resources where they are needed the most.

Numerical posssibilities / challenges are investigated by Marco Kupiainen (SMHI) and mathematicians at Uppsala University (Sweden).



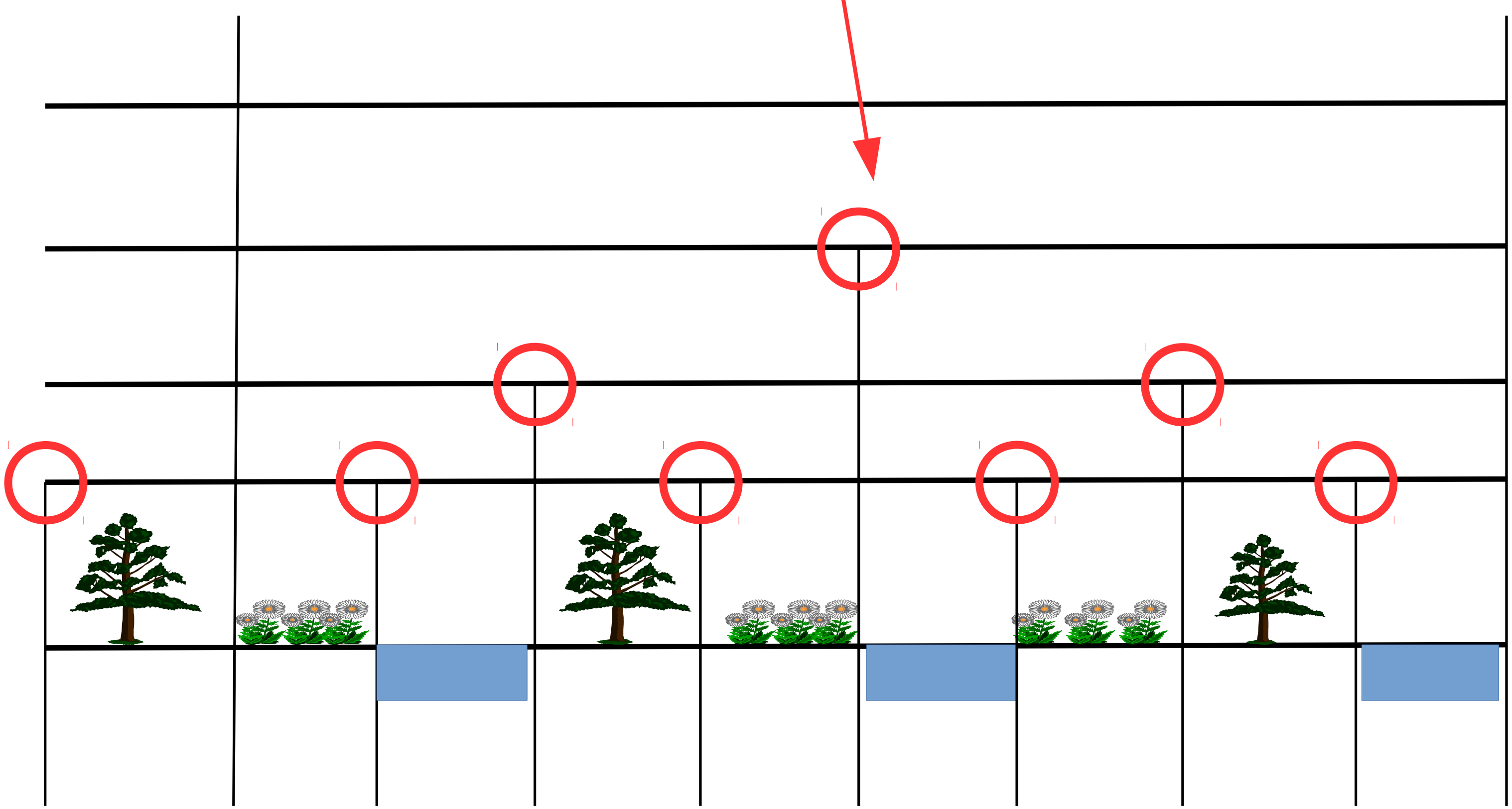
Horizontal resolution = f(scale of relevant processes)

- **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.**



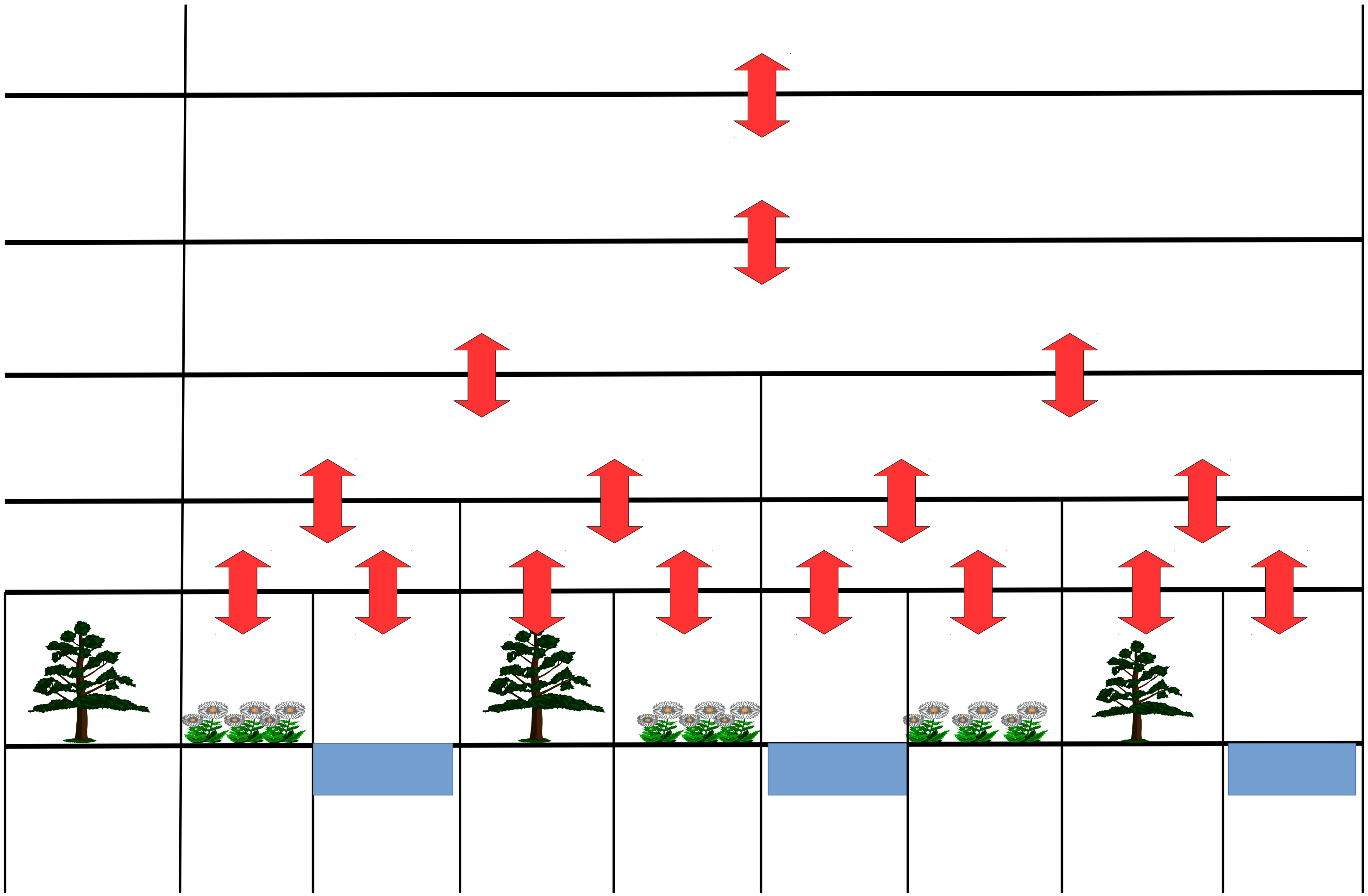
Horizontal resolution = f(scale of relevant processes)

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(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).**