Implementation of Roughness Sublayer in SURFEX

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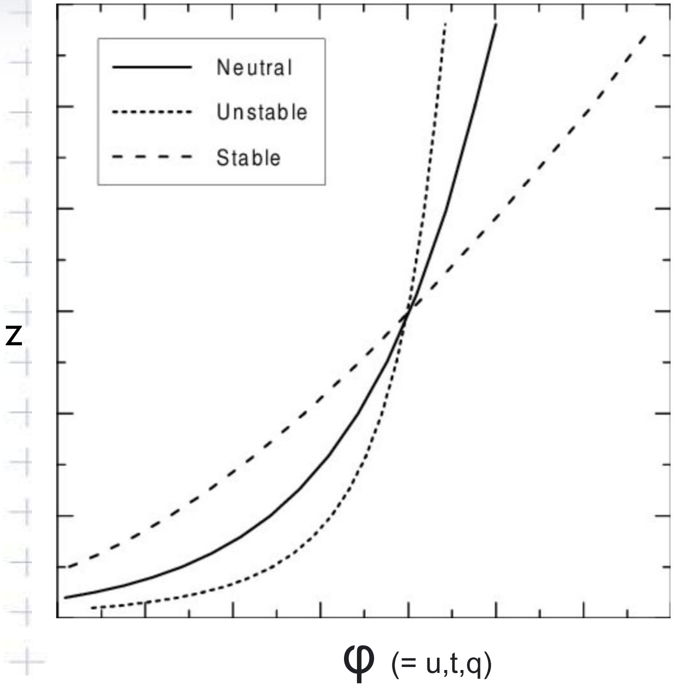
Outline

- MOST recap
- Quick overview of RSL (Harman & Finnigan 2007)
- RSL implementation in SURFEX
- Some results using Harmonie-46 with new physics
- Some discussion
- Plans for validation: Offline runs
- Conclusions & final remarks

Monin-Obukhov similarity theory (MOST)



- Simple and effective scaling law for the surface layer.
- Used for multiple purposes (NWP, climate modelling…):
  - Diagnostics / profiles of wind /scalar variables
  - Evaluation of turbulent fluxes: SEB, etc.
- φ: universal functions in the surface layer, depending on the stability parameter ζ=z/L, L=M-O length
- MOST is only valid for heights $z \gg z_0$, typically z>5-10z_0
- With current vertical resolutions in NWP, the lowest atmospheric (coupling) level over tall canopies is often where MOST loses validity → Roughness sublayer

$$\frac{kz}{\varphi_*}\frac{d\varphi(z)}{dz} = \phi_\varphi(\zeta)$$

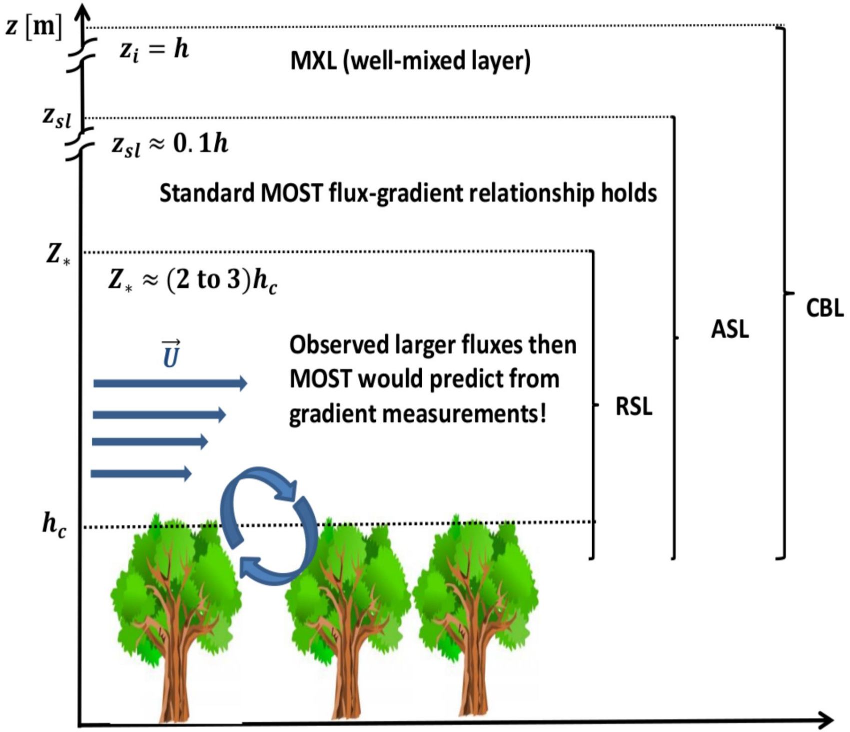
Diagnostics →

$$u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right) + \psi(z, z_0, L)\right]$$

Fluxes →

$$\overline{u'w'} = \frac{-u_* K_m}{kz}\phi_m(z/L)$$

Roughness sublayer (Harman & Finnigan 2007)



$$\frac{kz}{\varphi_*}\frac{d\varphi(z)}{dz} = \phi_\varphi(\zeta)\,\hat{\phi}(\zeta,\delta_\omega)$$

- Original MOST flux-gradient relationships are modified by HF07 RSL functions $\hat{\phi}_\varphi$ to account for enhanced vertical mixing close to a (tall) canopy.

$$\hat{\phi}_\varphi = 1 - c_{1\varphi} \exp\left[-\frac{\beta\, c_{2\varphi}(z-d)}{l}\right],$$

$$c_{1\varphi} = \left(1 - \frac{\kappa\, S_c}{2\beta}\right)\exp\left(\frac{c_{2\varphi}}{2}\right),\ c_{2\varphi} = 0.5,$$

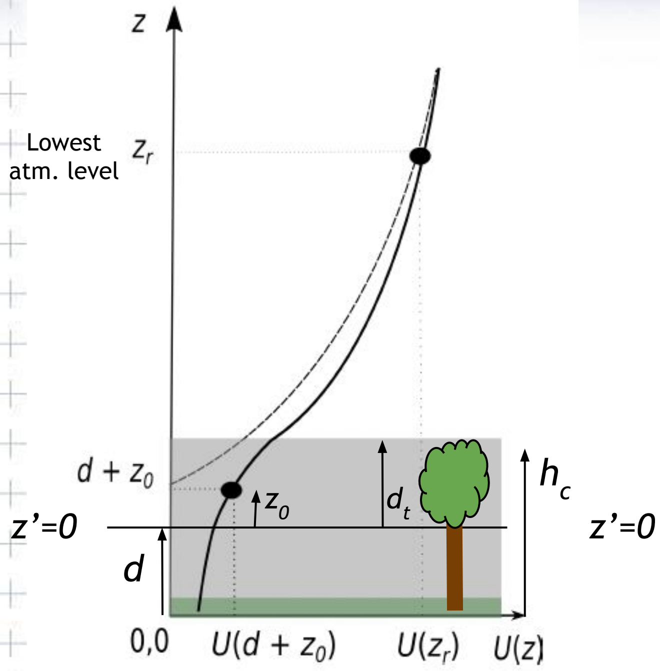
$$S_c = 0.5 - \tanh L_c/L$$

$$l = 2\beta^3 L_c$$

$$L_c = (c_d a)^{-1} = \frac{4h}{\mathrm{LAI}}$$

- RSL functions depend both on stability and canopy characteristics ($\beta = \beta(L_c, L)$).

Roughness sublayer (Harman & Finnigan 2007)



$$d = h_c - d_t, \quad d_t = \beta^2 L_c,$$

$$L_c = \left(c_d\, a\right)^{-1}, \beta = u_* / \overline{u}$$

- d_t & z_0 (stability dependant displacement height and roughness lengths)

$$d_t = h - d_0 = \frac{l_m}{2\beta} = \beta^2 L_c,$$

$$z_0 = d_t \exp\left[-\frac{k}{\beta}\right] \exp\left[-\psi_m\left(\frac{d_t}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)\right] \exp\left[\int_{d_t}^{\infty} \frac{\phi_m\left(1-\hat{\phi}_m\right)}{z'} dz'\right]$$

- Drag coefficients at the lowest atmospheric level (z_r):

$$C_D = \frac{\kappa^2}{\left[\ln(\frac{z_r}{z_{0m}}) - \Psi_m(\frac{z_r}{L}) + \Psi_m(\frac{z_{0m}}{L}) + \hat{\Psi}_m(z_r) - \hat{\Psi}_m((z_{0m})\right]^2}$$

$$C_H = \frac{\kappa^2}{\left[\ln(\frac{z_r}{z_{0h}}) - \Psi_h(\frac{z_r}{L}) + \Psi_h(\frac{z_{0h}}{L}) + \hat{\Psi}_h(z_r) - \hat{\Psi}_h(z_{0h})\right]} \frac{1}{\left[\ln(\frac{z_r}{z_{0m}}) - \Psi_m(\frac{z_r}{L}) + \Psi_m(\frac{z_{0m}}{L}) + \hat{\Psi}_m(z_r) - \hat{\Psi}_h(z_{0m}\right]}$$

Surface fluxes

$$H = \rho_a c_p C_H V_a (T_s - T_a) \qquad |\overline{w'V'}|_s = C_D |V_a|^2 = u_*^2$$

Roughness sublayer in NWP / climate models

HF07's RSL has been recently incorporated in some NWP / land surface models:

- Lee, J., Hong, J., Noh, Y., and Jiménez, P. A.: Implementation of a roughness sublayer parameterization in the Weather Research and Forecasting model (**WRF version 3.7.1**) and its evaluation for regional climate simulations, Geosci. Model Dev., 13, 521–536,2020.

- Bonan, G. B., Patton, E. G., Harman, I. N., Oleson, K. W., Finnigan, J. J., Lu, Y., and Burakowski, E. A.: Modeling canopy-induced turbulence in the Earth system: a unified parameterization of turbulent exchange within plant canopies and the roughness sublayer (**CLM-ml v0**), Geosci. Model Dev., 11, 1467–1496, 2018.

In these examples the RSL is applied to the **vegetated tile**.
HF07 RSL can also be adapted for use in the urban tile (*Theeuwes et al., BLM, 2019*).

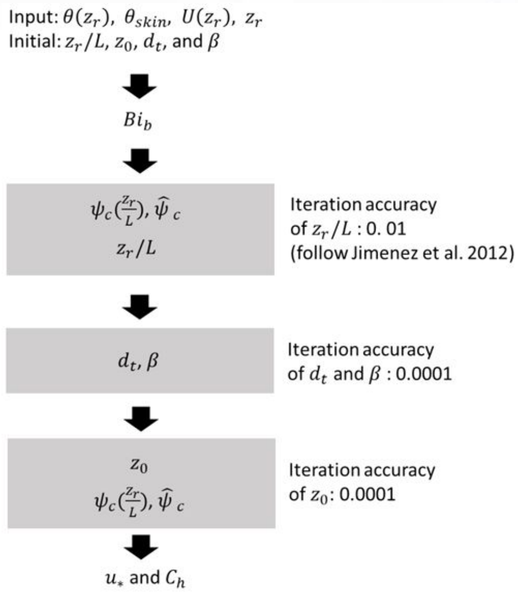


Diagram of the numerical (iterative) resolution of the RSL parameterization (Lee et al (2020)

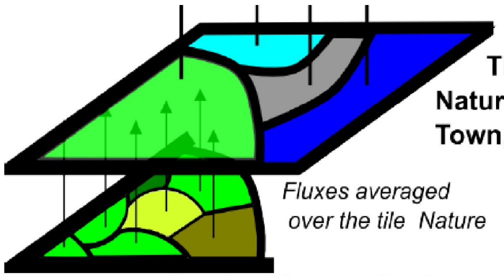
HF07 RSL implementation in SURFEX

- The nature tile in SURFEX runs in agrupations of different vegetation types (patches).

- HF07's RSL theory is expected to represent the turbulent exchange above the 'forested' patches in a more physically sound way, but it can also be applied to "low vegetation" patches (RSL will simply collapse into MOST at heights far enough from the roughness elements).

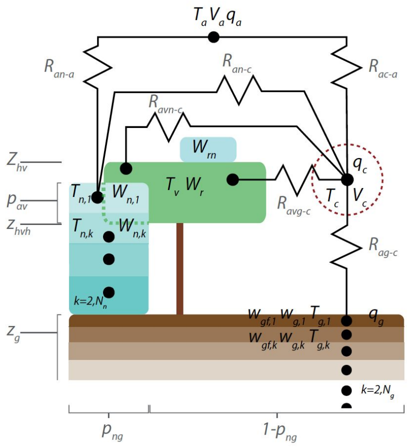
- Currently too many surface layer theories coexist in SURFEX (ISBA/ISBA MEB, 10m/2m diagnostics...)

- **We look for maximum consistency in the representation of the surface layer. This means:**
  - **Implement HF07's RSL for all patches**
  - **Use it for sfc-atm drag / flux computations**
  - **Use it for diagnostics of U_{10m} / T_{2m} / Q_{2m}**



HF07 RSL implementation in SURFEX

- Currently two different ways of computing surface fluxes coexist in SURFEX:
  - "OLD" ISBA: One single "composite" energy budget for Soil-Vegetation-Snow.
  - ISBA- MEB: Separate (coupled) energy budgets for vegetation, soil & snow.
- Different patches can run different versions of the physics.
- For example, SURFEX in Harmonie:
  - Harmonie43h2.1: F-R soil, 2 patches: open land (ISBA) and forest (ISBA)
  - Harmonie46hxx : DIF soil, 2 patches: open land (ISBA and forest (ISBA-MEB)
  - Harmonie4xhxx?? DIF soil, N patches, all running ISBA-MEB
- **In our RSL implementation:**
  - **We focus in integrating HF07 RSL into ISBA-MEB.**
  - **For completeness & consistency, we also want it to be usable with "old" ISBA.**



ISBA-MEB turbulence pathways

RSL in SURFEX - ISBA

$$H = \rho_a c_p C_H V_a (T_s - T_a) \quad (4.183)$$

$$LE = LE_{gl} + LE_v + L_i (E_s + E_{gf}) \quad (4.184)$$

$$E_{gl} = (1 - veg)(1 - p_{sng})(1 - \delta_i)\, \rho_a C_H V_a (h_u q_{sat}(T_s) - q_a) \quad (4.185)$$

$$E_v = veg(1 - p_{snv})\rho_a C_H V_a h_v (q_{sat}(T_s) - q_a) \quad (4.186)$$

$$E_s = p_{sn} \rho_a C_H V_a (q_{sat}(T_s) - q_a) \quad (4.187)$$

$$E_{gf} = (1 - veg)(1 - p_{sng})\, \delta_i\, \rho_a C_H V_a (h_{ui}\, q_{sat}(T_s) - q_a) \quad (4.188)$$

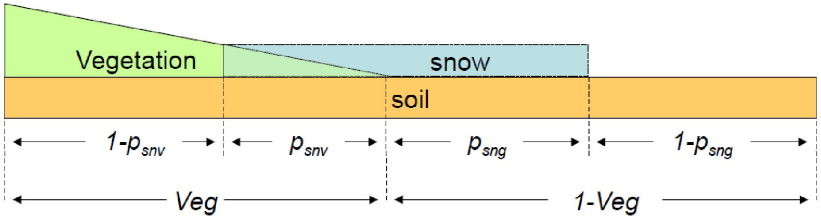
$$LE(T_{sn1}) = LE_{sl} + L_i E_s \quad (4.189)$$

$$E_{sl} = \delta_{sn}\, \rho_a C_{Hs} V_a (q_{sat}(T_{sn1}) - q_a) \quad (4.190)$$

$$E_s = (1 - \delta_{sn})\, \rho_a C_{Hs} V_a (q_{sat}(T_{sn1}) - q_a) \quad (4.191)$$

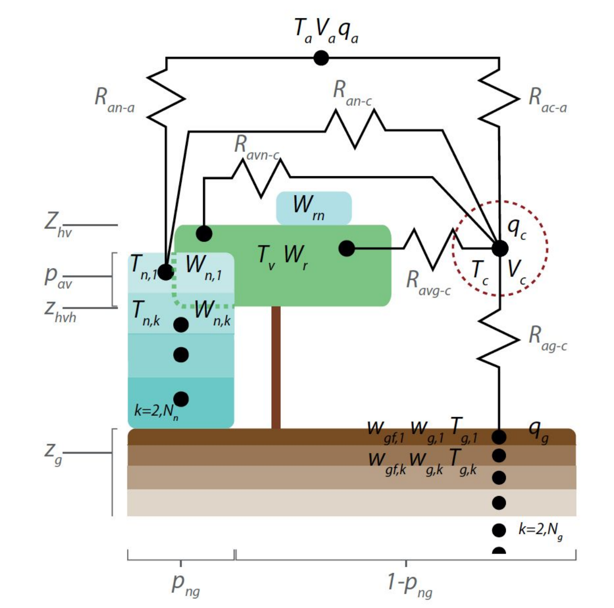
$$\delta_{sn} = w_{sl1}/w_{sl\,max\,1}; \qquad 0 \le \delta_{sn} \le 1 \quad (4.192)$$

$$|\overline{w'V'}|_s = C_D |V_a|^2 = u_*^2 \quad (4.207)$$



- New subroutine RSL_EFFECTS computes RSL versions of the drag coefficients C_D & C_H when the scheme is active.
- The original subroutines (SURFACE_CD, SURFACE_AERO_COND) are still used when the patch is completely unvegetated (e.g. rocks, which have undefined LAI or H_VEG) > Temporary fix

HF07 RSL in SURFEX - ISBA MEB



- MEB computes separate (but coupled) energy budgets for vegetation, soil & snow: 6 aerodynamic resistance pathways.

- RSL is only applied to evaluate the sfc-atmosphere resistances (drags):
  - $R_{ac-a} = (C_{HN} V_a)^{-1}$: between canopy air & atmosphere
  - $R_{an-a} = (C_{HN} V_a)^{-1}$: between the snowpack & atmosphere

All other intra-canopy turbulence computations are kept unchanged,
Also the old MEB estimation for the displacement height → Temporary fix.

HF07 RSL in SURFEX - 2m & 10m diagnostics

- Current interpolation options for U10m, T2m, Q2m in SUREFX (N2M=1,2,3 in CLS_WIND, CLS_TQ) are based in traditional MOST and therefore the diagnostic method should be updated.

- New subroutine UTQ_RSL computes the diagnostics at 2m & 10m above the new coordinate system, based on the new RSL (integrated) flux-profile relationships. Example for U_{10m}:

$$u10m = \frac{u_*}{\kappa}[\ln(\frac{10}{z_{0m}}) - \Psi_m(\frac{10}{L}) + \Psi_m(\frac{z_{0m}}{L}) + \hat{\Psi}_m(10) - \hat{\Psi}_m(z_{0m})]$$

- The original diagnostic subroutines are still used when the patch is completely unvegetated (e.g. rocks, which have undefined LAI or H_VEG)

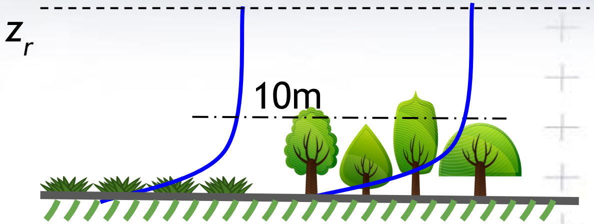
About verification of diagnostics in forested areas

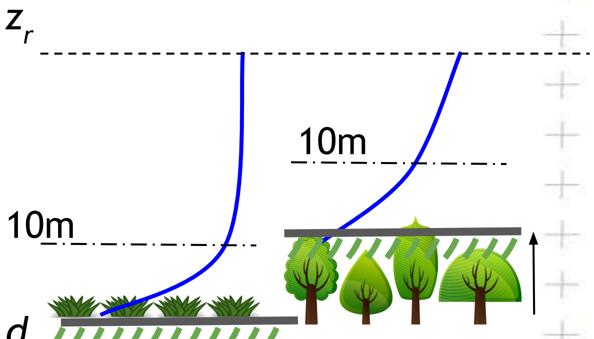
- 2 patches (ISBA/ISBA): U_{10m} / T_{2m} /Q_{2m} are “grid averages” of the corresponding diagnostics for the patches. There’s no displacement height in the forested patch (PATCH2) (i.e. , the wind profile is unrealistic).

- 2 patches (ISBA / ISBA MEB): U_{10m} / T_{2m} /Q_{2m} are “grid averages” of the corresponding diagnostics for the patches. The forested patch considers a displacement height, i.e. U_{10m_PATCH2} is evaluated 10m above the displacement height *d* (which is seen as the surface by the atmosphere).

- 2 patches (ISBA / ISBA RSLMEB): As above, but *d* is stability dependant, and PATCH 1 also runs RSL.

- A typical atmospheric station over a forested area is located in forest clearings so...what would be the most fair way to compare model and observations in forests?





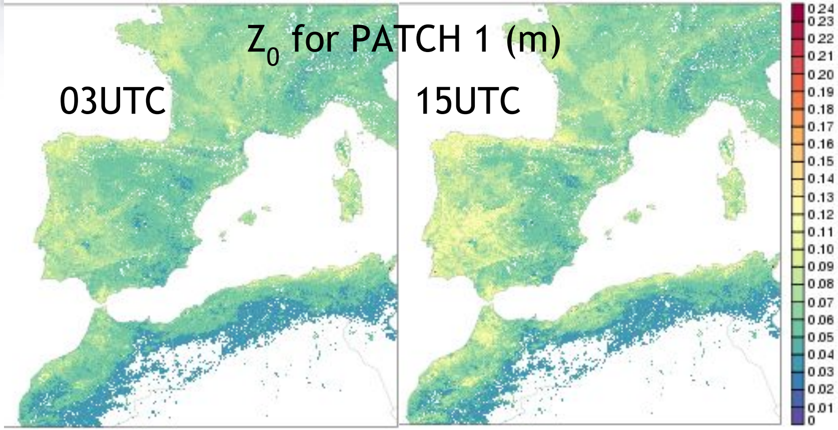
RSL tests in Harmonie

- Tests were done in Harmonie's pre-CY46h1 branch : EKF/ISBA-DIF/ISBA-ES/MEB (for patch2)/gridPP/Titan/pysurfex

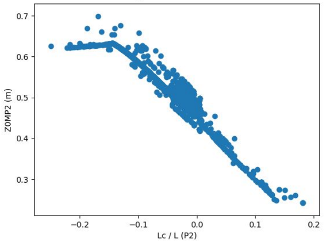
- Short experiments with/without HF07 RSL implementation over IBERIA & METCOOP domains, to check the stability of the RSL implementation and observe the general impact in fluxes and 2m/10m diagnostics.

- 10-day experiments with only 10-day warm-up: too little for soil spin-up with new surface physics (DIF/MEB) but enough for sensitivity experiments.

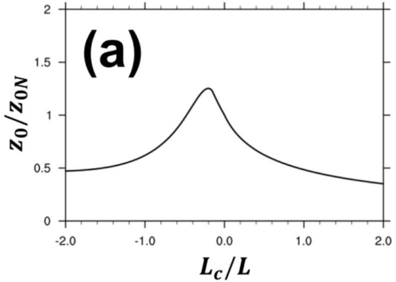
RSL tests in Harmonie: Consistency tests



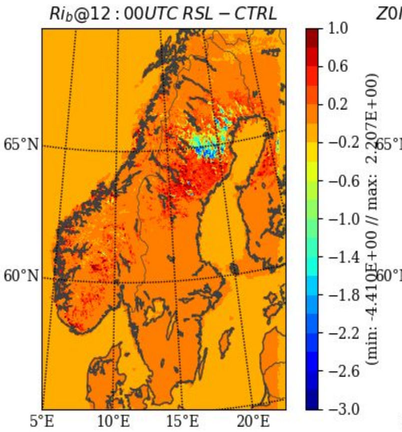
- Z_0 is stability dependent, with maximum values close to neutral stability.

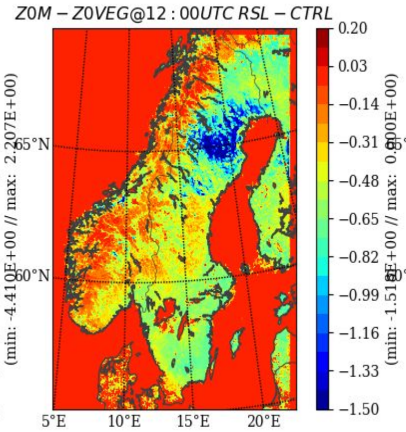


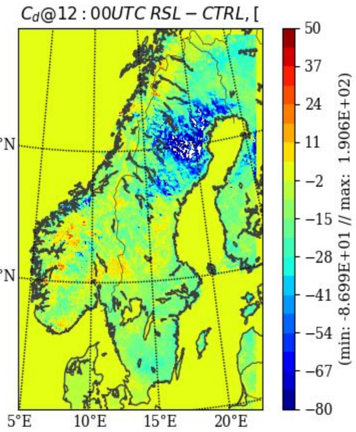
RSLMEB run



Lee et al (2020)

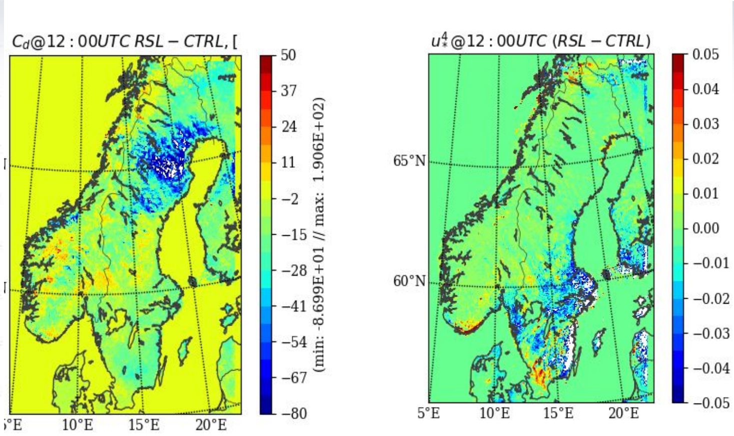


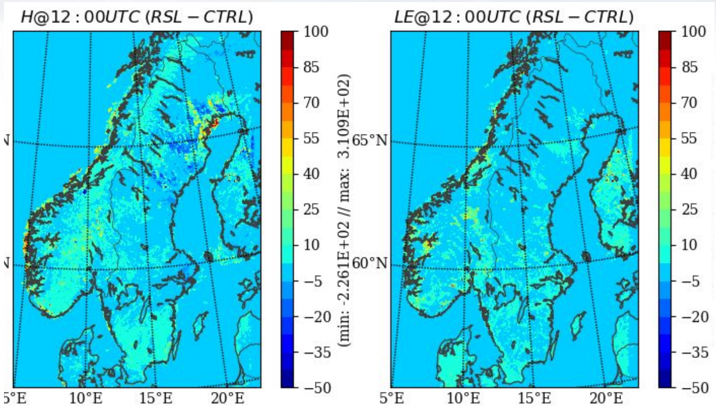


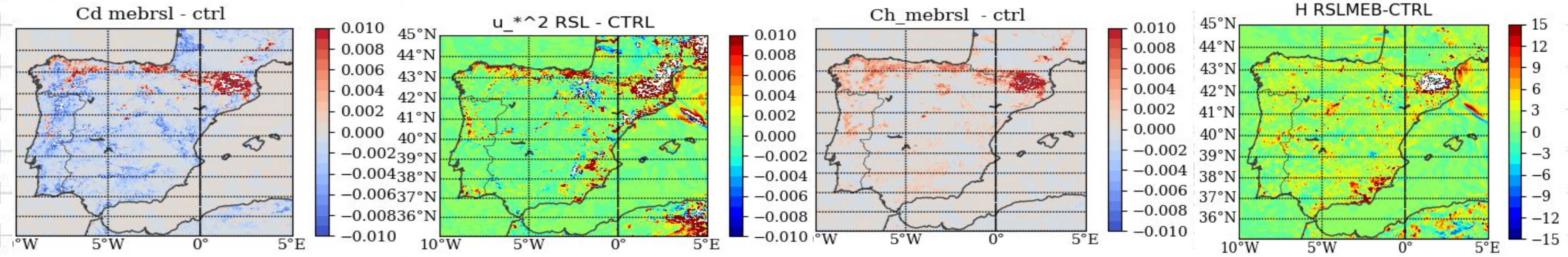


- Z_0 is the main driver for changes in C_D & C_H

RSL tests in Harmonie: Consistency tests - fluxes



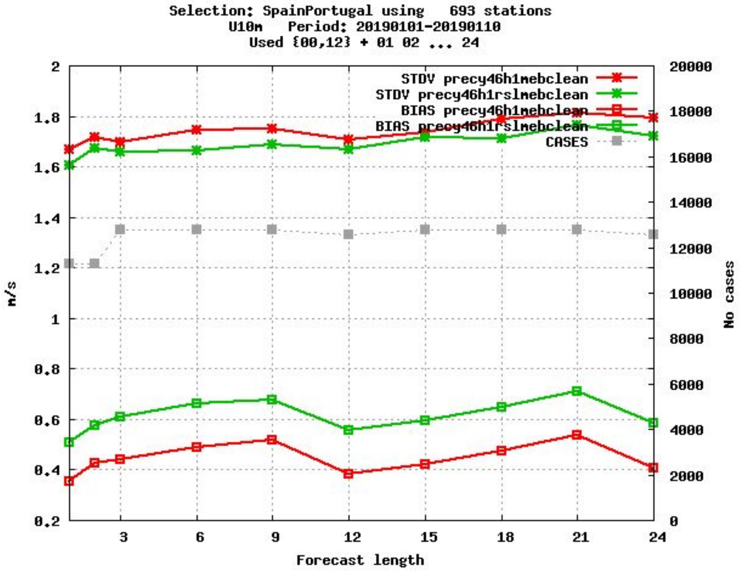


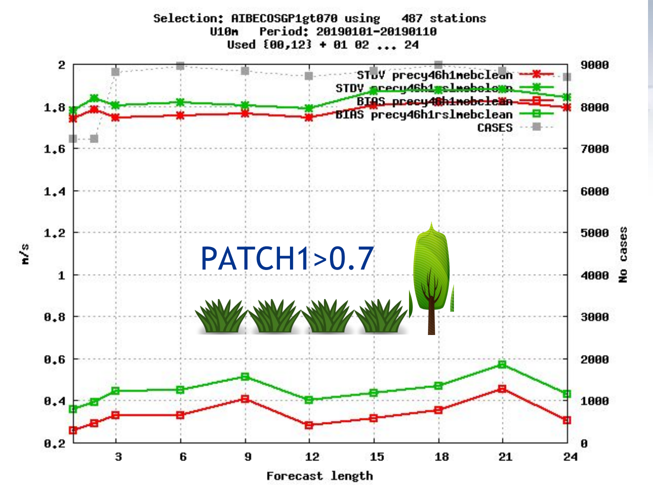


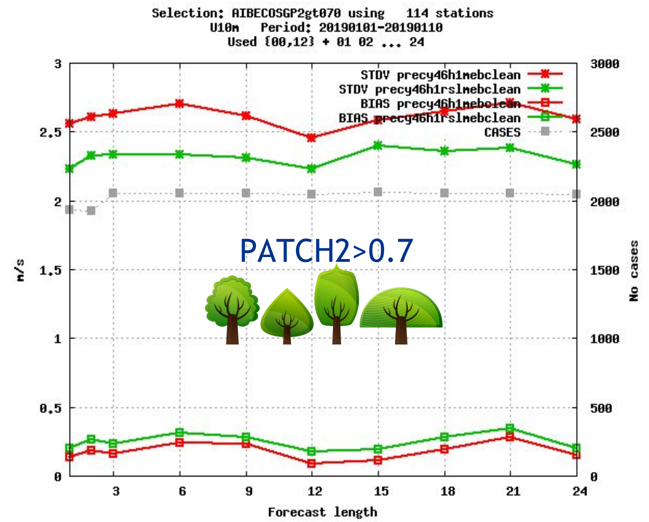
C_D- u_* correlation, as expected

Unexpectedly poor C_H - LE/H correlation

RSL tests in Harmonie: Impact in verification - U_{10m}



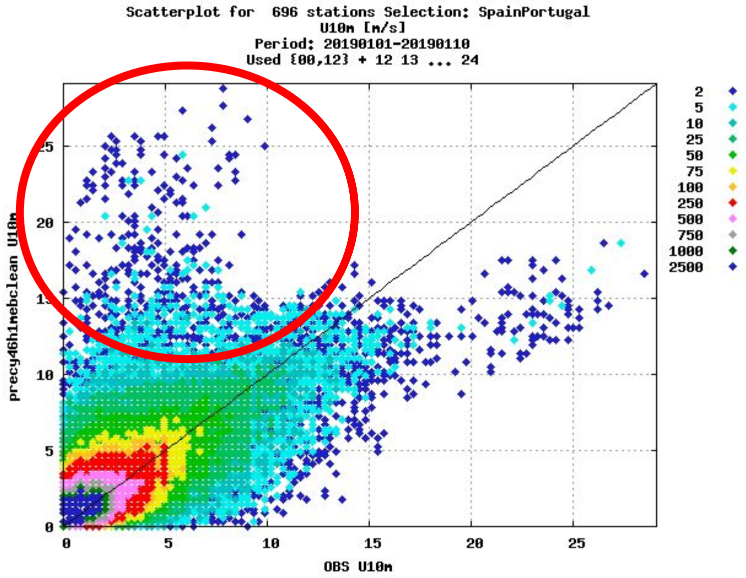


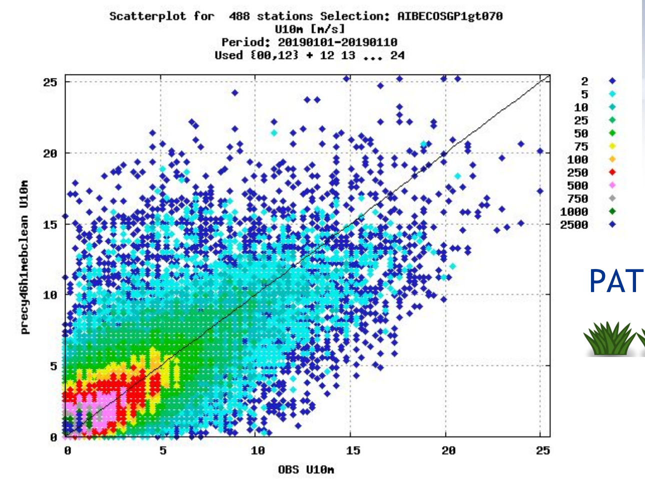


: CTRL (Cy46 DIF+MEB)

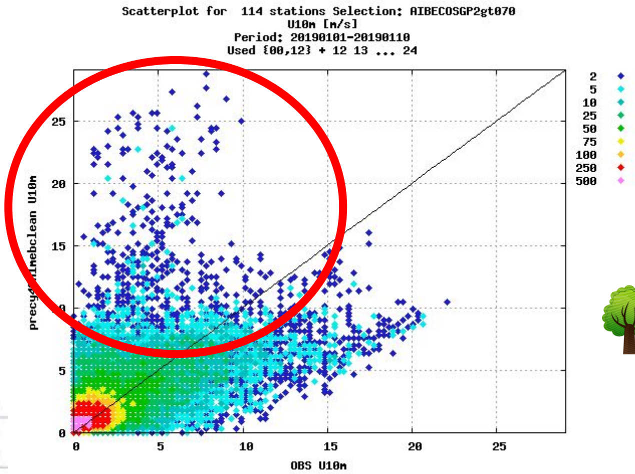
: RSL (Cy46 DIF+MEB + RSL)

CTRL (Cy46 DIF+MEB)





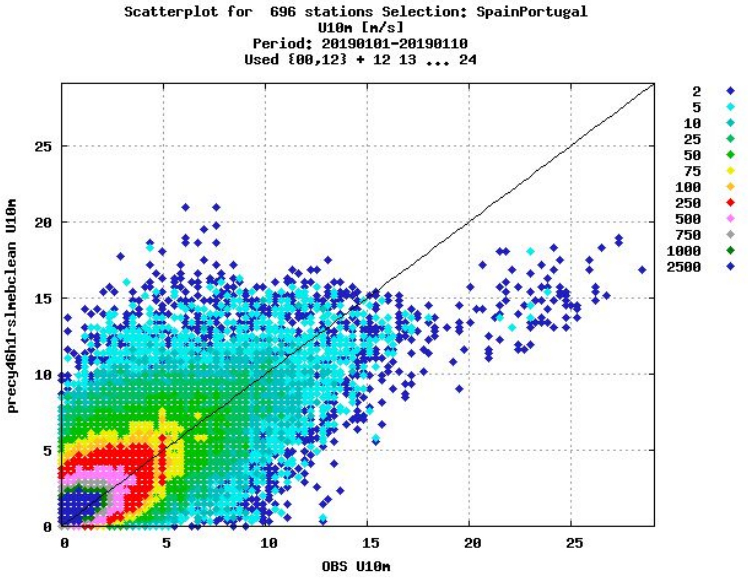
PATCH1>0.7



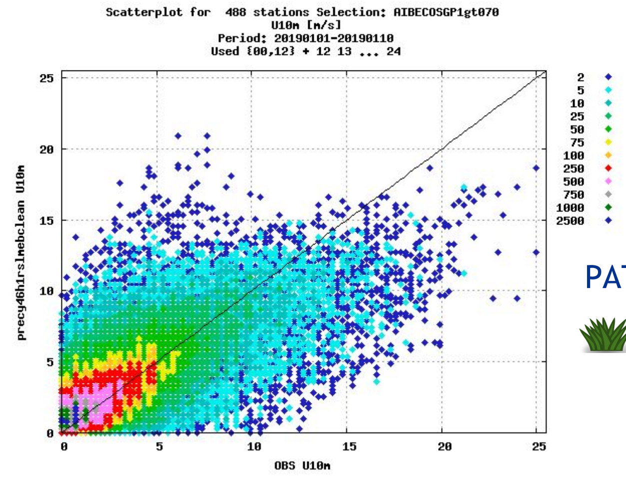
PATCH2>0.7

Strong overestimation, mainly produced in forested areas...

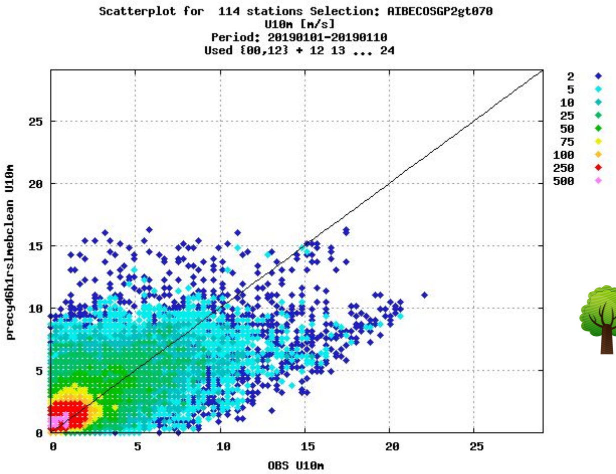
RSL (Cy46 DIF+MEB + RSL)



…it is much reduced with the RSL scheme



PATCH1>0.7



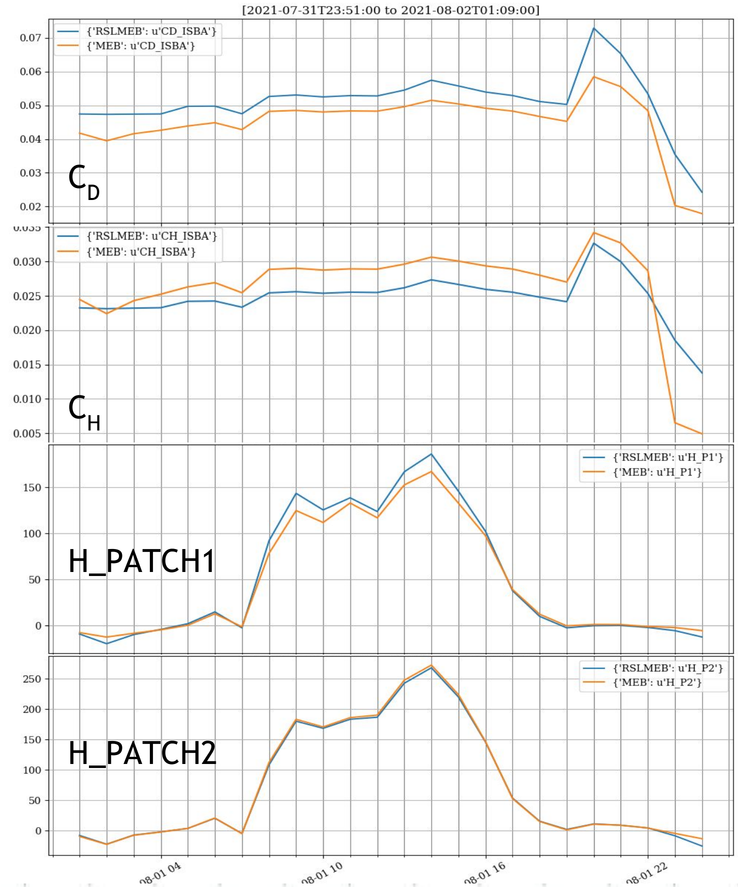
PATCH2>0.7

Next steps: OFFLINE SURFEX runs

- We switched to offline SURFEX runs over a small domain (15x15 km) in Scandinavia using NWP forcing (pysurfex)

- Debug H/LE flux calculation

- Find permanent solutions for temporary fixes (e.g. drag computations over rocks/no vegetation)



Next steps: OFFLINE SURFEX runs

- Validation experiments:
  - Use forcing data from observational sites with different vegetation characteristics (e.g. ICOS stations)
  - Study the impact of the RSL scheme in SEB and compare with observations.
  - Make final tunings to the RSL implementation.

An ACCORD-funded scientific visit to MF/CNRM is planned for the fall of 2021, to finish these works and possibly test the RSL scheme also in Meso-NH, in collaboration with Aaron Boone and Quentin Rodier

Conclusions & final remarks

- HF07 RSL is a fix to the MOST flux-profile relationships, which accounts for the modification of the flow and surface fluxes due to the presence of the canopy.

- Drag coefficients with HF07 RSL are evaluated from z/L instead of f(Ri). This is more scientifically robust, specially for the stable regime where the applicability of MOST for Ri>0.2-0.25 is compromised (Grachev et al. 2013).

- A first implementation into SURFEX is ready and tested offline and in NWP; it works technically, with promising results (reduced wind outliers) and some potential bugs found (MEB fluxes).

- The RSL code has impact in many parts of SURFEX. The scheme must be fully integrated in the SURFEX system, looking for internal consistency.

Thank you!