Introducing a roughness-sublayer in the vegetation-atmosphere coupling of HARMONIE-AROME

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1 Introduction

In the past 40 years, many studies showed that the standard flux-gradient relations, which are based on the similarity theory, are not fully applicable over a surface covered with high roughness elements (e.g. Thom et al. 1975; Raupach 1979; Garratt 1980; Cellier and Brunet 1992; Simpson et al. 1998; Mölder et al. 1999; Shapkalijevski et al. 2016). This is due to the canopy-induced turbulent mixing as a consequence from the interaction between the roughness elements and the atmospheric flow - a process that has not been explicitly treated in the standard surface similarity formulations. The effects of the so called roughness sublayer (RSL) on the surface-atmosphere coupling became more important since the lowest atmospheric level in NWP systems has been placed closer to the canopies (vegetation, urban), entering the layer (RSL) where the standard flux-gradient coupling relationships need a revision. This in turn affects the effective surface fluxes of momentum, energy and gases between the canopy and the atmosphere.

The present work aims at integrating the most advanced theory of the RSL into the SURFEX model (v8.1), adding increased physical details in the classical similarity theory over a vegetated surface. We have therefore developed a code of the RSL parameterization based on the Harman and Finnigan's RSL theory (Harman 2012; Harman and Finnigan 2008; Harman and Finnigan 2007), and have implemented it as a subroutine within the SURFEX framework. By doing so, we account for the altered turbulent exchange of momentum and energy in the coupling layer between the canopy and the atmosphere.

To be more efficient, robust and consistent with the RSL implementation in SURFEX, we have established a direct collaboration between the SURFEX developers (especially Multi-energy Balance (MEB) module developers), Meso-NH experts, and HARMONIE-AROME developers. To do so, we have used the ACCORD scientific visit opportunity to accomplish a visit to Météo-France (Toulouse).

Details of the code and the technical implementation in SURFEX shall be presented in a separate technical documentation. In what follows, preliminary results on the effects of the incorporated RSL parameterization in SURFEX on vegetation-atmosphere exchange properties shall be investigated. Since the latter defines the lower boundary forcing in atmospheric models, a further investigation of the RSL effects on the atmospheric boundary-layer state in HARMONIE-AROME and Meso-NH shall be provided and documented.

2 Implementation

We have incorporated the RSL parameterization in SURFEXv8.1 as independent optional subroutine and tested it *offline* , as well as *online*, as coupled to HARMONIE-AROME (from cy43h2.1.1) and to Meso-NH-v5.5.0. The RSL parameterization modifies the soil-vegetation-atmosphere transport (SVAT) of energy and momentum mainly by modifying the computation of the drag coefficients of momentum and heat (Harman 2012). The theoretical concept for the RSL implementation here was similar to the procedure presented in Harman (2012), as well as in more recent RSL implementations in GCM (Bonan et al. 2018) and WRF (Lee et al. 2020). Details of the implementation procedure and modified subroutines currently can be found here, and also at the 43rd EWGLAM conference.

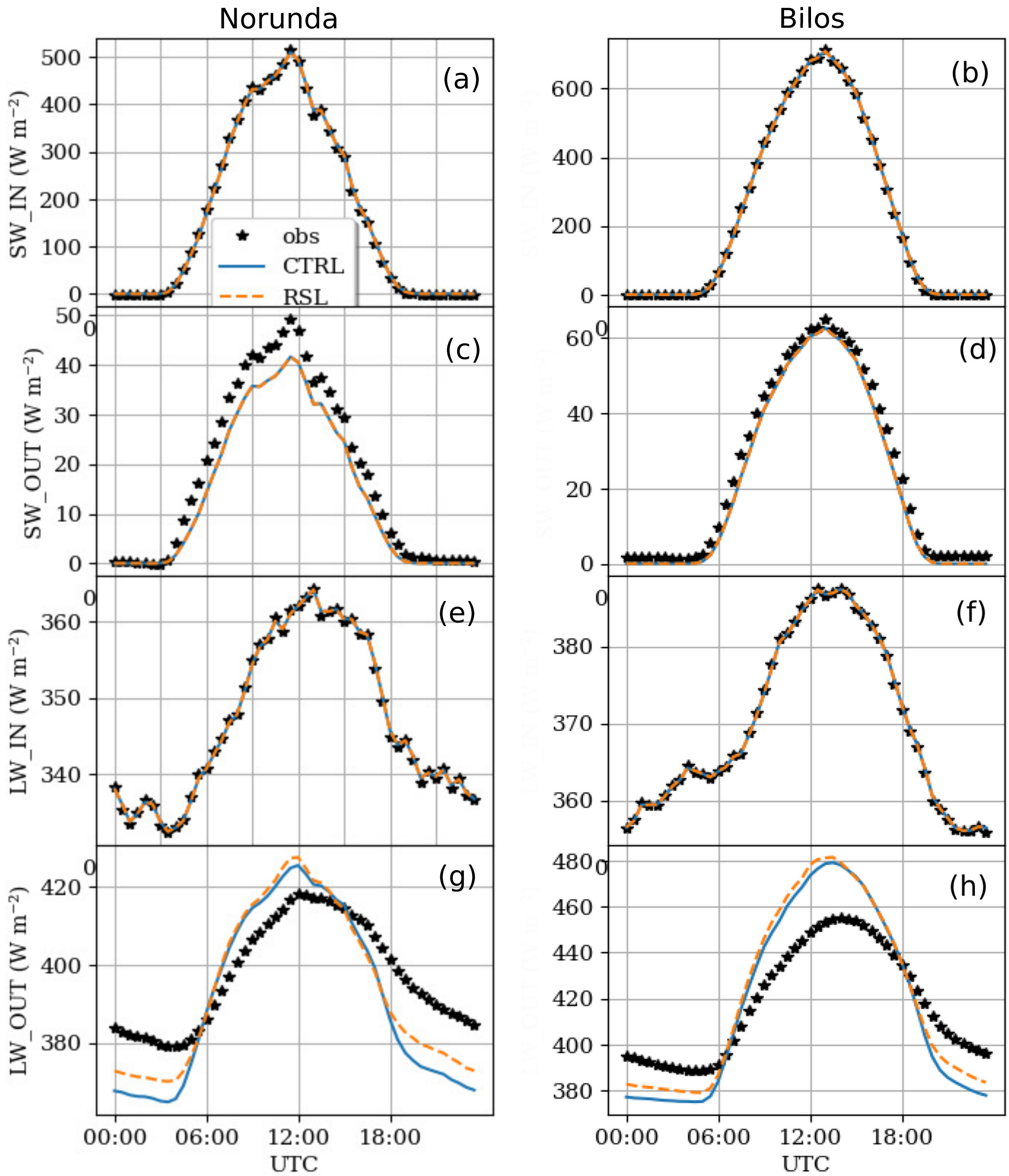

Figure 1: *Diurnal cycle of the observed versus the modelled (using ISBA-MEB) 30-min. averaged radiation fluxes above the canopy over the Norunda (a, c, e, g) and Bilos (b, d, f, h) observatories. Black symbols represent the observed radiation fluxes; the orange dashed line and blue solid line show the SURFEX offline outputs with and without the RSL, respectively.*

The SVAT coupling in SURFEXv8.1 is done through the traditional "composite" energy balance in ISBA (Noilhan and Planton 1989), or through the more advanced multi-energy balance (ISBA-MEB) scheme (Boone et al. 2017; Napoly et al. 2017). Thus, the RSL subroutines can be activated in each of these options. By setting $\mathrm{LRSL} = \mathrm{TRUE/FALSE}$ in the SURFEX namelist, the RSL parameterization is activated/deactivated automatically. Only when activated, the ISBA or ISBA-MEB scheme, uses 'dynamical' roughness lengths and displacements heights within the RSL parameterization. Also, when activated, a new output for the roughness lengths is set (X001Z0M and X002Z0M, for patch 1 (e.g. unforested) and patch 2 (forested), respectively). Given that the RSL collapses into traditional MOST when displacement height tends to zero, the implementation was done for both forested and unforested patches. Our aim is, by taking care of the SURFEX coding principles and standards, to prepare the RSL parameterization code for an optional usage in the next official version of SURFEX (v9).

3 Application and validation

3.1 Offline case studies

So far, we have set three realistic SURFEX offline case experiments (with and without the RSL parameterization) in forested areas, where long term flux-gradient measurements are available. This was done to further explore the canopy and the roughness effects on turbulent exchange properties between the vegetation and the atmosphere by validating the model results against tower flux-gradient observations. The case studies were developed at three locations: *i*) Norunda in Sweden, *ii*) Bilos in Salles (France) (both as a part of the Integrated Carbon Observation System - ICOS), as well as *iii*) BERMS (Boreal Ecosystem Research and Monitoring Sites) in Canada. All three ecosystems are similar (Boreal needleleaf evergreen plant functional type in SURFEX) with varying average canopy height between 10 and 29 meters, and similar canopy density/sparsity (e.g. leaf area index (LAI) between 1 and 3). 30 minutes average meteorological observational data (wind speed, temperature, humidity, radiation) has been used to force the simulations at 58 meters for Norunda case, 15.6 m for Bilos case, and 37 meters for BERMS case, respectively (heights above the ground surface). Observed fluxes and gradients above the canopy have been used to validate the simulation performance (see Figs. 1 - 3).

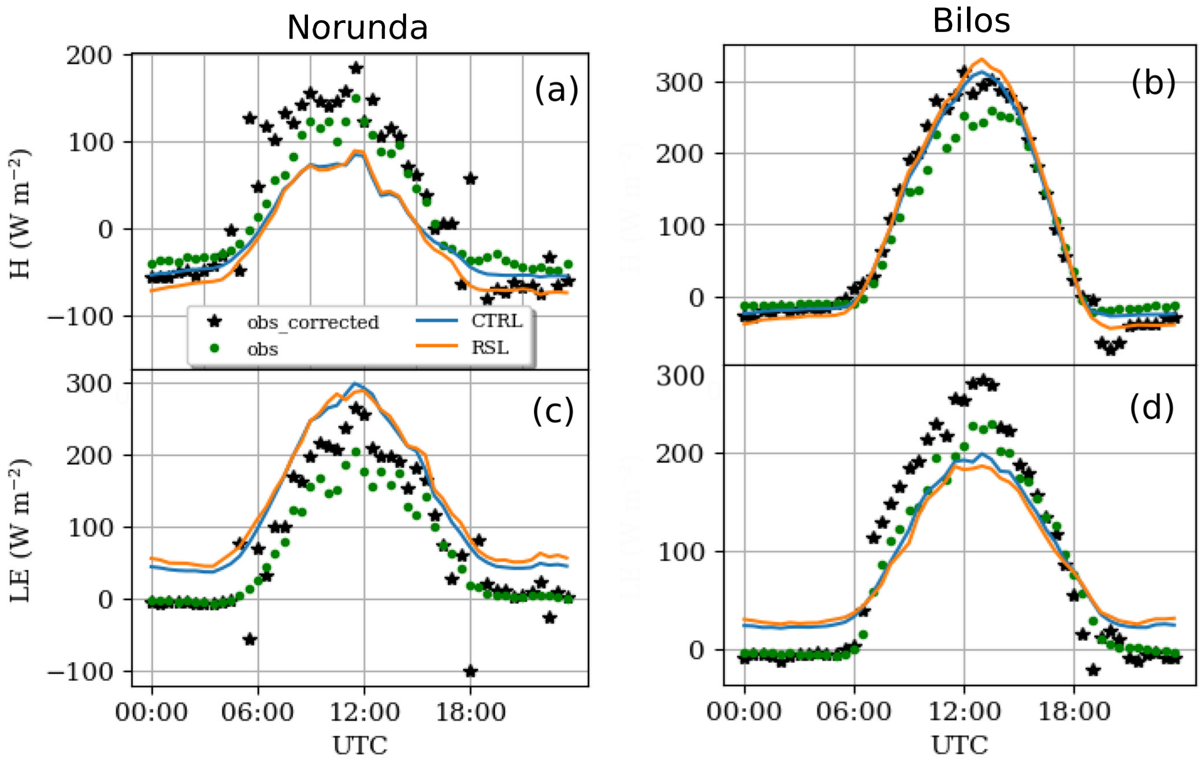

Figure 2: *Diurnal cycle of the observed versus the modelled (using ISBA-MEB) 30-min. averaged sensible (H) and latent (LE) fluxes above the canopy at the Norunda (a, c) and Bilos (b, d) observatories. Observed fluxes (green solid dots represents the eddy co-variance technique applied on raw data) are corrected (black symbols) using the Bowen ratio method (Blanken et al. 1997).*

Here we mainly present results from the simulations at Norunda and Bilos, as these sites are within the Met-CoOp and France domains of HARMONIE-AROME. They correspond to the average diurnal cycles during the period of the simulations: 8-31 August, 2019 for Norunda and 1 June - 9 September, 2021 for Bilos. Prior to these periods, a short spinup period of 7 days for Norunda and 45 days for Bilos was run (a subject of continuous data availability). The initial state of the soil temperatures was obtained from the ICOS observations, while the initial soil humidities were established by assuming the soil moisture proportional to the field capacity. Although soil moisture observations are available for both sites, these were not used in the current simulations to avoid uncertainty in relation to the unknown soil textures. Some additional sensitivity shall be provided in the future however, but for the purpose of validation the RSL contribution in the SURFEX SVAT scheme (the aim of the current study), this type of sensitivity is irrelevant.

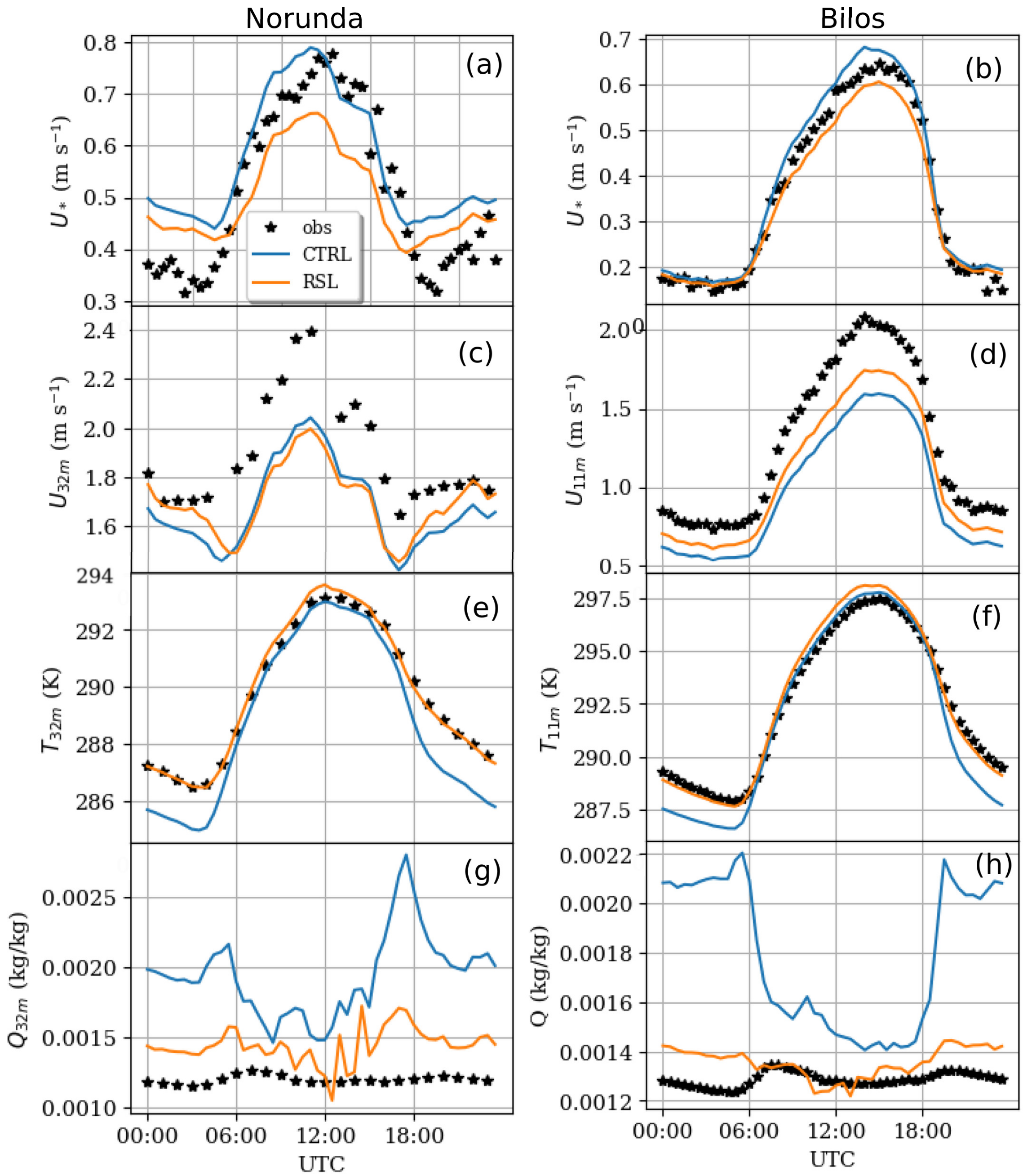

Figure 3: *Diurnal cycle of the observed versus the modelled (using ISBA-MEB) 30-min. friction velocity (u_*), modulus of the wind speed (U), temperature (T) and specific humidity (Q) above the canopy at Norunda observatory (a, c, e, g) and at Bilos observatory (b, d, f, h).*

Radiation forcing of the model above the canopy, as incoming short-wave (↓SW) and long-wave (↓LW) energy, resulted in reasonable simulation of the outgoing radiation partitions (↑SW and ↑LW) and thus the net available energy overall. More precisely however, there was a slight an overestimation of the outgoing long-wave radiation during daytime, as well as its underestimation during nighttime (up to 20 W m^{-2}) (Fig. 1g and 1h). The latter was followed by a larger underestimation of the daytime sensible heat (H) between the canopy and the forcing level over Norunda (up to about 70 W m^{-2} on average), while the latent heat (LE) partitioning was overestimated for about 50 W m^{-2} (Fig. 2a – 2c). H over Bilos was simulated well, but LE was still unrealistically overestimated during nighttime and underestimated during daytime (Fig. 2b – 2d). The unsatisfactory results for the LE, in general, require some additional investigation, especially the unrealistic positive moisture flux during nighttime (Fig. 2c – 2d). However, more important for this study is that the activation of the RSL effects in the vegetation-atmosphere coupling did not show strong influence on both H and LE, except the slight improvement in the modelled nighttime cooling (Fig. 2a and 2b). A larger improvement due to the inclusion of the RSL parameterization is found on the modelled dynamics within the roughness sublayer, as represented by the friction velocity u_*, and the wind speed just above the canopy (Fig. 3a – 3d). This led to a clear improvement in the diagnostically calculated wind speed at Bilos, while at Norunda the improvement due to the RSL parameterization was mainly during nighttime; decrease of friction velocity and increase of wind speed. The worst model dynamics in general over the Norunda can be related to the presence of more complex boundary-layer dynamics. For instance, the diurnal cycle of wind speed at 58 m had a secondary maximum during nighttime, suggesting the presence of low-level jets (LLJ). While these LLJs were already absent (or largely decreased) at the level of 32 m, the interpolated wind speed at this level showed their existence. Meanwhile, the temperature ((Fig. 3e and 3f)) and specific humidity diagnostics (Fig. 3g and 3h) above the canopy were equally improved at both sites due to the RSL presence.

Preliminary results showed similar behaviour for both ISBA and ISBA-MEB with repect to RSL inclusion, but more consistent comparison shall be additionally provided.

3.2 Online simulations

HARMONIE-AROME (Bengtsson et al. 2017) Several simulations with and without the RSL parameterization in the vegetation-atmosphere coupling in full three-dimensional HARMONIE-AROME setup have been conducted. The simulations were done over the IBERIA and METCOOP domains to illustrate different topographical and climatological characteristics. The ten days of simulations for each of the domains had spinup time of ten days. A summary of the simulations is shown in Table 1.

Table 1: *HARMONIE-AROME simulation setups*

Domain	IBERIA	METCOOP
System version (ISBA-FR)	cy43h2.1.1	cy43h2.1.1
System version (ISBA-DIF/MEB)	pre-cy46h1	pre-cy46h1
Simulation time (after spinup)	10 days	10 days
Simulation date(s)	20190101 - 20190110	20210415 - 20210425

The presence of the RSL parameterization in vegetation-atmosphere coupling of HARMONIE-AROME systematically reduced the scatter in the diagnosed wind speed at 10 m when compared to standard meteorological observations (at stations throughout the domains) (Fig. 4). More precise validation of the HARMONIE-AROME flux-gradient output above tall vegetation (e.g. forests) cannot be provided by using observations from these standard meteorological stations. Flux-gradient observations from towers within forests should be used instead (e.g. Norunda or Bilos observatory; work in progress).

Meso-NH (Lac et al. 2018) To test the implementation RSL parameterization and its effects on the online SURFEX vegetation-atmosphere coupling in Meso-NH, we have set a simple and well studied experiment over the largely vegetated La Réunion Island in the tropics, a French department in the Indian Ocean. This has

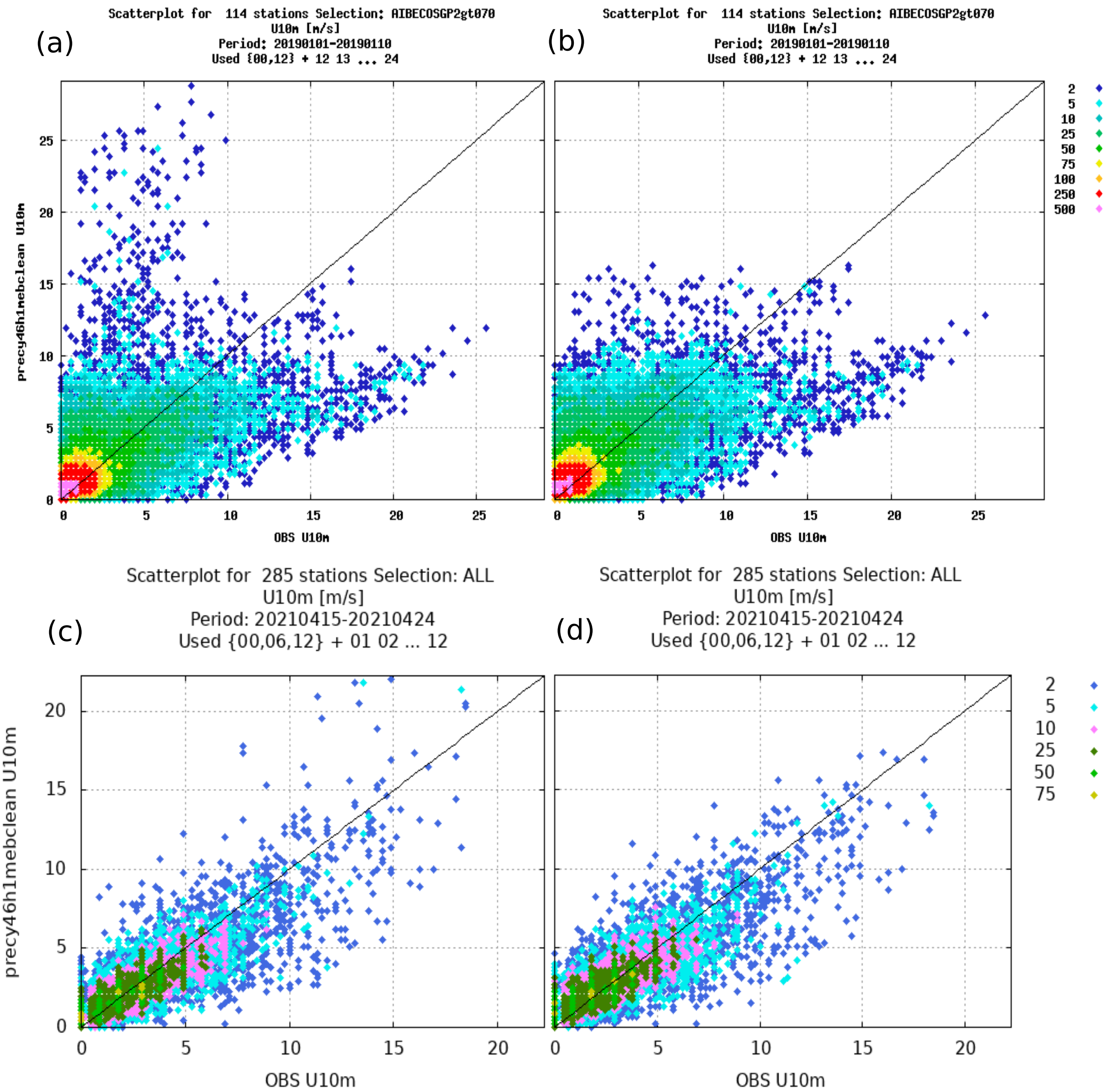

Figure 4: *Scatterplot of the modelled by HARMONIE-AROME and the observed wind speed at 10 m over the IBERIA ((a)-(b)) and METCOOP/Sweden ((c)-(d)) domains without ((a)-(c)) and with the RSL parameterization ((b) and (d)), respectively. The scatterplots for the IBERIA simulation correspond to a selection of stations where the fraction of forest is larger than 70%.*

been done on the basis of ISBA-FR approach. An example of the qualitative differences of the near-surface meteorology in ISBA-FR with and without the RSL parameterization are shown in Fig. 5. Decreased wind speeds in the field are result of the stability dependent roughness lengths, which in the composite ISBA is a constant fraction of the vegetation height only.

3.3 Discussion and outlook

The surface-atmosphere coupling in forested areas, in the case of the SURFEX offline runs is done at levels where forcing data is available (e.g. tower observation in the above cases). This (forcing) data is usually set

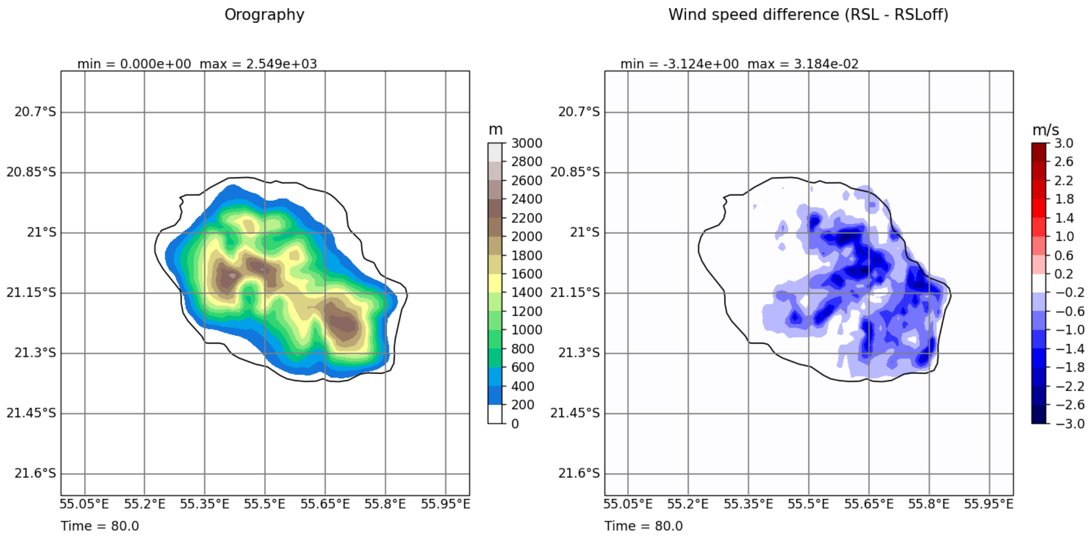

Figure 5: *The absolute difference of the wind-speed field at lowest model level over the La Réunion Island, as diagnosed by the vegetation-atmosphere coupling scheme with and without RSL parameterization.*

(well) above the canopy to meet the assumptions required by the surface theory (e.g. constant vertical flux in height). However, for the online SURFEX simulations, the surface-atmosphere coupling in forested areas (e.g. PATCH2) is done at a height set at the lowest atmospheric level (z_n), which is independent from the surface cover properties (heterogeneity) and thus *a priori* assumed that the meteorological conditions at z_n are similar to those above the canopy top in reality; then, the vegetation-atmosphere coupling is virtually done between the z_n and the displacement height (the zero vertical coordinate for the atmospheric model). Due to the assumptions made here, a point validation of online SURFEX simulations over the presented case studies (e.g. HARMONIE-AROME) are expected to vary from the results presented based on the offline SURFEX output.

This is exactly the purpose of the authors' current activity. The aim is to set up full 3D HARMONIE-AROME simulations for the given time periods, August 2019 and summer 2021, over the Swedish and the Spanish domains, respectively. Similar analysis as presented here for the offline cases shall be provided for the extracted grid points of the online NWP output at Norunda and Bilos, as well as its validation against the tower observations. The results of the offline and the online simulations shall be compared and further discussed.

4 Conclusions

We studied the consistency of the RSL implementation in both ISBA and ISBA-MEB vegetation-atmosphere coupling schemes in SURFEX and HARMONIE-AROME. We also investigated the RSL effects on the surface fluxes and diagnostics in SURFEX offline and online (HARMONIE-AROME, Meso-NH) experiments by using high-quality flux-gradient observations above canopies.

The preliminary results showed consistent implementation of the RSL parameterizations in SURFEX offline and online experiments. The SURFEX offline validation showed satisfactory agreement in representing the dynamics and the thermodynamics above the canopy at Norunda. The presence of the RSL parameterization decreased the somewhere-present bias between the observed and modelled fluxes and gradients in both ISBA and ISBA-MEB coupling, with a larger improvement in representing the diurnal cycle of momentum fluxes and the diagnostic wind speed above the canopy. Additionally, the online HARMONIE-AROME simulations showed consistent reduction in diagnostic wind-speed scatter above Iberian and Scandinavian forests.

Additional online HARMONIE-AROME and Meso-NH simulations with and without the RSL parameterization over Sweden and France/Spain should provide a valuable information about the differences of the offline and online SVAT schemes in SURFEX and thus the NWP performance in simulation near-surface exchange processes above forested areas.

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