Reinitialised versus continuous regional climate simulations using ALARO-0 coupled to the land surface model ~~SURFEX~~SURFEXv5

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Abstract. ~~The potential of the implementation of the land surface model SURFEX in the atmospheric ALARO-0 modelconfiguration of~~ For the simulation of the regional climate with limited area models, the common method for dynamical downscaling is the continuous approach with initial and lateral boundary conditions from the reanalysis or the global climate model. The simulation potential can be improved by applying an alternative approach of reinitialising the atmosphere, combined with either a daily reinitialised or a continuous surface. We evaluated the ~~ALADIN system is tested in a~~ dependence of the simulation potential on the running mode of the regional climate model ALARO coupled to the land surface model SURFEX, and driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data. Three types of downscaling simulations were carried out for a 10-year period covering 1991 to 2000, over a Western European domain at 20 km horizontal resolution: (1) a continuous simulation of both the atmosphere and the surface; (2) a simulation with daily reinitialisations for both the atmosphere and the surface; and (3) a simulation with daily reinitialisations of the atmosphere while the surface is kept continuous~~regional climate simulation. This contribution is evaluated with respect to the regional climate simulated by the original setup of ALARO-0 with ISBA. Next, an assessment has been performed to evaluate the continuous setup with an upper air daily reinitialised setup, where the surface is kept in a freely continuousmode~~. The results ~~show that the introduction of SURFEX improves or has~~ showed that the daily reinitialisation of the atmosphere improved the simulation of the 2 m temperature for all seasons. It revealed a neutral impact on the ~~2 m temperature and the daily total precipitation . More importantly, the use of an upper air daily reinitialised atmosphere outperforms the setup with a continuousatmosphere,~~ daily precipitation totals during winter, but the results were improved for the summer when the surface was kept continuous. The behaviour of the three model simulations varied among different climatic regimes. Their seasonal cycle for the 2 m temperature ~~in winter and summer, and for~~ and daily precipitation totals was very similar for a Mediterranean climate, but more variable for temperate and continental climate regimes. Commonly, the summer climate is characterised by strong interactions between the atmosphere and the ~~summer daily total precipitation. The differences between the two downscaling setups in the 2 m temperature and precipitation interacts with the soil moisture. This coupling is strong for the continental areas, which motivates the~~ surface. The results for summer demonstrated that the use of a ~~coupled land-atmosphere model to optimise~~ daily reinitialisated atmosphere improved the representation of the partitioning of the surface energy fluxes.

Therefore, we recommend to use the alternative approach of the daily reinitialisation of the atmosphere for the simulation of the regional climate.

1 Introduction

The first long-range simulation of the general circulation of the atmosphere ~~was performed by ?~~dates back to 1956 (?). Today it is still the primary tool for climate projections. However, due to limiting computer resources, the current horizontal resolution of 100-200 km is still coarse. A higher resolution and more spatial details can be obtained by nesting a regional climate model (RCM), over a smaller domain, into a coarse-resolution global climate model (GCM). This is also referred to as dynamical downscaling. The ~~RCM uses the~~ GCM or global reanalysis provides the large-scale ~~features from the GCM or from a global reanalysis as~~ meteorological and surface fields to the RCM as initial and lateral boundary conditions~~(LBCs). This way the~~. The global features are thus translated into regional and local conditions over the region of interest (?). Hence, RCMs allow to run climate simulations over a smaller domain with higher horizontal resolution and with an affordable computing cost.

Since the late 60's, the ~~Numerical Weather Predictions~~ numerical weather prediction (NWP) community uses ~~so-called~~ high-resolution limited area models~~(LAM). ? were the first to use the numerical approach~~. The numerical approach was first used for a regional climate simulation by ?. Their climate simulation used the NWP model in forecasting mode with ~~frequent reinitialisations~~ short-term reinitialisations of the initial conditions. To be able to run ~~without these frequent reinitialisations, i.e. in~~ them without these short-term reinitialisations, the regional climate community applied monthly to multidecadal simulations, with only one single initialisation of the large-scale fields and frequent updates of the lateral boundary conditions (?). These so-called long-term ~~continuous mode, the climate community has increasingly developed the~~ continuous simulations required improvements in the representation of physical processes in ~~RCMs. Still, this~~ the RCMs. This continuous simulation is still the most common in the RCM community (?). Nonetheless, the simulated large-scale ~~circulation deviates~~ fields deviate from the driving ~~LBCs, when~~ lateral boundary conditions, by applying the continuous ~~mode (?).~~ approach (?).

The accuracy of the dynamical downscaling has improved by using short-term reinitialisations ~~(???). These~~ (????). All these authors showed the advantage of using short-term reinitialisations by ~~reducting~~ reducing systematic errors. However, only few authors adopted this method, mainly because of its higher computational costs.

~~Most studies (???)~~ Most studies (???) dealing with the evaluation of reinitialised versus continuous climate simulations, covered only short time periods. The 24-hourly reinitialised simulation of the precipitation, in particular of the precipitation pattern, improved as compared to the continuous simulation (?). ~~Their~~ This last mentioned analysis covered only a short time period, one month in 2002 during a large flooding event in the Elbe river catchment. Changing the period of reinitialisation, from monthly to 10-daily, ~~the experiments of ? showed~~ a reduction in systematic errors has been shown for precipitation when using the 10-day reinitialisation (?). Even in a 20-year RCM simulation forced by reanalysis data, the sequence of events was better preserved by using ~~frequent~~ short-term reinitialisations (?).

~~The model used in this study is the ALARO-0 model configuration of the ALADIN system. This setup will short-handedly referred to as ALARO-0 henceforth. This model configuration is used by the Royal Meteorological Institute of Belgium (RMI)~~

~~for its operational numerical weather forecasts. ALARO-0 has already proven its ability for regional climate modelling with daily reinitialisations (??). The model initially used the Interaction Soil-Biosphere-Atmosphere Interaction (ISBA) land surface scheme (??). The setup of ALARO-0 with ISBA has been validated for continuous climate simulations and is now contributing to the EURO-CORDEX project (??). Meanwhile the more recent land surface scheme of Météo-France SURFace EXternalisiée (SURFEX, ?) has been implemented in the ALARO-0 version. With respect to NWP applications,~~ A model approach with short-term reinitialisations demands additional simulation time at each reinitialisation start. This time is required to reach dynamical equilibrium between the lateral boundary conditions and the internal model physics and dynamics (?). Beyond 24 hours small perturbations in the initial conditions of the ~~introduction of SURFEX within ALARO-0 has shown neutral to positive effects on the 2 m temperature, 2 m relative humidity, 10 m wind speed and on the precipitation scores compared to the previously used ISBA scheme (?). Therefore, the evaluation of SURFEX within ALARO-0 is highly demanding for regional climate simulations.~~

~~Our study consists of three objectives. The first objective is to test the potential of~~ atmosphere have only limited impact on the simulation potential (?). In contrast to the atmosphere, the surface takes a longer time to reach dynamical equilibrium with the overlaying atmosphere, in the ~~implementation of SURFEX within ALARO-0 with respect to~~ order of a few weeks to several seasons, depending on the depth of the ~~original setup of ALARO-0 with ISBA, in a continuous regional climate setup using boundary conditions from ERA-Interim.~~ soil layer.

The surface interacts with the climate through the soil moisture and soil temperature, by influencing the surface energy budget (?). The soil moisture controls the partitioning of the incoming energy into a latent and sensible heat flux. The ~~second objective is~~ soil moisture limitation on the evapotranspiration is largest during the summer (?). The availability of soil moisture for evapotranspiration is determined by the 2 m temperature (?). As the surface-atmosphere interactions play a crucial role in the representation of the current and future climate, it is important to validate the model with ground observations. The FLUXNET database provides data on the surface energy fluxes, based on eddy covariance measurements (?).

The objective of this study was to evaluate the ~~continuous setup with an upper air daily reinitialised setup, where the surface is simulated continuously. Regarding the second setup, the boundary conditionsof sea surfacetemperature (SST) were reinitialised daily together with the upper air. Therefore one expects to see improvements for~~ simulation potential of three regional climate downscaling approaches with different update frequencies of the initial conditions: (1) a continuous simulation of both the atmosphere and the surface; (2) a simulation with daily reinitialisations for both the atmosphere and the surface; and (3) a simulation with daily reinitialisations of the atmosphere while the surface is kept continuous. We used the ALARO model to dynamically downscale the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim, ?). Within this study, ALARO was coupled to the ~~second method over continental parts of the domain, but not so much in coastal areas. A study of a coupling with a sea model is outside the scope of this paper. Beside the two setups with a continuously simulated surface, a setup with a daily reinitialisation of the~~ land surface ~~is not recommended since this setup limits the equilibrium of the surface physics (soil moisture and temperature) , which is particularly desirable in long-term climate modelling (?). The third objective is to examine the performance of the two downscaling approaches with respect to the land surface feedback, more specifically the soil moisture feedback. It was hypothesized that the differences in temperature and~~

~~precipitation between the downscaling approaches are related to differences in soil moisture. The availability of soil moisture is related to the distribution of the energy fluxes (**?**). Therefore, their daily cycle was analysed for particular locations in this study.~~ model of Météo-France SURFace Externalisée (SURFEX, **?**). We evaluated the mean 2 m temperature and mean daily total precipitation by comparing with the 0.22° ECA&D E-OBS dataset (**?**), and the surface energy fluxes by comparing with the FLUXNET database (**?**). The analysis covered a 10-year period from 1991 to 2000, for a domain encompassing Western Europe.

The ~~land-atmosphere feedback was evaluated for the summer season only. The processes that control the soil moisture feedback to the climate system, result in different a coupling strength for summer and winter. It is strongest during summer, when the surface is characterised by local interactions between land surface and the overlaying atmosphere (**???**). This is in contrast to the winter climate variability, which is primarily determined by large-scale circulation, as the atmospheric circulation anomalies are well correlated during winter with the SST anomalies (**?**).~~

~~The regional climate model and experimental design~~ models, experimental design and observational datasets are described in section 2. The results for the mean surface parameters are covered in section 3. Section ~~3 covers the observational datasets. The results with respect to the first and second objective are addressed in section 4. Next, section 5~~ 4 demonstrates the results with respect to the ~~third objective~~surface energy budget. Finally, conclusions are given in section ~~6.~~ 5.

2 Model and experimental design

2.1 Model definition

The ~~European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis (**?**) was dynamically downscaled with the RCM ALARO-0. ERA-Interim provided lateral boundary conditions for the period of 1979 until now, at a horizontal resolution of $\approx$ 79 km. The RCM ALARO-0 is a version of~~ regional climate model used in this study is the ALARO model version 0, a configuration of the Aire Limitée Adaptation Dynamique Développement International (ALADIN) model with improved physical parameterisations (**?**). The ALADIN model is the ~~LAM~~ limited area model version of the Action de Recherche Petite Echelle Grande Echelle Integrated Forecast system (ARPEGE-IFS) (**??**). ARPEGE is a global spectral model, with a Gaussian grid for the grid-point calculation. The vertical ~~discretization~~ discretisation is done according to a ~~following-terrain~~ terrain-following pressure hybrid coordinate. ALARO-0 has been developed with the ARPEGE Calcul Radiatif Avec Nebulosité (ACRANEB) scheme for radiation based on **?**.

~~We simulated the regional climate of~~ This ALARO-0 ~~coupled to the land surface model SURFEX. Originally,~~ model configuration is being operated at the Royal Meteorological Institute of Belgium (RMI) for its operational numerical weather forecasts since 2010. The new physical parameterisation within the ALARO-0 model was specifically designed to be run at convection-permitting scales, with a particular focus on an improved convection and cloud scheme, developed by **?** and further improved by **?** and **?**. The ALARO-0 model domain is centered at 46.47° N and 2.58° E with a dimension of 149 x 149 horizontal grid points and spacing of 20 km in both horizontal axes, in a Lambert conformal projection (Fig. 1). The domain encompasses Western Europe. The model consists of 46 vertical layers with the lowest model level at 17 km and the model top extending up to 72 km.

The parameterisation of the ~~parameterisation for the~~ land surface in ALARO-0 was ~~simulated using~~ initially with the land surface ~~model ISBA(**??**). Later on, the Town Energy Balance (TEB), a parameterisation for urban areas, was developed by **?**. Recently, ISBA and TEB were combined and externalised into SURFEX, based on the algorithm of **?**. SURFEX is based on a tiling approach. The tiles provide information on the surface fluxes for different types of surfaces: nature, town, inland water and ocean. A parameterisation exists for each component of the surface, more particularly ISBA for the nature type and TEB for the town type. Each tile is divided in different patches, according to the tile type. These patches correspond to the plant functional types described in ECOCLIMAP version~~ scheme Interaction Soil-Biosphere-Atmosphere (ISBA, **??**). This scheme was designed for NWP and climate models, and describes heat and water exchanges between the low-level atmosphere, the vegetation and the soil, by using either a diffusion method (**?**), or a force restore method based on two or three layers (**?**). Using the initial setup with ISBA, ALARO-0 has proven its skill for regional climate modelling with daily reinialisations (**??**). In addition, this setup has been validated for continuous climate simulations and is now contributing to the EURO-CORDEX project (**??**). Meanwhile the more recent land surface model SURFEX, with additional parameterisations for other surface types than nature, has been implemented in the ALARO-0 model. With respect to NWP applications, the introduction of SURFEXv5 within ALARO-0 has shown neutral effects on the winter 2 ~~(**?**). ECOCLIMAP is a 1 km horizontal resolution global land cover database that is provided with SURFEX. It assigns the tile fraction to SURFEX together with the corresponding physical parameters. The soil component in ISBA provides vertical soil water and heat transfer by either a diffusion method (**?**), or a~~ m temperature and on the vertical profile of the wind speed. However, it has shown positive effects on the summer 2 m temperature, 2 m relative humidity, and resulted in improved precipitation scores compared to the previously used ISBA model (**?**). Next to the validation of this setup for NWP, the implementation of SURFEXv5 within ALARO-0 is highly demanding for long-term climate simulations. In this study, SURFEX uses the two-layer force restore method ~~based on two or three layers (**?**). A two-layer version of ISBAwas used in this contribution~~for ISBA. The first layer is the surface superficial layer, that directly interacts with the atmosphere, and the second layer is the combined bulk surface and rooting layer, which is determined at the depth were soil moisture flux becomes negligible for a period of about one week and is thus more important as a reservoir for soil moisture during dry periods (**?**).

~~The atmospheric forcing was provided by ALARO-0 to SURFEX . The source code of SURFEX is implemented as a model library that is independent from the atmospheric model. At each model time step, the atmospheric forcing consisted of the upper-air temperature, specific humidity, wind speed and direction, atmospheric pressure computed at the lowest atmospheric level (≈ 17 m) and incoming global radiation, incoming longwave radiation and total precipitation. Next, SURFEX simulated momentum, heat and water fluxes, and the standard meteorological variables as the 2 m temperature and relative humidity and 10 m wind using the interpolation method of **?**.~~ SURFEX is based on a tiling approach. The tiles provide information on the surface fluxes according to the type of surface: nature, town, inland water and ocean. The initial parameterisation ISBA for the nature tile was conserved, and parameterisations for the other surface tiles were added, such as the Town Energy Balance scheme (TEB, **?**) for the town tile. TEB uses a canopy approach with three urban energy budgets for the layers roof, wall and road. The ISBA and TEB schemes were combined, together with parameterisation schemes for inland water and oceans, and externalised, based on the algorithm of **?**. Each tile is divided in different patches, according to the tile type. These patches correspond to the plant functional types described in ECOCLIMAP (**?**). ECOCLIMAP is a 1 km horizontal resolution global land cover database and assigns the tile fraction and corresponding physical parameters to SURFEX.

~~Recently, the performance of the ALARO-0 model driven by~~

2.2 Experimental design

The regional climate model was driven by initial and lateral boundary conditions provided by the ERA-Interim ~~has been evaluated within the Coordinated Regional Climate Downscaling Experiment on the European Domain (EURO-CORDEX, **??**. The horizontal resolution of the EURO-CORDEX domain is 0.11° (≈ 12 km) and it encompasses Europe, North Africa and a considerable part of Russia as well. In contrast to the EURO-CORDEX domain, the domain in our study is smaller.~~ reanalysis, available at a horizontal resolution of ca. 79 km. The ~~present study was done in the framework of another project, for which a domain encompassing Western Europe is sufficient. The domain is centered at 46.47° N and 2.58° E with a dimension of 149x149 horizontal grid points and spacing of 20 km in both horizontal axes (Fig. **??**). Due to computational limitations, the domain horizontal resolution cannot be similar to the EURO-CORDEX horizontal resolution. The model consists of 46 vertical layers with a model top extending up to 72 km. ALARO uses a~~ **?** relaxation zone consisted of eight grid points irrespective of the resolution.

2.3 ~~Experimental design~~

~~For the present study,~~ The zonal and meridional wind components, atmospheric temperature, specific humidity, surface pressure and surface components were provided every 6 hrs as lateral boundary conditions and interpolated hourly. They were introduced as initial conditions accross the domain. A spin-up time was considered for the model to reach equilibrium between the lateral boundary conditions and the internal model physics (**?**). For the sake of a good understanding, the following description makes a distinction between atmospheric spin-up time, typically of a ~~first downscaling simulation of ALARO-0 coupled to SURFEX was done in a continuous mode for both atmosphere and surface (hereafter called CON, Table 5). It started at~~ few days, and surface spin-up time, typically of a few months to one year. The analysis covered a 10-year period from 00UTC on 01 January ~~1990, and ran continuously until~~ 1991 to 00UTC on ~~1 January 2000. The first year was treated as a spin-up year, and the analysis period covers the 10-year period~~ 01 January ~~1991 to 31 December 2000. The output was stored every 3 hrs for the atmospheric variables and daily for the SURFEX variables, e.g. deep soil moisture. The SST was updated each month during the simulation to avoid discrepancies throughout the year.~~ 2001. Although the 10-year length is arbitrary, it is sufficiently long to include some inter-annual variability and to generate a reasonable sample of extreme events. The use of a NWP model in a long-term climate setting for the performance of extreme precipitation events for a 10-year period was recently demonstrated ~~by **?**.~~

~~The second downscaling simulation of~~ (?). To evaluate the sensitivity of the model to the update frequency of the initial conditions, three types of downscaling approaches were conducted with ALARO-0 coupled to ~~SURFEX was initialised daily with ERA-Interim combined with a continuous running~~ SURFEXv5.

The first downscaling approach was done by simulating the model in a continuous mode for both the atmosphere and the surface (hereafter called ~~FS, Table 5), starting at 12UTC~~ CON ("CONtinuous"), Fig. 2). The model was simulated from 00UTC on 01 ~~March each year , with a spinup period of 3 months. This was done in parallel for all the years 1990 to 2000, and the analysis period covered the 10-year period~~ January 1990, and ran continuously until 00UTC on 01 January 2001. The first year was treated as both atmospheric and surface spin-up time, and was excluded from the analysis. The simulations were interrupted and restarted monthly to allow for SSTs to be updated. Other surface parameters that were updated monthly using the climatological values from ECOCLIMAP were the vegetation fraction, surface roughness length, surface emissivity, surface albedo, sand and clay fractions.

In the second downscaling approach, the model was reinitialised daily for both the atmosphere as the surface (herafter called DRI ("Daily ReInitialisation"), Fig. 2). The model started at 12UTC on 01 January 1991~~to 31 December 2000. The output was stored every 3 hours for the atmospheric variables and daily for the SURFEX variables. Each daily simulation extended up to~~ , and each reinitialisation ran for 60 hrs~~, of which the~~ . The first 36 ~~hrs~~ hours were treated as ~~spinup time. The last 24 hrs were saved for the atmospheric conditions. The soil variables evolved freely after the first initialisation and were never corrected or nudged in the course of the simulation. This method allowed the surface conditions to be continuous, whereas the atmosphere was reinitialised daily~~atmospheric spin-up time, and were excluded from the analysis. By applying this downscaling approach, the regional model stays close to the driving fields (?). As the driving fields provided daily reanalysed data, a spin-up for the surface was redundant.

~~A third simulation was applied for both CON and FS (Table 1). A 3-month summer period from~~ The third downscaling approach tries to find the best compromise between previous approaches. The atmosphere was reinitalised daily and the surface was simulated continuously with one single initialisation (hereafter called FS ("Free Surface"), Fig. 2). This allowed the model to simulate the atmospheric fields close to the driving fields, together with a surface in equilibrium state. The model was simulated from 12UTC on 01 ~~June 2000 to~~ March 1990 until 31 ~~August~~ May 1991, and the atmosphere was reinitialised daily for a simulation time of 60 hrs. The first 36 hrs were treated as atmospheric spin-up time, and were excluded from the analysis. The surface conditions were kept continuous and joined after the atmospheric spin-up time with the surface conditions of the previous daily simulation. In contrast to the atmospheric spin-up time, the surface spin-up lasted from 01 March 1990 until 31 May 1990, and this 3-monthly period was excluded from the analysis. Although CON required one year spin-up time, 3 months were sufficient for the FS deep soil moisture to reach equilibrium state, when starting in March (not shown). The simulations were done in parallel for each year from 1990 to 2000~~was simulated, but unlike previous simulations, the output from SURFEX was stored hourly. This allowed us to analyse the diurnal cycle of the parameters related to the surface radiation budget.~~

~~The first simulation was compared against the ALARO-0 simulations done within the framework of EURO-CORDEX, that used the land surface scheme ISBA. The output from the EURO-CORDEX simulations was subset to the time period of interest and regridded to the study domain and to a 20 km horizontal resolution (called hereafter CRDX, Table 5), to compare it with~~

~~the results of both downscaling strategies. This comparison allowed to examine the effect of SURFEX on the climate mode, as was previously done for NWP (?).~~ , and the 3 monthly spin-up time was replaced by the analysis of the previous year.

The model output at every 3 hrs was used for the model evaluation. The evaluation of ~~the atmospheric variables~~ atmospheric variables for winter and summer was done for seven subdomains across Europe, to cover the spatial variability of the domain (Fig. ~~??~~1). This was in agreement with the subdomains that were used in the EURO-CORDEX community (**?**) and that were defined earlier in the framework of the ~~PRUDENCE project~~ project "Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects" (PRUDENCE) (**?**). The subdomains used in this study ~~are~~ were the British Isles (BI), the Iberian Peninsula (IP), Mid-Europe (ME), France (FR), the Alps (AL), the Mediterranean (MD) and Eastern Europe (EA). For ~~both MD~~ the subdomains IP, ME, and EA, ~~only part of their domains were used, as our domain is not covering the total subdomain, and also the relaxation zone was excluded.~~ the yearly cycle of the atmospheric variables was evaluated. These selected subdomains covered a range of climatic regimes. Additionally, the surface energy fluxes were analysed. As land-surface processes play an important role primarily during summer, the model output was stored at every hour for the summer period of June-July-August (JJA) during the 10-year period. We evaluated the partitioning of the sensible and latent heat fluxes by the daily maximum Bowen Ratio (BR, **?**) for the summer periods from 1996 to 2000 for the total study domain, and compared the selected FLUXNET stations with their corresponding model grid points. The corresponding daily maximum BRs were analysed for the 10-year summer period from 1991 to 2000. When the value is lower (higher) than 1, the latent heat flux is higher (lower) than the sensible heat flux. The diurnal cycles of all surface energy fluxes were analysed and validated against observations.

3 ~~Observational data~~

2.1 ~~E-OBS gridded dataset~~Observational reference data

The results of the climate simulations were validated against E-OBS, a daily high-resolution gridded observational dataset (**?**). The dataset consists of the daily mean temperature, the daily maximum and minimum temperature, and the daily precipitation ~~sum~~total. The most recent version v12.0 was selected on the 0.22° rotated pole grid, corresponding to a 25 km horizontal resolution in Europe. It covers the period 01 January 1950 to 30 June 2015. With respect to previous versions of E-OBS, some improvements include the new precipitation data series for countries southeast of the Baltic Sea, updated Slovakian series for all variables, updated Croatian series for all variables and a highly extended network for Catalonia, Spain. These improvements also concerned our area of interest and time period of interest. In order to validate the model data, the ~~E-OBS data~~ ALARO-0 data at 20 km horizontal resolution were bilinearly interpolated towards ~~the ALARO-0 20 km~~ E-OBS at 25 km horizontal resolution and replotted to our study domain. A careful interpretation of E-OBS was necessary, as this regridded non-homogeneously distributed network ~~implied~~ applied a smoothing out of extreme precipitation and consequently a large underestimation of the mean precipitation (**?**).

2.2 ~~Eddy covariance data~~

~~The FLUXNET database~~ For the validation of the surface fluxes distribution in the model, we used measurements from the FLUXNET Level 3 flux tower database (?). It provides information on the energy ~~exchanges~~ exchange between the ecosystem and the atmosphere~~(?)~~. FLUXNET is a global network, and consists of flux towers using the eddy covariance method to monitor carbon dioxide and water vapor exchange rates, and energy flux densities. ~~The technique exists since the late 1950s, yet only recently continuous flux measurements are possible~~No gap-filling has been done and the comparison to the model output was only done at hours when no gaps occurred. A number of stations were already part of a separate flux measurement network (?). However, only a few stations provided data for the first operating years ~~and so, only the year 2000 was selected for the evaluation of the model with regard to the observations. The model was compared with the station that was nearest to the model grid box. The model resolution is quite low, and thus the grid point consisted of more land covers beside the particular land cover of the station. Therefore, only~~ covering the period 1996 to 2000. Two FLUXNET stations were selected, that provided data during this period and where the model grid cell represented more than 50% of the corresponding land cover, to show energy fluxes that were representative for the particular land cover. The selected ecosystem towers cover different climatic regimes (Fig. ~~1)were~~1): (1) Vielsalm in Belgium, a temperate climate, at an altitude of 491 m with a tower height of 40 m and ~~mainly~~ covered by deciduous broadleaved forest and evergreen coniferous, and (2) Collelongo in Italy, a Mediterranean climate, at an altitude of 1645 m with a tower height of 32 m and mainly covered by deciduous broadleaved forest.

3 Validation of the mean model state

3.1 Spatial distribution

3.1.1 Daily mean 2 m temperature

The spatial ~~distribution~~ distributions of the 10-year daily mean temperature bias ~~of CRDX, CON~~ (absolute, (model - observed)) of CON, DRI and FS simulations ~~are~~ were compared to E-OBS (Fig. ~~??a,b~~3), for the winter (DJF: December-January-February) and summer (JJA: June-July-August) season. The average biases during winter and summer for ~~CRDX, CON~~CON, DRI and FS for the entire domain as well as for specific subdomains are presented in Table ~~2. CRDX simulates~~ 5. CON simulated a cold bias in general, except for northern Africa, with a pronounced orographic effect, for both winter and summer (Fig. ~~??~~3c,d). ~~Within the EURO-CORDEX ensembles, it was shown that the cold bias over the Iberian Peninsula was stronger compared to other subdomains (?), which is also presented here by a cold bias of -3.27 °C, though the Alps and the Mediterranean also result in even stronger biases.~~ The cold bias over the ~~domain is~~ entire domain was less pronounced in summer ~~than in winter, shown by the average bias of the total domain of -2.94~~ with a value of -0.6 °~~C and -0.62~~ C compared to the winter bias of -1.8 °~~C respectively~~C (Table 5). Moreover, the Iberian Peninsula ~~and Mediterranean show very small biases, as a result of compensating cold and warm biases. Still, a strong summer bias of -1.77~~ was well simulated during summer as compared to

E-OBS, resulting in a bias of -0.5 °C~~is obvious at the Alps.~~ . Additionally, the biases of the Mediterranean and Eastern Europe resulted in similar small biases, due to compensating errors as can be seen from (Fig. 3d).

With respect to ~~CRDX, CONdemonstrates~~ CON, DRI demonstrated a reduction of ~~20-30 % for the cold mean~~ the cold bias during winter ~~for the Iberian Peninsula and the Mediterranean (Table 2). Besides,the British Isles, Mid-Europe, France and Eastern Europe show a bias reduction of ≈ 1~~ and summer, most prominent at the eastern part of the domain (Fig. 3e,f). This resulted in a smaller bias for Eastern Europe of -0.3 °C ~~or more than 40 % for CON compared to CRDX, resulting in~~ and 0.0 °C for DRI relative to CON which had a bias of ~~-1 to -2~~ -1.1 °C ~~for these subdomains. In contrast to the largely improved winter bias (Fig. ??e), CON has a slightly positive and slightly negative to neutral impact on the summer bias compared to CRDX (Fig. ??f)Overall, the biases are smaller in summer compared to the winter biases. The largest bias reduction appears over Eastern Europe, with a reduction of nearly 60 %, while it is decreased for the Mediterranean with about 30 %, and increased with 40-70 % for the British Isles,~~ and -0.5 °C for winter and summer respectively (Table 5). Other subdomains showing a large improvement of the ~~Iberian Peninsula and~~ 2 m temperature simulation by DRI, were Mid-Europe and the Alps with a winter bias of -0.7 °C and -1.4 °C respectively that is about half of the bias of CON, and a summer bias of -0.3 °C and -0.8 °C, even more than half of the bias of CON for these subdomains.

The performance of the FS simulation ~~is different from CON, both~~ was different for winter and summer as compared to CON and DRI (Fig. ~~??~~3g,h). The ~~winter total mean bias is improved, resulting in -1.03 °C compared to -2.94 °C and -1.85 °C for CRDX and CON respectively (Table 2). For~~ simulation of the 2 m temperature during winter was best of all three approaches when using FS. Large parts of the domain resulted in biases close to zero, such as the British Isles, France, Mid-Europe ~~, France~~and Eastern Europe ~~, the winter mean bias is reduced with ≈ 60-70 %, and it is reduced with ≈ 40 % for the Iberian Peninsula and the Mediterranean. Similarly to CON , the cold bias remains over the Alps, and is reduced with 30 %~~(Fig. 3g). The bias decreased by ca. 1 °C in FS compared to CON for these subdomains (Table 5). During summer, the sign of the bias ~~reverses~~ reversed from negative to positive~~for many subdomains.~~ , except for some isolated areas (Fig. 3h). The Alps were much better presented by FS, resulting in a zero bias as compared to CON and DRI which showed a bias of -1.8 °C and -0.8 °C (Table 5). For the Iberian Peninsula and the Mediterranean, compensating biases ~~result in a~~ resulted in positive and close to zero ~~bias.~~ summer biases (Fig. 3h). Mid-Europe, France and Eastern Europe ~~are~~ were mainly characterised by a positive bias of around 1 °C ~~. The Alps are much better presented by FS , compared to CON .~~ (Table 5). The summer absolute bias simulated by FS was very similar to CON for the Iberian Peninsula and the Mediterranean, but slightly enhanced for Eastern Europe with ca. 0.6 °C.

In summary, CON ~~underestimates~~ underestimated winter and summer 2 m temperature with 1-2 °C on average. With respect to ~~CRDX, CONshows~~ CON, DRI and FS showed a positive effect ~~in Europe~~ during winter and ~~neutral to positive effect in summer, despite being slightly enhanced for particular subdomains. However, the summer bias is largely improved in Eastern Europewhen using CON compared to CRDX. The use of FS improves~~ summer. In spite of a slight enhancement by FS of the bias during summer for Eastern Europe, the winter bias was improved for most subdomains by using FS. Overall, the use of a daily reinitialised atmosphere improved the representation of the 2 m temperature for both winter and summer compared to ~~CON~~a continuous simulation of the atmosphere.

3.1.2 Daily accumulated precipitation

The spatial ~~distribution~~ distributions of the 10-year daily accumulated precipitation bias ~~of CRDX, CON and FS are~~ (relative, (model-observed)/observed) of CON, DRI and FS were compared to E-OBS, for the winter and the summer seasons (Fig. ~~??~~4). The mean biases during winter and summer for ~~CRDX, CON~~CON, DRI and FS are presented for the entire domain as well as for the specific subdomains in Table ~~3~~2. The precipitation pattern of E-OBS during winter ~~shows~~ displayed highest values of > 3 mm day^{-1} over Portugal, northwestern Spain, western England, Scotland and Ireland, the Adriatic Coast and the northern flanks of the Alps (Fig. ~~??~~4a,b). During summer, similar amounts of rainfall ~~are~~ were concentrated over the Alps and the Carpathians, while lowest values of < 1 mm day^{-1} at the Iberian Peninsula, the Mediterranean and northern Africa.

~~CRDX shows a general wet biasin winter and summer~~During winter, all simulations demonstrated a similar spatial variability of the wet bias, except for a dry bias in northern Africa (Fig. ~~??c,d).~~ 4c,e,g). In general, ALARO was forced towards the too wet driving fields of ERA-Interim (?), which can explain part of the overestimated precipitation. More particularly, the overestimation ~~is strongest in winter in~~ of winter precipitation was strongest in the Mediterranean and Eastern Europe ~~(46.74 % and 54.07 %) and during summer for the Iberian Peninsula (49.35 %). In addition, excessive amounts of rainfall appear near the Adriatic coast, southern Italy, and southern France (Fig. ??c,d). Similarly to CRDX, CON overestimates winter precipitation, except for northern Africa (Fig. ??e). The largest wet bias in winter is present in the Mediterranean, while the bias in Eastern Europe is reduced with ≈ 37~~ with values of 46.0 % and 35.3 % respectively (Table 2). However, the bias averaged over the entire domain was larger for FS with ca. 36% compared to ~~CRDX (Table 3). The subdomains France and Mid-Europe show 10-20 % less overestimation of the precipitation as compared with CRDX (Table 3).~~ less than 25 % for CON and DRI. This corresponded to a higher precipitation bias of 10-20 % for all specific subdomains and even more than 50% higher for the Mediterranean.

During summer, the ~~precipitation bias is much more different for CON compared to CRDX~~ simulations showed different spatial variability (Fig. ~~??f). While CRDX results in a large overestimation of the precipitation, CONproduces much smaller biases for most subdomains with a reduction of 10-100~~ 4d,f,h). Regarding CON, the sumer precipitation bias was reduced over the continental part as compared to winter and positive and negative biases occurred over the southern part of the domain (Fig. 4d). The Mediterranean expressed a high wet bias of 60.5%, ~~except for the Alps and~~ but the ~~Mediterranean (Table 3). However, the~~ absolute values ~~for precipitation in summer are~~ in summer were close to zero~~for the Mediterranean~~, as it is characterised by a climate with dry summers (Fig. ~~??~~4b).

~~The performance of FS is different than CON for both seasons~~ The bias pattern over the continental part was very similar for DRI compared to CON during summer, while Southern Europe showed increased wet biases (Fig. ~~??g,h~~4f). The ~~wet bias during winter is slightly enhanced for all subdomains (Table 3). However, the values are in the same order of magnitude for the continental subdomains. The deterioration is largest for the British Isles, the Iberian Peninsulaand the Mediterranenan. Their wet bias degrades with over 100 %, corresponding to an absolute increase of 1.21 mm day^{-1}. These subdomains are exactly under the influence of the Atlantic Ocean~~ Iberian Peninsula, France and the Mediterranean ~~Sea. As winter is mostly characterised by transient stratiform precipitation systems, the problem of the doubled precipitation bias for these~~

~~subdomains arrives mainly from SSTs that are reinitialised daily instead of simulated continuously. During summer however, the precipitation biases for the British Isles, the Iberian Peninsula, the Alps and the Mediterranean are very similar for FS compared to~~ demonstrated a bias of 30.0%, 18.3% and 84.8% respectively compared to 11.5%, 12.0% and 60.7% with CON (Table ~~3). This contrasts to Mid-Europe, France~~ 2). The performance of FS was similar to CON for Southern and Eastern Europe (Fig. 4h). This contrasted to the continental part of the domain, where the precipitation signal ~~reverses and a dry bias~~ reversed and dry biases occurs, though it ~~is~~ was rather small (~~-6.92 % for Mid-Europe, -13.45 % for~~ -7.0% for France, ~~-8.38~~ -13.4% for Mid-Europe, -8.2% for Eastern Europe respectively). ~~Still, the excessive amounts at the western coast of the UK and the mountains are present and similar to CON~~ Consequently, the summer precipitation was simulated better by FS than CON and DRI.

In summary, the ~~wet bias as represented by CRDX is reduced by using CON both~~ model was characterised by a wet bias in winter and summer. ~~This reduction is strongest during summer~~The spatial variability during winter was very similar for all simulations, but during summer the precipitation showed a different behaviour. For the southern part of the domain, DRI established increased precipitation biases, while FS was more different to CON for the continental part, but not so much for the southern part. ~~This is in line with earlier conclusions by ? showing that SURFEX reduces the total accumulated precipitation during summer compared to ISBA.~~ The use of ~~FS has~~ a daily reinitialised atmosphere in DRI and FS had a neutral impact on the winter precipitation~~with respect to CON, except for the Mediterranean, where the SSTs could be the factor explaining the difference. During summer , FS improves the results, and introduces some small positive biases~~. FS improved the summer precipitation bias. Therefore, the combination of the daily reinitialised atmosphere together with a continuous surface is crucial in summer to get the best results.

3.2 Mean annual cycle

3.2.1 Daily mean 2 m temperature

To validate specific subdomains within the larger domain on a monthly scale, the mean annual cycles of the downscaled simulations ~~are compared with~~ were compared to the observations (Fig. ~~??~~5). We focused on the following subdomains (Fig. ~~??~~1): (1) the Iberian Peninsula at the western boundary of the domain with its warm and dry summer climate~~,~~; (2) Mid-Europe with its ~~transitional climate,~~ temperate climate; and (3) Eastern Europe at the eastern boundary of the domain with its continental climate.

The daily mean 2 m temperature ~~reaches~~ reached about 23 °C ~~at~~ in the Iberian Peninsula, while it ~~rises~~ raised to 20 °C in Mid-Europe and Eastern Europe (Fig. ~~??~~5a,b,c). For ~~the~~ these selected subdomains, ~~the downscaled simulations show~~ all downscaled simulations presented very similar autumn (SON: September-October-November) temperatures, but ~~underestimate~~ underestimated them with respect to E-OBS. ~~For winter and spring (MAM), FS is closer to the observations, whereas CON underestimates the~~ Regarding the other seasons, the simulations revealed a different behaviour in the representation of the 2 ~~m temperatures. Regarding summer, the selected subdomains show different model behaviour~~ m temperature with respect to the observations.

~~At~~ For the Iberian Peninsula, ~~both CON and FS underestimate~~ the 2 m ~~summer temperature~~ temperature was generally underestimated for all seasons (Fig. ~~??~~5a). ~~However, FS is~~ Except for autumn, FS was closer to the observations ~~than CON~~ as compared to CON and DRI, resulting in a ~~summer temperature bias of only 1~~ yearly mean temperature of 12.5 °C~~compared to 2~~ , which was closer to the observed yearly mean temperature of 13.7 °C as compared to 11.6 °C ~~by CON.~~ and 11.9 °C by CON and DRI respectively. The summer 2 m temperature was well simulated by FS for this subdomain. For Mid-Europe, ~~FS (CON)overestimates (underestimated)~~ CON and DRI underestimated the 2 m temperature for all seasons, whereas FS was very close to the observations from February to May (Fig. 5b). However, FS overestimated the summer 2 m temperature and CON and DRI underestimated the summer 2 m temperature. Still, the yearly mean ~~is~~ value of 9.0 °C by FS was very close to the ~~observations with FS (Fig. ??b). Similarly to~~ observational mean of 9.3 °C. In contrast to the Iberian Peninsula and Mid-Europe, DRI and FS demonstrated almost identical behaviour for the simulation of the 2 m temperature for Eastern Europe during winter and spring (MAM: March-April-May) (Fig. 5c). Their simulation was very close to the observations, whereas CON underestimated the 2 m temperature. Similar to Mid-Europe, FS ~~(CON) slightly overestimates (underestimates)~~ overestimated the summer 2 m temperature with ca. 1 °C and CON underestimated the summer 2 m temperature with ca. 1 °C in Eastern Europe~~(Fig. ??c).~~ . Yet again, the yearly mean ~~results in a very small difference using FS~~ value of 8.5 °C by FS was very similar as compared to the observations ~~, while larger differences occur using CON~~ with a value of 8.6 °C , while largest differences occurred using CON with a value of 7.5 °C.

In summary, the yearly mean temperature ~~is~~ was underestimated by CON ~~, while FS is very close to E-OBS. The difference between the downscaled simulations is about 1-2 °C.~~ for all subdomains. Along the selected subdomains, there ~~are~~ were larger differences between the simulations in Mid-Europe and Eastern Europe as compared to the Iberian Peninsula. DRI was able to simulate the 2 m temperature better for Mid-Europe and Eastern Europe as compared to CON for winter, spring, and summer. The yearly mean 2 m temperature was best represented by FS. However, the summer 2 m temperature was overestimated by FS for Mid-Europe and Eastern Europe, but neither CON nor DRI simulated well the summer 2 m temperature with respect to the observations.

3.2.2 Daily accumulated precipitation

~~Similarly~~ Similar to temperature, the monthly means of the daily accumulated precipitation, averaged over the 10-year period, are shown in Fig. ~~??~~ 5 for the Iberian Peninsula, Mid-Europe and Eastern Europe. When comparing the observations, the yearly cycle ~~is~~ was most pronounced at the Iberian Peninsula, with minimum precipitation values of ca. 0.5 mm day^{-1} during summer, and maximum precipitation values of ~~≈~~ ca. 3 mm day^{-1} during spring, autumn and beginning of the winter (Fig. ~~??~~5d). The precipitation in Mid-Europe ~~reaches~~ reached highest values of ~~≈ 2.5~~ ca. 3 mm day^{-1} during summer (Fig. ~~??~~5e). The continental climate of Eastern Europe ~~results in~~ presented average values of 1 mm day^{-1} for winter and spring, while most rainfall ~~occurs~~ occurred in the summer ~~with values up to~~ of ca. 2.5 mm day^{-1} (Fig. ~~??~~5f).

In general, the agremeent of the simulations was largest in autumn. For the Iberian Peninsula, the ~~yearly~~ seasonal pattern of the downscaled simulations ~~follows the~~ followed the seasonal pattern of E-OBS (Fig. ~~??~~5d). The model simulations ~~represent~~ represented an overestimation of the precipitation for all seasons. This overestimation ~~is~~ was stronger in winter and in spring, and is in agreement with ?. For these two seasons, E-OBS ~~shows~~ showed an undercatch of the precipitation, which might ~~amplify~~ have amplified the model biases (?). CON and ~~FS compare very well~~DRI were closer to the observations than FS in winter and spring, resulting in ~~mean yearly values of 1.94~~ yearly mean values of 1.9, 2.0, and 2.1 mm day^{-1} ~~and 2.09~~ respectively for CON, DRI and FS, as compared to the observational mean value of 1.7 mm day^{-1}~~respectively~~. In Mid-Europe, the model ~~overestimates~~ overestimated the precipitation for most of the year, except for summer (Fig. ~~??~~5e). During summer, FS ~~shows~~ showed a large underestimation~~compared to CON, despite an overestimation during winter and spring. The agreement of CON and FS is largest in autumn~~, whereas CON and DRI showed a similar pattern of overestimated precipitation. The precipitation in Eastern Europe ~~is~~ was overestimated by the model during most of the year, except for summer. (Fig. ~~??f) The agreement between CON and FS is largest during summer and autunm in Mid-Europe. The simulated winter months and spring show larger differences between the downscaling approaches, with higher precipitation by FS than CON .~~ 5f, ?). All simulations demonstrated considerable agreement on the estimation of the summer precipitation. The yearly mean precipitation by CON was lowest with 2.0 mm day^{-1} and highest when using FS with 2.1 mm day^{-1}, as compared to 1.6 mm day^{-1} by the observations (Fig. 5f).

In summary, the ~~downscaled simulations overestimate~~ three downscaling approaches overestimated the precipitation, except for an underestimation ~~during summer~~for Mid-Europe and Eastern Europe in particular months. On a yearly basis, the differences between CON~~and FS are~~ , DRI and FS were small, but on a monthly basis, the magnitude of differences ~~depends~~ depended strongly on the region of interest. There ~~are larger differences~~ were larger differences between the model simulations for Mid-Europe and Eastern Europe compared to the small differences ~~at~~ for the Iberian Peninsula.

4 ~~Land-atmosphere feedback~~Validation of surface fluxes

The ~~land-atmosphere feedback is strongest during summer, as the land surface is characterised by more local interactions with the overlaying atmosphere (?). Therefore, the following analysis focuses on this season only. We evaluated the differences in the 2 m temperature and the daily accumulated precipitation between the two downscaled simulations. We assumed two-way interactions between the precipitation/temperature and the soil moisture. This feedback mainly concerns the soil moisture at root zone, where the soil moisture impacts the climate by affecting the plants' transpiration (??).~~

4.1 ~~Effect of downscaling setup on atmospheric and surface variables~~

~~The average differences were evaluated between FS and CON for the daily mean 2 m temperature, the daily accumulated precipitation and the daily relative deep soil moisture~~ spatial distributions of the 5-year daily maximum Bowen Ratio (BR) of CON, DRI and FS were compared to FLUXNET observations, for the summer period only (Fig. ~~??~~6a,b,c). The ~~soil moisture is represented as the volumetric water content, which corresponds to the soil moisture volume to the total soil volume (expressed in m^3/m^3~~corresponding spatial distributions of the 10-year daily maximum BR of CON, DRI and FS were evaluated with respect to the results for the 5-year period (Fig. 6d,e,f). The ~~second model layer was selected to represent the deep soil moisture. Figure ??a shows that the temperature differences are mainly positive and the largest mean differences of > 2 °C are situated~~

~~over France, Mid-Europe and Eastern Europe. The smallest differences of 0.5-1.5 °C are situated at the Iberian Peninsula, the Mediterranean, the British Isles and the Alps. The precipitation differences are mostly negative with values of -20 % to -40 % for Mid-Europe, and mixed positive and negative for the Iberian Peninsula and the Mediterranean~~ mean diurnal cycles of the surface energy fluxes are illustrated over the 5-year summer period 1996-2000 for the FLUXNET stations of Vielsalm and Collelongo and their corresponding model grid points (Fig. ~~??b). The extreme differences in northern Africa are related to boundary effects, as the relaxation zone was not excluded here, hence they are not physical.~~

~~Finally, the soil moisture differences are primarily negative with 20 % drier soils for Mid-Europe, the British Isles and Eastern Europe, while no differences between FS and CON are present at the Iberian Peninsula and Mediterranean~~ 7, Table 3).

The daily maximum BR showed a strong gradient of increasing values towards the south of the domain (Fig. ~~??~~6a,b,c). ~~We focused again on the previously selected subdomains with distinct climate regimes, as they represented the largest variation in the soil moisture results. For Mid-Europe and Eastern Europe, the deep soil moisture simulated by FS decreases more sharply during the spring compared to the deep soil moisture simulated~~ However, large differences appeared for the three downscaling approaches, particularly for the continental part of the domain. Relatively low values of 0 to 1 were represented by CON, ~~and reaches lower minima during summer (Fig. ??b,c). Besides, the values simulated by FS are not able to restore to the values simulated by CON towards the end of the year. This leads to drier soils in FS compared to CON for these particular subdomains. The soil moisture deficit simulated by FScould amplify the summer temperature extremes (?). This is in contrast to the Iberian Peninsula, where the difference in deep soil moisture between CON and FS is small during spring and only enhances from the end of summer onwards (Fig. ??a)~~ while DRI showed BR values of 0.5 to 1 and highest values of 2 to 3 were expressed by FS.

4.1 ~~Soil moisture-temperature/precipitation feedback~~

~~We did not evaluate a one-way effect of the difference (between the downscaled simulations) of one variable on the difference of the other variable, i. e. a cause and effect relationship. Instead, we assumed a two-way interaction between the differences of soil moisture and the differences of temperature/precipitation. Therefore, a correlation analysis was applied, which looked as follows. First, the mean difference was calculated between FS and CON for each summer. Then, the correlation in time per grid point was determined without any spatial correlation.~~

~~The temperature differences are mostly negatively correlated to the soil moisture differences~~ When the value is lower (higher) than 1, the latent heat flux is higher (lower) than the sensible heat flux. The FLUXNET observations for Vielsalm and Collelongo were displayed, and indicated best agreement with DRI (Fig. 6b), expressed by values of 1.12 and 1.32 respectively (Table 3). Though this validation was based on 5 summer periods only from 1996 to 2000, it was still robust as indicated by the corresponding plot for the 10-year summer period from 1991 to 2000 (Fig. ~~??a),while the precipitation differences were mostly positively correlated to the soil moisture differences (Fig. ??b). A different feedback can be observed for France,Mid-Europe, the Alps and Eastern Europe versus the British Isles, the Iberian Peninsula and the Mediterranean (Table ??). With respect to the correlation of soil moisture difference with 2 m temperature (precipitation) difference, the former subdomains show values of 0.32-0.55 (0.24-0.40), considerably larger than the values of 0.05-0.25 (0.15-0.17)for the latter subdomains (Table~~

~~??). Therefore, the coupling is stronger for the former subdomains compared to the latter ones. A contrast exists between on the one hand an area, including France, Mid-Europe, the Alps and Eastern Europe, where the climate is sensitive to the choice of the downscaling setup, through a land-atmosphere feedback, and on the other hand an area, including the British Isles, the Iberian Peninsula and the Mediterranean, where this feedback is weaker and the climate is not impacted by the choice of the downscaling setup.~~ 6d,e,f, Table 3). In spite of highest BR values presented by FS, the stations of Vielsalm and Collelongo were located into isolated parts of lower BR, indicated by the average values of 0.61 and 0.83 respectively (Table 3).

4.1 ~~Distribution of energy fluxes~~

~~The soil moisture impacts the partitioning of the energy fluxes (?). Therefore, the summer daily cycle of the energy fluxes was evaluated for selected stations from FLUXNET, and their corresponding model grid points. The station Vielsalm in Belgium (BE-Vie) is located in the region that shows a strong negative (positive) correlation between the soil moisture difference and temperature (precipitation) difference (Fig. ??). The other station Collelongo in Italy (IT-Col) is located in the region that shows low correlations between the variable differences.~~

~~The daily cycle of the net radiation , latent heat flux, sensible heat flux and soil heat flux for the observations and the downscaled simulationsis~~ The net radiation was underestimated for all simulations (Table 3), but this underestimation was larger for Collelongo, which could be related to its complex topography. The model generally underestimated H, and overestimated LE. The ground heat flux (G) showed much higher values than the observed ones. G is dependent on the soil temperature, which is overestimated by the land surface model. This is due to the representation of the soil-surface leaf litter in the model. **?** showed that without an explicit formulation of water and energy exchanges within the residue layer, their surface model overestimated LE, G and soil temperature and underestimated H. As the net radiation and ground heat flux were simulated very similarly for all simulations, they were not shown in Fig. ~~??. The net radiation is well simulated for BE-Vie, compared to the observations~~ 7.

For Vielsalm, H was simulated well by DRI and FS during nighttime and daytime, whereas CON underestimated H during daytime (Fig. ~~??a,b). This is in contrast to IT-Col, for which a much lower net radiation is simulated (Fig. ??c,d). This is probably related to the location of IT-Col on a high elevation. The soil heat flux is overestimated by the model, which could be related to an overestimated soil temperature in the model. The simulation of the sensible and latent heat flux very much depended on the location. For BE-Vie, both CONand FS resulted in higher fluxes compared to FLUXNET observations (Fig. ??a,b). However, while CON results in~~ 7a). The daily maximum H by CON was only 118 W^{-2}, as compared to 151 and 139 W^{-2} for DRI and FS respectively (Table 3). Yet again, this validation was only done for 5 summer periods from 1996 to 2000, but the corresponding daily maximum values for the 10-year summer period 1991-2000 indicated that the 5-year period was representative for the validation of the fluxes (Table 3). The LE was overestimated by all simulations, but the difference with the observations was smallest for DRI, while it was highest for CON. The daily maximum BR was lower than 1 for all downscaling approaches (Table 3). This means that they all simulated a higher latent than sensible heat flux~~, FS results in a higher sensible than latent heat flux. This relation can also be expressed by the Bowen Ratio (BR), the ratio between the sensible and the latent heat flux. When the value is lower (higher) than 1, the latent heat flux is higher (lower) than the sensible heat flux. The BR for~~

~~BE-Vie at 12UTC was 1.20 for the observations, while it was 0.82 and 1.26 for~~. Still, DRI and FS showed higher values for BR than CON. Therefore, the partitioning of the surface energy fluxes was better represented by DRI and FS for the station of Vielsalm.

For Collelongo, H was underestimated by the model during daytime and overestimated during nighttime, except for DRI which demonstrated a good agreement with the observations. Yet again, the model overestimated LE during daytime, except for DRI. The daily maximum H for DRI of 247 W^{-2} was close to the observed value of 253 W^{-2}, whereas CON and FS ~~respectively. In other words, CONresults in a higher latent than sensible heat flux for BE-Vie, which does not agree with FS and~~ simulated much lower values of 159 W^{-2} and 197 W^{-2} respectively (Table 3). The simulated LE showed the largest difference with the observed one using CON. Regarding BR, the simulation by DRI with a value of 1.35 was in very good agreement with the observations. ~~Consequently, CON and FS simulate differently the energy heat fluxes and more importantly, FS is much better~~ The DRI simulation resulted in the correct partitioning of the surface energy fluxes at Collelongo. CON was not performing well in simulating the correct partitioning~~of the fluxes, with respect to the observations. In contrast to BE-Vie, the simulated sensible heat flux at IT-Col by both CON and FS is lower than the latent heat flux, resulting a BR of 0.81 and 0.82 at 13UTC respectively, compared to a BR of 1.23 at 13UTC for the observations (Fig. ??c, d). Consequently, the energy heat fluxesat IT-Col are not influenced by the downscaling setup, which is in agreement with the previous findings~~, while FS had already much improved as compared to CON.

In summary, RN was underestimated by the model, whereas H was underestimated and LE was overestimated. However, DRI performed well for H at Vielsalm and for LE at Collelongo. For Colellongo, this resulted in a correct simulation of the partitioning of the surface energy fluxes, translated into an excellent value for BR. Least well simulated were CON and G. The use of a daily reinitialised atmosphere improved the correct partitioning of the surface energy fluxes. FS could not improve the representation of the surface energy fluxes for both stations with respect to DRI. The validation of G was not conclusive, as this parameter needs to be revised with an improved residue layer.

5 Conclusions

An assessment of ~~two downscaling setups~~ three downscaling approaches has been performed using the regional climate model ALARO-0 coupled to the land surface model ~~SURFEX, with boundary conditions of~~ SURFEXv5, with lateral and initial boundary conditions from ERA-Interim. ~~We evaluated this contribution with respect to the regional climate simulated by the original setup of~~ The simulations were applied for a 10-year period from 1991 to 2000, for a Western European domain. The performance of ALARO-0 ~~with ISBA. The present study corroborates the finding of ?, that the use of the SURFEX scheme improves the performance of the ALARO-0 configuration of the ALADIN system~~with SURFEX has already been validated for NWP applications (?), but not yet for long-term climate simulations.

We compared the common used ~~method~~ approach of a continuous climate simulation with ~~the newer method~~ two alternative aprooaches of frequently reinitialising the RCM simulation towards its driving field~~. FS outperforms CON for summer and winter~~, combined with either a daily reinitialised or continuous surface. The use of a daily reinitialised atmosphere outperformed the continuous approach for winter and summer 2 m temperature, and detoriorated the summer precipitation. ~~The winter precipitation by FS is slightly degraded~~ However, the use of a continuous surface next to a daily reinitialised atmosphere improved the summer precipitation with respect to ~~CON, but is still similar to CRDX. However, the biases are doubled for the Brisish Isles, the Iberian Peninsula and the Mediterranean when using FS as compared to CON~~the continuous approach. Furthermore, it improved the winter 2 m temperature, whereas it resulted in a neutral impact on the summer 2 m temperature and the winter precipitation, despite a slight deterioration at the Mediterranean. The SSTs were ~~not simulated freely, but~~ reinitialised daily together with the ~~upper air. Therefore, the problems occur around the islands and the peninsula, which are under the influence of the ocean and the Mediterranean Sea. More importantly, this is not a problem for~~ atmosphere, as compared to the monthly updated SSTs in the continuous approach.

The seasonal cycle of the 2 m temperature and precipitation was different for three selected subdomains that covered large climate variability. Both the temperature climate of Mid-Europe and the continental climate of Eastern Europe indicated more seasonal variability than the Mediterranean climate of the Iberian Peninsula. The simulation of the 2 m temperature had improved when applying daily reinitialised atmosphere with continuous surface, despite an overestimation of the summer 2 m temperature~~, as it is mostly locally driven by the surface in contrast to the precipitation, which is influenced by transient stratiform systems during winter~~. The model disagreed more for precipitation, because of the forcing towards the too wet driving field of ERA-Interim and the low spatial coverage by the observations in some regions. It was clear that the agreement for the precipitation between the model and the observations was highest during summer, while other seasons showed stronger deviations.

~~The differences in~~ During summer, the interaction between the land surface and the overlaying atmosphere is largest. The 2 m temperature ~~and precipitation between the downscaling setups during summer are demonstrated by an interaction~~ interacts with the soil moisture ~~. The drier soils represented by FS~~ and influences the partitioning of the surface energy fluxes. The daily reinitialisation of the atmosphere improved the representation of a correct partitioning, though the latent heat was highly overestimated for Vielsalm and resulted in a too low value as compared to ~~CON can be coupled to the atmospheric variables, and help reveal a land-atmosphere feedback. Furthermore, the coupling strength depends on the particular subdomain. A strong coupling exists for the continental part including France, Mid-Europe, the Alps and Eastern Europe, whereas a weak coupling exists for the British Isles,~~ the ~~Iberian Peninsula and the Mediterranean. In addition, the opposite partitioning of the latent and sensible heat fluxes of the two downscaling simulations at BE-Vie confirms this land-atmosphere feedback. Moreover, the comparison with the energy fluxes distribution at IT-Col supports our finding that the coupling strength has been impacted by the choice of the downscaling setup.~~ FLUXNET observations. Still, this approach outperformed the use of a continuous simulation. For a more comprehensive analysis, we recommend to include more FLUXNET stations. A more in-depth analysis on the interaction between 2 m temperature, precipitation, and surface energy fluxes can reveal soil-moisture-temperature coupling (?), but this lies outside the scope of this study.

In conclusion, this study demonstrated that the approach of a daily reinitialised atmosphere was superior over the continuous approach. The use of a continuous surface next to a daily reinitialised atmosphere even improved the winter temperature and summer precipitation. The latter approach is highly recommended in a setup with GCM forcing, as imperfect initial and lateral boundary conditions are applied.

~~In conclusion, this study demonstrates that the method of an upper air daily reinitialised atmopshere with a free surface is superior over continental areas while the weakness of the SST reinitialisation should be tackled by implementing a sea or an ocean model.~~

Code availability The used ALADIN codes, along with all related intellectual property rights, are owned by the Members of the ALADIN consortium. Access to the ALADIN System, or elements thereof, can be granted upon request and for research purposes only. The used SURFEX Codes are freely available, together with the ECOCLIMAP database, at http://www.cnrm-game-meteo.fr/

Data availability This study is based on large datasets written in .FA and .lfi format. The relevant output is exported to R datasets. Due to licensing restrictions, this model output is not made publicly available. However, for the purpose of the review, the data can be made available for the editor and reviewer upon request, by contacting Julie Berckmans.

Author contributions. J. Berckmans performed the model simulations CON, DRI and FS and analysed the results. J. Berckmans drafted the manuscript. O. Giot and R. De Troch designed R-tools for the analysis. O. Giot designed the experiment CON. R. Hamdi designed the experiment DRI and FS and developed the model code for the implementation of SURFEX within ALARO-0. P. Termonia and R. Ceulemans provided overall guidance during the project. R. Ceulemans and R. Hamdi were the project contractor. All co-authors contributed to the writing and the revising of the manuscript.

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The daily mean 2 m temperature bias (°C) and RMSE (in brackets) between the downscaled simulations and E-OBS for the total domain and the subdomains (BI, IP, FR, ME, AL, MD, EA) during DJF and JJA for the 10-year period 1991-2000.

The daily mean 2 m temperature bias (°C) and RMSE (in brackets) between the downscaled simulations and E-OBS for the total domain and the subdomains (BI, IP, FR, ME, AL, MD, EA) during DJF and JJA for the 10-year period 1991-2000.**Table 1.** ~~Overview on the experiments with ALARO coupled to SURFEX carried out in the present study and on the existing experiment with ALARO using ISBA.Acronym Description Land surface model Downscaling setup Reference Historical PeriodCRDX ALARO-0 20 km ISBA Continuous atmosphere - E-OBS 01-01-1991 - 31-12-2000 continuous surface CON ALARO-0 20 km SURFEX Continuous atmosphere - E-OBS 01-01-1991 - 31-12-2000 continuous surface FS ALARO-0 20 km SURFEX Reinitialised atmosphere - E-OBS 01-01-1991 - 31-12-2000 continuous surface CON-FS ALARO-0 20 km SURFEX Both downscaling setups FLUXNET 01-06-2000 - 31-08-2000~~

The daily mean 2 m temperature bias (°C) and RMSE (in brackets) between the downscaled simulations and E-OBS for the total domain and the subdomains (BI, IP, FR, ME, AL, MD, EA) during DJF and JJA for the 10-year period 1991-2000.

		TOTAL	BI	IP	FR	ME	AL	
DJF	~~CRDX~~ CON	~~-2.94~~ -1.8 (2.5)	~~-2.08~~ -1.1 (2.0)	~~-3.27~~ -2.2 (2.7)	~~-2.73~~ -1.5 (2.2)	~~-2.49~~ -1.3 (2.0)	~~-3.98~~ -3.0 (3.8)	~~-3.35~~ -2.4
	~~CON~~ DRI	~~-1.85~~ -1.2 (2.8)	~~-1.21~~ -1.0 (2.7)	~~-2.24~~ -1.6 (2.7)	~~-1.54~~ -1.2 (2.9)	~~-1.20~~ -0.7 (2.6)	~~-2.99~~ -1.4 (3.4)	~~-2.55~~ -2.1
	FS	~~-1.03~~ -1.0 (2.8)	~~-0.40~~ -0.3 (2.8)	~~-1.30~~ -1.3 (2.5)	~~-0.71~~ -0.7 (2.8)	~~-0.36~~ -0.4 (2.6)	~~-2.10~~ -2.1 (3.8)	~~-1.38~~ -1.2
JJA	~~CRDX~~ CON	~~-0.62~~ -0.6 (2.0)	~~-1.22~~ -1.7 (2.0)	~~-0.25~~ -0.5 (1.7)	~~-0.72~~ -1.2 (1.9)	~~-1.35~~ -1.3 (1.9)	~~-1.77~~ -1.8 (2.6)	~~-0.59~~ -0.5
	~~CON~~ DRI	~~-0.60~~ -0.1 (2.3)	~~-1.71~~ -0.9 (2.0)	~~-0.43~~ -0.3 (2.2)	~~-1.19~~ -0.7 (2.4)	~~-1.28~~ -0.3 (2.1)	~~-1.77~~ -0.8 (2.3)	~~-0.38~~ -0.6
	FS	~~0.84~~ 0.9 (2.7)	~~-0.71~~ -0.7 (2.2)	~~0.51~~ 0.5 (2.4)	~~1.02~~ 1.0 (3.1)	~~1.19~~ 1.3 (2.8)	~~-0.02~~ -0.0 (2.5)	~~0.75~~ 0.7

Table 2. The daily accumulated precipitation bias (%) and RMSE (in brackets) between the downscaled simulations and E-OBS for the total domain and the subdomains (BI, IP, FR, ME, AL, MD, EA) during DJF and JJA for the 10-year period 1991-2000.

		TOTAL	BI	IP	FR	ME	AL	
DJF	~~CRDX~~ CON	~~20.23~~ 16.6 (3.8)	~~-3.44~~ 4.5 (4.5)	~~15.60~~ 16.1 (4.6)	~~32.74~~ 29.0 (3.6)	~~29.49~~ 25.4 (2.7)	~~18.75~~ 11.2 (4.7)	~~46.~~
	~~CON~~ DRI	~~15.62~~ 20.9 (4.8)	~~4.39~~ 6.6 (5.2)	~~15.73~~ 21.2 (5.6)	~~28.56~~ 26.8 (4.8)	~~24.46~~ 27.9 (3.8)	~~9.17~~ 24.1 (6.3)	~~46.~~
	FS	~~34.50~~ 36.3 (5.4)	~~16.63~~ 16.9 (5.5)	~~30.84~~ 31.3 (6.2)	~~37.52~~ 38.2 (5.2)	~~34.67~~ 35.7 (4.0)	~~24.31~~ 26.7 (6.7)	~~109.5~~
JJA	~~CRDX~~ CON	~~25.68~~ 12.1 (4.2)	~~30.48~~ 24.7 (4.4)	~~49.35~~ 11.5 (2.9)	~~23.22~~ 12.0 (4.4)	~~30.78~~ 11.9 (5.0)	~~28.45~~ 32.6 (7.3)	~~23.~~
	~~CON~~ DRI	~~11.23~~ 22.5 (4.7)	~~25.98~~ 27.0 (4.7)	~~11.75~~ 30.0 (3.4)	~~11.99~~ 18.3 (5.1)	~~11.78~~ 8.8 (5.5)	~~32.50~~ 48.2 (8.9)	~~64.~~
	FS	~~3.19~~ 3.6 (4.5)	~~18.73~~ 17.4 (4.6)	~~13.14~~ 13.0 (3.2)	~~-6.92~~ -7.0 (4.6)	~~-13.45~~ -13.4 (5.1)	~~23.49~~ 23.5 (8.3)	~~56.~~

~~The correlation of the difference (FS-CON) in daily deep soil moisture (WG2) and the difference in daily 2 m temperature (T2M), and in daily accumulated precipitation(RR), for the total domain and the subdomains (BI, IP, FR, ME, AL, MD, EA) during JJA for the 10-year period 1991-2000.~~

Table 3. The daily maximum surface energy fluxes (Wm^{-2}) averaged over the 5-year JJA period 1996-2000 and the 10-year period 1991-2000 (in brackets).

	~~TOTAL~~	~~BI~~ RN	~~IP~~ H	~~FR~~ LE	~~ME~~ G	~~AL~~ BR
Vielsalm	~~MD~~ OBS	~~EA~~ 417	151	134	11	1.12
~~COR:DIFF_WG2-DIFF_T2M~~	~~-0.19~~ CON	~~-0.05~~ 395 (404)	~~-0.25~~ 118 (113)	~~-0.55~~ 250 (261)	~~-0.32~~ 47 (47)	~~-0.38~~ 0.47 (0.43)
	~~-0.16~~ DRI	~~-0.40~~ 388 (398)	151 (159)	195 (193)	57 (58)	0.78 (0.82)
~~COR:DIFF_WG2-DIFF_RR~~	~~0.21~~ FS	~~0.15~~ 405 (411)	~~0.15~~ 139 (152)	~~0.40~~ 229 (221)	~~0.30~~ 46 (49)	~~0.33~~ 0.61 (0.69)
Collelongo	~~0.17~~ OBS	~~0.24~~ 538	253	192	-1.39	1.32
	CON	480 (481)	159 (147)	270 (289)	111 (108)	0.59 (0.51)
	DRI	496 (494)	247 (232)	183 (194)	143 (140)	1.35 (1.19)
	FS	501 (498)	197 (191)	236 (247)	111 (110)	0.83 (0.77)

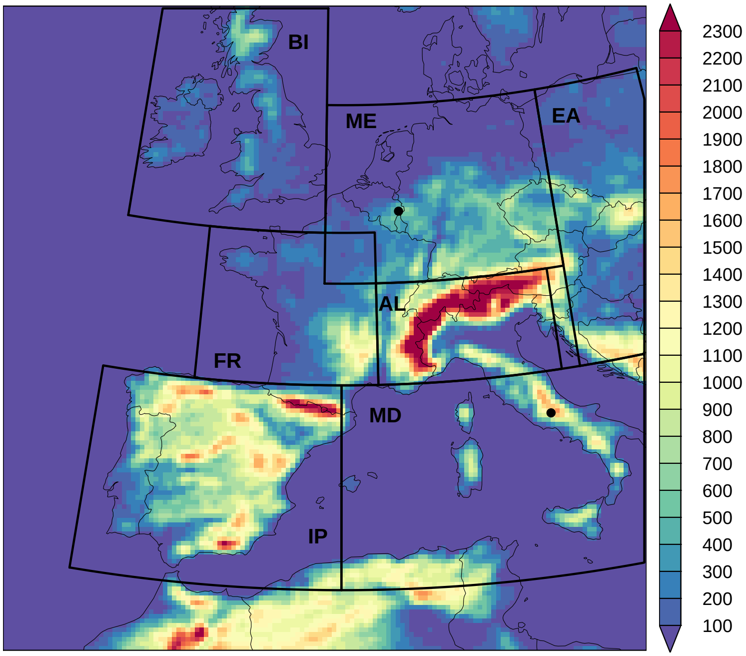


Figure 1. The total domain on 20 km horizontal resolution and the subdomains (BI, IP, FR, ME, AL, MD, EA) based on the subdomains selected in the EURO-CORDEX framework. The color represents the orography (m) in the ALARO+SURFEX setup. The two black dots represent the FLUXNET stations ~~BE-Vie (~~Vielsalm ~~,~~(Belgium) and ~~IT-Col (~~Collelongo ~~,~~(Italy).

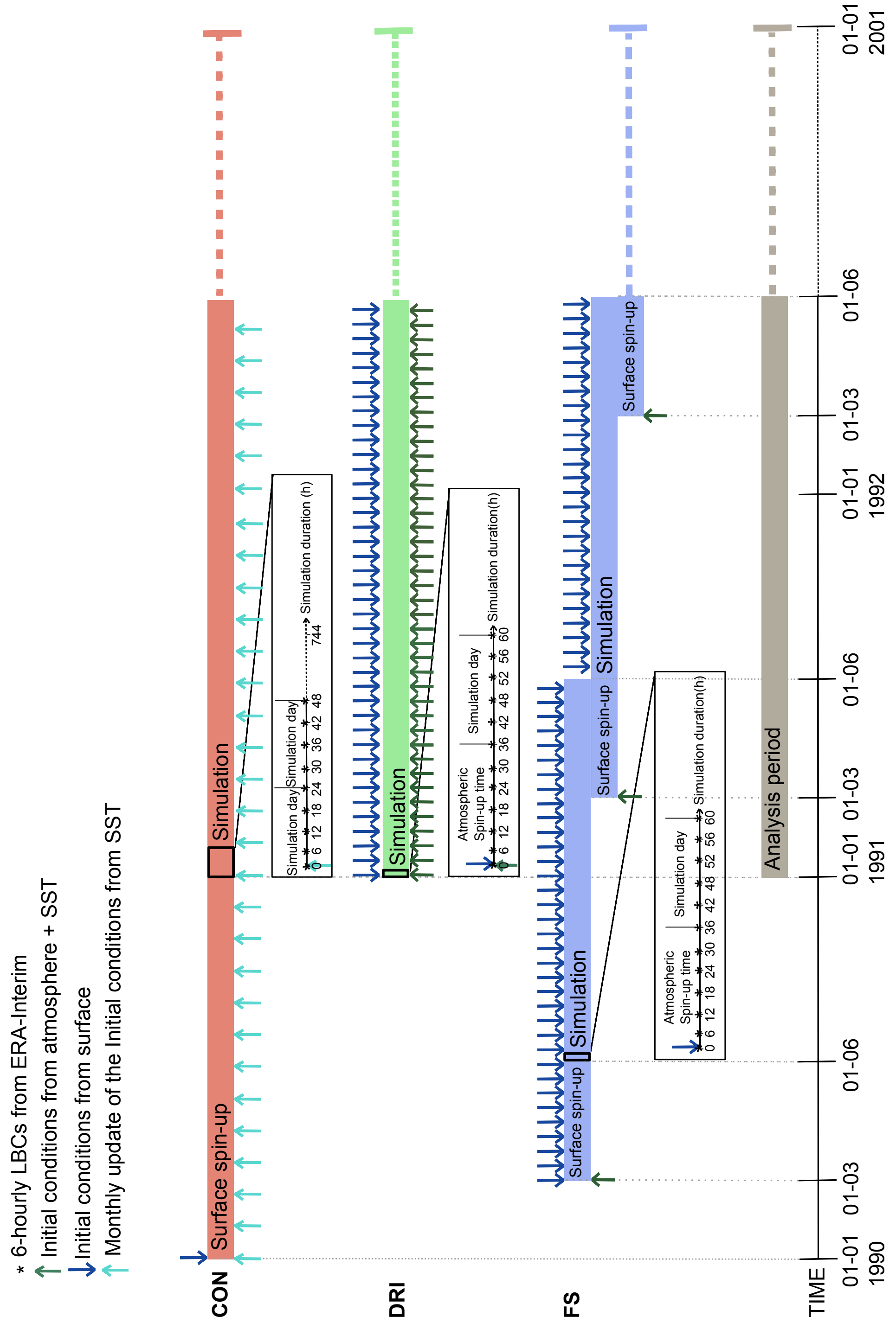


Figure 2. The setup of the three downscaling approaches CON, DRI and FS used in this study. It represents the spin-up time for the different simulations, the analysis period of the total experiment and the update frequency of the lateral and initial boundary conditions.

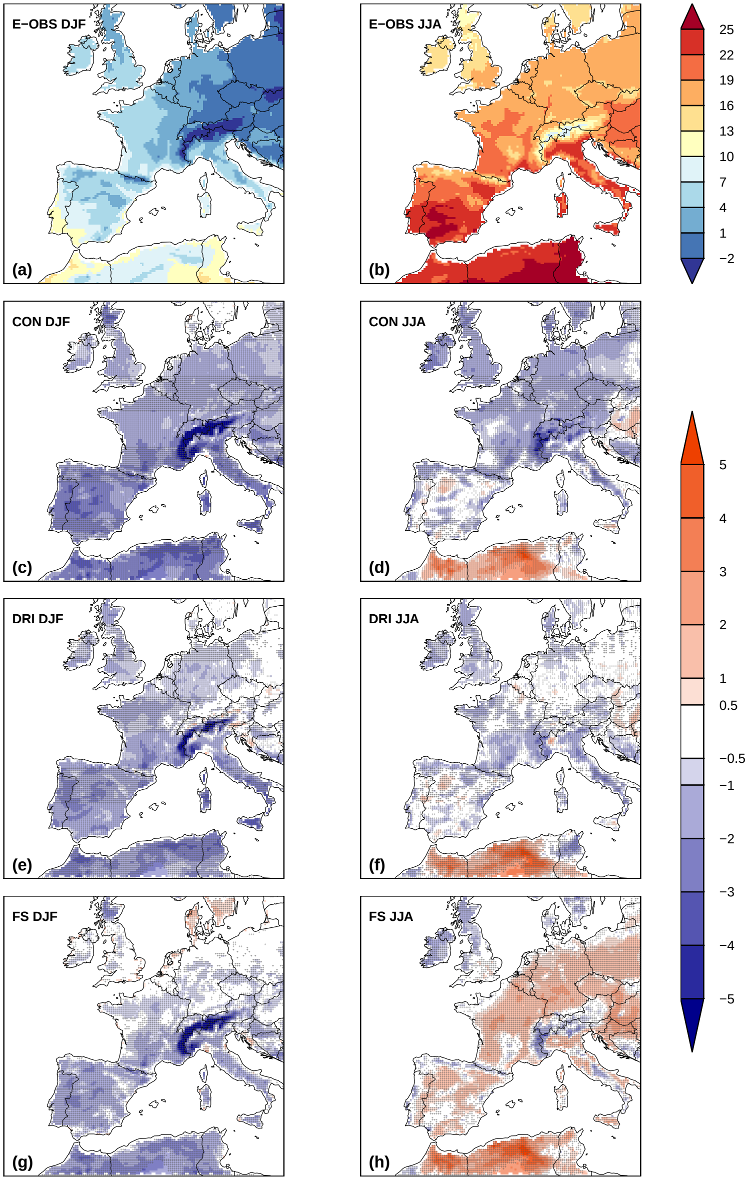


Figure 3. Daily mean 2 m temperature ~~, absolute~~ (°C) for E-OBS DJF (a) and JJA (b), and absolute bias (°C) of the model with E-OBS for ~~CRDX~~ CON DJF (c) and JJA (d), for ~~CON~~ DRI DJF (e) and JJA (f) and for FS DJF (g) and JJA (h), all at a 20 km horizontal resolution for ~~a~~ the 10-year period 1991-2000. The dots represent the grid points with a significant difference at 5%, using the Student's t-test with a null hypothesis stating that the means of the model and observations are equal.

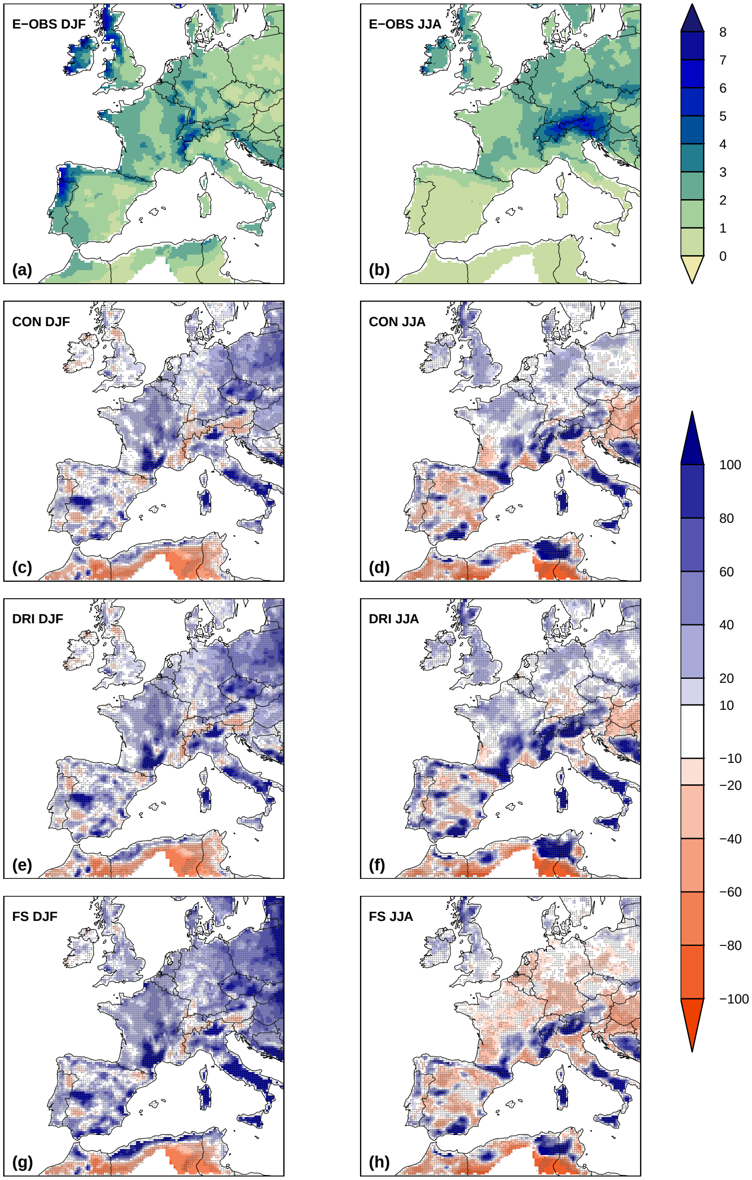
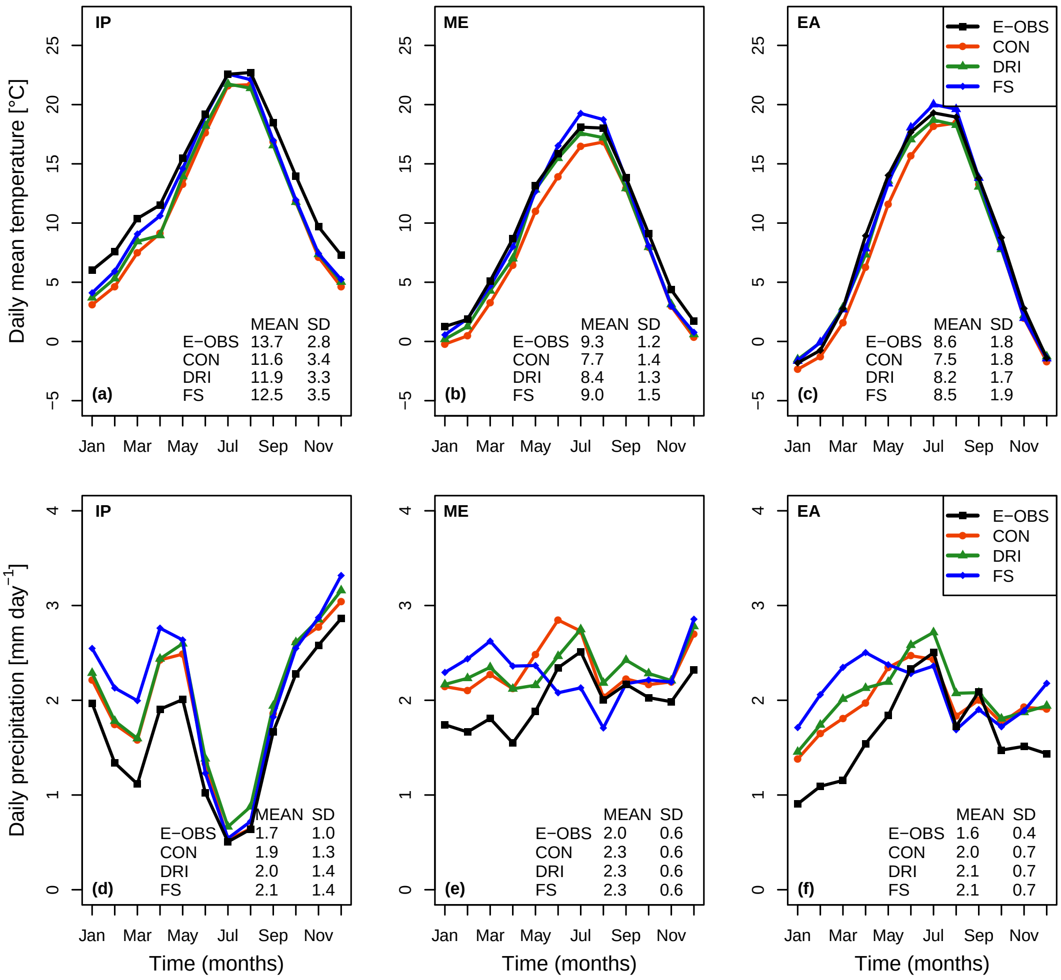


Figure 4. Daily accumulated precipitation ~~, absolute~~ (mm day^{-1}) for E-OBS DJF (a) and JJA (b), and relative bias (%) of the model with E-OBS for ~~CRDX~~ CON DJF (c) and JJA (d), for ~~CON~~ DRI DJF (e) and JJA (f) and for FS DJF (g) and JJA (h), all at a 20 km horizontal resolution for a 10-year period 1991-2000. The dots represent the grid points with significant different variations at 5%, using the F-test with a null hypothesis stating that the variances of the model and observations are equal.



~~Mean annual cycle of the~~ , and daily ~~deep soil moisture~~ accumulated precipitation (~~m^3/m^3~~mm day^{-1}) ~~averaged over a 10-year period 1991-2000 with E-OBS,CONF and FS~~ for (~~a~~d) the Iberian Peninsula, (~~b~~e) Mid-Europe, and (~~c~~f) Eastern Europe, averaged over the 10-year period 1991-2000. Both the mean and standard deviation (SD) are displayed as text.

~~Mean annual cycle of the~~ , and daily ~~deep soil moisture~~ accumulated precipitation (~~m^3/m^3~~mm day^{-1}) ~~averaged over a 10-year period 1991-2000 with E-OBS,CONF and FS~~ for (~~a~~d) the Iberian Peninsula, (~~b~~e) Mid-Europe, and (~~c~~f) Eastern Europe, averaged over the 10-year period 1991-2000. Both the mean and standard deviation (SD) are displayed as text.

Figure 5. Mean annual cycle of the daily 2 m temperature (°C) ~~and daily accumulated precipitation (mm) averaged over a 10-year period 1991-2000~~ with E-OBS, CON and FS for (a) the Iberian Peninsula, (b) Mid-Europe, and (c) Eastern Europe.~~Difference between CON and FS for a 10-year JJA period 1991-2000 for (a) daily 2 m temperature ((FS-CON), in °C), (b) daily accumulated precipitation ((FS-CON/CON), in %) and (c) daily deep soil moisture ((FS-CON/CON), in %).~~

~~Mean annual cycle of the~~ , and daily ~~deep soil moisture~~ accumulated precipitation (~~m^3/m^3~~mm day^{-1}) ~~averaged over a 10-year period 1991-2000 with E-OBS,CONF and FS~~ for (~~a~~d) the Iberian Peninsula, (~~b~~e) Mid-Europe, and (~~c~~f) Eastern Europe, averaged over the 10-year period 1991-2000. Both the mean and standard deviation (SD) are displayed as text.

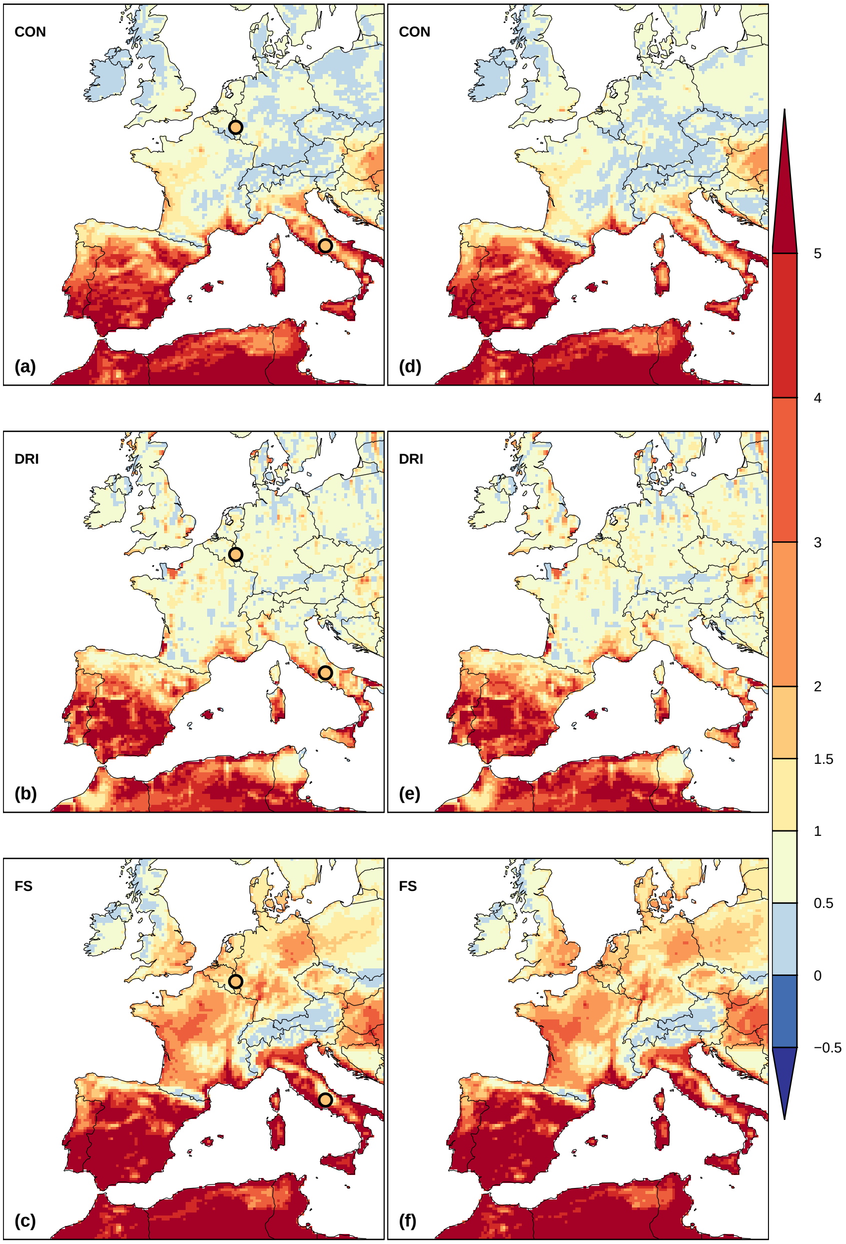


Figure 6. ~~Correlation between~~ Daily maximum Bowen ratio averaged over the ~~difference in daily deep soil moisture~~ 5 year JJA period 1996-2000 for (~~(FS-CON/CON~~a) CON, ~~in %~~(c) DRI and (~~a~~e) FS and averaged over the ~~difference in 2 m temperature~~ 10-year JJA period 1991-2000 for (~~(FS-CON~~b) CON, ~~in °C~~(d) DRI and (~~b~~f) FS. The dots represent the ~~difference in accumulated precipitation~~ values for the FLUXNET stations Vielsalm (Belgium) and Collelongo (~~FS-CON/CON~~Italy)~~, in %)~~.~~Significant grid boxes at 0.05 level are identified with black dots.~~

~~Daily cycle of the energy fluxes (W m^{-2}) in JJA 2000 for (a) FLUXNET observations at BE-Vie, (b) CON and FS at BE-Vie, (c) FLUXNET observations at IT-Col and (d) CON and FS at IT-Col.~~

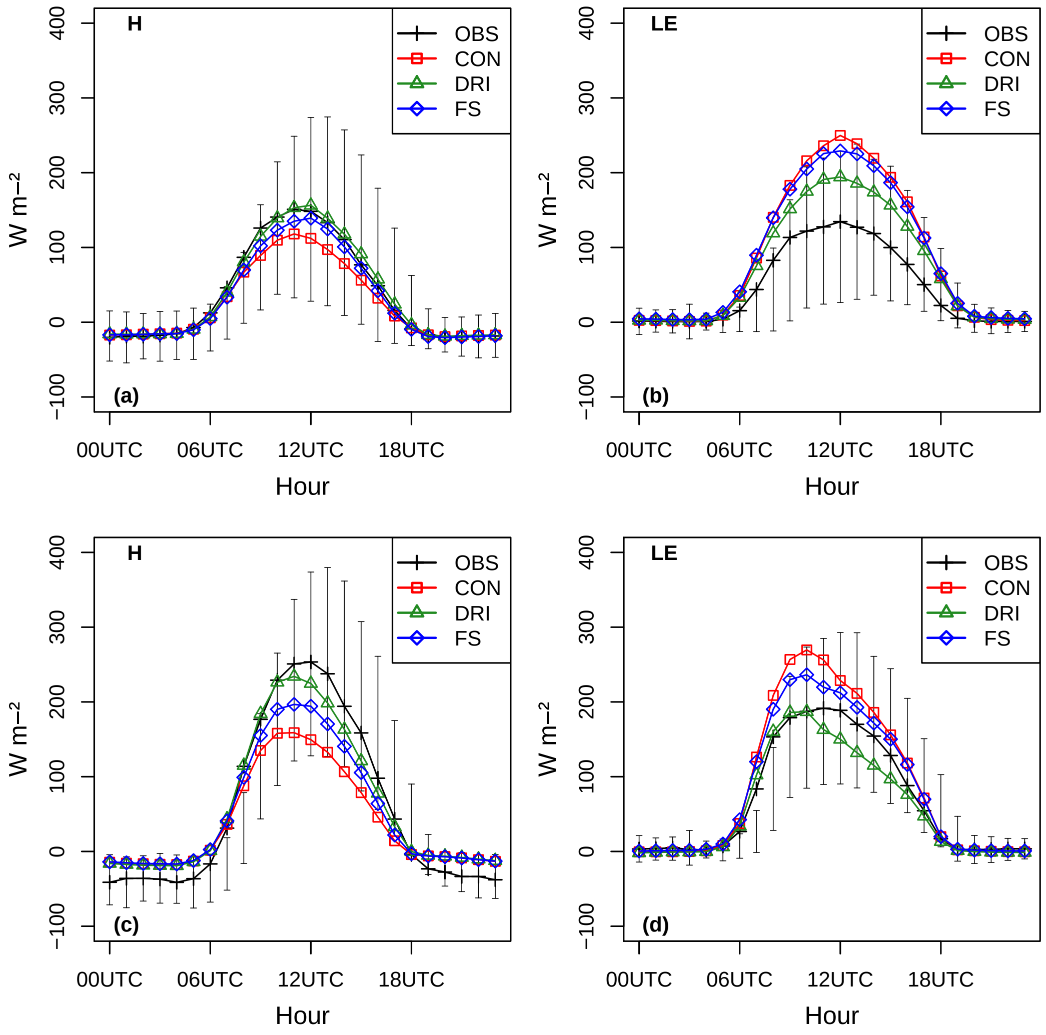


Figure 7. Daily cycle of the energy fluxes (W m^{-2}) in JJA 1996-2000 for Vielsalm in the top row and Collelongo in bottom row for (a,c) H, and (b,d) LE, for the FLUXNET observations and their corresponding model grid points by CON, DRI and FS. The error bars represent the standard deviation of the observations.