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

Julie Berckmans[1,2], Olivier Giot[1,2], Rozemien De Troch[1,3], Rafiq Hamdi[1,3], Reinhart Ceulemans[2], and Piet Termonia[1,3]

[1]Royal Meteorological Institute, Brussels, Belgium
[2]Centre of Excellence PLECO (Plant and Vegetation Ecology), Department of Biology, University of Antwerp, Antwerp, Belgium
[3]Department of Physics and Astronomy, Ghent University, Ghent, Belgium

Correspondence to: Julie Berckmans (julie.berckmans@meteo.be)

Abstract. 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 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. The results 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 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 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 surface. The results for summer demonstrated that the use of a 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 dates back to 1956 (Phillips, 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 GCM or global reanalysis provides the large-scale meteorological and surface fields to the RCM as initial and lateral boundary conditions. The global features are thus translated into regional and local conditions over the region of interest (Giorgi, 2006). 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 prediction (NWP) community uses high-resolution limited area models. The numerical approach was first used for a regional climate simulation by Dickinson et al. (1989). Their climate simulation used the NWP model in forecasting mode with short-term reinitialisations of the initial conditions. To be able to run 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 (Giorgi and Mearns, 1999). These so-called long-term continuous simulations required improvements in the representation of physical processes in the RCMs. This continuous simulation is still the most common in the RCM community (Leung et al., 2003). Nonetheless, the simulated large-scale fields deviate from the driving lateral boundary conditions, by applying the continuous approach (von Storch et al., 2000).

The accuracy of the dynamical downscaling has improved by using short-term reinitialisations (Kotlarski et al., 2012; Qian et al., 2003; Lo et al., 2008; Lucas-Picher et al., 2013). All these authors showed the advantage of using short-term reinitialisations by reducing systematic errors. However, only few authors adopted this method, mainly because of its higher computational costs. Most studies (Kotlarski et al., 2012; Qian et al., 2003; Lo et al., 2008) 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 (Kotlarski et al., 2012). 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, a reduction in systematic errors has been shown for precipitation when using the 10-day reinitialisation (Qian et al., 2003). Even in a 20-year RCM simulation forced by reanalysis data, the sequence of events was better preserved by using short-term reinitialisations (Lucas-Picher et al., 2013).

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 (Giorgi and Mearns, 1999). Beyond 24 hours small perturbations in the initial conditions of the atmosphere have only limited impact on the simulation potential (Anthes et al., 1989). In contrast to the atmosphere, the surface takes a longer time to reach dynamical equilibrium with the overlaying atmosphere, in the order of a few weeks to several seasons, depending on the depth of the soil layer.

The surface interacts with the climate through the soil moisture and soil temperature, by influencing the surface energy budget (Giorgi and Mearns, 1999). The soil moisture controls the partitioning of the incoming energy into a latent and sensible heat flux. The soil moisture limitation on the evapotranspiration is largest during the summer (Seneviratne et al., 2010). The availability of soil moisture for evapotranspiration is determined by the 2 m temperature (Jaeger et al., 2009). 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 (Baldocchi et al., 2001).

The objective of this study was to evaluate the 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, Dee et al., 2011). Within this study, ALARO was coupled to the land surface model of Météo-France SURFace Externalisée (SURFEX, Masson et al., 2013). We evaluated the mean 2 m temperature and mean daily total precipitation by comparing with the 0.22° ECA&D E-OBS dataset (Haylock et al., 2008), and the surface energy fluxes by comparing with the FLUXNET database (Baldocchi et al., 2001). The analysis covered a 10-year period from 1991 to 2000, for a domain encompassing Western Europe.

The models, experimental design and observational datasets are described in section 2. The results for the mean surface parameters are covered in section 3. Section 4 demonstrates the results with respect to the surface energy budget. Finally, conclusions are given in section 5.

2 Model and experimental design

2.1 Model definition

The 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 (Gerard et al., 2009). The ALADIN model is the limited area model version of the Action de Recherche Petite Echelle Grande Echelle Integrated Forecast system (ARPEGE-IFS) (Bubnová et al., 1995; ALADIN International Team, 1997). ARPEGE is a global spectral model, with a Gaussian grid for the grid-point calculation. The vertical discretisation is done according to a terrain-following pressure hybrid coordinate. ALARO-0 has been developed with the ARPEGE Calcul Radiatif Avec Nebulosité (ACRANEB) scheme for radiation based on Ritter and Geleyn (1992). This ALARO-0 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 Gerard and Geleyn (2005) and further improved by Gerard (2007) and Gerard et al. (2009). 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 land surface in ALARO-0 was initially with the land surface scheme Interaction Soil-Biosphere-Atmosphere (ISBA, Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996). 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 (Boone and Wetzel, 1999), or a force restore method based on two or three layers (Noilhan and Planton, 1989). Using the initial setup with ISBA, ALARO-0 has proven its skill for regional climate modelling with daily reinialisations (Hamdi et al., 2012; De Troch et al., 2013). In addition, this setup has been validated for continuous climate simulations and is now contributing to the EURO-CORDEX project (Giot et al., 2016; Jacob et al., 2014). 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 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 (Hamdi et al., 2014). 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 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 (Noilhan and Planton, 1989).

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, Masson, 2000) 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 Best et al. (2004). Each tile is divided in different patches, according to the tile type. These patches correspond to the plant functional types described in ECOCLIMAP (Masson et al., 2003). ECOCLIMAP is a 1 km horizontal resolution global land cover database and assigns the tile fraction and corresponding physical parameters to SURFEX.

2.2 Experimental design

The regional climate model was driven by initial and lateral boundary conditions provided by the ERA-Interim reanalysis, available at a horizontal resolution of ca. 79 km. The Davies (1976) relaxation zone consisted of eight grid points irrespective of the resolution. 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 (Giorgi and Mearns, 1999). For the sake of a good understanding, the following description makes a distinction between atmospheric spin-up time, typically of a 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 1991 to 00UTC on 01 January 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 (Lindstedt et al., 2015). 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 SURFEXv5.

The first downscaling approach was done by simulating the model in a continuous mode for both the atmosphere and the surface (hereafter called CON ("CONtinuous"), Fig. 2). The model was simulated from 00UTC on 01 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, and each reinitialisation ran for 60 hrs. The first 36 hours were treated as atmospheric spin-up time, and were excluded from the analysis. By applying this downscaling approach, the regional model stays close to the driving fields (von Storch et al., 2000). As the driving fields provided daily reanalysed data, a spin-up for the surface was redundant.

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 March 1990 until 31 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, 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 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 (Kotlarski et al., 2014) and that were defined earlier in the framework of the project "Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects" (PRUDENCE) (Christensen et al., 2007). The subdomains used in this study 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 the subdomains IP, ME, and EA, 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, Bowen, 1926) 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.

2.3 Observational reference data

The results of the climate simulations were validated against E-OBS, a daily high-resolution gridded observational dataset (Haylock et al., 2008). The dataset consists of the daily mean temperature, the daily maximum and minimum temperature, and the daily precipitation 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 ALARO-0 data at 20 km horizontal resolution were bilinearly interpolated towards 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 applied a smoothing out of extreme precipitation and consequently a large underestimation of the mean precipitation (Haylock et al., 2008).

For the validation of the surface fluxes distribution in the model, we used measurements from the FLUXNET Level 3 flux tower database (Baldocchi et al., 2001). It provides information on the energy 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. 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 (Aubinet et al., 2000). However, only a few stations provided data for the first operating years 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): (1) Vielsalm in Belgium, a temperate climate, at an altitude of 491 m with a tower height of 40 m and 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 distributions of the 10-year daily mean temperature bias (absolute, (model - observed)) of CON, DRI and FS simulations were compared to E-OBS (Fig. 3), for the winter (DJF: December-January-February) and summer (JJA: June-July-August) season. The average biases during winter and summer for CON, DRI and FS for the entire domain as well as for specific subdomains are presented in Table 1. CON simulated a cold bias in general, except for northern Africa, with a pronounced orographic effect, for both winter and summer (Fig. 3c,d). The cold bias over the entire domain was less pronounced in summer with a value of -0.6 °C compared to the winter bias of -1.8 °C (Table 1). Moreover, the Iberian Peninsula was well simulated during summer as compared to E-OBS, resulting in a bias of -0.5 °C. 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 CON, DRI demonstrated a reduction of the cold bias during winter 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 and 0.0 °C for DRI relative to CON which had a bias of -1.1 °C and -0.5 °C for winter and summer respectively (Table 1). Other subdomains showing a large improvement of the 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 was different for winter and summer as compared to CON and DRI (Fig. 3g,h). The 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 and Eastern Europe (Fig. 3g). The bias decreased by ca. 1 °C in FS compared to CON for these subdomains (Table 1). During summer, the sign of the bias reversed from negative to positive, 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 1). For the Iberian Peninsula and the Mediterranean, compensating biases resulted in positive and close to zero summer biases (Fig. 3h). Mid-Europe, France and Eastern Europe were mainly characterised by a positive bias of around 1 °C (Table 1). 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 underestimated winter and summer 2 m temperature with 1-2 °C on average. With respect to CON, DRI and FS showed a positive effect during winter and 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 a continuous simulation of the atmosphere.

3.1.2 Daily accumulated precipitation

The spatial distributions of the 10-year daily accumulated precipitation bias (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 CON, DRI and FS are presented for the entire domain as well as for the specific subdomains in Table 2. The precipitation pattern of E-OBS during winter 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 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.

During winter, all simulations demonstrated a similar spatial variability of the wet bias, except for a dry bias in northern Africa (Fig. 4c,e,g). In general, ALARO was forced towards the too wet driving fields of ERA-Interim (Lucas-Picher et al., 2013), which can explain part of the overestimated precipitation. More particularly, the overestimation of winter precipitation was strongest in the Mediterranean and Eastern Europe 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 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 simulations showed different spatial variability (Fig. 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%, but the absolute values in summer were close to zero, as it is characterised by a climate with dry summers (Fig. 4b). 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. 4f). The Iberian Peninsula, France and the Mediterranean demonstrated a bias of 30.0%, 18.3% and 84.8% respectively compared to 11.5%, 12.0% and 60.7% with CON (Table 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 reversed and dry biases occurs, though it was rather small (-7.0% for France, -13.4% for Mid-Europe, -8.2% for Eastern Europe respectively). Consequently, the summer precipitation was simulated better by FS than CON and DRI.

In summary, the model was characterised by a wet bias in winter and 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. The use of a daily reinitialised atmosphere in DRI and FS had a neutral impact on the winter precipitation. 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 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 temperate climate; and (3) Eastern Europe at the eastern boundary of the domain with its continental climate.

The daily mean 2 m temperature reached about 23 °C in the Iberian Peninsula, while it raised to 20 °C in Mid-Europe and Eastern Europe (Fig. 5a,b,c). For these selected subdomains, all downscaled simulations presented very similar autumn (SON: September-October-November) temperatures, but underestimated them with respect to E-OBS. Regarding the other seasons, the simulations revealed a different behaviour in the representation of the 2 m temperature with respect to the observations.

For the Iberian Peninsula, the 2 m temperature was generally underestimated for all seasons (Fig. 5a). Except for autumn, FS was closer to the observations as compared to CON and DRI, resulting in a yearly mean temperature of 12.5 °C, which was closer to the observed yearly mean temperature of 13.7 °C as compared to 11.6 °C 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, 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 value of 9.0 °C by FS was very close to the 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 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. Yet again, the yearly mean value of 8.5 °C by FS was very similar as compared to the observations 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 was underestimated by CON for all subdomains. Along the selected subdomains, there 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

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 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 reached highest values of ca. 3 mm day^{-1} during summer (Fig. 5e). The continental climate of Eastern Europe presented average values of 1 mm day^{-1} for winter and spring, while most rainfall occurred in the summer 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 seasonal pattern of the downscaled simulations followed the seasonal pattern of E-OBS (Fig. 5d). The model simulations represented an overestimation of the precipitation for all seasons. This overestimation was stronger in winter and in spring, and is in agreement with Lucas-Picher et al. (2013). For these two seasons, E-OBS showed an undercatch of the precipitation, which might have amplified the model biases (Rauscher et al., 2010). CON and DRI were closer to the observations than FS in winter and spring, resulting in yearly mean values of 1.9, 2.0, and 2.1 mm day^{-1} respectively for CON, DRI and FS, as compared to the observational mean value of 1.7 mm day^{-1}. In Mid-Europe, the model overestimated the precipitation for most of the year, except for summer (Fig. 5e). During summer, FS showed a large underestimation, whereas CON and DRI showed a similar pattern of overestimated precipitation. The precipitation in Eastern Europe was overestimated by the model during most of the year, except for summer. (Fig. 5f, Lucas-Picher et al., 2013). 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 three downscaling approaches overestimated the precipitation, except for an underestimation for Mid-Europe and Eastern Europe in particular months. On a yearly basis, the differences between CON, DRI and FS were small, but on a monthly basis, the magnitude of differences depended strongly on the region of interest. There were larger differences between the model simulations for Mid-Europe and Eastern Europe compared to the small differences for the Iberian Peninsula.

4 Validation of surface fluxes

The 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 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 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. 7, Table 3).

The daily maximum BR showed a strong gradient of increasing values towards the south of the domain (Fig. 6a,b,c). 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, while DRI showed BR values of 0.5 to 1 and highest values of 2 to 3 were expressed by FS. 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. 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).

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. Wilson et al. (2012) 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. 7.

For Vielsalm, H was simulated well by DRI and FS during nighttime and daytime, whereas CON underestimated H during daytime (Fig. 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. 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 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. 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, 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 three downscaling approaches has been performed using the regional climate model ALARO-0 coupled to the land surface model SURFEXv5, with lateral and initial boundary conditions from ERA-Interim. The simulations were applied for a 10-year period from 1991 to 2000, for a Western European domain. The performance of ALARO-0 with SURFEX has already been validated for NWP applications (Hamdi et al., 2014), but not yet for long-term climate simulations.

We compared the common used approach of a continuous climate simulation with two alternative aprooaches of frequently reinitialising the RCM simulation towards its driving field, 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. However, the use of a continuous surface next to a daily reinitialised atmosphere improved the summer precipitation with respect to 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 reinitialised daily together with the 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. 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.

During summer, the interaction between the land surface and the overlaying atmosphere is largest. The 2 m temperature interacts with the soil moisture 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 the 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 (Jaeger et al., 2009), 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.

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/surfex///spip.php?rubrique8.

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.

Acknowledgements. We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu). This work used eddy covariance data acquired and shared by the FLUXNET community. The validation data have been collected and prepared by the individual site PIs and their teams. We would like to thank Marc Aubinet (Vielsalm) and Giorgio Matteucci (Collelongo) for contributing data to this study. This research was funded by the Belgian Federal Science Policy Office under the BRAIN.be program as MASC contract #BR/121/A2. The authors also thank Annelies Duerinckx (Royal Meteorological Institute of Belgium, Brussels) for the useful discussions.

Appendix: References

ALADIN International Team: The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research, WMO Bulletin, 46, 317–324, 1997.

Anthes, R., Kuo, Y., Hsie, E., Low-Nam, S., and Bettge, T.: Estimation of espisodic and climatological skill and uncertainty in regional numerical models, Quaterly Journal of the Royal Meteorological Society, 115, 770–792, 1989.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology, Advances in Ecological Research, 30, 113–175, 2000.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw U, K., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities, Bulletin of the Americal Meteorological Society, 82, 2415–2435, 2001.

Best, M. J., Beljaars, A., Polcher, J., and Viterbo, P.: A proposed structure for coupling tiled surfaces with the planetary boundary layer, Journal of Hydrometeorology, 5, 1271–1278, 2004.

Boone, A. A. and Wetzel, P. J.: A simple method for modeling sub-grid soil texture variability for use in an atmospheric climate model, Journal of the Meteorological Society of Japan, 77, 317–333, 1999.

Bowen, I.: The ratio of heat losses by conduction and by evaporation from any water surface, Physical Review Letters, 27, 779–787, 1926.

Bubnová, R., Hello, G., Bénard, P., and Geleyn, J.-F.: Integration of the fully elastic equations cast in the hydrostatic pressure terrain-following coordinate in the framework of the ARPEGE/Aladin NWP system, Monthly Weather Review, 123, 515–535, 1995.

Christensen, J. H., Carter, T. R., Rummukainen, M., and Amanatidis, G.: Evaluating the performance and utility of regional climate models: the PRUDENCE project, Climate Change, 81, 1–6, 2007.

Davies, H. C.: A lateral boundary formulation for multi-level prediction models, Quaterly Journal of the Royal Meteorological Society, 102, 405–418, 1976.

De Troch, R., Hamdi, R., Van De Vyver, H., Geleyn, J.-F., and Termonia, P.: Multiscale performance of the ALARO-0 Model for simulating extreme summer precipitation climatology in Belgium, Journal of Climate, 26, 8895–8915, 2013.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, 2011.

Dickinson, R. E., Errico, R. M., Giorgi, F., and Bates, G. T.: A regional climate model for the Western United States, Climatic Change, 15, 383–422, 1989.

Gerard, L.: An integrated package for subgrid convection, clouds and precipitation compatible with the meso-gamma scales, Quaterly Journal of the Royal Meteorological Society, 133, 711–730, 2007.

Gerard, L. and Geleyn, J.-F.: Evolution of a subgrid deep convection parametrization in a limited area model with increasing resolution, Quaterly Journal of the Royal Meteorological Society, 131, 2293–2312, 2005.

Gerard, L., Piriou, J.-M., Brožková, R., Geleyn, J.-F., and Banciu, D.: Cloud and precipitation parameterization in a meso-gamma-scale operational weather prediction model, Monthly Weather Review, 137, 3960–3977, 2009.

Giorgi, F.: Regional climate modeling: status and perspectives, Journal of Physics, 139, 101–118, 2006.

Giorgi, F. and Mearns, L. O.: Introduction to special section: regional climate modeling revisited, Journal of Geophysical Research, 104, 6335–6352, 1999.

Giot, O., Termonia, P., Degrauwe, D., De Troch, R., Caluwaerts, S., Smet, G., Berckmans, J., Deckmyn, A., De Cruz, L., De Meutter, P., Duerinckx, A., Gerard, L., Hamdi, R., Van den Bergh, J., Van Ginderachter, M., and Van Schaeybroeck, B.: Validation of the ALARO-0 model within the EURO-CORDEX framework, Geoscientific Model Development, 9, 1143–1152, 2016.

Hamdi, R., Van de Vyver, H., and Termonia, P.: New cloud and microphysics parameterisation for use in high-resolution dynamical downscaling: application for summer extreme temperature over Belgium, International Journal of Climatology, 32, 2051–2065, 2012.

Hamdi, R., Degrauwe, D., Duerinckx, A., Cedilnik, J., Costa, V., Dalkilic, T., Essaouini, K., Jerczynki, M., Kocaman, F., Kullmann, L., Mahfouf, J.-F., Meier, F., Sassi, M., Schneider, S., Váña, F., and Termonia, P.: Evaluating the performance of SURFEXv5 as a new land surface scheme for the ALADINcy36 and ALARO-0 models, Geoscientific Model Development, 7, 23–39, 2014.

Haylock, M. R., Hofstra, N., Tank, A. M. G. K., Klok, E. J., Jones, P. D., and New, M.: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006, Journal of Geophysical Research, 113, D20 119, 2008.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., and Yiou, P.: EURO-CORDEX: new high-resolution climate change projections for European impact research, Regional Environmental Change, 14, 563–578, 2014.

Jaeger, E., Stöckli, R., and Seneviratne, S.: Analysis of planetary boundary layer fluxes and land-atmosphere coupling in the regional climate model CLM, Journal of Geophysical Research, 114, 1–15, 2009.

Kotlarski, S., Hagemann, S., Krahe, P., Podzun, R., and Jacob, D.: The Elbe river flooding 2002 as seen by an extended regional climate model, Journal of Hydrology, 472-473, 169–183, 2012.

Kotlarski, S., Keuler, K., Christensen, O. B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., and Wulfmeyer, V.: Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble, Geoscientific Model Development, 7, 1297–1333, 2014.

Leung, L. R., Mearns, L. O., Giorgi, F., and Wilby, R. L.: Regional climate research, Bulletin of the American Meteorological Society, 84, 89–95, 2003.

Lindstedt, D., Lind, P., Kjellström, E., and Jones, C.: A new regional climate model operating at the meso-gamma scale: performance over Europe, Tellus, 67, 1–23, 2015.

Lo, J. C.-F., Yang, Z.-L., and Pielke Sr., R. A.: Assessment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model, Journal of Geophyical Research, 113, 1–16, 2008.

Lucas-Picher, P., Boberg, F., Christensen, J. H., and Berg, P.: Dynamical downscaling with reinitializations: a method to generate finescale climate datasets suitable for impact studies, Journal of Hydrometeorology, 14, 1159–1174, 2013.

Masson, V.: A physically-based scheme for the urban energy budget in atmospheric models, Boundary-Layer Meteorology, 94, 357–397, 2000.

Masson, V., Champeaux, J.-L., Chauvin, F., Meriguet, C., and Lacaze, R.: A global database of land surface parameters at 1 km resolution in meteorological and climate models, Journal of Climate, 16, 1261–1282, 2003.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.-C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.-L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.-F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., and Voldoire, A.: The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes, Geoscientific Model Development, 6, 929–960, 2013.

Noilhan, J. and Mahfouf, J.-F.: The ISBA land surface parameterisation scheme, Global and Planetary Change, 13, 145–159, 1996.

Noilhan, J. and Planton, S.: A simple parameterization of land surface processes for meteorological models, Monthly Weather Review, 117, 536–549, 1989.

Phillips, N. A.: The general circulation of the atmosphere: a numerical experiment, Quarterly Journal of the Royal Meteorological Society, 82, 123–164, 1956.

Qian, J.-H., Seth, A., and Zebiak, S.: Reinitialized versus continuous simulations for regional climate downscaling, Monthly Weather Review, 131, 2857–2874, 2003.

Rauscher, S. A., Coppola, E., Piani, C., and Giorgi, F.: Resolution effects on regional climate model simulations of seasonal precipitation over Europe, Climate Dynamics, 35, 685–711, 2010.

Ritter, B. and Geleyn, J.-F.: A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations, Monthly Weather Review, 120, 303–325, 1992.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling., A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125–161, 2010.

von Storch, H., Langenberg, H., and Feser, F.: A spectral nudging technique for dynamical downscaling purposes, Monthly Weather Review, 128, 3664–3673, 2000.

Wilson, T., Meyers, T., Kochendorfer, J., Anderson, M., and Heuer, M.: The effect of soil surface litter residue on energy and carbon fluxes in a deciduous forest, Agricultural and forest meteorology, 161, 134–147, 2012.

Table 1. 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	MD	EA
DJF	CON	-1.8 (2.5)	-1.1 (2.0)	-2.2 (2.7)	-1.5 (2.2)	-1.3 (2.0)	-3.0 (3.8)	-2.4 (3.1)	-1.1 (2.0)
	DRI	-1.2 (2.8)	-1.0 (2.7)	-1.6 (2.7)	-1.2 (2.9)	-0.7 (2.6)	-1.4 (3.4)	-2.1 (3.2)	-0.3 (2.8)
	FS	-1.0 (2.8)	-0.3 (2.8)	-1.3 (2.5)	-0.7 (2.8)	-0.4 (2.6)	-2.1 (3.8)	-1.2 (2.7)	-0.4 (2.8)
JJA	CON	-0.6 (2.0)	-1.7 (2.0)	-0.5 (1.7)	-1.2 (1.9)	-1.3 (1.9)	-1.8 (2.6)	-0.5 (2.0)	-0.5 (1.8)
	DRI	-0.1 (2.3)	-0.9 (2.0)	-0.3 (2.2)	-0.7 (2.4)	-0.3 (2.1)	-0.8 (2.3)	-0.6 (2.3)	0.0 (2.1)
	FS	0.9 (2.7)	-0.7 (2.2)	0.5 (2.4)	1.0 (3.1)	1.3 (2.8)	-0.0 (2.5)	0.7 (2.5)	1.2 (2.8)

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	MD	EA
DJF	CON	16.6 (3.8)	4.5 (4.5)	16.1 (4.6)	29.0 (3.6)	25.4 (2.7)	11.2 (4.7)	46.0 (6.2)	35.3 (2.3)
	DRI	20.9 (4.8)	6.6 (5.2)	21.2 (5.6)	26.8 (4.8)	27.9 (3.8)	24.1 (6.3)	41.6 (7.1)	45.7 (3.1)
	FS	36.3 (5.4)	16.9 (5.5)	31.3 (6.2)	38.2 (5.2)	35.7 (4.0)	26.7 (6.7)	108.5 (9.9)	64.1 (3.5)
JJA	CON	12.1 (4.2)	24.7 (4.4)	11.5 (2.9)	12.0 (4.4)	11.9 (5.0)	32.6 (7.3)	60.7 (3.5)	-2.6 (5.4)
	DRI	22.5 (4.7)	27.0 (4.7)	30.0 (3.4)	18.3 (5.1)	8.8 (5.5)	48.2 (8.9)	84.8 (3.8)	6.8 (5.9)
	FS	3.6 (4.5)	17.4 (4.6)	13.0 (3.2)	-7.0 (4.6)	-13.4 (5.1)	23.5 (8.3)	52.4 (3.6)	-8.2 (5.7)

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).

		RN	H	LE	G	BR
Vielsalm	OBS	417	151	134	11	1.12
	CON	395 (404)	118 (113)	250 (261)	47 (47)	0.47 (0.43)
	DRI	388 (398)	151 (159)	195 (193)	57 (58)	0.78 (0.82)
	FS	405 (411)	139 (152)	229 (221)	46 (49)	0.61 (0.69)
Collelongo	OBS	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)

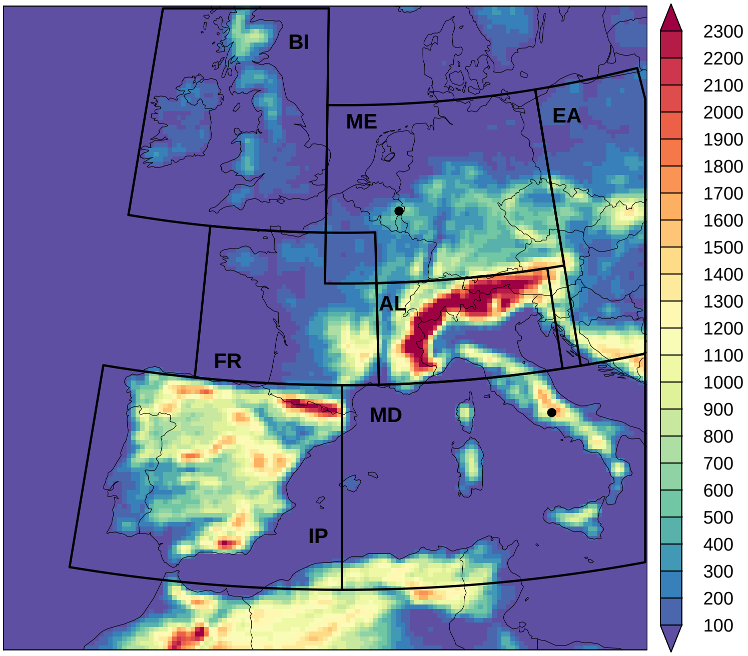

Figure 1. The total domain on 20 km horizontal resolution and the subdomains (BI, IP, FR, ME, AL, MD, EA) based on the subdomains selected in the EURO-CORDEX framework. The color represents the orography (m) in the ALARO+SURFEX setup. The two black dots represent the FLUXNET stations Vielsalm (Belgium)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

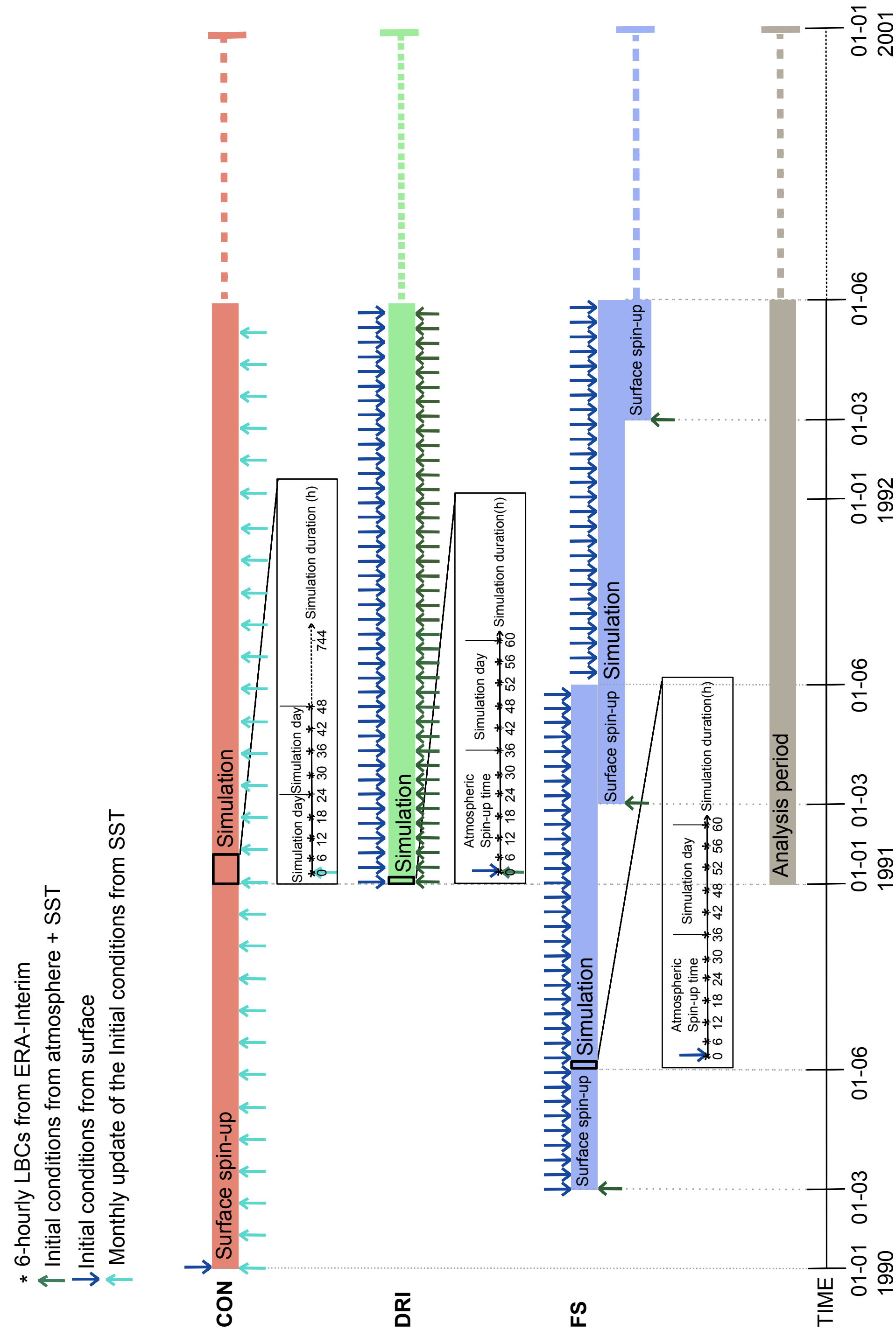

Figure 2. The setup of the three downscaling approaches CON, DRI and FS used in this study. It represents the spin-up time for the different simulations, the analysis period of the total experiment and the update frequency of the lateral and initial boundary conditions.

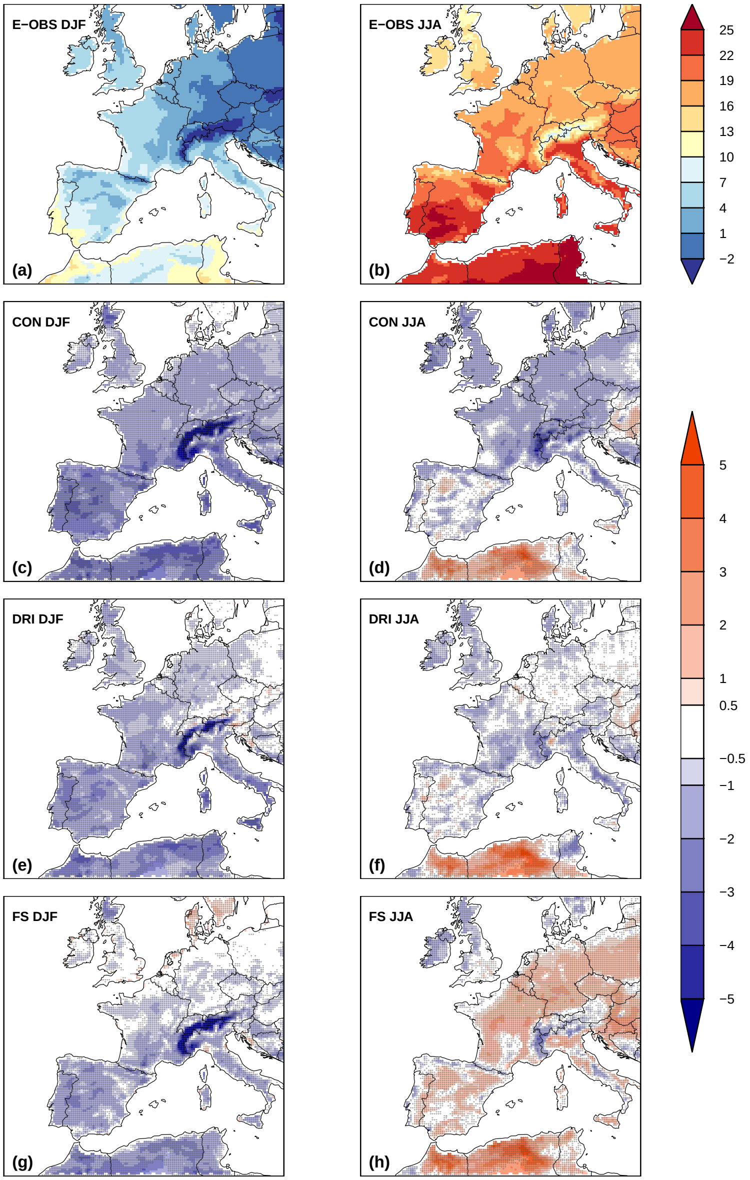

Figure 3. Daily mean 2 m temperature (°C) for E-OBS DJF (a) and JJA (b), and absolute bias (°C) of the model with E-OBS for CON DJF (c) and JJA (d), for DRI DJF (e) and JJA (f) and for FS DJF (g) and JJA (h), all at a 20 km horizontal resolution for the 10-year period 1991-2000. The dots represent the 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.

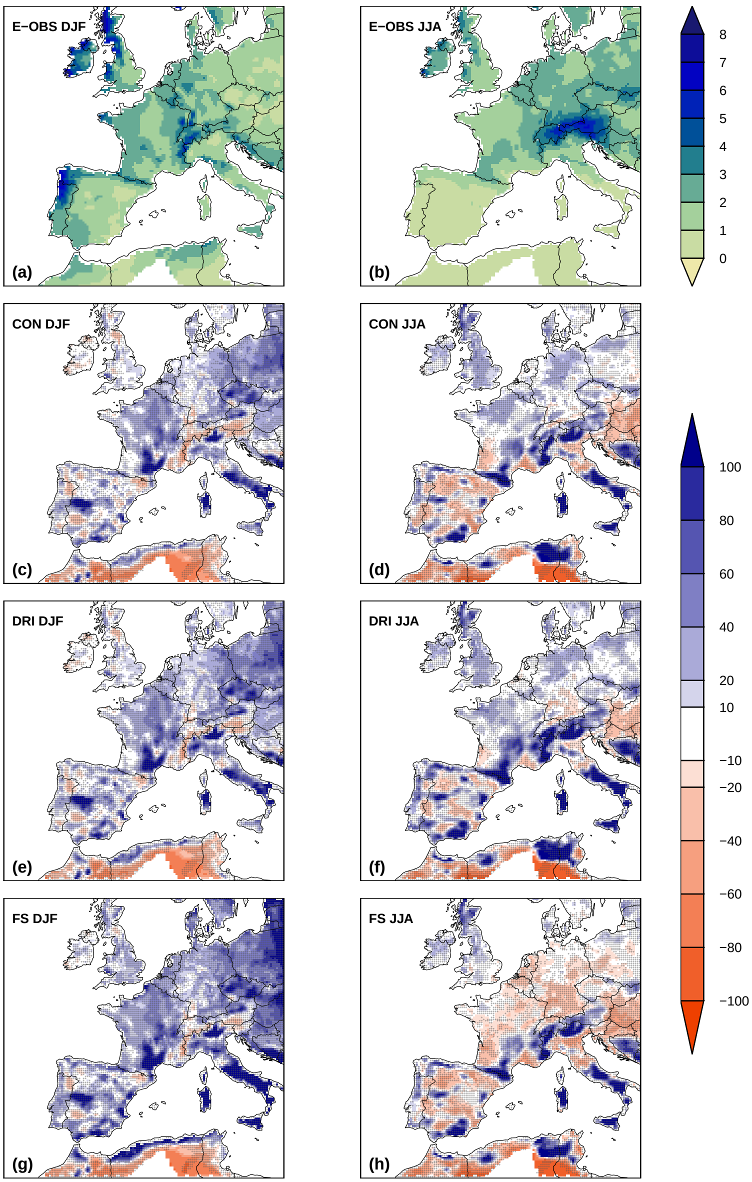

Figure 4. Daily accumulated precipitation (mm day^{-1}) for E-OBS DJF (a) and JJA (b), and relative bias (%) of the model with E-OBS for CON DJF (c) and JJA (d), for DRI DJF (e) and JJA (f) and for FS DJF (g) and JJA (h), all at a 20 km horizontal resolution for a 10-year period 1991-2000. The dots represent 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.

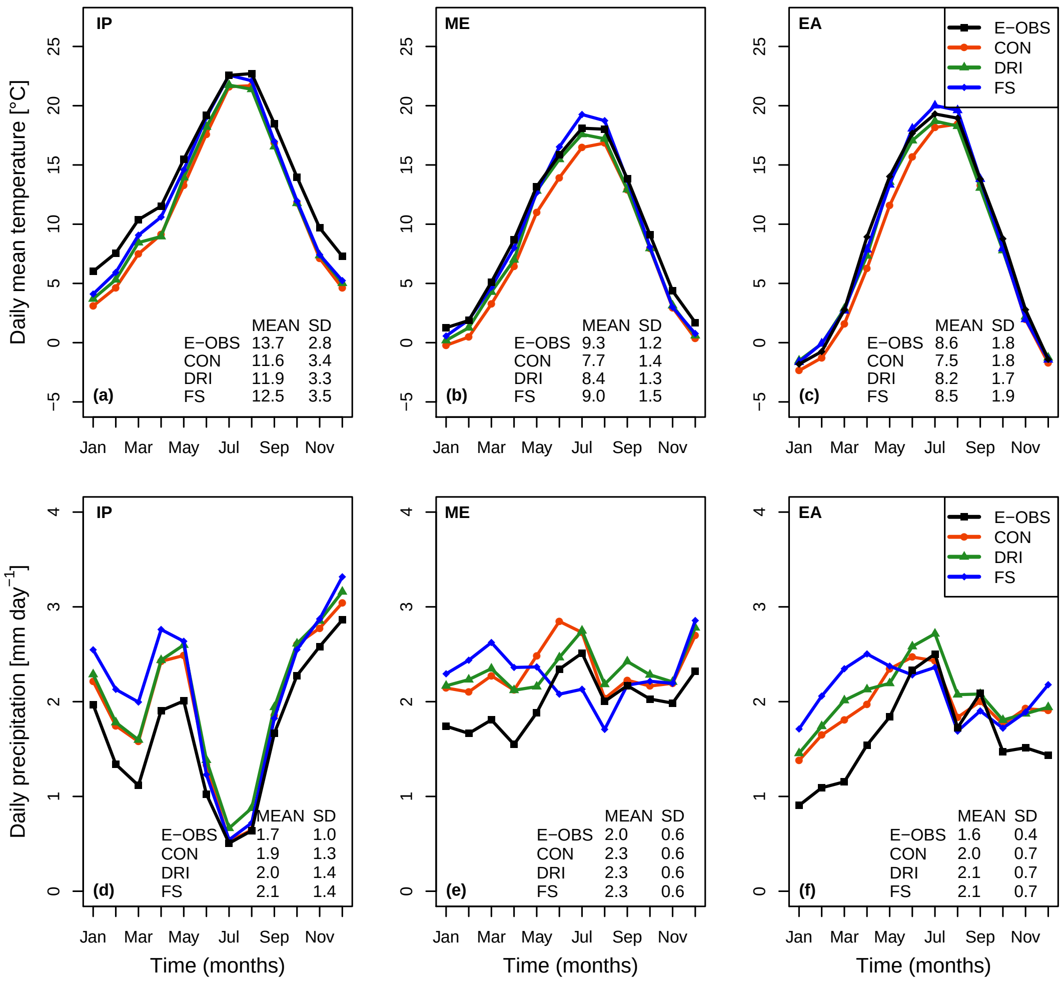

Figure 5. Mean annual cycle of the daily 2 m temperature (°C) with E-OBS, CON and FS for (a) the Iberian Peninsula, (b) Mid-Europe, and (c) Eastern Europe, and daily accumulated precipitation (mm day^{-1}) for (d) the Iberian Peninsula, (e) Mid-Europe, and (f) Eastern Europe, averaged over the 10-year period 1991-2000. Both the mean and standard deviation (SD) are displayed as text.

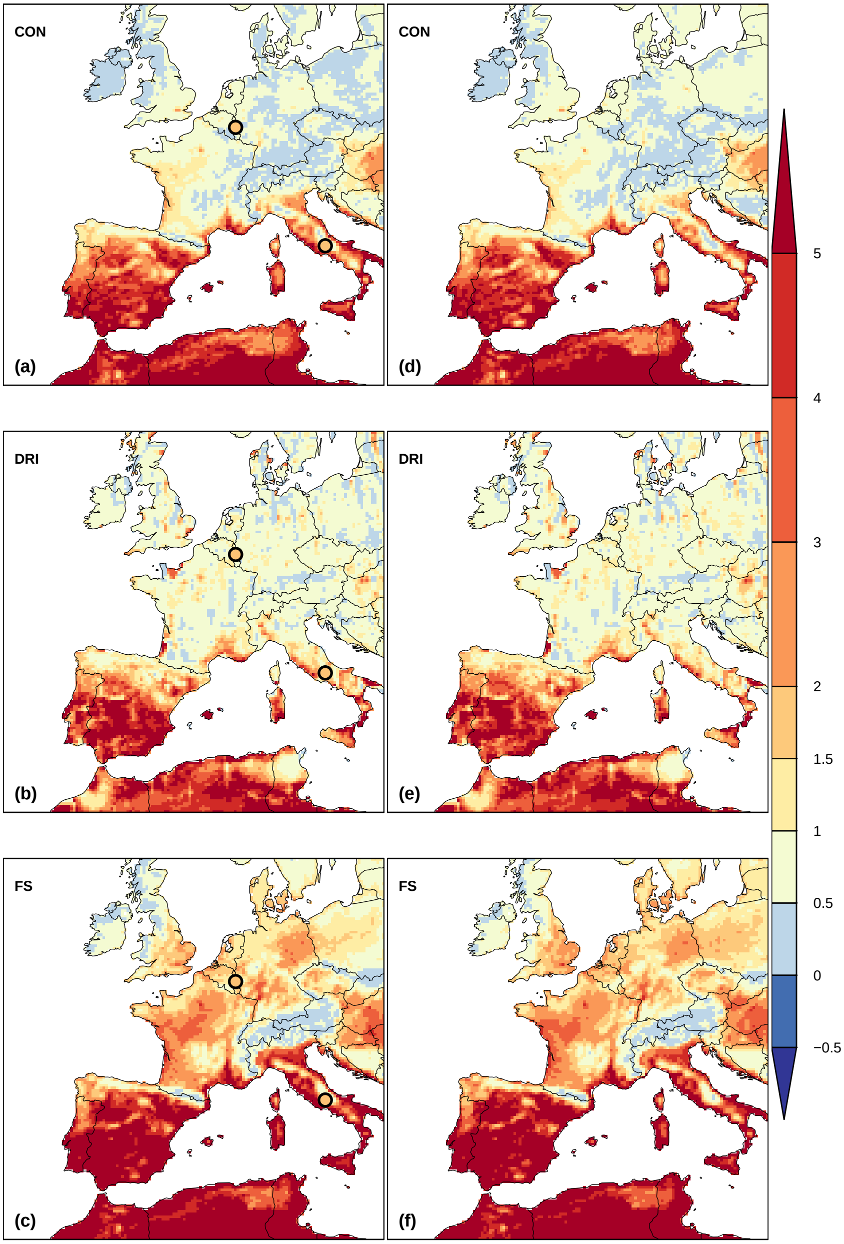

Figure 6. Daily maximum Bowen ratio averaged over the 5 year JJA period 1996-2000 for (a) CON, (c) DRI and (e) FS and averaged over the 10-year JJA period 1991-2000 for (b) CON, (d) DRI and (f) FS. The dots represent the values for the FLUXNET stations Vielsalm (Belgium) and Collelongo (Italy).

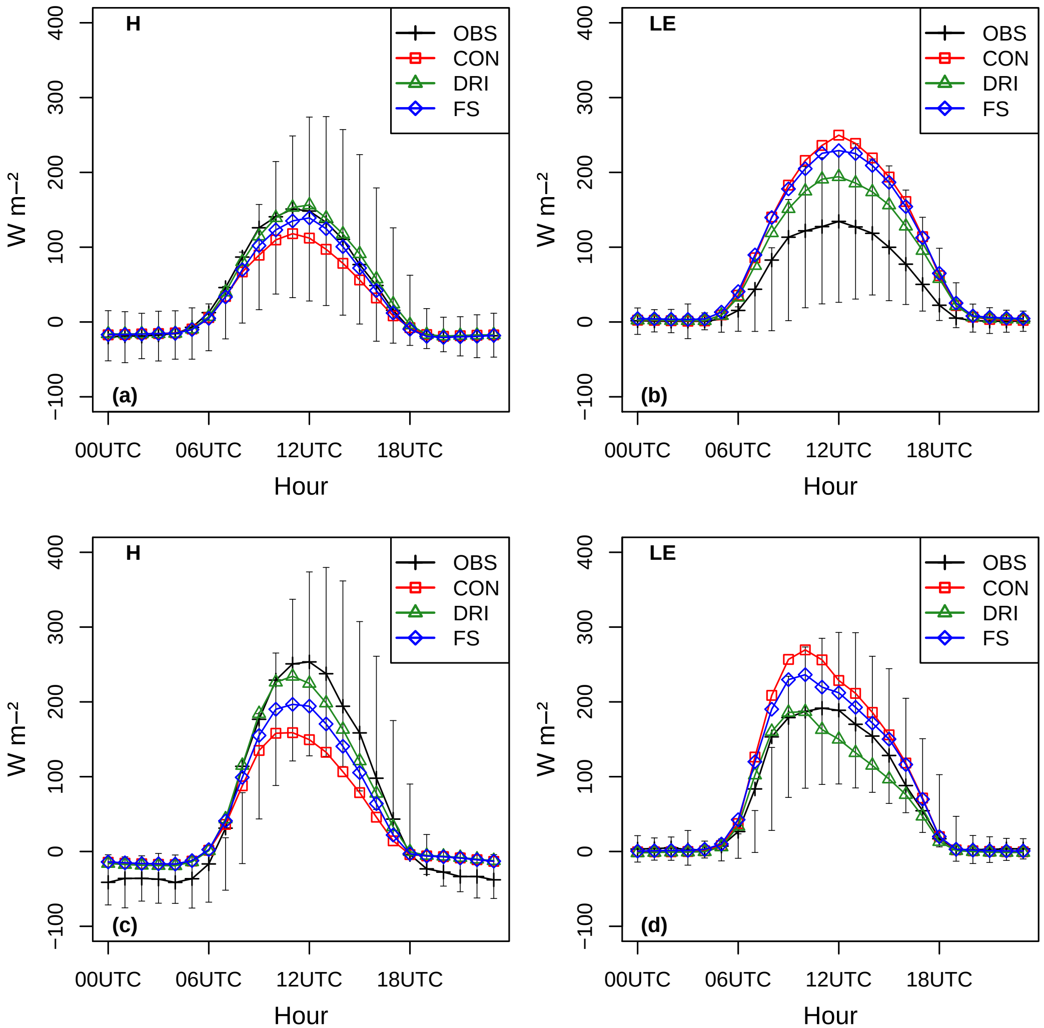

Figure 7. Daily cycle of the energy fluxes (W m^{-2}) in JJA 1996-2000 for Vielsalm in the top row and Collelongo in bottom row for (a,c) H, and (b,d) LE, for the FLUXNET observations and their corresponding model grid points by CON, DRI and FS. The error bars represent the standard deviation of the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