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On the ability of RegCM4 regional climate model to simulate surface solar radiation patterns over Europe: an assessment using satellite-based observations

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Abstract

In this work, we assess the ability of RegCM4 regional climate model to simulate surface solar radiation (SSR) patterns over Europe. A decadal RegCM4 run (2000–2009) was implemented and evaluated against satellite-based observations from the Satellite Application Facility on Climate Monitoring (CM SAF) showing that the model simulates adequately the SSR patterns over the region. The SSR bias between RegCM4 and CM SAF is $+1.5\,\%$ for MFG (Meteosat First Generation) and $+3.3\,\%$ for MSG (Meteosat Second Generation) observations. The relative contribution of parameters that determine the transmission of solar radiation within the atmosphere to the deviation appearing between RegCM4 and CM SAF SSR is also examined. Cloud macrophysical and microphysical properties such as cloud fractional cover (CFC), cloud optical thickness (COT) and cloud effective radius (Re) from RegCM4 are evaluated against data from CM SAF. The same procedure is repeated for aerosol optical properties such as aerosol optical depth (AOD), asymmetry factor (ASY) and single scattering albedo (SSA), as well as other parameters including surface broadband albedo (ALB) and water vapor amount (WV) using data from MACv1 aerosol climatology, from CERES satellite sensors and from ERA-Interim reanalysis. It is shown here that the good agreement between RegCM4 and satellite-based SSR observations can be partially attributed to counteracting effects among the above mentioned parameters. The contribution of each parameter to the RegCM4-CM SAF SSR deviations is estimated with the combined use of the aforementioned data and a radiative transfer model (SBDART). CFC, COT and AOD are the major determinants of these deviations on a monthly basis; however, the other parameters also play an important role for specific regions and seasons. Overall, for the European domain, the underestimation of CFC by RegCM4 is the most important cause of the SSR overestimation on an annual basis.

1 Introduction

Modeling climate on a regional scale is essential for assessing the impact of climate change on society, economy and natural resources. Regional climate models are limited-area models that simulate climate processes being often used to downscale dynamically global model simulations or global reanalysis data for specific regions in order to provide more detailed results (Laprise, 2008; Rummukainen, 2010). Several studies suggest that we can benefit from the use of regional climate models, especially due to the higher resolution of stationary features like topography, coastlines and from the improved representation of small-scale processes such as convective precipitation (see Flato et al., 2013, and references therein). Usually, regional climate models are evaluated and "tuned" according to their ability to simulate temperature and precipitation (e.g. Giorgi et al., 2012; Vautard et al., 2013; Kotlarski et al., 2014). However, as discussed in Katragkou et al. (2015), the role of other climatological parameters should be included in the evaluation procedure of regional climate models.

For example, the ability of regional climate models to assess surface solar radiation (SSR) patterns has not received so much attention despite the fact that SSR plays a core role in various climatic processes and parameters such as: (1) evapotranspiration (e.g. Teuling et al., 2009), (2) hydrological cycle (e.g. Allen and Ingram, 2002; Ramanathan et al., 2001; Wang et al., 2010; Wild and Liepert, 2010), (3) photosynthesis (e.g. Gu et al., 2002; Mercado et al., 2009), (4) oceanic heat budget (e.g. Lewis et al., 1990; Webster et al., 1996; Bodas-Salcedo et al., 2014), (5) global energy balance (e.g. Kim and Ramanathan, 2008; Stephens et al., 2012; Trenberth et al., 2009; Wild et al., 2013) and solar energy production (Hammer et al., 2003) and largely affects temperature and precipitation. The same stands for the parameters that drive SSR levels, such as cloud macrophysical and microphysical properties (cloud fractional cover CFC, cloud optical thickness COT and cloud effective radius Re), aerosol optical properties (aerosol optical depth AOD, asymmetry factor ASY and single scattering albedo SSA), surface broadband albedo (ALB) and atmospheric water vapor amount (WV). However, during the last years, there were a few regional climate model studies focusing on the SSR levels or the net surface shortwave radiation, either to examine the dimming/brightening effect (e.g. Zubler et al., 2011; Chiacchio et al., 2015) or to evaluate the models (e.g. Jaeger et al., 2008; Markovic et al., 2008; Kothe and Ahrens, 2010; Kothe et al., 2011, 2014; Güttler et al., 2014). These studies highlight the dominating effect of cloud cover and surface albedo.

In this work, we go a step further, proceeding to a detailed evaluation of the ability of RegCM4 regional climate model to simulate SSR patterns over Europe taking into account not only CFC and ALB but also COT, Re, AOD, ASY, SSA and WV. For the scopes of this study, the same parameters are extracted from satellite-based observational data (CM SAF, CERES), data from an aerosol climatology (MACv1) and data from the ERA-Interim reanalysis (see Table 1). First a decadal simulation (2000–2009) is implemented with the model and the output is evaluated against observations from the EUMETSAT geostationary satellites of CM SAF. SSR data from the Meteosat First Generation (MFG) satellites are available for the period 2000–2005 while data from the Meteosat Second Generation (MSG) satellites are available for the period 2006–2009. These data are characterized by a high spatial (~ 3–$5\,\mathrm{km}$) and temporal resolution (15–30 min) and have been validated in the past, constituting a well-established product. In Sect. 2.1, the basic features of the model are described along with the simulation setup and the way various parameters are calculated by the model. In Sects. 2.2 and 2.3, a description of the satellite data from CM SAF and the other data which are used for the evaluation of RegCM4 is given, while, in Sect. 2.4, we discuss the methodology followed in this manuscript. Section 3.1 includes the evaluation of RegCM4 SSR against data from MFG and MSG, Sects. 3.2 and 3.3 the evaluation of CFC, COT and Re against data from MSG, Sect. 3.4 the comparison of RegCM4 AOD, ASY and SSA with data from MACv1 aerosol climatology and Sect. 3.5 the comparison of RegCM4 WV and ALB with data from ERA-Interim reanalysis and CERES satellite sensors, respectively. The CFC, COT, Re, AOD, ASY, SSA, ALB and WV datasets where chosen so as to be consistent with the CM SAF SSR dataset. The potential contribution of various parameters to the RegCM4-CM SAF SSR differences is estimated with the combined use of the data mentioned above and a radiative transfer model for the MSG SSR period (2006–

2009). The results are presented in Sect. 3.6, while the main findings of this manuscript are summarized in Sect. 4.

2 Model description, data and methods

2.1 RegCM4 description and simulation setup

In this work, a decadal (2000–2009) simulation was implemented with RegCM4.4 (hereafter denoted as RegCM4 or RegCM) for the greater European region with an horizontal resolution of 50 km. The model's domain extends from 65° W to 65° E and 15 to 75° N including the largest part of the Sahara Desert and part of Middle East (see Fig. S1 in the Supplement of this manuscript). RegCM is a hydrostatic, sigma-p regional climate model with a dynamical core based on the hydrostatic version of NCAR-PSU's Mesoscale Model version 5 (MM5) (Grell et al., 1994). Specifically, RegCM4 is a substantially improved version of the model compared to its predecessor RegCM3 (Pal et al., 2007) by means of software code and physics (e.g. radiative transfer, planetary boundary layer, convection schemes over land and ocean, land types and surface processes, ocean-air exchanges). Details on the historical evolution of RegCM from the late 1980s until today and a full description of RegCM4's basic features are given in Giorgi et al. (2012).

Data from ECMWF's ERA-Interim reanalysis were used as lateral boundary conditions. RegCM4 through a simplified aerosol scheme accounts for anthropogenic SO_2, sulfates, organic and black carbon (Solmon et al., 2006). The emissions of these anthropogenic aerosols are based on monthly, timed-dependent, historical emissions from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Lamarque et al., 2010) with one year spin up time (1999). This inventory is used by a number of climate models in support of the most recent report of the Intergovernmental Panel on Climate Change (IPCC, 2013). The model also accounts for maritime particles through a 2-bin sea salt scheme (Zakey et al., 2008) and for dust through a 4-bin approach (Zakey et al., 2006). For our simulation, the MIT-Emanuel convection scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999) was used. Convection is triggered when the buoyancy level is higher than the cloud base level. The cloud mixing is considered episodic and inhomogenous, the convective fluxes being based on a model of sub-cloud-scale updrafts and downdrafts (Giorgi et al., 2012). Zanis et al. (2009) reported for RegCM3 that the low stratiform clouds are systematically denser and more persistent with the use of the Grell (Grell, 1993) convective scheme than with the Emannuel scheme, a result with major importance for the cloud- radiation feedback. The boundary layer scheme of Holtslag et al. (1990) was utilized while the Subgrid Explicit Moisture Scheme (SUBEX) handles large-scale cloud and precipitation computations. The ocean flux scheme was taken from Zeng et al. (1998) with the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1993) accounting for land surface processes.

The Community Climate Model version 3 (CCM3) (Kiehl et al., 1996) radiative package handles radiative transfer within RegCM4. The CCM3 scheme employs the δ-Eddington approximation following its predecessor (CCM2) (Briegleb, 1992). Especially for the short-wave radiation, the radiative transfer model takes into account the effect of atmospheric water vapor and greenhouse gasses, aerosol amount and optical properties per layer (e.g. aerosol optical thickness, asymmetry factor, single scattering albedo) as well as cloud macrophysical (e.g. cloud fractional cover) and microphysical properties per layer (e.g. effective droplet radius, liquid water path, cloud optical thickness) and land surface properties (surface albedo). The radiative transfer equation is solved for 18 discrete spectral intervals from 0.2 to 5 µm for the 18 RegCM vertical sigma layers from 50 hPa to the surface.

The effect of clouds on shortwave radiation is manifested by CFC, cloud droplet size and cloud water path (CWP) which is based on the prognostically calculated parameter of cloud water amount (Giorgi et al., 2012). Within the model, the effective droplet radius for liquid clouds (Rel) is considered constant (10 µm) over the ocean while over land it is given as a function of temperature (Kiehl et al., 1998; Collins et al., 2004). On the other hand, the ice particle effective radius (Rei) is given as a function of normalized pressure, starting from

10 µm. The equations used for the calculation of Rel and Rei are given below.

$$\mathrm{Rel} = \begin{cases} 5\,\mu\mathrm{m} & T > -10\,^{\circ}\mathrm{C} \\ 5 - 5\left(\frac{T+10}{20}\right)\,\mu\mathrm{m} & -30\,^{\circ}\mathrm{C} \le T \le -10\,^{\circ}\mathrm{C} \\ \mathrm{Rei} & T < -30\,^{\circ}\mathrm{C} \end{cases} \tag{1}$$

$$\mathrm{Rei} = \begin{cases} \mathrm{Rei_{min}} & p/p_s > p_I^{\mathrm{high}} \\ \mathrm{Rei_{min}} - (\mathrm{Rei_{max}} - \mathrm{Rei_{min}}) \left[\frac{(p/p_s) - p_I^{\mathrm{high}}}{p_I^{\mathrm{high}} - p_I^{\mathrm{low}}}\right]\,\mu\mathrm{m} & p/p_s \le p_I^{\mathrm{high}} \end{cases} \tag{2}$$

where $\mathrm{Rei_{max}} = 30\,\mu\mathrm{m}$, $\mathrm{Rei_{min}} = 10\,\mu\mathrm{m}$, $p_I^{\mathrm{high}} = 0.4$ and $p_I^{\mathrm{low}} = 0.0$. The fraction (f_{ice}) of cloud water that consists of ice particles is given as a function of temperature (T), the fraction (f_{liq}) of the liquid water droplets being calculated as f_{liq}=1-f_{ice}.

$$f_{\mathrm{ice}} = \begin{cases} 0 & T > -10\,^{\circ}\mathrm{C} \\ -0.05\,(T+10) & -30\,^{\circ}\mathrm{C} \le T \le -10\,^{\circ}\mathrm{C} \\ 1 & T < -30\,^{\circ}\mathrm{C} \end{cases} \tag{3}$$

Then, the radiative properties of liquid and ice clouds in the shortwave spectral region are given by the following parameterizations, originally found in Slingo (1989) and revisited by Briegleb et al. (1992).

$$\mathrm{COT}_{\mathrm{ph}}^{\lambda} = \mathrm{CWP}\left[a_{\mathrm{ph}}^{\lambda} + \frac{b_{\mathrm{ph}}^{\lambda}}{\mathrm{Re_{ph}}}\right] f_{\mathrm{ph}} \tag{4}$$

$$\omega_{\mathrm{ph}}^{\lambda} = 1 - c_{\mathrm{ph}}^{\lambda} - d_{\mathrm{ph}}^{\lambda}\mathrm{Re_{ph}} \tag{5}$$

$$g_{\mathrm{ph}}^{\lambda} = e_{\mathrm{ph}}^{\lambda} + f_{\mathrm{ph}}^{\lambda}\mathrm{Re_{ph}} \tag{6}$$

$$\phi_{\mathrm{ph}}^{\lambda} = \left(g_{\mathrm{ph}}^{\lambda}\right)^2 \tag{7}$$

where superscript λ denotes the spectral interval and subscript ph denotes the phase (liquid/ice). Also, ω is the single scattering albedo, g is the asymmetry factor and ϕ is the phase function of clouds. It has to be highlighted here that all the equations presented above are given in Kiehl et al. (1998) and Collins et al. (2004) with a slightly different annotation. The coefficients a–f for liquid clouds are given in Slingo (1989), while for ice clouds in Ebert and Curry (1992) for the four pseudo-spectral intervals (0.25–0.69, 0.69–1.19, 1.19–2.38 and 2.38–4.00 µm) employed in the radiative scheme of RegCM. Especially for COT, in this paper we calculated it for the spectral interval 0.25–0.69 µm for both liquid and ice clouds so as to be comparable to the CM SAF satellite retrieved COT at 0.6 µm (see Sect. 2.2). Following the approach of Cess (1985), to derive the bulk COT for the whole atmospheric column, the COTs calculated for each layer are simply added. The total COT for each layer is calculated by merging the COT values for liquid and ice clouds.

Within RegCM, CFC at each layer is calculated from relative humidity and cloud droplet radius. The surface radiation flux in RegCM4 is calculated separately for the clear and cloud covered part of the sky. The total CFC for each model grid-cell is an intermediate value between the one calculated using the random overlap approach, which leads to a maximum cloud cover, and the one found by assuming a full overlap of the clouds appearing in different layers, which minimizes cloud cover. As discussed in Giorgi et al. (2012), this approach allows for a more realistic representation of surface radiative fluxes.

2.2 CM SAF satellite data

To evaluate the RegCM4 SSR simulations described previously, we use high resolution satellite data from the SIS (Surface Incoming Shortwave radiation) product of CM SAF. The datasets were obtained from EUMETSAT's MFG (DOI:10.5676/EUM_SAF_CM/RAD_MVIRI/V001) and MSG (DOI:10.5676/EUM_SAF_CM/CLAAS/V001) geostationary satellites. SSR data are available from 1983 to 2005 from six Meteosat First Generation satellites (Meteosat 2–7) and from 2005 onwards from Meteosat Second Generation satellites (Meteosat 8–10). These satellites fly at an altitude of $\sim$ 36 000 km, being located at longitudes around 0° above the equator and covering an area extending from 80° W to 80° E and from 80° S to 80° N. In the case of MFG satellites, the SSR data are retrieved from measurements with the Meteosat Visible and Infrared Instrument (MVIRI) sensor. MVIRI is a radiometer that takes measurements at 3 spectral bands (visible, water vapor, infrared) every 30 min. SSR is retrieved using MVIRI's broadband visible channel (0.45–1 μm) only, at a spatial resolution of ~ 2.5 km (at the sub-satellite point). The data are afterwards re-gridded at a $0.03^{\circ} \times 0.03^{\circ}$ regular grid.

The MagicSol–Heliosat algorithm, used for the derivation of the SSR data analyzed in this work, has been extensively described in several papers (see Posselt et al., 2011a, b, 2012, 2014; Mueller et al., 2011; Sanchez-Lorenzo et al., 2013). The algorithm includes a modified version of the original Heliosat method (Beyer et al., 1996; Cano et al., 1986). Heliosat utilizes the digital counts obtained from the visible channel to calculate the so-called effective cloud albedo. The modified version incorporates the determination of the monthly maximum normalized digital count (for each MVIRI sensor) that serves as a self-calibration parameter. To derive the clear-sky background reflection, a 7 day running average of the minimum normalized digital counts is used instead of fixed monthly mean values. This method minimizes changes appearing in the radiance data recorded by different MVIRI sensors due to the transition from the one Meteosat satellite to the other, ensuring an as much as possible homogeneous dataset. Then, the clear-sky irradiances are derived using the look-up-table based clear-sky model MAGIC (Mueller et al., 2009) and finally SSR is retrieved by combining them with the effective cloud albedo.

On the other hand, MSG satellites carry the Spinning Enhanced Visible and Infrared Imager (SEVIRI), a radiometer taking measurements at 12 spectral bands (from visible to infrared) every 15 min with a spatial resolution of ~ 3 km (at the sub-satellite point). The data used here are available at a $0.05^{\circ} \times 0.05^{\circ}$ regular grid. The SEVIRI broadband high-resolution visible channel (HRV) which is very close to MVIRI's broadband visible channel cannot be used for the continuation of the SSR dataset, since, unlike MVIRI, it does not cover the full earth's disk. On the other hand, the use of one of the SEVIRI's narrow band visible channels directly in the same algorithm as MVIRI (MagicSol) is not feasible, first of all, because of the spectral differences with MVIRI's broadband visible channel, and second, because of the sensitivity of cloud albedo to spectral differences of the land surfaces below the clouds (especially for vegetated areas) (see Posselt et al., 2011a, 2014). In this case, an artificial SEVIRI broadband visible channel that corresponds to MVIRI's broadband visible channel is simulated following the approach of Cros et al. (2006). SEVIRI's two narrow band visible channel (0.6 and 0.8 µm) and MVIRI's broadband channel spectral characteristics are used to establish a simple linear model. This model is afterwards applied to SEVIRI's 0.6 and 0.8 µm radiance measurements to calculate the broadband visible channel radiance (see Posselt et al., 2014, for more details).

The CM SAF SSR satellite-based product is characterized by a threshold accuracy of 15 $W m^{-2}$ for monthly mean data and 25 $W m^{-2}$ for daily data (Mueller et al., 2011; Posselt et al., 2012, 2014; Sanchez-Lorenzo et al., 2013). Posselt et al. (2012) evaluated CM SAF SSR data on a daily and monthly basis against ground-based observations from 12 BSRN (Baseline Surface Radiation Network) stations around the world, showing that both daily and monthly CM SAF data are below the target accuracy for $\sim$ 90 % of the stations. Specifically for Europe, Sanchez-Lorenzo et al. (2013) using monthly SSR data from 47 GEBA (Global Energy Balance Archive) ground stations proceeded to a detailed validation of the CM SAF SSR dataset for the period 1983–2005. They found that CM SAF slightly overestimates SSR by 5.2 $W m^{-2}$ (4.4 % in relative values). Also, the mean absolute bias was found to be 8.2 $W m^{-2}$ which is below the accuracy threshold of 15 $W m^{-2}$ (10 $W m^{-2}$ for the CM SAF retrieval accuracy and 5 $W m^{-2}$ for the surface measurements uncertainties). Applying the Standard Normal Homogeneity Test (SNHT) Sanchez-Lorenzo et al. (2013) revealed that the MFG SSR data over Europe can be considered homogeneous for the period 1994–2005. Recently, Posselt et al. (2014) verified the results of the previous two studies by using a combined MFG-MSG SSR dataset spanning from 1983 to 2010. They found that the monthly mean dataset exhibits a mean absolute bias of 8.15 $W m^{-2}$ compared to BSRN which is again below the accuracy threshold of CM SAF. Also, the dataset was found to be homogeneous for the period 1994–2010 in most of the investigated regions except for Africa.

To investigate the differences appearing between the RegCM4 and CM SAF SSR fields we also use CFC, COT and Re CM SAF observations from MSG satellites for the period 2004–2009. A description of this cloud optical properties product, also known as CLAAS (CLoud property dAtAset using SEVIRI), can be found in Stengel et al. (2014). The MSG NWC software package v2010 is used for the detection of cloudy pixels, the determination of their type (liquid/ice) and their vertical placement (Derrien and Le Gléau, 2005; NWC-SAF, 2010). The detection of cloudy pixels is based on a multispectral threshold method incorporating parameters such us illumination (e.g. daytime, twilight, night-time, sunglint) and type of surface. According to Kniffka et al. (2014), the CM SAF Cloud Mask accuracy is $\sim 90\,\%$ (successful detection of cloudy pixels for $\sim 90\,\%$ of the cases) when evaluated against satellite data from CALIOP/CALIPSO and CPR/CloudSat. The bias of the CFC product was found to be 2 and 3 % for SEVIRI's when compared to ground-based data from SYNOP (lidar-radar measurements) and satellite-based data from MODIS, respectively (Stengel et al., 2014). The Cloud Physical Properties (CPP) algorithm (Roebeling et al., 2006; Meirink et al., 2013) is used to retrieve COT at 0.6 µm, Re and CWP. The algorithm is based on the use of SEVIRI's spectral measurements at the visible (0.64 µm) and near infrared (1.63 µm) (Nakajima and King, 1990). First, COT and Re are retrieved for the cloudy pixels and then CWP is given by the following equation:

$$\mathrm{CWP}_{\mathrm{ph}} = 2/3\rho_{\mathrm{ph}}\mathrm{Re}_{\mathrm{ph}}\mathrm{COT}_{\mathrm{ph}} \tag{8}$$

where ph stands for the clouds' phase (liquid/ice) and ρ is the density of water. According to Stengel et al. (2014), the CM SAF COT bias was estimated at -9.9 % compared to MODIS observations. The corresponding bias for CWP is -0.3 % for liquid phase clouds and -6.2 % for ice phase clouds. COT and CWP data are available from CM SAF at a spatial resolution of $0.05^\circ \times 0.05^\circ$ on a daily basis. In this work, Re values were calculated from the COT and CWP CM SAF available data using Eq. (8).

2.3 Other data

In addition to the CM SAF SSR and cloud optical properties data used for the evaluation of RegCM4, we also use ancillary data from other sources, namely, AOD, ASY and SSA at 550 nm monthly climatological values from the MACv1 climatology (Kinne et al., 2013), monthly climatological broadband surface shortwave fluxes retrieved from CERES sensors aboard EOS TERRA and AQUA satellites for a 14 year period starting from 3/2000 (Kato et al., 2013) and finally monthly mean total column WV data from ECMWF's ERA-Interim reanalysis (Dee et al., 2011) for the period 2006–2009. All the data were obtained at a spatial resolution of $1^{\circ} \times 1^{\circ}$. It has to be highlighted that these data are similar to the ones used as input within the MAGIC clear sky radiative transfer code (Mueller et al., 2009) which is used for the calculation of CM SAF SSR. Therefore, they can be used in order to examine the reasons for possible deviations appearing between RegCM4 and CM SAF SSR (see Sect. 2.4). To our knowledge, the uncertainty of the MACv1 aerosol parameters used here has not been reported somewhere in detail. However, due to the methodology followed for the production of the MACv1 climatology, the MACv1 data are consistent with the AERONET ground network. The CERES broadband surface albedo over land exhibits a relative bias of -2.4 % compared to MODIS. Specifically, over deserts, the relative bias drops to -2.1 % (Rutan et al., 2009). A detailed evaluation of the ERA-Interim WV total column product does not exist. Only recently, the upper troposphere-lower stratosphere WV data were evaluated against airborne campaign measurements showing a good agreement (30 % of the observations were almost perfectly represented by the model) (Kunz et al., 2014).

2.4 Methodology

In this study, first, the RegCM4 SSR fields are evaluated against SSR fields from CM SAF (MFG for 2000–2005 and MSG for 2006–2009) for the European region (box region in Fig. S1). Prior to the evaluation, the model and satellite data are averaged on a monthly basis and brought to a common $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution. It has to be mentioned that the same temporal and spatial resolution was used for all the data utilized in this study.

Maps with the normalized mean bias (NMB) (hereafter denoted as bias) are produced on an annual and seasonal basis. NMB is given by the following equation:

$$\text{NMB} = \frac{\sum_{i=1}^{N}(\text{RegCM}_i - \text{CMSAF}_i)}{\sum_{i=1}^{N}\text{CMSAF}_i} 100\,\% = \left(\frac{\overline{\text{RegCM}}}{\overline{\text{CMSAF}}} - 1\right) 100\,\% \tag{9}$$

where RegCM_i and CMSAF_i represent the RegCM4 and CM SAF mean values for each month i, N is the number of months and $\overline{\text{RegCM}}$, $\overline{\text{CMSAF}}$ are the RegCM4 and CM SAF mean values. The statistical significance of the results at the 95 % confidence level is checked by means of a two independent sample t test:

$$t = (\overline{\text{RegCM}} - \overline{\text{CMSAF}}) / \sqrt{\left(\sigma^2_{\text{RegCM}} + \sigma^2_{\text{CMSAF}}\right)/N} \tag{10}$$

where σRegCM and σCMSAF are the standard deviations of RegCM4 and CM SAF total means. When $|t|$ is greater than a critical value that depends on the degrees of freedom (here $2n-1$) the bias is considered statistically significant. In addition to the whole European region (EU), the land covered (LA) and ocean covered (OC) part of Europe, seven other sub-regions are defined for the generalization of our results: Northern Europe (NE), Central Europe (CE), Eastern Europe (EE), Iberian Peninsula (IP), Central Mediterranean (CM), Eastern Mediterranean (EM) and Northern Africa (NA) (see Figs. 1a and S1). The bias on an annual and seasonal basis is calculated per region. Apart from bias, other statistical metrics (correlation coefficient R, normalized standard deviation NSD, modified normalized mean bias MNMB, root mean square error RMSE) are also defined, calculated and presented in the Supplement of this manuscript. The latitudinal variability of model and satellite-based SSR is examined by means of seasonal plots. Finally, the seasonal variability of SSR from RegCM4 and CM SAF and their differences is investigated for each of the 10 regions mentioned above. The same procedure is done separately for MFG data (2000–2005) and MSG data (2006–2009) to see if the two datasets lead to similar results. Our results are mostly focused on MSG satellite-based observations, since CFC and cloud optical properties data are only available from MSG SEVIRI.

In order to interpret the observed differences between RegCM4 and CM SAF SSR, the same detailed procedure is repeated for CFC and COT for the period 2004–2009. CFC and COT are the two major determinants of the transmission of shortwave radiation through clouds (Gupta et al., 1993) and along with AOD constitute the major controllers of SSR (Kawamoto and Hayasaka, 2008). Therefore, we also proceed to a detailed comparison of RegCM4 AOD at 550 nm (AOD_{550}) against MACv1 climatological data. However, other cloud (Re) and aerosol (ASY, SSA) related parameters also play a significant role. Here, RegCM4 Re is evaluated against observational data from CM SAF while RegCM4 ASY and SSA are compared against climatological data from MACv1 (see Supplement). Specifically, the comparison of RegCM4 data with MACv1 does not constitute an evaluation of the RegCM4 aerosol-related parameters, like in the case of the cloud-related parameters above, since, MACv1 data (Kinne et al., 2013) are climatological (based on a combination of models and observations) and not pure observational data. However, a similar climatology (Kinne et al., 2006) is used for the production of CM SAF SSR (Trentmann et al., 2013). In addition, Mueller et al. (2014) showed that the use of MACv1 aerosol climatology instead of the Kinne et al. (2006) climatology does not affect significantly the CM SAF SSR product. Hence, this comparison allows us to reach useful conclusions about the effect of aerosol representation within RegCM4 on the simulated SSR fields by the model. The same stands for the comparison of RegCM4 ALB data with climatological data from CERES satellite sensors and RegCM4 WV data with WV data from ERA-Interim reanalysis (see Supplement). The CERES ALB 14 year climatology is temporally constant, similar to the CERES climatology used for the production of CM SAF SSR (Trentmann et al., 2013). Finally, the ERA-Interim WV data used here are the same with the WV data incorporated by the radiative scheme of CM SAF. Unlike the RegCM4 evaluation results, the comparison results discussed in this paragraph are presented in the Supplement.

Apart from a qualitative approach, we also proceed to a quantitative study of the reasons that lead to deviations between the RegCM4 and CM SAF SSR. Using data from RegCM4 and CM SAF and the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi et al., 1998), we estimate the potential relative contribution of the parameters CFC, COT, Re, AOD, ASY, SSA, ALB and WV to the percent RegCM4-CM SAF SSR difference (ΔSSR), over the 7 sub-regions mentioned above. ΔSSR is given by Eq. (11), expressing the percentage of SSR deviation caused by the observed difference between RegCM4 and CM SAF for each parameter (p). First, a SBDART simulation is implemented with a 3 h timestep for the 15th day of each month (Ming et al., 2005) using monthly mean RegCM4 data as input (control run) for each region. The average of all the timesteps per month expresses the monthly SSR flux ($\mathrm{SSR}_{\mathrm{control}}$). The SSR fields simulated with SBDART are almost identical to the RegCM4 SSR fields. This indicates that SBDART indeed can be used to study the sensitivity of RegCM4's radiative scheme to various parameters. Then, several SBDART simulations are implemented in the same way, replacing each time only one of the aforementioned input parameters with corresponding values from CM SAF, MACv1 or ERA-Interim ($\mathrm{SSR}(p)$). $\mathrm{SSR}_{\mathrm{control}}$ and $\mathrm{SSR}(p)$ are then used in Eq. (11) to calculate ΔSSR for each month (i) and parameter (p).

$$\Delta\mathrm{SSR}^{i}(p) = 100\left(\mathrm{SSR}^{i}_{\mathrm{control}} - \mathrm{SSR}^{i}(p)\right)/\mathrm{SSR}^{i}_{\mathrm{control}} \quad (11)$$

The results of this analysis are presented by means of bar plots for each sub-region. In addition, a method like the one introduced by Kawamoto and Hayasaka (2008, 2010, 2011), which is based on the calculation of the sensitivities of SSR on CFC, COT, AOD and WV, was also implemented with similar results (not shown here).

3 Results and discussion

3.1 Surface solar radiation

As discussed above, first, we examine the CM SAF and RegCM4 bias patterns for the MFG (2000–2005) and MSG (2006–2009) periods, separately. This work focuses on the MSG dataset, since, cloud properties data which are used in order to investigate the reasons of the observed bias between CM SAF and RegCM4 at a later stage, are only available from MSG. However, we investigate both periods to examine if the observed biases are valid for the whole simulation period and ensure that there are no differences when using the one or the other dataset. As shown in Fig. S2a and b, the annual bias patterns are similar for both MFG-RegCM4 and MSG-RegCM4. The main feature is a low negative bias over land and a low positive bias over ocean. Overall, the RegCM4 simulations slightly overestimate SSR compared to CM SAF over Europe with a bias of $+1.5\,\%$ in the case of MFG and $+3.3\,\%$ in the case of MSG, while SSR from RegCM4 is much closer to SSR from CM SAF over land (bias of $-1.6\,\%$ for MFG and $+0.7\,\%$ for MSG) than over ocean (bias of $+7.2\,\%$ for MFG and $+8.1\,\%$ for MSG). These values can be found in Table 2 for the RegCM4-MSG period along with the corresponding values for the 7 sub-regions of interest appearing in Fig. 1a while the same values for the RegCM4-MFG period can be found in Table S1 of the Supplement. It has to be highlighted, that hereafter, only results for the MSG CM SAF SSR dataset are presented within the paper while the results for the MFG dataset are included in the Supplement.

As presented in Fig. 1, some differences appear in the seasonal bias patterns. A strong positive bias is observed during winter over Northern Europe. For the rest of the regions the winter patterns are very close to the spring and the annual patterns. Contrary to the annual patterns, in summer, the positive bias extends over Europe until the latitudinal zone of 50° N, while in autumn the bias patterns are pretty similar with the annual ones. In winter, the RegCM4 simulations overestimate SSR compared to CM SAF for the whole European domain, the bias being $+3.9\,\%$. Over land the bias is nearly zero ($+0.1\,\%$) while over ocean there is a significant bias of $+11.3\,\%$. As shown in Fig. 1a, NE is by far the sub-region with the strongest bias ($+52.4\,\%$). The seasonal and annual model and satellite-derived values with the corresponding biases and their statistical significance at the 95 % confidence level according to a two independent sample t test appear in Table 2. The latitudinal variability of RegCM4 SSR, CM SAF SSR and their difference is presented in Fig. 2a. Overall, RegCM4 slightly overestimates SSR at latitudes lower than $\sim 40^{\circ}$ N, then a negligible difference between RegCM4 and CM SAF is observed until the latitudinal zone of $\sim 52^{\circ}$ N, while, a significant difference is observed for higher latitudes. In spring, a zero bias is observed between the model and CM SAF for Europe. When discriminating between land and ocean covered regions a negative bias is observed over land ($-2.9\,\%$) and a positive over ocean ($+5.2\,\%$). The regions with the highest negative bias are NE ($-14.2\,\%$), EE ($-13.5\,\%$) and CE ($-9.1\,\%$), while the regions with the highest positive bias are NA ($+8.4\,\%$), CM ($+7.9\,\%$) and EM (+6.7 %) (see Table 1). This is also reflected in Fig. 2b where RegCM4 clearly overestimates SSR for latitudes less than $\sim 44^\circ$ N, significantly underestimating SSR thereafter. In summer, a positive bias of $+6.2\,\%$ is calculated for the whole European domain, the bias being $+4.4\,\%$ over land and $+9.4\,\%$ over ocean. As seen in Table 2, the bias is positive for all the sub-regions ranging from $+2.3\,\%$ (EE) to $+10.4\,\%$ (CM) except for NE ($-9.4\,\%$). RegCM4 clearly overestimates SSR for latitudes less than $\sim 55^\circ$ N and underestimates SSR for higher latitudes (Fig. 2c). A positive bias of $+2.4\,\%$ is found for Europe in autumn with the corresponding values being $-0.9\,\%$ over land and $+8.4\,\%$ over ocean covered regions. EE ($-9.8\,\%$) and CE ($-7.2\,\%$) are the regions with the strongest negative bias while the regions with the strongest positive bias are the ones at the south, namely, NA ($+5.5\,\%$), CM ($+5.3\,\%$) and EM ($+5.0$) (see also Table 2). This is also seen in Fig. 2d where RegCM4 overestimates SSR for latitudes less than $\sim 42^\circ$ N.

The seasonal variability of RegCM4 SSR, CM SAF SSR and their difference for the whole European domain, for the land and ocean covered part of Europe as well as for the 7 subregions of interest are presented in Fig. 3a–j. For Europe as a whole, the largest difference between RegCM4 and CM SAF SSR is observed in summer, July being the month with the highest RegCM4-CM SAF difference ($20.3\,\mathrm{W\,m^{-2}}$). Over land, the difference between RegCM4 and CM SAF SSR is nearly zero for winter and autumn months. During spring, in March and April, RegCM4 underestimates SSR while in summer SSR is overestimated, especially in July. On the contrary, over ocean, SSR is overestimated by RegCM4 for the total of the months. The highest RegCM4-CM SAF differences are observed during the warm period (May–September). Over NE, RegCM4 underestimates SSR for the months from March to September and overestimates SSR during the winter months. The seasonal variability of the difference between RegCM4 and CM SAF is pretty similar over CE and EE. The simulations underestimate SSR in spring (especially during April) and autumn and overestimate SSR in summer. Over IP, SSR is overestimated again in May and during the summer and underestimated in February, March, November and December. For CM and EM, the seasonal variability of the difference between RegCM4 and CM SAF is almost identical. RegCM4 significantly overestimates SSR from April to October while for the rest of the months the difference is nearly zero. Finally, over NA, the seasonal variability of the difference is close to the one appearing over CM and EM, but here, SSR is overestimated by RegCM4 also in March.

3.2 Cloud fractional cover

CFC plays a determinant role for the SSR levels. Therefore, we compare the CFC patterns simulated with RegCM4 against CFC patterns from MSG CM SAF for the common period 2004–2009. Overall, CFC is underestimated by RegCM4 over Europe by 24.3 % on annual basis (13.7 % over land and 38.4 % over ocean) despite the fact that over specific regions (e.g. within IP and NA) CFC is overestimated (see Table 3). Underestimation is observed for the total of the four seasons, NA being the only region with a bias of +8.1 % in winter and a bias of +13.1 % in autumn (see Table S3). As shown in Fig. 4a–d, the underestimation of CFC from RegCM4 is stronger over ocean especially in summer, while strong overestimation is observed over regions in western NA in winter and spring, eastern NA in summer and the whole NA during autumn. The latitudinal variability of RegCM4 CFC, CM SAF CFC and their difference is presented in Fig. 5. A clear, strong underestimation of CFC from RegCM4 is observed for all the latitudinal bands and seasons apart from latitudes around 30° N where CFC is slightly overestimated in autumn. The seasonal variability of RegCM4 CFC, CM SAF CFC and their difference for the whole European domain, for the land and ocean covered part of Europe and for the 7 sub-regions of interest are presented in Fig. 6a–j. CFC is underestimated steadily by RegCM4 throughout a year, the underestimation being much stronger over the ocean than over land (see Fig. 6b and c). This underestimation is observed for all the sub-regions except for NA where CFC is underestimated from April to September and overestimated for the rest of the months.

Generally, lower CFCs would lead to higher SSR levels. However, a comparison of the SSR bias patterns appearing in Fig. 1a–d with the CFC bias patterns appearing in Fig. 4a–d and also of the biases appearing in Tables 1 and S3 reveals that for some areas and seasons the RegCM4-CM SAF SSR deviations cannot be explained through the corresponding CFC deviations (e.g. land covered regions during spring and autumn). This is in line with the findings of Katragkou et al. (2015) where the WRF-ISCCP SSR deviations could not always be attributed to CFC deviations. As discussed there the role of microphysical cloud properties should also be taken into account. Following this, in the next paragraph we go a step further, taking into account the effect of COT.

3.3 Cloud microphysical properties

3.3.1 Cloud optical thickness

COT is a measure of the transparency of clouds and along with CFC determines the transmission of shortwave radiation through clouds (Gupta et al., 1993). In this paragraph, the RegCM4 COT patterns are compared against COT patterns from MSG CM SAF for the common period 2004–2009. Overall, COT is overestimated by RegCM4 over Europe by 4.3 % on annual basis, the bias being positive over land (+7.3 %) but negative over ocean (−2.5 %) (see Table 3). In addition, COT bias varies with seasons, being positive in spring and autumn and negative in winter and summer (see Table S5). As shown in Fig. 7a–d, positive biases are mostly observed over land covered regions of CE, EE and NE and negative biases over NA and the regions around the Mediterranean Sea. In fact, there is a strong latitudinal variability of the RegCM4-CM SAF COT difference for all the seasons as presented in Fig. 8a–d. RegCM4 underestimates COT for latitudes below $\sim 45^{\circ}$ N in winter, spring and autumn and for latitudes below $\sim 50^{\circ}$ N in summer. The seasonal variability of RegCM4 COT, CM SAF COT and their difference for the whole European domain, for the land and ocean covered part of Europe and for the 7 sub-regions of interest are presented in Fig. 9a–j. In general, the RegCM4-CM SAF COT difference is not steadily positive or negative but varies from month to month over both land and ocean. RegCM4 steadily overestimates COT throughout a year only over NE and underestimates COT over CM and NA. It has to be highlighted that there are no COT retrievals over NE for December and January due to a limited illumination at that latitudes during this period of the year. This is also the reason for the missing grid cells appearing in the top-right corner of Fig. 7a–d.

A comparison of the SSR bias patterns appearing in Fig. 1a–d with the CFC (Fig. 4a–d) and the COT (Fig. 7a–d) bias patterns reveals that COT could explain part of the RegCM4-CM SAF SSR deviations that could not be explained through CFC (e.g. NE, CE, EE). The same conclusions can be reached by comparing the seasonal variability of SSR, CFC and COT over the region of interest (see Figs. 3, 6 and 9). However, other parameters are expected to be responsible for the remaining unexplained RegCM4-CM SAF SSR deviation.

3.3.2 Cloud effective radius

Re is a microphysical optical property expressing the size of cloud droplets in the case of liquid clouds and the size of ice crystals in the case of ice clouds. Re of liquid (Rel) and ice (Rei) clouds plays a critical role in the calculation of the optical thickness of clouds as well as their albedo (see Eqs. 4–7 in Sect. 2.1). The evaluation of RegCM4 Rel and Rei against observational data from CM SAF reveals a significant underestimation over the whole European domain (bias of $-36.1\,\%$ for Rel and $-28.3\,\%$ for Rei). In the case of ice clouds, the biases over land and ocean do not differ significantly. On the contrary, for liquid clouds, the bias over land is more than double the bias over ocean (see Table 3). This is due to the very low RegCM4 Rel values appearing over land while the CM SAF dataset does not exhibit such a land-ocean difference. A possible explanation for this could be the fact that for liquid clouds a different approach is used over land (constant Rel of $10\,\mu m$) and ocean (Eq. 1) while for ice clouds the parameterization is the same for land and ocean (Eq. 2). The fact that the average Rel value over land ($5.65 \pm 1.06\,\mu m$) is very close to the lowest Rel boundary ($5\,\mu m$) according to Eq. (1), possibly points towards an underestimation of the liquid cloud height and vertical development. Also, this Rel land-ocean difference is in charge of the COT land-ocean difference (see Table 3) according to Eq. (4). In general, the underestimation of Re would result into more reflective clouds and hence into underestimated SSR levels. It has to be mentioned here that the monthly variability of RegCM4 Rel and Rei, CM SAF Rel and Rei and their difference for the whole

European domain, for the land and ocean covered part of Europe and for the 7 sub-regions are presented in the Supplement of this manuscript. A constant underestimation of Rel and Rei is observed for the whole Europe (see Figs. S6 and S8).

3.4 Aerosol optical properties

As discussed in Sect. 2.4, AOD along with CFC and COT constitute the major controllers of SSR. A comparison of the RegCM4 AOD_{550} seasonal patterns with climatological AOD_{550} values from MACv1 is presented in Fig. S10a–d. On an annual basis, RegCM4 overestimates AOD over the region of NA (bias of +25.0 %) (see Table 3). The overestimation is very strong during winter being much weaker in spring and autumn (see Table S9). This overestimation over regions affected by dust emission has been discussed comprehensively in Nabat et al. (2012) and has to do with the dust particle size distribution schemes utilized by RegCM4 (Alfaro and Gomes, 2001; Kok, 2011). Nabat et al. (2012) showed that the implementation of Kok (2011) scheme generally reduces the dust AOD overestimation in RegCM4 over the Mediterranean basin. However, a first climatological comparison of RegCM4 dust AODs with data from CALIOP/CALIPSO (A. Tsikerdekis, personal communication, 2015) has shown that both schemes overestimate dust AOD over Europe and therefore the selection of a specific dust scheme is not expected to change drastically our results. On the contrary, AOD is significantly underestimated over the rest of the domain. This should be expected as RegCM does not account for several types of aerosols, anthropogenic (e.g. nitrates, ammonium and secondary organic aerosols, industrial dust) and natural (e.g. biogenic aerosols) which potentially play an important role (Kanakidou et al., 2005; Zanis et al., 2012). This overestimation/underestimation dipole in winter, spring and autumn is also reflected in Fig. S11. RegCM4 overestimates AOD for latitudes below $\sim 40^\circ$ N in winter, for latitudes below $\sim 35^\circ$ N in spring and for a narrow latitudinal band ($\sim$ 30–33° N) in autumn. In summer, RegCM4 steadily underestimates AOD compared to MACv1. The seasonal variability of RegCM4 AOD_{550}, MACv1 AOD_{550} and their difference for the whole European domain, for the land and ocean covered part of Europe and for the 7 sub-regions of interest are presented in Fig. S12a–j. In general, RegCM4 clearly underestimates AOD throughout a year over regions that are not affected heavily by Sahara dust transport. This underestimation would cause an overestimation of SSR if all the other parameters were kept constant. The opposite stands for the region of NA where AOD, except for summer, is significantly overestimated.

As in the case of COT and Re, in order to fully assess the contribution of aerosols to the observed RegCM4-CM SAF SSR deviations, one has to take into account ASY and SSA apart from AOD. A comparison of RegCM4 ASY and SSA with climatological values from MACv1 reveals a small underestimation from RegCM4 over Europe (bias of −1.1 and −4.2 % respectively). While SSA is underestimated for the total of the investigated subregions, in some cases ASY is slightly overestimated (see Table 3). This is apparent in Figs. S13 and S15 where the RegCM4-CM SAF NMB maps are presented along with the latitudinal variability of the two products.

3.5 Other parameters

Apart from the major (CFC, COT, AOD) and minor (Re, ASY, SSA) SSR determinants which are discussed above in detail, there are also a number of other parameters that could impact the simulation skills of RegCM4 compared to CM SAF, since these parameters are used as input within the radiative scheme of the model.

As it was previously discussed, WV is another parameter that affects the transmission of solar radiation within the atmosphere. RegCM4 is found here to overestimate WV compared to ERA-Interim reanalysis all over Europe with a bias of ~ 12 %. This becomes more than obvious when looking into the seasonal and latitudinal variability of the two datasets (see Figs. S17 and S18).

In line with the study of Güttler et al. (2014), RegCM4 exhibits a significant underestimation of ALB over CE, EE and NA (see Table 3) compared to climatological data from CERES (see Sect. 2.3). In general, there is a striking difference between land and ocean covered regions (Figs. S19 and S20). Over land RegCM4 underestimates ALB by 28.3 % while over ocean ALB is strongly overestimated by 131 %. As it was previously highlighted, the comparisons of RegCM4 with non-observational data presented in this paragraph do not constitute an evaluation of RegCM4. However, these comparisons give us an insight into how several parameters affect the ability of RegCM4 to simulate SSR.

3.6 Assessing the effect of various parameters on RegCM's SSR

As discussed in detail in Sect. 2.4, the contribution of each one of the aforementioned parameters in the deviation between RegCM4 and CM SAF SSR is assessed quantitatively with the use of SBDART radiative transfer model. The results of this analysis are presented in Fig. 10. The percent contribution of each parameter to the RegCM4-CM SAF SSR difference is calculated on a monthly basis. Results for NE are not included in this manuscript, since COT and Re are not available from CM SAF during winter (December, January) and also due to the low insolation levels for several months at high latitudes.

As seen in Fig. 10a, the percent RegCM4-CM SAF SSR difference (ΔSSR) over CE is mostly determined by CFC, COT and AOD. However, for specific months, Re and the other parameters also play an important role leading to an underestimation of SSR. The effect of CFC ranges from a significant SSR underestimation (ΔSSR of $-23.6\,\%$ for April) to a significant SSR overestimation (ΔSSR of $+10.0\,\%$ for June). Apart from July, COT leads to an underestimation of SSR, April being the month with the highest underestimation (ΔSSR of $-13.3\,\%$). AOD on the other hand, leads to an overestimation of SSR over CE ranging from $+4.6\,\%$ (June) to $+9.5\,\%$ (January).

In line with CE, ΔSSR over EE is mostly determined by CFC, COT and AOD (Fig. 10b). Apart from April, CFC leads to an overestimation of SSR, December being the month with the highest overestimation ($+22.9\,\%$). Apart from June and July, COT causes an underestimation of SSR, March/August being the month with the highest/lowest underestimation (-15.8/$-0.2\,\%$). On the other hand, AOD leads to an overestimation of SSR the whole year, December/May being the month with the highest/lowest overestimation ($+12.3$/$+4.2\,\%$). Re also plays a role leading to an underestimation of SSR, that ranges from $-1.06\,\%$ (July) to $-2.5\,\%$ (February). All the other parameters play a minor role, generally leading to an underestimation of SSR.

Over IP, despite the fact that the dominant parameters are CFC and COT, for some months AOD, SSA and Re contribute substantially in ΔSSR (Fig. 10c). CFC leads to an overestimation of SSR, January/September being the month with the highest/lowest overestimation of SSR (+9.1/+1.1 %). COT causes an important overestimation of SSR from April to October (e.g. +3.7 % in June) and a significant underestimation during March (−2.8 %). On the other hand, Re leads to an underestimation of SSR that ranges from −1.3 % in April to −0.3 % in August. The same stands for SSA with an average annual SSR underestimation of −1.2 %, while AOD exhibits a mixed behavior leading to either underestimation (a maximum of −6.1 % in December) or overestimation (a maximum of +4.9 % in March).

As seen in Fig. 10d, ΔSSR over CM is mostly determined by CFC, COT, AOD and SSA. CFC causes a significant overestimation of SSR ranging from +3.2 % (July) to +11.9 % (December). COT leads to an overestimation of SSR on an annual basis, October being the month with the highest overestimation (+4.6 %). AOD causes an overestimation of SSR over CM for the period from March to October (average ΔSSR of +2.2 %) and an underestimation during winter (average ΔSSR of −2.3 %). SSA on the other hand, causes an underestimation of SSR on an annual basis ranging from −0.5 % (July) to −1.9 % (December).

ΔSSR over EM is dominated by the relative contribution of CFC, AOD and COT (see Fig. 10e). CFC causes an overestimation of SSR on an annual basis ranging from +1.7 % (August) to +12.2 % (December). Apart from February, AOD causes a significant overestimation ranging from +0.5 % (March) to +6.0 % (September). Apart from March, COT leads to an overestimation of SSR, February being the month with the highest overestimation (+4.3 %). SSA also plays a role, in some cases comparable in magnitude to that of COT or AOD (e.g. January, March).

Over NA ΔSSR is largely determined by AOD, SSA and COT (Fig. 10f). AOD causes a significant underestimation of SSR during the period from November to April (a maximum of −15.3 % for February) and an overestimation from June to September (a maximum of +3.9 % for July). COT leads to a significant SSR overestimation on an annual basis ranging from +1.3 % (June) to +4.8 % (September). SSA leads to a significant underestimation of

SSR, January being the month with the highest underestimation (ΔSSR of −3.7 %). Important is the contribution of ALB which also causes an SSR underestimation on annual basis (average ΔSSR of −1.0 %). It has to be highlighted here, that due to the high insolation levels over the region of NA, the ΔSSR values correspond to higher absolute RegCM4-CM SAF SSR deviations than in regions at higher latitudes. Also, the low cloud coverage in the region leads to an update of the role of aerosol related parameters as shown in Fig. 10f.

Concluding, for the total of the six sub-regions, CFC and AOD are the most important factors that determine the SSR overestimation by RegCM4 on an annual basis. The underestimation of CFC and AOD by the model causes an annual overestimation of SSR by 4.8 % and 2.6 %, respectively.

4 Conclusions

In the present study, a decadal simulation (2000-2009) with the regional climate model RegCM4 is implemented in order to assess the model's ability to represent the SSR patterns over Europe. The RegCM4 SSR fields are evaluated against satellite-based observations from CM SAF. The annual bias patterns of RegCM4-CM SAF are similar for both MFG (2000-2005) and MSG (2006-2009) observations. The model slightly overestimates SSR compared to CM SAF over Europe, the bias being +1.5 % for MFG and +3.3 % for MSG observations. Moreover, the bias is much lower over land than over ocean while some differences appear locally between the seasonal and annual bias patterns.

In order to understand the RegCM4-CM SAF SSR deviations, CFC, COT and Re data from RegCM4 are compared against observations from CM SAF (MSG period). For the same reason, AOD, ASY, SSA, WV and ALB from RegCM4 are compared against data from MACv1, ERA-Interim reanalysis and CERES since these data are similar to the ones used as input in the retrieval of CM SAF SSR.

CFC is significantly underestimated by RegCM4 compared to CM SAF over Europe by 24.3 % on annual basis. Part of the bias between REGCM4 and CM SAF SSR can be explained through CFC with the underestimation of CFC leading to a clear overestimation of SSR. It was also found that RegCM4 overestimates COT compared to CM SAF on an annual basis suggesting that COT may explain part of the RegCM4-CM SAF SSR deviations that could not be explained through CFC over specific regions. In addition, RegCM4 underestimates significantly Rel and Rei compared to CM SAF over the whole European domain on an annual basis. A comparison of the RegCM4 AOD seasonal patterns with AOD values from the MACv1 aerosol climatology reveals that RegCM4 overestimates AOD over the region of NA and underestimates it for the rest of the European domain. ASY and SSA are slightly underestimated by the model. The comparison of RegCM4 WV against data from ERA-Interim reanalysis, reveals a clear overestimation over Europe. In line with previous studies, RegCM4 underestimates ALB significantly over CE, EE and NA compared to climatological data from CERES with a striking difference between land and ocean.

The combined use of SBDART radiative transfer model with RegCM4, CM SAF, MACv1, CERES and ERA-Interim data for the common period 2006–2009 shows that the difference between RegCM4 and CM SAF SSR is mostly explained through CFC, COT and AOD deviations. In the majority of the regions, CFC leads to an overestimation of SSR by RegCM4. In some cases, COT leads to an underestimation of SSR by RegCM4, while for the majority of the regions leads to an overestimation. Apart from NA, where AOD leads to a significant underestimation of RegCM4 SSR, AOD is generally responsible for the overestimation of SSR. The other parameters (Re, ASY, SSA, WV and ALB) play a less significant role, except for NA where they have a significant impact on the RegCM4-CM SAF SSR deviations. Overall, CFC and AOD are the major determinants of the SSR overestimation by RegCM4 on an annual basis. The underestimation of CFC and AOD by the model causes an annual overestimation of SSR by 4.8 % and 2.6 %, respectively.

Overall, it is shown in this study that RegCM4 simulates adequately the SSR patterns over Europe. However, it is also shown that the model overestimates or underestimates significantly several parameters that determine the transmission of solar radiation in the atmosphere. The good agreement between RegCM4 and satellite-based SSR observations from CM SAF is actually a result of the contradicting effect of these parameters. Our results suggest that there should be a reassessment of the way these parameters are represented within the model so that SSR is not only well simulated but also for the right reasons. This would also allow for a safer investigation of the dimming/brightening effect since the SSR deviations would be safely dedicated to the one or the other parameter. It is suggested here that a similar approach should be implemented in the future to the same or other regional climate models with various setups also utilizing new satellite products (e.g. CM SAF SARAH).

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Table 1. List of the parameters being analyzed in this work, their sources, the original resolution at which the data were acquired and the corresponding time periods.

Parameter	Source	Resolution	Period
SSR	CM SAF MFG	0.03° x 0.03°	2000–2005
SSR	CM SAF MSG	0.05° x 0.05°	2006–2009
CFC	CM SAF MSG	0.05° x 0.05°	2004–2009
COT	CM SAF MSG	0.05° x 0.05°	2004–2009
Re	CM SAF MSG	0.05° x 0.05°	2004–2009
AOD	MACv1	1° x 1°	Climatology
ASY	MACv1	1° x 1°	Climatology
SSA	MACv1	1° x 1°	Climatology
ALB	CERES	1° x 1°	Climatology
WV	ERA-Interim	1° x 1°	2006-2009
All above	RegCM4	50km x 50 km	2000-2009

Table 2. Average RegCM4 SSR and CM SAF SSR (MSG SEVIRI) with their standard deviations ($\pm 1\sigma$) and the corresponding Normalized Mean Bias (NMB) per season and region. When the difference between RegCM4 and CM SAF SSR is statistically significant at the 95 % confidence level due to a two independent sample t test, the NMB values are marked with bold letters while in the opposite case they are marked with an asterisk. Positive NMBs are italic while negative NMBs are underlined. ANN corresponds to annual, DJF to winter, MAM to spring, JJA to summer and SON to autumn results.

	ANN			DJF			MAM		
	MOD	SAT	bias	MOD	SAT	bias	MOD	SAT	bias
EU	175.0 ± 106.5	169.3 ± 96.7	***3.3***	77.1 ± 57.1	74.2 ± 57.2	***3.9***	206.8 ± 83.0	206.7 ± 67.0	0.0*
LA	173.1 ± 106.9	171.9 ± 97.2	***0.7***	78.1 ± 61.0	78.0 ± 60.8	0.1*	202.7 ± 85.7	208.7 ± 68.6	**−2.9**
OC	178.2 ± 105.6	164.9 ± 95.7	***8.1***	75.3 ± 49.7	67.7 ± 49.8	***11.3***	213.8 ± 77.8	203.2 ± 64.2	***5.2***
NE	104.0 ± 81.2	113.7 ± 93.4	**−8.5**	19.3 ± 12.0	12.7 ± 16.8	***52.4***	137.6 ± 53.4	160.4 ± 60.8	**−14.2**
CE	134.5 ± 89.2	136.1 ± 83.1	**−1.2**	42.3 ± 20.8	42.8 ± 24.4	−1.1*	158.1 ± 55.6	174.0 ± 51.3	**−9.1**
EE	132.3 ± 92.0	139.5 ± 89.8	**−5.2**	37.5 ± 17.5	38.8 ± 22.1	**−3.4**	155.2 ± 61.2	179.4 ± 57.7	**−13.5**
IP	197.9 ± 95.1	194.7 ± 84.4	***1.7***	91.7 ± 26.9	98.6 ± 27.5	**−7.0**	224.8 ± 56.5	224.0 ± 46.3	0.4*
CM	209.8 ± 98.6	195.1 ± 85.1	***7.5***	97.3 ± 29.1	96.7 ± 27.1	0.6*	243.7 ± 59.2	225.9 ± 46.2	***7.9***
EM	219.3 ± 101.6	205.6 ± 90.3	***6.7***	105.1 ± 36.8	101.8 ± 33.7	***3.3***	251.4 ± 68.8	235.6 ± 54.4	***6.7***
NA	261.8 ± 82.3	243.8 ± 69.5	***7.4***	164.7 ± 35.2	161.8 ± 31.9	***1.8***	303.8 ± 41.3	280.2 ± 33.7	***8.4***

	JJA			SON		
	MOD	SAT	bias	MOD	SAT	bias
EU	281.6 ± 70.6	265.2 ± 55.2	***6.2***	126.3 ± 77.4	123.3 ± 71.3	***2.4***
LA	278.6 ± 71.7	267.0 ± 55.0	***4.4***	124.9 ± 79.0	126.1 ± 72.8	**−0.9**
OC	286.7 ± 68.2	262.1 ± 55.3	***9.4***	128.7 ± 74.5	118.6 ± 68.4	***8.4***
NE	198.7 ± 45.5	219.4 ± 43.3	**−9.4**	52.9 ± 38.2	53.4 ± 44.3	−1.0*
CE	245.6 ± 47.9	228.9 ± 38.2	***7.3***	84.4 ± 46.8	90.9 ± 48.2	**−7.2**
EE	248.4 ± 44.9	242.8 ± 36.5	***2.3***	80.1 ± 46.0	88.8 ± 48.8	**−9.8**
IP	317.5 ± 29.1	296.3 ± 32.3	***7.2***	148.6 ± 53.9	151.8 ± 50.4	**−2.1**
CM	331.3 ± 27.3	299.9 ± 25.1	***10.4***	157.7 ± 53.5	149.8 ± 45.4	***5.2***
EM	339.3 ± 29.1	312.8 ± 28.1	***8.5***	171.8 ± 63.0	163.7 ± 55.9	***5.0***
NA	353.5 ± 20.5	320.5 ± 21.7	***10.3***	217.2 ± 49.5	205.8 ± 39.7	***5.5***

Table 3. Annual Normalized Mean Bias (NMB) of RegCM4-CM SAF CFC, COT, Rel and Rei, RegCM4-MACv1 ASY and SSA, RegCM4-CERES ALB and RegCM4-ERA-Interim WV. When the difference between RegCM4 and CM SAF or CERES or ERA-Interim is statistically significant at the 95 % confidence level due to a two independent sample t test, the NMB values are marked with bold letters while in the opposite case they are marked with an asterisk. Positive NMBs are italic while negative NMBs are underlined. The regions are listed in alphabetical order.

	CFC	COT	Rel	Rei	AOD	ASY	SSA	ALB	WV
EU	**–24.3**	***4.3***	**–36.1**	**–28.3**	**–35.3**	**–1.1**	**–4.2**	***1.6***	***12.0***
LA	**–13.7**	***7.3***	**–47.7**	**–26.4**	**–32.1**	**–1.8**	**–4.3**	**–28.3**	***11.4***
OC	**–38.4**	**–2.5**	**–18.3**	**–31.1**	**–42.0**	***0.1***	**–4.1**	***131.1***	***12.8***
NE	**–20.3**	***54.3***	**–32.8**	**–31.3**	**–75.9**	***1.0***	**–5.6**	***5.2***	***13.1***
CE	**–19.7**	***24.1***	**–45.1**	**–24.0**	**–63.6**	*0.0**	**–5.9**	**–22.7**	***14.0***
EE	**–16.0**	***30.9***	**–44.6**	**–24.2**	**–64.6**	***2.1***	**–3.5**	**–40.7**	***10.8***
IP	**–13.7**	**–13.9**	**–46.1**	**–27.3**	**–7.4**	**–1.5**	**–4.8**	**–3.8**	***14.4***
CM	**–31.2**	**–30.7**	**–26.7**	**–27.6**	**–19.3**	**–0.7**	**–3.5**	***85.9***	***10.4***
EM	**–28.8**	**–22.0**	**–29.3**	**–28.4**	**–34.2**	**–0.0**	**–2.3**	***35.4***	***10.9***
NA	*0.4**	**–39.8**	**–47.3**	**–30.0**	***25.0***	**–7.9**	**–3.5**	**–26.4**	***8.7***

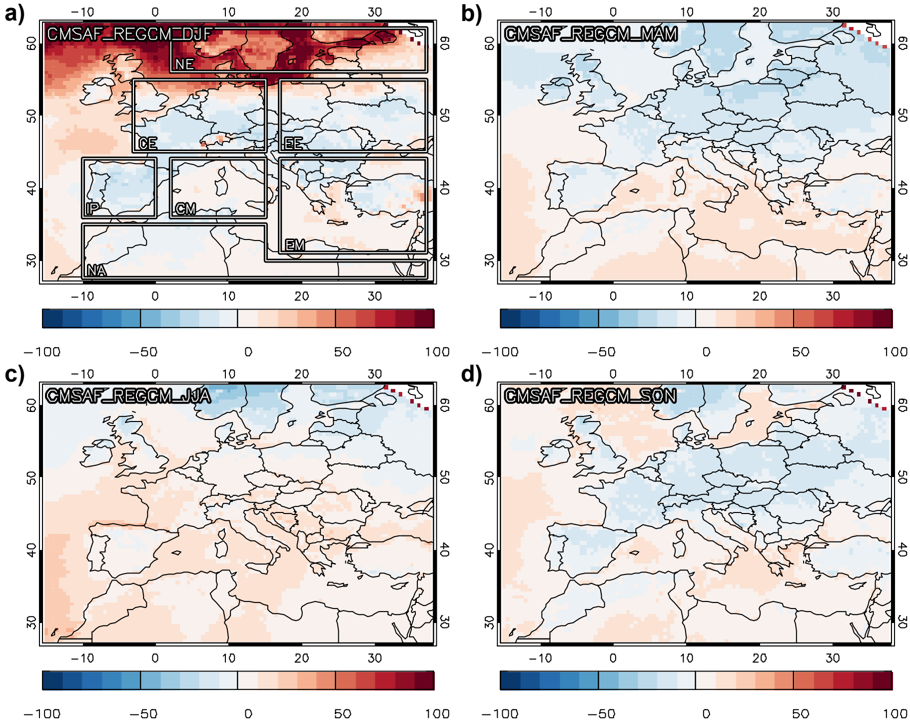

Figure 1. Seasonal NMB patterns of RegCM4-CM SAF SSR over Europe for **(a)** winter (DJF), **(b)** spring (MAM), **(c)** summer (JJA) and **(d)** autumn (SON) from MSG SEVIRI observations. The 7 sub-regions used for the generalization of the results are marked in Fig. 1a: Northern Europe (NE), Central Europe (CE), Eastern Europe (EE), Iberian Peninsula (IP), Central Mediterranean (CM), Eastern Mediterranean (EM) and Northern Africa (NA).

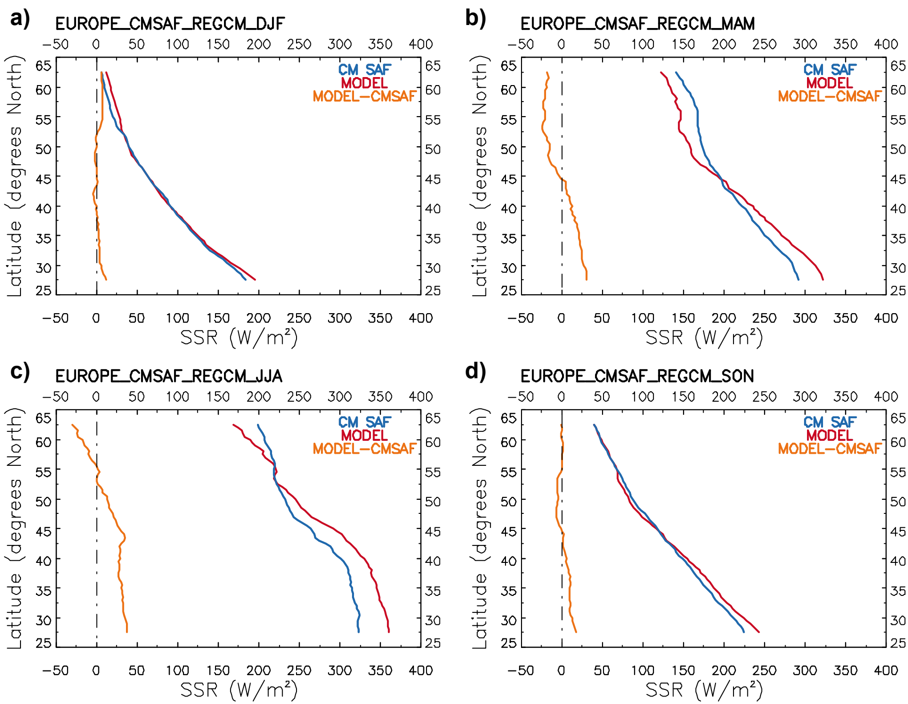

Figure 2. Latitudinal variability of RegCM4 SSR (red), CM SAF SSR (blue) and their difference (orange) over Europe for **(a)** winter (DJF), **(b)** spring (MAM), **(c)** summer (JJA) and **(d)** autumn (SON) from MSG SEVIRI observations.

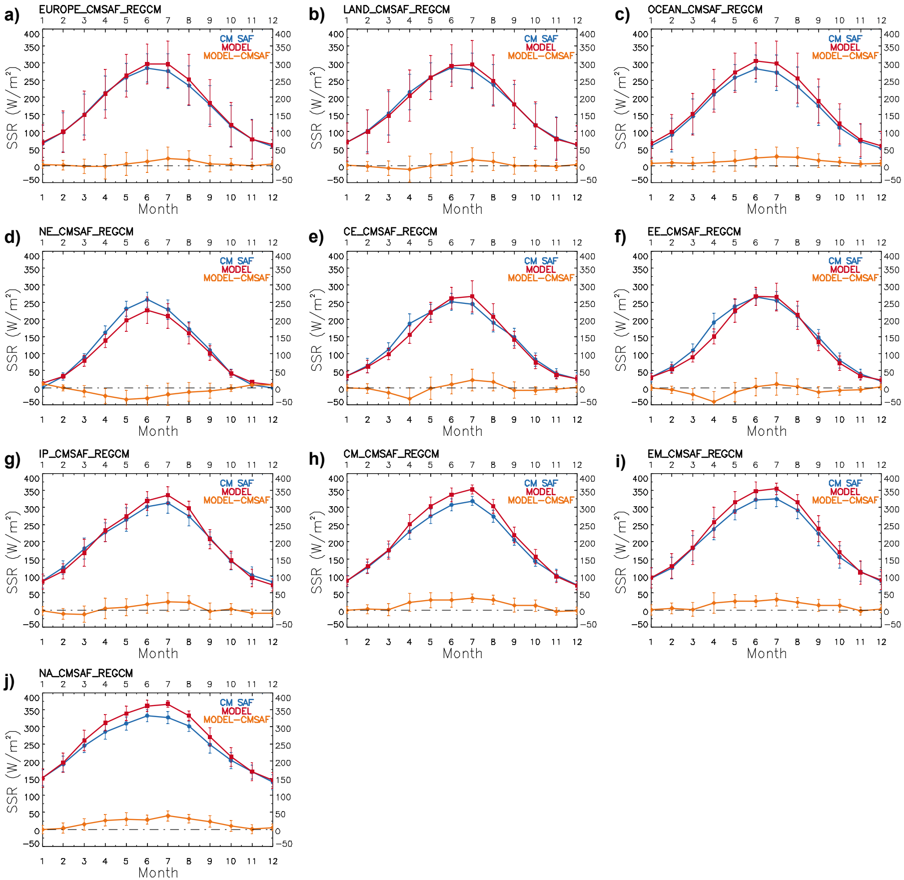

Figure 3. Seasonal variability of RegCM4 SSR (red), CM SAF SSR (blue) and their difference (orange) over **(a)** the whole Europe, **(b)** Land, **(c)** Ocean, **(d)** NE, **(e)** CE, **(f)** EE, **(g)** IP, **(h)** CM, **(i)** EM, **(j)** NA from MSG SEVIRI observations.

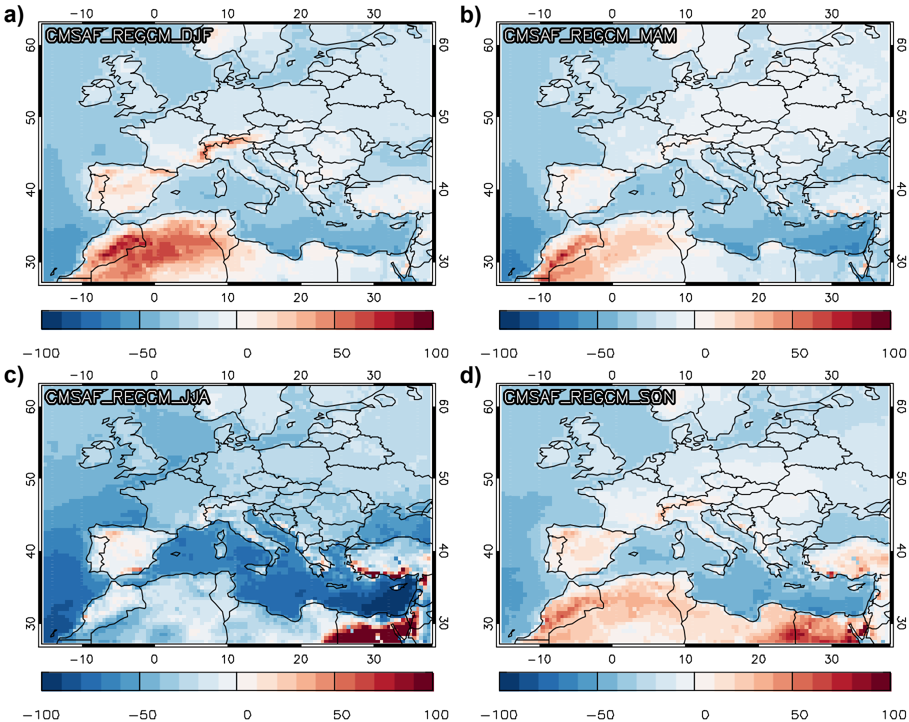

Figure 4. The same as Fig. 1 but for RegCM4 and CM SAF CFC.

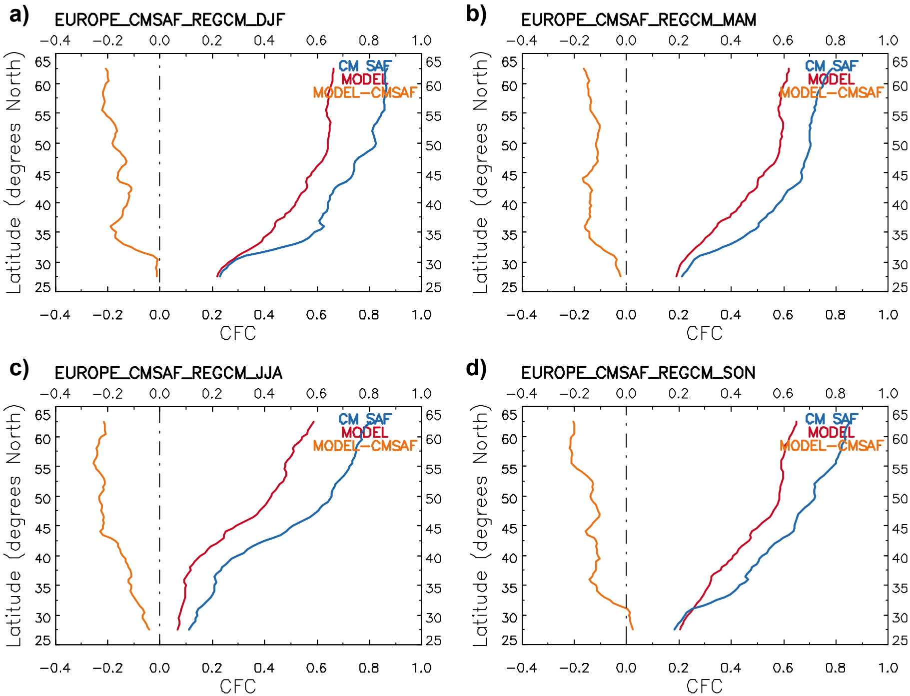

Figure 5. The same as Fig. 2 but for RegCM4 and CM SAF CFC.

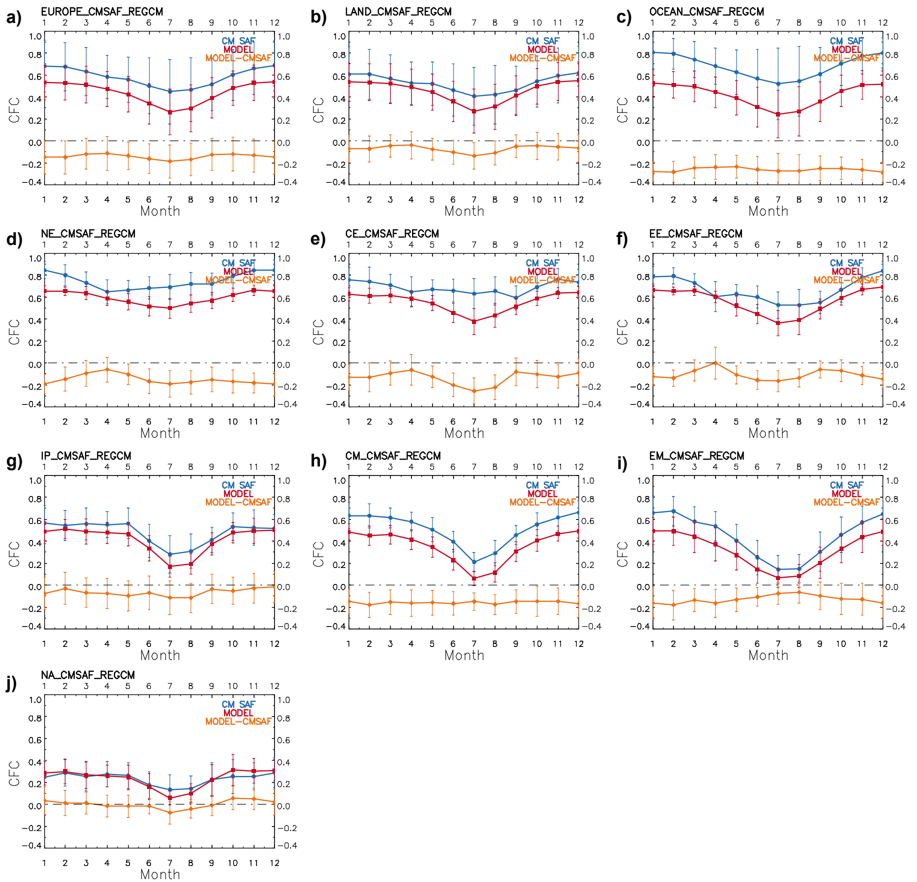

Figure 6. The same as Fig. 3 but for RegCM4 and CM SAF CFC.

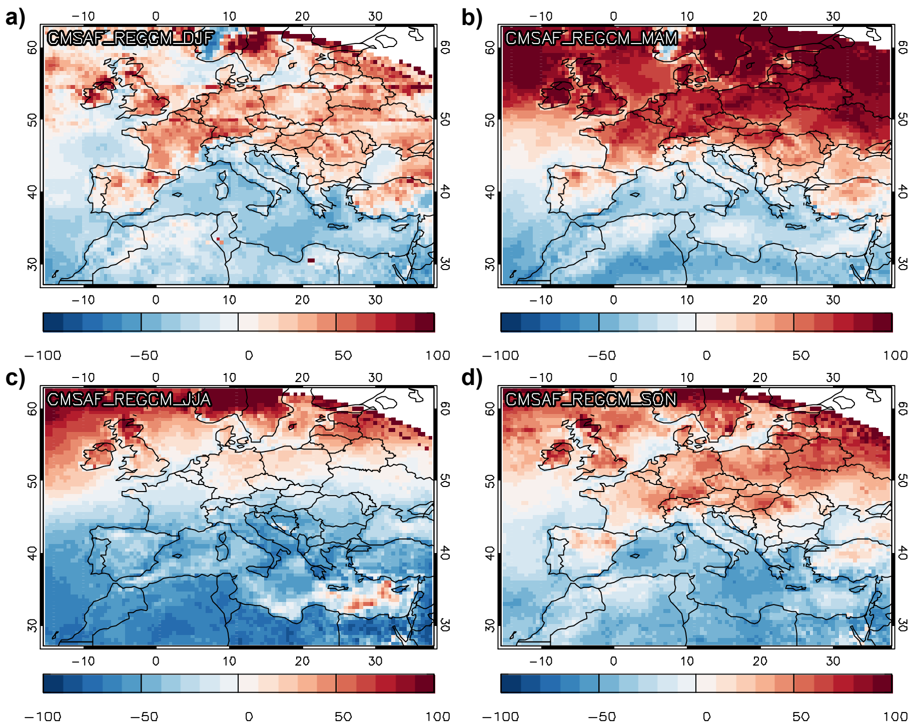

Figure 7. The same as Fig. 1 but for RegCM4 and CM SAF COT.

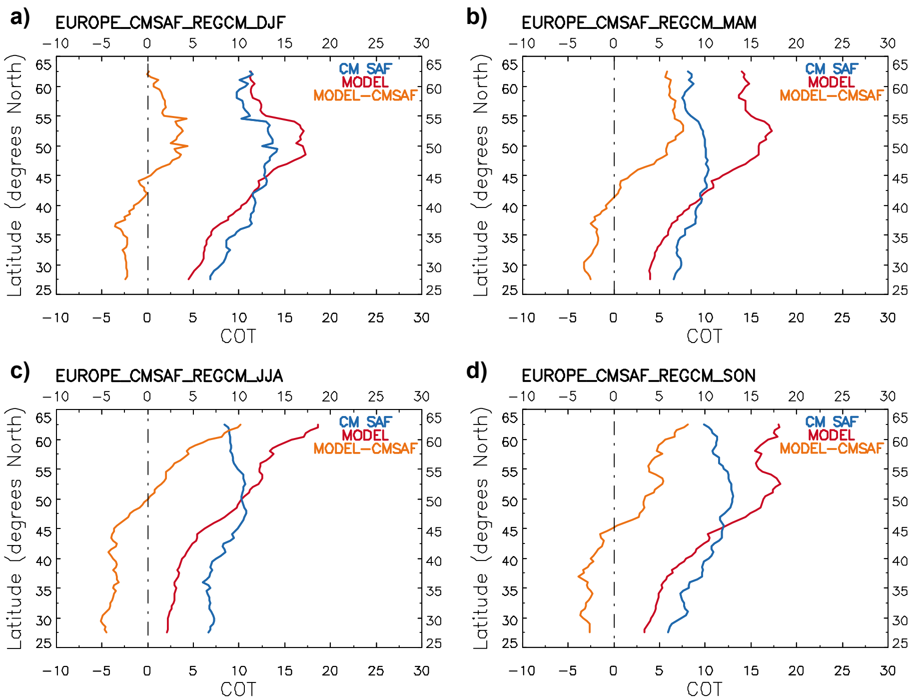

Figure 8. The same as Fig. 2 but for RegCM4 and CM SAF COT.

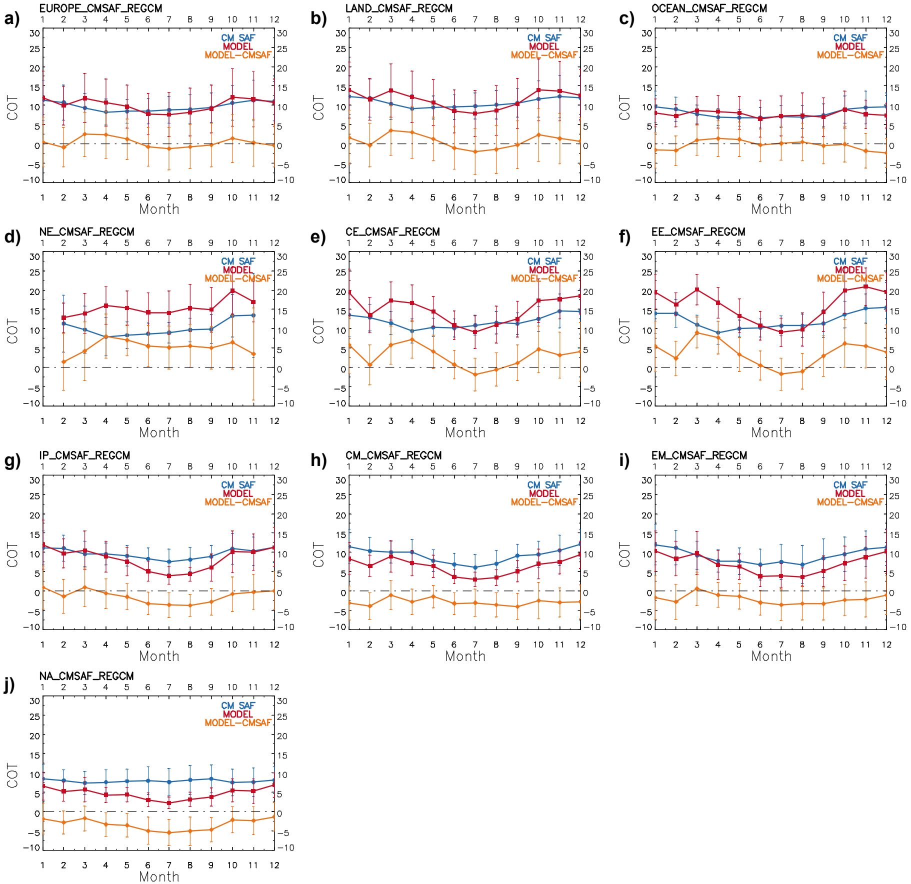

Figure 9. The same as Fig. 3 but for RegCM4 and CM SAF COT.

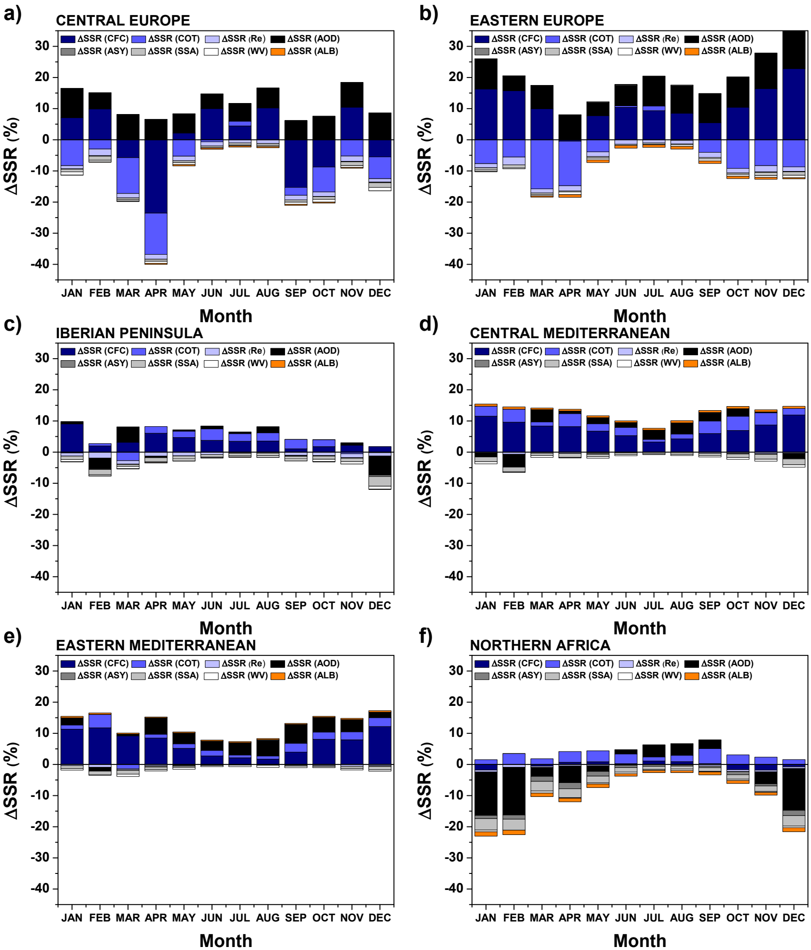

Figure 10. ΔSSR (%) caused by CFC, COT, Re, AOD, ASY, SSA, WV and ALB for **(a)** CE, **(b)** EE, **(c)** IP, **(d)** CM, **(e)** EM and **(f)** NA.