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Key Points:
- A regional climate system model over the Euro-Mediterranean includes aerosols
- Aerosol changes are needed to reproduce observed climate trends since 1980
- Aerosols play an essential role in the brightening and warming since 1980

Correspondence to:
P. Nabat,
pierre.nabat@meteo.fr

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Contribution of anthropogenic sulfate aerosols to the changing Euro-Mediterranean climate since 1980

Pierre Nabat[1], Samuel Somot[1], Marc Mallet[2], Arturo Sanchez-Lorenzo[3], and Martin Wild[4]

[1]Météo-France, CNRM-GAME, UMR3589, Toulouse, France, [2]Laboratoire d'Aérologie, UMR5560, Toulouse, France, [3]Department of Physics, University of Girona, Girona, Spain, [4]Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland

Abstract Since the 1980s anthropogenic aerosols have been considerably reduced in Europe and the Mediterranean area. This decrease is often considered as the likely cause of the brightening effect observed over the same period. This phenomenon is however hardly reproduced by global and regional climate models. Here we use an original approach based on reanalysis-driven coupled regional climate system modeling to show that aerosol changes explain 81 ± 16% of the brightening and 23 ± 5% of the surface warming simulated for the period 1980–2012 over Europe. The direct aerosol effect is found to dominate in the magnitude of the simulated brightening. The comparison between regional simulations and homogenized ground-based observations reveals that observed surface solar radiation and land and sea surface temperature spatiotemporal variations over the Euro-Mediterranean region are only reproduced when simulations include the realistic aerosol variations.

1. Introduction

The climate system is strongly influenced by aerosols from natural and anthropogenic sources [*Kaufman et al.*, 2002], through both their direct and indirect effects [e.g., *Charlson et al.*, 1992; *Rap et al.*, 2013]. Recent studies have notably discussed the possible role of anthropogenic aerosols in the North Atlantic climate variability [*Booth et al.*, 2012; *Zhang et al.*, 2013]. Since the 1980s industrialized countries and notably Europe have undergone a dramatic reduction of sulfur and other anthropogenic emissions, due to both new air pollution legislation in many developed countries and economic crises in the 1980s in eastern Europe [*Streets et al.*, 2006]. Besides, *Mishchenko et al.* [2007] have found a global decrease of aerosol optical depth (AOD) between 1991 and 2005. Over the Euro-Mediterranean region, this decrease of about -0.05 decade^{-1} between 1979 and 2009 [*Nabat et al.*, 2013] represents a removal of more than half of the total aerosol content, in line with aerosol variations recently reported by *Chin et al.* [2014]. In parallel, an increase of surface shortwave radiation, referred as the brightening effect, has been observed over the same period, following a widespread dimming of about 30 years [*Gilgen et al.*, 1998; *Wild et al.*, 2005]. Over Europe, these decadal variations in surface solar radiation (SSR) are found both in clear-sky and cloudy conditions [*Norris and Wild*, 2007; *Wild*, 2009], excluding changes in cloud cover as the only cause, and suggesting a contribution from aerosols [*Wild et al.*, 2005; *Ruckstuhl et al.*, 2008].

From the modeling side, most of the climate models used for the Coupled Model Intercomparison Projects 3 and 5 (CMIP3 and CMIP5) underestimate the SSR trends in cloudy and clear-sky conditions, both for the dimming and brightening periods [*Ruckstuhl and Norris*, 2009; *Allen et al.*, 2013; *Cherian et al.*, 2014], indicating a possible underestimation of aerosol direct radiative forcing or deficiencies in aerosol emission inventories. Differences in interhemispheric temperature trends have also been shown in CMIP3 models [*Wild*, 2012], which underestimate (overestimate) the warming in the brightening (dimming) period.

At the Euro-Mediterranean scale, several regional simulations within the ENSEMBLES EU-project [*Lorenz and Jacob*, 2010] have shown that the simulated temperature trends over the period 1960–2001 were smaller than observed. More recent global [*Folini and Wild*, 2011] and regional [*Zubler et al.*, 2011] simulations in Europe, considering transient or constant aerosol emissions from the 1950s to the 2000s, reveal distinct patterns of dimming and brightening effects for AOD and clear-sky radiation, in line with in situ observations, but diverging results for all-sky SSR because of the influence of clouds. To our knowledge, while many general circulation models hardly reproduce the observed all-sky radiation trend, no regional

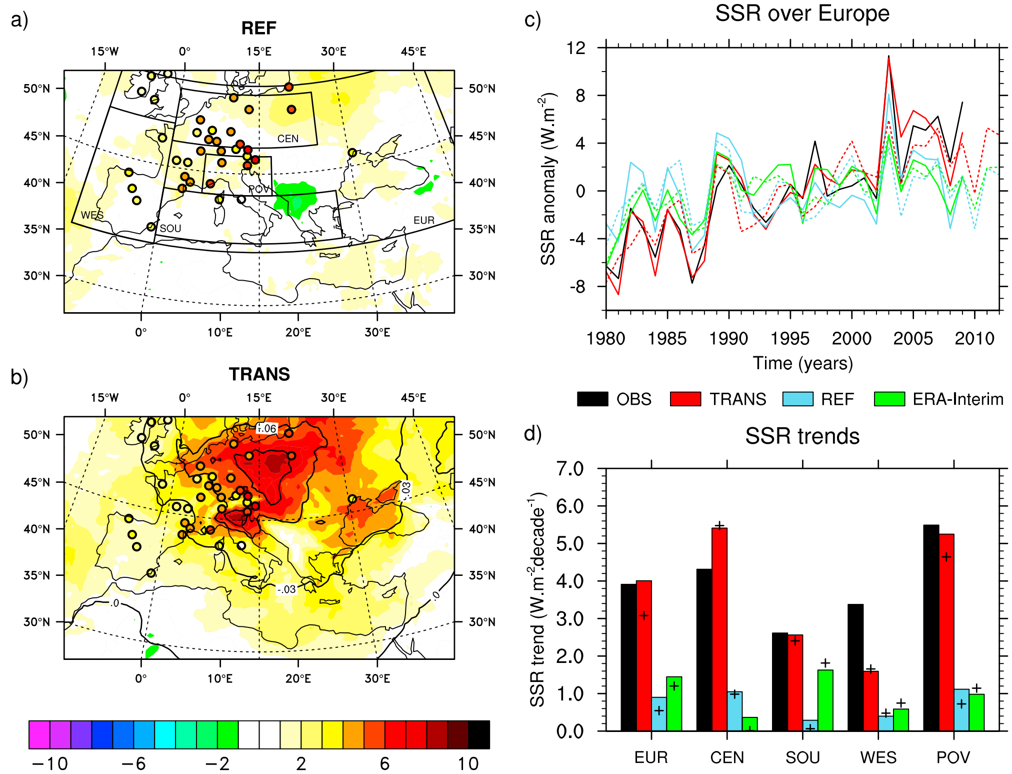

Figure 1. Evaluation of all-sky downward surface solar radiation (SSR) trends. Comparison of annual mean trends in W m^{-2} decade^{-1} for the (a) REF and (b) TRANS simulations over the period 1980–2009. Homogeneous observations from the Global Energy Balance Archive (GEBA) and Spanish network have been added in colored points; AOD trends (decade^{-1}) are indicated by the contour lines in Figure 1b; (c) SSR annual mean series averaged over the locations of the stations (solid lines) for the REF (blue) and TRANS (red) simulations, ERA-Interim (green), and observations (average over all stations) shown as solid black line. SSR annual mean series averaged over entire Europe domain (EUR, defined in Figure 1a) are shown as dotted lines for REF, TRANS, and ERA-Interim. (d) SSR trends averaged over the locations of the stations (bars) contained in different domains defined in Figure 1a (EUR = Europe, CEN = Central Europe, SOU = South Europe, WES = Western Europe, and POV = Po Valley) for the period 1980–2009 and over these whole domains for the period 1980–2012 (black crosses) for the observations, REF and TRANS simulations, and ERA-Interim.

climate simulations have been able to match the observed full-sky brightening and the associated surface temperature trend. It then remains an open challenge in climate modeling, limiting our understanding of the Euro-Mediterranean climate variability.

Here this brightening effect is studied using for the first time an ocean-atmosphere coupled reanalysis-driven regional approach. The aim is to focus on the brightening period in order to estimate the impact of the aerosol decrease since the 1980s on both the decadal variations of SSR and their consequences on land and sea surface temperature over the Euro-Mediterranean region.

2. Methodology

Simulations have been performed with the fully coupled Regional Climate System Model from Météo-France/CNRM named CNRM-RCSM4 [*Nabat et al.*, 2014], including a regional representation of the atmosphere (ALADIN-Climate, 50 km resolution), the land surface (ISBA, 50 km resolution), the ocean (NEMOMED8, 10 km resolution), and the river (TRIP, 50 km resolution) components. Aerosols (five types: sulfate, black carbon, organic matter, desert dust, and sea salt) are included through monthly interannual AOD climatologies [*Nabat et al.*, 2013]. This data set has been built from both satellite-derived (for the total AOD) and model-simulated (for the speciation between the aerosol types) products, in order to obtain the best estimate of the aerosol forcing. More details are available in *Nabat et al.* [2013]. Aerosols are taken into account in the longwave and shortwave radiative scheme using optical properties defined in the same reference. Direct, semidirect, and first indirect radiative forcings are thus taken into account. The first indirect

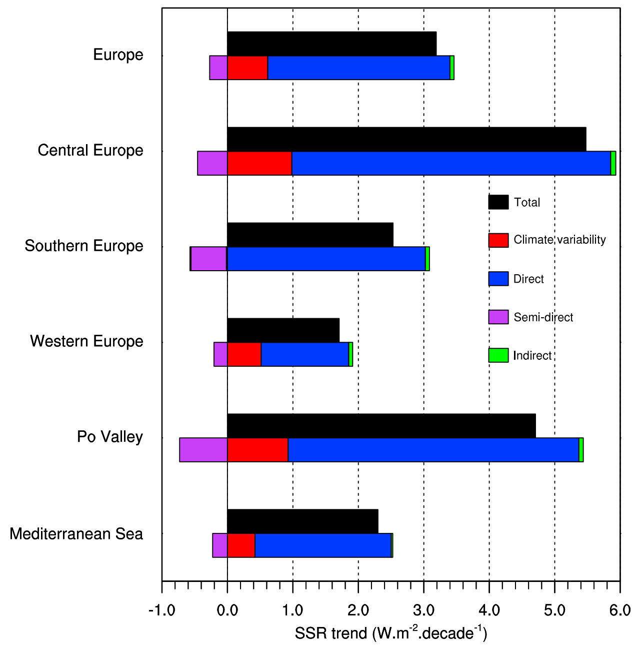

Figure 2. Contribution of climate variability and the different aerosol effects. SSR trends (W m^{-2} decade^{-1}) over the period 1980–2012 for the domains defined in Figure 1a, separated between climate variability and aerosol effects (direct, semidirect, and indirect).

effect consists in representing the relationship between sulfate aerosols and the concentration and radius of the cloud droplets [*Quaas and Boucher*, 2005]. Two simulations, TRANS and REF, respectively, with and without time-varying AOD over the period 1980–2012, have been carried out using CNRM-RCSM4 driven by the ERA-Interim reanalysis [*Dee et al.*, 2011] in terms of wind, temperature, humidity, and surface pressure. The AOD for each aerosol type in the REF simulation is provided by the average of the corresponding AOD from the climatology over the 2003–2009 period. Only sulfate AOD is time varying in TRANS, the four other species have the same AOD as in REF since they have not shown significant trends [*Nabat et al.*, 2013]. Volcanic forcing and the evolution of greenhouse gases (GHG) are also included. Land use and cover do not evolve. More details on the configuration of the model can be found in *Nabat et al.* [2014]. The contribution of direct, semidirect, and indirect effects has been calculated using online diagnostics (for direct effect) and additional simulations without the indirect effect. In order to evaluate downward SSR and temperature, regions have been defined according to contrasts in observed trends (see Figure 1a).

In addition to these simulations, an ensemble of 10 simulations using different initial conditions (without aerosol trend) has been achieved in order to assess the robustness of the results. This ensemble enables to calculate a confidence interval at the level 0.05 using the Student's test: $\pm$ 0.1 W m^{-2}decade^{-1} for the SSR trend and $\pm$0.01°C decade^{-1} for the 2 m temperature trend. Besides, the error on the climate trends also comes from the AOD trend, which has been estimated to -0.05 ± 0.01°C decade^{-1} according to the ensemble of the Atmospheric Chemistry Climate Model Intercomparison Project models used in *Nabat et al.* [2013]. A hypothesis of linearity enables to provide as a consequence a confidence interval of $\pm$ 0.5 W m^{-2}decade^{-1} for the SSR trend and $\pm$ 0.015°C decade^{-1} for the temperature trend. The choice of the regional model is another source of uncertainties, which however requires a multimodel study.

3. Aerosol and Radiation Trends

We first focus on the impact of aerosol variations on SSR. Figure 1 presents the simulated SSR in the REF and TRANS simulations with average trends on different regions, as well as the AOD variations. In TRANS, sulfate AOD evolves as established in the study of *Nabat et al.* [2013] with a strong decrease (between −0.07 and −0.11 decade^{-1}) over Central Europe and the Po Valley, alleviated between −0.02 and −0.06 decade^{-1} in surrounding regions (Figure 1b). Clear-sky downward SSR (not shown), directly depending on aerosols, is constant in REF, while it strongly increases in TRANS (+3.9 W m^{-2} decade^{-1} over Europe), in line with the evolution of AOD, reaching 7.3 W m^{-2} decade^{-1} in Central Europe where AOD trend is −0.07 decade^{-1} . These results are in agreement with previous studies [*Folini and Wild*, 2011; *Zubler et al.*, 2011].

Considering all-sky downward SSR, Figures 1a and 1b also reveal a net contrast between the trends in TRANS and REF. TRANS simulates a significant increase (+3.2 W m^{-2} decade^{-1} over Europe, see Figure 1a for the definition of regional domains), in line with the sulfate AOD decrease. Central Europe (+5.5 W m^{-2} decade^{-1}) and the Po Valley (+4.7 W m^{-2} decade^{-1}) are the most affected regions (locally up to +8.5 W m^{-2} decade^{-1}). On the contrary, REF shows weaker SSR trends, ranging from −2 to +3 W m^{-2} decade^{-1}, linked to natural climate variability driven by ERA-Interim and related cloud cover changes. Despite a slight decrease in cloud

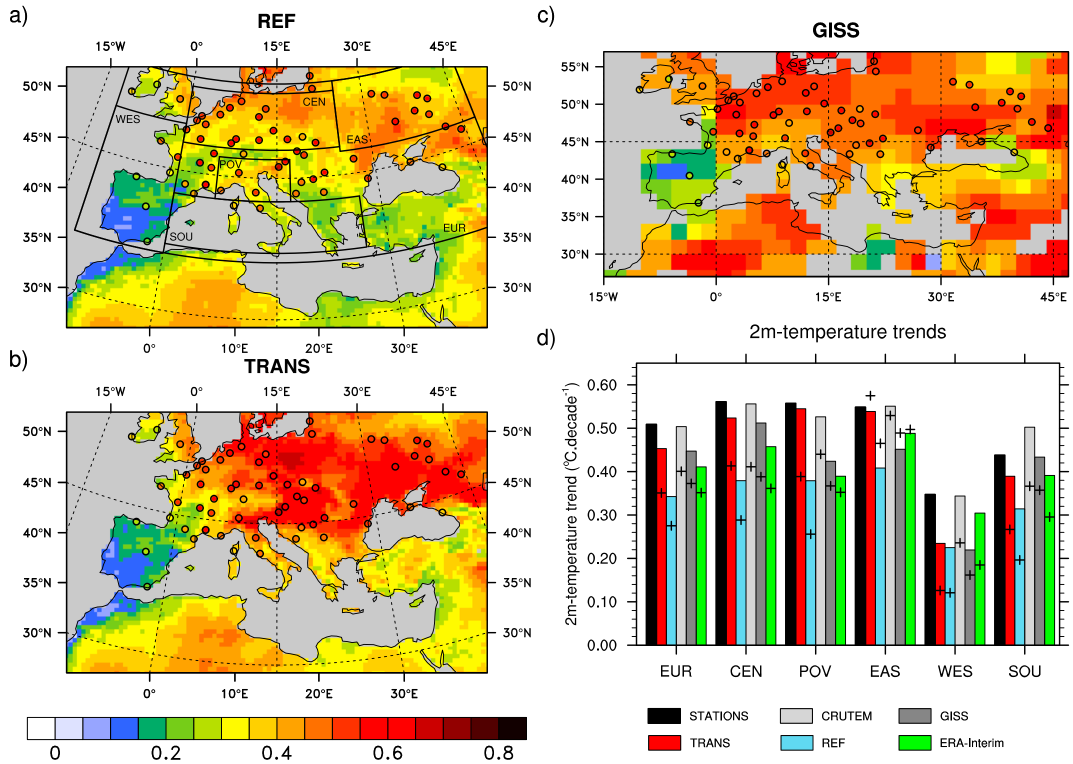

Figure 3. Evaluation of land near-surface temperature trends. Comparison of T2m trends (°C decade^{-1}) over the period 1980–2007 for the (a) REF and (b) TRANS simulations over the period 1980–2007, as well as for (c) Goddard Institute for Space Studies (GISS) analysis. Observations (STATIONS) from the Météo-France, HISTALP, and ECA networks have been added in colored points. (d) T2m trends averaged over the stations (bars) of different domains defined in Figure 3a (EUR = Europe, CEN = Central Europe, POV = Po Valley, EAS = Eastern Europe, WES = Western Europe, and SOU = South Europe) for the period 1980–2007 and over these whole domains for the whole period 1980–2012 (black crosses) for the observations, REF and TRANS simulations, and ERA-Interim.

cover both in REF (−0.3% decade^{-1}) and in TRANS (−0.4% decade^{-1}), the brightening in the all-sky fluxes in TRANS is lower than in the clear-sky fluxes, probably because the direct effect of aerosols is partially masked by the presence of clouds.

Long-term series of observed ground-based SSR from the Global Energy Balance Archive (GEBA) [*Gilgen et al.*, 1998] and Spanish network have recently been homogenized in Europe [*Sanchez-Lorenzo et al.*, 2013a, 2013b]. Compared to these 37 temporal series, both simulations are able to capture observed interannual variability (Figure 1c, correlation coefficient after removal of the trend is 0.90 in both simulations). However, the observed downward SSR trends (+3.9 W m^{-2} decade^{-1} on average for all the stations) are better reproduced at the collocated locations in Europe in TRANS (Figure 1d, +4.0 W m^{-2} decade^{-1}) than in REF (+0.9 W m^{-2} decade^{-1}), as well as ERA-Interim (+1.4 W m^{-2} decade^{-1}) which has no time-varying aerosols but differences in the cloud cover changes. The contrast between the localization of the highest (Central Europe, Po Valley) and lowest trends (British Isles, western France, Southern Europe) is captured only by TRANS (Figure 1). In addition, the spatial correlation between trend values in observations and simulations is significantly improved from 0.10 in REF to 0.42 in TRANS. Uncertainties in the intensity of the aerosol reduction since the 1980s [*Nabat et al.*, 2014] and in the representation of the aerosol effects [*Stier et al.*, 2013], as well as a misrepresentation of the clouds in the model [*Nabat et al.*, 2014], might explain the slight differences in Central and Western Europe. Over Eastern Europe, TRANS (+4.0 W m^{-2} decade^{-1}) also simulates an important brightening compared to REF (+1.4 W m^{-2} decade^{-1}), but the lack of homogenized observed series prevents a proper evaluation in this region. It is worth mentioning that all the differences between TRANS and REF trends are higher than the confidence interval provided by the ensemble spread (0.1 W m^{-2} decade^{-1}), reinforcing the robustness of the results.

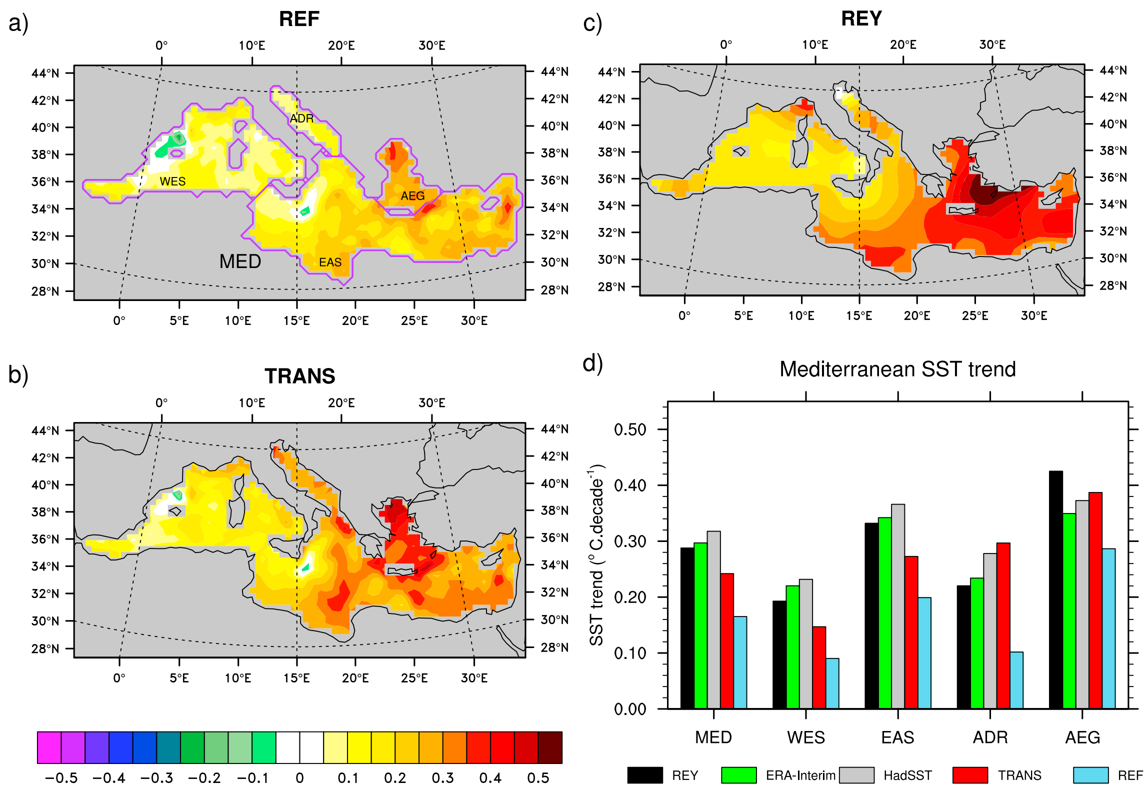

Figure 4. Evaluation of Mediterranean sea surface temperature trends. Comparison of annual mean SST trends in °C decade^{-1} for the (a) REF and (b) TRANS simulations over the period 1982–2012, as well as for the (c) Reynolds (REY) data set. (d) SST trends over the period 1982–2012 averaged over different domains defined in Figure 4a (MED = Mediterranean Sea, WES = Western basin, EAS = Eastern basin, ADR = Adriatic Sea, and AEG = Aegean Sea) for the observations (REY, ERA-Interim, and HadSST) and the REF and TRANS simulations.

Additional simulations without the first indirect effect have been performed to explain the evolution of SSR in different regions (Figure 2). In parallel, a second call to the radiation scheme is used to estimate the direct effect. The SSR trend difference between TRANS and REF is considered as the sum of the direct, the indirect, and the semidirect effects. The climate variability contribution refers to the radiation trend simulated in REF, caused by the evolution in weather conditions (atmospheric dynamics, clouds, …) coming from the lateral boundary forcing (ERA-Interim) that impose the true climate chronology. This constitutes one of the main differences with similar studies performed with general circulation models. Note that the observed evolution of greenhouse gases is also included in both simulations. The climate variability contribution remains weak (+0.6 W m^{-2} decade^{-1} over Europe) compared to the total SSR trend. The three other terms, representing the contribution of the aerosol effects (direct, semidirect, and indirect) caused by the sulfate decrease since 1980, reach 81±16% over Europe. The direct effect, maximal in Eastern and Central Europe in line with aerosol trends, represents the most important part of the trend (87%, +2.8 W m^{-2} decade^{-1} over Europe), while the semidirect and indirect effects have weaker contributions, respectively, −0.4 and +0.1 W m^{-2} decade^{-1} over Europe. The semidirect effect has indeed been shown to be positive over Europe [*Nabat et al.*, 2014] because of circulation changes and related cloud cover changes, so that a decrease in sulfate aerosols explains a decrease in the semidirect forcing. However, the reduction in sulfate particles involves a decrease of the number of cloud droplets at the same humidity (first indirect effect), and consequently a decrease of the cloud albedo and an increase of the solar surface radiation.

4. Aerosols and Climatic Variability

The brightening caused by the sulfate aerosol decrease could also favor an increase of the surface temperature. Figures 3 and 4 present the comparison of both simulations, respectively, in terms of land 2 m temperature (T2m) and Mediterranean sea surface temperature (SST). The warming over the period 1980–2012 is found to be higher in TRANS than in REF for both parameters. In that sense, the aerosol decrease here is an additional contribution to the GHG-induced warming modulated by the climate variability, and it represents 23 ± 5% of the total simulated T2m warming over Europe, as a conservative estimate knowing that the lateral boundaries from both simulations remain unchanged.

The Goddard Institute for Space Studies [GISS, *Hansen et al.*, 2010] and the Climate Research Unit [CRUTEM4, *Jones et al.*, 2012] provide homogenized gridded analyses of T2m built from ground-based measurements. Over the period 1980–2012, the comparison to these homogenized gridded data sets (GISS: 0.37 and CRUTEM4: 0.40°C decade^{-1} over Europe, Figures 3c and 3d) reveals a better agreement in T2m for TRANS (0.35°C decade^{-1}) than for REF (0.28°C decade^{-1}), notably in Italy, Greece, Benelux, the Po Valley, and Turkey. Note that the difference between TRANS and REF is also significative at the level 0.05, as the confidence interval from the ensemble spread is 0.01°C decade^{-1}.

An evaluation of the simulation has also been achieved against ground-based T2m observations from different stations of Météo-France (homogenized time series) [*Dubuisson et al.*, 2014], HISTALP [*Auer et al.*, 2007], and the ECA [*Klein-Tank et al.*, 2002] networks and presented in Figure 3. The improvement brought by the TRANS simulation is confirmed by this comparison to ground-based observations over the common period 1980–2007 (Figure 3d), as the warming simulated by TRANS is closer to these observations than REF. Besides, the spatial correlation coefficient of the trend indeed increases from 0.52 in REF to 0.70 in TRANS. The highest differences between TRANS and REF are found in the regions of maximal AOD decrease (Po Valley, Central, and Eastern Europe, Figure 3d). Note that local land use and cover changes are not included and could explain a part of the discrepancies, notably over Western Europe.

With regards to SST (Figure 4), an increase of the warming is also noticed in TRANS (+0.24°C decade^{-1}) compared to REF (+0.17°C decade^{-1}) over the period 1982–2012, particularly visible in the northeastern basins of the Mediterranean Sea, such as the Ligurian, Adriatic, and Aegean Seas, under the influence of sulfate aerosols in summer. Compared to ERA-Interim (+0.30°C decade^{-1}) and long-term observations (*Reynolds et al.* [2002]: 0.29°C decade^{-1} and HadSST, *Kennedy et al.* [2011]: 0.32°C decade^{-1}) available over the period 1982–2012 (Figures 4c and 4d), a clear improvement in the TRANS simulation can be found for the Mediterranean SST, particularly in these northern basins. In addition, the increase in downward SSR over the Mediterranean Sea, higher in TRANS (+2.3 W m^{-2} decade^{-1}) than in REF (+0.4 W m^{-2} decade^{-1}), is partially balanced by the other terms of the heat budget, notably an increase in the latent heat loss (+2.3 in TRANS against +1.0 W m^{-2} decade^{-1} in REF). However, the simulated averaged SST trend over the Mediterranean Sea remains lower than the observations. A reason could be that in the model SST refers to the uppermost ocean layer [*Nabat et al.*, 2014], namely, the first 6 m, which could be colder and less affected by aerosols than the skin SST observed by satellites.

5. Conclusion Remarks

This study has shown the strong contribution of anthropogenic sulfate aerosols to the regional climate change over Europe and the Mediterranean area over the past three decades. A reanalysis-driven coupled regional approach using CNRM-RCSM4 has been applied for the first time to demonstrate the impact of the sulfate aerosol changes on radiation and temperature decadal variations, by means of two simulations including or discarding the sulfate aerosol decrease. The comparison with homogenized observations has revealed that the brightening effect and the associated warming in land and sea surface temperature can only be simulated when including the sulfate aerosol decrease since 1980. Otherwise, surface radiation and temperature trends are underestimated over the 1980–2012 period. The aerosol effect thus explains 81 ± 16% of the simulated SSR trend, the direct effect representing the highest contribution, and dominates over changes in cloud cover due to climate variability. Aerosol trend has also contributed to 23 ± 5% of the warming in Europe over the 1980–2012 period and significantly to the Mediterranean SST warming. This work suggests that utmost attention should be paid to aerosol evolution in order to assess past and future regional climate change, notably in regions where aerosol loads have recently increased, for example, in China and India [*Lu et al.*, 2011; *Chin et al.*, 2014].

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