An on-line modelling study of the direct effect of atmospheric aerosols over Europe

Laura PALACIOS, Rocío BARÓ, Pedro JIMÉNEZ-GUERRERO
Department of Physics, Regional Campus of International Excellence "Campus Mare Nostrum", Campus de Espinardo, University of Murcia, 30100, Murcia, Spain.
pedro.jimenezguerrero@um.es

Received: 10/04/2015
Accepted: 23/09/2015

Abstract
Atmospheric aerosols affect human health, ecosystems, materials, visibility and Earth's climate. Those effects are studied in this present work and depend mainly on the aerosol optical properties and how they influence the Earth's radiation budget. Such properties can be divided on direct and semi-direct effect, produced by the scattering and absorption of radiation; and indirect effect, which influences the aerosols-cloud interactions. The aim of this work is to assess the direct effect through the study of the mean temperature; the radiation that reaches the Earth's surface and at the top of the atmosphere; and the interaction of these meteorological variables with particulate matter (PM_{10}). Results indicate decreases in temperature and radiation that reaches the Earth's surface, together with increases in the outgoing radiation at top of the atmosphere, and changes in the particulate matter, thus proving a colder climate due to the direct effect of atmospheric aerosols.
Key words: Aerosol, optical properties, scattering, absorption, Earth's radiation budget, direct, semi-direct and indirect effect.

Estudio de modelización on-line del efecto directo de los aerosoles atmosféricos sobre Europa

Resumen
Los aerosoles atmosféricos provocan efectos sobre la salud humana, los ecosistemas, los materiales, la visibilidad y el clima terrestre. Estos últimos efectos son objetos de estudio en el presente trabajo y dependen, principalmente, de las propiedades ópticas de los aerosoles y como éstas influyen en el balance radiativo terrestre. Dichos efectos se pueden dividir en efecto directo y semi-directo, producidos por la dispersión y absorción de la radiación; y efecto indirecto, en el que los aerosoles interaccionan con las nubes. El objetivo principal de este trabajo es evaluar el efecto directo mediante el estudio de las variables medias de temperatura; radiación que llega a la superficie de la Tierra y que sale del tope de la atmósfera; y la interacción de estas variables meteorológicas con la materia particulada (PM_{10}). Los resultados indican descensos en la temperatura y la radiación que llega a la superficie de la Tierra, aumentos en la radiación que sale del tope de la atmósfera y variaciones en la materia particulada, resultando así en un enfriamiento del clima debido al efecto directo de los aerosoles atmosféricos.
Palabras clave: Aeorosol, propiedades ópticas, dispersión, absorción, balance radiativo terrestre, efecto directo, semi-directo e indirecto.

ISSN: 0214-4557
http://dx.doi.org/10.5209/rev_FITE.2015.v27.51198

Normalized reference
Palacios L., Baró R, Jiménez-Guerrero P. (2015). An on-line modelling study of the direct effect of atmospheric aerosols over Europe. *Física de la Tierra*, Vol. 27, 157-173.

1. Introduction

Atmospheric aerosols are particles suspended in the atmosphere affecting air quality, damaging human health and the environment. Epidemiological data have shown that an increased level of particles can raise the human morbidity and mortality (Pope et al., 2009). Also, atmospheric aerosols concern negatively to ecosystems (Lovett et al., 2009); produce corrosion and affectation of materials (EEA, 2010); and cause many of the effects on visibility (Hinds, 1999). Moreover, they play a wider role in atmospheric chemistry and biogeochemical cycles in the Earth system, for instance, by carrying nutrients to ocean ecosystems (Boucher et al., 2013).

With respect to their effects on climate, aerosol particles interact with solar radiation and clouds. Generally, modelling tools and observations indicate that anthropogenic aerosols have had a cooling influence on Earth since preindustrial time. The main mechanisms affecting the radiative budget are the solar radiation scattering and absorption of aerosols (direct effect); and the cloud and precipitation alteration, affecting both the radiation and the hydrology (called indirect effect) (Papadimas et al., 2012). Scattering aerosols increase the brightness of the planet, producing cooling forcing, with the same order of magnitude as aerosols affecting reflectivity of clouds. Absorption aerosols, like black carbon, produce heating forcing. This radiative forcing produces a disturbance in the energetic balance of the radiative budget. The atmospheric aerosol direct and indirect radiative forcing is estimated to have a similar magnitude as the positive radiative forcing of the increasing concentrations of greenhouse gases (Buseck and Schawartz, 2003). However, the uncertainty of the aerosols effects on the Earth's radiative budget is far greater than other forcing climate agent.

The IPCC Fifth Assessment Report (AR5) classifies the aerosol radiative effects in two different groups (Boucher et al., 2013; Hartmann et al., 2013). The radiative forcing from aerosol–radiation interactions (RFari) encompasses radiative effects from anthropogenic aerosols before any adjustment takes place and corresponds to what is usually referred to as the aerosol direct effect. Rapid adjustments induced by aerosol radiative effects on the surface energy budget, the atmospheric profile and cloudiness contribute to the effective radiative forcing (ERF) from aerosol–radiation interactions (ERFari). They include what has earlier been referred to in the scientific literature as the direct and semi-direct effect. Myhre (2009) make the necessary adjustments to the observations to account for forcing in cloudy regions and pre-industrial concentrations to estimate an ERFari of -0.3 ± 0.2 W m^{-2}. A second phase of AeroCom model (Aerosol Comparisons between Observations and Models) results gives an ERFari estimate of de -0.35 W m^{-2}, with a model range of about -0.60 to -0.13 W m^{-2} (Myhre et al., 2013).

On the other hand, the radiative forcing from aerosol–cloud interactions (RFaci) refers to the instantaneous effect on cloud albedo due to changing concentrations of cloud condensation and ice nuclei, also known as the Twomey effect (Twomey, 1977). The effective radiative forcing produced by the indirect effect (ERFaci) was assessed to be -0.7 W m^{-2} with a –1.8 to –0.3 W m^{-2} uncertainty range (Boucher et al., 2013).

To summarize, the effective radiative forcing due to aerosol–radiation interactions that takes rapid adjustments into account (ERFari) is assessed to be –0.45 (–0.95 to +0.05) W m^{-2}. The total effective radiative forcing due to aerosols (ERFari + ERFaci, excluding the effect of absorbing aerosol on snow and ice) is assessed to be –0.9 (–1.9 to –0.1) W m^{-2} with medium confidence (Boucher et al., 2013). Therefore, we can clearly identify the large uncertainty in quantifying the forcing caused by aerosols on the Earth's radiative balance, because the chemical, physics and optical proprieties of aerosol are extremely variable in space and time due to the short atmospheric lifetime of aerosols and that their emissions are not uniform (Forster et al., 2007).

Hence, the main objective of the current contribution is to investigate to what extent aerosol meteorology interactions affect the results of WRF-Chem simulations on the European scale on a seasonal scale and to quantify the effects of the aerosol-radiation interactions (direct effect). As an extensive model evaluation for the meteorological variables and particulate is presented by Brunner et al. (2015) and Im et al. (2015), the scope of this paper is limited to the discussion of the impact of aerosol-meteorology feedback effects due to the direct effect.

2. Methodology

The simulations for Europe discussed in this paper were performed with WRF-Chem version 3.4.1 (Grell et al., 2005) for the entire year 2010 with identical physics options, grid spacing, and input. Two time periods were studied: wintertime, represented by January, February and March (JFM) and summertime, represented by July, August and September (JAS).

The simulation SI2 that is considered as the baseline case does not include any explicit aerosol-meteorology interactions at all. No direct aerosol radiative effect is considered and a fixed value of 250 cloud droplet per cm^3 is specified in the cloud microphysics module. The case SI1 includes only the aerosol direct effect on radiation according to Fast et al. (2006) and Chapman et al. (2009).

A sensitivity analysis was performed in order to study the aerosol direct effect, where SI2 was taken as the reference simulation. We have assessed the differences between SI1 and SI2. Positive (negative) values mean that SI2 has higher (lower) values than the SI1 case. Meteorological variables such as temperature at 2 meters (T2), shortwave radiation upward on top of the atmosphere (SWUPT), shortwave radiation downward at the bottom (SWDNB), and air quality variables such as PM10 were studied.

For a detailed description of the simulations, the reader is referred to Forkel et al. (2015). However, a brief description of the modelling methodology taken from the aforementioned work is described below.

The following physics options were applied for all simulations: Rapid Radiative Transfer Method for Global (RRTMG) longwave and short-wave radiation scheme; the Yonsei University (YSU) PBL scheme; the NOAH land-surface model and the updated version of the Grell-Devenyi scheme with radiative feedback.

For all simulations discussed in this paper the same grid spacing of 23 km was applied with 270 by 225 grid cells (Lambert Conformal Conic projection with center at 50N and 12E (Figure 1). The modelling domain covers Europe and a portion of Northern Africa and as well as large areas affected by the Russian forest fires. In the vertical direction the atmosphere up 50 hPa is resolved into to 33 layers with a higher resolution close to the surface.

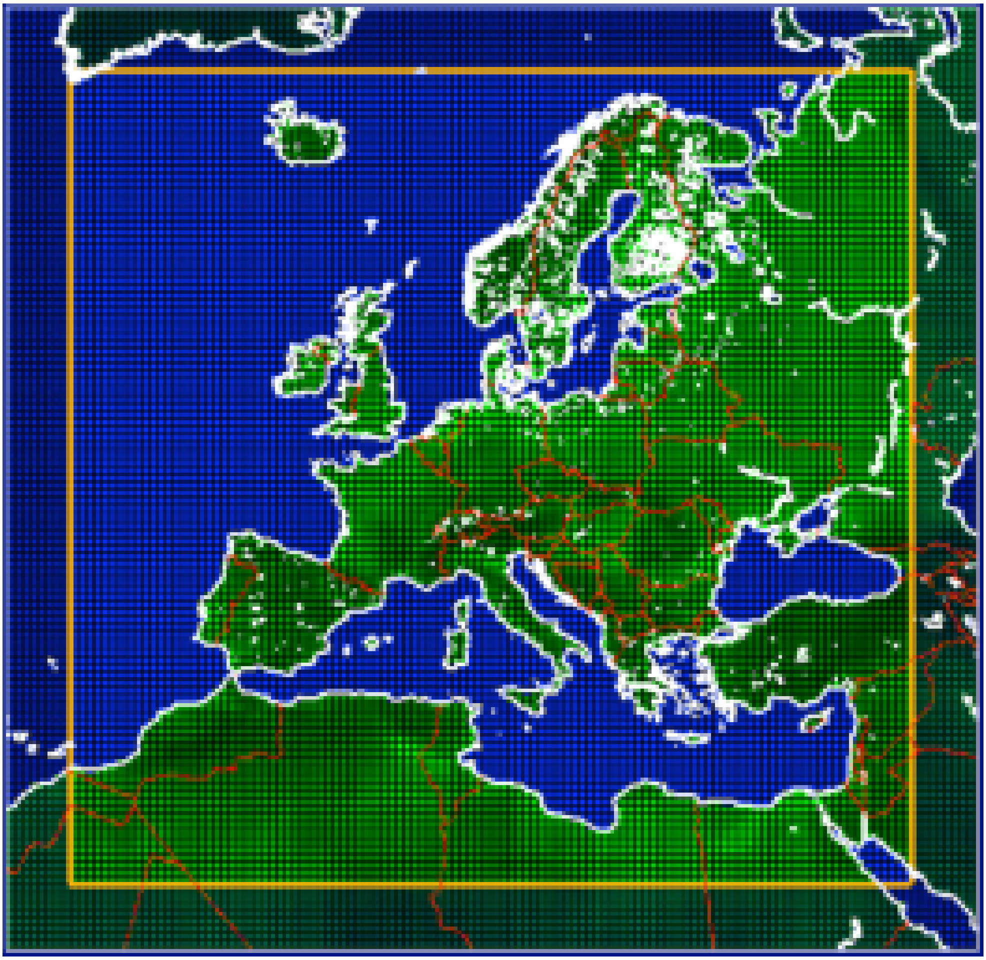

Figure 1. CORDEX-compliant modelling domain used in the simulations.

Initial and boundary conditions for the meteorological variables were obtained from 3-hourly data with 0.25° resolution (analysis at 00 and 12 UTC and respective forecasts 3/6/9 hours) from the ECMWF operational archive. 3-hourly chemistry boundary conditions for the main trace gases and particulate matter concentrations were available from the ECMWF IFS-MOZART model run from the MACC-II project (Monitoring Atmospheric Composition and Climate – Interim Implementation, Inness et al., 2013) 1.125° spatial resolution.

Anthropogenic emissions for the EU domain provided by the TNO (Netherlands Organization for Applied Scientific Research) from a recent update of the TNO MACC emissions inventory (http://www.gmes-atmosphere.eu/; Kuenen et al., 2014, Pouliot et al., 2012, 2014) were applied.

Biomass burning emission data have been calculated from global fire emission data that have been supplied from the integrated monitoring and modelling system for wild-land fires (IS4FIRES) project (Sofiev et al. 2009) with 0.1 x 0.1 degree spatial resolution. Day and night vertical injection profiles were also provided. WRF-Chem emission species have been calculated by speciation following Andreae and Merle (2001) and Wiedinmyer et al (2011). However, no heat release due to the fires was taken into account. According to the directives for the AQMEII phase2 simulations no volcanic emissions were considered in spite of the Eyjafjallajökull eruption in spring 2010.

Biogenic emissions are based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) model (Guenther et al. 2006). MEGAN is on-line coupled with WRF-Chem and makes use of simulated temperature and solar radiation.

3. Results and discussion

3.1. 2-m Temperature

Figures 2 and 3 represent the 2-m mean temperature (T2) for the two study periods (JFM and JAS, respectively). All the figures include: (a) the base case value of the variable, (b) differences between the base case and that including the direct effect (SI2-SI1); and (c) the associated Taylor diagram.

The Taylor diagrams (Taylor, 2001) for winter and summer 2010 (Figures 2 [c] and 3 [c]) indicate that the mean variation over the entire domain between the two simulations is small, both in terms of standard deviation and correlation coefficient. Figures 2 [b] and 3 [b] indicate that the differences in T2 do not exceed 0.3 K. Positive values over the entire domain mean that the inclusion of the direct aerosol effects lead to a decrease of the mean T2. For the winter period (Figure 2 [b]) the largest differences are found in North African area, with maximum values of 0.2 K lower due to the inclusion of the direct aerosol effect. This could be related to the presence of mineral dust from the Sahara Desert, increasing the aerosol scattering phenomena. For the summer period (Figure 3 [b]), maximum difference values of 0.3 K are observed on the south of the Iberian Peninsula and North Africa (also due to the high levels of Saharan dust); and in the area of Russia. Differences in Russia are due to the large amount of aerosols emitted into the atmosphere by forest fires occurred during the summer of 2010.

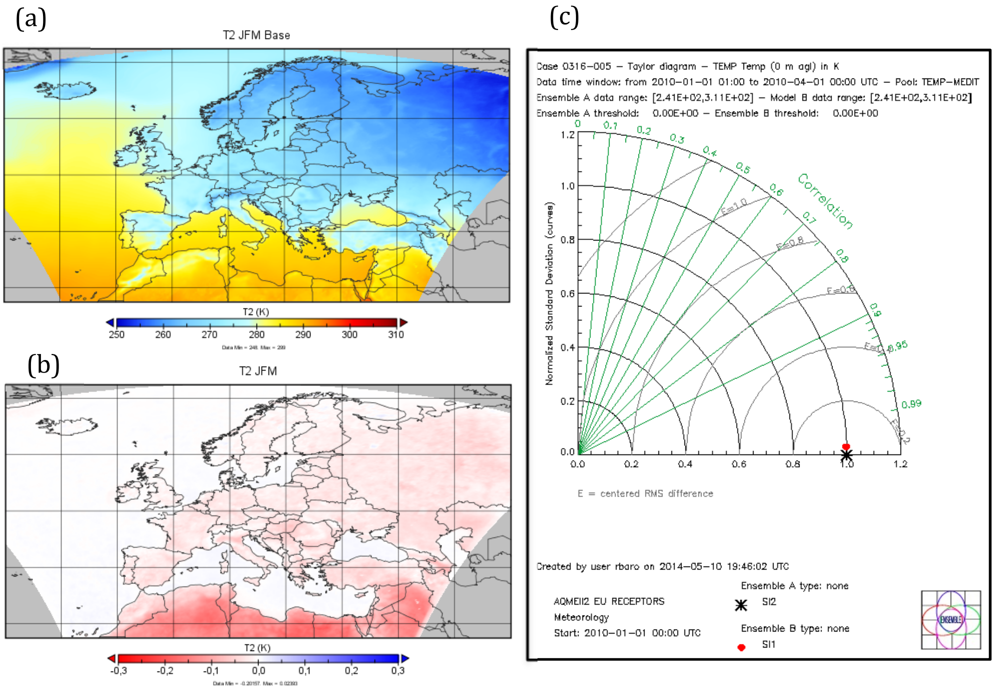

Figure 2. Results of the average 2-m temperature (T2) for the winter period (K): (a) base case; (b) difference between the base case and that including the direct effect; (c) associated Taylor diagram (black star – Simulation SI2, red point – Simulation SI1).

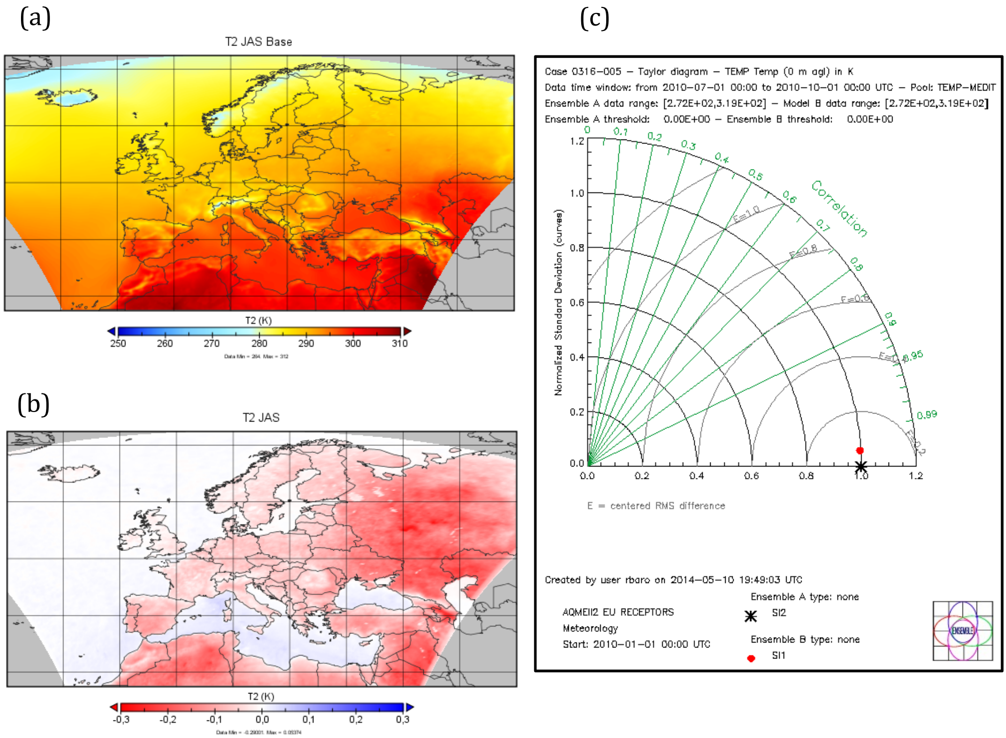

Figure 3. Id. Figure 2 but for the summer months.

3.2. Shortwave downward radiation at the bottom

Figures 4 and 5 show the average values of SWDNB for the two periods studied (JFM and JAS, respectively). The Taylor diagrams (Figures 4 [c] and 5 [c]) indicate that the mean changes in the whole domain are small, slightly reducing the variability (standard deviation) when including the aerosol-radiation interactions in the simulations. Regarding the direct aerosol effect on the SWDNB, both in winter (Figure 4 [b]) and summer (Figure 5 [b]), a decrease of the incoming solar radiation on Earth's surface is observed especially on Europe (positive differences, red color). As commented before, this can be explained by the scattering of the radiation by aerosols. We can see that this decrease is higher during summer (difference up to 27 W m^{-2}) than winter (11 W m^{-2}), as during summer the amount of incoming radiation on surface (Figure 5 [a]) and the aerosol scattered radiation is higher than in winter. The maximum differences are found over the Russian and Portuguese area due to the fires during the summer of 2010.

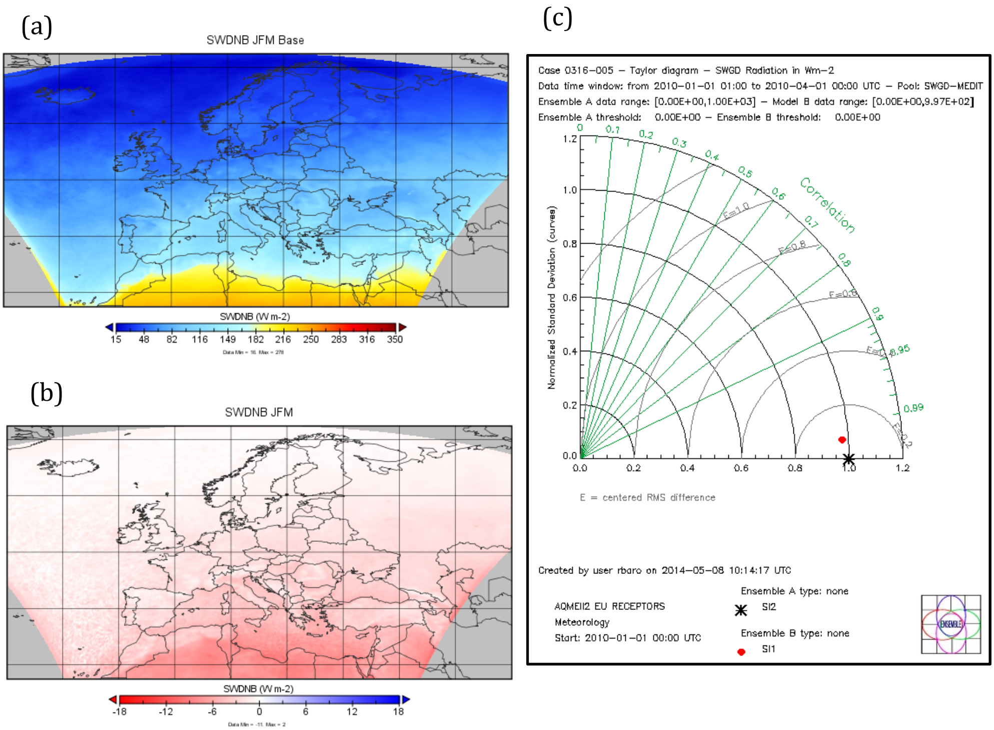

Figure 4. Results of the average shortwave radiation downward the surface of the Earth for the winter period (W m^{-2}): (a) base case; (b) difference between the base case and that including the direct effect; (c) associated Taylor diagram (black star – Simulation SI2, red point – Simulation SI1).

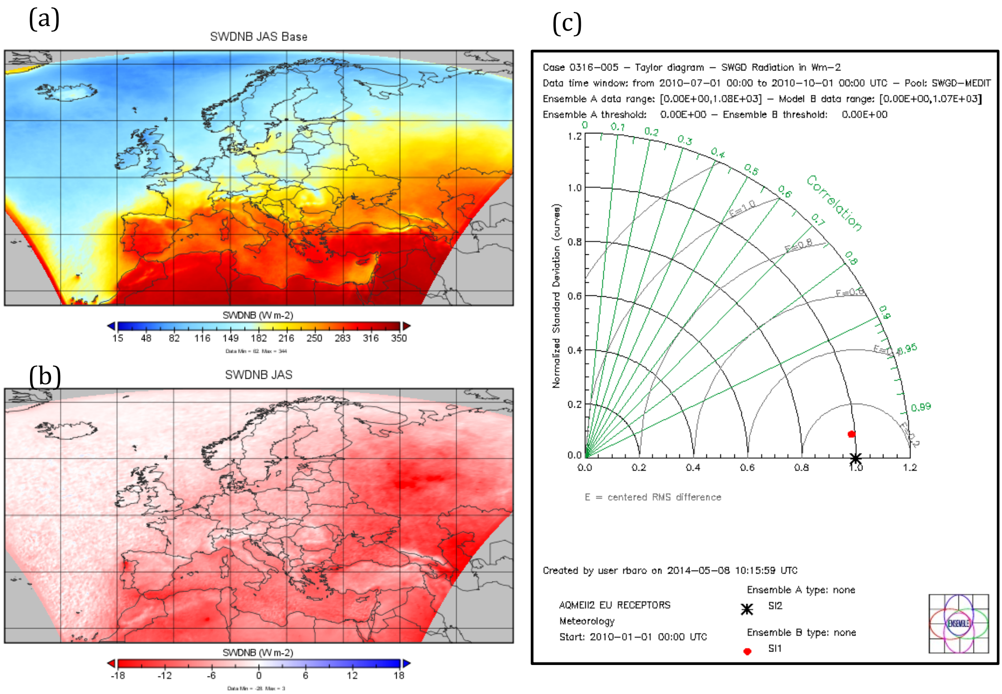

Figure 5. Id. Figure 4 but for the summer months.

3.3. Shortwave upward radiation at the top of the atmosphere

Figures 6 and 7 show the average values of SWUPT for the two studied periods (JFM and JAS, respectively). Data of SWUPT were not available on the platform web ENSEMBLE, so there is no Taylor diagram information available.

Generally, there are negative differences over the domain, (Figures 6[b] and 7[b]), meaning that SWUPT is higher when considering the direct aerosol effects. Incoming solar radiation is affected by scattering phenomena in the atmosphere that lead to an increase on the SWUPT. Moreover, there is an increase on the reflected radiation in North of Africa and over the Mediterranean Sea that can be explained due to the desert dust and salt sea aerosols, which scatter the radiation.

In summer, represented in Figure 7(b), there are two areas areas where SWUPT shows a negative maximum (-8 W m^{-2}): Russia and Northern Portugal (due to the fires in summer 2010) and the Mediterranean and the Black Sea, where the reflected radiation is explained by the presence of sea salt aerosols.

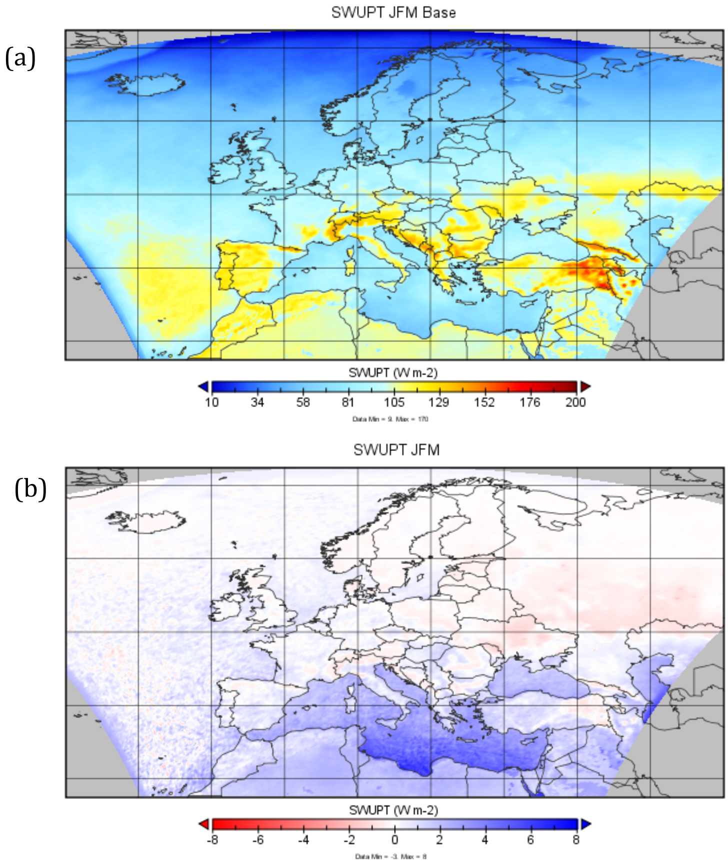

Figure 6. Results of the average shortwave radiation upward on the TOA for the winter period (W m-2): (a) base case and (b) difference between the base case and that including the direct effect.

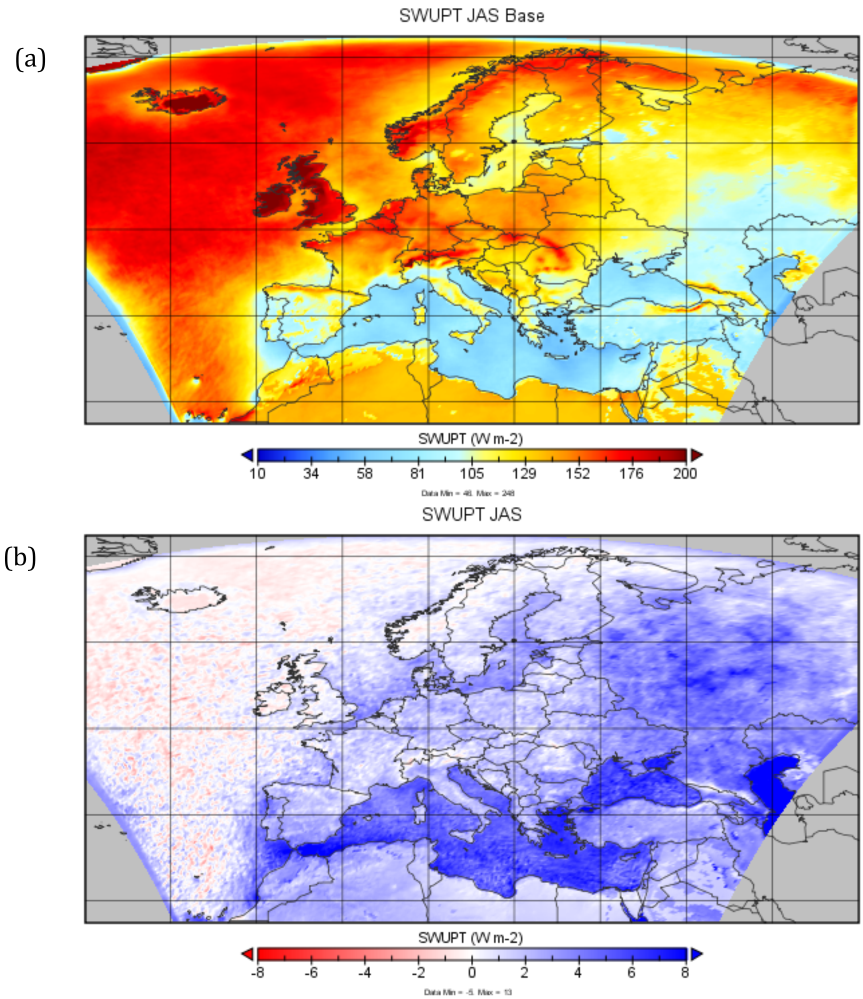

Figure 7. Id. Figure 6 but for the summer months.

3.4. PM_{10}

Figures 8 and 9 show the average values of particle matter smaller than 10 µm for the two studied periods (JFM and JAS, respectively). In both Taylor diagrams (Figures 8 [c] and 9 [c]) it can be seen that the mean changes over all domain are also very small. In general, for this variable there are also small average differences on the whole domain, but a large local effect.

During winter (Figure 8) only small changes are modelled over Northern Africa (lower than 3 µg m^{-3}) due to a negative feedback on aerosol emissions. Lower levels of PM_{10} (positive differences) when including aerosol-radiation interactions in this area can be explained because of the decrease of the T2 due to the presence of aerosols, also reduce the intensity on the local winds and decrease the emission of the dust particle.

On the other hand, higher levels of PM_{10} (differences between base case and simulation with direct effect are negative), over Russia and North of Portugal (up to 27 µg m^{-3}) are modelled during summertime (Figure 9). This is due to the presence of black carbon aerosols (main type of aerosol emitted during fires). The semi-direct effect here increases the atmospheric stability (reduced planetary boundary layer) and thus increases the concentrations of aerosols in the simulations including the aerosol direct radiative effects. Changes over Northern Africa can be attributed to the aerosol-dust negative feedbacks, as explained for wintertime.

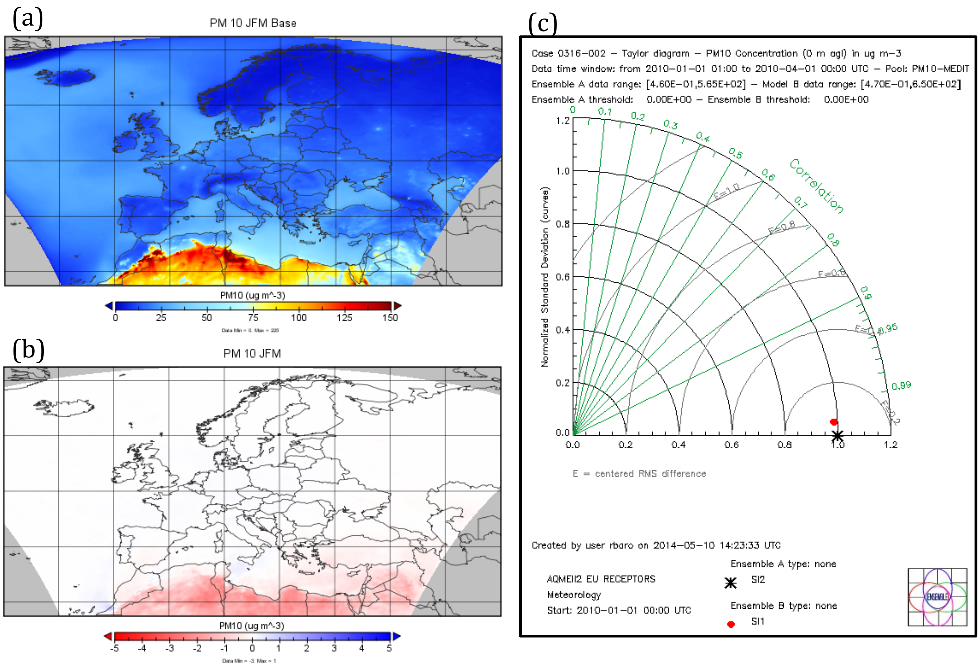

Figure 8. Results of the average PM10 levels for the winter period (µg m-3): (a) base case; (b) difference between the base case and that including the direct effect; (c) associated Taylor diagram (black star – Simulation SI2, red point – Simulation SI1).

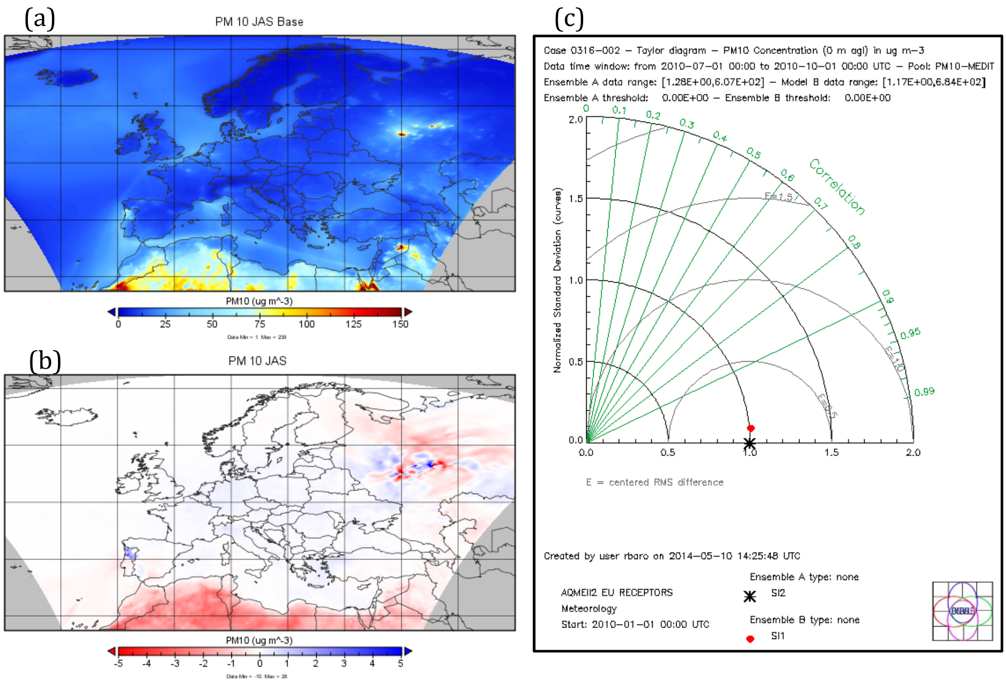

Figure 9. Id. Figure 8 but for the summer months.

4. Conclusions

The presence of aerosols in the atmosphere, and the inclusion of the aerosol-radiation interactions in WRF-Chem simulations can have an important impact on the local values of meteorological and air quality variables. For instance, this radiative effect leads to a decrease on the SWDNB, being the importance of this effect higher during summer (difference up to 27 W m^{-2}) than in winter (11 W m^{-2}). A lower SWDNB involves lower temperatures in the target domain. The decrease of the T2 is explained by the scattering effects of atmospheric aerosols, which increases the reflection of the incoming solar radiation causing a cooling effect. Differences in 2-m temperature are up to -0.3 K for both winter and summer.

The inclusion of aerosol radiative feedbacks also explains the increase on the SWUPT, up to 8 W m^{-2}. Small variations have also been observed in the amount of PM_{10} (until 3 µg m^{-3}) due to the interaction between aerosols and meteorological variables affected by the changes on radiation.

Therefore, the inclusion of atmospheric aerosols, both anthropogenic and natural, may produce an important effect on the Earth's climate. However, the study of the aerosol effects from a climate perspective needs for longer simulations time, having a proper climatic representativeness. Hence, further research is necessary in order to reduce the uncertainties of the aerosol effects over meteorological/climatic variables and to improve the knowledge in this field.

Acknowledgements
The authors acknowledge the project CGL2010-22158-C02-02, CGL2013-48491-R and RYC-2010-05688 of Ministerio de Economía y Competitividad and FEDER the support to carry out this research. The work has been possible thanks to the support of the initiative Air Quality Modelling Evaluation International Initiative (AQMEII) Phase 2.

References

ANDREAE, M. & P. MERLET (2009). Emission of trace gases and aerosols from biomass burning, *Global. Biogeochem. Cycles.* 15(4), 955–966.

BOUCHER, O., D. RANDALL, P. ARTAXO, ET AL. 2013. Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G. K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

BRUNNER, D., O. JORBA, N. SAVAGE ET AL. (2015). Comparative Analysis of meteorological performance of coupled chemistry-meteorology models in the context of AQMEII phase 2. *Atmos. Environ.,* 115, 470-498, doi:10.1016/j.atmosenv.2014.12.032.

BUSECK, P. R. & S. E. SCHAWARTZ (2003). *Tropospheric Aerosols*. Treatise on Geochemistry. London: Keeling, R. F. Elservier, 142pp

CHAPMAN, E. G., W. GUSTAFSON, R. C. EASTER, J. C. BARNARD, S. J. GHAN, M. S. PEKOUR, & J. D. FAST (2009). Coupling aerosol-cloud-radiative processes in the WRF-Chem model: Investigating the radiative impact of elevated point sources. *Atmos. Chem. Phys*, 9(3), 945–964.

EEA, 2010. *The european environment. State and outlook 2010*. European environmental agency. Copenhagen.

FAST, J. D., W. I. GUSTAFSON JR, R. C. EASTER ET AL. (2006). Evolution of ozone, particles, and aerosol direct radiative forcing in the vicinity of Houston using a fully coupled meteorology-chemistry-aerosol model. *J. Geophys. Res*, 111(D21):D21305.

FORKEL, R., A. BALZARINI, R. BARO, R. ET AL (2015). Analysis of the WRF-Chem contributions to AQMEII phase 2 with respect to aerosol radiative feedbacks on meteorology and pollutants distributions. *Atmos . Environ.,* 115, 630-645, doi:10.1016/j.atmosenv.2014.10.056.

FORSTER, P., V. RAMASWAMY, P. ARTAXO ET AL. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

GRELL, G. A., S. E. PECKHAM, R. SCHMITZ, S.A MCKEEN, G. FROST, W. C. SKAMAROCK & B. EDERY (2005). Fully coupled "online" chemistry within the WRF model. *Atmos. Environ,,* 39(37), 6957-6975.

GUENTHER, A., T. KARL, P. HARLEY, C. WIEDINMYER, P. PALMER & C. GERON (2006). Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). Atmos. Chem. Phys, 6(11), 3181–3210.

HARTMANN, D.L., A.M.G. KLEIN TANK, M. RUSTICUCCI ET AL. (2013). Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

HINDS, W (1999). *Aerosol Technology: Properties, behaviour, and measurement of airborne particles*. New York: Wiley.

IM, U., R. BIANCONI, E. SOLAZZO ET AL (2015). Evaluation of operational online-coupled regional air quality models over Europe and North America in the context of AQMEII phase2. Part II: particulate matter. *Atmos. Environ.,* 115, 421-441, doi:10.1016/j.atmosenv.2014.08.072.

INNESS, A., F. BAIER, A. BENEDETTI ET AL. (2013). The MACC reanalysis: an 8 year data set of atmospheric composition. Atmos. Chem. Phys, 13, 4073-4109.

KUENEN, J. J. P., A. J. H. VISSCHEDIJK, M. JOZWICKA & H. A. C. DENIER VAN DER GON (2014). TNO-MACC_II emission inventory; a multi-year (2003–2009) consistent high-resolution European emission inventory for air quality modelling. *Atmos. Chem. Phys*, 14(20), 10963-10976.

LOVETT, G. M., T. H. TEAR, D. C. EVERS, S. E. FINDLAY, B. J. COSBY, J. K. DUNSCOMB, C. T. DRISCOLL, & K. C. WEATHERS (2009). Effects of air pollution on ecosystems and biological diversity in the eastern United States. *Ann. New York Acad. Sci*, 1162(1), 99–135.

MYHRE, G (2009). Consistency between satellite-derived and modeled estimates of the direct aerosol effect. *Sci*, 325, 187 - 190.

MYHRE, G., B. H. SAMSET, M. SCHULZ ET AL. (2013). Radiative forcing of the direct aerosol effect from Aerocom Phase II simulations. *Atmos. Chem. Physics*, 13(4), 1853–1877.

PAPADIMAS, C., N. HATZIANASTASSIOU, C. MATSOUKAS, M. KANAKIDOU, N. MIHALOPOULOS & I. VARDAVAS (2012). The direct effect of aerosols on solar radiation over the broader. *Atmos. Chem. Phys*, 12, 7165-7185.

POPE, C. A., M. EZZATI & D. W. DOCKERY (2009). Fine-particulate air pollution and life expectancy in the United States. *N. Engl. J. Med*, 360(4), 376–386.

POULIOT, G., T. PIERCE, H. D. VAN DER GON, M. SCHAAP, M. MORAN & U. NOPMONGCOL (2012). Comparing emission inventories and model-ready emission datasets between Europe and North America for the AQMEII project. *Atmos. Environ*, 53, 4–14.

POULIOT, G., H. A. D. VAN DER GON, J. KUENEN, J. ZHANG, M. D. MORAN, M. D & P. A. MAKAR (2014). Analysis of the emission inventories and model-ready emission datasets of Europe and North America for phase 2 of the AQMEII project. *Atmos. Environ*, doi:10.1016/j.atmosenv.2014.10.061.

SOFIEV, M., R. VANKEVICH, M. LOTJONEN, M. PRANK, V. PETUKHOV, T. ERMAKOVA & J. KUKKONEN (2009). An operational system for the assimilation of the satellite information on wild-land fires for the needs of air quality modelling and forecasting. *Atmos. Chem. Phys*, 9(18), 6833-6847.

TAYLOR, K.E. (2001). Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res*., 106, 7183-7192.

TWOMEY, S (1977). Influence of pollution on shortwave albedo of clouds. *J. Atmos. Sci*, 34, 1149-1152.

WIEDINMYER, C., S. K. AKAGI, R .J. YOKELSON, L. K. EMMONS, J. A. AL-SAADI, J. J. ORLANDO & A. J. SOJA (2011). The Fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning. *Geosci. Model Dev*, 4, 625–641.