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Research Article

Investigation of aerosol direct radiative forcing during a dust storm using a regional climate model over Turkiye

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ABSTRACT

Dust particles originating from arid zones can be transported long distances and change the radiation budget. Understanding atmospheric aerosols and their radiative forcing is important to determine their global and regional climate effects. The aim of this study is to simulate the dust transport event that occurred on March 22, 2018, using RegCM-4.5 and investigate the radiative forcing effect of Saharan dust particles. The model was run with the 4 dust bin chemistry option and the direct effect of aerosols on the regional radiation balance was investigated. Validation of the model was made by a comparison between simulated aerosol optical depth (AOD) and MODIS satellite data. The radiative forcing at the top and surface was calculated at all sky conditions. During the dust episode, the shortwave radiative forcing was ranging between -3 and -50 W/m^2 at surface and -2 and -22 W/m^2 at top of atmosphere while the longwave radiative forcing was between 0.5 and 8 W/m^2 at surface and 0.2 and 2 W/m^2 at top of atmosphere over Turkiye. In Istanbul it produced a cooling up to -18 W/m^2 at surface and -9 W/m^2 at top of atmosphere, a warming up to 3.5 W/m^2 at surface and 0.6 W/m^2 at top of atmosphere.

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INTRODUCTION

Aerosols are liquid or solid particles that suspended in the atmosphere. Their sizes span between 0.2 nanometers and 500 micrometers. Although their residence time in the atmosphere is short (from hours to weeks), their concentrations and properties can vary substantially depending on time and location [1, 2]. Atmospheric aerosol particles have both natural sources such as volcanic action, sea spray, mineral dust, biologic aerosols, and, forest fire smokes and anthropogenic sources such as fuel combustion, industrial processes, and transport. They can also be formed by precursor gasses [3].

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Mainly aerosol species are mineral dust, sea spray, volcanic ash, dimethyl sulphide, and biogenic volatile organic compounds. Dust is the most abundant aerosol in the atmosphere in terms of mass with an annual global emission rate of 1000–4000 Tg [4]. Although dust storms are the primary source of dust, anthropogenic sources account for 30% of the dust load [5]. Arid and semiarid regions such as the Sahara-Sahel region of northern Africa and central Asia are the major dust sources in the World. There are several studies reported dust particle concentrations throughout Europe, Asia, Africa, and even Alaska [5, 6, 7, 8, 9].

Aerosols have a strong impact on Earth's climate as they can alter the radiation budget through their direct and indirect effects [10]. Atmospheric aerosols directly affect the climate by interacting with shortwave (SW) radiation and longwave (LW) radiation and produce cooling or warming depending their physical and optical properties. While most of the atmospheric aerosol components cause negative radiative forcing and cool the Earth's surface with scattering solar radiation, some of them such as black carbon (BC) make a positive forcing with absorption [4]. This absorption can lead heat of the atmosphere and have impact on cloud evaporation. They also have indirect climate effects. They cause changes in the radiative and microphysical properties of the clouds by activating the cloud condensation nuclei [11].

Although satellite retrievals provide us regular global data for a better understanding of aerosol forces, there are still uncertainties in the radiative effect of aerosols at regional scale due to changes in dust concentrations and microphysical and optical properties [12, 13, 14].

Regional climate models are suitable tools for simulating and predicting aerosol concentrations in any domain. In the literature, there are various types of climate modelling studies investigating atmospheric aerosol radiative forcing. Agacayak et al. [15] used RegCM4.1 to simulate dust transport during March 2008 over Turkiye. They found shortwave radiative forcing between −71.4 W/m^2 and −33 W/m^2 in the Aegean Region and between −61.9 W/m^2 and −28.8 W/m^2 in the Marmara region at surface and at top of atmosphere, respectively. While the longwave radiative forcing was found between 10.7 W/m^2 and 4.4 W/m^2 in the Aegean region and between 6.9 W/m^2 and 4 W/m^2 in the Marmara Region, respectively. Tsikerdekis et al. [16] investigated direct and semi-direct effects of North African dust transport using RegCM4 for historical and future periods. They reported direct+semi-direct radiative forcing effect on the shortwave radiation between −13.8 W/m^2 and −10.7 W/m^2 for the period 1999-2009 and between −15.8 W/m^2 and −11.0 W/m^2 for the period 2089-2099 over the Sahel and the Sahara, respectively. Nabat et al. [17] used a fully coupled regional climate system model, CNRM-RCSM4, and calculated similar values to those of Tsikerdekis et al. (2018) over Northern Africa. Shortwave surface direct radiative forcing effect was found as -19.7 W/m^2 while the longwave radiative forcing effect was found as 4.8 W/m^2.

There is a scarcity in the studies that exhibit the radiative effect of dust transport in the Northwestern part of Turkiye, where is exposed to incursion on several days over a calendar year. In this study, the impact of a mineral dust transport from the Saharan desert into Turkiye is investigated. The longwave and shortwave radiative forcing at the top and surface were calculated using the RegCM-4.5 and the

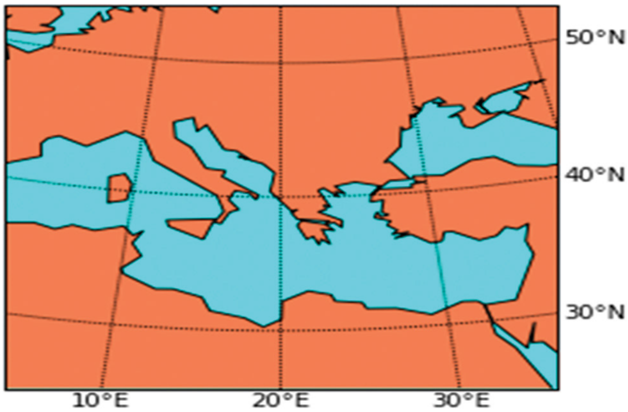

Figure 1. Study Domain used in RegCM-4.5 simulation.

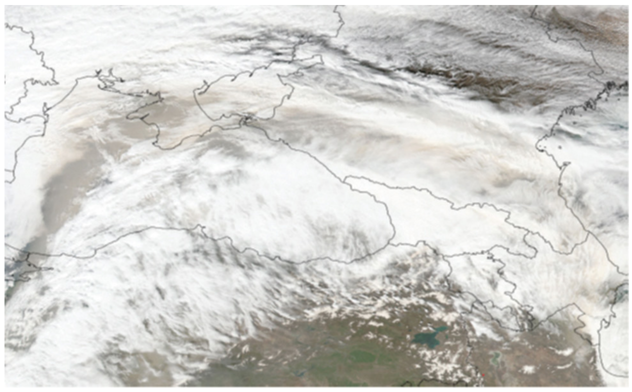

Figure 2. View of the dust transport on March 22, 2018 [24].

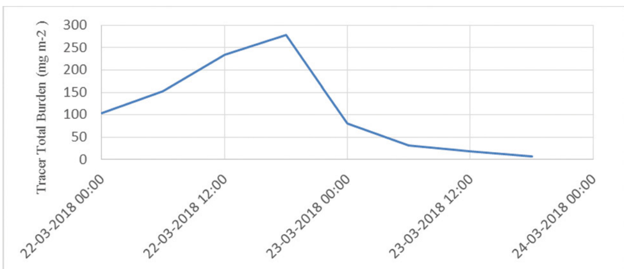

Figure 3. Dust total burden (mg/m2) over Istanbul.

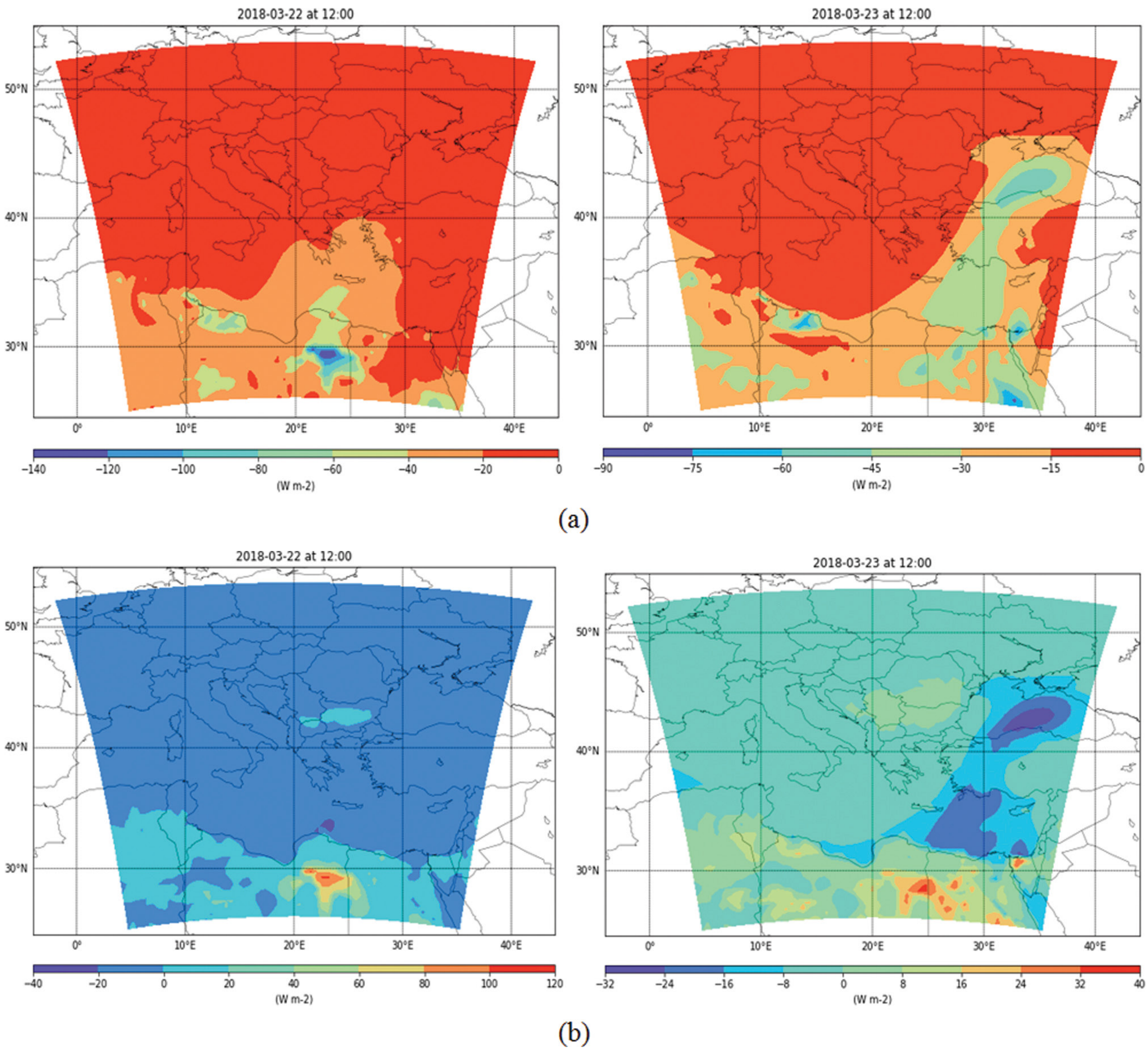

Figure 4. The shortwave direct radiative forcing (a) at surface and (b) at top of atmosphere.

results were validated against MODIS satellite data. Quite few studies are present for showing the radiative effect of dust transport in the Northwestern part of Turkiye, where is exposed to incursion on several days over a calendar year.

MATERIALS AND METHODS

RegCM-4.5 Model Setup

In this study, a regional climate model (RegCM), version 4.5 was employed to simulate the dust transport event in Istanbul on March 22, 2018. The model was developed at National Center of Atmospheric Research (NCAR) as part of the Community Climate System Model (CCSM). It has both hydrostatic and non-hydrostatic options. It provides several options for physics and chemistry mechanisms. For land surface processes the model was configured with community land model version 4.5 (CLM45) option. The physics parameterization of the model consists of Holtslag boundary layer scheme [18], Grell cumulus convection scheme, SUBEX explicit moisture scheme [19] and Zeng et al (1998) ocean flux scheme [20]. The longwave and shortwave radiation can be calculated with RRTM (the Rapid Radiative Transfer Model) or CCM (Community Climate Model) options. In this study, the default CCM scheme [21] was used. The model was implemented on lambert conformal projection and it includes 18 vertical sigma pressure levels with 5 hPa top pressure. The study domain included Northern Africa, Middle and Eastern Europe, and Ukraine

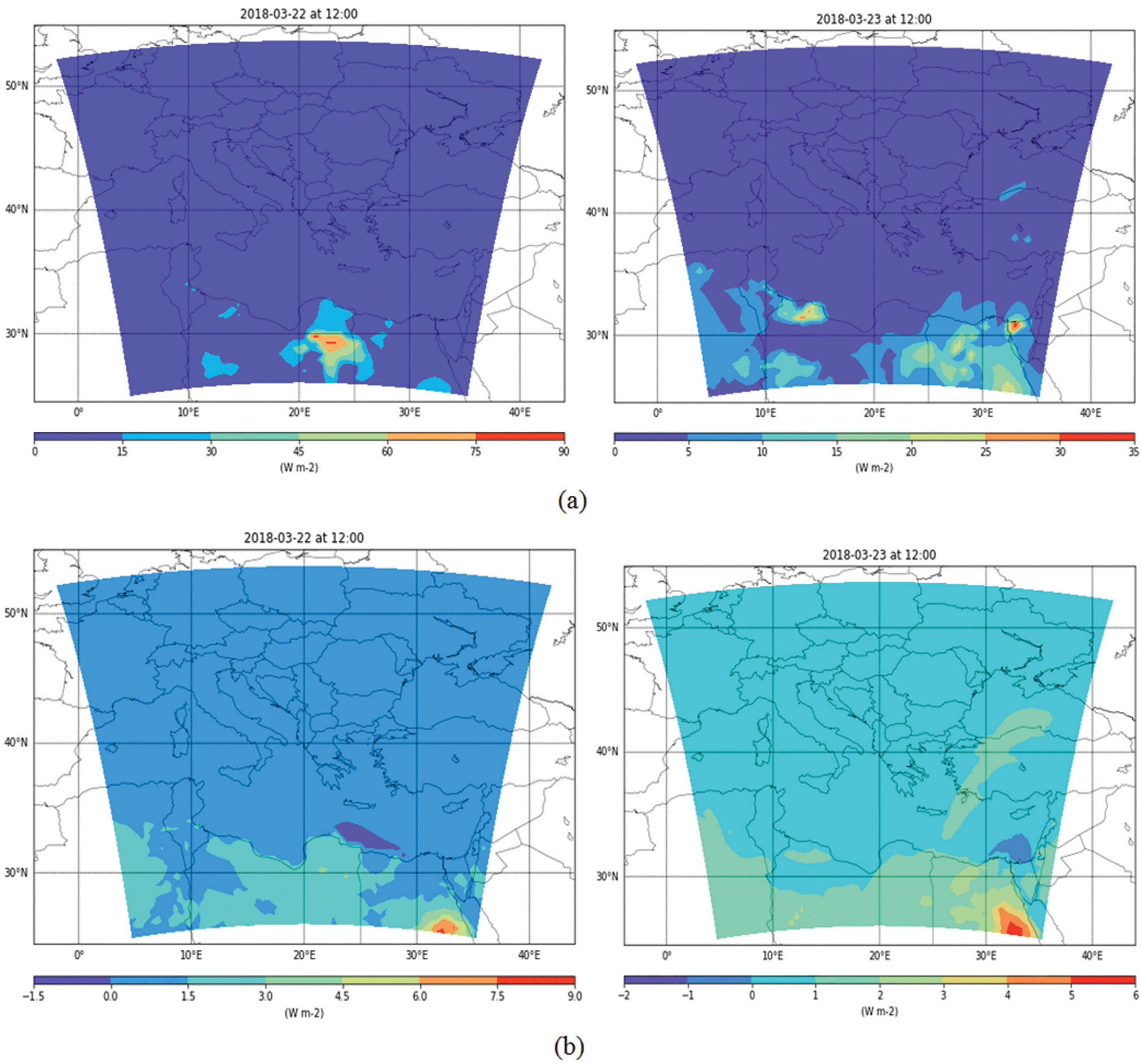

Figure 5. The longwave direct radiative forcing (a) at surface and (b) at top of atmosphere.

(Figure 1). It has 50 km grid point horizontal resolution and 64 grids points in the N/S and E/W direction which centered at 40.0 latitude and 20.0 longitude. 6 hourly ERA Interim reanalysis dataset (EIN15) with 1.5^0x1.5^0 horizontal grid resolution was used to build initial and boundary conditions. Weekly optimal interpolation (OI_WK) was selected for the sea surface temperature (SST) data. The model runtime period was between March 22, 2018 and March 24, 2018. Dust option of the chemistry module was activated for this run [22]. Kok's dust scheme [23] was selected. The scheme has four size bins which are named DUST1, DUST2, DUST3, and DUST4 and corresponding to 0.01-1.0, 1.0-2.5, 2.5-5.0, and 5.0-20.0 μm size intervals, respectively. In this study, aerosol interaction with radiation was enabled allowing them to reflect, disperse, absorb, and re-emit radiation. The model was run with chemistry option in order to see the effect of aerosols on radiative forcing.

Satellite Data

MODIS (the MODerate resolution Imaging Spectroradiometer) satellite of NASA retrieves the optical thickness of atmospheric aerosol across the oceans and continents. Here, we used it for the validation of the model. The AOD values obtained from the model simulation was compared with MODIS data. The view of the dust transport

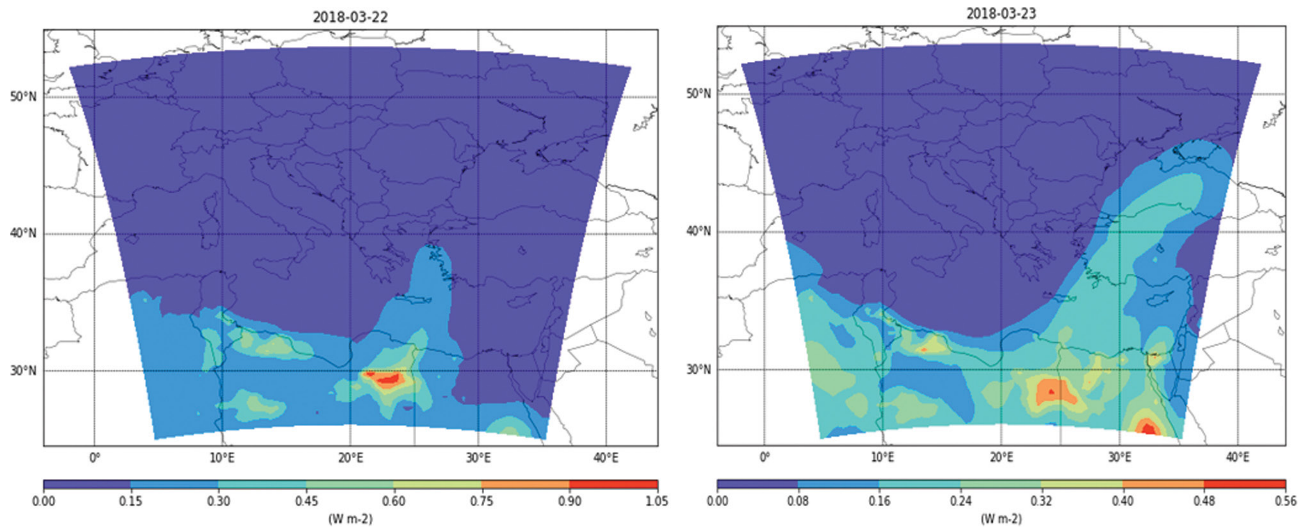

Figure 6. The daily averages of aerosol optical depth (AOD).

event was captured by MODIS on March 22, 2018 and shown in Figure 2.

RESULTS AND DISCUSSION

Tracer Total Dust Burden

The model generates dust burden within each grid cell by running the dust chemistry option. The total dust burden indicates the dust load which has the unit of mass per area. Figure 3 shows the tracer total dust burden concentrations calculated for Istanbul.

The dust eroded from Libya and reached Istanbul. The peak was occurred on March 22 at 18:00 and the highest tracer total burden was calculated as 278 mg/m^2 in Istanbul. The concentrations of the highest burden at different size bins were 42 mg/m^2, 70 mg/m^2, 61 mg/m^2, and 105 mg/m^2 for DUST1, DUST2, DUST3, and DUST4, respectively. The majority of the dust was between 5 and 20 µm. Its share was about 38% of the whole transported dust.

Aerosol Radiative Forcing

Dust particles reduce incoming shortwave radiation by scattering and absorbing shortwave radiation and preventing it from reaching the Earth's surface. Depending on the surface albedo, dust increase or decrease the outgoing shortwave flux. In the longwave spectrum, they have similar radiative effect as greenhouse gases. The upward Earth's longwave radiation is mostly absorbed by coarse particles, which are then reemitted and resulting in an increase in the incoming longwave flux to the Earth's surface [25, 26, 27].

According to the simulation results estimated shortwave direct radiative forcing at surface and at top of atmosphere was graphically shown in Figure 4. The shortwave radiative forcing ranged between -3 and -50 W/m^2 at surface, -2 and -22 W/m^2 at top of atmosphere over Turkiye. Higher absolute value of radiative forcing was observed during the incursion. It reached to the values of -18 W/m^2 at surface and -9 W/m^2 at top of atmosphere on March 22, 2018, respectively, over Istanbul.

Figure 5 shows the longwave radiative forcing at surface and top of atmosphere. Over Turkiye, it was between 0.5 and 8 W/m^2 at surface, 0.2 and 2 W/m^2 at top of atmosphere. In Istanbul the highest values 3.5 W/m^2 and 0.6 W/m^2 was calculated at surface and at top of atmosphere, respectively. Our results showed consistency with the study conducted by Kaskaoutis et al. [28] in which they found similar results over Athens with the synergy of OPAC and SBDART models during the same period. They reported radiative forcing values between -40 and -50 W/m^2 at surface and between -5 and -30 W/m^2 at the top of atmosphere. Pérez et al. [29] estimated extremely higher values for a Saharan dust outbreak that occurred April 2002 utilizing the RegCM3 model. The highest shortwave radiative forcing value was calculated -300 W/m^2 at surface and 50 W/m^2 at top of atmosphere over Turkiye. The longwave forcing was around -20 and 20 W/m^2 at surface and top of atmosphere.

Aerosol Optical Depth

Figure 6 presents the daily averages of aerosol optical depth over the study area. These AOD results were estimated by our models results. The model estimated AOD data was compared with Terra satellite AOD retrieval. The retrieval AOD data in Istanbul were 0.12 and 0.26 for March 22 and March 23, respectively. The model results were 0.13 and 0.15 for March 22 and March 23, respectively. The results of the model was in good agreement with the satellite retrieval results especially for the day before the transport. However, a lower prediction was observed for the incursion. We also would like to note that satellite image was hindered by clouds in most regions around Istanbul. Only some small grids by 0.1 x 0.1 was available.

CONCLUSION

In this study, RegCM-4.5 was implemented in order to determine the radiative forcing effect of atmospheric aerosols over Istanbul during a dust storm on March 22, 2018. The shortwave direct radiative forcing of aerosols caused a decrease over Turkiye between 2 and 50 W/m^2 while the longwave radiative forcing responsible for an increase between 0.2 and 8 W/m^2. The dust transport period was checked by MODIS satellite data image of NASA. The model could capture the transport route correctly and represented the dust plume over Turkiye with high accuracy. The validation of the model was done by comparing the AOD values of the simulation and satellite over the same area. It is found that the model was able to simulate regional aerosol dynamics around the study area. Estimation of dust and its effect on radiative forcing will be more important in the forthcoming years. It is expected that the dust emission amount and intensity will change with the global climate change. This is not only for air pollution concerns but also affects the efficiency of solar panels for power generation. This can result in decreased air quality or reduced power generation. Hereby, we recommend here to make simulations using different global circulation models for the area in concern.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Boucher O. Atmospheric aerosols. In: Boucher O, editor. Atmospheric aerosols: Properties and climate impacts. 1st ed. Dordrecht: Springer; 2015. pp. 9–24. [CrossRef]

[2] Fu Q. Radiation transfer in the atmosphere | Radiation, Solar. In: Zhang F, North G, Pyle JC, editors. Encyclopedia of atmospheric sciences. 2nd ed. Amsterdam: Elsevier; 2015. pp. 1–4. [CrossRef]

[3] Tomasi C, Lupi A. Primary and secondary sources of atmospheric aerosol. In: Tomasi C, Fuzzi S, Kokhanovsky A, editors. Atmospheric aerosols: Life cycles and effects on air quality and climate. 1st ed. Weinheim: Wiley; 2017. [CrossRef]

[4] Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change IPCC; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; p. 1535.

[5] Barnaba F, Gobbi GP. Aerosol seasonal variability over the Mediterranean region and relative impact of maritime, continental and Saharan dust particles over the basin from MODIS data in the year 2001. Atmos Chem Phys 2004;4:2367–2391. [CrossRef]

[6] Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood, J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R. Changes in atmospheric constituents and in radiative forcing. Chapter 2. In Climate Change 2007. The Physical Science Basis 2007.

[7] Miller RL, Tegen I, Perlwitz J. Surface radiative forcing by soil dust aerosols and the hydrologic cycle. J Geophys Res Atmos 2004;109:D04203. [CrossRef]

[8] Cavazos C, Todd MC, Schepanski K. Numerical model simulation of the Saharan dust event of 6–11 March 2006 using the Regional Climate Model version 3 (RegCM3). J Geophys Res Atmos 2009;114:D12109. [CrossRef]

[9] Stone RS, Anderson GP, Andrews E, Dutton EG, Shettle EP, Berk A. Incursions and radiative impact of Asian dust in northern Alaska. Geophys Res Lett 2007;34:L14815. [CrossRef]

[10] Kaufman YJ, Tanre´ D, Boucher O. A satellite view of aerosols in the climate system. Nature 2002;419:215–223. [CrossRef]

[11] Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY. 2007.

[12] IPCC, 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

[13] Calvo AI, Alves C, Castro A, Pont V, Vicente AM, Fraile R. Research on aerosol sources and chemical composition: past, current and emerging issues. Atmos Res 2013;120:1–28. [CrossRef]

[14] Reid JS, Hyer EJ, Johnson RS, Holben BN, Yokelson RJ, Zhang J, et al. Observing and understanding the Southeast Asian aerosol system by remote sensing: An initial review and analysis for the Seven Southeast Asian Studies (7SEAS) program. Atmos Res 2013;122:403–468. [CrossRef]

[15] Agacayak T, Kindap T, Unal A, Pozzoli L, Mallet M, Solmon F. A case study for Saharan dust transport over Turkey via RegCM4. 1 model. Atmos Res 2015;153:392–403. [CrossRef]

[16] Tsikerdekis A, Zanis P, Georgoulias AK, Alexandri G, Katragkou E, Karacostas T, et al. Direct and semi-direct radiative effect of North African dust in present and future regional climate simulations. Clim Dyn 2019;53:4311–4336. [CrossRef]

[17] Nabat P, Somot S, Mallet M, Sevault F, Chiacchio M, Wild M. Direct and semi-direct aerosol radiative effect on the Mediterranean climate variability using a coupled regional climate system model. Clim Dyn 2015;44:1127–1155. [CrossRef]

[18] Holtslag AAM, De Bruijn EIF, Pan HL. A high resolution air mass transformation model for short-range weather forecasting. Mon Weather Rev 1990;118:1561–1575. [CrossRef]

[19] Pal JS, Small EE, Eltahir EAB. Simulation of regional-scale water and energy budgets: Representation of subgrid cloud and precipitation processes within RegCM. J Geophys Res Atmos 2000;105:29579–29594. [CrossRef]

[20] Zeng X, Zhao M, Dickinson RE. Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using toga coare and tao data. J Clim 1998;11:2628–2644. [CrossRef]

[21] Kiehl JT, Hack JJ, Bonan GB. Description of the NCAR community climate model (CCM3). National Center for Atmospheric Research, Boulder. Climate and Global Dynamics Div.; 1996.

[22] Kuzu SL, Yavuz E. Comparison of RegCM dust schemes by monitoring an aeolian dust transport episode. Air Qual Atmos Health 2021;14:2047–2057. [CrossRef]

[23] Kok JF. A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle. Proc Natl Acad Sci USA 2011;108:1016–1021. [CrossRef]

[24] Earth Observatory. Natural Event. Available at: https://earthobservatory.nasa.gov/topic/natural-event. Accessed on March 23, 2021.

[25] Choobari OA, Zawar-Reza P, Sturman A. The global distribution of mineral dust and its impacts on the climate system: A review. Atmos Res 2014;138:152–165. [CrossRef]

[26] Hansell RA, Tsay SC, Ji Q, Hsu NC, Jeong MJ, Wang SH, et al. An assessment of the surface longwave direct radiative effect of airborne Saharan dust during the NAMMA field campaign. J Atmos Sci 2010;67:1048–1065. [CrossRef]

[27] Liao H, Seinfeld JH. Radiative forcing by mineral dust aerosols: sensitivity to key variables. J Geophys Res Atmos 1998;103:31637–31645. [CrossRef]

[28] Kaskaoutis DG, Dumka UC, Rashki A, Psiloglou BE, Gavriil A, Mofidi A, et al. Analysis of intense dust storms over the eastern Mediterranean in March 2018: Impact on radiative forcing and Athens air quality. Atmos Environ 2019;209:23–39. [CrossRef]

[29] Pérez C, Nickovic S, Pejanovic G, Baldasano JM, Ozsoy E. Interactive dust-radiation modeling: A step to improve weather forecasts. J Geophys Res Atmos 2006;111:16206. [CrossRef]