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CLEAR-SKY RADIATIVE AND TEMPERATURE EFFECTS OF DIFFERENT AEROSOL CLIMATOLOGIES IN THE COSMO MODEL

ABSTRACT. We estimated the effects of the different aerosol climatologies in the COSMO mesoscale atmospheric model using long-term aerosol measurements and the accurate global solar irradiance observations at ground at the Moscow State University Meteorological Observatory (Russia) and Lindenberg Observatory (Germany) in clear sky conditions. The differences in aerosol properties have been detected especially during winter months. There is a better agreement of MACv2 aerosol climatology with measurements for Moscow conditions compared with Tegen aerosol climatology. However, we still have a systematical negative bias of about 2-3% in global solar irradiance at ground for both sites. A noticeable sensitivity of air temperature at 2 meters to the net radiation changes of about 1°C per 100 Wm-2 due to aerosol has been evaluated, which approximately is around -0.2 – -0.3°C, when accounting for real aerosol properties.

KEY WORDS: aerosol, radiative processes, COSMO model, aerosol climatologies, temperature effects, AERONET.

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INTRODUCTION

Aerosol is one of the key factors, which has a significant influence on scattering and absorption of solar irradiance in the atmosphere and on climate (Boucher et al. 2013). Due to large variation in its composition aerosol may have different optical properties. The uncertainty in aerosol properties of the atmosphere affects the accuracy of radiative flux simulation and may provide significant errors in evaluating different parameters in numerical weather prediction (NWP) models (Tanre et al. 1984; Ritter and Geleyn 1992).

There are several approaches to account for aerosol properties in the models: to compute directly their properties or to use various aerosol climatologies. The first approach is computationally very time consuming and need exact data on emission rates of different aerosol precursors, which are often unavailable. Therefore, the second approach (the application of aerosol climatologies) is usually applied in the different atmospheric models. One of the well-known atmospheric models is the COSMO (COnsortium for Small-scale MOdeling) model, which is widely used in different countries for the operational weather forecasting and climate modelling (www.cosmo-model.org).

Different aerosol climatologies optionally can be used in the COSMO model. The Tanre aerosol climatology (Tanre et al. 1984) is characterized by large biases compared with the observations. Another aerosol climatology is a well-known Tegen aerosol dataset (Tegen et al. 1997), which is usually applied in the model computations. Since recent time a new aerosol MACv2 (Max Planck Institute Aerosol Climatology version 2) climatology developed by Kinne et al. (2013) is also available as the input aerosol dataset in the COSMO model. However, the quality of the Tegen and MACv2 aerosol climatologies has not been thoroughly tested using long-term ground-based aerosol datasets. Therefore, the main objectives of the study were the following:

1. To evaluate the uncertainties of Tegen and MACv2 aerosol climatologies against long-term aerosol datasets at the Moscow State University Meteorological Observatory (MSU MO, Russia) and Lindenberg Observatory (LO, Germany) and to estimate the radiative effects of these uncertainties for clear sky conditions.

2. To test radiative simulations in COSMO model against radiative density flux measurements (global solar irradiance) at both sites in cloudless situations.

3. To estimate temperature effects of aerosol properties using COSMO model.

We would like to emphasize that since the locations of the sites are inside the Eurasian continent, the obtained results concern mainly the effects of continental aerosols.

MATERIALS AND METHODS

The COSMO model is a non-hydrostatic mesoscale atmospheric model (Doms et al. 2011a; Doms et al. 2011b). In Russian Federation it is being utilized in operational mode as a COSMO-Ru configuration (Rivin et al. 2015). Model has been actively developed during last several years. However, the methods implemented for radiation transfer calculations and the corresponding databases remained unchanged. An algorithm of radiation transfer calculation is based on the two-stream approach and takes into account the extinction by atmospheric gases (H_2O, CO_2, O_3, O_2, CH_4), clouds and aerosols. Radiation transfer equation is solved for several spectral intervals: 3 within solar and 5 within thermal part of spectrum (Ritter and Geleyn, 1992). Prognostic or diagnostic model variables determine optical properties of atmospheric layers. Content of water vapor and cloud liquid/ice water, as well as air temperature are prognostic variables while ozone, carbon dioxide and aerosols contents are specified according to the prescribed climatological values. As it was already mentioned two variants of aerosol climatology (Tanre et al. 1984, Tegen et al. 1997) can be chosen for simulations in the COSMO model, but recently the new MACv2 aerosol climatology has been also implemented within the framework of the international

$T^2(RC)^2$ (Testing and Tuning of Revised Cloud Radiation Coupling, 2015-2019) project.

In the Tegen climatology the optical properties of 5 aerosol types (sea salt, soil dust, organic, black carbon, sulfate aerosol) are considered. The climatology has monthly temporal resolution and 4°x5° horizontal spatial resolution. The MACv2 climatology takes into account for the recent developments in aerosol modelling and experimental data and is a combination of the model ensemble data and observations. It provides all necessary aerosol input parameters for the radiative computations in different spectral intervals for fine and coarse aerosol modes. It is also possible to retrieve an anthropogenic aerosol mode from this climatology. MACv2 aerosol climatology has monthly temporal resolution and provides 1°x1° spatial fields.

Testing the aerosol climatologies was made against long-term aerosol datasets at the MSU MO (www.momsu.ru) and Lindenberg observatory (https://rcccm.dwd.de/EN/aboutus/locations/ observatories/mol/mol.html). The MSU MO site (thereafter, Moscow) is a part of AERONET (Aerosol Robotic NETwork) network (Holben et al. 1998) and the aerosol dataset applied in the study includes the continuous long-term measurements over 2001 – 2014 period (version 2.0, level 2.0) with additional cloud screening and NO_2 correction according to the approach described in (Chubarova et al. 2016). At the Lindenberg Observatory (thereafter, Lindenberg) the AERONET site has been in operation only since 2013. Therefore, for increasing the volume of data for the statistical analysis we also included the aerosol dataset obtained there from Precision Filter Radiometer (PFR) aerosol sun photometers measurements over the 2003-2013 period.

We used radiative measurements by Kipp&Zonen CNR-4 net radiometer at Moscow and by the BSRN (Baseline Surface Radiation Network) type of radiative instruments – at Lindenberg. We focused mainly on the measurements of global solar irradiance. However, for obtaining surface albedo we also used reflected shortwave irradiance. Water vapor retrievals were also obtained using AERONET algorithm at 940 nm channel. In addition, we used upper – air soundings (temperature, water vapor) at both sites as well as ozonezonde dataset - at Lindenberg. At Moscow air temperature measurements at 2 meters were analyzed using routine observations and Vaisala automatic weather station. At Lindenberg the data from the automatic weather station were used. In order to reveal clear sky situations we used hourly visual observations at both sites. The data were chosen over the snowless period during 2014-2015 when the absence of cloudiness was recorded both in observations and COSMO model output for more than 5-hour continuous series. As a result, for Moscow we identified 11 days and for Lindenberg – 6 days with these conditions. In overall, 103 cases of one-hour global solar irradiance averages supported with different meteorological and aerosol datasets were used in the comparisons.

RESULTS AND DISCUSSION

Analysis of aerosol climatologies

Long-term measurements of different aerosol properties using AERONET at the Moscow MSU MO and AERONET/PFR data at the Lindenberg Observatory provide a testbed for comparisons of the aerosol climatologies. Fig. 1 demonstrates seasonal changes in main aerosol radiative parameters (aerosol optical thickness at 550nm (AOT), single scattering albedo (SSA), and factor of asymmetry ASY)[1] obtained from the aerosol climatologies and long-term observations

[1] *AOT is determined as* $AOT = -\cos Z_0{}^\circ In \frac{S_\lambda}{S_{O\lambda}}$ *, where Zo-zenith angle,* S_λ*- spectral direct irradiance ,* $S_{0\lambda}$*-spectral direct irradiance at the TOA.* $SSA_\lambda=\beta_{sc\lambda}/\beta_{ext\lambda}$*, where* $\beta_{ext\lambda}$ *-extinction coefficient,* $\beta_{sc\lambda}$*-scattering coefficient (1/cm).* $g=\frac{1}{2}\int_{-1}^{1}\cos\theta P(\theta)d(\cos\theta)$*, where θ is the scattering angle, P(θ)is the aerosol phase function;*

at both sites. We used median values in measurement dataset to avoid the bias due to fire smoke aerosol, which dominated in Moscow region in some months of 2002 and 2010. One can see an overestimation of MACv2 and Tegen climatologies in most months for both sites. For Moscow conditions the AOT seasonal cycle in Tegen climatology is characterized by much less seasonal variations (variation coefficient, VC=14%), while MACv2 climatology has similar seasonal changes compared with the observations which in turn have the highest variations (respectively VC=26% and VC=34%). However, in winter months the AOT even in MACv2 climatology is higher than the observed data. Presumably, it is due to cloud contamination effect which does not fully accounted while compiling the model and standard AERONET observations in MACv2 dataset (see the discussion on the quality of standard V2 AERONET version in (Chubarova et al. 2016)). In addition, in the MACv2 climatology there is a shift of local AOT minimum from June to May.

For Lindenberg both climatologies have much smaller seasonal changes compared with observations and significantly overestimate AOT. Variation coefficients are similar for all datasets: 20%, 18% and 21% respectively. Single scattering albedo (SSA) obtained from aerosol climatologies is in a good agreement with the observations

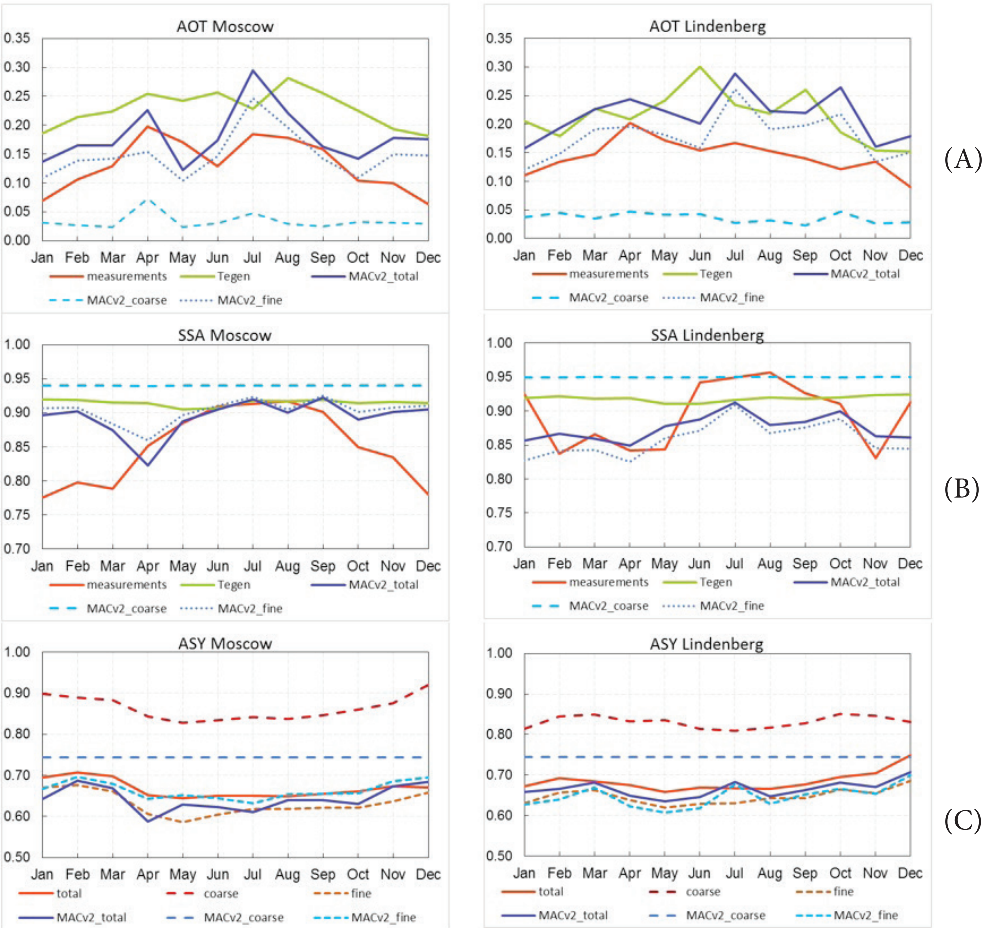


Fig. 1. Monthly variability in aerosol optical thickness at 550 nm (AOT) (a), single scattering albedo (SSA) (b) and asymmetry factor (ASY) (c) according to different aerosol climatologies for Moscow and Lindenberg

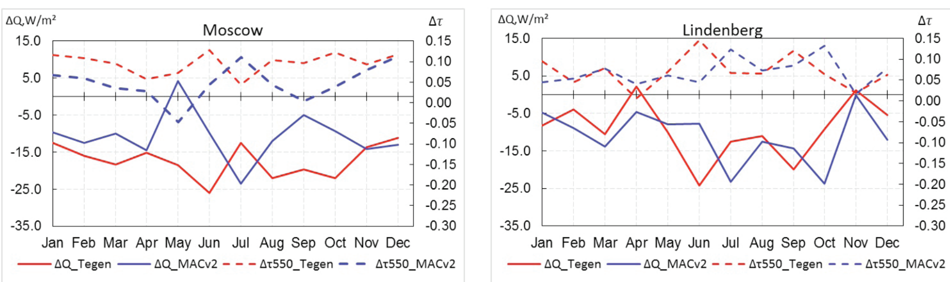
during warm period (Fig. 1b). However, in winter one can see its noticeable overestimation in both climatologies (note, that we use final calibrated SSA data at level 1.5 due to the lack of statistics at level 2, but the quality of these data has been thoroughly tested). We should note that at both sites SSA values from Tegen climatology practically do not vary throughout a year, while MACv2 SSA variations are closer to the observed values. Asymmetry factor from MACv2 also demonstrates a satisfactory agreement with the observations (Fig. 1c). However, for the coarse aerosol mode in real conditions it is much higher than that in MACv2 climatology. Since a fraction of this aerosol mode is small this inconsistency does not affect the total values of asymmetry factor, which agree well with the observations.

Using the obtained aerosol parameters from the climatologies and the observations we calculated global solar irradiance (Q) at ground and the corresponding difference ($\Delta Q=Q_{climatalogy}-Q_{obs}$) (Fig. 2). Radiative simulations were fulfilled using a modified CLIRAD radiative transfer code (Tarasova and Fomin, 2005) for noon conditions for the central day of a month. For Moscow (Fig. 2a) for the Tegen climatology Q values are underestimated on 11-26 W/m^2 while for MACv2 the difference É¢Q varies from -23 to +4 W/m^2. Annual mean difference for the MACv2 climatology is closer to the observations than that for the Tegen climatology (-10.8 W/m^2 compared with -17.3 W/m^2).

For Lindenberg both climatologies provide underestimation of global solar irradiance of about 10 W/m^2 for annual means compared with the Q values simulated with the aerosol input parameters taken from observations. Both of them have lower solar irradiance for almost all months mainly due to the overestimated *AOT*. At the same time, for the Tegen climatology in April and November in conditions with only small *AOT* overestimation (ΔAOT = 0.01-0.02) we observe even positive bias in solar irradiance (1-2 W/m^2) due to the large difference in SSA. For these months Tegen climatology provides much higher SSA values (0.92) compared with the observations (0.85). Note, that in Tegen climatology 10-20 % of aerosol optical thickness over Europe relates to black carbon aerosol, that should significantly increase the absorption especially in visible spectrum. However, this is not enough to explain the lower SSA values observed at Moscow site, which probably occur due to smaller aerosol size.

Comparisons of global solar irradiance

The comparisons between simulated and observed global solar irradiance datasets were fulfilled for different aerosol conditions and solar zenith angles. The examples of the diurnal cycles of simulated and observed *Q* values for a particular day in Moscow and Lindenberg are shown in Fig. 3. One can see that for both sites the observations of global irradiance are higher than the COSMO



(A) (B)

Fig. 2. The difference in monthly mean aerosol optical thickness compared with long-term aerosol measurements and absolute difference in global solar irradiance computed with different aerosol climatologies against simulations with the observed aerosol parameters for Moscow (a) and Lindenberg (b). Simulations were made for local noon

model simulations for both climatologies mainly due to overestimating in their AOT values. These results are in agreement with those obtained using the CLIRAD radiative transfer simulations with different aerosol datasets (see Fig.2). The overall differences in AOT for the selected clear sky cases and in global shortwave irradiance Q are shown in Fig.4 for both sites. The application of MACv2 climatology provides better agreement: the difference *ΔAOT* decreases from -0.16 to -0.12 for Moscow and from -0.23 to -0.14 for Lindenberg. These differences are statistically significant at α = 0.05. However, the overestimation of *AOT* is still large. This positive bias results in the underestimation by 2-3 % in global solar irradiance simulated by COSMO radiative algorithm for both aerosol climatologies. The differences in *dQ/Q* % between the climatologies are not statistically significant. We should note that the relative difference (*dQ/Q*) should be much higher, however, the old radiative scheme used in COSMO model is responsible for the 5 % positive bias in radiative simulations (Poliukhov et al. 2017a). The exact radiative transfer simulations would have the overall bias of about 7-8 % for the same cases.

Temperature effects

The instant temperature effects of aerosol were analyzed using different COSMO model

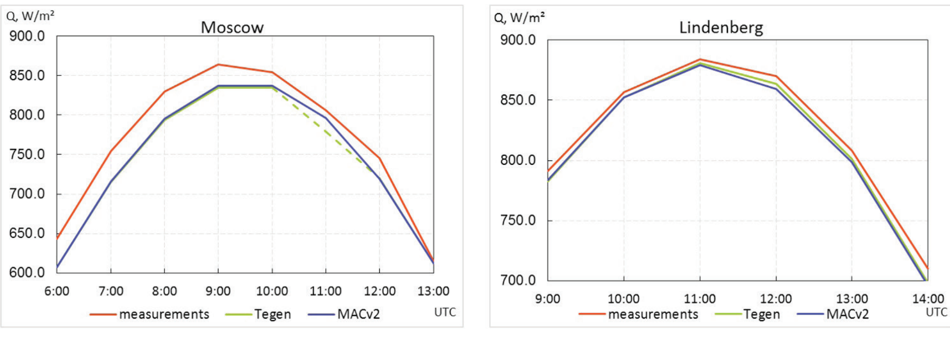


Fig. 3. The examples of diurnal cycle in the global solar irradiance (Q) from the measurement data and COSMO model with different (Tegen and MACv2) aerosol datasets in clear sky conditions in Moscow (04.07.2015) (a) and Lindenberg (02.07.2015) (b)

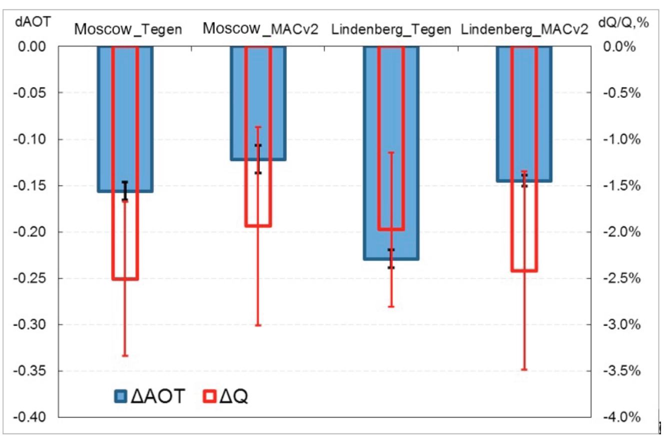


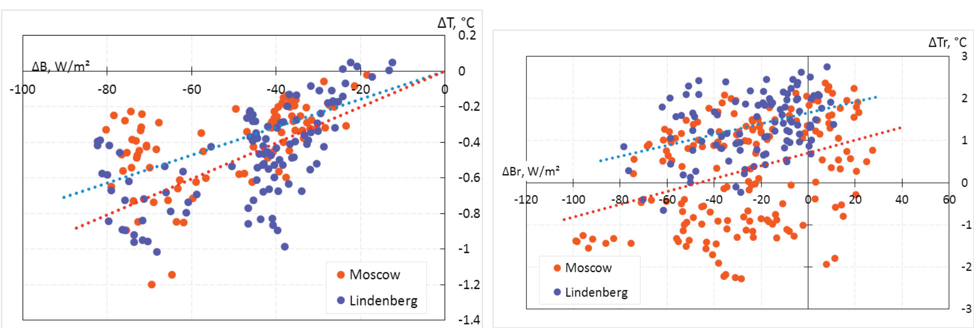
Fig. 4. The mean difference in aerosol optical thickness at 550nm ($\Delta AOT=AOT_{obs}-AOT_{model}$) and in global solar irradiance *$dQ/Q=(Q_{model}-Q_{obs})/Q_{obs}$,%)* according to COSMO model runs and observations at Moscow and Lindenberg. Clear sky conditions

runs with different aerosol climatologies and with zero aerosol conditions for the same clear sky days which are used in the analysis. Since aerosol over continental Europe is characterized by weak absorption in visible spectral range it should provide the negative effect on temperature at ground level. To account the changes in all the aerosol properties (AOT, SSA, factor of asymmetry) we chose net shortwave irradiance at ground as an aggregated characteristic. Net shortwave radiation is the difference in downwelling and upwelling shortwave irradiance and it also accounts for surface albedo effects, which play, however, minor role in our snowless conditions. We analyzed the dependence of difference in air temperature at 2 meters (ΔT) simulated in conditions with and without aerosols to the corresponding difference in net radiation (ΔB) to estimate the temperature sensitivity to aerosol. The results are shown in Fig. 5a. The negative values in net radiation at ground level due to aerosol provide negative effects on temperature difference. The difference in temperature should reach zero when ΔB=0 in conditions with zero AOT.

For Moscow and Lindenberg we obtained a pronounced statistically significant dependence which provides similar aerosol temperature effects. For Moscow this effect is about 0.8 ±0.2°C per 100 W/m^2, which is in agreement with our previous estimates (Poliukhov et al. 2017b), and for Lindenberg this value is about 1.0±0.3°C per 100 W/m^2 with correlation coefficients r=0.5-0.6. The observed deviations may occur due to some slight variations in other parameters (water vapor, differences in profiles, etc.) in COSMO model runs.

Another testing was made using similar approach but in comparisons with observations. In this case we should have much more deviations due to the influence of the uncertainty in actual atmospheric parameters which may differ from the simulated ones. Fig. 5b demonstrates the difference between the observed and simulated temperature at 2 meters (ΔTr) as a function of the difference between observed and simulated net radiation (ΔBr). We obtained the same tendency with the increase of positive temperature shift with positive bias in net radiation, which is mainly a function of aerosol loading. The gradients are similar to those obtained in the previous pure model experiment (see Fig. 5a). These results confirm the pronounced temperature sensitivity to aerosol loading via its influence on net radiation at ground.

For estimating typical aerosol temperature effects for Moscow and Lindenberg, the changes in net radiation due to the changes in corresponding aerosol properties against aerosol–free conditions should be used. These temperature effects comprise about -0.2 – -0.3°C for typical aerosol over these sites.



(A) (B)

Fig. 5. The sensitivity of temperature at 2 meters to the shortwave net radiation changes. a) Temperature variations versus the changes in shortwave net radiation simulated by COSMO model with and without aerosol; b) Difference between the observed and simulated temperature as a function of the difference between the observed and simulated shortwave net radiation

CONCLUSIONS

The application of the new MACv2 climatology in COSMO model in comparison with the Tegen climatology allowed us to evaluate the uncertainties in radiative fluxes and temperature at 2 meters for the cloudless atmosphere over the continental area in Central and Eastern Europe.

The comparisons with long-term aerosol measurements revealed some deficiency in MACv2 climatology in winter months and the bias in May-June local AOT maxima. The Tegen climatology was characterized by much higher values than the observations and does not reproduce the existing seasonal cycle in different characteristics.

The results obtained for two sites (Moscow, Russia and Lindenberg, Germany) have revealed the same tendency of the AOT overestimation in both aerosol climatologies (with smaller difference for the new MACv2 climatology) and in the corresponding differences of global solar irradiance between the model simulations and observations.

Using both model and measurement datasets we showed that MACv2 climatology provides better agreement with observations in Moscow. However, still the difference with observations was not small that resulted in systematical negative bias of about 2-3 % in global solar irradiance at ground estimated in the model.

The analysis of aerosol temperature effects in the model has revealed the sensitivity of temperature at 2 meters to the changes in net radiation at ground due to aerosol of about 0.8-1°C per 100 W/m^2. The existence of this dependence was confirmed by the comparisons between the simulated data and observations.

Hence, we can state that continental type of aerosol causes a pronounced temperature effect, and therefore the application of accurate aerosol may improve the temperature forecast in COSMO model. This could be possible via application and further development of COSMO-ART (Aerosols and Reactive Trace Gases) or CAMS (Copernicus Atmosphere Monitoring Service) aerosol forecast schemes.

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REFERENCES

Boucher O., Randall D., Artaxo P., Bretherton C., Feingold G., Forster P., Kerminen V.-M., Kondo Y., Liao H., Lohmann U., Rasch P., Satheesh S.K., Sherwood S., Stevens B., and Zhang X.Y. (2013). Clouds and Aerosols. In:T.FStocker, ed.,ClimateChange 2013:The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change1st ed. New York, Cambridge University Press, pp 571-659.

Chubarova N. Y., Poliukhov A. A., and Gorlova I. D. (2016). Long-term variability of aerosol optical thickness in Eastern Europe over 2001–2014 according to the measurements at the Moscow MSU MO AERONET site with additional cloud and NO 2 correction. Atmospheric Measurement Techniques, 9(2), pp. 313-334.

Doms G. and Baldauf M. (2011a). A Description of the Nonhydrostatic Regional COSMO model. Part I: Dynamics and Numerics. Consortium for Small-Scale Modelling, Deutscher Wetterdienst (DWD).

Doms G., Foerstner J., Heise E., Herzog H.-J., Mironov D., Raschendorfer M., Reinhardt T., Ritter B., Schrodin R., Schulz J.-P., and Vogel G. (2011b). A Description of the Nonhydrostatic Regional

COSMO-Model. Part II: Physical Parameterization. Consortium for Small-Scale Modelling, Deutscher Wetterdienst (DWD).

Holben B.N., Eck T.F., Slutsker I., Tanre D., Buis J.P., Setzer A., Vermote E., Reagan J.A., Kaufman Y., Nakajima T., Lavenu F., Jankowiak I., and Smirnov A. (1998). AERONET—A federated instrument network and data archive for aerosol characterization. Remote sensing of environment, 66(1), pp 1-16.

Polukhov A.A., Chubarova N.Y., Rivin G.S., Shatunova M.V. and Tarasova T.A. (2017a). Assessment of the clear sky radiation simulated using COSMO model based on precise calculation and observation in Moscow. Proceedings of Hydrometcentre of Russia. 364. pp.38-52.

Poliukhov A., Chubarova N., Kinne S., Rivin G., Shatunova M., and Tarasova T. (2017b). Comparison between calculations of shortwave radiation with different aerosol datasets and measured data at the MSU MO (Russia). AIP Conference Proceeding. 1810(1), p. 100006.

Tanré D., Geleyn J. F., and Slingo J. M. (1984). First results of the introduction of an advanced aerosol-radiation interaction in the ECMWF low resolution global model. Aerosols and their climatic effects, pp 133-177.

Tarasova T. A. and Fomin B. A. (2007). The use of new parameterizations for gaseous absorption in the CLIRAD-SW solar radiation code for models. Journal of Atmospheric and Oceanic Technology, 24(6), pp. 1157-1162.

Tegen I., Hollrig P., Chin M., Fung I., Jacob D., and Penner J. (1997). Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results. Journal of Geophysical Research: Atmospheres, 102(D20), pp 23895-23915.

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