Air quality and cloud effects on surface solar radiation over urban and rural areas in Greece

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Abstract: In this work, the effects of aerosols, clouds and tropospheric NO_2 on surface solar radiation (SSR) are studied over urban and rural areas in Greece by performing simulations with the Santa Barbara DISORT Atmospheric Radiative Transfer (SBDART) model for the period 2005-2019. Ground-based and satellite observations are used as input. More specifically, aerosol optical properties are taken from Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the EOS Aqua satellite, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite and the MACv2 climatology, cloud optical properties are taken from MODIS/Aqua, O_3 and NO_2 vertical column data from the Ozone Monitoring Instrument (OMI) aboard the EOS Aura satellite and surface albedo data from the CLARA-A2 satellite product. The calculated SSR values are compared against satellite-based observations from the Satellite Application Facility on Climate Monitoring (CM SAF) and measurements from ground stations. In order to assess the radiative effect of each parameter on SSR, simulations with and without the presence of aerosols, clouds and tropospheric NO_2 are performed discussing the observed differences between rural and urban areas.

1 Introduction

Surface solar radiation (SSR) affects many climatic elements including the evapotranspiration, the hydrological cycle, the photosynthesis and plant productivity, the atmospheric and oceanic circulation, the global energy budget, etc. (e.g. Wild et al. 2008, Mercado et al. 2009). The importance of solar radiation led to the monitoring of SSR levels since the first decades of the 20th century, the first station being established in 1923 in Sweden. Today, SSR measurements are available via global ground-based radiation networks (e.g. GEBA, BSRN). Obviously, these networks cannot measure SSR consistently at every single spot on Earth, a gap filled by satellite measurements during the last four decades (since the early 1980s). Various satellite missions played a vital role in improving our knowledge on the Earth energy balance. Down and up-welling solar radiation at the top of the atmosphere (TOA) is measured directly by satellite sensors while the surface solar radiation fluxes are estimated indirectly with the synergistic use of radiative transfer models, empirical models or machine learning techniques with satellite and ground-based measurements of various physical parameters. Some of the most popular SSR satellite products (e.g. CM SAF) are derived taking into account aerosol climatologies rather than measurements and hence they cannot capture accurately the temporal variability induced by interannual or abrupt changes in atmospheric aerosol loading. This could be crucial for regions like the Eastern Mediterranean which is at the crossroads of different transport pathways that bring air masses from Europe, Africa and Asia leading to significant aerosol variability (Lelieveld et al. 2002).

SSR in the area depends on a number of parameters, the most important being clouds, aerosols, and water vapor (Alexandri et al. 2017). This study was based on climatological data showing that clouds are responsible for a decrease of the solar radiation of ~63 W/m^2 on an annual basis, with aerosols (~18 W/m^2) and water vapor (~9 W/m^2) following. SSR might also be affected by ozone (O_3) levels and some trace gases (e.g. nitrogen dioxide - NO_2) depending on the season and the local human activities. Specifically, for the effect of NO_2 on SSR to our knowledge there are only a couple of studies which suggest that this gas may potentially play a significant role in local radiative forcing under certain conditions and over heavily polluted areas (Solomon et al. 1999, Vasilkov et al. 2009).

Here, we study for the first time the radiative effect of aerosols and tropospheric NO_2, two basic air quality indexes, and clouds together. This research is implemented within the project "Long-term variability of solar radiation in Greece: effect of air quality and clouds" and focuses on Greece for the period 2005-2019. Within the project, a system that incorporates satellite-based observations, climatological data and a radiative transfer model has been developed. The system allows for calculating the radiative effect of aerosols, clouds and tropospheric NO_2. In this paper, we show selected results for two areas in Greece, Thessaloniki, a typical coastal city in the heart of Eastern Mediterranean (urban area) and a rural area close to Herakleion, Crete (at the premises of Hellenic Center for Marine Re-search).

2 Data and Methodology

2.1 Data

A core product of this research is the MODIS/Aqua Collection 6.1 Level-2 aerosol and cloud product (MYDATML2). For aerosols, the merged "Dark Target" and "Deep Blue" algorithm aerosol optical depth (AOD_{550}) dataset is used while for clouds, the cloud fraction (CF), cloud optical thickness (COT), cloud effective radius (CER), cloud top pressure (CTP), cloud phase (CP; liquid, ice, undetermined), and precipitable water (PW; near-infrared algorithm) datasets are used. Apart from AOD_{550}, the other optical properties are taken from the MACv2 aerosol climatology, namely single scattering albedo (SSA), asymmetry factor (ASY) and AOD at eight different wavelengths (350, 450, 550, 650, 1000, 1600, 2200 and 3000 nm). To account for the vertical variability of aerosols with the atmosphere, aerosol extinction coefficient profiles at 532 nm from the CALIOP/CALIPSO monthly Level-3 product are used. From OMI/AURA we take O_3 total column data (Level-3, OMTO3d) as well as tropospheric and stratospheric NO_2 data (Level-2, QA4-ECV). Broadband surface albedo (SAL) data are taken from the CLARA-A2 satellite product which is based on measurements from the AVHRR sensors onboard polar orbiting NOAA and METOP satellites while surface topography is from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) elevation model. Finally, SSR data from the CM SAF SARAH-2 satellite dataset and ground stations were used for validation purposes.

2.2 Methodology

For the scope of this research an updated version of the SBDART radiative transfer model has been developed (hereafter denoted as SBDART-NO2). More specifically, NO_2 absorption cross-sections from Burrows et al. (2008) have been incorporated in the model so that absorption of solar radiation by NO_2 at the 231-794 nm spectral range is taken into account. SBDART has been used in aerosol and cloud studies in the past and hence a more detailed representation of NO_2 absorption in the spectral region where the gas primarily absorbs was missing. On top of that, we have also modified the original code so that it accepts tropospheric (0-10 km) and stratospheric (10-100 km) NO_2 column data. The NO_2 column input data modify the SBDART predefined profiles based on US standard atmosphere pressure data.

An IDL automated programming tool was developed that "feeds" the SBDART radiative transfer model with various monthly gridded datasets at a uniform spatial resolution (here 0.125° x 0.125° ~ 12.5 km) and executes the model, assuming a monthly mean daily solar zenith angle (SZA) and daytime duration based on geometrical calculations. SBDART-NO_2 is executed 3 times per month, one assuming clear skies, one assuming skies covered by liquid clouds and one assuming skies covered by ice clouds. To account for the relative contribution of each of the three runs to each grid cell's monthly SSR value the system weights with the liquid and ice cloud fraction and the clear sky part of each grid cell.

As mentioned above the data used here were gridded at a common 0.125° x 0.125° spatial resolution. This was selected as a good compromise between the pixel resolution of the different core products used here, namely the MODIS aerosol dataset (10 km at nadir), the cloud datasets (5 km at nadir) and the OMI/AURA NO_2 data (13 km x 24 km at nadir). A common gridding methodology was followed for those 3 products on a daily basis. Each observation was weighted by its fractional area (%) within the grid cell when averaging on a daily basis. Finally, the data were averaged on a monthly basis. For all the other products a bilinear interpolation has been used and climatological monthly means were calculated.

Our system is used here for the grid cells covering two areas in Greece an urban (Thessaloniki) and a rural one (Herakleion). Our SSR calculations are compared against satellite-based observations from the CM SAF and pyranometric measurements from the stations located in the two areas. The radiative effect of aerosols (direct), clouds and tropospheric NO_2 (direct) on SSR is shown along with the radiative efficiency of aerosols and tropospheric NO_2. The radiative effect of each component is equal to the difference between two simulations, one with and one without this component.

3 Results

Our SSR monthly data were compared against ground-based pyranometric observations from the stations of Thessaloniki and Herakleion for the period 2005-2013. Overall, there is a good agreement between our SBDART simulated data and the ground data with a correlation coefficient R of 1 and a normalized mean bias (NMB) of -12% and -8%, respectively. We performed various tests, including changes in the aerosol profile, using ground-based ASY, SSA and

Ångström exponent measurements from the AERONET, using climatological values for O_3 and water vapor, etc. The observed underestimation persisted, leading us to the conclusion that it could possibly be related to the cloud retrievals from MODIS/Aqua and the fact that these data, which are retrieved at noon, are assumed to be representative for the whole day.

Our results for Thessaloniki are very close to the values (bias of ~10%) given for the same station in the electronic supplement of Papadimas et al. (2012) where a similar approach with the one we use was followed. The comparison with CM SAF SARAH-2 returns similar results with an R of 1 and a NMB of -13% and -9%, respectively.

The radiative effect of aerosols (ARE) on annual basis is estimated at ~-12 W/m^2 over Thessaloniki and ~-13 W/m^2 over Herakleion while in both cases the radiative effect of tropospheric NO_2 is negligible, 0.11 and 0.05 W/m^2 respectively. The radiative effect of liquid and ice clouds is estimated at ~-39 and ~-24 W/m^2 over Thessaloniki and ~-36 and ~-17 W/m^2 over Herakleion in line with Alexandri et al. (2017). These results are shown in Figure 2. We see that despite that Herakleion is a rural station ARE is comparable to that over Thessaloniki as it accepts pollution from the North and the local sources but most importantly it is heavily affected by episodic Sahara dust events. ARE values calculated here are comparable to the average values calculated for the whole Mediterranean Basin (-16.5 W/m^2) by Papadimas et al. (2012).

The radiative efficiency of aerosols (AReff) and tropospheric NO_2 (NO_2Reff) is shown in Figure 3. Over Thessaloniki AReff is estimated at -92 W/m^2 per unit AOD while over Herakleion at -62 W/m^2 per unit AOD. The corresponding values for NO_2Reff are -0.0049 W/m^2 and -0.0879 W/m^2 per 1 x 10^{15} molecules/cm^2.

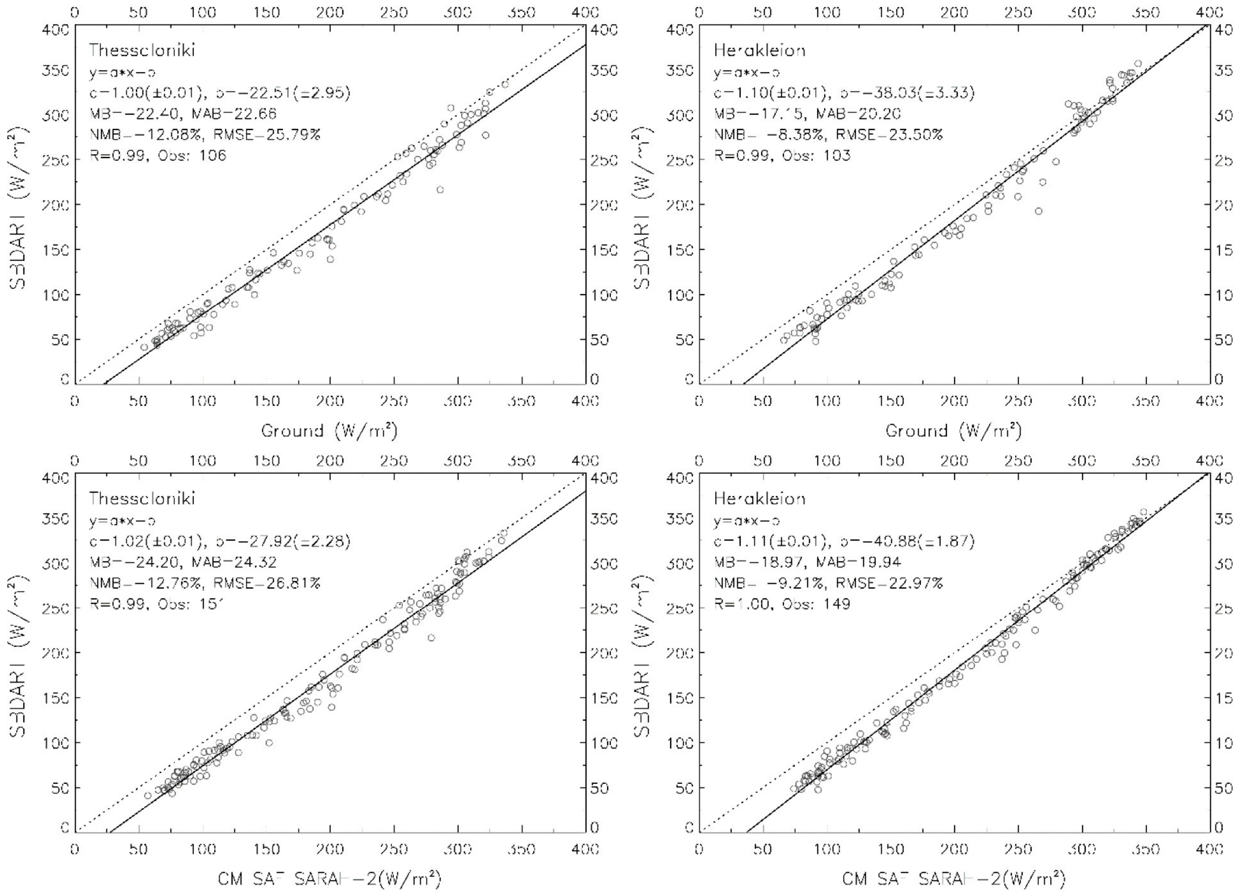

Fig. 1. Evaluation of our simulations against ground-based measurements for the period 2005-2013 for Thessaloniki (upper left panel) and Herakleion (upper right panel). The lower panels show a comparison against data from the CM SAF SARAH-2 satellite dataset.

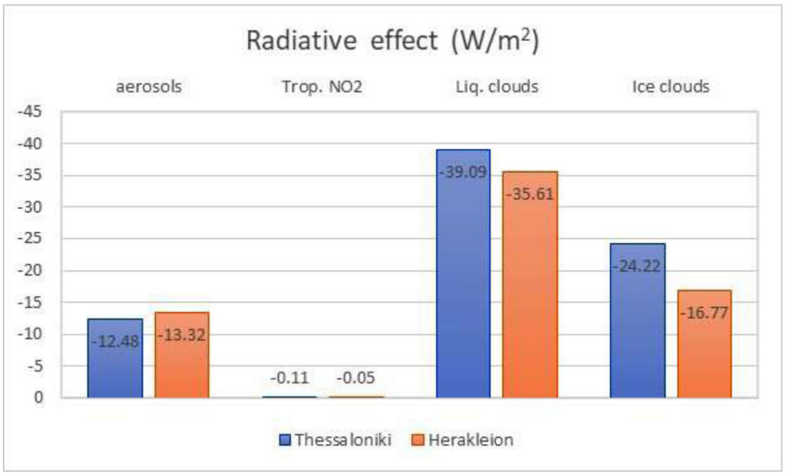

Fig. 2. Radiative effect of aerosols, tropospheric NO_2, and liquid and ice clouds over Thessaloniki and Herakleion on an annual basis for the period 2005-2019.

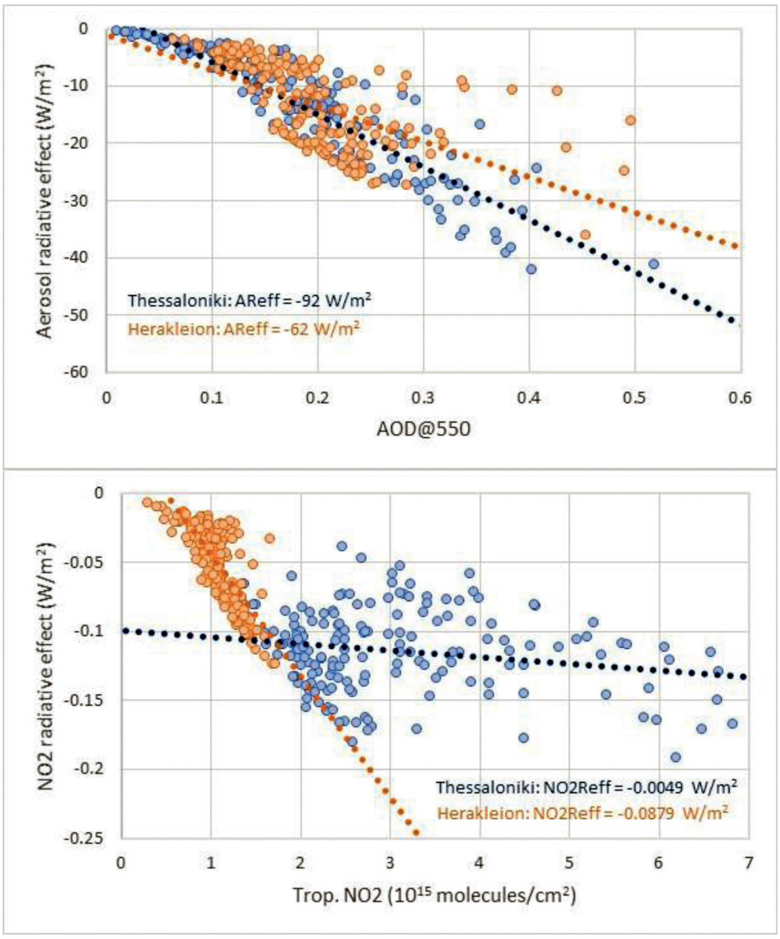

Fig. 3. Radiative efficiency of aerosols over Thessaloniki and Herakleion on an annual basis for the period 2005-2019 (upper panel). The same for tropospheric NO_2 is shown in the lower panel.

4 Conclusions

Here we show for the first time the radiative effect of aerosols and tropospheric NO_2, two basic air quality indexes, and clouds together over two areas in Greece, Thessaloniki (urban) and Herakleion (rural). For the scope of this research a system based on a modified version of the well known SBDART radiative transfer model that accounts for NO_2 absorption in the UV/VIS was developed. Our SSR simulations show a good agreement with ground and satellite-based observations. ARE is estimated at ~-12 W/m² over Thessaloniki and ~-13 W/m² over Herakleion with the radiative effect of tropospheric NO_2 being negligible. The radiative effect of liquid and ice clouds is estimated at ~-39 and ~-24 W/m² over Thessaloniki and ~-36 and ~-17 W/m^2 over Herakleion. Over Thessaloniki and Herakleion, AReff is estimated at -92 W/m^2 and -62 W/m^2 per unit AOD, respectively, while NO_2Reff is very low. Concluding, it is shown that clouds and aerosols are driving the radiative balance in the area while NO_2 has a negligible effect.

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