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Cloud effects on the solar and thermal radiation budgets of the Mediterranean basin

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ABSTRACT

The cloud effects on the shortwave (SW), longwave (LW) and net all-wave radiation budgets of the Mediterranean basin were computed using a detailed radiative transfer model together with satellite and reanalysis data for surface and atmospheric properties. The model radiation fluxes at TOA were validated against CERES and ERBE satellite data, while at the Earth's surface they were validated against ground-based GEBA and BSRN station measurements. The cloud radiative effects were obtained for low, middle, high-level clouds, and for total cloud cover. Overall for the basin, the effect on solar radiation is to produce radiative cooling at the top of atmosphere (TOA) and at the surface that more than balances the warming effects on terrestrial radiation. The result is a net radiative cooling at TOA and at the surface, equal to -18.8 and -15.9 Wm^{-2}, respectively. The low-level clouds are most important for the TOA budget through significant SW reflection and little LW emission to space. High clouds play an important role in net surface cooling (-9.8 Wm^{-2}) through the combination of SW reflection to space and a much reduced LW warming effect at the surface. The geographical patterns of the effects are mainly characterized by a strong south to north increasing gradient. The seasonal variation of net radiative effects is dominated by solar radiation with maxima in spring and minima in winter.

1. Introduction

Clouds strongly affect the radiation budget of the Earth-atmosphere system and it has been long recognized (e.g. Abbot and Fowle, 1908; London, 1957; Manabe and Wetherald, 1967) that they modulate the global albedo, temperature distribution and the general circulation of the atmosphere. They cover about 60% of the Earth's surface (Rossow and Schiffer, 1999; Vardavas and Taylor, 2011) and are the most important regulators of the Earth's climate. Only small changes in their properties, e.g. a few percent change in cloud cover, can overwhelm radiative effects associated with anthropogenic forcings arising from changes in greenhouse gases and aerosols. Models have shown that the Earth's climate is sensitive to cloud distributions and cloud radiative properties, which are highly variable, and that changes in these properties can significantly affect climate. Various cloud-climate feedbacks arising from cloud radiative forcing have been proposed (e.g. Hartmann, 1993; Stephens, 2005; IPCC, 2007; Shen et al., 2011).

In the last few decades advances in measurements related to the solar and thermal radiation budget and to cloud properties, mainly through observations from geo-synchronous and polar orbiting satellites, have greatly improved our knowledge of how clouds affect the Earth's radiation budget, especially at the top of atmosphere (TOA). The availability of validated models (Randles et al., 2013) and input data has resulted in a considerable improvement in the assessment of cloud radiative effects. However, despite these advances, cloud-climate feedbacks continue to represent the major source of uncertainty in

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climate change estimates (IPCC, 2007). The cloud radiative effect (CRE) can be obtained from numerical climate models that rely on approximations for cloud physical and radiative properties. However, these often result in inadequate representations of cloudiness (e.g. Fowler and Randall, 1994; Lin and Zhang, 2004; Chepfer et al., 2008) and hence CRE (e.g. Allan, 2011). On the other hand, detailed radiative transfer models (RTMs) that include satellite derived surface and atmospheric radiative properties offer a more reliable assessment of CRE. RTM based studies, despite differences in the computed radiative fluxes (e.g. Randles et al., 2013), are considered as more reliable tools for obtaining the global radiation budget (Raschke et al., 2012).

Many studies have obtained CREs on the global scale (e.g. Cess and Potter, 1988; Ramanathan et al., 1989; Gupta et al., 1993; Ridout and Osmond, 1996; Kiehl and Trenberth, 1997; Chen et al., 2000; Raschke et al., 2005; Wilber et al., 2006; Su et al., 2010; Oreopoulos and Rossow, 2011; Stackhouse et al., 2011) and others for specific regions (e.g. Rieland and Stuhlmann, 1993; Mace et al., 2006; Min et al., 2010; Du et al., 2011). The Mediterranean basin, being a semi-enclosed system, is ideal for monitoring and assessing climate change (Vardavas and Taylor, 2011) with strong indications of reductions in rainfall and increases in temperature (IPCC, 2007). Nevertheless, to date there has been no study to assess cloud radiative effects over the region. In fact, very few studies have been performed to estimate CREs for the Mediterranean region and these have been at local scales and for short periods (Galli et al., 2004; Pozo-Vázquez et al., 2004; Ebell et al., 2011; Chiacchio and Vitolo, 2012; Kelektsoglou et al., 2011). The present study provides for the first time an estimate of CREs over the whole Mediterranean basin (28.75°–48.75°N and 16.25°W–38.75°E) for the 24-year period from 1984 to 2007. The CRE computations are obtained with a detailed spectral RTM that has been applied in a series of SW and LW radiation budget studies (e.g. Hatzianastassiou et al., 2004, 2005, 2007; Fotiadi et al., 2005; Hatzidimitriou et al., 2004; Pavlakis et al., 2004) for the globe. The SW, LW and net all-wave CREs are computed at TOA, in the atmosphere and at the surface, and separately for low, middle and high-level clouds. The model CREs at TOA are evaluated against state-of-the-art Earth Radiation Budget Experiment (ERBE, Kiehl and Trenberth, 1997) and Clouds and Earth's Radiant Energy System (CERES, Loeb et al., 2005) satellite measurements. At the surface the model radiative fluxes are compared to station measurements from the reference networks of Global Energy Balance Archive (GEBA, Gilgen and Ohmura, 1999) and Baseline Surface Radiation Network (BSRN, Ohmura et al., 1998; McArthur, 2005).

In Section 2, a brief description of the radiative transfer model and its input data is given, while Section 3 presents the results of the evaluation of model computations (fluxes and CREs) against satellite and surface measurements. The spatial and temporal distribution of CREs is discussed in Section 4, with emphasis on SW, LW and net all-wave components, and conclusions are drawn in Section 5.

2. Model and input data

2.1. Model

Radiation fluxes were computed with a deterministic spectral radiative transfer model based on a detailed radiative–convective model developed for climate studies (Vardavas and Carver, 1984; Vardavas and Taylor, 2011). This model has been extensively used in computations of the Earth's shortwave (SW) and longwave (LW) radiation budgets at scales ranging from local/regional to global, and its full description can be found in the references given above and also in Vardavas and Taylor (2011), therefore only a brief description is provided here. The RTM computes spectrally the atmospheric shortwave (SW) and longwave (LW) radiation fluxes at the top of the atmosphere, at the Earth's surface and within the atmosphere on a $2.5° \times 2.5°$ grid with a temporal resolution of one month.

For shortwave radiation, the radiative transfer equations are solved for 118 separate wavelengths for the ultraviolet–visible–near infrared (UV–Vis–NIR) part of the spectrum (0.20–1 μm) and for 10 bands for the IR part (1–10 μm), using the modified delta-Eddington method of Joseph et al. (1976). The model takes into account Rayleigh scattering and absorption due to atmospheric gas molecules, (O_3, O_2, CO_2, H_2O, and CH_4) as well as the presence of aerosol particles. Surface topography is taken into account while surface reflectivity is computed for every pixel by considering four types of surface: land, ocean, snow and ice. Sea surface reflectivity is computed using Fresnel reflection, corrected for a non-smooth surface. A detailed description of the SW model, a validation at the surface against data from BSRN and GEBA as well as a validation at TOA against ERBE S4 scanner data, can be found in Hatzianastassiou et al. (2004) and Hatzianastassiou et al. (2005).

For longwave radiation the atmosphere is divided into layers of about 5 hPa thickness to ensure that the atmospheric layers are optically thin with respect to the Planck mean longwave opacity and simple transmission coefficients are used which depend on the amount of absorbing molecules in each layer. Expressions for the fluxes can be found in Hatzianastassiou et al. (1999), and a full presentation and discussion of the model in Pavlakis et al. (2004) and a validation of surface LW radiation against BSRN station measurements and TOA fluxes against ERBE S-10N data in Pavlakis et al. (2004), Hatzidimitriou et al. (2004) and Matsoukas et al. (2005). The sky is divided into clear and cloudy fractions. The cloudy fraction includes three non-overlapping layers of low, middle and high-level clouds.

2.2. Model input data

All of the cloud meteorological data were taken from the ISCCP-D2 data set, which supplies monthly means in 2.5-degree equal-angle grid-boxes for the period 1984–2007 (Rossow and Schiffer, 1999). The model input data include cloud cover fractions for low, middle, and high-level clouds (derived from 15 individual types for water and ice clouds), the corresponding cloud scattering/absorption optical depth, cloud-top pressure and temperature as well as cloud geometrical thickness. Surface data such as snow/ice cover and albedo were also taken from the ISCCP-D2 data set.

The O_3 column amount was taken from the Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS). Data for aerosol optical depth, single scattering albedo and asymmetry parameter were taken from MODIS (Moderate Resolution Imaging Spectroradiometer) and supplemented by GADS (Global Aerosol Data Set, Koepke et al.,