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Shortwave radiative forcing due to long-term changes of total ozone column over the Iberian Peninsula

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HIGHLIGHTS

- SW ozone RF from 1979 to 1981 to present-day period was $+0.14$ W m^{-2} on annual average.
- The visible spectral range represents about 79% of the SW ozone RF.
- The ozone forcing efficiency makes possible to derive future SW ozone RF values.

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ABSTRACT

This paper focuses on analyzing the shortwave (SW; 280–3000 nm) radiative forcing associated with changes in total ozone column (TOC) under cloud- and aerosol-free conditions over the Iberian Peninsula during the last three decades (1979–2012). For this goal, net solar irradiances at the tropopause are simulated by the LibRadtran radiative transfer code using as input TOC data from the ERA-Interim reanalysis. The results showed large inter-annual variability of the SW ozone RF values, e.g., the largest difference between two consecutive years is about 0.26 W m^{-2} between 1990 and 1991. The linear relationship between SW ozone RF and TOC changes allowed to determinate SW ozone efficiency (ozone forcing per unit of TOC) from the slope of the regression line (-0.011 W m^{-2} per Dobson Unit). From this efficiency and long-term projections of future TOC recovery, the estimation of the SW ozone RF for the period 2000–2100 was -0.34 W m^{-2} over the Iberian Peninsula. On the other hand, average conditions during three consecutive years (2010–2011–2012) were chosen to represent the present-day state. Hence, for the entire study region, the SW ozone RF from 1979 to 1981 to present-day period was $+0.14$ W m^{-2} on annual average, showing higher values for the Northerner than for the Southerner latitudes. The marked seasonal pattern of long-term ozone trends over northern midlatitudes observed by previous studies produces notable differences in the seasonal ozone RF, with the largest forcing values occurring in spring ($+0.26$ W m^{-2}). Summer months present an ozone RF of $+0.11$ W m^{-2}, while autumn and winter values are below 0.1 W m^{-2}. Finally, a detailed spectral analysis showed that the visible range (400–700 nm) represents about 79% of the SW ozone RF, followed by far by the ultraviolet range (280–400) with a relative contribution of 18%, and the infra-red interval with a low percentage of 3%.

1. Introduction

The stratospheric ozone layer plays a key role in atmospheric chemistry since it absorbs part of the solar shortwave (SW) radiation protecting life on the Earth's surface from the most energetic ultraviolet (UV) rays. Additionally, tropospheric ozone (air pollutant) acts as a major greenhouse gas by means of the absorption and emission of thermal longwave (LW) radiation. Thus, atmospheric ozone interacts with both SW and LW radiation affecting the radiative budget of the atmosphere (McFarlane, 2008). To quantify the impact of these interactions, the ozone radiative forcing (RF) is defined as the imbalance in net (down minus up) radiative flux at the tropopause resulting from the variations of the ozone concentration (Ramaswamy et al., 2001).

Variations in the total ozone column (TOC) have become an issue of major concern since the discovery of the springtime ozone hole over Antarctica (Farman et al., 1985). At northern mid-latitudes, it has been observed a statistically significant decline of TOC values from the late 1970s to the mid 1990s (e.g., Solomon, 1999; Staehelin et al., 2001; Harris et al., 2008) followed by a

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stabilization and an incipient recovery to present (e.g., Krzyscin et al., 2005; Weatherhead and Andersen, 2006). One of the reports of the World Meteorological Organization (WMO, 2011) stated that TOC for the period 2006–2008 was approximately 2.5% and 3.5% lower than pre-1980 values for 60°N–60°S and the globe, respectively. This TOC decrease has allowed that more solar radiation can penetrate to the surface/troposphere system giving a positive SW ozone RF, while the LW ozone RF is negative. In this sense, one of the reports of the Stratospheric Processes And their Role in Climate (SPARC CCMVal, 2010) estimated both SW and LW forcings due to TOC changes from 1970s to 2004 by means of 16 chemistry-climate model simulations. This report gave averaged global annual values of ozone RF between $+0.05$ and $+0.30$ W m^{-2} for SW range and between -0.45 and $+0.20$ W m^{-2} for LW range (see its Fig. 10.21). The wide range found for LW forcing values is related to their strong dependence on the altitude of the ozone changes (Wang et al., 1993; Schwarzkopf and Ramaswamy, 1993; Gauss et al., 2006). Thus, the LW ozone forcing will be much weaker if ozone changes take place in the middle than in the lower stratosphere due to the infrared opacity of the atmosphere between the mid-stratosphere and the tropopause. Therefore, accuracy knowledge of the ozone profile trends is needed to obtain reliable values of the LW ozone RF. In contrast, the SW ozone RF mainly depends on changes of the total ozone column (Forster and Shine, 1997; Forster, 1999) and, hence, can be directly evaluated from radiative transfer codes using as input either ground-based or satellite-derived TOC datasets.

The atmospheric ozone exhibits a selective absorption of SW radiation with a substantial attenuation of UV radiation in the Hartley and Hugging bands located between 195 and 350 nm (Iqbal, 1983). Additionally, the atmospheric ozone also presents two weak absorption bands in the visible (between 420 and 700 nm) and near infrared spectral regions (between 700 and 1048 nm), called Chappuis and Wulf bands, respectively (e.g., Minaev and Kozlo, 1997; Brion et al., 1998; Orphal, 2003). This partial absorption of the UV, visible and near-infrared solar radiation by atmospheric ozone is the main responsible for the thermal structure of the stratosphere (Zhong et al., 2008). However, the discussion of the SW ozone RF are generally focused on the ultraviolet spectral region since UV radiation changes may force variations in the tropospheric and stratospheric dynamics (e.g. planetary wave propagation) affecting the Arctic Oscillation pattern (e.g., Shindell et al., 2001), and in the tropospheric chemistry (e.g., decrease in the CH_4 and CO growth rates due to changes in concentrations of the hydroxyl radical) affecting the balance of solar radiation absorption in the troposphere (e.g., Bekki et al., 1994; Tourpali et al., 2003). To our knowledge, no paper analyzes in detail the contribution of each spectral range to the whole solar shortwave spectrum.

In this framework, this paper focuses on the analysis of the SW RF associated with TOC changes under cloud- and aerosol-free conditions from the late 1970s to 2012 at the Iberian Peninsula. The contribution of each spectral region (i.e., UV, visible and near-infrared) to the SW ozone RF besides its seasonal behavior is studied in detail. Additionally, the ozone forcing efficiency (i.e., SW ozone RF per unit of TOC) is also quantified in order to project future values of the SW ozone RF over the study region. For all these goals, TOC values from the ERA-Interim reanalysis for the period 1979–2012 are used as input in a radiative transfer code.

The paper is organized as follows. Section 2 describes the TOC data used in this work. Section 3 introduces the methodology employed to obtain the SW ozone RF. Results and discussion are presented in Section 4. Finally, Section 5 summarizes the main conclusions of the work.

2. Total ozone data

TOC data over the Iberian Peninsula were inferred from the ERA-Interim reanalysis (Simmons et al., 2007; Dee and Uppala, 2009) which is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). This global atmospheric reanalysis covers the period from 1979 to present on a resolution of 1.5° × 1.5°. A great variety of TOC data from satellite instruments are assimilated in ERA-Interim: Solar Backscatter Ultraviolet Radiometer, SBUV (McPeters et al., 2013), Ozone Monitoring Instrument, OMI (Levelt et al., 2006), Total Ozone Mapping Spectrometer, TOMS (Antón et al., 2010), Global Ozone Monitoring Experiment, GOME (Loyola et al., 2011), Michelson Interferometer for Passive Atmospheric Sounding, MIPAS (Fischer and Oelhaf, 1996), Microwave Limb Sounder, MLS (Waters et al., 2006) and Scanning Imaging Absorption Spectrometer for Atmospheric Chartography, SCIAMACHY (Bovensmann et al., 1999). Dee et al. (2011) (see their Fig. 15) show the timeline of all ozone instruments assimilated in ERA-Interim.The quality of the ERA-Interim TOC data was proved by previous studies. For instance, Dragani (2011) found differences between reanalysis and satellite-reference data within ±5 Dobson Units, DU (<2%). TOC 6-h data were downloaded from the ECMWF data server and daily averaged afterward for the Iberian Peninsula with spatial coverage 34.5° N–45° N/10.5° W–4.5° E latitude/longitude (88 grid points).

3. Method

SW RF at the tropopause due to changes in total ozone column from a reference period (generally in the later 1970s and early 1980s) to a particular subsequent period is defined as

$$\mathrm{RF} = I - I_{\mathrm{ref}} \tag{1}$$

where I_{ref} and I are the net (down minus up) solar irradiances at the tropopause averaged for the reference and particular subsequent period, respectively, assuming all atmospheric constituents invariable except the total ozone column. In this work, the SW ozone RF is obtained for cloud- and aerosol-free conditions and for a 30-yr period (1982–2012), using the average of three years (1979–1981) as the background state. The choice of the reference period is a crucial decision in the analysis of the ozone RF. Thus, in order to avoid possible atypical high or low TOC values during a particular year, we have decided to work with the average of those three years as reference period. Additionally, it can be assumed that the ozone layer during this period was weakly affected by chlorofluorocarbons (CFCs) and other ozone depleting substances.

The ozone RF can be estimated by above expression following the definition given by Ramaswamy et al. (2001) which allows the stratospheric temperature to readjust to equilibrium following radiative perturbation. Moreover, an “instantaneous” ozone RF can be also derived from Equation (1) using simulated solar irradiances without stratospheric temperature adjustment. Aghedo et al. (2011) showed that the total (SW plus LW) ozone RF could be overestimated by up 20% when the stratospheric temperature adjustment is not taken into account. Nevertheless, according to Forster and Shine (1997), the SW component of the ozone RF varies less than 1% by a stratospheric temperature change, so it was decided in this work to perform the radiative simulations without stratospheric adjustment.

The downwelling and the upwelling solar irradiances at the tropopause were simulated by means of the UVSPEC model included in LibRadtran software package (1.6-beta version) developed by Mayer and Kylling (2005). The solar irradiances were retrieved in the UV-B (280–320 nm), UV-A (320–400 nm), visible