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Research Paper

A comparison of stratospheric photochemical response to different reconstructions of solar ultraviolet radiative variability

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ABSTRACT

We present calculations of stratospheric chemical abundances variations between different levels of solar activity using a simple photochemistry model in transient chemistry mode. Different models for the reconstruction of the solar spectrum, as well as observations from the SOLar STellar Irradiance Comparison Experiment (SOLSTICE) and Spectral Irradiance Monitor (SIM) on the SOlar Radiation and Climate Experiment (SORCE) satellite, are used as inputs to the calculations. We put the emphasis on the MOnte CArlo Spectral Solar Irradiance Model (MOCASSIM) reconstructions, which cover the spectral interval from 150 to 400 nm and extend from 1610 to present. We compare our results with those obtained with the Naval Research Laboratory Solar Spectral Irradiance (NRLSSI) model as well as with the Magnesium-Neutron Monitor (MGNM) model over a period of time spanning the ascending phase of Cycle 22. We also perform the calculations using SORCE composite spectra for the descending phase of Cycle 23 and with the reconstructed MOCASSIM, NRLSSI and MGNM spectra for the same period for comparison. Finally, we compare the chemical abundances obtained for the Maunder Minimum with those obtained for the Cycle 23 minimum (in March 2009) and find that stratospheric ozone concentration was slightly higher during the recent minimum, consequent to the small positive variability between the MOCASSIM spectra for both epochs, especially below 260 nm. We find that the response in stratospheric ozone is not only dependent on the variability amplitude in the solar spectrum (especially in the 200–240 nm band), but also significantly on the base level of the minimum solar spectrum.

1. Introduction

The total solar irradiance variability is well known since the satellite measurements of the solar constant became available (Fröhlich and Lean, 2004). Even if it only accounts for a small fraction of the energy output, the ultraviolet (UV) part of the spectrum accounts for about 15% of this variability (Lean, 1997). Since the Sun is responsible for essentially all the energy input on Earth, it is reasonable to suppose that its variability might influence the Earth's atmosphere. The direct contribution of solar radiative variability to recent tropospheric global warming is quite certainly negligible (Forster et al., 2007), especially in comparison with anthropogenic forcing, but the Sun may have been a cause of past climate changes. A good example is the coincidence between the Maunder Minimum, a period of drastically reduced solar activity between 1645 and 1715, and the Little Ice Age, when the temperatures were notably lower in the Northern Hemisphere. Despite this surprising coincidence, the Sun's influence on surface temperatures is not well understood, even though it is generally accepted that stratospheric temperatures and dynamics, as well as patterns of oscillations and circulation in the troposphere, are coupled with the solar cycle (Gray et al., 2010). The evidences for an influence on atmosphere dynamics and chemistry are numerous, especially in the stratosphere, where the solar UV radiation is mostly absorbed by the ozone layer, increasing the solar heating and photolysis rates during the solar maximum.

An important part of the ozone formation–destruction is described by the Chapman cycle, which involves photons with $\lambda < 300$ nm and $\lambda < 240$ nm in the photolysis of O_3 and O_2 respectively:

$$O_2 + h\nu \rightarrow O + O \quad (\lambda < 240\text{ nm}) \tag{1}$$

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$$O + O_2 + M \rightarrow O_3 + M \quad (2)$$

$$O_3 + h\nu \rightarrow O_2 + O(^1D) \quad (\lambda < 300\ \text{nm}) \quad (3)$$

$$O(^1D) + M \rightarrow O + M \quad (4)$$

$$\text{Net:}\ O_3 + h\nu \rightarrow O_2 + O$$

(Eqs. (R1)–(R3), Jacob, 1999). Here the third body M is any inert molecule that can remove the excess energy from the reaction and dissipate it as heat. For instance, we expect that a wavelength-dependent increase in solar irradiance, with higher variability at shorter wavelengths, should lead to an increase in O_3 production through an increased photolysis of O_2. In addition to reactions (1)–(4), the chemical destruction of stratospheric ozone also depends on the details of the spectral irradiance through additional photolysis reactions, such as, for example, the catalytic loss of ozone through catalytic destruction by the radical family HO_x. This process converts three molecules of ozone into two molecules of O_2. The H, OH and HO_2 radicals are referred to as the HO_x family.

The stratospheric response in ozone concentration and distribution to solar variability has been studied using numerical models of various complexity and different representations of solar variability (e.g. Fleming et al., 1995; Egorova et al., 2004; Gruzdev et al., 2009; Haigh et al., 2010; Kubin et al., 2011; Merkel et al., 2011; Swartz et al., 2012; Shapiro et al., 2013). Globally, all models show a positive variation at higher solar irradiance in ozone concentrations in the middle stratosphere, which decreases with altitude and typically becomes negative in the lower mesosphere. The amplitude of this ozone variation however depends on the model and solar variability representation used. For instance, Haigh et al. (2010) compared the ozone variation resulting from the data from the Spectral Irradiance Monitor (SIM) and SOLar STellar Irradiance Comparison Experiment (SOLSTICE) on board the SOlar Radiation and Climate Experiment (SORCE) satellite (Harder et al., 2009), with that of the Naval Research Laboratory Solar Spectral Irradiance (NRLSSI) model (Lean, 2000). The ultraviolet irradiance show a variability 4–6 times higher in SORCE measurements than in NRLSSI. This results in a positive ozone response almost 3 times stronger in the middle stratosphere and an inversion of the response at and above the stratopause when using SORCE data.

Recent studies using Chemistry-Climate Models (CCMs) found globally consistent results when using SORCE data (Merkel et al., 2011; Swartz et al., 2012; Shapiro et al., 2013). However, the inherently high complexity of CCMs makes it difficult to single out individual processes and to intercompare ozone responses when different CCMs are involved. For instance, Shapiro et al. (2013) applied in addition a 1D radiative–convective model with interactive photochemistry to identify regions of the atmosphere that are particularly sensitive to the representation of SSI used. Swartz et al. (2012) applied a 2D coupled model to examine how direct radiative and photochemical responses separately contribute to the response.

The present paper focuses on the effect of solar variability on photochemistry alone in the stratosphere. Indeed, photochemistry and radiation are the drivers of the stratospheric response to solar irradiance variation. They are also well-constrained processes that should provide a good level of intercomparability across various models. Furthermore, they allow us to easily dissect various spectral contributions and identify individual processes. This makes simple photochemistry models excellent candidates for studying and intercomparing the stratospheric responses to different representations of the solar irradiance variability.

Here, we use the photochemical equatorial column model detailed in Muncaster et al. (2012) to evaluate the change in chemical families between two levels of solar activity, being either a minimum and a maximum of a given cycle, or two important minima. To do so, we use different representations of the solar spectrum during these time periods, obtained with different reconstructions and with the SOLSTICE and SIM instruments onboard SORCE. Our objective is to quantify the difference in the ozone response due to the differences between those reconstructed spectra and to assess the importance of precise measurements and modelling of the solar spectrum.

We extracted each reconstruction's fractional variability and multiplied it with a spectrum observed at low activity on November 11, 1993: ATLAS-3 (Thuillier et al., 2003), in order to isolate the effects of solar variability only and to avoid those related with the absolute calibration of the spectra. The next section presents an overview of the model used for solar spectral irradiance reconstructions, the MOnte CArlo Spectral Solar Irradiance Model (MOCASSIM; Bolduc et al., 2012, 2014). Section 3 introduces two other spectral solar irradiance models and observations used for the stratospheric photochemistry simulations. Section 4 describes the photochemistry model used to perform the chemical species abundances calculations. Section 5.1 presents results for the ascending phase of Cycle 22 and descending phase of Cycle 23, obtained with the Naval Research Laboratory Spectral Solar Irradiance (NRLSSI) model, the MaGnesium–Neutron Monitor (MGNM) model, the MOCASSIM model and the SORCE spectra (Cycle 23 only). Section 5.2 compares the ozone concentration during minimum activity using the original reconstructed spectra from each model and the ATLAS-3 spectrum to illustrate the effect of absolute calibration. Finally, we present a comparison between the Cycle 23 minimum and the Maunder Minimum using MOCASSIM in Section 5.3.

2. The MOCASSIM model

MOCASSIM is described in detail in Bolduc et al. (2012, 2014). It is an adapted version of the total solar irradiance (TSI) model proposed by Crouch et al. (2008), which is based on data-driven Monte Carlo simulation of sunspots emergence, fragmentation and erosion. The resulting time-evolving area distribution of magnetic structures is used as input for a four-component model for SSI, including spots, faculae, network, and quiet Sun. More specifically, the SSI is calculated by adding the wavelength-dependent contribution from the spots, faculae and network to a quiet Sun baseline. This baseline was initially represented by a synthetic, non-magnetic spectrum (Kurucz, 1991), but the departure from the observed solar spectrum below $\lambda = 200$ nm motivated the change to an observed spectrum, ATLAS-3 (Thuillier et al., 2003), obtained during a period of low activity.

For a given wavelength, the ATLAS-3 flux is read (or interpolated if the wavelength does not fall exactly on ATLAS-3 wavelength grid). Then the spots' contrast with respect to the quiet Sun is estimated by the monochromatic flux ratio from a Kurucz's synthetic spectrum with $T_{\text{eff}} = 5250$ K and with $T_{\text{eff}} = 5750$ K, the first being roughly the average temperature of a spot and the second representing the quiet Sun. The Kurucz's spectrum is sufficiently accurate to estimate the spots' contrast even at shorter wavelengths because it is negligible compared to the facular brightening. The spots' contribution to the irradiance is calculated by multiplying their contrast by their total area as given by the fragmentation/erosion Monte Carlo simulation mentioned above. The contribution from the faculae is estimated similarly, with the exception that their contrast is calculated with the simple black-body inversion procedure described in Solanki and Unruh (1998). As for the network contribution, it is simulated stochastically by drawing a random number every day, distributed as