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Research Paper

Evaluation of the inter-annual variability of stratospheric chemical composition in chemistry-climate models using ground-based multi species time series

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ABSTRACT

The variability of stratospheric chemical composition occurs on a broad spectrum of timescales, ranging from day to decades. A large part of the variability appears to be driven by external forcings such as volcanic aerosols, solar activity, halogen loading, levels of greenhouse gases (GHG), and modes of climate variability (quasi-biennial oscillation (QBO), El Niño-Southern Oscillation (ENSO)). We estimate the contributions of different external forcings to the interannual variability of stratospheric chemical composition and evaluate how well 3-D chemistry-climate models (CCMs) can reproduce the observed response-forcing relationships. We carry out multivariate regression analyses on long time series of observed and simulated time series of several traces gases in order to estimate the contributions of individual forcings and unforced variability to their internannual variability. The observations are typically decadal time series of ground-based data from the international Network for the Detection of Atmospheric Composition Change (NDACC) and the CCM simulations are taken from the CCMVal-2 REF-B1 simulations database. The chemical species considered are column O_3, HCl, NO_2, and N_2O. We check the consistency between observations and model simulations in terms of the forced and internal components of the total interannual variability (externally forced variability and internal variability) and identify the driving factors in the interannual variations of stratospheric chemical composition over NDACC measurement sites. Overall, there is a reasonably good agreement between regression results from models and observations regarding the externally forced interannual variability. A much larger fraction of the observed and modelled interannual variability is explained by external forcings in the tropics than in the extratropics, notably in polar regions. CCMs are able to reproduce the amplitudes of responses in chemical composition to specific external forcings. However, CCMs tend to underestimate very substantially the internal variability and hence the total interannual variability for almost all species considered. This lack of internal variability in CCMs might partly originate from the surface forcing of these CCMs by analysed SSTs. The results illustrate the potential of NDACC ground-based observations for evaluating CCMs.

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1. Introduction

The variability of stratospheric chemical composition occurs on a broad spectrum of time scales, ranging from hours to decades. Some of this variability involves couplings between chemistry and dynamics and, more generally, chemistry-climate interactions and is driven by external forcings (e.g. volcanic aerosols, solar activity, halogen loading (e.g. CFCs and halons), levels of greenhouse gases (GHG)) and modes of climate variability (e.g. QBO, ENSO). These forcings are thought to be responsible for most of the interannual variability in stratospheric chemical composition. Many observational studies have attempted to link variations in stratospheric chemical composition, in particular ozone, to these forcings. Although several studies have considered vertically resolved ozone datasets (e.g. Zawodny and McCormick, 1991; Brunner et al., 2006; Randel and Anne, 2011), the most commonly analysed datasets are satellite column ozone data. Studies of global satellite data records such as TOMS (Total Ozone Mapping Spectrometer) or SAGE (Stratospheric Aerosol and Gas Experiment) have documented the impact of the QBO on column ozone (Bowman, 1989; Zawodny and McCormick, 1991; Randel and Janel, 1994; Yang and Tung, 1994; Baldwin et al., 2001; Randel and Fei, 2007). Tropical column ozone variations were found to be approximately in phase with equatorial zonal wind near 30 hPa, an indicator of the QBO, whereas the extra-tropical column ozone anomalies tended to be out of phase with the tropical signal. Linear regressions showed that the mean amplitude of the QBO signal is about 2–4% of the mean column ozone (WMO, 1999). The ENSO is also known to influence column ozone (Shiotani, 1992; Randel and Janel, 1994; Steinbrecht et al., 2006). However, unlike the QBO, the effects of ENSO on column ozone are mostly visible in the zonal distribution. Another significant source of variability in ozone is the variations in stratospheric aerosol loading which are predominantly controlled by volcanic eruptions (Thomason et al., 1997; McCormack et al., 1997; Vernier et al., 2011). The strongest global ozone anomaly was observed just after the volcanic eruption of Mount Pinatubo in 1991 with a decrease of about 3–4% over a 2-year period following the eruption (Randel et al., 1995); larger decreases in column ozone, of order 5–10%, were observed locally in northern hemisphere middle and high latitudes (Bojkov et al., 1993; Randel et al., 1995; Coffey, 1996; Zerefos et al., 1997; Robock, 2000). Studies of ground-based ozone records extending over three decades have indicated the existence of a decadal variation in column ozone that is approximately in phase with the solar cycle (Angell, 1988; Zerefos et al., 1997; Austin et al., 2008). This is supported by analyses of global satellite ozone records since 1979 showing evidence for a decadal oscillation of column ozone with maximum amplitude ($\sim$2–4%) at low latitudes (Chandra and McPeters, 1994; McCormack et al., 1997; Hood, 1997; WMO, 2007; Randel and Fei, 2007). As noted by Solomon et al. (1996), the occurrence of two major volcanic eruptions nine years apart during each of the last two declining phases in solar activity could lead to some confusion in separating volcanic and solar effects on ozone. This should not strongly influence trend estimates for the long time records, but may have implications for isolation of the solar cycle in short observational records. Chandra (1991) also showed the possible importance of the phase of the QBO in the ozone response to solar variability.

The effects of forcings on the stratospheric variability of other chemical species have also been studied. Although the main focus was on the trends, other components of the variability were also analysed in some of these observational studies. For example, variations in NO_2 column have already been decomposed and attributed to a range of forcings (QBO, ENSO, aerosols and solar activity) (Zawodny and McCormick, 1991; Liley et al., 2000; Struthers et al., 2004; Gruzdev, 2008; Cook and Roscoe, 2009; Dirksen et al., 2011).

The links between stratospheric chemical composition and forcings have also been investigated using coupled chemistry-climate models (CCMs) (e.g. WMO, 2003). Obviously, the ability of a model to reproduce theses links depends on its ability to simulate correctly the processes involved in the relationship between forcing and response. For example, the effects of solar variability on stratospheric composition involve photochemical processes such as the photolysis of molecular oxygen, radiative heating and the associated dynamical response (Wohltmann et al., 2007; Gray et al., 2010). Also, the effects of varying stratospheric aerosol loading involve heterogeneous chemical processes and radiative heating (Robock, 2000; Wohltmann et al., 2007).

Within the framework of the international CCMVal/SPARC (Chemistry-Climate Model Validation activity/Stratospheric Processes And their Role in Climate) programme, state-of-the-art CCMs forced by natural and anthropogenic external forcings have been used to simulate past changes in stratospheric chemical composition. Ozone CCM simulations have been evaluated against a range of satellite observations with respect to climatologies (i.e. zonal mean distribution) and long-term trends (Eyring et al., 2006; CCMVal et al., 2010). Model-calculated column ozone responses to external forcing were also evaluated using multi linear regression analysis (Austin et al., 2008; CCMVal et al., 2010;). The evaluation was mostly carried out over large latitudinal bands representative of the tropics, mid-latitudes and polar regions. Regarding the QBO, models with forced or internally generated QBO were generally able to reproduce the latitudinal variations of the QBO signal in column ozone. Nonetheless, CCMs forced with observed QBO tended to overestimate the amplitude of the column ozone response. Some of the models with internally generated QBO had problems reproducing the periodicity of the QBO and hence of the QBO-induced ozone signal (CCMVal et al., 2010). For the ENSO, the column ozone signal was comparable in most CCMs but could not be assessed against observations because of the large interannual variability and the weakness of the ozone column signal in observations (CCMVal et al., 2010). Regarding the aerosol loading, CCMs showed a considerable spread in their response to volcanic eruptions although most models were forced by a common dataset for the time-varying stratospheric aerosol surface area density (SAD) distribution. The models displayed differing degrees of sensitivity to aerosol levels, leading to different ozone losses. None of the models reproduced the observed hemispheric asymmetry in post-Pinatubo ozone losses, for either full hemispheric means or for mid-latitudes (CCMVal et al., 2010). Finally, regarding solar variability, the column ozone signal was reasonably well represented in models. Most CCMs reproduced 70–80% of the observed solar signal in global column ozone (averaged between 60°S and 60°N) (CCMVal et al., 2010). However, the vertical structure of the tropical solar signal in ozone did not seem to be correctly reproduced in models (Austin et al., 2008).

The purpose of the present study is to assess how well CCMs are able to reproduce the effects of specific forcings on stratospheric chemical composition at NDAAC (Network for the Detection of Atmospheric Composition Change, http://www.ndsc.ncep.noaa.gov/) measurement sites. The model performance in simulating the links between forcings and stratospheric composition is critical for the level of confidence in future model projections. Although the CCMVal programme (Eyring et al., 2006, CCMVal et al., 2010) did assess the performances of the models with respect to a range of chemical species, the evaluation was carried out with zonal mean data and the focus was on long-term trends and on the effects of external forcing on stratospheric ozone. Here, instead of using composite satellite data and a zonal mean representation, the evaluation uses long time series of quality-controlled ground-based observations from the NDACC. An evaluation